NATIONAL ENERGY TECHNOLOGY LABORATORY

TECHNO-ECONOMIC ANALYSIS OF NATURAL GAS FUEL CELL PLANT CONFIGURATIONS

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Disclaimer

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TABLE OF CONTENTS

LIST OF EXHIBITS

ACRONYMS AND ABBREVIATIONS

AC	Alternating current
Aspen	Aspen Plus®
ASR	Area specific resistance
ASU	Air separation unit
atm, Atm.	Atmospheres
Atmos.	Atmospheric
ATR	Auto-thermal reformer
BB	Bituminous Baseline
BOP	Balance of plant
Btu	British thermal unit
Btu/h	British thermal unit per hour
Btu/kWh	British thermal unit per kilowatt hour
Btu/lb	British thermal unit per pound
Btu/scf	British thermal unit per standard cubic foot
C	Cost of equipment in plant section
CCS	Carbon capture and sequestration
CF	Capacity factor
CH_4	Methane
cm	Centimeter
CO	Carbon monoxide
CO_2	Carbon dioxide
COE	Cost of electricity
CPU	CO_2 purification unit
C_{ref}	Cost of equipment in reference plant area or section
CRT	Cathode ray tube
DC	Direct current
DCS	Distributed control system
DG	Distributed generation
DGFC	Distributed generation fuel cell
DOE	Department of Energy
E	Stack inlet gas Nernst potential
EOR	Enhanced oil recovery
EPC	Engineer/procure/construct
Excl.	Excluding
Ext.	External
F_{ref}	Capacity of reference plant area or section
ft	Foot, feet
gpm	Gallons per minute
GW	Gigawatt
h/hr	Hour
H_2	Hydrogen
H_2O	Water
HHV	Higher heating value
HP	High pressure
HRSG	Heat recovery steam generator
HX, HTX	Heat exchanger
I&C	Instrumentation and control
IG	Integrated gasification
IGCC	Integrated gasification combined cycle
IGFC	Integrated gasification fuel cell
in	Inch
Int.	Internal
IP	Intermediate pressure
IR	Internal reformation
ISO	International Standards Organization
kg/GJ	Kilogram per gigajoule
kg/h	Kilogram per hour
kJ	Kilojoules
kJ/h	Kilojoules per hour
kJ/kg	Kilojoules per kilogram
kW	Kilowatt
kWe	Kilowatts electric
kWh	Kilowatt-hour
lb	Pound
lb/h	Pounds per hour
lb/MWh	Pounds per megawatt hour
LCOE	Levelized cost of electricity
LHV	Lower heating value
LP	Low pressure
m	Meters
mA	Milliamperes
m^3/min	Cubic meter per minute
mA/cm^2	Current density
MJ/scm	Megajoule per standard cubic meter
mm	Millimeter
MMBtu	Million British thermal units (also shown as 10^6 Btu)

MMBtu/h	Million British thermal units (also shown as 10^6 Btu) per hour
MMkJ	Million kilojoules (also shown as 10^6 kJ)
MMkJ/h	Million kilojoules (also shown as 10^6 kJ) per hour
mol%	Composition bases on molar percentage of constituents
MP	Multi-physics
MPa	Megapascals
MU	Make up
mW	Milliwatt
MW, MWe, Mwe	Megawatt electric
mW/cm^2	Power density
MWh	Megawatt-hour
N	Number of study plant areas or sections in parallel
N/A	Not applicable
N_{ref}	Number of reference plant areas or sections in parallel
NETL	National Energy Technology Laboratory
NG	Natural gas
NGCC	Natural gas combined cycle
NGFC	Natural gas fuel cell
NGIN	Natural gas inlet
NOAK	Nth of a kind
NOx	Oxides of nitrogen
O&M	Operation and maintenance
O_2	Oxygen
OP	Overpotential of cell
OTC	Oxygen to carbon
PC	Pulverized coal
PNNL	Pacific Northwest National Laboratory
ppb	Part per billion
ppbv	Part per billion
ppmv	Parts per million volume
Press.	Pressurized
psia	Pounds per square inch absolute
psig	Pounds per square inch gauge
QGESS	Quality Guidelines for Energy System Studies
R&D	Research and development
Ref.	Reformation
ROM	Reduced order model
S	Scaling factor for plant areas or section cost
SC	Supercritical
sCO_2	Supercritical CO_2
SOA	State of the art
SOFC	Solid oxide fuel cell
T	Temperature
T&S	Transport and storage
TASC	Total as spent cost
TDA	TDA Research Inc.
TOC	Total overnight cost
tonne	Metric ton (1000 kg)
TPC	Total plant cost
TRL	Technology Readiness Level
U_F	Fuel utilization
V	Potential of cell
V-I	Voltage-current
VGR	Vent gas recirculation
vol%	Volume percent
$/MMBtu	Dollars per million British thermal units
$/MWh	Dollars per megawatt hour
U.S.	United States
y/yr	Year
WT	Water treatment
°C	Degrees Celsius
°F	Degrees Fahrenheit

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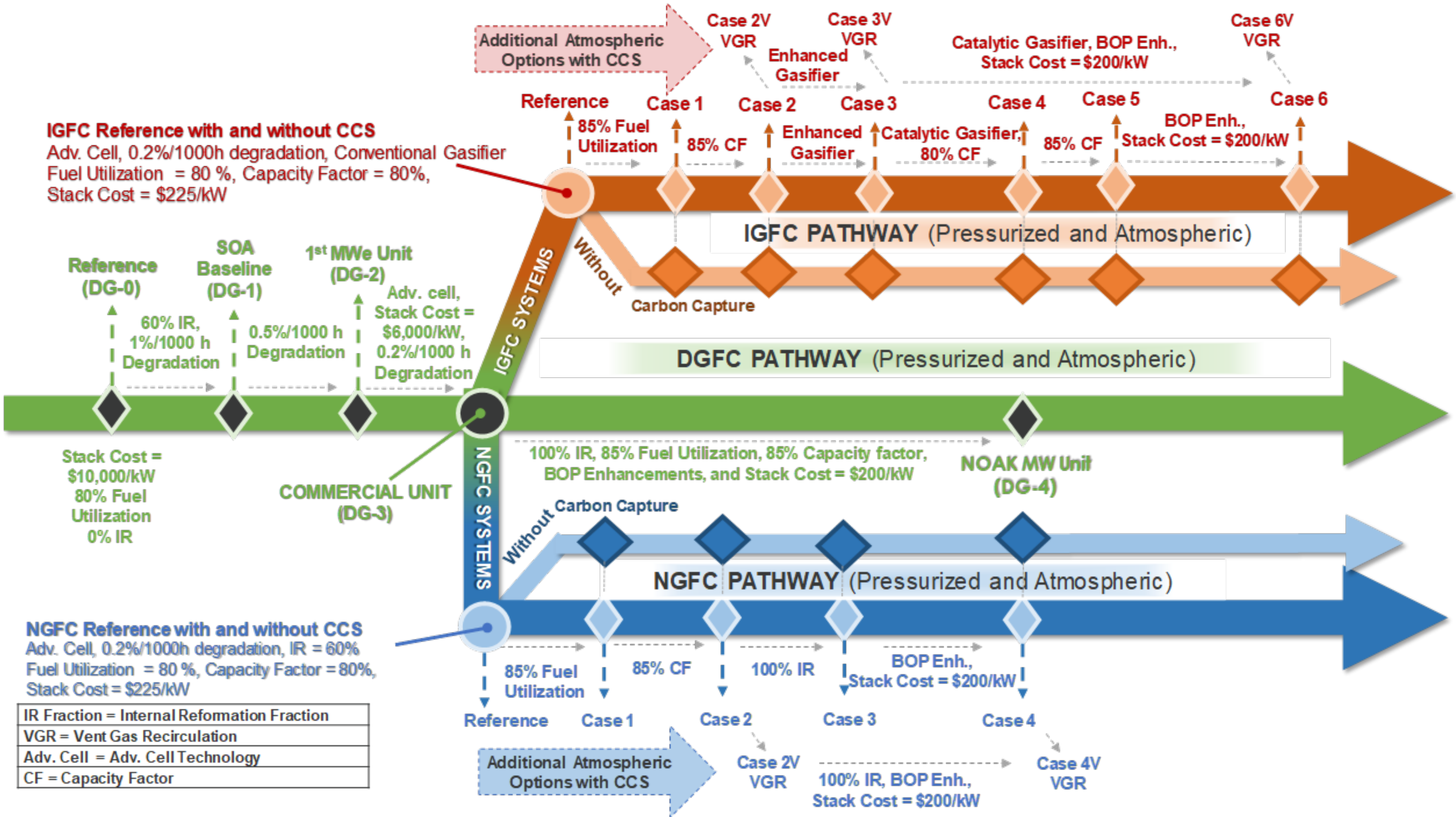
EXECUTIVE SUMMARY

The United States (U.S.) Department of Energy (DOE) Office of Fossil Energy and Carbon Management (FECM) and the National Energy Technology Laboratory (NETL) have been pursuing the development of solid oxide fuel cell (SOFC) technology to enable future power generation systems that are consistent with the cornerstones of the DOE mission—to ensure America's security and prosperity by addressing its energy and environmental challenges through transformative science and technology solutions. The U.S. DOE FECM SOFC Program is currently focused on the development of low-cost, highly efficient, and reliable SOFC power systems. NETL's SOFC technology development roadmap is aligned with near-term market opportunities in the distributed generation sector to validate and advance the technology while paving the way for utility-scale (> 50 MW) natural gas and coal-derived synthesis gas-fueled applications via progressively larger system demonstrations. The present study represents a part of a series of system evaluations being developed at NETL to aid in prioritizing technological advances along research pathways to the realization of utility-scale SOFC systems, a transformational goal of the fuel cell program. In particular, the system performance of utility-scale natural gas fuel cell (NGFC) systems with and without carbon dioxide (CO_2) capture is presented. The objective of the study is to provide targeted research and development (R&D) guidance to the FECM SOFC Program and SOFC commercial developers to accelerate technology deployment.

The implemented fuel cell technology is assumed to be a planar cell configuration with separated anode and cathode off-gas streams for this study. The overall framework for the SOFC system R&D pathway considered in this study is depicted in Exhibit ES-1, which considers anticipated improvements in SOFC electrochemical performance and system configuration supported by the SOFC technology development roadmap, combined with concomitant advances in plant operation and maintenance (O&M) and component technologies. With a commercially viable small-scale (≈1 MWe) distributed generation fuel cell (DGFC) system as a basis, the development of utility-scale systems is envisioned to proceed along two parallel pathways based on the fuel feedstock. The NGFC pathway is based on development of natural gas based SOFC systems while the integrated gasification fuel cell (IGFC) relies on synthesis gas (syngas) generated via coal gasification. This report describes the results of the NGFC pathway exclusively. The DGFC and IGFC pathways are described in separate NETL technical reports.

Two parallel developmental scenarios—one with the SOFC operating at atmospheric pressure and one based on pressurized SOFC operation—were considered as part of the NGFC development pathway. An SOFC operating pressure of three atmospheres was assumed based on previous studies, which found insignificant cost benefits for pressures higher than three atmospheres, and pressurized SOFC systems that have been generally proposed and operated by commercial vendors.

Exhibit ES-1. Solid Oxide Fuel Cells Pathway Studies



IR Fraction = Internal Reformation Fraction	
VGR = Vent Gas Recirculation	
Adv. Cell = Adv. Cell Technology	
CF = Capacity Factor	

The SOFC technology and system characteristics, listed in Exhibit ES-2, of the established commercial DGFC unit (as shown in the DGFC developmental roadmap in Exhibit ES-1) was assumed as the basis for the reference NGFC system.

Exhibit ES-2. Reference NGFC System Characteristics

SOFC Parameters	Values
SOFC Performance	Advanced Cell – 50% reduction in ohmic and polarization losses relative to the state-of-the-art technology (SOA)
Degradation Rate	0.2% per 1000 h
System Fuel Utilization	80%
Stack Cost	$225/kWe
Internal Reformation	60%
Capacity Factor	85%
Inverter Efficiency	97%

The specific NGFC pathway cases analyzed in this study are listed in Exhibit ES-3 and Exhibit ES-4 for systems without and with carbon capture and sequestration (CCS), respectively. Case 1 represents an increase in fuel utilization from 80 percent to 85 percent based on the confidence gained from DGFC systems. Enhanced reliability of balance-of-plant (BOP) components combined with optimized O&M is reflected by an increase in capacity factor to 85 percent in Case 2. Realization of complete internal reformation technology is assumed in Case 3 while Case 4 considers potential enhancements in air separation unit (ASU) technology and inverter technology, along with a reduction in stack cost to $200/kW. In the case of systems with CCS, an attractive high-efficiency vent gas recirculation (VGR) configuration, which enables fuel utilization values >95 percent is also explored with systems described by Cases 2 and 4.

An SOFC Reduced Order Model (ROM) developed by the Pacific Northwest National Laboratory (PNNL) in collaboration with NETL was used to estimate the SOFC performance. The ROM, while being computationally effective for system studies, provides detailed information about the state of the stack, such as the internal temperature gradient, generally not available from simple performance models often used to represent the SOFC. Such information can be important in system optimization studies to preclude operation under off-design conditions that can adversely impact overall system reliability.

The design and cost bases for this pathway study closely follow the bases applied in the NETL Bituminous Baseline (BB) report so that direct performance and cost comparisons can be made with the conventional fossil-fuel power plant results estimated in that report. [1]

The results of the pathway studies, summarized in Exhibit ES-5 through Exhibit ES-8, represent the potential future benefits of NGFC technology development.

Exhibit ES-3. NGFC Pathway Cases without CCS

<table>
<tr><th>Case Designation</th><th>Pathway Parameter</th><th>Case ID</th><th>SOFC Pressure (atm)</th><th>Internal Reformation (%)</th><th>SOFC Technology</th><th>Capacity Factor (%)</th><th>Degradation (%/1000 h)</th><th>Fuel Utilization (%)</th><th>Inverter Efficiency</th><th>Stack Cost ($/kW)</th></tr>
<tr><td rowspan="2">Reference (Case 0)</td><td rowspan="2">Reference Without CCS</td><td>ANGFC0A</td><td>1</td><td rowspan="6">60</td><td rowspan="10">Advanced Cell</td><td rowspan="4">80</td><td rowspan="10">0.2</td><td rowspan="2">80%</td><td rowspan="8">97%</td><td rowspan="8">225</td></tr>
<tr><td>PNGFC0A</td><td>3</td></tr>
<tr><td rowspan="2">Case 1</td><td rowspan="2">85% Fuel Utilization</td><td>ANGFC1A</td><td>1</td><td rowspan="8">85%</td></tr>
<tr><td>PNGFC1A</td><td>3</td></tr>
<tr><td rowspan="2">Case 2</td><td rowspan="2">85% Capacity Factor</td><td>ANGFC2A</td><td>1</td><td rowspan="6">85</td></tr>
<tr><td>PNGFC2A</td><td>3</td></tr>
<tr><td rowspan="2">Case 3</td><td rowspan="2">100% Internal Reformation</td><td>ANGFC3A</td><td>1</td><td rowspan="4">100</td></tr>
<tr><td>PNGFC3A</td><td>3</td></tr>
<tr><td rowspan="2">Case 4</td><td rowspan="2">BOP Enhancements
20% ASU Power Reduction, Inverter Efficiency 98%, Stack Cost Reduction</td><td>ANGFC4A</td><td>1</td><td rowspan="2">98%</td><td rowspan="2">200</td></tr>
<tr><td>PNGFC4A</td><td>3</td></tr>
</table>

Exhibit ES-4. NGFC Pathway Cases with CCS

<table>
<tr><th>Case Designation</th><th>Pathway Parameter</th><th>Case ID</th><th>SOFC Pressure (atm)</th><th>Internal Reformation (%)</th><th>SOFC Technology</th><th>Capacity Factor (%)</th><th>Degradation (%/1000 h)</th><th>Fuel Utilization (%)</th><th>Inverter Efficiency</th><th>Stack Cost ($/kW)</th></tr>
<tr><td rowspan="2">Reference (Case 0)</td><td rowspan="2">Reference with CCS</td><td>ANGFC0B</td><td>1</td><td rowspan="7">60</td><td rowspan="12">Advanced Cell</td><td rowspan="4">80</td><td rowspan="12">0.2</td><td rowspan="2">80%</td><td rowspan="9">97%</td><td rowspan="9">225</td></tr>
<tr><td>PNGFC0B</td><td>3</td></tr>
<tr><td rowspan="2">Case 1</td><td rowspan="2">85% Fuel Utilization</td><td>ANGFC1B</td><td>1</td><td rowspan="4">85%</td></tr>
<tr><td>PNGFC1B</td><td>3</td></tr>
<tr><td rowspan="2">Case 2</td><td rowspan="2">85% Capacity Factor</td><td>ANGFC2B</td><td>1</td><td rowspan="8">85</td></tr>
<tr><td>PNGFC2B</td><td>3</td></tr>
<tr><td>Case 2BV</td><td>With VGR</td><td>ANGFC2BV</td><td>1</td><td>> 90%</td></tr>
<tr><td rowspan="2">Case 3</td><td rowspan="2">100% Internal Reformation</td><td>ANGFC3B</td><td>1</td><td rowspan="5">100</td><td rowspan="4">85%</td></tr>
<tr><td>PNGFC3B</td><td>3</td></tr>
<tr><td rowspan="2">Case 4</td><td rowspan="2">BOP Enhancements
20% ASU Power Reduction, Inverter Efficiency 98%, Stack Cost Reduction</td><td>ANGFC4B</td><td>1</td><td rowspan="3">98%</td><td rowspan="3">200</td></tr>
<tr><td>PNGFC4B</td><td>3</td></tr>
<tr><td>Case 4BV</td><td>With VGR</td><td>ANGFC4BV</td><td>1</td><td>> 90%</td></tr>
</table>

Exhibit ES-5. Atmospheric NGFC Plants with CCS Results Summary

Case		Case 0	Case 1	Case 2	Case 2BV	Case 3	Case 4	Case 4BV
Internal Reformation (%)		60				100		
SOFC Degradation Rate (%/1000 h)		0.2						
Fuel Utilization (%)		80	85		97.5	85		97.5
Capacity Factor (%)		80		85				
Inverter Efficiency (%)		97					98	
SOFC Stack Cost ($/kW)		225					200	
Performance								
SOFC Parameters	Current Density (mA/cm²)	400	400	400	400	400	400	400
	Cell Potential (V)	0.875	0.866	0.866	0.865	0.855	0.855	0.848
	Power Density (mW/cm²)	350	346	346	346	342	342	339
Gross Power (kWe)		**713,048**	**710,326**	**710,326**	**712,709**	**694,360**	**693,950**	**700,617**
Auxiliary Loads (kWe)		**62,922**	**60,279**	**60,279**	**62,732**	**46,224**	**43,920**	**50,439**
Air Separation Unit (kWe)		19,955	16,754	16,754	6,889	9,464	7,499	0
CO_2 Drying, Purification and Compression (CPU) (kWe)		25,895	25,323	25,323	39,259	23,104	22,883	37,094
Blowers (kWe)		7,919	9,862	9,862	9,671	6,197	6,138	7,235
Steam Cycle and Miscellaneous (kWe)		9,153	8,341	8,341	6,912	7,452	7,400	6,110
Net Power (kWe)		**650,126**	**650,047**	**650,047**	**649,978**	**648,136**	**650,030**	**650,178**
NG Flowrate (lb/h)		169,965	166,190	166,190	155,900	151,700	150,248	142,100
Net Electric Efficiency, HHV (%)		**57.9**	**59.2**	**59.2**	**63.1**	**64.7**	**65.5**	**69.2**
Net Plant Heat Rate, HHV (Btu/kWh)		5,895	5,765	5,765	5,408	5,278	5,212	4,928
CO_2 Capture rate (%)		**97.8**	**97.8**	**97.8**	**93.3**	**98.1**	**98.1**	**91.7**
CO_2 Captured (tonnes per year)		1,399,003	1,367,654	1,453,133	1,299,505	1,329,578	1,316,844	1,165,365
CO_2 Emissions (lb/MWhgross)		14.8	15.2	15.2	37.9	12.1	12.0	41.7
CO_2 Emissions (lb/MWhnet)		**16.2**	**16.6**	**16.6**	**41.5**	**12.9**	**12.8**	**44.9**
Raw Water Consumption (gpm/MWnet)		2.34	2.03	2.03	1.63	1.63	1.61	1.25
Cost								
Total Plant Cost (TPC) (1000$)		868,437	838,860	838,860	770,233	739,560	721,477	638,269
Total Overnight Cost (TOC) (1000$)		1,057,252	1,021,362	1,021,308	938,024	900,205	878,320	777,532
Total As-Spent Cost (TASC) (1000$)		1,155,576	1,116,349	1,116,289	1,025,260	983,924	960,003	849,843
Levelized Cost of Electricity ($/MWh)								
Variable Costs		32.6	31.9	31.6	29.8	29.2	28.5	27.0
Fuel Costs		26.1	25.5	25.5	23.9	23.3	23.0	21.8
Variable O&M Costs		6.5	6.5	6.1	5.9	5.8	5.4	5.2
Fixed O&M Costs		6.5	6.3	5.9	5.5	5.3	5.2	4.7
Capital Costs		17.9	17.3	16.3	15.0	14.4	14.0	12.4
Total LCOE (excluding T&S)		**57.0**	**55.6**	**53.9**	**50.3**	**48.9**	**47.7**	**44.1**
T&S		3.1	3.0	3.0	2.7	2.8	2.7	2.4
Total LCOE (including T&S)		**60.1**	**58.6**	**56.9**	**53.0**	**51.7**	**50.4**	**46.5**

Exhibit ES-6. Atmospheric NGFC Plants without CCS Results Summary

Case		Case 0	Case 1	Case 2	Case 3	Case 4
Internal Reformation (%)		60			100	
SOFC Degradation Rate (%/1000 h)		0.2				
Fuel Utilization (%)		80	85			
Capacity Factor (%)		80		85		
Inverter Efficiency (%)		97				98
SOFC Stack Cost ($/kW)		225				200
Performance						
SOFC Parameters	Current Density (mA/cm^2)	400	400	400	400	400
	Cell Potential (V)	0.867	0.862	0.862	0.857	0.857
	Power Density (mW/cm^2)	347	345	345	343	343
Gross Power (kWe)		**669,409**	**670,720**	**670,720**	**662,670**	**662,528**
Auxiliary Loads (kWe)		**19,346**	**20,603**	**20,603**	**12,545**	**12,452**
Air Separation Unit (kWe)		3,320	3,260	3,260	0	0
CO_2 Drying, Purification and Compression (CPU) (kWe)		0	0	0	0	0
Blowers (kWe)		7,940	10,011	10,011	5,890	5,837
Steam Cycle and Miscellaneous (kWe)		8,087	7,332	7,332	6,655	6,615
Net Power (kWe)		**650,063**	**650,117**	**650,117**	**650,125**	**650,076**
NG Flowrate (lb/h)		159,790	157,070	157,070	144,200	142,890
Net Electric Efficiency, HHV (%)		**61.6**	**62.6**	**62.6**	**68.2**	**68.8**
Net Plant Heat Rate, HHV (Btu/kWh)		5,543	5,448	5,448	5,001	4,956
CO_2 Capture rate (%)		0.0	0.0	0.0	0.0	0.0
CO_2 Captured (tonnes per year)		0	0	0	0	0
CO_2 Emissions (lb/MWhgross)		**575.8**	**565.6**	**565.6**	**524.3**	**519.7**
CO_2 Emissions (lb/MWhnet)		593.0	583.6	583.6	534.5	529.6
Raw Water Consumption (gpm/MWnet)		3.05	2.73	2.73	2.16	2.14
Cost						
Total Plant Cost (TPC) (1000$)		593,305	584,869	584,869	530,446	509,537
Total Overnight Cost (TOC) (1000$)		725,408	715,072	715,036	647,086	621,790
Total As-Spent Cost (TASC) (1000$)		792,871	781,574	781,534	707,265	679,616
Levelized Cost of Electricity ($/MWh)						
Variable Costs		30.5	30.0	29.7	27.4	26.8
Fuel Costs		24.5	24.1	24.1	22.1	21.9
Variable O&M Costs		6.0	5.9	5.6	5.3	4.9
Fixed O&M Costs		4.6	4.5	4.2	3.9	3.8
Capital Costs		12.3	12.1	11.4	10.3	9.9
Total LCOE (excluding T&S)		47.3	46.6	45.4	41.7	40.5
T&S		0.0	0.0	0.0	0.0	0.0
Total LCOE (including T&S)		47.3	46.6	45.4	41.7	40.5

Exhibit ES-7. Pressurized NGFC Plants with CCS Results Summary

Case		Case 0	Case 1	Case 2	Case 3	Case 4
Internal Reformation (%)		60			100	
SOFC Degradation Rate (%/1000 h)		0.2				
Fuel Utilization (%)		80	85			
Capacity Factor (%)		80		85		
Inverter Efficiency (%)		97				98
SOFC Stack Cost ($/kW)		225				200
Performance						
SOFC Parameters	Current Density (mA/cm^2)	400	400	400	400	400
	Cell Potential (V)	0.904	0.898	0.898	0.868	0.868
	Power Density (mW/cm^2)	362	359	359	347	347
Gross Power (kWe)		**805,089**	**830,082**	**830,082**	**740,186**	**737,413**
Auxiliary Loads (kWe)		**154,900**	**180,096**	**180,096**	**90,225**	**87,342**
Air Separation Unit (kWe)		23,336	20,242	20,242	10,012	7,282
CO_2 Drying, Purification and Compression (CPU) (kWe)		24,458	24,277	24,277	22,183	21,918
Blowers (kWe)		98,711	127,861	127,861	51,081	50,471
Steam Cycle and Miscellaneous (kWe)		8,395	7,715	7,715	6,949	6,887
Net Power (kWe)		**650,189**	**649,987**	**649,987**	**649,962**	**650,071**
NG Flowrate (lb/h)		161,140	159,945	159,945	146,200	144,458
Net Electric Efficiency, HHV (%)		**61.1**	**61.5**	**61.5**	**67.3**	**68.1**
Net Plant Heat Rate, HHV (Btu/kWh)		5,588	5,549	5,549	5,072	5,011
CO_2 Capture rate (%)		97.7	97.7	97.7	97.9	97.9
CO_2 Captured (tonnes per year)		1,324,217	1,314,654	1,396,819	1,279,612	1,264,343
CO_2 Emissions (lb/MWhgross)		**14.2**	**14.5**	**14.5**	**11.6**	**11.5**
CO_2 Emissions (lb/MWhnet)		17.6	18.5	18.5	13.2	13.1
Raw Water Consumption (gpm/MWnet)		1.88	1.55	1.55	1.35	1.34
Cost						
Total Plant Cost (TPC) (1000$)		922,304	927,010	927,010	757,361	739,234
Total Overnight Cost (TOC) (1000$)		1,125,577	1,131,492	1,131,428	924,124	902,154
Total As-Spent Cost (TASC) (1000$)		1,250,355	1,258,432	1,258,363	1,024,360	1,000,222
Levelized Cost of Electricity ($/MWh)						
Variable Costs		31.2	31.0	30.7	28.2	27.5
Fuel Costs		24.7	24.5	24.5	22.4	22.1
Variable O&M Costs		6.5	6.5	6.2	5.8	5.4
Fixed O&M Costs		7.0	7.0	6.6	5.5	5.4
Capital Costs		19.4	19.5	18.4	15.0	14.6
Total LCOE (excluding T&S)		**57.6**	**57.6**	**55.7**	**48.7**	**47.6**
T&S		2.9	2.9	2.9	2.6	2.6
Total LCOE (including T&S)		**60.5**	**60.5**	**58.6**	**51.3**	**50.2**

Exhibit ES-8. Pressurized NGFC Plants without CCS Results Summary

<table>
<tr><th colspan="2">Case</th><th>Case 0</th><th>Case 1</th><th>Case 2</th><th>Case 3</th><th>Case 4</th></tr>
<tr><td colspan="2">Internal Reformation (%)</td><td colspan="3">60</td><td colspan="2">100</td></tr>
<tr><td colspan="2">SOFC Degradation Rate (%/1000 h)</td><td colspan="5">0.2</td></tr>
<tr><td colspan="2">Fuel Utilization (%)</td><td>80</td><td colspan="4">85</td></tr>
<tr><td colspan="2">Capacity Factor (%)</td><td colspan="2">80</td><td colspan="3">85</td></tr>
<tr><td colspan="2">Inverter Efficiency (%)</td><td colspan="4">97</td><td>98</td></tr>
<tr><td colspan="2">SOFC Stack Cost ($/kW)</td><td colspan="4">225</td><td>200</td></tr>
<tr><td colspan="7">Performance</td></tr>
<tr><td rowspan="3">SOFC Parameters</td><td>Current Density (mA/cm^2)</td><td>400</td><td>400</td><td>400</td><td>400</td><td>400</td></tr>
<tr><td>Cell Potential (V)</td><td>0.852</td><td>0.845</td><td>0.845</td><td>0.825</td><td>0.825</td></tr>
<tr><td>Power Density (mW/cm^2)</td><td>341</td><td>338</td><td>338</td><td>330</td><td>330</td></tr>
<tr><td colspan="2">Gross Power (kWe)</td><td>783,508</td><td>794,567</td><td>794,567</td><td>722,228</td><td>721,488</td></tr>
<tr><td colspan="2">Auxiliary Loads (kWe)</td><td>133,384</td><td>144,518</td><td>144,518</td><td>71,573</td><td>70,979</td></tr>
<tr><td colspan="2">Air Separation Unit (kWe)</td><td>16,980</td><td>15,330</td><td>15,330</td><td>0</td><td>0</td></tr>
<tr><td colspan="2">CO_2 Drying, Purification and Compression (CPU) (kWe)</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td colspan="2">Blowers (kWe)</td><td>110,856</td><td>123,320</td><td>123,320</td><td>67,325</td><td>66,744</td></tr>
<tr><td colspan="2">Steam Cycle and Miscellaneous (kWe)</td><td>5,548</td><td>5,868</td><td>5,868</td><td>4,248</td><td>4,235</td></tr>
<tr><td colspan="2">Net Power (kWe)</td><td>650,124</td><td>650,049</td><td>650,049</td><td>650,655</td><td>650,509</td></tr>
<tr><td colspan="2">NG Flowrate (lb/h)</td><td>132,950</td><td>120,055</td><td>120,055</td><td>139,050</td><td>137,850</td></tr>
<tr><td colspan="2">Net Electric Efficiency, HHV (%)</td><td>61.4</td><td>59.9</td><td>59.9</td><td>70.7</td><td>71.3</td></tr>
<tr><td colspan="2">Net Plant Heat Rate, HHV (Btu/kWh)</td><td>5,558</td><td>5,695</td><td>5,695</td><td>4,823</td><td>4,782</td></tr>
<tr><td colspan="2">CO_2 Capture rate (%)</td><td>0.0</td><td>0.0</td><td>0.0</td><td>0.0</td><td>0.0</td></tr>
<tr><td colspan="2">CO_2 Captured (tonnes per year)</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td colspan="2">CO_2 Emissions (lb/MWhgross)</td><td>494.6</td><td>500.1</td><td>500.1</td><td>464.9</td><td>461.4</td></tr>
<tr><td colspan="2">CO_2 Emissions (lb/MWhnet)</td><td>596.2</td><td>611.3</td><td>611.3</td><td>516.5</td><td>512.1</td></tr>
<tr><td colspan="2">Raw Water Consumption (gpm/MWnet)</td><td>1.29</td><td>1.39</td><td>1.39</td><td>0.72</td><td>0.71</td></tr>
<tr><td colspan="7">Cost</td></tr>
<tr><td colspan="2">Total Plant Cost (TPC) (1000$)</td><td>618,812</td><td>629,499</td><td>629,499</td><td>520,503</td><td>506,808</td></tr>
<tr><td colspan="2">Total Overnight Cost (TOC) (1000$)</td><td>759,605</td><td>772,409</td><td>772,365</td><td>638,092</td><td>621,494</td></tr>
<tr><td colspan="2">Total As-Spent Cost (TASC) (1000$)</td><td>856,504</td><td>872,450</td><td>872,402</td><td>715,509</td><td>697,261</td></tr>
<tr><td colspan="7">Levelized Cost of Electricity ($/MWh)</td></tr>
<tr><td colspan="2">Variable Costs</td><td>26.2</td><td>24.3</td><td>23.9</td><td>26.6</td><td>26.0</td></tr>
<tr><td colspan="2">Fuel Costs</td><td>20.4</td><td>18.4</td><td>18.4</td><td>21.3</td><td>21.1</td></tr>
<tr><td colspan="2">Variable O&M Costs</td><td>5.8</td><td>5.8</td><td>5.5</td><td>5.3</td><td>4.9</td></tr>
<tr><td colspan="2">Fixed O&M Costs</td><td>4.9</td><td>5.0</td><td>4.7</td><td>3.9</td><td>3.9</td></tr>
<tr><td colspan="2">Capital Costs</td><td>13.3</td><td>13.5</td><td>12.7</td><td>10.4</td><td>10.2</td></tr>
<tr><td colspan="2">Total LCOE</td><td>44.4</td><td>42.8</td><td>41.4</td><td>41.0</td><td>40.0</td></tr>
</table>

DISCUSSION OF PATHWAY RESULTS

The impact of the technological developments and the cost reduction assumptions considered in the present pathway study on the performance and cost of an NGFC plant are discussed in this section. The results from the various cases are consolidated to provide guidance to the DOE-FECM Solid Oxide Fuel Cell Program.

System Performance and Efficiency

The efficiencies of the various NGFC plants considered in the two pathways are shown in Exhibit ES-9. For an atmospheric NGFC plant without CCS, the higher heating value (HHV) efficiency varies from a value of 61.6 percent for the reference plant to a value of 68.8 percent for the Case 4 advanced plant with complete internal (on cell) reformation. Inclusion of CCS imposes an efficiency penalty of ≈3.0–3.5 percentage points. Pressurization generally results in an increase in efficiency over the atmospheric NGFC cases except for the Reference Case 0 and Case 1 without CCS due to the additional injection of natural gas required to get the desired turbine inlet temperature in these pressurized cases. The atmospheric NGFC plant with VGR (and with CCS) results in an efficiency value of 69.2 percent, which is higher than most of the plants, including the plants without CCS, and is second only to the Case 4 pressurized system without CCS. The VGR concept enables operating at a fuel utilization of 97.5 percent while the in-stack utilization is maintained below 50 percent. The VGR configuration enables an NGFC plant with CCS that is ≈4 percentage points higher than a comparable atmospheric NGFC plant without VGR.

As expected with the underlying SOFC technology advantages, the NGFC efficiencies are significantly higher than the values for comparable conventional technologies including the supercritical pulverized coal (SC PC) and F-class natural gas combined cycle (NGCC) plants with CCS [1] shown in Exhibit ES-9. The reference atmospheric NGFC plant without CCS eclipses the system performance of both an advanced H-class NGCC plant and a natural gas-based Allam-cycle supercritical CO_2 plant (sCO_2), whose HHV efficiencies are between 53 and 54 percent, by over 7 percentage points. The efficiency advantage relative to the conventional plants increases to over 20 percentage points with the advances in NGFC technology (Case 4).

The technology advancement in natural gas internal reformation capability from 60 percent to 100 percent has the highest influence on the system efficiency in the case of plants without CCS, as indicated by the waterfall plot in Exhibit ES-10. For atmospheric NGFC plants with CCS, the benefits of VGR significantly outweigh benefits from other technological advancements as shown in Exhibit ES-11. The BOP enhancements resulted only in modest gains since the ASU parasitic load is lower for the 100 percent internal reformation cases.

Exhibit ES-9. HHV Efficiency of the Pathway NGFC Plant Configurations

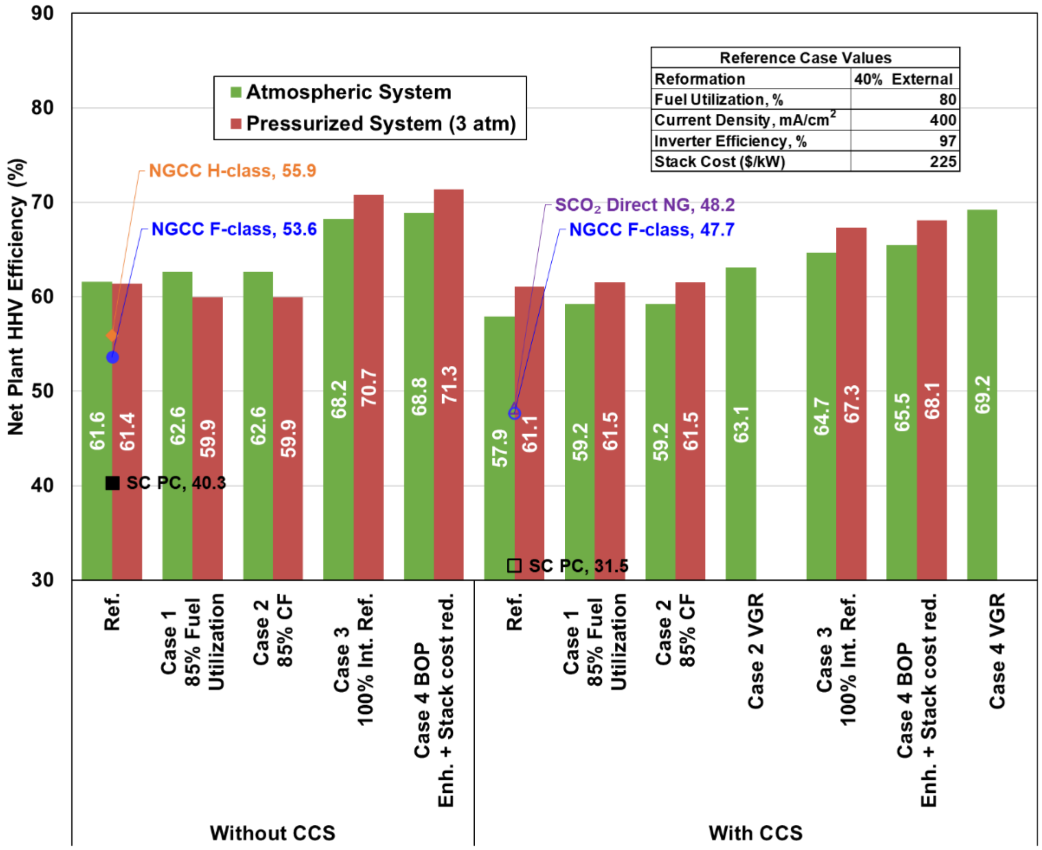


Exhibit ES-10. Technology Developments and Efficiency Improvements for NGFC Plant Configurations without CCS

Reference Case Values	
Reformation	40% External
Fuel Utilization, %	80
Current Density, mA/cm^2	400
Inverter Efficiency, %	97
Stack Cost ($/kW)	225

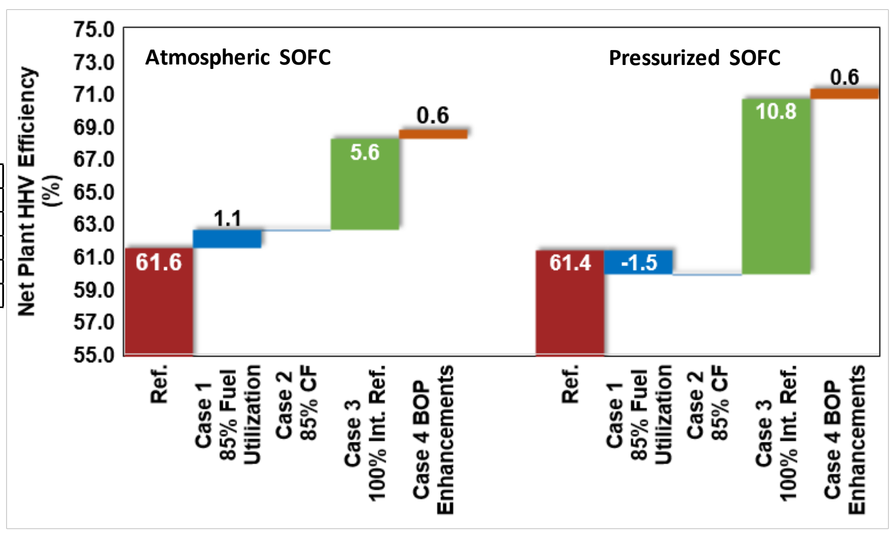
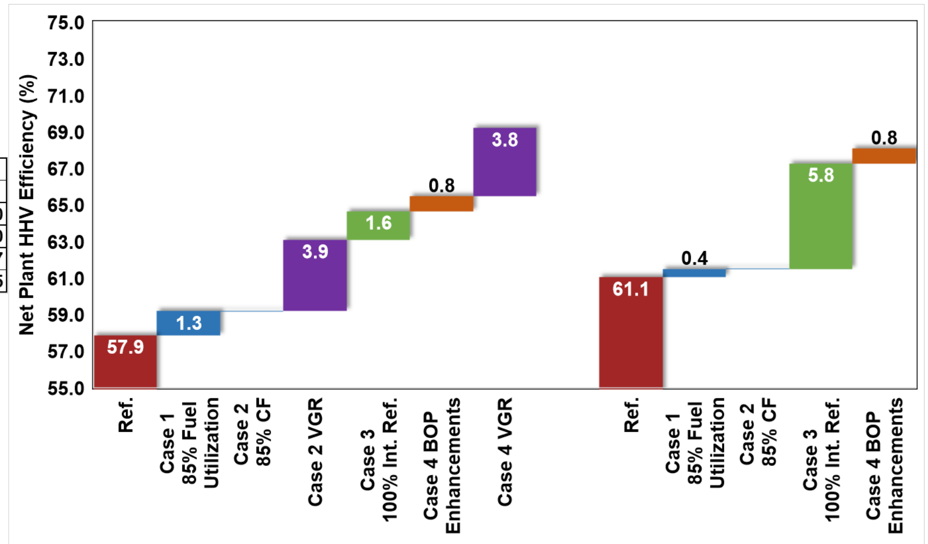


Exhibit ES-11. Technology Developments and Efficiency Improvements for NGFC Plant Configurations with CCS

Reference Case Values	
Reformation	40% External
Fuel Utilization, %	80
Current Density, mA/cm^2	400
Inverter Efficiency, %	97
Stack Cost ($/kW)	225



NGFC Plant Costs

The 100 percent internal reformation case results in the lowest total plant cost (TPC) for the NGFC plants without CCS, as shown in Exhibit ES-12, attributable to the high plant efficiency and the elimination of the external reformer. The pressurized configurations generally result in a higher TPC relative to the atmospheric systems primarily due to the increased enclosure (pressure vessel) cost. The TPC of NGFC plants with CCS are considerably lower than the TPC of other technologies with CCS while the NGFC plant costs without CCS are competitive even with F-Class NGCC units.

The levelized cost of electricity (LCOE) (without transport and storage [T&S]) of the reference NGFC plant with CCS is lower by ≈$14/MWh than the LCOE of an F-class NGCC system with CCS as shown in Exhibit ES-13.[a] The advanced NGFC plants with CCS are projected to result in LCOEs that are ≈$23–60/MWh lower than the LCOE of all the other technologies. In the case of systems without CCS, the NGFC systems are economically competitive with the F-class NGCCs. The VGR configuration substantially mitigates the LCOE penalty of CCS (by nearly half). The components of the LCOE of NGFC systems with and without T&S costs are shown in Exhibit ES-14 and Exhibit ES-15 respectively, which show the reduction in capital and variable O&M (fuel) components along the pathways.

The difference in LCOEs between an NGFC plant with and without CCS is significantly smaller than the corresponding penalties for conventional technologies. The SOFC is essentially an oxyfuel reactor, and along with the sealed design generally used to separate the air and fuel, it forms a highly effective inherent carbon separator (that produces power); it produces a concentrated CO_2 effluent that is ready for CCS with minimal incremental costs. This

[a] The LCOE for H-class have been estimated to be ~$36/MWh in the study by Uysal. [25] However, these were not included on the charts since the costs are based on a 1 GW plant capacity and the financial parameters used are different than the baseline studies.

underscores the leading role played by SOFC-based systems in meeting DOE-FECM's environmental vision.

Exhibit ES-12. Comparison of the TPC of the NGFC Plant Configurations

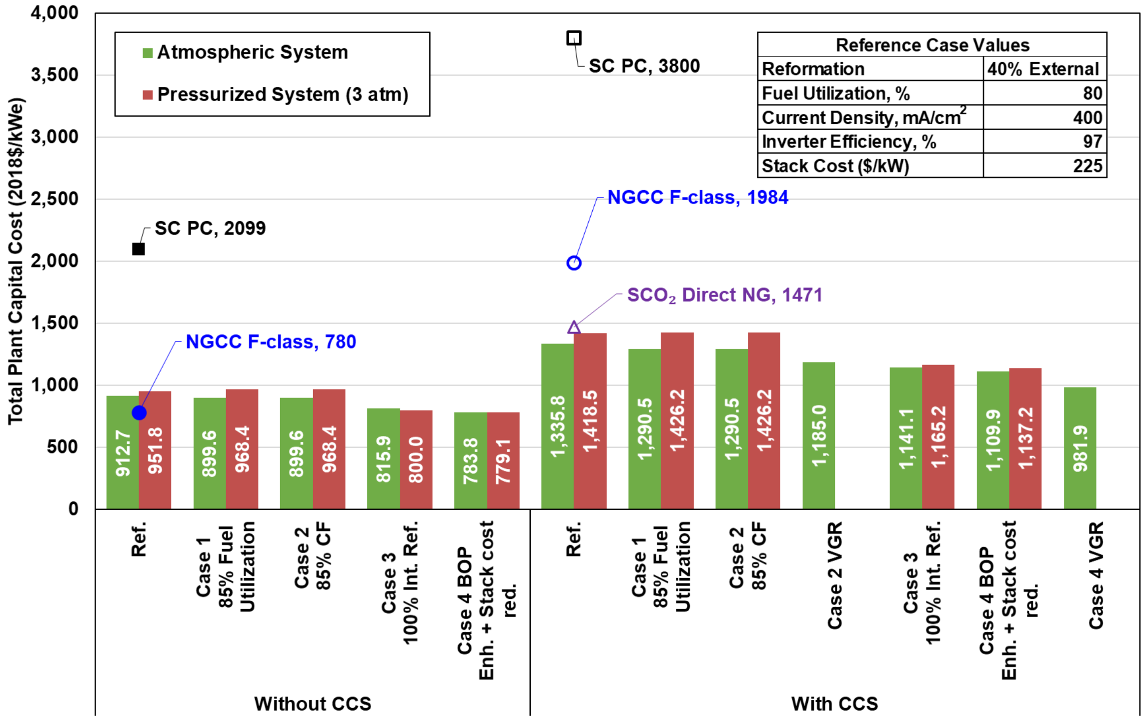


Exhibit ES-13. Comparison of the LCOE (without T&S) of the NGFC Plant Configurations

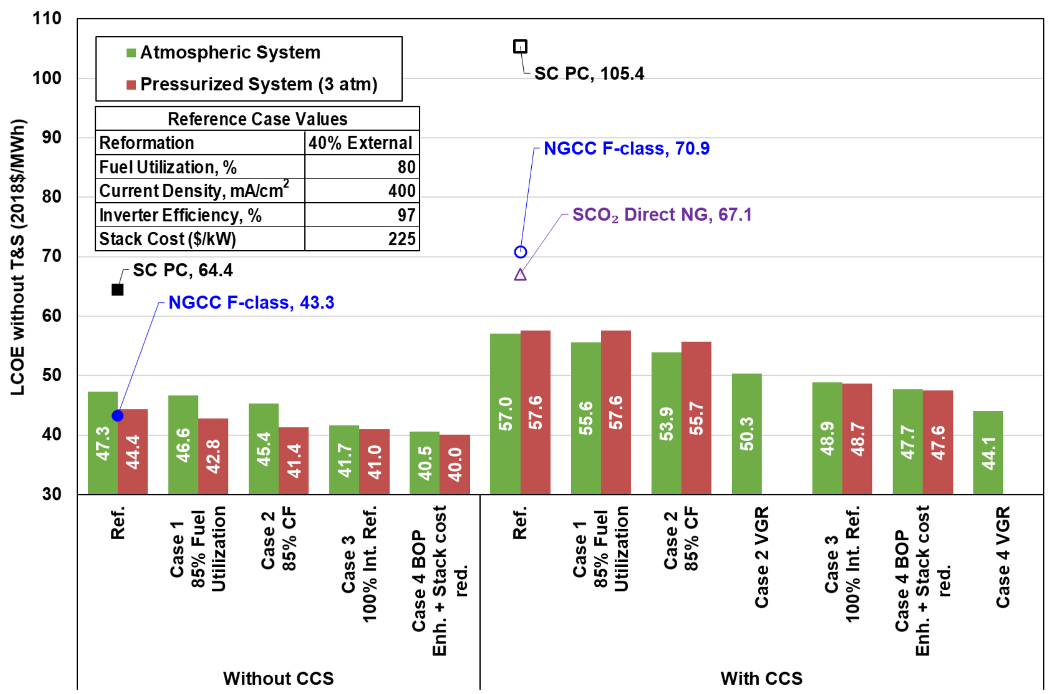


Exhibit ES-14. LCOE Breakdown (with T&S) of the NGFC Plant Configurations

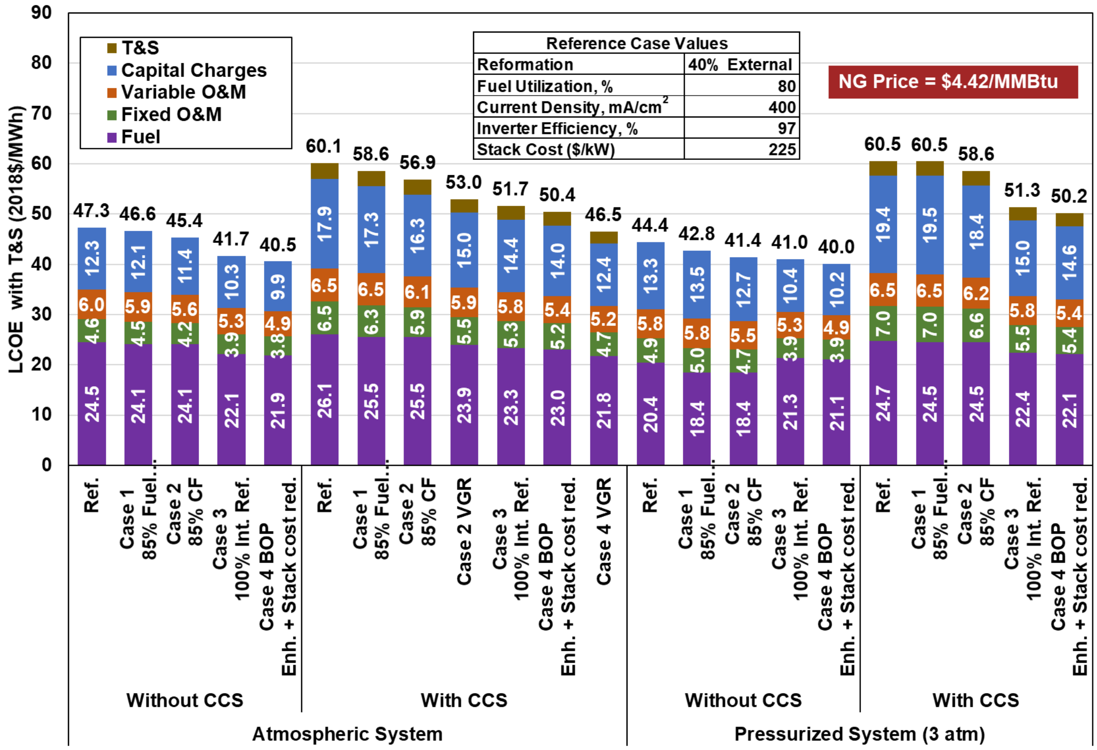
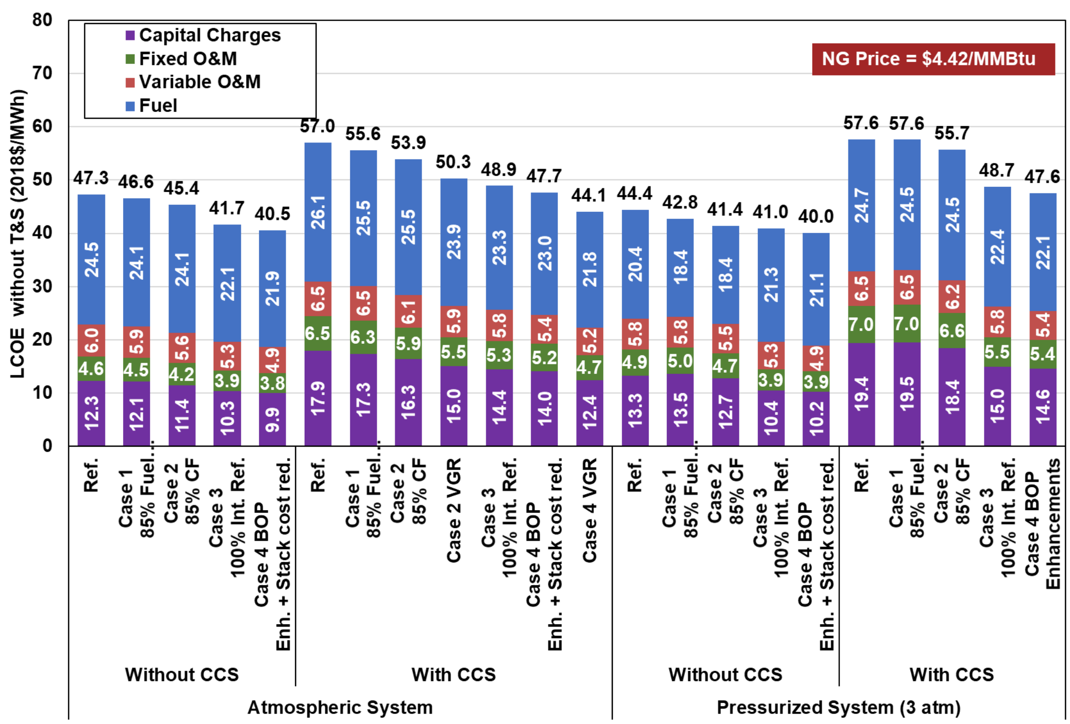


Exhibit ES-15. LCOE Breakdown (without T&S) of the NGFC Plant Configurations



The progression of LCOE with pathway technology developments, cost reductions, and increased availability are shown in Exhibit ES-16 and Exhibit ES-17 for the NGFC plants without and with CCS respectively. In the case of NGFC plants without CCS, the largest reduction in LCOE, ≈$3.7/MWh, is associated with the technology advancement to enable 100 percent internal reformation. The VGR configurations yield the largest LCOE reduction (≈$3.6/MWh) for the NGFC plants with CCS. The pathways, which represent practical and realizable steps consistent with the Fuel Cell Program, lead to a NGFC system with capture that has a significantly low LCOE (at a natural gas price of $4.42/MMBtu) relative to conventional heat-engine based technologies with CCS. The pathways also lead to NGFC plants without CCS that are economically competitive with F-class and J-class NGCC plants.

Although pressurization does not appear to have a significant advantage in the cases analyzed here, pressurized configurations could be found to be attractive as a hybrid system where operational flexibility aspects may be attractive.

Exhibit ES-16. Progression of Plant LCOE (without T&S) along the NGFC Pathway without CCS

Reference Case Values	
Reformation	40% External
Fuel Utilization, %	80
Current Density, mA/cm^2	400
Inverter Efficiency, %	97
Stack Cost ($/kW)	225

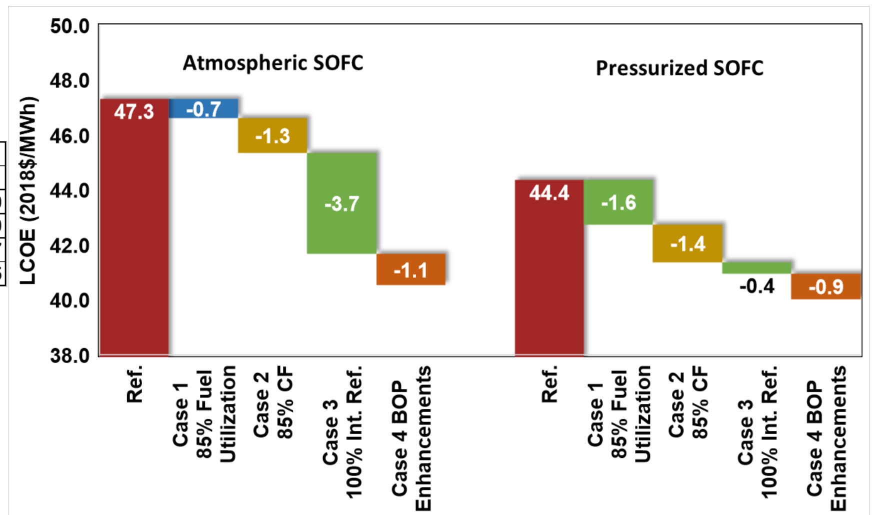
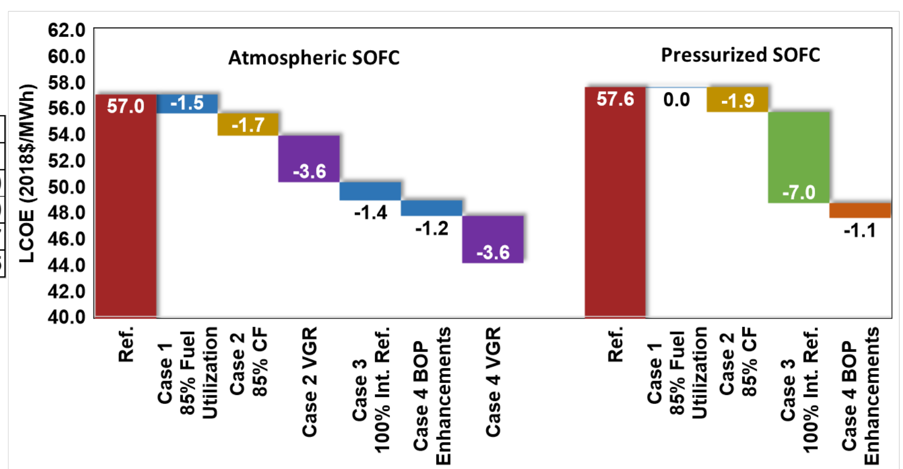


Exhibit ES-17. Progression of Plant LCOE (without T&S) along the NGFC Pathway with CCS

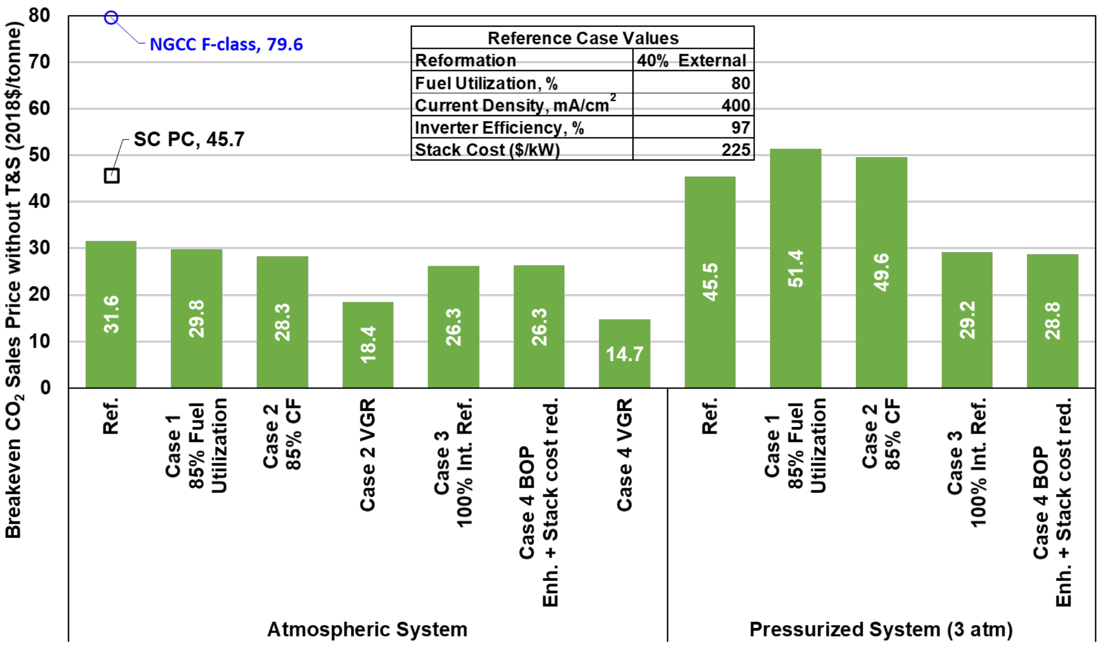
Reference Case Values	
Reformation	40% External
Fuel Utilization, %	80
Current Density, mA/cm^2	400
Inverter Efficiency, %	97
Stack Cost ($/kW)	225



Cost of CO_2 Captured

The breakeven CO_2 sale price (the price of CO_2 that is required to pay for the difference in LCOE between a plant with and without CCS) for the pathway NGFC cases are shown in Exhibit ES-18. All the atmospheric NGFC plants and advanced pressurized plants considered herein have a breakeven CO_2 sales price that is well below the $40/tonne of CO_2 generally considered to be an achievable selling price for pure CO_2 for EOR purposes. The NGFC system with the VGR configuration results in a break-even price that is below $15/tonne, which could make this system highly competitive with other CO_2 sources.

Exhibit ES-18. Break-even Sale Price of CO_2 Captured for the Different NGFC Plant Configurations

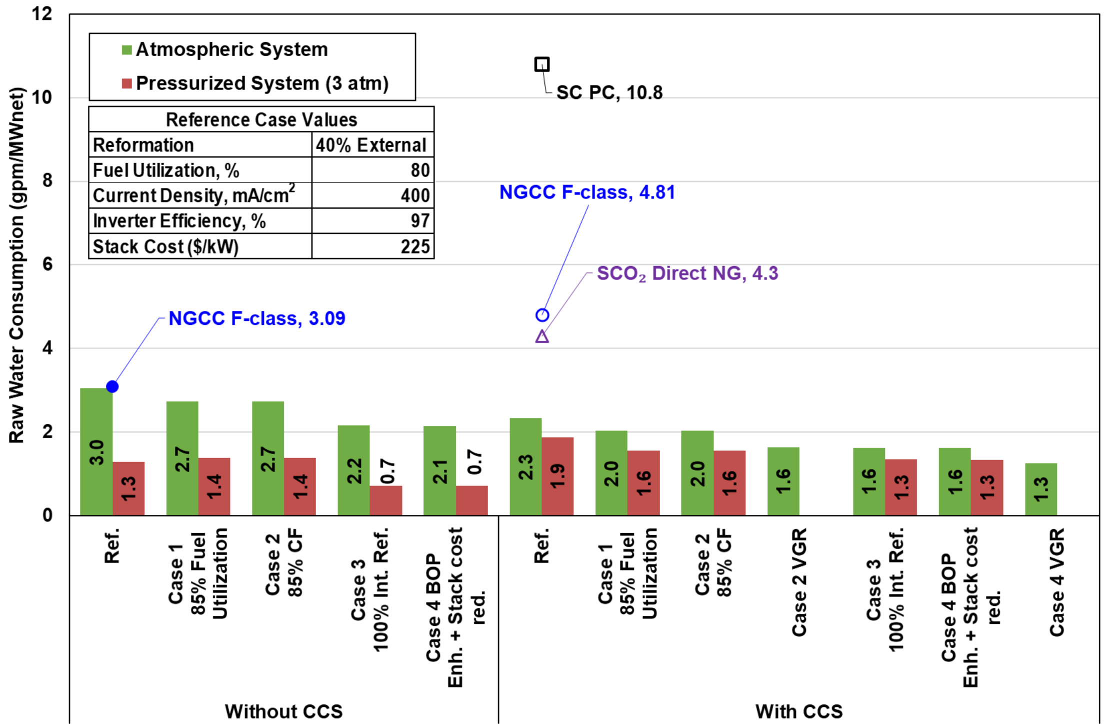


Reference Case Values	
Reformation	40% External
Fuel Utilization, %	80
Current Density, mA/cm^2	400
Inverter Efficiency, %	97
Stack Cost ($/kW)	225

Water Consumption

The NGFC plants result in significantly lower water consumption compared to SC PC and NGCC plants as shown in Exhibit ES-19. The NGFC plant water consumption is dominated by steam-cycle the cooling water make-up requirements. Without the steam bottoming cycle, the advanced NGFC plant Case 3 and Case 4 with 100 percent internal reformation do not require any external steam and can result in a net production of water (not shown in the figure).

Exhibit ES-19. Water Consumption for the Various NGFC Plant Configurations



Effect of Natural Gas Price

The LCOE of the reference NGFC plant and the best advanced NGFC plant (Case 4 with VGR) with CCS is shown in Exhibit ES-20 as function of natural gas price. The variation of the LCOE of a conventional F-class NGCC plant with CCS is also shown along with the LCOE of an SC PC plant, which does not depend directly on the price of natural gas. While both the NGFC and the NGCC plant LCOEs increase with increase in the price of natural gas, the slope of the dependency is less steep for the for the former (NGFC) relative to the latter (NGCC) due to the higher plant efficiencies. The NGFC plants with CCS show a significant economic advantage relative to other systems at natural gas prices between $2–15/MMBtu. Even at high natural gas prices, the advanced NGFC plant maintain a significant advantage relative to an SC PC plant although IGFC plants may become competitive.

In plants without CCS, there is a natural gas price (≈$8/MMBtu) beyond which the conventional NGFC units overcome the slight LCOE advantage of the NGCC plant at low gas prices as shown in Exhibit ES-21. While the advanced NGFC configuration without CCS is economically advantageous relative to NGCC systems, the SC PC system becomes competitive at natural gas prices > ≈$9/MMBtu.

Exhibit ES-20. Influence of Natural Gas Price on the LCOE (excl. T&S) of NGFC Plant Configurations with CCS

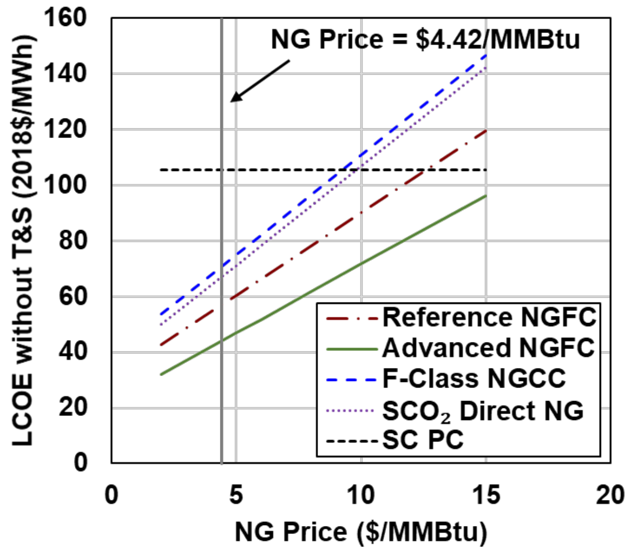
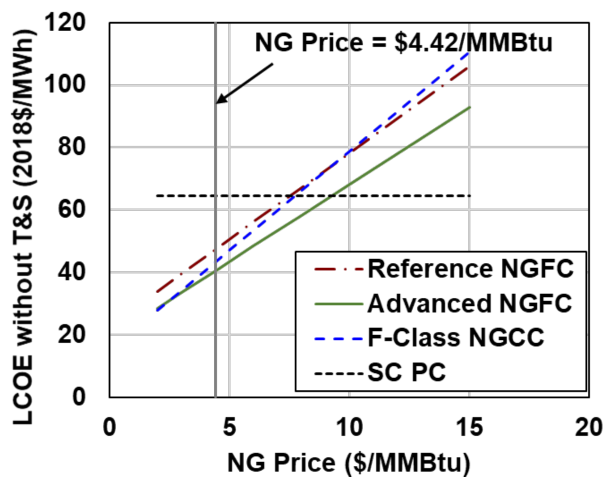


Exhibit ES-21. Influence of Natural Gas Price on the LCOE of NGFC Plant Configurations without CCS



In summary,

- Technology development and cost reduction steps that can cumulatively result in an increase of over 12 percentage points in NGFC plant efficiency accompanied by over 23 percent reduction in the associated LCOE were identified and quantified.
- Development of technologies that enable increased internal reformation of natural gas fuel, along with the implementation of the VGR concept for plants with CCS, had the highest impact on the LCOE of the NGFC plant. The advanced NGFC plant based on complete internal reformation of the natural gas and VGR, which has the highest efficiency and lowest LCOE among all the plants considered in this report, fits well within the DOE transformational technology timeframe.

- The advanced NGFC plant with complete internal reformation and VGR has the lowest CO_2 emission footprint and the lowest water consumption relative to any other conventional power generation technology without CCS.
- The LCOE for the NGFC power plant with CCS is attractive compared to the conventional NGCC with CCS. The LCOE of NGFC plants without CCS were also found to be competitive with NGCC technologies. The competitiveness of NGFC without CCS increases as the price of natural gas increases due to the much higher efficiency of the NGFC plants, although higher natural gas prices may tend to favor coal-based plants.
- The results presented in this study are for SOFC systems operating at a nominal current density of 400 mA/cm^2 consistent with today's technology. Operating at higher current densities could potentially reduce the capital costs (since a lower number of SOFCs may be needed to achieve the desired power rating) while increasing production costs due to the concomitant loss of efficiency. The usage of PNNL SOFC-ROM enables the evaluation of the trade-off between these costs, which intended to be explored through future sensitivity studies.

1 INTRODUCTION

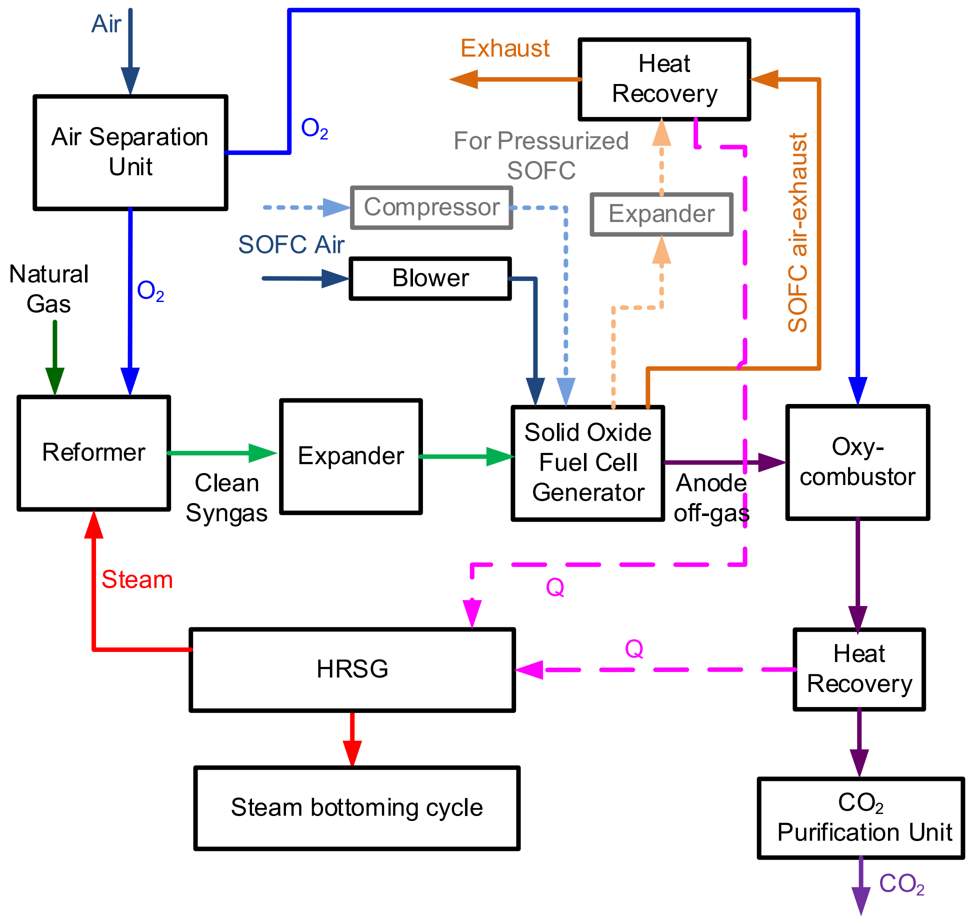
Solid oxide fuel cell (SOFC) technology, through its nearly reversible electrochemical conversion of chemical potential into electric power, has the potential for significantly higher electric efficiency power systems relative to conventional Carnot-cycle-based heat engines. In addition, the oxy-combustion of unutilized fuel in a sealed SOFC system renders itself readily available for carbon capture and sequestration (CCS) with the requirement of only a small oxy-combustor downstream of the fuel cell to combust the remaining fuel (Electrochemical utilization of fuels varies typically between 75 and 90 percent for current fuel cell technology). The heat rejected by the fuel cell system can be recovered further in a combination of Brayton and Rankine cycles, depending on whether the fuel cell system is operating at elevated or atmospheric pressures.

Accordingly, the United States (U.S.) Department of Energy (DOE) National Energy Technology Laboratory (NETL) has been pursuing the development of the SOFC technology to enable future power generation systems that are consistent with the cornerstones of the DOE mission— to ensure America's security and prosperity by addressing its energy, environmental and nuclear challenges through transformative science and technology solutions. The U.S. DOE FECM SOFC Program is currently focused on the development of low-cost, highly efficient, and reliable SOFC power systems.

The present study represents a part of a series of system evaluations being developed at NETL to aid in prioritizing technological advances along research pathways to the realization of utility-scale SOFC systems, a transformational goal of the fuel cell program. In particular, the system performance of utility-scale (>50 MWe) natural gas fuel cell (NGFC) systems with and without carbon dioxide (CO_2) capture is presented. The NGFC power plant is analogous to a natural gas combined cycle (NGCC) power plant, but with the gas turbine power island replaced with an SOFC power island.

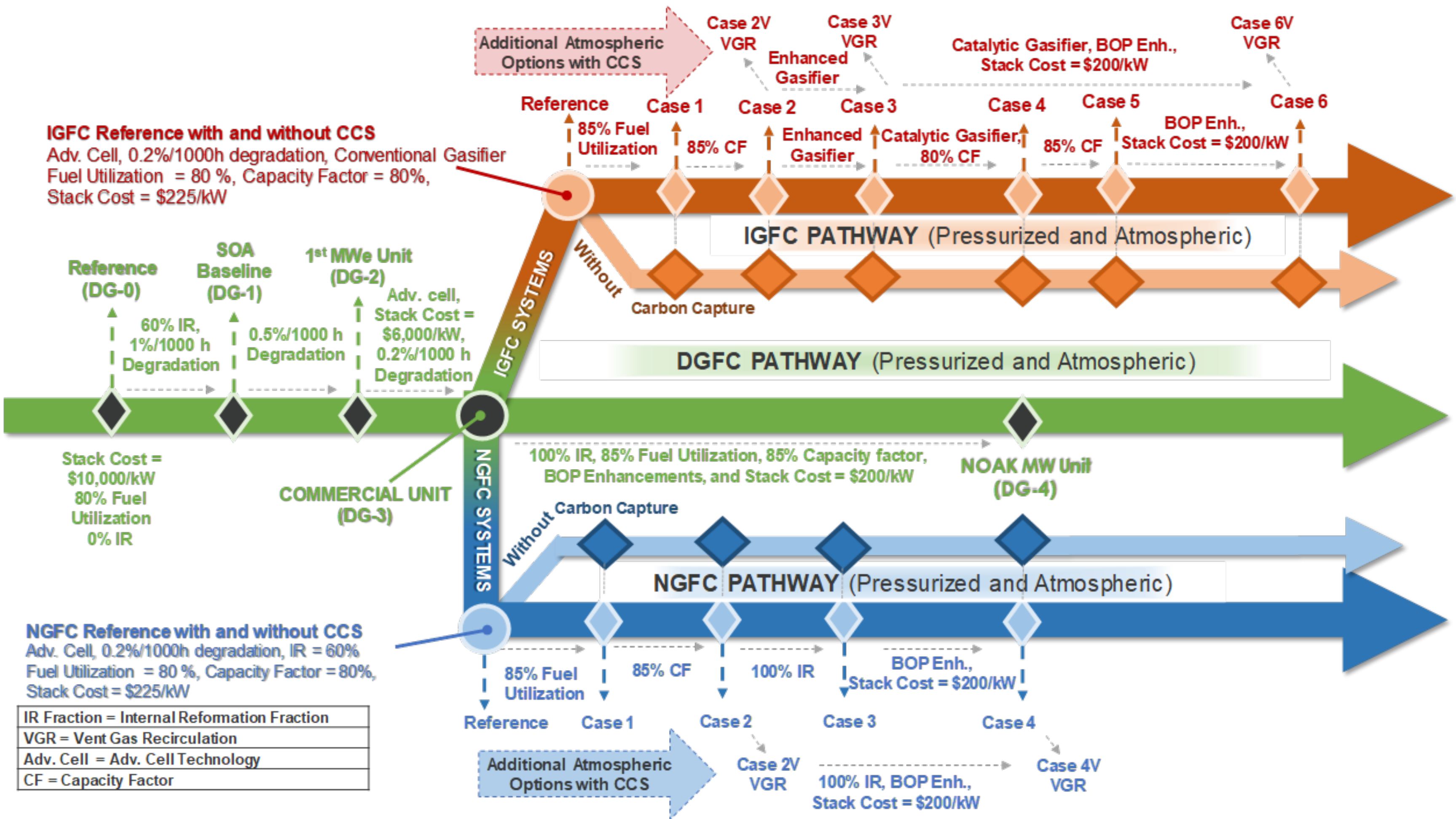
A general schematic block flow diagram of the NGFC system with carbon capture is shown in Exhibit 1-1. Desulfurized natural gas with less than 100 ppb of sulfur is sent to an oxygen (O_2)-driven auto-thermal reformer (ATR) where it is converted to syngas, which fuels the SOFC system after expansion to the desired SOFC operating pressure. Part or all the desulfurized natural gas may bypass the ATR to increase the methane content of the syngas entering the SOFC, which offers cost and performance advantages. In systems featuring a pressurized SOFC generator, a major portion of the compression work needed to supply air at pressure to the generator is recovered by expanding the SOFC air exhaust gas back to atmospheric pressure (as shown by the dotted lines in Exhibit 1-1). An air separation unit (ASU) supplies O_2 to the reformer and to the oxy-combustor to enable efficient capture of CO_2. The cooled anode exhaust from the heat recovery steam generator (HRSG) is further purified to pipeline specifications in a CO_2 purification unit (CPU). For systems without carbon capture, the O_2 supply to the reformer and the combustor may be substituted with air. Further, the expansion of the anode-off gas to atmospheric pressure is accomplished downstream of the SOFC generator with an additional expander (anode expander) before recovering heat for steam generation in the case of pressurized SOFC operation.

Exhibit 1-1. NGFC System Configuration with CCS



The fuel cell technology is assumed to be a planar cell configuration with separated anode and cathode off-gas streams for the present pathway studies. The overall framework for the SOFC system research and development (R&D) pathway considered in this study is depicted in Exhibit 1-2, which considers anticipated improvements in SOFC electrochemical performance and system configuration supported by the SOFC technology development roadmap combined with concomitant advances in plant operation and maintenance (O&M) and component technologies. With commercially viable small-scale (≈1 MWe) distributed generation fuel cell (DGFC) system as a basis, the development of utility scale systems is envisioned to proceed along two parallel pathways based on the fuel feedstock. The NGFC pathway is based on development of natural gas based SOFC systems while the integrated gasification fuel cell (IGFC) relies on synthetic gas (syngas) generated via coal gasification. The results of only the NGFC pathway are discussed in this report. The DGFC and IGFC pathways are described in separate NETL technical reports.

Exhibit 1-2. Solid Oxide Fuel Cell Pathway Studies



The SOFC technology and system characteristics, listed in Exhibit 1-3, of the established commercial DGFC unit (as shown in the DGFC developmental roadmap[b] in Exhibit 1-2) was assumed as the basis for the reference NGFC system.

Exhibit 1-3. Reference NGFC System Characteristics

SOFC Parameters	Values
SOFC Performance	Advanced Cell – 50% reduction in Ohmic and Polarization losses relative to the state-of-the-art technology (SOA)
Degradation Rate	0.2% per 1000 h
System Fuel Utilization	80%
Stack Cost	$225/kWe
Internal Reformation	60%
Capacity Factor	85%
Inverter Efficiency	97%

Two parallel developmental scenarios—one with the SOFC operating at atmospheric pressure and one based on a pressurized SOFC operation—were considered as part of the NGFC pathways. From previous studies, which found insignificant cost benefits for pressures higher than three atmospheres and based on pressurized SOFC systems that have been generally proposed and operated by industrial vendors, an SOFC operating pressure of 3 atm was assumed in the present calculations.

The specific NGFC pathway cases analyzed in this study are listed in Exhibit 1-4 and Exhibit 1-5 for systems without and with CCS respectively. Case 1 represents an increase in fuel utilization from 80 to 85 percent based on the confidence gained from DGFC systems. Enhanced reliability of balance of plant (BOP) components combined with optimized O&M is reflected by an increase in capacity factor to 85 percent in Case 2. Realization of complete internal reformation technology is assumed in Case 3 while Case 4 considers potential enhancements in ASU technology and inverter technology, along with a reduction in stack cost to $200/kW. In the case of systems with CCS, an attractive high-efficiency vent gas recirculation (VGR) configuration, which enables fuel utilization values >95 percent, is also explored with systems reflected by Cases 2 and 4.

Each NGFC case is designated by a numbering system—"XNGFCYZ*"—where X = A or P depending on whether the SOFC is operating under atmospheric or pressurized conditions respectively, Y represents the case number, Z = B or A depending on whether the system features CCS or not, and * is a wildcard letter used to designate special configurations such as the vent gas recirculation concept.

[b] The DGFC pathway is discussed in an alternate report.

The design and cost bases for this pathway study closely follow the bases applied in the NETL Bituminous Baseline (BB) report so that direct performance and cost comparisons can be made with the conventional fossil-fuel power plant results estimated in that report. [1]

The results represent the potential future benefits of NGFC technology development. Performance and cost projections for the NGFC plants are compared with conventional heat-engine based technologies.

The balance of this report is organized as follows:

- Section 2 provides the basis for the technical and cost evaluations.
- Section 3 describes the major plant components that are applied throughout the case studies.
- Section 4 describes the plant simulations and presents the results for Scenario 1: atmospheric-pressure NGFC cases and their corresponding pathway parameters and NGFC with and without CCS are considered.
- Section 5 describes the Scenario 2 plant simulations and presents the results for the pressurized-SOFC and NGFC cases and their corresponding pathway parameters. NGFC with and without CCS are considered.
- Section 6 provides a discussion of all the pathway results and provides DOE with a basis to select the most appropriate development path for NGFC, and to measure and prioritize the contribution of its R&D program to future power systems technology.
- Section 7 presents the major conclusions from the study.

Exhibit 1-4. NGFC Pathway Cases without CCS

<table>
<tr><th>Case Designation</th><th>Pathway Parameter</th><th>Case ID</th><th>SOFC Pressure (atm)</th><th>Internal Reformation (%)</th><th>SOFC Technology</th><th>Capacity Factor (%)</th><th>Degradation (%/1000 h)</th><th>Fuel Utilization (%)</th><th>Inverter Efficiency</th><th>Stack Cost ($/kW)</th></tr>
<tr><td rowspan="2">Reference (Case 0)</td><td rowspan="2">Reference Without CCS</td><td>ANGFC0A</td><td>1</td><td rowspan="6">60</td><td rowspan="10">Advanced Cell</td><td rowspan="4">80</td><td rowspan="10">0.2</td><td rowspan="2">80%</td><td rowspan="8">97%</td><td rowspan="8">225</td></tr>
<tr><td>PNGFC0A</td><td>3</td></tr>
<tr><td rowspan="2">Case 1</td><td rowspan="2">85% Fuel Utilization</td><td>ANGFC1A</td><td>1</td><td rowspan="8">85%</td></tr>
<tr><td>PNGFC1A</td><td>3</td></tr>
<tr><td rowspan="2">Case 2</td><td rowspan="2">85% Capacity Factor</td><td>ANGFC2A</td><td>1</td><td rowspan="6">85</td></tr>
<tr><td>PNGFC2A</td><td>3</td></tr>
<tr><td rowspan="2">Case 3</td><td rowspan="2">100% Internal Reformation</td><td>ANGFC3A</td><td>1</td><td rowspan="4">100</td></tr>
<tr><td>PNGFC3A</td><td>3</td></tr>
<tr><td rowspan="2">Case 4</td><td rowspan="2">BOP Enhancements
20% ASU Power Reduction, Inverter Efficiency 98%, Stack Cost Reduction</td><td>ANGFC4A</td><td>1</td><td rowspan="2">98%</td><td rowspan="2">200</td></tr>
<tr><td>PNGFC4A</td><td>3</td></tr>
</table>

Exhibit 1-5. NGFC Pathway Cases with CCS

<table>
<tr><th>Case Designation</th><th>Pathway Parameter</th><th>Case ID</th><th>SOFC Pressure (atm)</th><th>Internal Reformation (%)</th><th>SOFC Technology</th><th>Capacity Factor (%)</th><th>Degradation (%/1000 h)</th><th>Fuel Utilization (%)</th><th>Inverter Efficiency</th><th>Stack Cost ($/kW)</th></tr>
<tr><td rowspan="2">Reference (Case 0)</td><td rowspan="2">Reference with CCS</td><td>ANGFC0B</td><td>1</td><td rowspan="7">60</td><td rowspan="12">Advanced Cell</td><td rowspan="4">80</td><td rowspan="12">0.2</td><td rowspan="2">80%</td><td rowspan="9">97%</td><td rowspan="9">225</td></tr>
<tr><td>PNGFC0B</td><td>3</td></tr>
<tr><td rowspan="2">Case 1</td><td rowspan="2">85% Fuel Utilization</td><td>ANGFC1B</td><td>1</td><td rowspan="4">85%</td></tr>
<tr><td>PNGFC1B</td><td>3</td></tr>
<tr><td rowspan="2">Case 2</td><td rowspan="2">85% Capacity Factor</td><td>ANGFC2B</td><td>1</td><td rowspan="8">85</td></tr>
<tr><td>PNGFC2B</td><td>3</td></tr>
<tr><td>Case 2BV</td><td>With VGR</td><td>ANGFC2BV</td><td>1</td><td>> 90%</td></tr>
<tr><td rowspan="2">Case 3</td><td rowspan="2">100% Internal Reformation</td><td>ANGFC3B</td><td>1</td><td rowspan="5">100</td><td rowspan="4">85%</td></tr>
<tr><td>PNGFC3B</td><td>3</td></tr>
<tr><td rowspan="2">Case 4</td><td rowspan="2">BOP Enhancements
20% ASU Power Reduction, Inverter Efficiency 98%, Stack Cost Reduction</td><td>ANGFC4B</td><td>1</td><td rowspan="3">98%</td><td rowspan="3">200</td></tr>
<tr><td>PNGFC4B</td><td>3</td></tr>
<tr><td>Case 4BV</td><td>With VGR</td><td>ANGFC4BV</td><td>1</td><td>> 90%</td></tr>
</table>

2 Pathway Study Basis

Systems models were developed under the Aspen Plus® (Aspen) platform to simulate the NGFC process configurations. The major equipment characterizations were used to generate capital and operating cost estimates for the NGFC plants. Performance and process limits were based upon published reports, information obtained from vendors and users of the technology, performance data from design/build utility projects, and/or best engineering judgment as described in the BB report. [1]

Capital and operating costs for most of the conventional equipment items were scaled based on the updated BB report cost estimates. [2] All the costs are reported in 2018 dollars, and the levelized cost of electricity (LCOE) is presented as the revenue requirement figure-of-merit for each of the cases.

The design basis for the pathway study, which is largely based on the BB report, [1] is reported in this section along with the environmental targets and cost assumptions.

2.1 Site Description

The plants in this report apply the site description assumptions used in the BB report. [1] The plants are fueled by natural gas, and are assumed to be located at a generic Midwestern site (Exhibit 2-2) operating at International Standards Organization (ISO) ambient conditions (Exhibit 2-1).

Exhibit 2-1. Site Ambient Conditions

Elevation, m (ft)	0 (0)
Barometric Pressure, MPa (psia)	0.10 (14.696)
Design Ambient Temperature, Dry Bulb, °C (°F)	15 (59)
Design Ambient Temperature, Wet Bulb, °C (°F)	11 (51.5)
Design Ambient Relative Humidity, %	60

Exhibit 2-2. Site Characteristics

Location	Greenfield, Midwestern U.S.
Topography	Level
Size, acres	150
Transportation	Rail
Water	Municipal (50%) / Groundwater (50%)
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 sequestered in a saline formation at a depth of 1,239 meters (4,055 feet)

2.2 Design Fuel

The design basis composition for the NGFC cases is the same as used in the BB report for NGCC plants (Exhibit 2-3). It is assumed that the natural gas has a total sulfur content of 5 ppmv and has no significant trace element content.

Exhibit 2-3. Natural Gas Composition

Component		Volume Percentage	
Methane	CH_4	93.1	
Ethane	C_2H_6	3.2	
Propane	C_3H_8	0.7	
n-Butane	C_4H_{10}	0.4	
Carbon Dioxide	CO_2	1.0	
Nitrogen	N_2	1.6	
	Total	100.0	
	LHV		HHV
kJ/kg	47,454		52,581
MJ/scm	34.71		38.46
Btu/lb	20,410		22,600
Btu/scf	932		1,032

Note: Fuel composition is normalized, and heating values are calculated.

2.3 SOFC Power Island Characterization

The SOFC simulations represent the expected operating conditions and performance capabilities of planar fuel cell technology, having split cathode and anode off-gas steams, and operating at both atmospheric-pressure and elevated-pressure conditions. Several assumptions were applied to estimate the performance of the NGFC power island. These assumptions were generally based on SOFC test data and internal vendor reports.

2.3.1 Estimation of Fuel Cell Operating Voltage

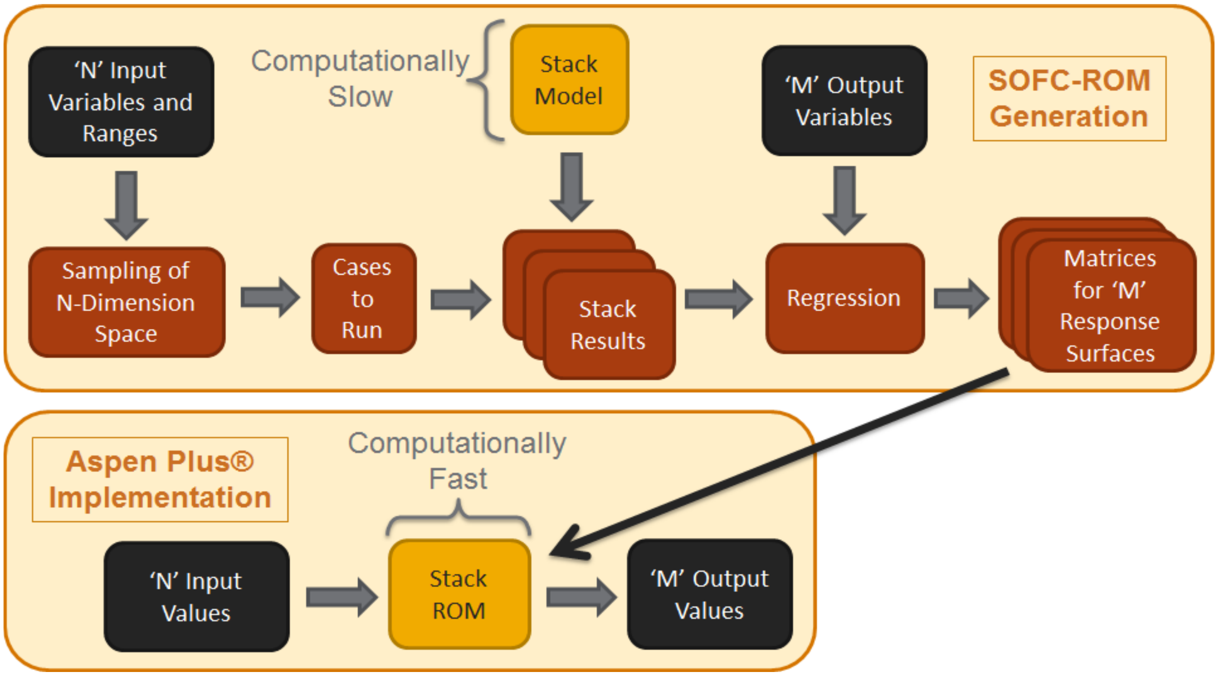
NETL's previous pathway studies [3], [4] are based on simplified representations of the SOFC performance at only a specific design point. While a variety of detailed computational models can be employed to predict the electrical performance along with the thermal and flow fields of SOFCs, these models are generally computationally intensive for use in system-level thermodynamic and material balance models typically used in techno-economic analyses. Through a collaboration with Pacific Northwest National Laboratory (PNNL), NETL has developed a reduced order model (ROM) that is based on detailed computational models of the SOFC stack. This model, which is referred to as PNNL-ROM here, is not computationally intensive, by design, and allows for effective use in system-level models. PNNL-ROM, in addition to the capability to predict the stack performance over the entire range of operating conditions, is designed to provide other desirable information about the state of the stack, such as internal temperature gradients, which can be critical constraints in system optimization studies.

PNNL-ROM was used to predict the SOFC performance along with the cell thermal fields for a given airflow and fuel flow for the NGFC studies. PNNL-ROM is based on the response surface methodology [5] with detailed SOFC stack model results to create a computationally efficient ROM for the stack that retains desirable information about its internal state. The response surface approach attempts to describe the behavior of a dependent or 'response' variable of interest based on the independent or 'explanatory' variables that are inputs to a given process or model. For the SOFC, the input variables could constitute operational parameters such as fuel/oxidant compositions, temperatures, flow rates, and utilizations. Response variables could include electrical performance characteristics such as stack voltage, power output, and efficiency. Peak cell/stack temperature, cell temperature gradient, or maximum local current density are among other response variables that may be of interest due to their influence on cell/stack structural stability and performance degradation.

The developed numerical process for ROM generation is shown schematically by the flow chart in Exhibit 2-4. The number of different model input variables and their range of values are assigned based on expected SOFC operating conditions. This defines the multi-dimensional design space for the problem, and random sampling is performed to define sets of parameters. Each sample set defines a modeling case to be run. The detailed stack model then runs each of the defined cases and collects the results. Based on the expected usage of the ROM, the output parameters of interest are also defined. The corresponding values for these parameters are then extracted from the case results, and regression is performed to a selected fitting function. The regression results provide a mathematical relationship describing the predicted response surface for each response variable as a function of the input variables. These response surfaces are then exported in a suitable format for integrating the ROM into the system model. This ROM then provides a computationally efficient predictor of a given stack's performance without integrating the entire detailed model directly into the system model and adding further nonlinear convergence iterations to that solution. Further details of PNNL-ROM, the regression methodology, and its validation can be found in "Use of a Reduced Order Model (ROM) to Simulate SOFC Performance in System Models." [6]

Although the ROM procedure is applicable to comprehensive 3-D models, the stack is presently modeled using PNNL's SOFC-multi-physics (SOFC-MP) software [7] that solves for the steady-state cell distributions of species, temperature, and current density. The underlying 1-D channel cell model represents a 550 cm^2 active area anode-supported cell with metal interconnects in a counter-flow configuration. The model assumes the water-gas shift reaction is in equilibrium but uses a first-order kinetic expression for the slower on-cell steam reforming of methane with an Ni/YSZ anode. [7]

Exhibit 2-4. Overview of the ROM Generation Procedure and Usage



The voltage-current (V-I) relationship for the cell within the stack model is defined by a user-defined function that returns a voltage based on the local temperature, species concentrations, and current density at each location of the cell's active area. The stack model iterates on the current density distribution until the cell voltage is converged. The cell voltage is calculated by subtracting expressions for the activation, ohmic, and concentration polarization losses from the open circuit voltage as given by the equation:

$$V_{cell} = V_{OC} - \eta_{act} - i * R - \eta_{conc}^{anod} - \eta_{conc}^{cath}$$

Where V_{cell} is the cell voltage, V_{OC} is the open circuit potential, η_{act} is the voltage loss due to activation polarization, R is the overall ohmic resistance, and $\eta_{conc}{}^{anod}$ and $\eta_{conc}{}^{catd}$ are voltage losses due to diffusion polarization at the anode and cathode respectively. The coefficients used in the polarization equations were selected to provide a V-I response representative of high performance state-of-the-art (SOA) planar cells operating under atmospheric conditions. The selected cell performance provides 0.8V at 400 mA/cm^2 operating at a temperature of 750 °C for a wet hydrogen (H_2) fuel (97 percent H_2, 3 percent water [H_2O]) with 75 percent fuel utilization and 12.5 percent air utilization (see "Use of a Reduced Order Model (ROM) to Simulate SOFC Performance in System Models" [6] for the full V-I characteristics)

2.3.2 SOFC Carbon Deposition Control

The SOFC stack inlet anode gas composition can induce the formation of solid carbon deposits, which can disrupt the normal performance of the stack. [8] Anode gas recirculation is used to control the anode gas inlet conditions to maintain an atomic oxygen to carbon (OTC) ratio greater than 2.1, which is a generally used criterion to prevent carbon deposition anywhere in the SOFC fuel flow domain. [9] Anode gas recirculation is accomplished using hot gas blowers and serves to keep the fuel utilization within the stack below acceptable limits from a flow distribution perspective.

2.3.3 Estimation of Steam Bottoming Cycle Performance

The anode off-gas stream is combusted with O_2 for the cases with carbon capture, while a portion of the SOFC cathode exhaust is utilized for combustion in cases without carbon capture. In both cases, the hot stream from the combustor exchanges heat in an HRSG to produce steam, which generates power in a subcritical steam bottoming cycle after satisfying process steam requirements. The subcritical steam cycle varies greatly in its steam conditions and capacity in the study cases, providing a relatively small proportion of the total plant generation output. In some cases, the heat recovery temperature available is relatively low and results in poor steam superheat conditions. Rather than perform detailed design for each of these unique steam bottoming cycles, the steam cycle performance was estimated using a nominal efficiency of 38.1 percent, which was based on simulations of steam cycles in select pathway cases. [4] This approach has been shown to result in efficiencies that could be ±1.5 percentage points lower or higher than fully simulated steam cycle model values depending on whether the SOFC is operating at atmospheric or elevated pressures, respectively. The auxiliaries for the steam cycle were scaled from the BB report [10] based on the steam cycle power output.

2.4 PLANT CHARACTERISTICS

The basis for the selection of several key plant characteristics is discussed below.

2.4.1 Plant Capacity Factor

The capacity factor for the reference and NGFC baseline plants is assumed to be 80 percent, identical to that of the BB report's integrated gasification combined cycle (IGCC) plants, with the plant operating at 100 percent of its rated capacity. Other pathway study cases consider the economic benefits of increased plant capacity factors that will be realized with improved plant availability through greater operating experience, optimized maintenance procedures, and advanced monitoring. This report assumes that the plant would be dispatched any time it is available and would be capable of generating maximum capacity when online. Therefore, the capacity factor and plant availability are equal.

2.4.2 Plant Generating Capacity

The plant net generating capacity for all of the study cases is 650 MWe consistent with other fossil fuel plants assessed in the BB report to facilitate a direct comparison of costs.

2.4.3 Plant Sparing Philosophy and Number of Parallel Process Trains

No major equipment spares are utilized in the plant. In practice, degradation of SOFC performance is mitigated by providing additional capacity in the form of extra SOFC surface area, coupled with operational strategies to maintain a constant power output as discussed in Section 2.6.13.

The plants consist of single train processing for the ASU, the natural gas reformer area, the oxy-combustion, and the steam-cycle power island, as illustrated in Exhibit 2-5 for an NGFC system with CCS, where the captured CO_2 is dehydrated, compressed, and purified in the CPU. The corresponding NGFC plant without CCS is shown in Exhibit 2-6. Syngas expansion and cathode gas expansion, additional components that are included for pressurized SOFC operation, are also assumed to interact with the SOFC power island that is highly modular, as explained in Section 2.4.6, and is designed for the shutdown and bypass of individual modules to enable turndown. Accordingly, the NGFC plant part-load performance is limited primarily by the syngas-supply component (reformer, ASU) and the heat recovery component (oxy-comb, HRSG, steam cycle) turndown limitations, and the turndown capability should be comparable to IGCC with CCS. The load-follow capability of the NGFC, on the other hand, is primarily limited by SOFC heat-up rate constraints.

Exhibit 2-5. General NGFC Plant Configuration with CCS

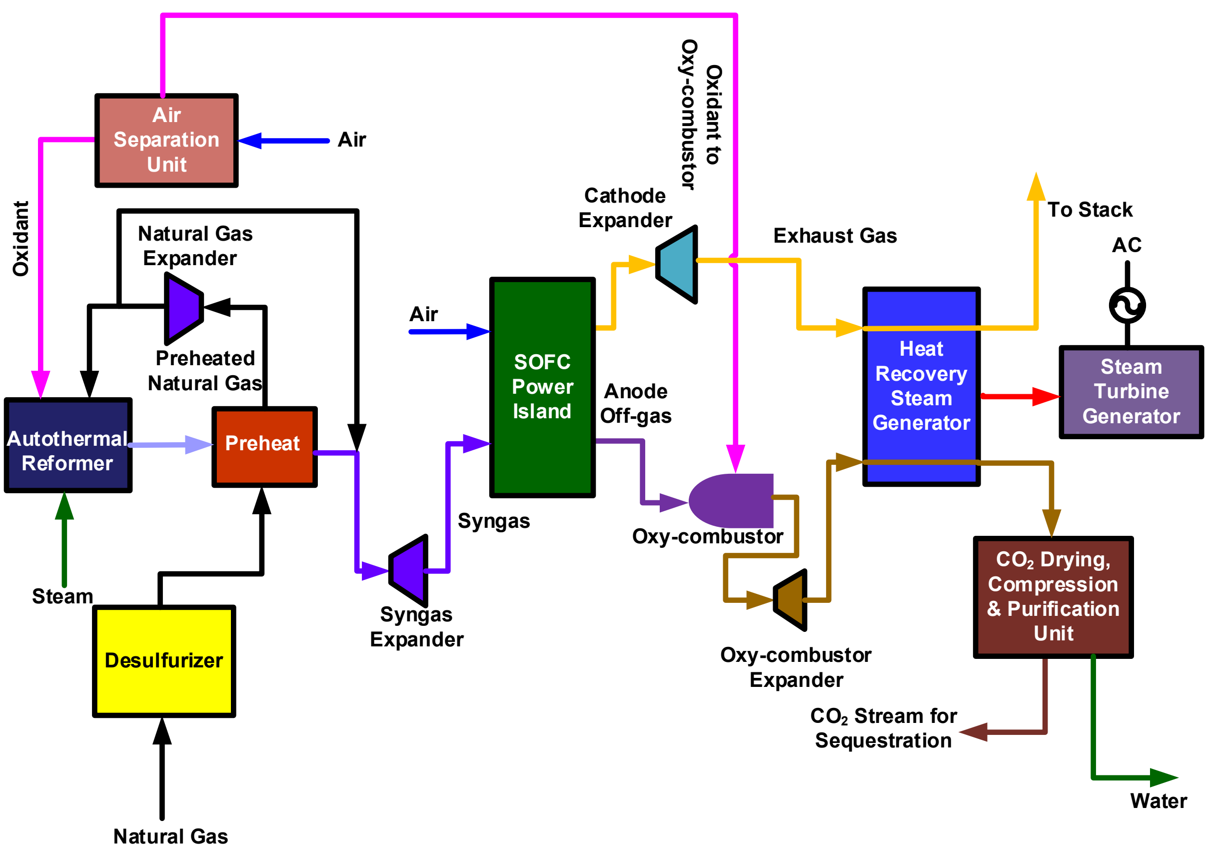
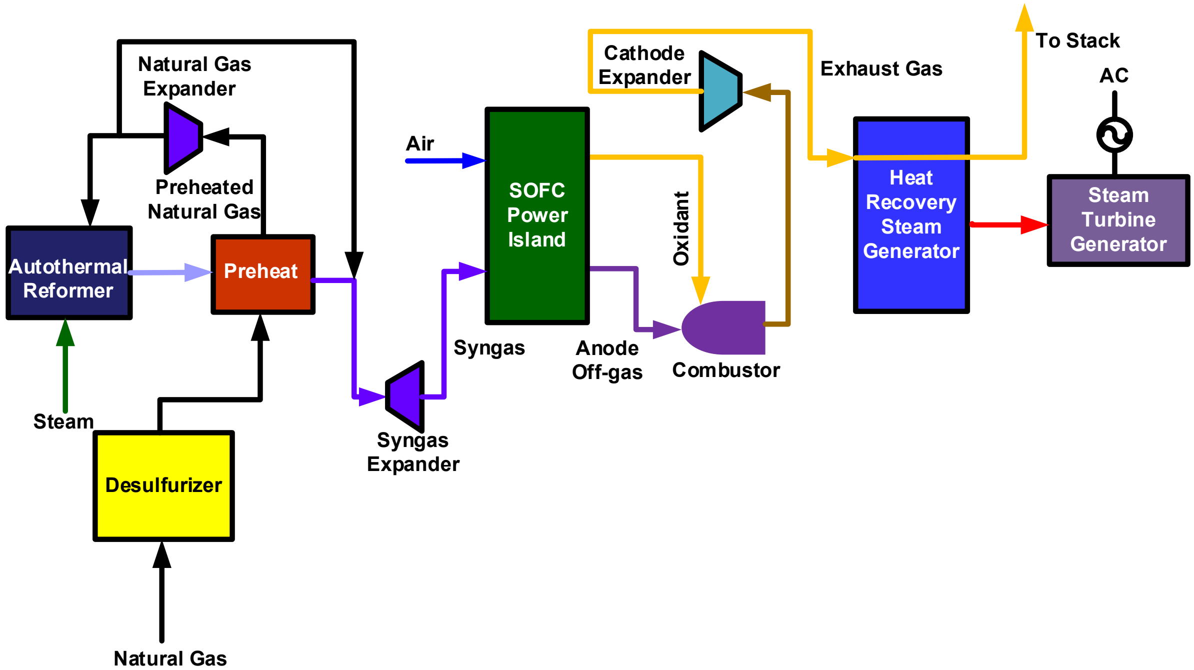


Exhibit 2-6. General NGFC Plant Configuration without CCS



2.4.4 Natural Gas Reforming Technology

The natural gas feed stream to the plant, delivered at 500 psia, is first preheated and expanded to the reformer working pressure. In the reference case with complete external reformation, all of the natural gas is reformed with steam and oxidant in an ATR to generate a high-heating value syngas, which is considered to be the most effective method to convert natural gas into a high-heating value syngas. [11], [12] In Case 1 and Case 2 only a portion of the natural gas feed (40 percent) is reformed in the ATR reflecting the SOA technology anticipated with the commercially viable DGFC system. This syngas is mixed with the remainder of the natural gas to yield a syngas having a methane content of about 30 mole-percent. In Case 3 and Case 4, the natural gas bypasses the ATR completely and is assumed to be reformed internally in an advanced SOFC unit.

2.4.5 Natural Gas Desulfurization Technology

The natural gas is desulfurized from its assumed 5 ppmv total sulfur content to 100 ppbv total sulfur using the low-temperature TDA Research Inc. (TDA) SulfaTrap™ sorbent before it is introduced to the plant. [13]

2.4.6 NGFC Power Island

The NGFC power island (refer Exhibit 2-5 and Exhibit 2-6) consists of a natural gas expander that expands the natural gas from its high-pressure condition down to the operating pressure of the reformer unit; a syngas expander that expands the syngas from its reformer outlet condition down to the operating pressure of the fuel cell unit; the SOFC power island with direct current

(DC) – alternating current (AC) inverters; an anode off-gas oxy-combustor; an HRSG that captures heat from the combusted anode off-gas; and a steam bottoming cycle.

The SOFC power island configuration is modular and is made up of a parallel train of 'sections' that are essentially assemblies of basic building blocks—the SOFC modules. SOFC modules are independently manufacturable units built upon the commercially viable 1 MWe class DGFC units that include planar SOFCs stacked and connected electrically in a convenient fashion. Each module is distinguished by an enclosure, which serves as a pressure and material boundary and houses the insulation system, the fuel and air distribution systems, the current collection systems, and the instrumentation and control (I&C) system in addition the SOFC stacks.

In the present study, the size of the modules was determined based on a nominal cell operating at a voltage of 0.8 V at a current density of 400 mA/cm^2, corresponding to a power density of 400 mW/cm^2. The module comprises several SOFC stacks, each consisting of 100 cells, each measuring 25 × 25 cm in cross-section, with an effective area of 550 cm^2. A 64-stack module was found to be suitable based on a variety of factors including the stack arrangement, module total current, module voltage rating, and shipping constraints. The 64-stack module, whose dimensions are listed in Exhibit 2-7 along with the salient assumptions, also aligns well with the development of a 1 MWe class systems currently being pursued under the fuel cell program. The enclosing pressure and material boundary for atmospheric and pressurized SOFC module are referred to as a "container" and "pressure" vessel respectively.

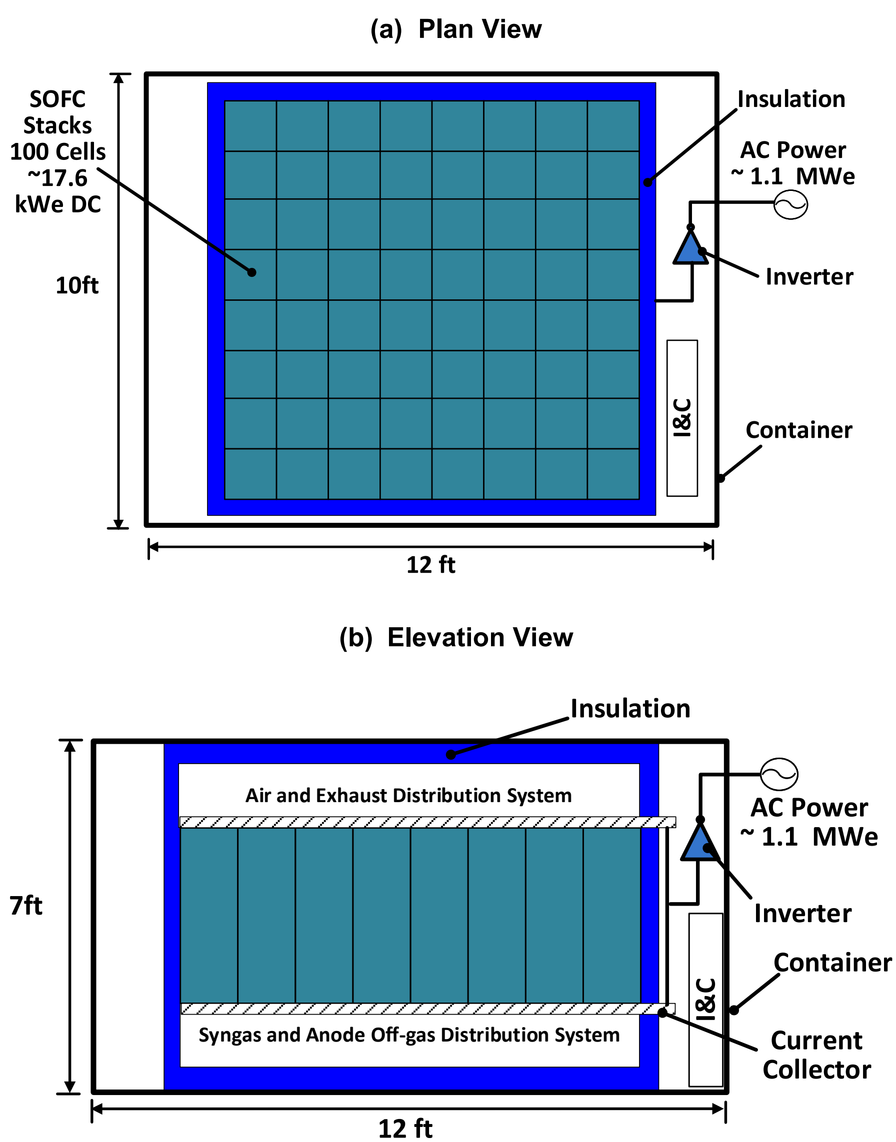
Exhibit 2-7. NGFC Module Sizing

Nominal Cell Potential (V)	0.8
Nominal Current Density (mA/cm^2)	400
Nominal Power Density (mW/cm^2)	320
Active Cell Area (cm^2)	550
Nominal Cell Current (A)	220
Cell Width in (cm)	9.84 (25)
Cell Length in (cm)	9.84 (25)
Cell Thickness in (mm)	0.315 (8)
Number of Cells per Stack	100
Nominal Stack Potential (V)	80
Nominal Stack Current (A)	220
Nominal Stack Power (kWe DC)	**17.6**
Stack Height (in)	31.5
Stack Pitch in Module Spanwise (x) Direction (in)	12.0
Stack Pitch in Module Lengthwise (z) Direction (in)	12.0
Insulation Thickness (in)	5
Additional spacing allowance for sub-systems	24
Spacing above and below stack for flow distribution	36
Number of Stacks per Module	64
Number of Stacks in Module Spanwise (x) Direction	8
Number of Stacks in Module Lengthwise (z) direction	8
Number of Cells per Module	**6400**

Total Current per Module (A)	**440**
Total Voltage per Module (V)	**2560**
Atmospheric SOFC Module rating (MWe DC)	**1.126**
Container/Vessel Head	Flat
Atmospheric SOFC Container Dimensions (ft)	**Width × Length × Height = 10 × 12 × 7**
Pressurized SOFC Vessel Dimensions (ft)	**Diameter × Length = 10 × 12**
Pressurized SOFC Vessel Diameter ft(in)	**9.9 (118.8)**

Plan and elevation views of the finalized SOFC module layout are shown schematically in Exhibit 2-8 (a) and (b), which also depict the major components that are considered to be within the module boundary for the present study.

Exhibit 2-8. NGFC Module Layout



Several SOFC modules are assembled into sections, which also houses SOFC BOP equipment such as heat exchangers, blowers, sectional I&C, and the power collection system for ease of thermal, flow, and power management. A section that consisted of 16 modules, as depicted by the layout in Exhibit 2-9, was deemed to be nominal in the present study from flow distribution and current collection perspectives. The power rating of the resulting section is ≈19 MWe and its salient electrical characteristics are listed in Exhibit 2-10. Trade-offs between the number of modules per section and the total system cost will be explored as a separate study.

Exhibit 2-9. SOFC Section Layout: Components and Dimension

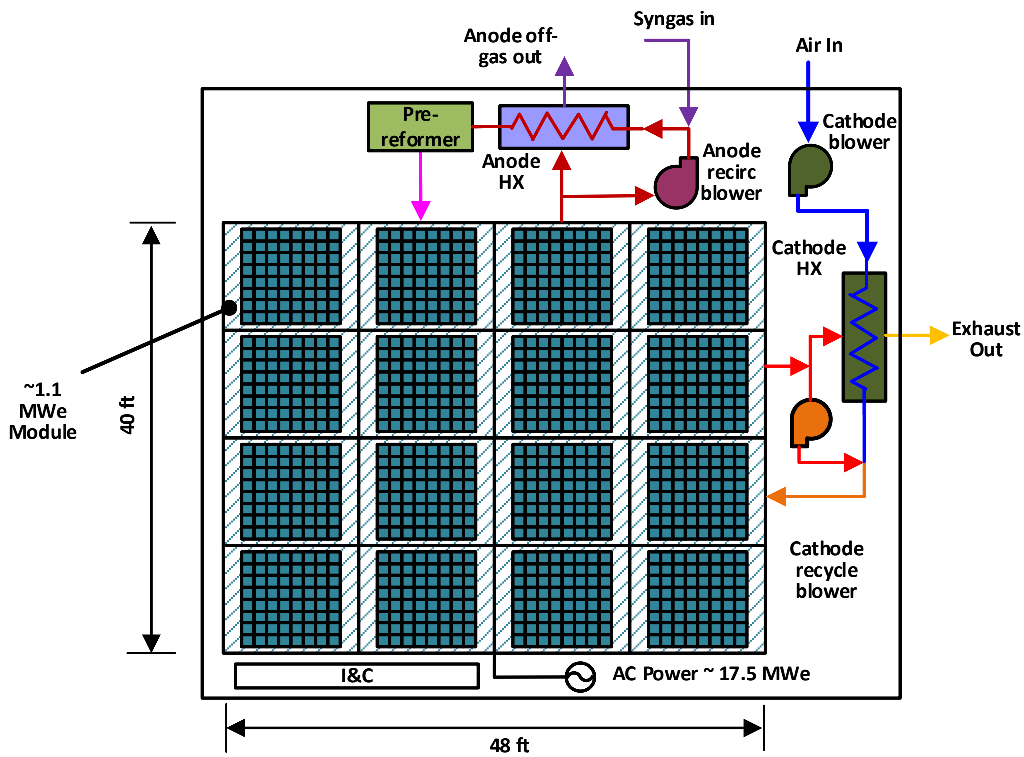
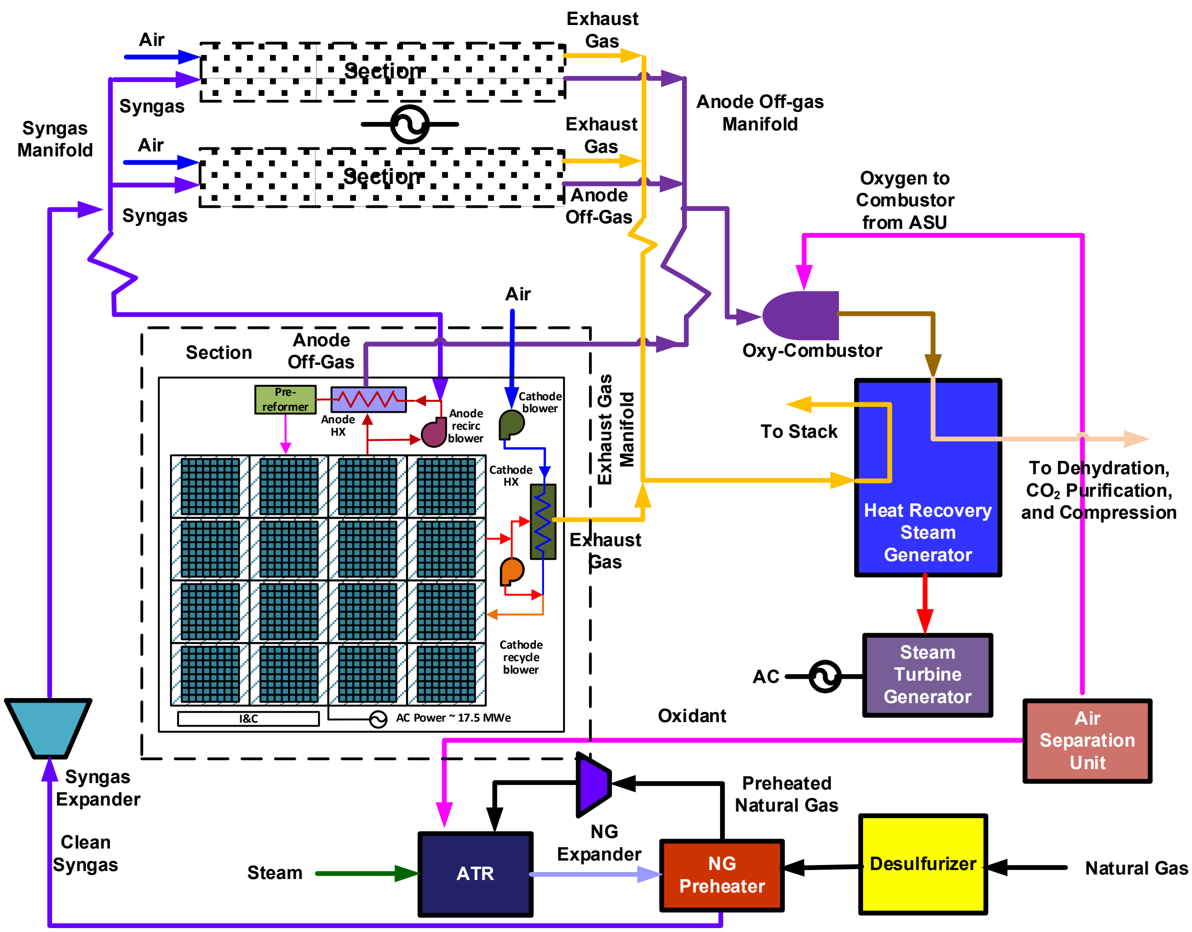


Exhibit 2-10. Characteristics of SOFC Section

Number of modules in parallel	4	
Number of modules in series	4	
Total current per section	1760	A
Total voltage per section	10240	V
Total power per section	17.6	MWe
Total current per section	1760	A

The overall system is a collection of sections, as shown in Exhibit 2-11, connected electrically in parallel, and pneumatically to produce the total rated power. A network of insulated pipes and ducts distribute the syngas from the central syngas expander to each section while the anode and cathode exhaust gases are collected and sent to a central oxy-combustor or combustor for plants with and without CCS, respectively. The pressurized SOFC system is nearly identical to the atmospheric system layout and features, in addition, a central cathode gas expander and a central oxy-combustor expander (for systems without CCS).

Exhibit 2-11. Atmospheric NGFC System Layout



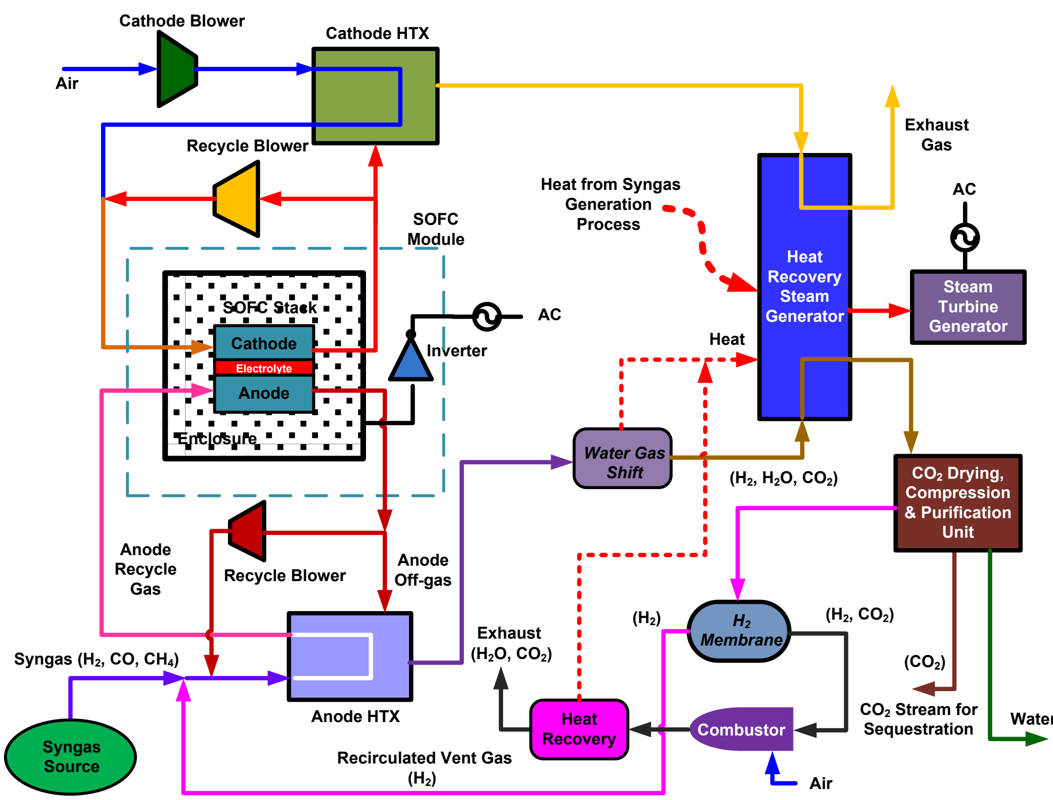
2.4.7 VGR Concept

The process diagram of the VGR in its most general form is shown in Exhibit 2-12. Unlike the usual SOFC-based systems, there is no oxy-combustor; the anode exhaust from the fuel cell flows through a water gas shift (WGS) reactor, which converts most of the CO to CO_2, before being fed to the CPU unit subsequent to heat recovery and dehydration. The vent gas stream remaining after the CO_2 separation in the CPU is rich in fuel containing mainly H_2 and CO_2. The H_2 in this mixture is separated using an H_2 membrane and fed back to mix with the fuel from the syngas source before entering the SOFC module. Depending on the CO_2 capture rate and the H_2 capture rate, exhausting a small portion of the CPU vent stream may be necessary due to mass balance considerations. However, the fuel energy in the exhausted residual fuel can be recovered in a normal air blown combustor. A conventional pressure swing adsorption process could also be used in place of the H_2 membrane.

The proposed system has several advantages:

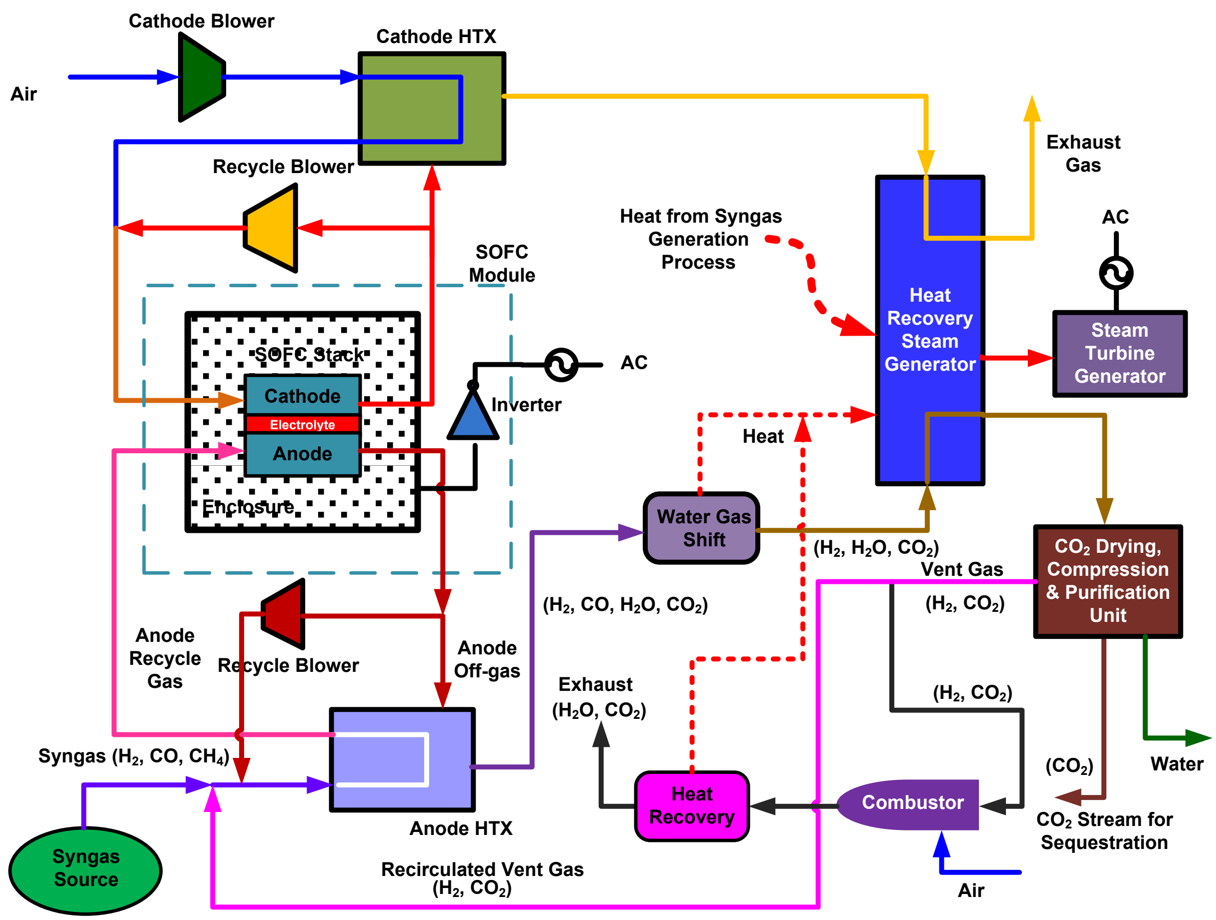
1. The single-pass fuel consumption across the fuel cell can be sufficiently low, even though an overall system fuel utilization of nearly 100 percent can be achieved by controlling the rate of VGR. This has a direct benefit on the system efficiency.
2. VGR also increases the chemical potential of the fuel entering the SOFC, thereby increasing the electrochemical (Nernst) potential and the system performance.
3. The oxy-combustor (along with its O_2 supply) is eliminated, lowering the ASU O_2 demand, and consequently, lowering the ASU parasitic load. In the case of an NGFC system with complete internal reformation, the ASU system is completely eliminated.
4. A higher VGR rate also makes the fuel cell system robust to fuel flow maldistributions and eases the design of fuel distribution systems.
5. At the same current load, the system allows operation at a cell voltage higher than conventional systems, alleviating performance degradation concerns.
6. The airflow rate to the SOFC system, which constitutes a major parasitic load, is also reduced due to the VGR serving as an additional coolant for removing the SOFC waste heat.
7. No additional technological advancements are needed to enable the system. It can be used with current technology.

Exhibit 2-12. Generalized Configuration of the VGR Concept



A more attractive version of the system without the need for a H_2 membrane is shown in Exhibit 2-13, where the CPU vent stream is directly fed back into the SOFC module fuel inlet without any separation of the H_2. The elimination of the feed stream compression required for the H_2 membrane, coupled with fuel losses due its < 100 percent effectiveness, are generally expected to offset adverse effects of the remnant CO_2 in the vent gas stream on the performance through dilution of the fuel entering the SOFC module. Further, elimination of the H_2 membrane, which is still in a developmental stage, results in improved cost savings and reliability.

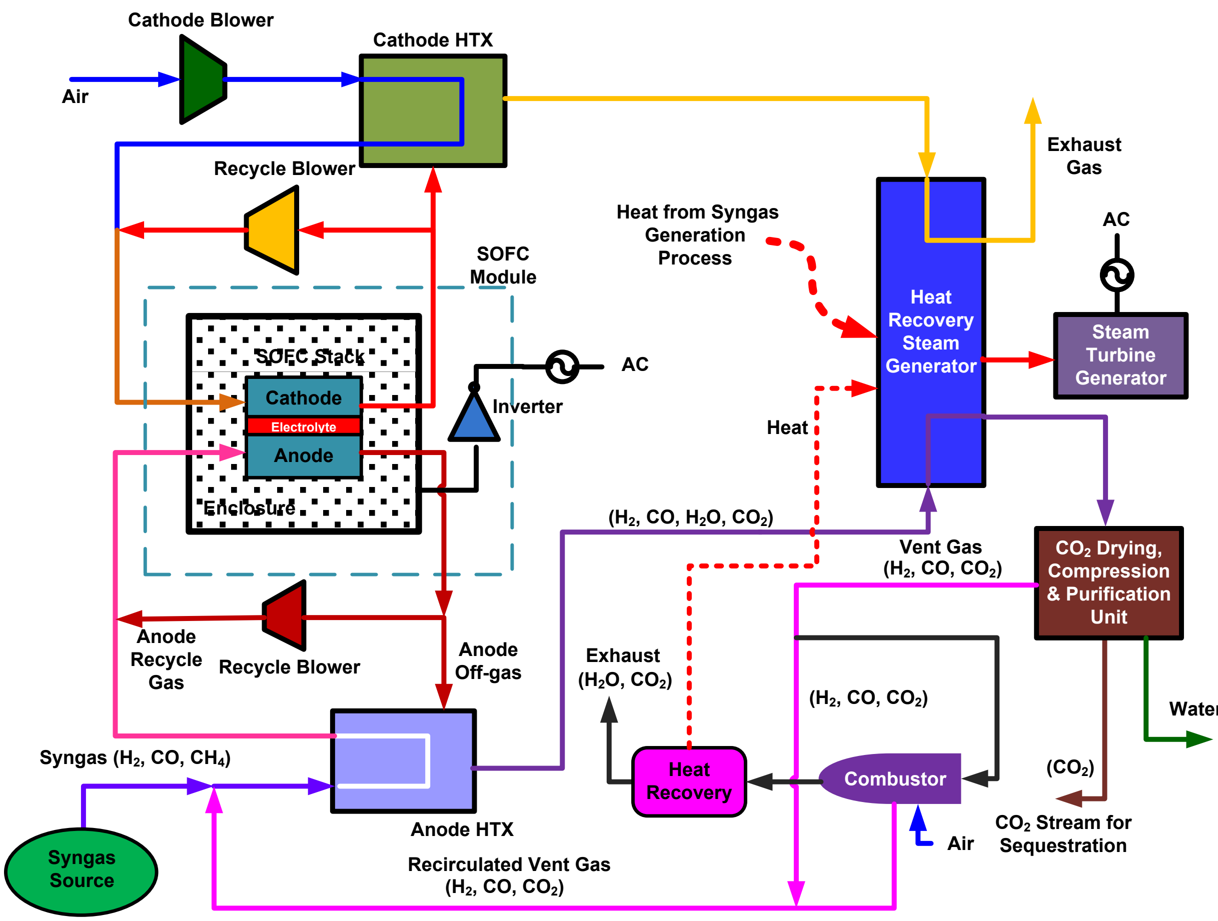
Exhibit 2-13. Configuration of the VGR concept without an H_2 Membrane



In this case, the recirculated vent gas contains CO and CO_2 and will need steam to maintain an oxygen-to-carbon ratio (OCR) of 2.1 to prevent carbon formation at the high temperatures within the SOFC module. The internal anode off-gas recirculation loop is accordingly an essential part of this system to avoid the need for external steam injection, which will have an adverse impact on the system efficiency and cost, to avoid carbon deposition due to any CO/CO_2 that mixes with the VGR. The combustor is located downstream of the CPU to maximize the rate of CO_2 capture and minimize any steam losses. Further, any valve needed to regulate the vent gas recirculation is in a cold region and can be easily controlled.

Exhibit 2-14 shows an alternate configuration of the proposed system, which eliminates the WGS reactor in addition to the H_2 membrane. This configuration is economically attractive and formed the basis for the VGR cases in the present study. Similar to the configuration with the H_2 membrane, exhausting a small portion of the CPU vent stream may be necessary due to mass balance considerations in the variants shown in Exhibit 2-14 and Exhibit 2-13, which also serves to limit the accumulation of inert species such as Nitrogen (N_2) and Argon (Ar) in the recirculating vent gas.

Exhibit 2-14. Configuration of the Proposed System without Both the WGS Reactor and the H_2 Membrane



2.4.8 Air Separation Unit

The conventional cryogenic ASU generates oxidant for use in two sections of the NGFC plant: the natural gas ATR, and the anode off-gas oxy-combustor. In this report, the ASU main air compressor discharge pressure was set at 0.5 MPa (79 psia), providing O_2 product at sufficient pressure, 0.16 MPa (23 psia), to operate the oxy-combustor for the atmospheric pressure SOFC applications. The ASU is designed to generate 99.5 percent pure O_2 for NGFC applications to maintain the sequestered CO_2 stream with low nitrogen and argon content. There is no opportunity for ASU air-side integration in the NGFC plant like there is in IGCC plants, and there is no need or benefit from nitrogen dilution of syngas in the NGFC. In this report, the ASU nitrogen product is used only for inert gas needs, with the remainder vented. The plant is designed with a single production train. The air compressor providing air to the process is powered by an electric motor.

2.4.9 CO_2 Capture Technology

The anode off-gas is combusted using 99.5 percent O_2 in an advanced oxy-combustor with excess O_2 limited to 1 mole percent. The combusted anode gas consisting of CO_2, water vapor, excess O_2, and minor traces of contaminants (sulfur species and oxides of nitrogen [NOx]) is sent to a CPU for compression, drying, and purification to pipeline/enhanced oil recovery (EOR) levels.[c] [14] In the CPU, the CO_2 is purified by liquefaction followed by flash separation and distillation. The cooling for the liquefaction is accomplished by an auto-refrigeration process. The CPU was designed to yield an O_2 content of 10 ppm in the CO_2 product stream.[d] The CPU cost was scaled based on an available quote.

2.5 ENVIRONMENTAL REQUIREMENTS

The emissions estimated to result from the NGFC plant are far lower than any current environmental regulations for fossil fuel power plants. It is assumed that plant permitting requirements will be based on these capabilities.

2.5.1 NGFC Emission Perspective

The NGFC plant emissions are insignificant because the total sulfur content in the natural gas must be less than 100 ppbv to protect the fuel cell materials. The oxy-combustor is a low NOx producing combustor, and all of the remaining contaminant species are sequestered with the CO_2. The plant has nearly 100 percent removal of all environmental contaminants, including CO_2. Water usage is also estimated to be extremely low in the NGFC plants. The pipeline natural gas is assumed to contain no particulate matter or trace elements, resulting in no control requirements being needed other than natural gas desulfurization.

2.6 ECONOMIC ANALYSIS

Capital and production cost estimates follow the economic basis applied in the BB report, which provides factored estimates developed for each plant section for conventional fossil fuel plants. [1] This report scales those costs for comparable plant sections that appear in the NGFC plants. Costs were factored using operating variables and scaling exponents appropriate for each system account. Costs for unique equipment in the NGFC plants were estimated using available generalized cost correlations or using cost estimates for comparable equipment reported in other power plant studies. In the case of the SOFC stack components, the estimated capital

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[c] The QGESS reference [14] recommends a CO_2 purity of at least 95 percent as a conceptual design basis for EOR purposes; however, distillation methods used to meet the more stringent O_2 concentration requirement of 100 ppmv or less generally result in 99.9 percent + CO_2 purity.

[d] An O_2 concentration of 10 ppmv in the CO_2 product stream was selected as the basis for conceptual design since it represents the lower limit of the range of values recommended in literature for EOR applications. [14] The number of distillation stages can be reduced slightly to design to the upper limit of 100 ppmv for O_2 concentration. [14] However, the impact of the associated small decrement in distillation cost on the overall cost is expected to be insignificant.

costs were based on current NETL technology development cost goals and SOFC vendor projections.

2.6.1 Estimate Scope

The estimates represent a complete power plant facility on a generic site. Site-specific considerations such as unusual soil conditions, special seismic zone requirements, or unique local conditions such as accessibility or local regulatory requirements are not considered in the estimates.

The estimate boundary limit is defined as the total plant facility within the "fence line," including coal receiving and water supply system, but terminating at the high voltage side of the main power transformers. The single exception to the fence line limit is in the CO_2 capture cases where costs are included for transport and storage (T&S) of the sequestered CO_2.

2.6.2 Capital Costs

NETL with KeyLogic Systems, Inc., and Black & Veatch developed the capital cost estimates for NGCC plants in the BB report using the company's in-house database and conceptual estimating models for each of the specific technologies. The estimating models are based on a reference bottom-up estimate for each major component. This provides a basis for subsequent comparisons and easy modification when comparing between specific case-by-case variations.

Some equipment costs for the cases were calibrated to reflect recent quotations and/or purchase orders. [1] These include, but are not limited to, the following equipment:

- Steam Turbine Generators
- Circulating Water Pumps and Drivers
- Cooling Towers
- Condensers
- Air Separation Units (partial)
- Main Transformers

Other key estimate considerations include the following:

- Labor costs are based on Midwest Merit Shop. Costs would need to be re-evaluated for projects at different locations or for projects employing union labor.
- The estimates are based on a competitive bidding environment, with adequate skilled craft labor available locally.
- Labor is based on a 50-hour work week (5-10 h days). No additional incentives such as per-diem or bonuses have been included to attract craft labor.
- While not included at this time, labor incentives may ultimately be required to attract and retain skilled labor depending on the amount of competing work in the region and the availability of skilled craft in the area at the time the projects proceed to

construction. Current indications are that regional craft shortages are likely over the next several years. The types and amounts of incentives will vary based on project location and timing relative to other work. The cost impact resulting from an inadequate local work force can be significant.

- The estimates are based on a greenfield site.
- The site is considered to be Seismic Zone 1, relatively level, and free from hazardous materials, archeological artifacts, or excessive rock. Soil conditions are considered adequate for spread footing foundations. The soil bearing capability is assumed adequate, so piling is not needed to support the foundation loads.
- Costs are limited to within the fence line, terminating at the high-voltage side of the main power transformers with the exception of costs included for T&S of the sequestered CO_2 in all capture cases.
- Engineering and Construction Management were estimated as a percent of bare erected cost were based on the BB report [1] for NGCC technologies. These costs consist of all home office engineering and procurement services as well as field construction management costs. Site staffing generally includes construction manager, resident engineer, scheduler, and various personnel for project controls, document control, materials management, site safety, and field inspection.
- All capital costs are presented as "Overnight Costs" in June 2018 dollars. Escalation to period-of-performance is specifically excluded.

The current-dollar, LCOE was calculated for each case using economic parameters for high-risk technologies resulting in a capital charge factor of 0.124.[e] The capital component of LCOE was calculated using the total overnight cost (TOC).

2.6.3 Plant Maturity

The pathway plants simulated include technologies at different commercial maturity levels, and the NGFC plants contain some advanced, immature technologies. The SOFC and oxy-combustion technologies are immature and unproven at commercial scale in power generation applications.

The developing SOFC technology performance and cost has been estimated through scaling to commercial levels by the SOFC developers. While commercial pre-combustion CO_2 removal technology could be applied in place of the oxy-combustion-based CO_2 removal, the advantages of oxy-combustion approach over pre-combustion CO_2 removal are so large that the oxy-combustion technology merits development support.

[e] The value of capital charge factor that has been historically used in previous baseline studies [10] has been used in the present study since the financial calculations for the latest baseline studies [1] were not finalized at the time of writing this report.

2.6.4 Exclusions

The capital cost estimate includes all anticipated costs for equipment and materials, installation labor, professional services (Engineering and Construction Management), contingency, and owner's costs. The following items are excluded from the capital costs:

- Site specific considerations – including, but not limited to, seismic zone, accessibility, local regulatory requirements, excessive rock, piles, laydown space
- Labor incentives in excess of a 5-day/10-hour work week
- Additional premiums associated with an engineer/procure/construct (EPC) contracting approach

2.6.5 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 total plant cost (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 because of continued technology development.

The project and process contingencies applied were taken from the BB report [1] for comparable equipment items. The contingencies applied are listed in Exhibit 2-15. No project contingency has been applied to the SOFC stack unit cost because these contingencies are already being incorporated by vendor estimates for the SOFC stack unit. A 15 percent project contingency has been applied to the ancillary components in the SOFC power island.

Exhibit 2-15. Project and Process Contingencies

Equipment Component	Project Contingency	Process Contingency
Natural Gas Desulfurization	0	0
ATR & Syngas Cooler	0	15
ASU & Oxidant Compressor	0	10
SOFC Power Island		
NG Expander/Syngas Expander/Oxy-combustor Expander	15	15
SOFC Reactor	0[f]	0[5]
Cathode Air Blower/Compressor	15	15
Cathode Recycle Gas Blower	15	15
Cathode Heat Exchanger	15	15
Cathode Gas Expander	15	15

[f] No contingency is applied; the SOFC reactor cost is based on an NETL development goal.

Equipment Component	Project Contingency	Process Contingency
Anode Heat Exchanger	15	15
Anode Recycle Gas Blower/Jet Pump	15	15
Oxy-Combustor	15	15
Oxy-Combustor Expander	15	15
Feedwater & Misc. BOP Systems	20	15–20[A]
HRSG, Ducting & Stack	20	15–20[A]
Steam Power System	20	15–20[A]
Cooling Water System	20	15–20[A]
Accessory Electric Plant	20	15–20[A]
Instrumentation & Control	20	15
Improvements to Site	20	20
Buildings & Structures	20	15

[A] Contingency varied for different cost items under the main category

2.6.6 Current-Dollar Levelized Cost of Electricity

The figure of merit, the LCOE without T&S, was determined as specified in the NETL Quality Guidelines for Energy System Studies (QGESS) using a simplified model derived from the NETL Power Systems Financial Model. [1] The cost premises applied in the BB report are applied in this report. The NGFC plants are treated as high-risk plants to generate LCOE values.

The first-year cost of natural gas used in this report is $4.42/MMBtu ($4.19/MMkJ) (cost of natural gas in 2018 dollars) in accordance with the BB report. [1]

2.6.7 Capital Costs

Following the basis in the BB report, [1] the capital costs at the TOC level include equipment, materials, labor, indirect construction costs, engineering, owner's costs, and contingencies. Where applicable, the cost of major plant sections in the study case plants were based on a scaled estimate from the BB report, applying the general cost-scaling equation

$$C = N * (C_{ref} / N_{ref}) * [(F / N) / (F_{ref} / N_{ref})]^S$$

where:

C is the cost of the study case plant section

N is the number of parallel sections in the study case plant

C_{ref} is the cost of the reference plant section

N_{ref} is the number of parallel sections in the reference plant

F is the scaling capacity for the study case plant section

F_{ref} is the scaling capacity for the reference plant section

S is the scaling factor characteristic of the plant section equipment (a fraction usually between 0.5 and 0.8)

In addition:

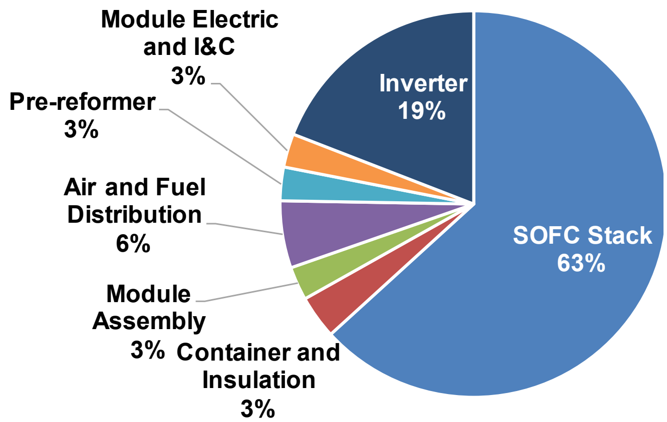
- The estimates represent n^{th}-of-a-kind (NOAK) offerings for everything except the natural gas reforming system, the natural gas desulfurization system, the CO_2 purification and compression system, and the oxy-combustor system, which are considered initial commercial offerings (i.e., first of a kind).
- The estimates represent a complete power plant facility, except for the exclusions listed in Section 2.6.4.
- The estimate boundary limit is defined as the total plant facility within the fence line and includes the water supply system and the CO_2 transport storage and monitoring. Electrical output within the fence line terminates at the high voltage side of the main power transformers.
- Costs are grouped according to a process/system-oriented code of accounts; all reasonably allocable components of a system or process are included in the specific system account in contrast to a facility, area, or commodity account structure.

2.6.8 SOFC Module Costs

The NETL goal of $225/kWe in 2018$ for the stack cost forms the basis for the SOFC cost calculations. The atmospheric SOFC module cost is itemized in Exhibit 2-16 according to the major components within the module (as in Exhibit 2-8). Wherever available, costs were scaled based on the references based on the references indicated. The cost of the container for atmospheric systems was estimated from commercial shipping container costs while costs for air distribution, fuel distribution, and current collectors were estimated based on authors' previous industrial experience. The SOFC stacks and Inverter account for nearly 85 percent of the module costs as shown by the cost distribution pie chart.

Exhibit 2-16. Atmospheric SOFC Module Costs

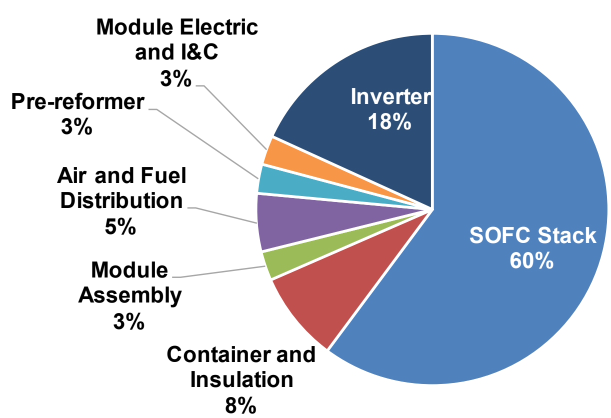
Module Costs (2018$/kWe AC) Atmospheric		
SOFC Stack	225	
Container	9	[15]
Insulation	4	[16]
Module Assembly	10	[16]
Air Distribution	10	Estimate
Fuel Distribution	10	
Module Current Collectors	5	
Module I&C	5	
Inverter	68	[17]
Total Module	356	



The corresponding costs for the pressurized SOFC module are shown in Exhibit 2-17 and differ only by the enclosure cost, which was estimated using Aspen Activated analyses and reflects the significantly higher cost for the pressure vessels required for pressurized SOFC operation.

Exhibit 2-17. Pressurized SOFC Module Costs

Module costs (2018$/kWe AC) Pressurized		
SOFC Stack	225	
Pressure Vessel	27	Estimated from Aspen Activated Analysis
Insulation	4	[16]
Module Assembly	10	[16]
Air Distribution	10	Estimate
Fuel Distribution	10	
Module Current Collectors	5	
Module I&C	5	
Inverter	68	[17]
Total Module	374	



2.6.9 Operation and Maintenance

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

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

There are two components of O&M costs: fixed O&M, which is independent of power generation, and variable O&M, which is proportional to power generation. The approach followed in estimating these costs is consistent with that applied in the BB report. [1]

2.6.10 Operating Labor

Operating labor cost was determined based on the number of operators required for each specific case. The average base labor rate used to determine annual cost is $38.50/h. The associated labor burden is estimated at 30 percent of the base labor rate. Six operators per shift are assumed in all cases.

2.6.11 Administrative and Support Labor

Labor administration and overhead charges are assessed at rate of 25 percent of the burdened O&M labor.

2.6.12 Maintenance Material and Labor

Maintenance cost was evaluated on the basis of relationships of maintenance cost to initial capital cost. This represents a weighted analysis in which the individual cost relationships were considered for each major plant component or section. The exception to this is the maintenance cost for the combustion turbines, which is calculated as a function of operating hours.

2.6.13 Stack Degradation and Production Costs

SOFCs have the potential to operate over a long period of time as demonstrated in laboratory scale tests, where operation for over five years has been demonstrated without appreciable loss of performance. [18] However, with current planar stack technologies, stack performance has been observed to decline over its lifetime, generally due to an increase in the apparent electrical resistance of the stack associated with a variety of material and design related factors, which limits the permissible current at the same voltage (in a constant potential operation mode). Performance degradation limits the operating lifetime of the capital intensive SOFC stack and forms a significant component of the production costs. The present study adopts the methodology developed in the previous pathway study [3] to estimate the production costs.

2.6.14 Consumables

The cost of consumables, including fuel, was determined based on individual rates of consumption, the unit cost of each specific consumable commodity, and the plant annual operating hours. Initial fills of the consumables, fuels, and chemicals are different from the initial chemical loadings, which are included with the equipment pricing in the capital cost. The quantities for initial fills and daily consumables were calculated on a 100 percent operating capacity basis. The annual cost for the daily consumables was then adjusted to incorporate the annual plant operating basis, or capacity factor. Exhibit 2-18 lists the catalyst and chemicals initial fill and consumption rate and the price bases applied in the evaluation.

Exhibit 2-18. Catalyst and Chemicals Consumption and Cost Basis

Chemical/Catalyst	Initial Fill Scaling Factor	Use Rate Scaling Factor	Price Assumption	Source
MU & WT chemicals	N/A	Raw water consumption	\$0.28/lb	[1]
ATR catalyst	Syngas rate	Syngas rate	\$602/m^3	Engineering Estimate
TDA natural gas sulfur sorbent	Sulfur capture rate	Sulfur capture rate	\$6.00/lb	Vendor data adjusted to 2018\$

2.6.15 Owner's Costs

The owner's costs to be included in the TOC were estimated following the procedures described in the BB report. [1]

2.7 Raw Water 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 available from various sources like boiler feedwater blowdown and condensate from CO_2 gas compression 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 surface-water 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 where it was withdrawn.

Raw water makeup was assumed to be provided 50 percent by a publicly owned treatment works and 50 percent from groundwater. Raw water withdrawal is defined as the water metered from a raw water source and used in the plant processes for all purposes, such as cooling tower makeup, or boiler feedwater makeup. The difference between withdrawal and process water returned to the source is consumption. Consumption represents the net impact of the plant on the water source.

Boiler feedwater blowdown was assumed to be treated and recycled to the cooling tower. The cooling tower blowdown was assumed to be treated and 90 percent returned to the water source with the balance sent for evaporation.

The largest consumer of raw water in all cases is cooling tower makeup. It was assumed that all cases utilized a mechanical draft, evaporative cooling tower, and all process blowdown streams were assumed to be treated and recycled to the cooling tower. A cooling water temperature of 16°C (60°F) with an approach of 5°C (8.5°F) is used. The cooling water range was assumed to be 11°C (20°F). The cooling tower makeup rate was determined using the following: [1]

- Evaporative losses of 0.8 percent of the circulating water flow rate per 10°F of range
- Drift losses of 0.001 percent of the circulating water flow rate
- Blowdown losses were calculated as follows:
    - Blowdown Losses = Evaporative Losses / (Cycles of Concentration - 1)

where Cycles of Concentration is a measure of water quality, and a mid-range value of 4 was chosen for this report.

The water balances presented in subsequent sections include the water demand of the major water consumers within the process, the amount of process water returned to the source, and the raw water consumption, by difference.

2.8 CO_2 TRANSPORT AND STORAGE

The CO_2 T&S cost is calculated as $10/tonne in accordance with the QGESS specifications. [19]

3 NGFC Plant Major Process Areas

The NGFC plant consists of several integrated process areas, the primary ones being ASU, the reformer area, the power island, and the CO_2 dehydration, compression, and purification area. Descriptions of these areas and their selected technologies are presented in this report section. Additional case-specific performance information is presented in the relevant pathway sections.

3.1 Air Separation Unit

The conventional cryogenic ASU generates oxidant for two sections of the NGFC plant: the natural gas ATR, and the anode off-gas oxy-combustor. In this report, the ASU main air compressor discharge pressure was set at 0.5 MPa (79 psia), providing O_2 product at sufficient pressure, 0.16 MPa (23 psia), to operate the oxy-combustor for the atmospheric pressure SOFC applications. The ASU is designed to generate 99.5 percent pure O_2 for NGFC applications to maintain the sequestered CO_2 stream with low nitrogen and argon content. Unlike IGCC plants, the opportunity for ASU air-side integration is limited for NGFC systems. Nitrogen dilution of syngas, while being detrimental to the SOFC performance, could also adversely impact the CCS process. In this report, the ASU nitrogen product is used only for inert gas needs, with the remainder vented. The plant is designed with a single production train. The air compressor providing air to the process is powered by an electric motor.

The performance and cost of the ASU in the present study are based on available quotes for a cryogenic ASU designs that were optimized for atmospheric oxy-combustion and used in NETL's oxy-combustion studies. [20] The ASU design yielded a 95 vol% pure O_2 stream at nearly atmospheric pressures while imposing an auxiliary electrical load of 195 kWh/tonne O_2 on the overall plant, which is consistent with the range of values generally cited in the literature. [21] Based on quotes from the same vendor for O_2 purities higher than 95 vol%, the parasitic load increase and the cost penalty for generation of the 99.5 percent O_2 purity stream in the present study was estimated to be 3.5 percent (ASU load ≈202 kWh/tonne O_2) and 4 percent respectively. As in the advanced oxy-combustion study, [20] an ASU performance improvement of 20 percent (ASU load ≈160 kWh/tonne O_2) is assumed without any cost penalty to reflect advances in ASU technology in Case 4.

The ASU representation applied for this evaluation is greatly simplified with the ASU performance taken into consideration in post-processing. An O_2 compressor is utilized in conjunction with the atmospheric ASU to pressurize the oxidant for the pressurized cases. The O_2 compressor is directly modeled, and the cost was scaled based on air compressor.

3.2 Natural Gas Reforming Area

Various types of natural gas reformers are commercially available to generate a syngas suitable for the NGFC power generation application. The major types include the steam-methane reformers, the partial oxidation reformer, and the ATR. Of these, the ATR is expected to be the cheapest and most reliable reformer available for the simple generation of syngas containing H_2 and carbon monoxide (CO) [12], [13] and is selected for use in this evaluation.

The ATR was first developed by Haldor Topsoe in the late 1950s. It consists of a refractory-lined pressure vessel that contains two reaction zones, a combustion zone followed by a catalytic reforming zone. Steam is mixed with pressurized natural gas in proportions that prevent soot formation within the high-temperature combustion zone. This mixture is preheated and fed to a burner nozzle fired with a pressurized, preheated O_2 stream. The burner nozzle is directed into the ATR combustion zone where partial oxidation of the fuel, heating, and recirculation mixing occurs, with temperature reaching up to 1900°C. Soot is prevented from forming in this zone if sufficient steam is provided.

The partially oxidized mixture then flows uniformly through internal, refractory distribution devices, into the catalytic reaction zone where methane is reformed and the water gas shift reaction proceeds. A near equilibrium condition is reached in this Ni-based catalyst zone, with exit temperature in the range of 900 to 1100°C. The Ni-based catalyst may be in the form of a packed bed or a honeycomb-supported structure that allows greater space velocity with acceptable pressure drop. Pressurized operation of the ATR for various synthesis applications is typical at pressures up to 60 atm, but low-pressure operation is also feasible.

The process diagram for the reformer area and the syngas feed to the SOFC unit for Case 1 and Case 2 is shown in Exhibit 3-1 (a) and (b) for pressurized and atmospheric scenarios. A natural gas expander is used to expand the high pressure (500 psia) natural gas to near atmospheric pressure before it enters the atmospheric ATR utilized for atmospheric SOFC operation. In the case of pressurized scenarios, instead of the natural gas expander, a syngas expander downstream of the high-pressure ATR is employed to expand 85 percent of the syngas to the operating pressure of the SOFC. The remaining portion of the high-pressure syngas is used to supply the motive force for anode gas recirculation using a jet-pump.

ATR bypass paths are included in both pathway cases to achieve the desired amount of reformation carried out external to the stack. Only 40 percent of the natural gas is reformed in the ATR for Case 1 and Case 2. The reformer syngas product is mixed with the remaining 60 percent of the natural gas feed resulting in an SOFC fuel gas stream with a methane (CH_4) content that is close to the highest value supported by current SOFC technology. The ATR is eliminated, and the incoming natural gas is directly fed into the SOFC unit in Case 3 and Case 4, which assumes complete reformation of natural gas internal to the SOFC unit. Exhibit 3-2 summarizes the operating conditions selected and the assumptions applied for the ATR in the present study. The ATR is assumed to be capable of achieving the equilibrium syngas composition with no soot formation or carbon loss.

The ATR is driven by O_2 for the NGFC system featuring CCS while an air-blown ATR is assumed for systems without CCS.

Exhibit 3-1. Autothermal Reforming and Syngas Feed to SOFC

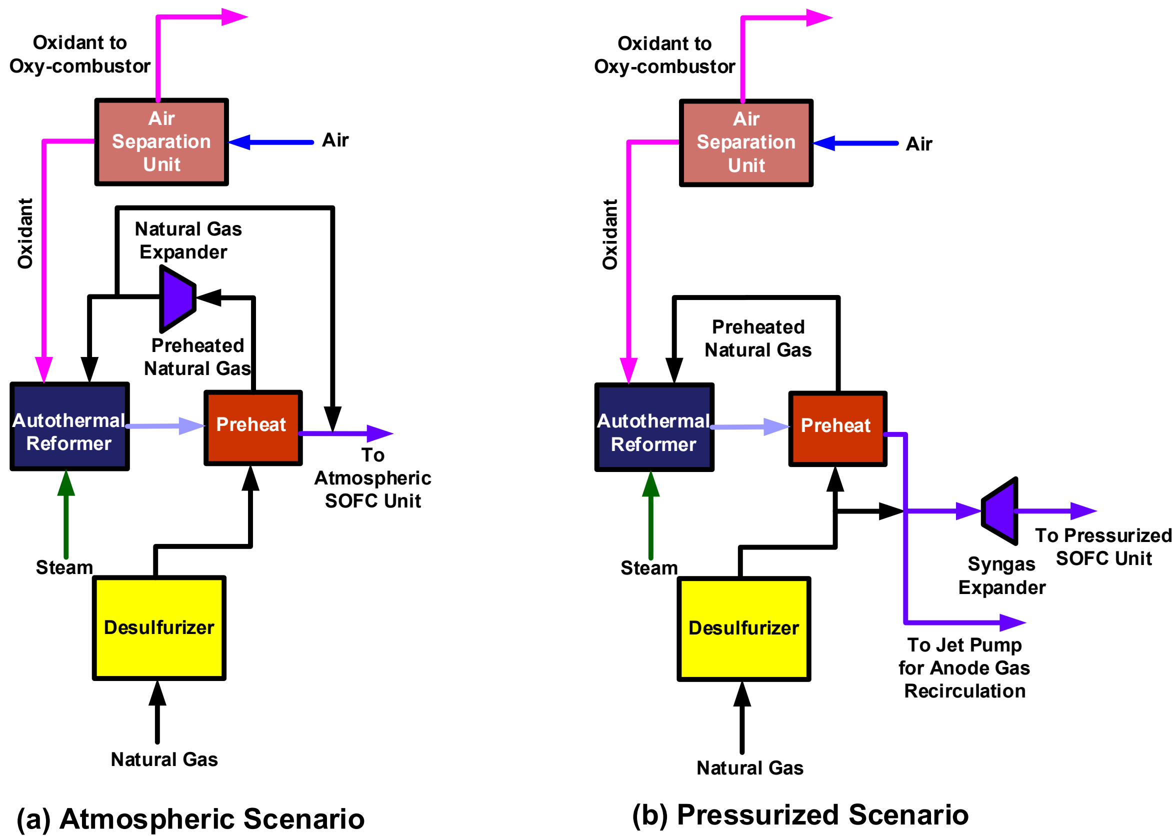


Exhibit 3-2. Natural Gas Reformer Section Operating Conditions and Assumptions

Parameter	With CCS		Without CCS	
Scenario	Atmospheric	Pressurized	Atmospheric	Pressurized
Oxidant	Oxygen		Air	
NG reformed, % of total	40			
Natural gas reformer				
Technology	Auto Thermal Reactor (ATR)			
Number reformers in parallel	1			
Exit temperature, °C (°F)	882 (1619)	938 (1721)	882 (1450)	788 (1450)
Exit pressure, MPa (psia)	0.14 (20)	3.10 (450)	0.14 (20)	3.10 (450)
Natural Gas preheat temperature, °C (°F)	477 (890)	204 (400)	477 (890)	204 (400)
Oxygen-to-reformer NG mass feed ratio	1.1			
Oxygen preheat temperature, °C (°F)	40 (104)	130 (265)	40 (104)	325 (617)
Steam-to-Natural Gas molar ratio	1.04			
Steam feed temperature, °C (°F)	149 (300)	466 (500)	149 (300)	466 (500)
Carbon loss, % of Natural gas carbon	0			
Raw syngas composition basis	Equilibrium			
SOFC feed gas methane content, mol%	25.0	17.8	27.6	22.5
Natural gas heater				
Technology	Tube-in-shell			
Number in parallel	1			
Outlet temperature, °C (°F)	129 (265)	804 (1480)	298 (569)	698 (1289)

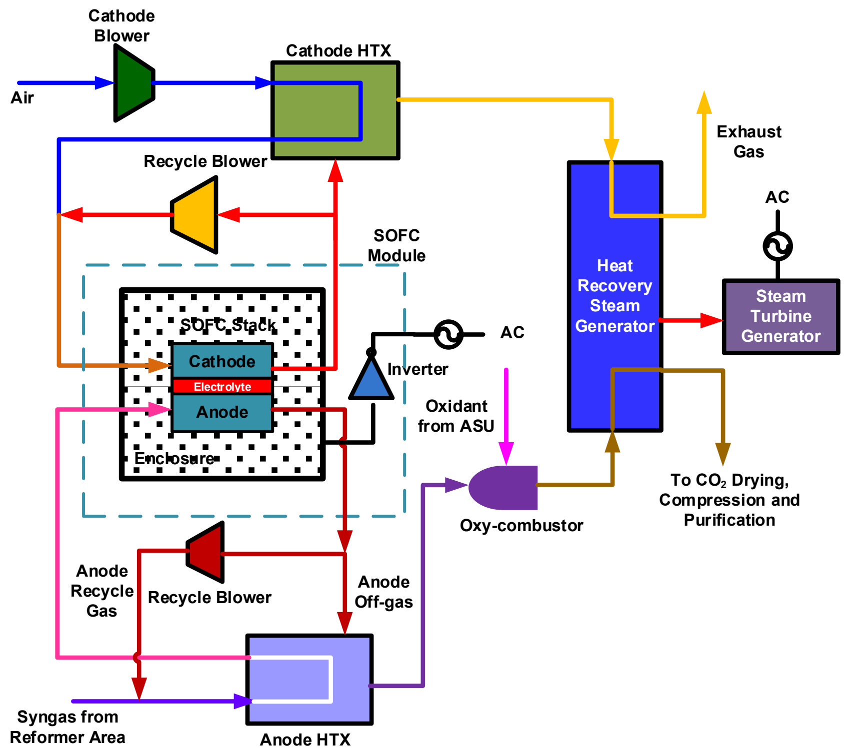
3.3 Power Island

The NGFC power island for Scenario 1 with atmospheric SOFC operation is shown in Exhibit 3-3 and consists of the SOFC unit with DC-AC inverter expander, an anode off-gas combustor, an HRSG that captures heat from the combusted anode off-gas, and a steam bottoming cycle. The power island for Scenario 1 includes a natural gas expander (Exhibit 2-5) that is utilized within the natural gas reforming area. The primary difference between systems with and without CCS is the utilization of the vitiated cathode gas as the oxidant for the combustion of the anode off-gas in the latter.

The NGFC power island for the pressurized Scenario 2, depicted in Exhibit 3-4, includes in addition, a syngas expander, a cathode gas expander, and, in the case of a system with CCS, an oxy-combustor expander.

Exhibit 3-3. Scenario 1 – Atmospheric NGFC Power Island with and without CCS

(a) With CCS



(b) Without CCS

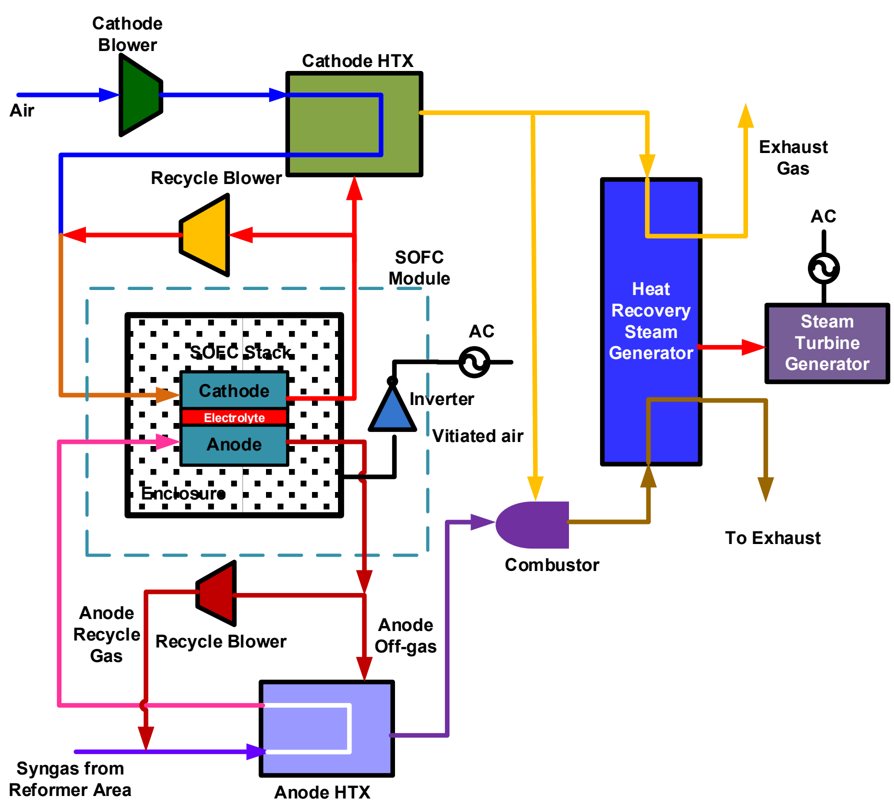
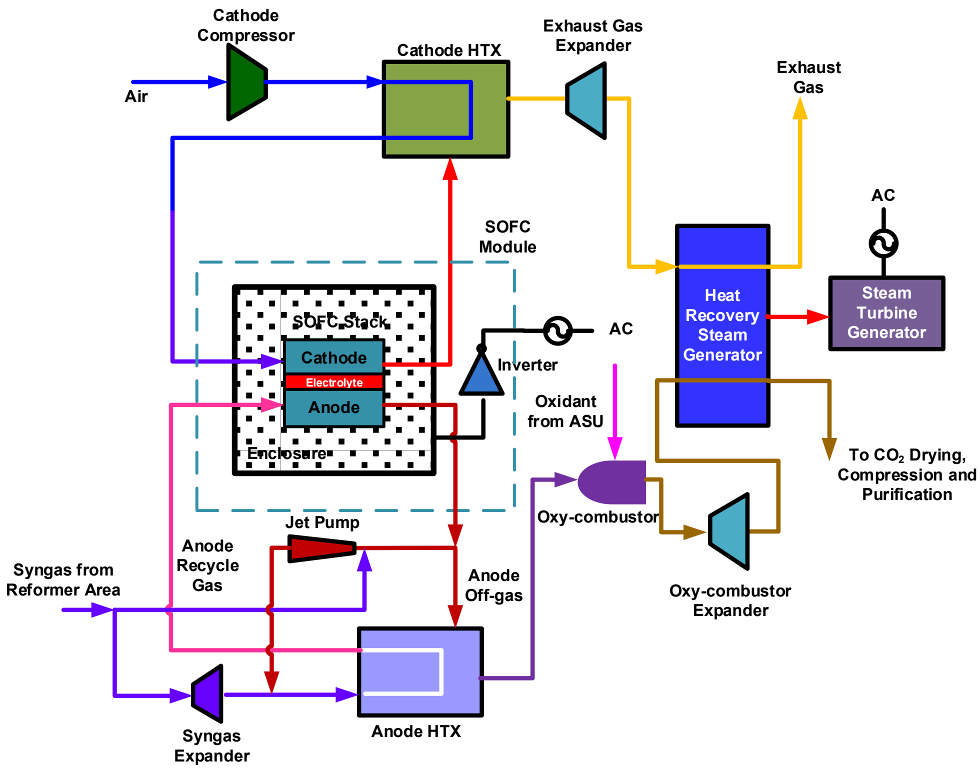
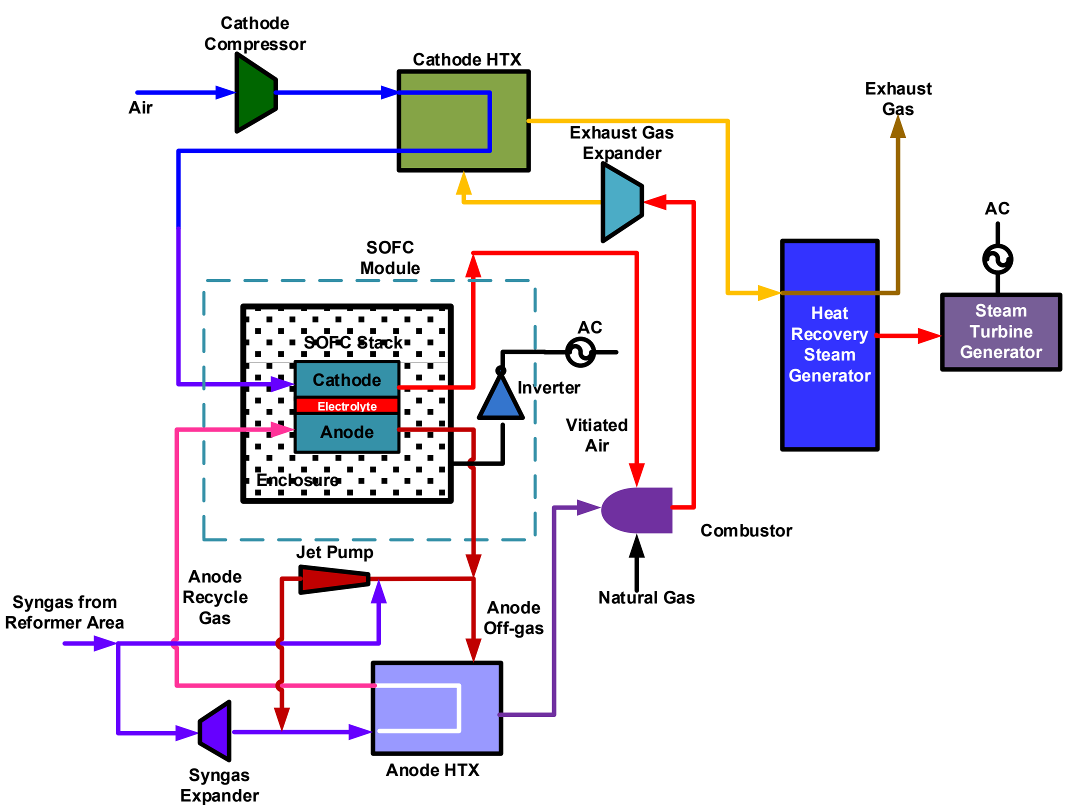


Exhibit 3-4. Scenario 2 – Pressurized NGFC Power Island with and without CCS

(a) With CCS



(b) Without CCS



3.3.1 Solid Oxide Fuel Cell Unit

The SOFC unit ancillary components consist of cathode air blowers, cathode heat exchangers that recuperatively heat the cathode air up to the fuel cell inlet temperature, cathode hot gas recycle blowers, anode heat exchangers that recuperatively heat the anode gas up to the fuel cell inlet temperature, and anode hot gas recycle blowers. Hot gas blowers capable of operation at the required conditions of the anode and cathode recycle gas streams are currently under development. [22]

The HRSG produces low-pressure and high-pressure process steam, and high-pressure power steam for the subcritical steam bottoming cycle. The cooling water system uses a mechanical draft, wet cooling tower arrangement.

For the operation of SOFC at elevated pressures assumed in Scenario 2, the cathode air is compressed to the pressurized fuel gas inlet pressure, and no cathode gas recycle is used. The cathode off-gas is expanded to atmospheric pressure to generate power to drive the cathode gas compressor. Anode gas recycle is accomplished using a syngas-driven jet pump in this pressurized case.

The major assumptions for the SOFC power island for the pathway cases are listed in Exhibit 3-5. The SOFC overpotential and degradation rate were varied parameters along the developmental pathway (see Exhibit 1-5). The anode recycle rate was adjusted to maintain a total O_2-to-carbon atomic ratio of at least 2.1 in the anode inlet gas in all the study cases to avoid carbon deposition in the fuel cell.

The anode off-gas is combusted using O_2 in an advanced oxy-combustor with excess O_2 limited to 1 mole percent. It is assumed that an anode off-gas oxy-combustor can be developed that can operate stably with 1 mole percent excess O_2.

Exhibit 3-5. SOFC Power Island Conditions and Assumptions

Parameters	Scenario 1	Scenario 2
Natural Gas/Syngas Expander		
Outlet pressure, MPa (psia)	0.14 (20)	0.34 (50)
Efficiency, adiabatic %	90	
Generator efficiency (%)	98	
Fuel Cell System		
Current density, mA/cm^2	400	
Reference case stack fuel utilization, %	70	
Cell stack inlet pressure, MPa (psia)	0.12 (15.1)	2.2 (285)
Reference case overall fuel utilization, %	80	
Oxygen to Carbon ratio	2.1	
Reference case stack fuel utilization, %	80	
Cell stack inlet temperature, °C (°F)	Determined from PNNL model	
Cell stack outlet temperature, °C (°F)	Computed in Aspen®	

Parameters	Scenario 1	Scenario 2
Stack anode-side pressure drop, MPa (psi)	0.00062 (0.11)	
Fuel Cell System Ancillary Components		
Anode gas recycle method	Hot gas fan	Fuel gas jet pump
Anode recycle gas fan efficiency, adiabatic %	80	N/A
Anode heat exchanger pressure drop, MPa (psi)	0.0014 (0.2)	
Cathode gas recycle method	Hot gas fan	None
Cathode recycle gas rate, %	50	0
Cathode recycle gas fan eff., adiabatic %	80	N/A
Cathode heat exchanger pressure drop, MPa (psi)	0.0055 (0.8)	
Cathode blower/compressor eff., adiabatic %	82	90
Cathode gas expander efficiency, adiabatic %	N/A	95
Reference Rectifier DC-to-AC efficiency, %	97	
Recycle blower motor drives eff., %	87.6	N/A
Other electric motor drives efficiency, %	95	95
Transformer efficiency, %	99.65	99.65

3.3.2 Heat Recovery Steam Generator and Steam Power Cycle

The BB report [1] provides a detailed description of the HRSG and steam power cycle process configuration and equipment in typical IGCC and NGCC power plants. The HRSG and steam power cycle for the NGFC cases evaluated in this report are expected to be similar in configuration and operating conditions to the comparable IGCC and NGCC systems. Only simplified simulation of the steam system was conducted in this evaluation, as described in Section 2.

3.4 CO_2 Dehydration, Purification, and Compression Area

After completion of heat recovery, the oxy-combustion off-gas stream is sent to the CPU for compression, drying, and purification to pipeline and EOR specifications.[g, h] An auto-refrigerated CPU process based on the process developed for the advanced oxy-combustion studies [20] is utilized in the present study.

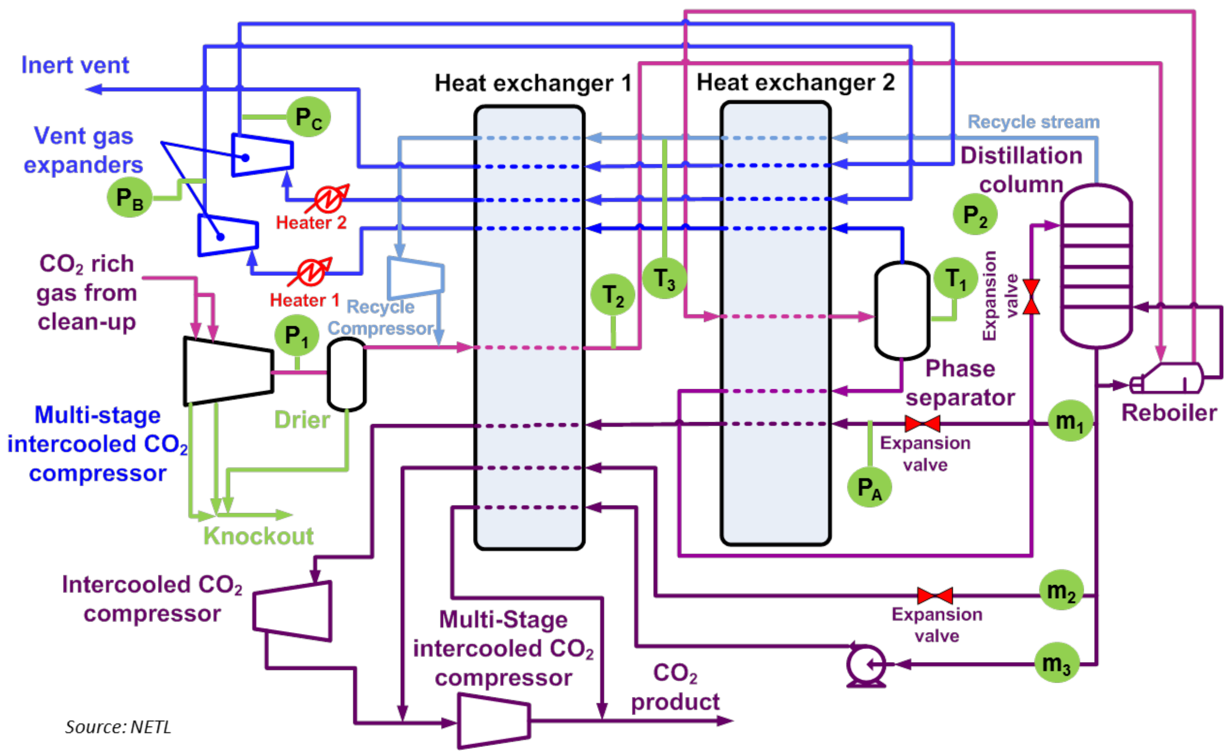
Exhibit 3-6 depicts the block diagram of the auto-refrigerated CPU process, which was developed based on the patents issued to Air Products and Chemicals, Inc. [23] and to Air Liquide. [24] Wet CO_2 rich gas from the flue gas desulfurizer is compressed to an initial pressure, P_1, (≈30 bar/435 psia) and is dried to remove moisture. The dried CO_2 rich gas is

[g] The QGESS reference [14] recommends a purity of the CO_2 at least 95 percent, as a conceptual design basis for EOR purposes; however, distillation methods used to meet the more stringent O_2 concentration requirement of 100 ppmv or less generally result in 99.9 percent + CO_2 purity.

[h] An O_2 concentration of 10 ppmv in the CO_2 product stream was selected as the basis for conceptual design since it represents the lower limit of the range of values recommended in literature [14] for EOR applications. The number of distillation stages can be reduced slightly to design to the upper limit of 100 ppmv for O_2 concentration. [14] However, the impact of the associated small decrement in distillation cost on the overall cost is expected to be insignificant.

purified to the specified levels by liquefaction followed by flash phase separation and distillation as in the external refrigeration process. However, cooling of the dried CO_2 gas down to a temperature, T_1 (≈-60 °F) is accomplished entirely through heat exchange with the cold non-condensables and the pure CO_2 product, part of which is expanded to satisfy the refrigeration needs, in heat exchangers HX1 and HX2 along with the reboiler of the distillation column. The reboiler boilup ratio of the distiller can be tuned to achieve the required CO_2 purity.

Exhibit 3-6. Auto-refrigerated CPU Process Developed for the Present Study



3.5 Accessory Electric Plant

The accessory electric plant consists of switchgear and control equipment, generator equipment, station service equipment, conduit and cable trays, and wire and cable. It also includes the main power transformer, all required foundations, and standby equipment.

3.6 Instrumentation and Control

An integrated plant-wide redundant microprocessor-based distributed control system (DCS) is provided. The control room houses an array of multiple monitors and keyboard units. The monitors/keyboard units are the primary interface between the generating process and operations personnel. The DCS incorporates plant monitoring and control functions for all the major plant equipment. The DCS is designed to be operational and accessible 99.5 percent of the time it is required. The plant equipment and the DCS are designed for automatic response to load changes from minimum load to 100 percent. Startup and shutdown routines are manually implemented, with operator selection of modular automation routines available. The exception to this, and an important facet of the control system for gasification, is the critical controller system, which is a part of the license package from the gasifier supplier and is a dedicated and distinct hardware segment of the DCS.

This critical controller system is used to control the ATR process. The partial oxidation of the fuel feed and O_2 feed streams to form a syngas product is a stoichiometric, temperature- and pressure-dependent reaction. The critical controller utilizes a redundant microprocessor executing calculations and dynamic controls at 100- to 200-millisecond intervals. The enhanced execution speeds as well as evolved predictive controls allow the critical controller to mitigate process upsets and maintain the reactor operation within a stable set of operating parameters.

4 Scenario 1: Atmospheric-Pressure SOFC System

The reference case is based on a commercially viable DGFC system and is subject to both performance and cost modifications in subsequent cases 1 through 4, representative of a pathway development scenario. Reference cases were evaluated for both systems with and without CCS.

4.1 Case 0: Atmospheric Reference Case Description

Case 0 assumes a plant featuring 60 percent internal reformation along with advanced cell technology. Exhibit 4-1 summarizes the performance and cost assumptions for this case, which are representative on the capabilities of a commercially viable DGFC system. The process diagrams for this case with and without CCS are depicted in Exhibit 4-5 and Exhibit 4-10 respectively.

Exhibit 4-1. SOFC Technology Parameters used for Reference Case 0

Parameter	Value
Reformation	40% External
SOFC Operating Pressure	Atmospheric
Cell Technology	Advanced Cell
Fuel Utilization, %	80
Current Density, mA/cm^2	400
Degradation, %/1000 h	0.2
Inverter Efficiency (%)	97
Stack Cost ($/kW)	225

In the case with CCS (Exhibit 4-5), natural gas (Stream 1) delivered to the plant at 500 psia is desulfurized and preheated using the hot ATR syngas stream. This natural gas stream is expanded to a pressure of 20 psia (Stream 2) before 40 percent of it enters the ATR. The remaining 60 percent bypasses the ATR to be reformed internally at the anode. A conventional ASU delivers 99.5 percent pure O_2 to the ATR (Stream 5) as well as to the anode off-gas oxy-combustor (Stream 6). The cooled ATR syngas stream is mixed with the ATR bypass, (Stream 8) and the recycled anode gas (Stream 9). The stream is then preheated by the anode heat exchanger and pre-reformed (Stream 10) to prevent cracking of higher-hydrocarbons and deleterious carbon formation. The anode off-gas (Stream 11) is combusted across the oxy-combustor, generating a hot combustion gas (Stream 15) having 1 percent excess O_2 content. The cooled combustion gas is dehydrated, purified, and compressed to 2215 psia in the CPU (Stream 16). The HRSG raises high-pressure steam for the steam bottoming cycle, 50 psia steam for the ATR, and low-pressure steam for the auxiliary processing needs.

On the cathode side, air (Stream 12) pressurized by the cathode air blower is preheated through the cathode heat exchanger and mixes with the recycled cathode gas to achieve the desired cathode inlet temperature (Stream 13) before being delivered to the SOFC cathode. The cathode air mixture not only provides the O_2 needed for the SOFC oxidation reactions but also acts as a coolant and serves to maintain an acceptable temperature distribution across the SOFC. The cathode off-gas passes through the cathode heat exchanger and is vented (Stream 14) after it exchanges heat in the HRSG.

Referring to the process diagram in Exhibit 4-10 for the case without CCS, the ATR is air blown, (Stream 3), while part of the vitiated air (Stream 13) is used to combust the residual fuel in the anode off-gas. The combustion gases are exhausted to the atmosphere after exchanging heat with the HRSG. The rest of the process diagram is identical to the CCS case.

4.1.1 Case 0: Atmospheric Reference Plant Performance

The performance of the reference atmospheric plant with and without CCS is summarized in Exhibit 4-2. In the reference plant, as shown in Exhibit 4-3, SOFC generates ≈81–82 percent of the gross power while the steam cycle produces ≈15–16 percent of the gross power. The auxiliary load for the plant without CCS is mainly dominated by the blower and steam cycle parasitic loads as shown as shown in Exhibit 4-4. The addition of CCS more than triples the auxiliary load, adversely affecting the performance of the reference plant with CCS whose HHV efficiency is lower by 3.7 percentage points relative to the HHV efficiency of the reference plant without CCS. For the reference CCS plant, the CO_2 compression and purification unit accounts for ≈41 percent of the auxiliary load followed by contributions from the ASU at 32 percent and the blowers at 13 percent.

The stream tables for the reference plants with and without CCS are listed in Exhibit 4-6 and Exhibit 4-11 for the corresponding points numbered in the process flow diagram shown in Exhibit 4-5 and Exhibit 4-10, respectively. Material and energy balance tables and the heat and material balance diagrams for the reference plant with CCS are shown in Exhibit 4-7, Exhibit 4-8, and Exhibit 4-9, respectively. The corresponding tables for the reference plant without CCS are shown in Exhibit 4-12, Exhibit 4-13, and Exhibit 4-14.

The reference NGFC plant with CCS consists of 34 parallel SOFC sections, each containing a single cathode heat exchanger, anode heat exchanger, cathode air blower, cathode recycle gas blower, and anode gas recycle blower. A single train configuration of oxy-combustor, HRSG, and steam power system is used in the plant.

4.1.2 Case 0: Atmospheric Reference Plant Costs

The capital costs and the O&M costs are listed in Exhibit 4-14 and Exhibit 4-15 for the reference plant with CCS. The ASU, CPU, and the steam cycle costs together make up about 45 percent of the plant capital costs while SOFC power island is the largest contributor at 32 percent as shown in Exhibit 4-16. The largest components of the BOP costs for the reference plant with CCS are the oxy-combustor (37 percent) and the cathode heat exchanger (24 percent) as shown in Exhibit 4-17. The costs for the reference plant without CCS are provided in Exhibit 4-18 to Exhibit 4-21 in a similar fashion. The addition of CCS results in 50 percent increase in capital costs, nearly 80 percent of which is attributable the ASU and CPU costs. The LCOE for Case 0 with CCS is estimated to be \$60.1/MWh and \$57.0/MWh with and without CO_2 T&S costs respectively. The addition of CCS to the reference plant is observed to increase the LCOE by \$12.8/MWh as shown in Exhibit 4-22.

Exhibit 4-2. Case 0 – Atmospheric Reference NGFC Plant with and without CCS – Performance Summary

Carbon Capture	With CCS	No CCS
Power Summary (Gross Power at Generator Terminals, kWe)		
SOFC Power	582,048	542,009
Natural Gas/Syngas Expander Power	21,000	19,700
Steam Turbine Power	110,000	107,700
Total Gross Power, kW_e	**713,048**	**669,409**
Auxiliary Load Summary, kWe		
Air Separation Unit Auxiliaries	0	0
Air Separation Unit Main Air Compressor	19,955	3,320[A]
Oxygen Compressor	0	0
Nitrogen Compressors	0	0
CO_2 Compressor	25,895	0
CO_2 Refrigeration	0	0
Boiler Feedwater Pumps	2,022	1,979
Condensate Pump	63	61
Circulating Water Pump	2,780	2,300
Cooling Tower Fans	1,440	1,180
Gas Turbine Auxiliaries	-	-
Steam Turbine Auxiliaries	84	82
Cathode Air Blower	5,271	5,258
Cathode Recycle Blower	2,430	2,428
Anode Recycle Blower	218	254
Miscellaneous Balance of Plant[B]	454	427
Transformer Losses	2,311	2,057
Total Auxiliaries, kW_e	**62,922**	**19,346**
Net Power, kW_e	650,126	650,063
Net Plant Efficiency, % (HHV)	57.88	61.56
Net Plant Heat Rate, kJ/kWh (Btu/kWh)	6,220 (5,895)	5,848 (5,543)
CO_2 Capture Rate, %	97.8	0.0
Condenser Cooling Duty, 10^6 kJ/h (10^6 Btu/h)	644 (610)	633 (600)
Natural Gas Feed Rate, kg/h (lb/h)	77,095 (169,965)	72,480 (159,790)
Thermal Input[C], kWt	1,123,206	1,055,965
Raw Water Withdrawal, m^3/min (gpm)	8.2 (2,162.8)	9.5 (2,509.7)
Raw Water Consumption, m^3/min (gpm)	5.75 (1,519.9)	7.49 (1,979.6)

[A] Reflects power needed to compress air to ATR pressure.
[B] Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads.
[C] HHV of Natural Gas is 52,449 kJ/kg (22,549 Btu/lb).

Exhibit 4-3. Case 0 – Atmospheric Reference NGFC Plant with and without CCS – Gross Power Distribution

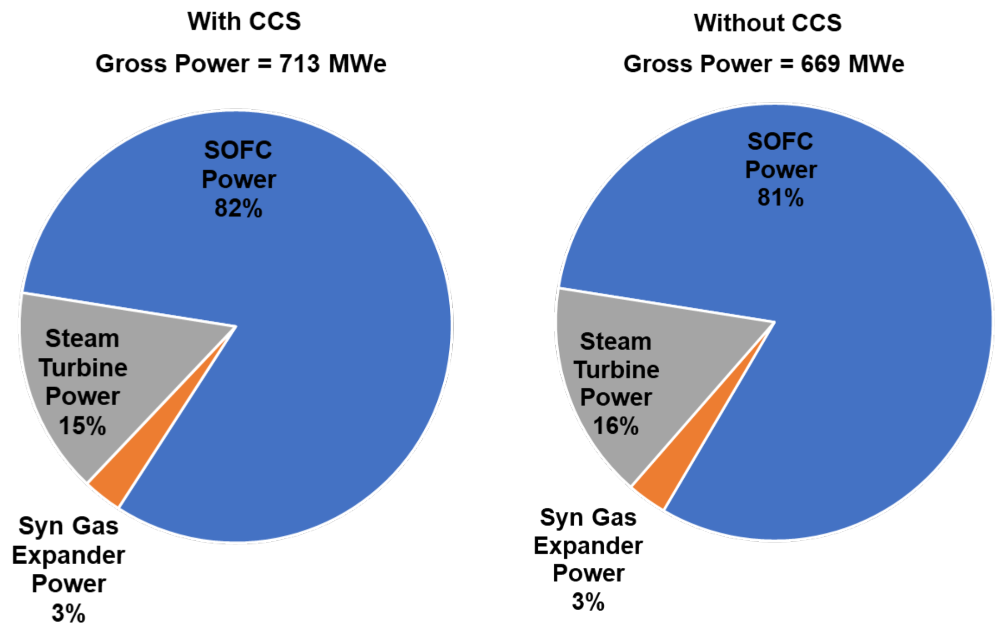


Exhibit 4-4. Case 0 – Atmospheric Reference Plant with and without CCS – Auxiliary Load Distribution

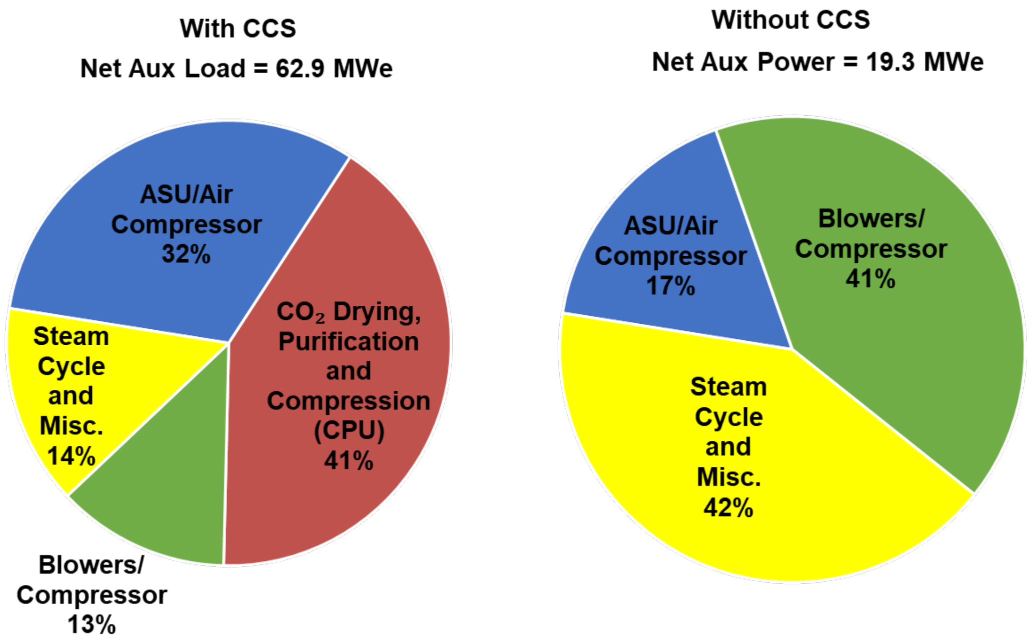


Exhibit 4-5. Case ANGFC0B – Atmospheric Reference NGFC Plant with CCS – Process Diagram

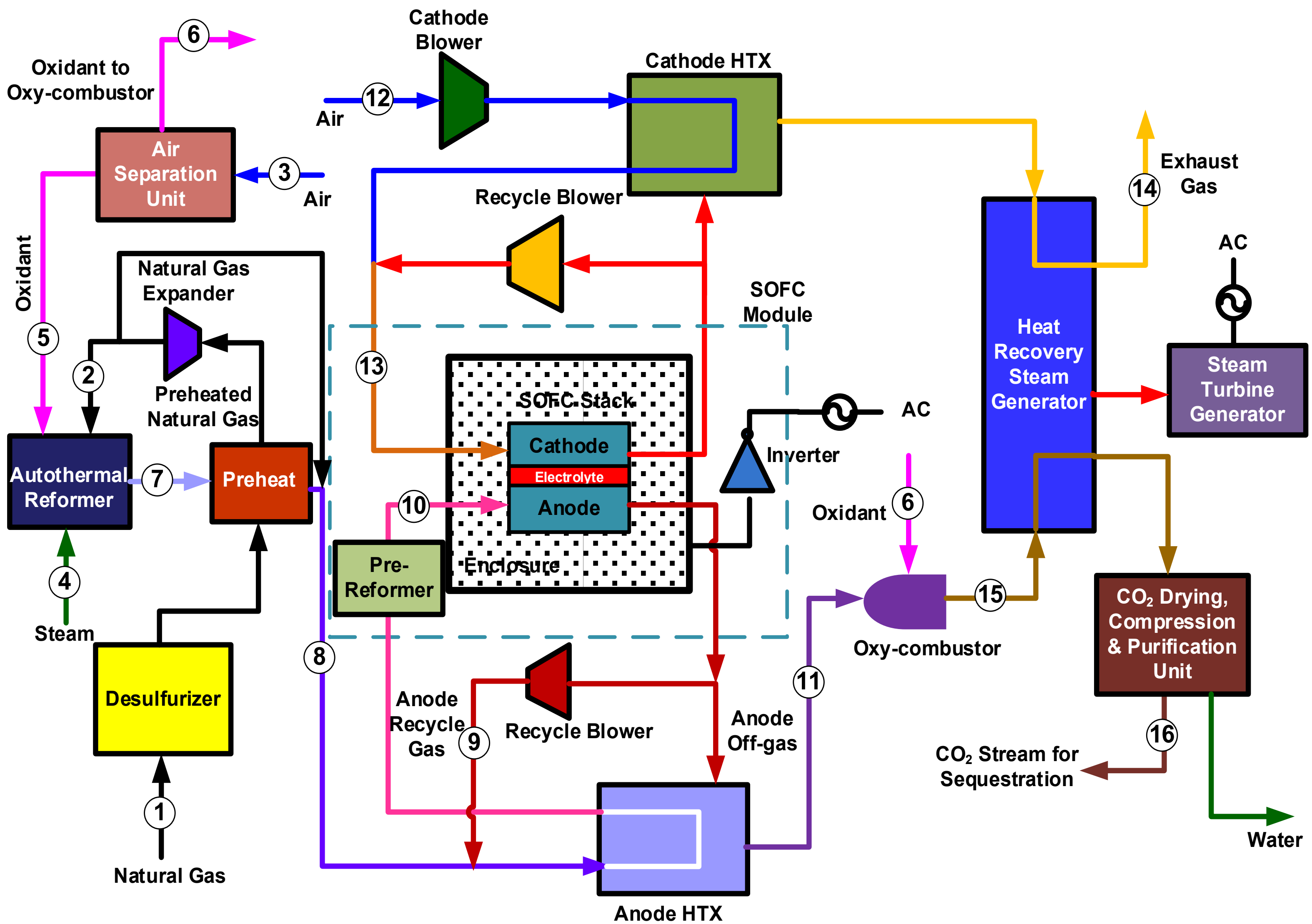


Exhibit 4-6. Case ANGFC0B – Atmospheric Reference NGFC Plant with CCS – Stream Table

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
V-L Mole Fraction																
Ar	0.0000	0.0000	0.0094	0.0000	0.0031	0.0031	0.0005	0.0003	0.0002	0.0003	0.0002	0.0094	0.0099	0.0104	0.0006	0.0000
CH_4	0.9310	0.9310	0.0000	0.0000	0.0000	0.0000	0.0002	0.2511	0.0001	0.0955	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1895	0.1384	0.0439	0.0667	0.0439	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0100	0.0100	0.0003	0.0000	0.0000	0.0000	0.0666	0.0514	0.2568	0.1959	0.2568	0.0003	0.0003	0.0003	0.2977	1.0000
H_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5194	0.3794	0.1633	0.3420	0.1633	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	0.0000	0.0000	0.0104	1.0000	0.0000	0.0000	0.2196	0.1604	0.5309	0.2939	0.5309	0.0104	0.0109	0.0115	0.6874	0.0000
N_2	0.0160	0.0160	0.7722	0.0000	0.0019	0.0019	0.0042	0.0074	0.0047	0.0057	0.0047	0.7722	0.8124	0.8570	0.0049	0.0000
C_2H_6	0.0320	0.0320	0.0000	0.0000	0.0000	0.0000	0.0000	0.0086	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_3H_8	0.0070	0.0070	0.0000	0.0000	0.0000	0.0000	0.0000	0.0019	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_4H_{10}	0.0040	0.0040	0.0000	0.0000	0.0000	0.0000	0.0000	0.0011	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
O_2	0.0000	0.0000	0.2077	0.0000	0.9950	0.9950	0.0000	0.0000	0.0000	0.0000	0.0000	0.2077	0.1664	0.1206	0.0094	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	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)	4,449	1,780	13,914	1,780	1,060	1,755	7,235	9,904	12,622	23,544	15,414	64,648	122,895	58,248	15,573	4,536
V-L Flowrate (kg/h)	77,095	30,838	401,485	32,062	33,922	56,199	96,822	143,078	284,857	427,936	347,873	1,865,360	3,525,926	1,660,566	404,072	199,630
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	15	477	15	149	40	27	882	268	706	559	531	15	617	132	1,574	36
Pressure (MPa, abs)	3.45	0.207	0.10	0.34	0.16	0.16	0.14	0.138	0.11	0.11	0.137	0.101	0.11	0.10	0.13	15.27
Enthalpy (kJ/kg)[A]	31.11	1,343.630	31.06	2,770.67	36.25	23.95	2,914.88	1,136.201	2,245.14	1,849.44	1,926.152	31.06	672.14	153.49	3,924.20	-209.17
Density (kg/m^3)	24.9	0.6	1.2	1.8	2.0	2.0	0.2	0.4	0.3	0.3	0.5	1.2	0.4	0.9	0.2	545.7
V-L Molecular Weight	17.328	17.328	28.854	18.015	32.016	32.016	13.383	14.446	22.568	18.176	22.568	28.854	28.690	28.509	25.947	44.010
V-L Flowrate (lb_{mol}/h)	9,809	3,924	30,676	3,924	2,336	3,870	15,950	21,835	27,827	51,905	33,983	142,524	270,938	128,414	34,332	10,000
V-L Flowrate (lb/h)	169,965	67,986	885,123	70,684	74,785	123,898	213,455	315,434	628,002	943,437	766,929	4,112,416	7,773,337	3,660,922	890,826	440,108
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	59	890	59	300	104	80	1,619	515	1,302	1,039	987	59	1,143	270	2,864	97
Pressure (psia)	500.0	30.0	14.7	50.0	23.0	23.0	20.0	20.0	16.2	16.2	19.9	14.7	15.3	14.7	18.9	2,215.0
Enthalpy (Btu/lb)[A]	13.4	577.7	13.4	1,191.2	15.6	10.3	1,253.2	488.5	965.2	795.1	828.1	13.4	289.0	66.0	1,687.1	-89.9
Density (lb/ft^3)	1.557	0.036	0.076	0.113	0.122	0.127	0.012	0.028	0.019	0.018	0.029	0.076	0.026	0.054	0.014	34.069

[A] Reference conditions are 32.02 F and 0.089 psia

Exhibit 4-7. Case ANGFC0B – Atmospheric Reference NGFC Plant with CCS – Material and Energy Balances

Carbon Balance

Carbon In		Carbon Out	
kg/hr(lb/hr)		kg/hr(lb/hr)	
NG	55,685 (122,764)	Stack Gas	233 (514)
Air (CO2)	283 (624)	CO_2 Product	54,482 (120,112)
		Exhaust	1,201 (2,647)
		ASU Vent	50 (111)
		Water KO	2 (4)
		Convergence Tolerance	0 (0)
Total	55,968 (123,388)	Total	55,968 (123,388)

Sulfur Balance

Sulfur In		Sulfur Out	
kg/hr(lb/hr)		kg/hr(lb/hr)	
NGIN	0 (0)	Elemental Sulfur	0 (0)
		Polishing Sorbent	0 (0)
		Convergence Tolerance	0 (0)
Total	0 (0)	Total	0 (0)

Energy Balance

	HHV	Sensible + Latent	Power	Total
Heat In GJ/hr (MMBtu/hr)				
NG	4,043.54 (3,832.54)	2.7 (2.6)		4,046.2 (3,835.1)
Fuel cell Air		57.9 (54.9)		57.9 (54.9)
Auxiliary Power			226.5 (214.7)	226.5 (214.7)
TOTAL	**4,044 (3,833)**	**60.6 (57.5)**	**226.5 (214.7)**	**4,330.7 (4,104.7)**
Heat Out GJ/hr (MMBtu/hr)				
CO_2 Out		-41.8 (-39.6)		-41.8 (-39.6)
Stack Flue Gas		254.9 (241.6)		254.88 (241.58)
Vents		18.4 (17.4)		18.40 (17.44)
Water outlets		30.5 (28.9)		30.53 (28.94)
Process Losses**		1523.7 (1444.2)		1,523.67 (1,444.16)
Difference***		-22.0 (-20.9)		-22.00 (-20.86)
Power			2,567.0 (2,433.0)	2,567.0 (2,433.0)
TOTAL	**0.0 (0.0)**	**1,763.7 (1,671.7)**	**2,567.0 (2,433.0)**	**4,330.7 (4,104.7)**

* Includes ASU compressor intercoolers & CO2 compressor intercoolers
** Includes accounting of losses such as inverter, transformer, generator, and motor losses
*** Calculated by difference to close the energy balance

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)
Condenser Makeup	**0.6 (154)**	**0.0 (0)**	**0.6 (154)**	**0.0 (0)**	**0.6 (154)**
Reformer Steam	0.5 (141)	0.0 (0)	0.5 (141)		
BFW Makeup	0.0 (13)	0.0 (0)	0.0 (13)		
Cooling Tower	**10.8 (2,859)**	**3.22 (850)**	**7.6 (2,008)**	**2.4 (643)**	**5.2 (1,365)**
CO2 Dehydration	0.0 (0)	3.22 (850)	-3.22 (-850)		
Total	**11.4 (3,013)**	**3.22 (850)**	**8.2 (2,163)**	**2.4 (643)**	**5.8 (1,520)**

Emissions

	kg/GJ ($lb/10^6Btu$)	Tonne/year (tons/year)	kg/MWh (lb/MWh)
SO2	0 (0)	0 (0)	0 (0)
NOx	0 (0)	0 (0)	0 (0)
Particulate	0 (0)	0 (0)	0 (0)
Hg	0 (0)	0 (0)	0 (0)
CO2	1559 (3626)	33,442 (36,864)	7 (15)

Exhibit 4-8. Case ANGFC0B – Reference Plant with CCS – Heat and Material Balance Diagram – ASU, ATR, and Power Island

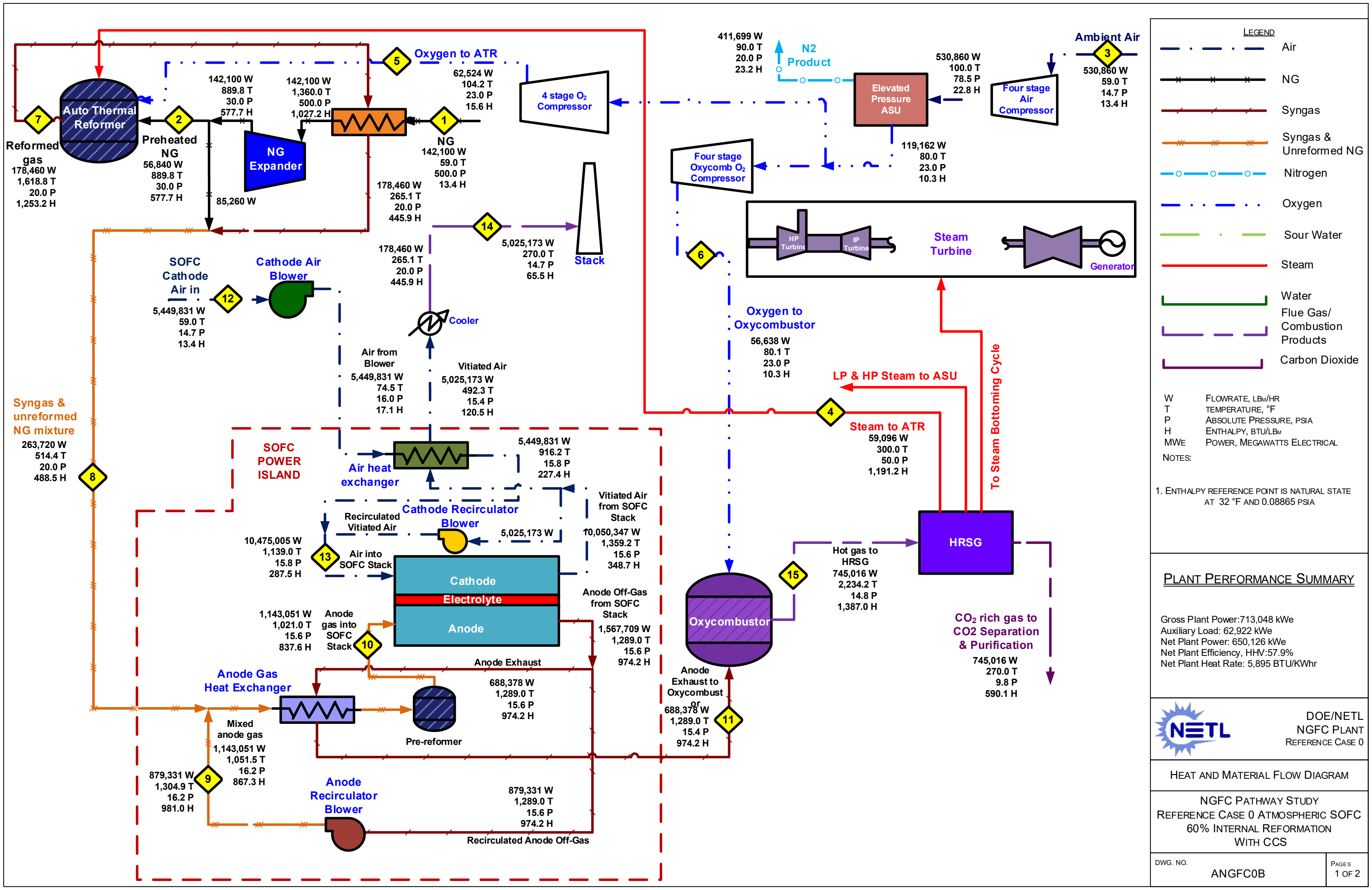


Exhibit 4-9. Case ANGFC0B – Reference Plant with CCS – Heat and Material Balance Diagram – CO_2 Dehydration, Purification, and Compression

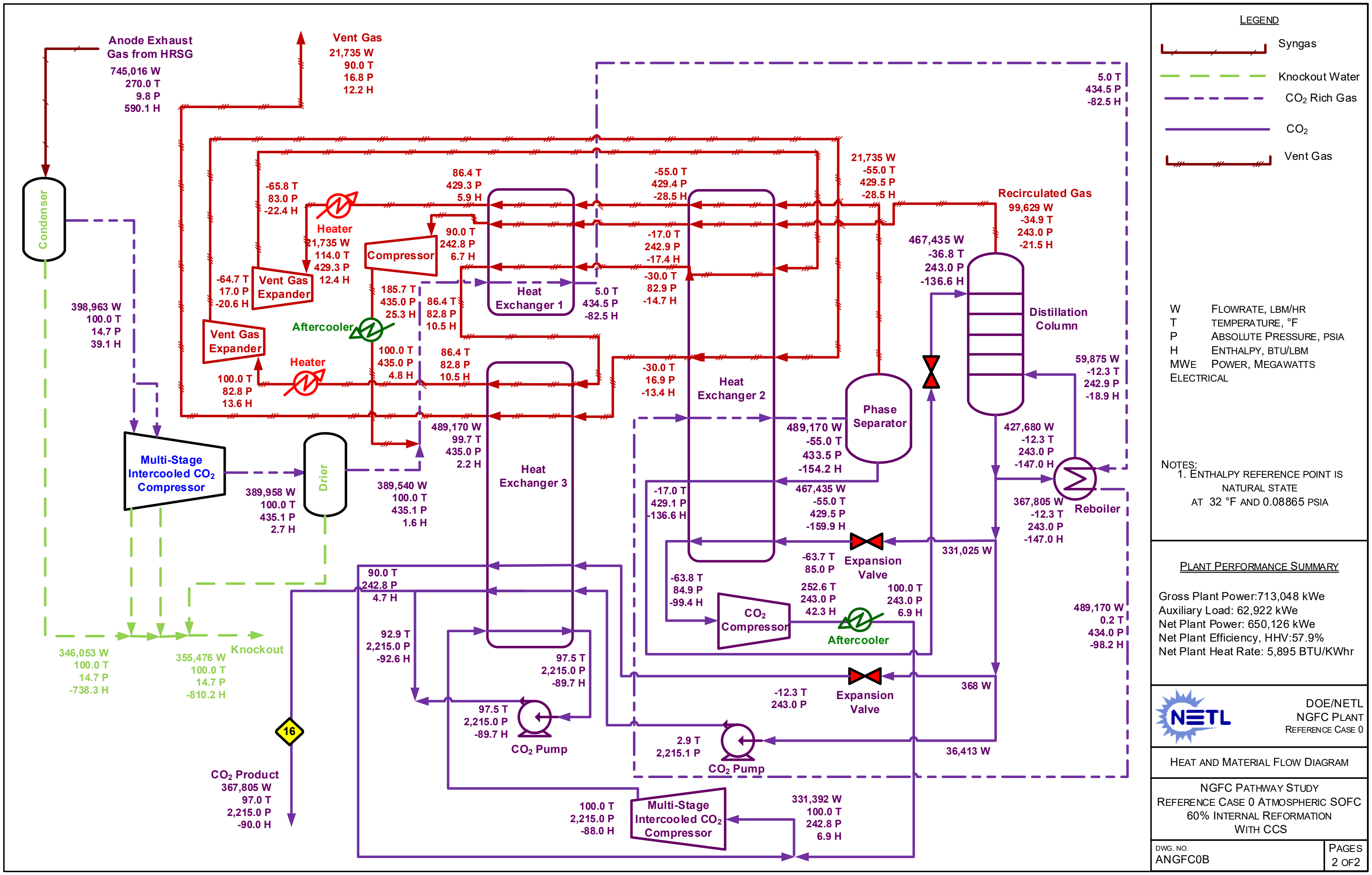


Exhibit 4-10. Case ANGFC0A – Atmospheric Reference NGFC Plant without CCS – Process Diagram

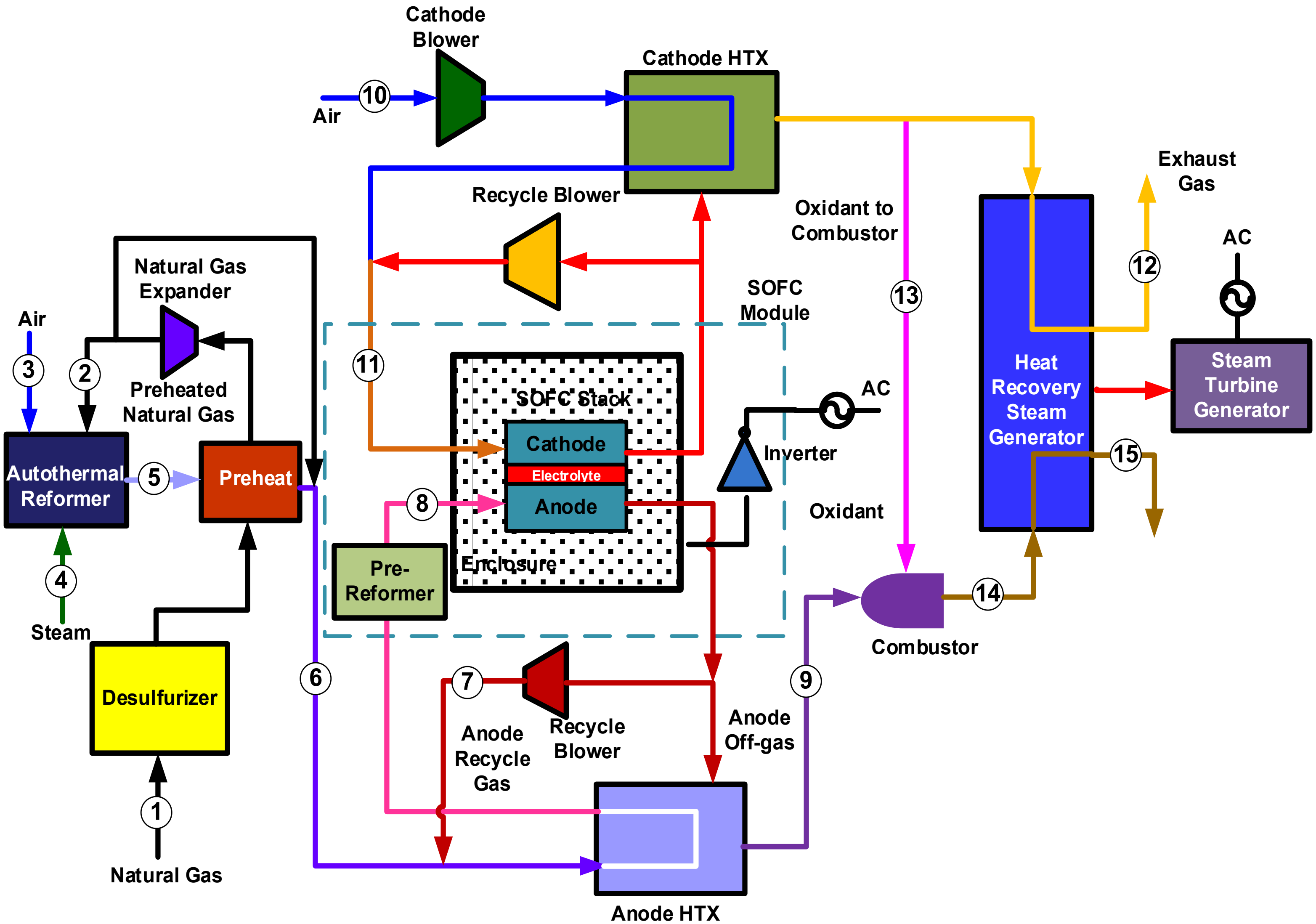


Exhibit 4-11. Case ANGFC0A – Atmospheric NGFC Reference Plant without CCS – Stream Table

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
V-L Mole Fraction															
Ar	0.0000	0.0000	0.0094	0.0000	0.0043	0.0034	0.0025	0.0028	0.0025	0.0094	0.0099	0.0104	0.0104	0.0061	0.0087
CH_4	0.9310	0.9310	0.0000	0.0000	0.0000	0.1782	0.0000	0.0702	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.1129	0.0913	0.0348	0.0534	0.0348	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0100	0.0100	0.0003	0.0000	0.0517	0.0437	0.2035	0.1482	0.2035	0.0003	0.0003	0.0003	0.0003	0.1444	0.2068
H_2	0.0000	0.0000	0.0000	0.0000	0.3414	0.2761	0.1293	0.2691	0.1293	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	0.0000	0.0000	0.0104	1.0000	0.1377	0.1113	0.4235	0.2211	0.4235	0.0104	0.0109	0.0115	0.0115	0.3397	0.0543
N_2	0.0160	0.0160	0.7722	0.0000	0.3520	0.2877	0.2063	0.2352	0.2063	0.7722	0.8100	0.8516	0.8516	0.5034	0.7210
C_2H_6	0.0320	0.0320	0.0000	0.0000	0.0000	0.0061	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_3H_8	0.0070	0.0070	0.0000	0.0000	0.0000	0.0013	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_4H_{10}	0.0040	0.0040	0.0000	0.0000	0.0000	0.0008	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
O_2	0.0000	0.0000	0.2077	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2077	0.1690	0.1262	0.1262	0.0064	0.0092
Total	1.0000	1.0000	1.0000	1.0000	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)	4,183	1,673	4,798	1,673	10,602	13,111	14,675	28,908	18,290	64,496	122,979	45,042	13,442	30,230	21,108
V-L Flowrate (kg/h)	72,480	28,992	138,455	30,143	197,589	241,077	347,802	588,878	433,469	1,860,980	3,529,569	1,285,079	383,510	816,978	652,643
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	15	477	15	149	788	353	708	561	557	15	618	132	204	1,077	38
Pressure (MPa, abs)	3.45	0.207	0.10	0.21	0.14	0.138	0.14	0.14	0.137	0.101	0.11	0.14	0.137	0.13	0.103
Enthalpy (kJ/kg)[A]	31.11	1,343.630	31.06	2,775.32	1,688.83	917.546	1,891.10	1,447.77	1,640.807	31.06	672.96	153.22	227.501	2,028.86	116.441
Density (kg/m^3)	24.9	0.6	1.2	1.1	0.3	0.5	0.4	0.4	0.5	1.2	0.4	1.1	1.0	0.3	1.2
V-L Molecular Weight	17.328	17.328	28.854	18.015	18.638	18.387	23.700	20.371	23.700	28.854	28.700	28.531	28.531	27.025	30.919
V-L Flowrate (lb_{mol}/h)	9,222	3,689	10,579	3,689	23,372	28,905	32,353	63,731	40,322	142,189	271,123	99,300	29,634	66,646	46,536
V-L Flowrate (lb/h)	159,790	63,916	305,240	66,453	435,609	531,483	766,771	1,298,254	955,635	4,102,759	7,781,367	2,833,113	845,494	1,801,129	1,438,832
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	59	890	59	300	1,450	668	1,306	1,042	1,035	59	1,144	270	399	1,971	100
Pressure (psia)	500.0	30.0	14.7	30.0	20.0	20.0	20.0	20.0	19.9	14.7	15.3	19.7	19.9	18.9	14.9
Enthalpy (Btu/lb)[A]	13.4	577.7	13.4	1,193.2	726.1	394.5	813.0	622.4	705.4	13.4	289.3	65.9	97.8	872.3	50.1
Density (lb/ft^3)	1.557	0.036	0.076	0.067	0.018	0.030	0.025	0.025	0.029	0.076	0.026	0.072	0.061	0.020	0.077

[A] Reference conditions are 32.02 F and 0.089 psia

Exhibit 4-12. Case ANGFC0A – Atmospheric Reference NGFC Plant without CCS – Material and Energy Balances

Carbon Balance

Carbon In		Carbon Out	
kg/hr(lb/hr)		kg/hr(lb/hr)	
NG	52,351 (115,414)	Stack Gas	179 (395)
Air (CO_2)	250 (550)	Exhaust	52,421 (115,570)
		Convergence Tolerance	0 (1)
Total	52,601 (115,965)	Total	52,601 (115,965)

Sulfur Balance

Sulfur In		Sulfur Out	
kg/hr(lb/hr)		kg/hr(lb/hr)	
NGIN	0 (0)	Elemental Sulfur	0 (0)
		Polishing Sorbent	0 (0)
		Convergence Tolerance	0 (0)
Total	0 (0)	Total	0 (0)

Energy Balance

	HHV	Sensible + Latent	Power	Total
Heat In GJ/hr (MMBtu/hr)				
NG	3,801.47 (3,603.10)	2.5 (2.4)		3,804.0 (3,605.5)
ASU Air		4.3 (4.1)		4.3 (4.1)
Fuel cell Air		57.8 (54.8)		57.8 (54.8)
Auxiliary Power			69.6 (66.0)	69.6 (66.0)
TOTAL	**3,801 (3,603)**	**66.5 (63.1)**	**69.6 (66.0)**	**3,937.6 (3,732.2)**
Heat Out GJ/hr (MMBtu/hr)				
Stack Flue Gas		272.9 (258.6)		272.89 (258.65)
Process Losses**		1326.1 (1256.9)		1,326.10 (1,256.90)
Difference***		-71.2 (-67.5)		-71.21 (-67.49)
Power			2,409.9 (2,284.1)	2,409.9 (2,284.1)
TOTAL	**0.0 (0.0)**	**1,527.8 (1,448.1)**	**2,409.9 (2,284.1)**	**3,937.6 (3,732.2)**

* Includes ASU compressor intercoolers & CO2 compressor intercoolers
** Includes accounting of losses such as inverter, transformer, generator, and motor losses
*** Calculated by difference to close the energy balance

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)
Condenser Makeup	**0.6 (153)**	**0.0 (0)**	**0.6 (153)**	**0.0 (0)**	**0.6 (153)**
Reformer Steam	0.5 (133)	0.0 (0)	0.5 (133)		
BFW Makeup	0.1 (20)	0.0 (0)	0.1 (20)		
Cooling Tower	**8.9 (2,357)**	**0.00 (0)**	**8.9 (2,357)**	**2.0 (530)**	**6.9 (1,827)**
0	0.0 (0)	0.00 (0)	0.00 (0)		
Total	**9.5 (2,510)**	**0.00 (0)**	**9.5 (2,510)**	**2.0 (530)**	**7.5 (1,980)**

Emissions

	kg/GJ ($lb/10^6 Btu$)	Tonne/year (tons/year)	kg/MWh (lb/MWh)
SO2	0 (0)	0 (0)	0 (0)
NOx	0 (0)	0 (0)	0 (0)
Particulate	0 (0)	0 (0)	0 (0)
Hg	0 (0)	0 (0)	0 (0)
CO2	57124 (132871)	1,225,321 (1,350,685)	261 (576)

Exhibit 4-13. Case ANGFC0A – Atmospheric Reference NGFC Plant without CCS – Heat and Material Balance Diagram – ASU, ATR, and Power Island

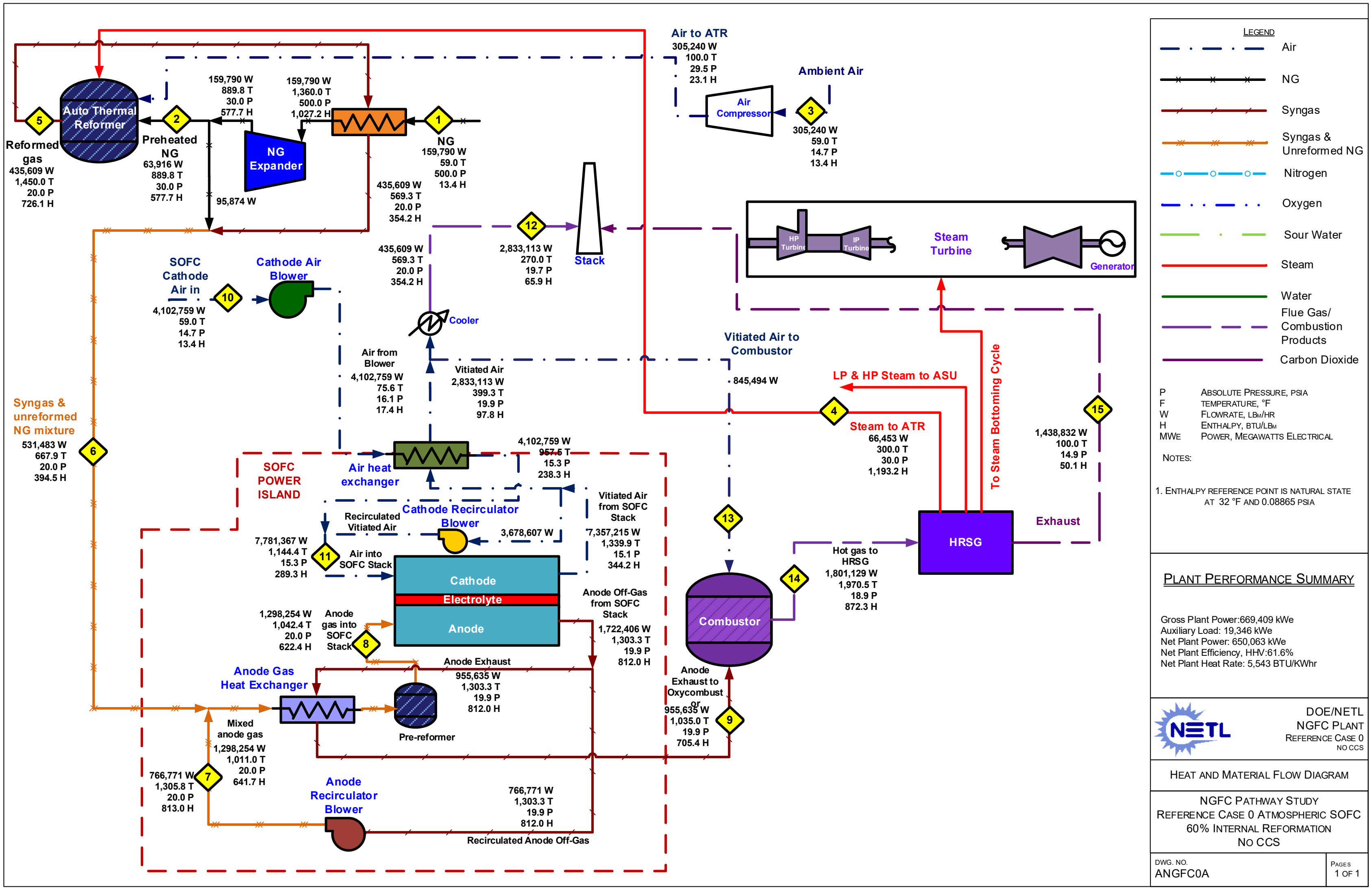


Exhibit 4-14. Case ANGFC0B – Atmospheric Reference NGFC Plant with CCS – Capital Costs

Cost Component	Cost ($1000)	Specific Cost ($/kWe AC)
	2018$	2018$
SOFC Module		
SOFC Stack	133,735	206
Container	5,277	8
Insulation	2,378	4
Module Assembly	5,944	9
Air Distribution	5,944	9
Fuel Distribution	5,944	9
Pre-reformer	5,944	9
Module Current Collectors	2,972	5
Module I&C	2,972	5
Inverter	40,418	62
Total SOFC Module with 10 % Extra Installed Area	211,526	325
NATURAL GAS EXPANDER	7,455	11
SOFC BOP		
Desulfurization System	1,999	3
Cathode Air Compressor	2,314	4
Cathode Gas Recycle Compressor	5,277	8
Cathode Heat Exchanger	14,080	22
Anode Recycle Compressor	814	1
Anode Heat Exchanger	339	1
Oxy-Combustor	21,554	33
Air, Exhaust, Fuel Flow Piping system	1,646	3
Section and Overall Assembly	1,646	3
Section I&C	823	1
Total SOFC BOP	50,492	78
TOTAL SOFC POWER ISLAND	269,474	414
ASU	127,672	196
AUTOTHERMAL REFORMER and Natural Gas Preheater	23,477	36
STEAM CYCLE		
HRSG, Ducting, and Stack	50,207	77
Steam Power System	51,856	80
Feedwater and Miscellaneous BOP systems	76,389	117
TOTAL STEAM CYLCE	178,452	274
CO_2 COMPRESSION & PURIFICATION		
CO_2 Purification	89,001	137
TOTAL CO_2 COMPRESSION & PURIFICATION	89,001	137
COOLING WATER SYSTEM	38,437	59
ACCESSORY ELECTRIC PLANT	75,508	116
INSTRUMENTATION & CONTROL	23,298	36
IMPROVEMENTS TO SITE	29,203	45
BUILDING & STRUCTURES	13,916	21
TOTAL PLANT COST (TPC)	868,437	1336
OWNER'S COSTS		
Preproduction Costs		
6 Months All Labor	6,125	
1 Month Maintenance Materials	1,031	
1 Month Non-fuel Consumables	410	
25% of 1 Months Fuel Cost at 100% CF	3,092	
2% of TPC	17,369	
Total Preproduction Costs	28,027	
Inventory Capital		
60-day supply of fuel and consumables at 100% CF	676	
0.5% of TPC (spare parts)	4,342	
Total Inventory Capital	5,018	
Initial Cost for Catalyst and Chemicals	1,756	
Land	300	
Other Owner's Costs	130,266	
Financing Costs	23,448	
TOTAL OWNER'S COSTS	188,815	
TOTAL OVERNIGHT COST (TOC)	1,057,252	1626
TASC Multiplier	1.093	
TOTAL AS-SPENT COST (TASC)	1,155,576	1777

Exhibit 4-15. Case ANGFC0B – Atmospheric Reference NGFC Plant with CCS – O&M Costs

Case:	**ANGFC0B**				**Cost Base:**	**Apr 2018**
Plant Size (MW, net):		**650**			**Capacity Factor:**	**80%**
Operating & Maintenance Labor						
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:	1.0	
Operating Labor Burden:		30.00	**% of base**	Operator:	4.3	
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:	1.0	
				Lab Techs, etc.:	1.0	
				Total:	**7.3**	
Fixed Operating Costs						
					Annual Cost	
					($)	**($/kW-net)**
				Annual Operating Labor:	$3,200,597	$4.92
				Maintenance Labor:	$6,600,121	$10.15
				Administrative & Support Labor:	$2,450,180	$3.77
				Property Taxes and Insurance:	$17,368,739	$26.72
				Total:	$29,619,637	$45.56
Variable Operating Costs						
					($)	**($/MWh-net)**
				Maintenance Material:	$9,900,181	$2.17
Stack Replacement						
		Life (y)	**$/kW AC**	**$/y per kW**		
SOFC Stack Replacement Cost		7.3	$223	$24.59	$15,984,337	$3.51
Consumables						
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (gal/1000):	0	1,246	$1.90	$0	$691,167	$0.15
Makeup and Wastewater Treatment Chemicals (lb):	0	9,278	$0.28	$0	$744,993	$0.16
NG Desulfur TDA Adsorbent (lb):	51,564	1256	$6.03	$310,916	$2,210,610	$0.49
ATR Catalyst (m^3):	2,401	1.7	$601.76	$1,445,136	$290,207	$0.06
			Subtotal:	$1,756,052	$3,936,977	$0.86
Waste Disposal						
ATR Catalyst (m^3):	0	1.7	$0.00	$0	$0	$0.00
			Subtotal:	$0	$0	$0.00
			Variable Operating Costs Total:	$1,756,052	$29,821,496	$6.54
Fuel Cost						
Natural Gas (MMBtu):	0	91,981	$4.42	$0	$118,719,581	$26.06
			Total:	$0	$118,719,581	$26.06

Exhibit 4-16. Case ANGFC0B – Atmospheric Reference NGFC Plant with CCS – Capital Cost Components

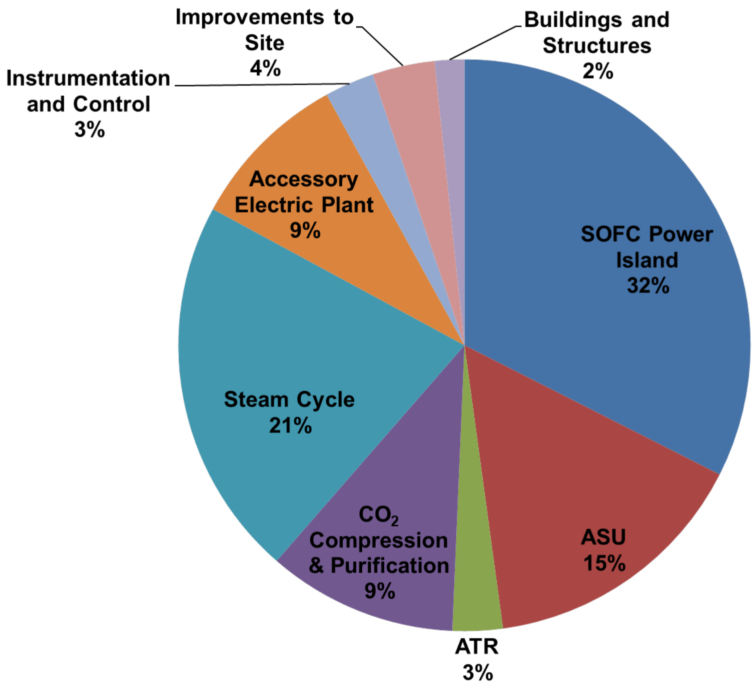


Exhibit 4-17. Case ANGFC0B – Atmospheric Reference NGFC Plant with CCS – BOP Cost Distribution

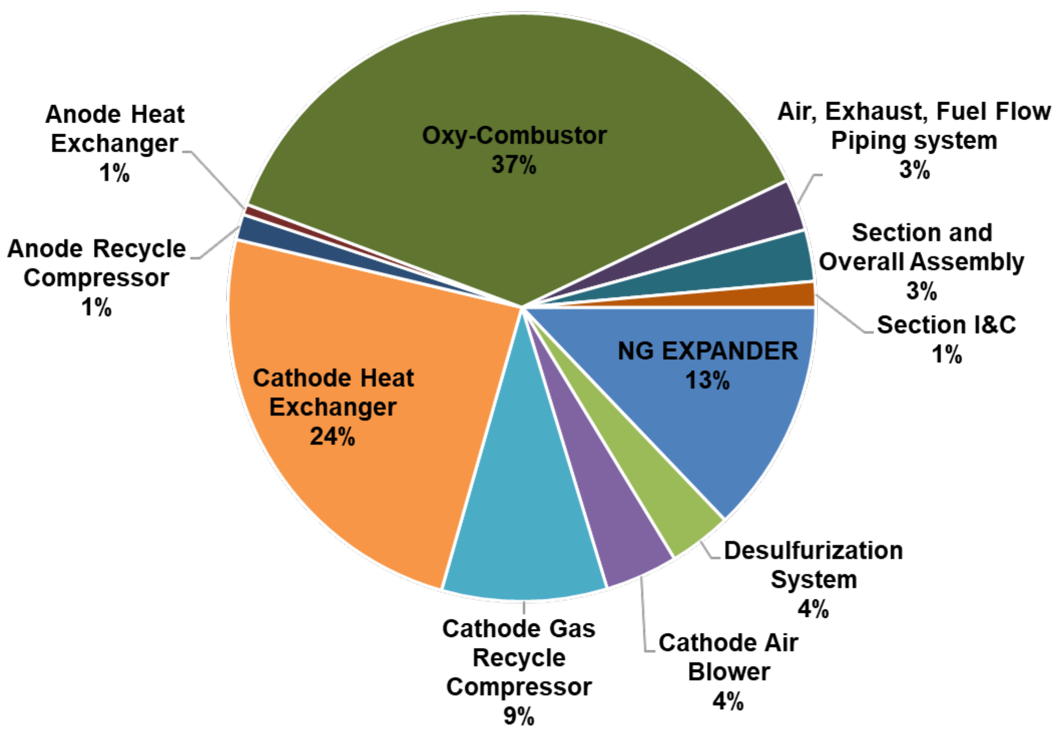


Exhibit 4-18. Case ANGFC0A – Atmospheric Reference NGFC Plant without CCS – Capital Costs

Cost Component	Cost ($1000)	Specific Cost ($/kWe AC)
	2018$	2018$
SOFC Module		
SOFC Stack	125,868	194
Container	4,966	8
Insulation	2,238	3
Module Assembly	5,594	9
Air Distribution	5,594	9
Fuel Distribution	5,594	9
Pre-reformer	5,594	9
Module Current Collectors	2,797	4
Module I&C	2,797	4
Inverter	38,040	59
Total SOFC Module with 10 % Extra Installed Area	199,084	306
NATURAL GAS EXPANDER	6,994	11
SOFC BOP		
Desulfurization System	1,894	3
Cathode Air Compressor	2,272	3
Cathode Gas Recycle Compressor	5,197	8
Cathode Heat Exchanger	14,956	23
Anode Recycle Compressor	830	1
Anode Heat Exchanger	10,150	16
Oxy-Combustor	20,482	32
Air, Exhaust, Fuel Flow Piping system	1,477	2
Section and Overall Assembly	1,477	2
Section I&C	738	1
Total SOFC BOP	59,472	91
TOTAL SOFC POWER ISLAND	265,549	408
ASU	1,191	2
AUTOTHERMAL REFORMER and Natural Gas Preheater	22,247	34
STEAM CYCLE		
HRSG, Ducting, and Stack	42,731	66
Steam Power System	50,943	78
Feedwater and Miscellaneous BOP systems	75,243	116
TOTAL STEAM CYLCE	168,917	260
CO_2 COMPRESSION & PURIFICATION		
CO_2 Purification	0	0
TOTAL CO_2 COMPRESSION & PURIFICATION	0	0
COOLING WATER SYSTEM	34,268	53
ACCESSORY ELECTRIC PLANT	40,390	62
INSTRUMENTATION & CONTROL	18,627	29
IMPROVEMENTS TO SITE	28,367	44
BUILDING & STRUCTURES	13,749	21
TOTAL PLANT COST (TPC)	593,305	913
OWNER'S COSTS		
Preproduction Costs		
6 Months All Labor	4,462	
1 Month Maintenance Materials	705	
1 Month Non-fuel Consumables	441	
25% of 1 Months Fuel Cost at 100% CF	2,907	
2% of TPC	11,866	
Total Preproduction Costs	20,380	
Inventory Capital		
60-day supply of fuel and consumables at 100% CF	714	
0.5% of TPC (spare parts)	2,967	
Total Inventory Capital	3,681	
Initial Cost for Catalyst and Chemicals	2,727	
Land	300	
Other Owner's Costs	88,996	
Financing Costs	16,019	
TOTAL OWNER'S COSTS	132,103	
TOTAL OVERNIGHT COST (TOC)	725,408	1116
TASC Multiplier	1.093	
TOTAL AS-SPENT COST (TASC)	792,871	1220

Exhibit 4-19. Case ANGFC0A – Atmospheric Reference NGFC Plant without CCS – O&M Costs

Case:	**ANGFC0A**				**Cost Base:**	**Apr 2018**
Plant Size (MW, net):	**650**				**Capacity Factor:**	**80%**
Operating & Maintenance Labor						
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:	1.0	
Operating Labor Burden:		30.00	**% of base**	Operator:	3.3	
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:	1.0	
				Lab Techs, etc.:	1.0	
				Total:	**6.3**	
Fixed Operating Costs						
					Annual Cost	
					($)	**($/kW-net)**
				Annual Operating Labor:	$2,630,628	$4.05
				Maintenance Labor:	$4,509,117	$6.94
				Administrative & Support Labor:	$1,784,936	$2.75
				Property Taxes and Insurance:	$11,866,098	$18.25
				Total:	$20,790,780	$31.98
Variable Operating Costs						
					($)	**($/MWh-net)**
				Maintenance Material:	$6,763,676	$1.48
Stack Replacement						
		Life (y)	**$/kW AC**	**$/y per kW**		
SOFC Stack Replacement Cost		7.3	$225	$24.80	$16,124,050	$3.54
Consumables						
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (gal/1000):	0	1,441	$1.90	$0	$799,728	$0.18
Makeup and Waste Water Treatment Chemicals (lb):	0	10,735	$0.28	$0	$862,008	$0.19
NG Desulfur TDA Adsorbent (lb):	48,477	1180	$6.03	$292,303	$2,078,271	$0.46
ATR Catalyst (m^3):	4,046	2.8	$601.76	$2,434,946	$488,978	$0.11
			Subtotal:	$2,727,250	$4,228,986	$0.93
Waste Disposal						
ATR Catalyst (m^3):	0	2.8	$0.00	$0	$0	$0.00
			Subtotal:	$0	$0	$0.00
			Variable Operating Costs Total:	$2,727,250	$27,116,712	$5.95
Fuel Cost						
Natural Gas (MMBtu):	0	86,474	$4.42	$0	$111,612,402	$24.50
			Total:	$0	$111,612,402	$24.50

Exhibit 4-20. Case ANGFC0A – Atmospheric Reference NGFC Plant without CCS – Capital Cost Components

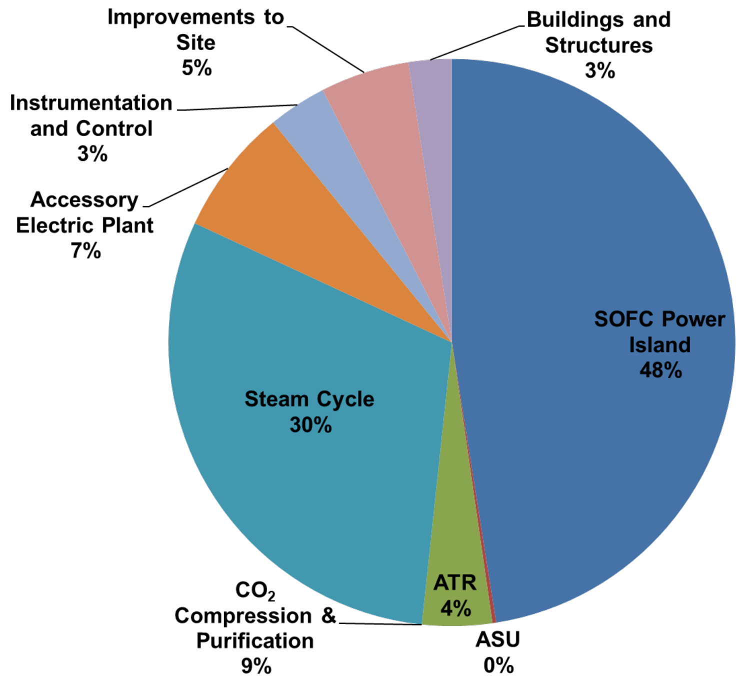


Exhibit 4-21. Case ANGFC0A – Atmospheric Reference NGFC Plant without CCS – BOP Cost Distribution

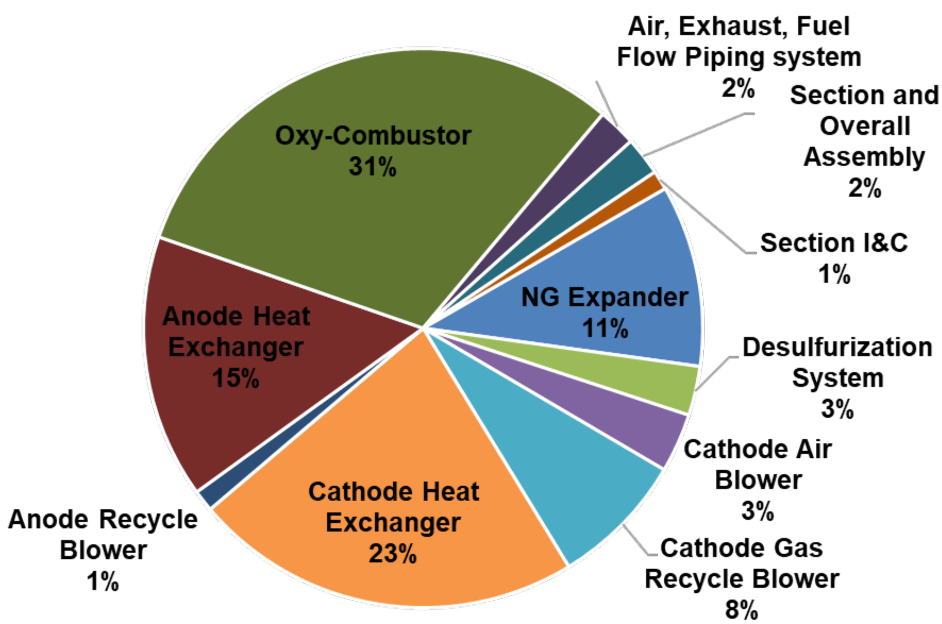


Exhibit 4-22. Case 0 – Atmospheric Reference NGFC Plant with and without CCS – Levelized Cost of Electricity

Levelized Cost of Electricity (2018$/MWh)		
Carbon Capture	With CCS	No CCS
Component	$/MWh	
Variable Costs	32.6	30.5
Fuel Costs	26.1	24.5
Variable O&M Costs	6.5	6.0
Fixed O&M Costs	6.5	4.6
Capital Costs	17.9	12.3
Total LCOE (excluding T&S)	57.0	47.3
T&S	3.1	0.0
Total LCOE (including T&S)	60.1	47.3

4.2 Case 4: Advanced Atmospheric NGFC Description

Case 4 assesses an advanced NGFC plant featuring the improvements made in Cases 1–3 along with additional improvements to various BOP components. The BOP improvements specific to Case 4 are a 20 percent power reduction on the ASU, an increase in inverter efficiency from 97 percent to 98 percent, and a stack cost reduction from 225 to 200 $/kWh. The SOFC technology parameters for this case are listed in Exhibit 4-23.

Exhibit 4-23. SOFC Technology Parameters Used for Case 4

Parameter	Value
Reformation	100% Internal
SOFC Operating Pressure	Atmospheric
Cell Technology	Advanced Cell
Fuel Utilization, %	85
Current Density, mA/cm^2	400
Degradation, %/1000 h	0.2
Inverter Efficiency (%)	98
Stack Cost ($/kW)	200

The major difference in the process diagrams between the advanced and reference atmospheric NGFC plants with CCS is the removal of the ATR due to the assumption of 100 percent internal reformation at the fuel cell anode, as seen in Exhibit 4-27. Desulfurized natural gas (Stream 1) is mixed with recycled anode gas (Stream 4) and preheated through the anode heat exchanger to achieve the anode inlet temperature (Stream 5). The preheated natural gas is pre-reformed before flowing through the anode. The anode off-gas (Stream 6) is mixed with 99.5 percent pure O_2 from a conventional ASU (Stream 3) and combusted across the oxy-combustor, generating a hot combustion gas (Stream 10) having 1 percent excess O_2 content. The combustion gas is cooled by the HRSG, which raises high-pressure steam for the steam bottoming cycle and low-pressure steam for the auxiliary processing needs. The cooled combustion gas is dehydrated, purified, and compressed to 2215 psia in the CPU (Stream 11).

On the cathode side, air (Stream 7) pressurized by the cathode air blower is preheated through the cathode heat exchanger and mixes with the recycled cathode gas to achieve the desired cathode inlet temperature (Stream 8) before being delivered to the SOFC cathode. The cathode air mixture not only provides the O_2 needed for the SOFC oxidation reactions but also acts as a coolant and serves to maintain an acceptable temperature distribution across the SOFC. The cell cooling is aided greatly by the reforming of methane throughout the cells, reducing the required flow of cathode air. The cathode off-gas passes through the cathode heat exchanger and is vented (Stream 9).

The configuration of Case 4 without CCS eliminates the CPU, and the ASU as displayed in Exhibit 4-32. The excess fuel gas in the anode off-gas stream is combusted with a portion of the exhaust gas issued from the cathode and heat is recovered, for process steam and steam cycle power generation before the exhaust is vented.

4.2.1 Case 4: Advanced Atmospheric NGFC Performance

Exhibit 4-24 summarizes the performance of the advanced atmospheric plants with and without CCS. In both configurations, as shown in Exhibit 4-25, the SOFC generates ≈88 percent of the gross power with the steam cycle generating the remaining 12 percent. The contribution of the SOFC to gross generation in the advanced plants is ≈6–7 percentage points larger compared to the reference NGFC plants, primarily due to the increased fuel utilization. The auxiliary load for the advanced plant without CCS is approximately evenly divided between the blower and steam cycle parasitic loads as shown in Exhibit 4-26. Compared to the reference plant without CCS the net auxiliary load of the advanced plant without CCS decreased by ≈35 percent. The inclusion of CCS more than triples the auxiliary load to the advanced plant and decreases the HHV efficiency by almost 3.4 percentage points. Compared to the reference plant with CCS, the advanced plant with CCS uses 30 percent less auxiliary power. This contributes to an increase of 7.6 percentage points in the advanced plant's HHV efficiency. The gain in efficiency is primarily due to the increased overall plant fuel utilization, the removal of the ATR (which would have consumed some fuel energy), and the benefits of decreased airflow requirements associated with increased internal reformation. The largest component to the auxiliary load of the advanced plant with CCS is the CO_2 compression and purification parasitic load at ≈52 percent.

The stream tables for the advanced plants with and without CCS are listed in Exhibit 4-28 and Exhibit 4-33 for the corresponding points numbered in the process flow diagram shown in Exhibit 4-27 and Exhibit 4-32 respectively. Material and energy balance tables and the heat and material balance diagrams for the reference plant with CCS are shown in Exhibit 4-29, Exhibit 4-30, and Exhibit 4-31 respectively. The corresponding tables for the reference plant without CCS are shown in Exhibit 4-34, and Exhibit 4-35.

There are 36 parallel SOFC sections in the plant, each containing a single cathode heat exchanger, anode heat exchanger, cathode air blower, cathode recycle gas blower, and anode gas recycle blower.

4.2.2 Case 4: Advanced Atmospheric NGFC Costs

Exhibit 4-36 and Exhibit 4-37 itemize the capital and O&M costs for the advanced atmospheric NGFC plant with CCS. The largest contribution to capital cost is the SOFC power island, making up ≈38 percent of the total as seen in Exhibit 4-38. Other significant costs include the steam cycle, the ASU, and the CPU, which contribute 21 percent, 11 percent, and 9 percent respectively. The largest component of the BOP costs is the cathode heat exchanger at 39 percent followed by the oxy-combustor at 34 percent as shown in Exhibit 4-39. The costs for the advanced plant without CCS are displayed in Exhibit 4-40 to Exhibit 4-43. The addition of CCS increases capital cost by over 40 percent, primarily due to the costs associated with the ASU and CPU. The LCOE for the advanced plant without CCS, as listed in Exhibit 4-44 is estimated to be $40.5/MWh. The addition of CCS increases the LCOE (without T&S) by $7.2/MWh. The LCOE with CO_2 T&S costs were observed to fall by $9.7/MWh as a result of the improvements made between Case 0 and Case 4.

Exhibit 4-24. Case 4 – Advanced Atmospheric NGFC Plant with and without CCS – Performance Summary

Carbon Capture	With CCS	No CCS
Power Summary (Gross Power at Generator Terminals, kWe)		
SOFC Power	611,250	582,528
Natural Gas/Syngas Expander Power	0	0
Steam Turbine Power	82,700	80,000
Total Gross Power, kW_e	**693,950**	**662,528**
Auxiliary Load Summary, kWe		
Air Separation Unit Auxiliaries	0	0
Air Separation Unit Main Air Compressor[A]	7,499	0
Oxygen Compressor	0	0
Nitrogen Compressors	0	0
CO_2 Compressor	22,883	0
CO_2 Refrigeration	0	0
Boiler Feedwater Pumps	1,520	1,470
Condensate Pump	47	46
Circulating Water Pump	2,090	1,730
Cooling Tower Fans	1,080	910
Gas Turbine Auxiliaries	-	-
Steam Turbine Auxiliaries	63	61
Cathode Air Blower	4,041	3,843
Cathode Recycle Blower	1,743	1,655
Anode Recycle Blower	354	339
Miscellaneous Balance of Plant[B]	402	382
Transformer Losses	2,198	2,016

Carbon Capture	With CCS	No CCS
Total Auxiliaries, kW_e	**43,920**	**12,452**
Net Power, kW_e	650,030	650,076
Net Plant Efficiency, % (HHV)	65.47	68.84
Net Plant Heat Rate, kJ/kWh (Btu/kWh)	5,499 (5,212)	5,229 (4,956)
CO_2 Capture Rate, %	98.1	0.0
Condenser Cooling Duty, 10^6 kJ/h (10^6 Btu/h)	485 (460)	464 (440)
Natural Gas Feed Rate, kg/h (lb/h)	68,151 (150,248)	64,814 (142,890)
Thermal Input[C], kWt	992,907	944,282
Raw Water Withdrawal, m^3/min (gpm)	5.8 (1,530.4)	6.8 (1,787.9)
Raw Water Consumption, m^3/min (gpm)	3.96 (1,047.3)	5.26 (1,388.9)

[A] Reflects power needed to compress air to ATR pressure.
[B] Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads.
[C] HHV of natural gas is 52,449 kJ/kg (22,549 Btu/lb).

Exhibit 4-25. Case 4 – Advanced Atmospheric NGFC Plant with and without CCS – Gross Power Distribution

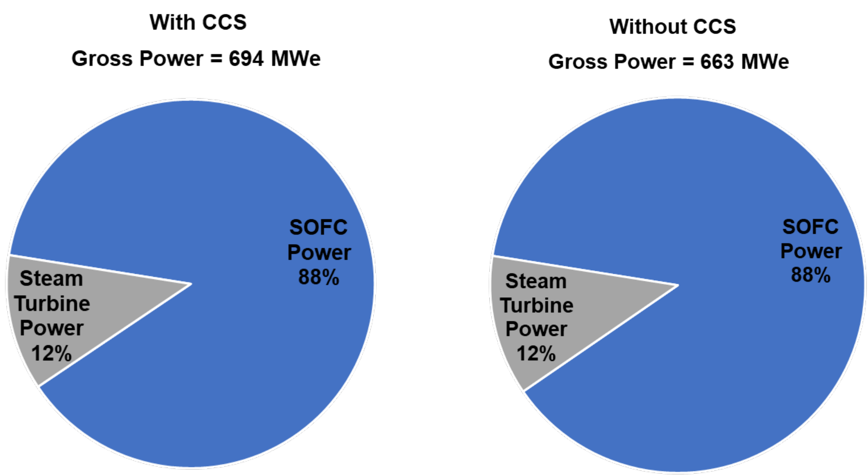


Exhibit 4-26. Case 4 – Advanced Atmospheric NGFC Plant with and without CCS – Auxiliary Load Distribution

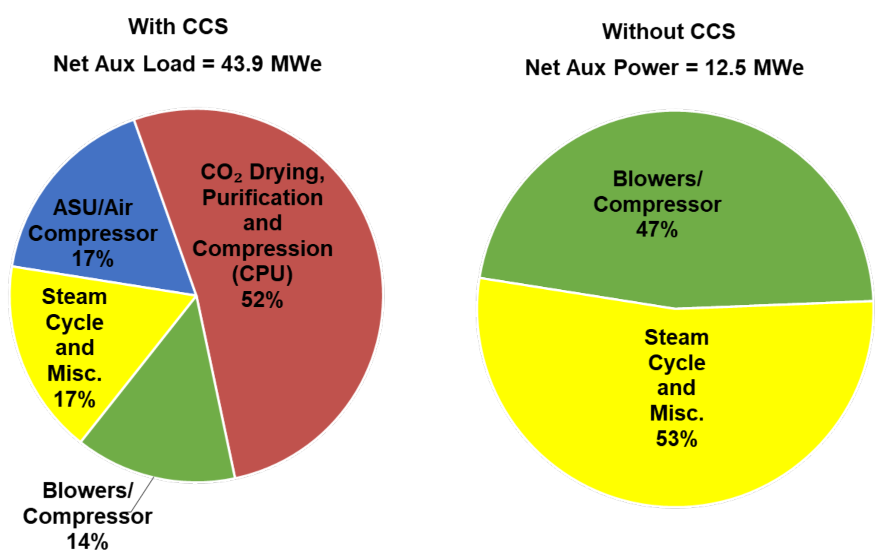


Exhibit 4-27. Case ANGFC4B – Advanced Atmospheric NGFC plant with CCS – Block Flow Diagram

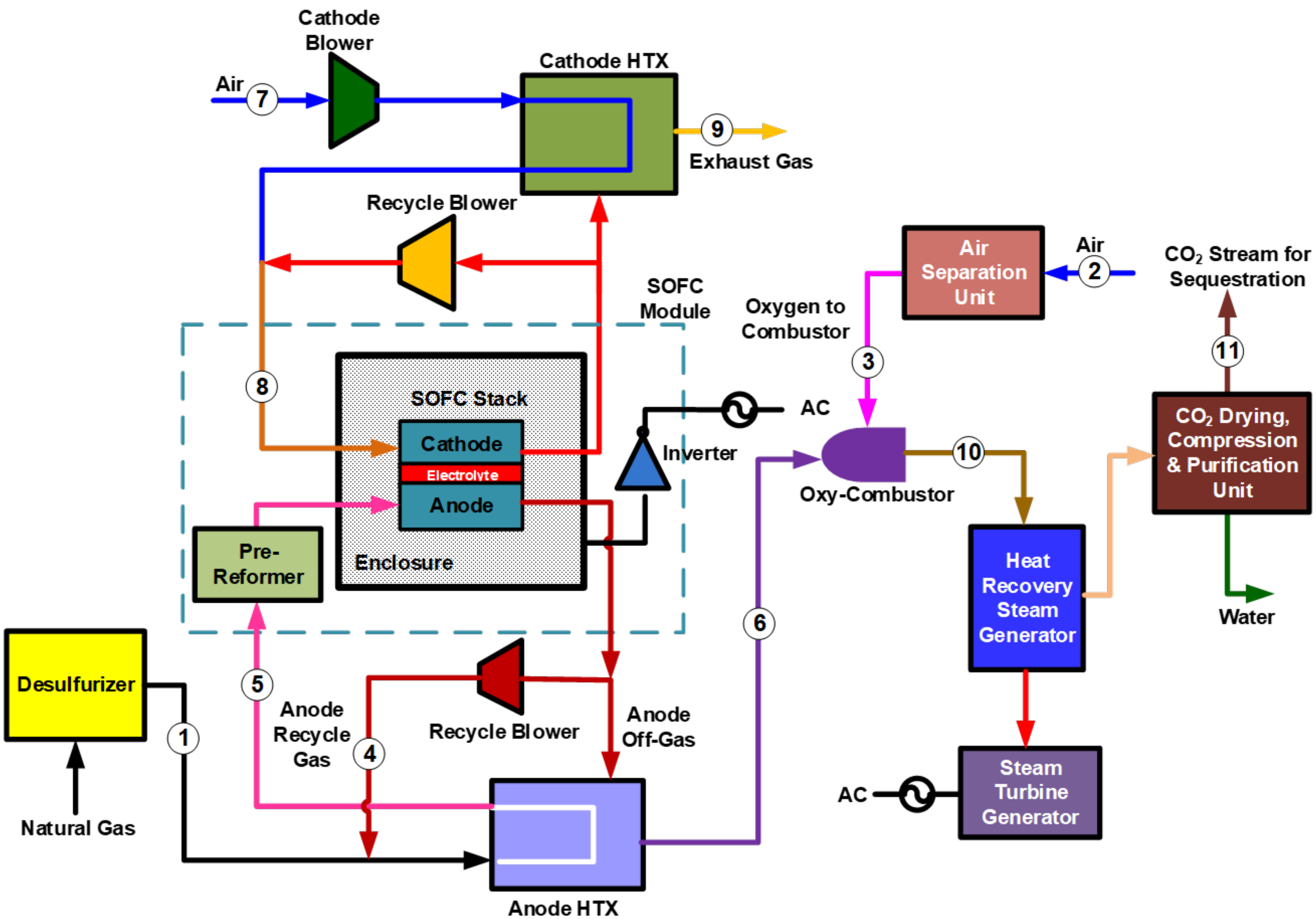


Exhibit 4-28. Case ANGFC4B – Advanced Atmospheric NGFC Plant with CCS – Stream Table

	1	2	3	4	5	6	7	8	9	10	11
V-L Mole Fraction											
Ar	0.0000	0.0094	0.0031	0.0000	0.0000	0.0000	0.0094	0.0101	0.0109	0.0003	0.0000
CH_4	0.9310	0.0000	0.0000	0.0001	0.1246	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0501	0.0392	0.0501	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0100	0.0003	0.0000	0.2900	0.2611	0.2900	0.0003	0.0003	0.0003	0.3367	1.0000
H_2	0.0000	0.0000	0.0000	0.1489	0.2371	0.1489	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	0.0000	0.0104	0.0000	0.5057	0.3316	0.5057	0.0104	0.0112	0.0121	0.6482	0.0000
N_2	0.0160	0.7722	0.0019	0.0052	0.0065	0.0052	0.7722	0.8291	0.8951	0.0054	0.0000
C_2H_6	0.0320	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_3H_8	0.0070	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_4H_{10}	0.0040	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
O_2	0.0000	0.2077	0.9950	0.0000	0.0000	0.0000	0.2077	0.1493	0.0816	0.0094	0.0000
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)	3,933	6,536	1,322	20,281	25,886	12,049	49,559	92,315	42,756	12,173	4,018
V-L Flowrate (kg/h)	68,151	188,597	42,334	481,137	549,287	285,849	1,429,991	2,642,284	1,212,293	328,183	176,853
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	15	15	27	717	510	594	15	624	132	1,580	36
Pressure (MPa, abs)	0.14	0.10	0.16	0.11	0.11	0.137	0.101	0.11	0.10	0.13	15.27
Enthalpy (kJ/kg)[A]	31.11	31.06	23.95	2,121.24	1,614.37	1,902.471	31.06	680.95	155.05	3,749.71	-208.83
Density (kg/m^3)	1.0	1.2	2.0	0.3	0.4	0.5	1.2	0.4	0.9	0.2	544.5
V-L Molecular Weight	17.328	28.854	32.016	23.723	21.219	23.723	28.854	28.622	28.354	26.960	44.010
V-L Flowrate (lb_{mol}/h)	8,671	14,410	2,915	44,713	57,069	26,564	109,259	203,520	94,260	26,836	8,859
V-L Flowrate (lb/h)	150,248	415,784	93,331	1,060,725	1,210,971	630,189	3,152,591	5,825,239	2,672,648	723,519	389,893
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	59	59	80	1,323	950	1,102	59	1,155	270	2,877	97
Pressure (psia)	20.0	14.7	23.0	16.2	16.2	19.9	14.7	15.3	14.7	18.9	2,215.0
Enthalpy (Btu/lb)[A]	13.4	13.4	10.3	912.0	694.1	817.9	13.4	292.8	66.7	1,612.1	-89.8
Density (lb/ft^3)	0.062	0.076	0.127	0.020	0.023	0.028	0.076	0.025	0.053	0.014	33.993

[A] Reference conditions are 32.02 F and 0.089 psia

Exhibit 4-29. Case ANGFC4B – Advanced Atmospheric NGFC Plant with CCS – Material and Energy Balances

Carbon Balance

Carbon In		**Carbon Out**	
kg/hr(lb/hr)		kg/hr(lb/hr)	
NG	49,225 (108,522)	Stack Gas	179 (394)
Air (CO2)	202 (446)	CO_2 Product	48,266 (106,408)
		Exhaust	957 (2,111)
		ASU Vent	24 (52)
		Water KO	1 (3)
		Convergence Tolerance	0 (0)
Total	49,427 (108,968)	Total	49,427 (108,968)

Sulfur Balance

Sulfur In		**Sulfur Out**	
kg/hr(lb/hr)		kg/hr(lb/hr)	
NGIN	0 (0)	Elemental Sulfur	0 (0)
		Polishing Sorbent	0 (0)
		Convergence Tolerance	0 (0)
Total	0 (0)	Total	0 (0)

Energy Balance

	HHV	**Sensible + Latent**	**Power**	**Total**
Heat In GJ/hr (MMBtu/hr)				
NG	3,574.46 (3,387.94)	2.4 (2.3)		3,576.9 (3,390.2)
ASU Air		5.9 (5.6)		0.0 (0.0)
Fuel cell Air		44.4 (42.1)		44.4 (42.1)
Auxiliary Power			158.1 (149.9)	158.1 (149.9)
TOTAL	**3,574 (3,388)**	**52.7 (49.9)**	**158.1 (149.9)**	**3,785.2 (3,587.7)**
Heat Out GJ/hr (MMBtu/hr)				
CO_2 Out		-36.9 (-35.0)		-36.9 (-35.0)
Stack Flue Gas		188.0 (178.2)		187.97 (178.16)
Vents		9.2 (8.7)		9.17 (8.69)
Water outlets		22.5 (21.3)		22.51 (21.34)
Process Losses**		1114.7 (1056.5)		1,114.68 (1,056.51)
Difference***		-10.4 (-9.8)		-10.38 (-9.84)
Power			2,498.2 (2,367.9)	2,498.2 (2,367.9)
TOTAL	**0.0 (0.0)**	**1,287.0 (1,219.9)**	**2,498.2 (2,367.9)**	**3,785.2 (3,587.7)**

* Includes ASU compressor intercoolers & CO2 compressor intercoolers
** Includes accounting of losses such as inverter, transformer, generator, and motor losses
*** Calculated by difference to close the energy balance

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)
Condenser Makeup	**0.0 (9)**	**0.0 (0)**	**0.0 (9)**	**0.0 (0)**	**0.0 (09)**
Reformer Steam	0.0 (0)	0.0 (0)	0.0 (0)		
BFW Makeup	0.0 (9)	0.0 (0)	0.0 (9)		
Cooling Tower	**8.1 (2,148)**	**2.37 (627)**	**5.8 (1,522)**	**1.8 (483)**	**3.9 (1,038)**
CO2 Dehydration	0.0 (0)	2.37 (627)	-2.37 (-627)		
Total	**8.2 (2,157)**	**2.37 (627)**	**5.8 (1,530)**	**1.8 (483)**	**4.0 (1,047)**

Emissions

	kg/GJ ($lb/10^6Btu$)	Tonne/year (tons/year)	kg/MWh (lb/MWh)
SO2	0 (0)	0 (0)	0 (0)
NOx	0 (0)	0 (0)	0 (0)
Particulate	0 (0)	0 (0)	0 (0)
Hg	0 (0)	0 (0)	0 (0)
CO2	1312 (3053)	28,153 (31,033)	5 (12)

Exhibit 4-30. Case ANGFC4B – Advanced Atmospheric NGFC Plant with CCS – Heat and Material Balance Diagram – ASU and Power Island

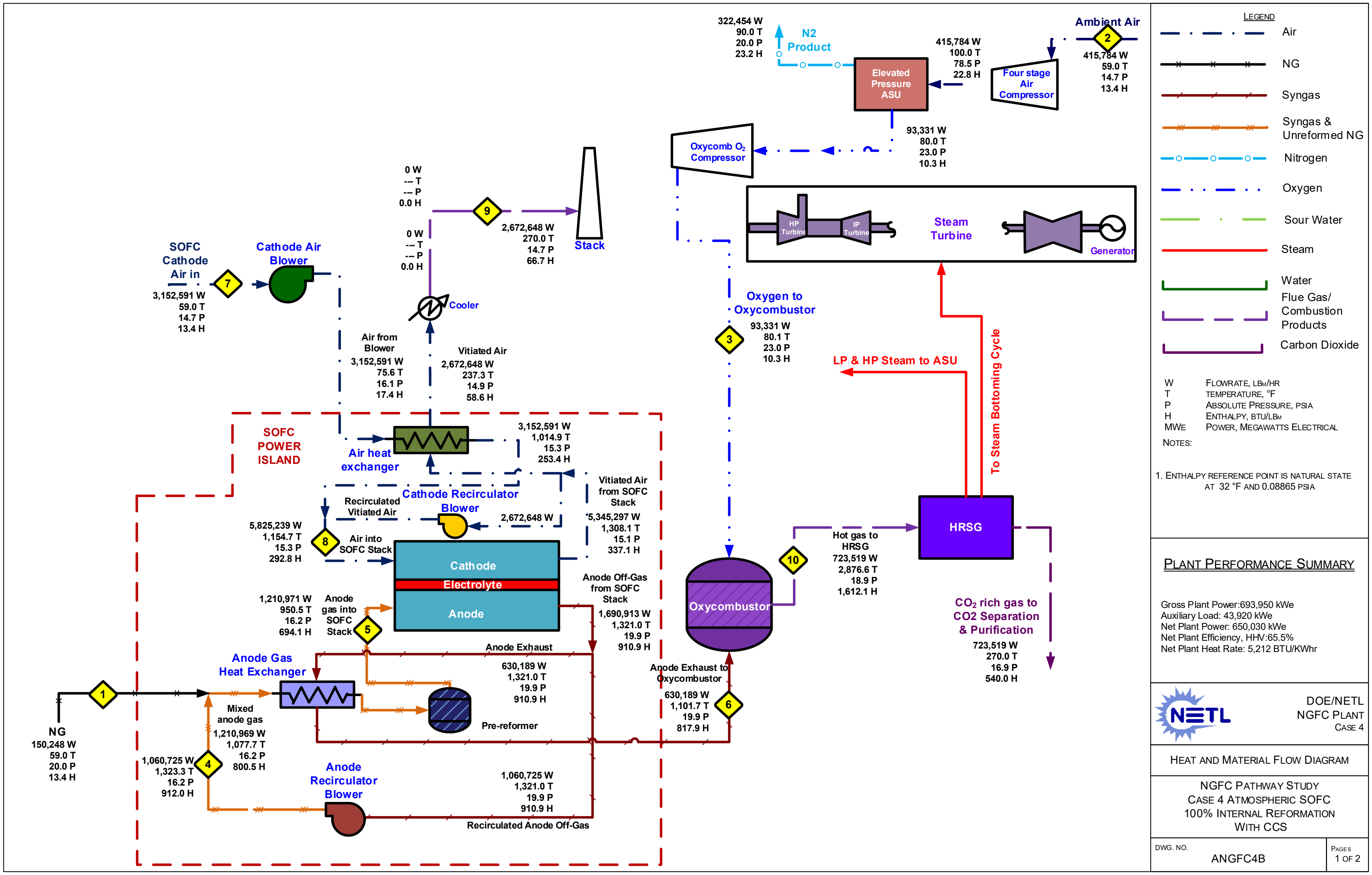


Exhibit 4-31. Case ANGFC4B – Advanced Atmospheric NGFC Plant with CCS – Heat and Material Balance Diagram – CO_2 Dehydration, Purification, and Compression

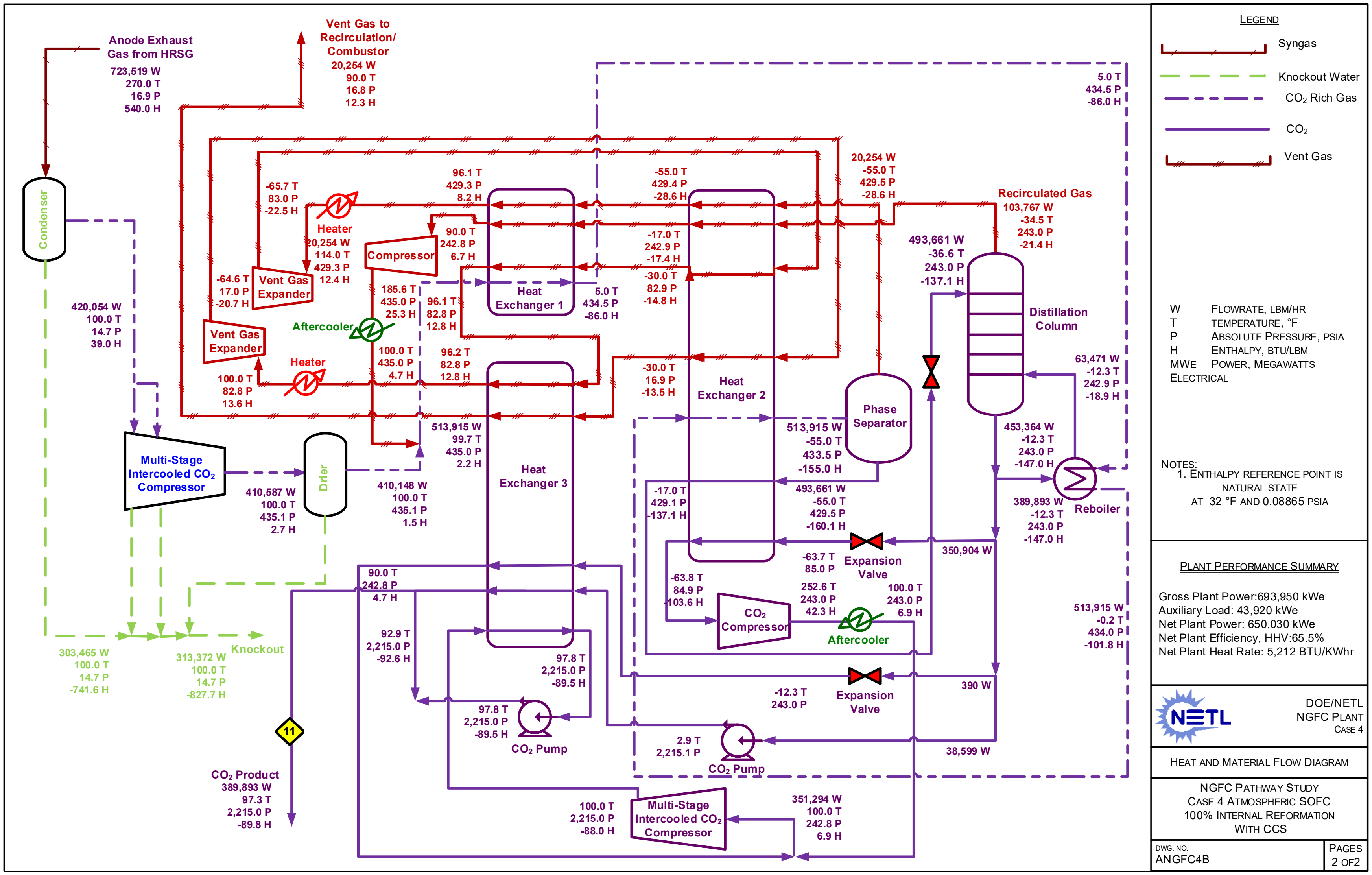


Exhibit 4-32. Case ANGFC4A – Advanced Atmospheric NGFC Plant without CCS – Block Flow Diagram

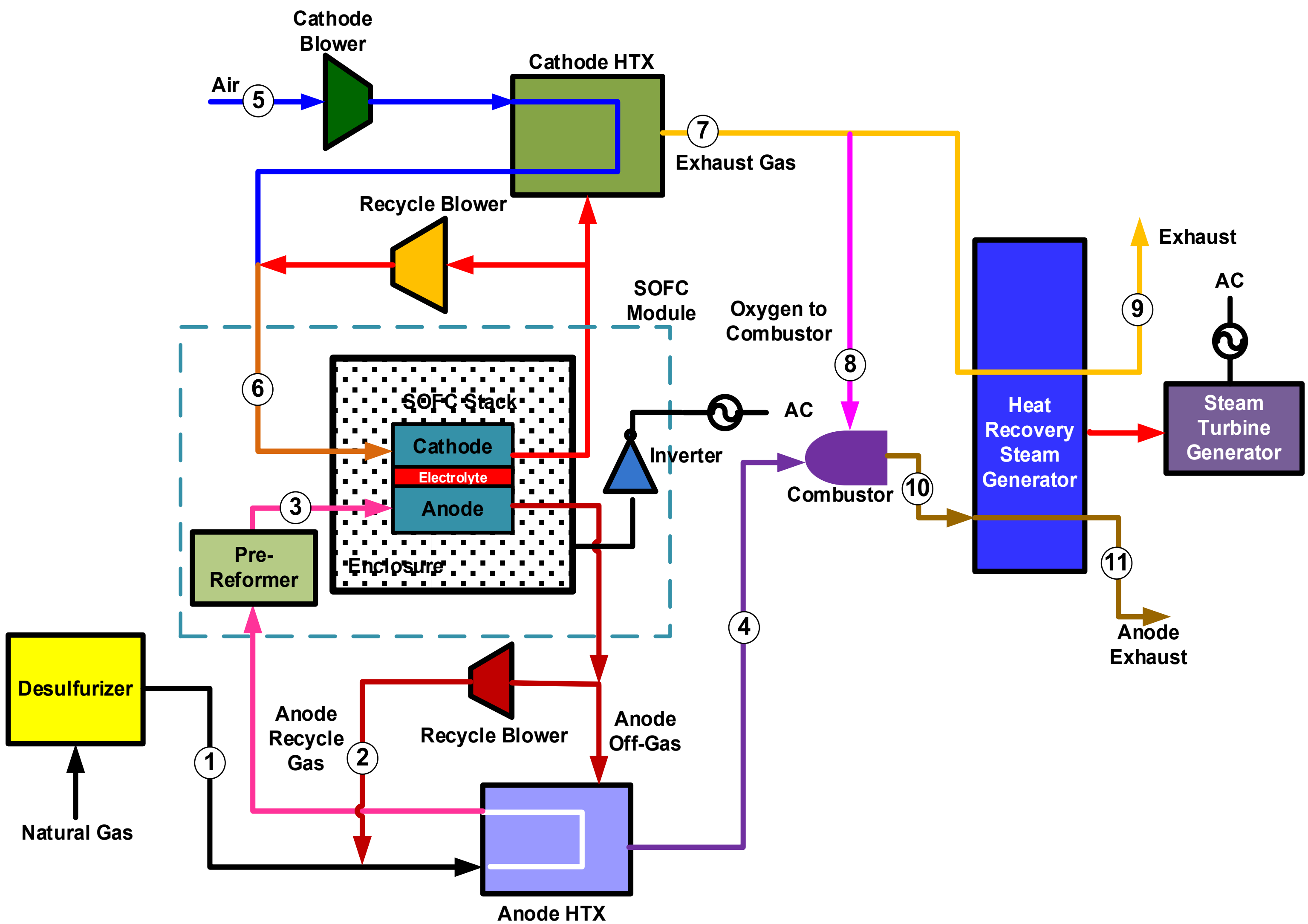


Exhibit 4-33. Case ANGFC4A – Advanced Atmospheric NGFC Plant without CCS – Stream Table

	1	2	3	4	5	6	7	8	9	10	11
V-L Mole Fraction											
Ar	0.0000	0.0000	0.0000	0.0000	0.0094	0.0101	0.0109	0.0109	0.0109	0.0065	0.0088
CH_4	0.9310	0.0001	0.1253	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0515	0.0409	0.0515	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0100	0.2886	0.2591	0.2886	0.0003	0.0003	0.0003	0.0003	0.0003	0.1513	0.2039
H_2	0.0000	0.1476	0.2343	0.1476	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	0.0000	0.5071	0.3339	0.5071	0.0104	0.0112	0.0121	0.0121	0.0121	0.2981	0.0543
N_2	0.0160	0.0052	0.0065	0.0052	0.7722	0.8291	0.8951	0.8951	0.8951	0.5393	0.7267
C_2H_6	0.0320	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_3H_8	0.0070	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_4H_{10}	0.0040	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	0.2077	0.1493	0.0816	0.0816	0.0816	0.0047	0.0063
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)	3,741	19,242	24,553	11,460	47,132	87,794	40,662	15,476	25,186	25,795	19,144
V-L Flowrate (kg/h)	64,814	456,460	521,274	271,851	1,359,961	2,512,885	1,152,924	438,797	714,127	710,647	590,837
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	15	727	520	602	15	625	107	107	132	952	38
Pressure (MPa, abs)	0.14	0.14	0.14	0.137	0.101	0.11	0.1	0.137	0.14	0.13	0.103
Enthalpy (kJ/kg)[A]	31.11	2,141.21	1,637.85	1,917.800	31.06	682.31	128.8	128.832	155.01	1,730.88	116.628
Density (kg/m^3)	1.0	0.4	0.4	0.4	1.2	0.4	0.9	1.2	1.1	0.4	1.2
V-L Molecular Weight	17.328	23.722	21.230	23.722	28.854	28.622	28	28.354	28.354	27.550	30.862
V-L Flowrate (lb_{mol}/h)	8,246	42,421	54,131	25,264	103,909	193,553	89,644	34,118	55,526	56,868	42,206
V-L Flowrate (lb/h)	142,890	1,006,322	1,149,212	599,329	2,998,201	5,539,963	2,541,762	967,381	1,574,381	1,566,710	1,302,573
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	59	1,341	968	1,115	59	1,157	224	224	270	1,746	100
Pressure (psia)	20.0	20.0	20.0	19.9	14.7	15.3	14.9	19.9	19.7	18.9	14.9
Enthalpy (Btu/lb)[A]	13.4	920.6	704.1	824.5	13.4	293.3	55.4	55.4	66.6	744.1	50.1
Density (lb/ft^3)	0.062	0.025	0.028	0.028	0.076	0.025	0	0.077	0.071	0.022	0.077

[A] Reference conditions are 32.02 F and 0.089 psia

Exhibit 4-34. Case ANGFC4A – Advanced Atmospheric NGFC Plant without CCS – Material and Energy Balances

Carbon Balance

Carbon In		Carbon Out	
kg/hr(lb/hr)		kg/hr(lb/hr)	
NG	46,814 (103,208)	Stack Gas	105 (232)
Air (CO2)	170 (374)	CO_2 Product	46,879 (103,350)
		0	0 (0)
		0	0 (0)
		0	0 (0)
		Convergence Tolerance	0 (1)
Total	46,984 (103,582)	Total	46,984 (103,582)

Sulfur Balance

Sulfur In		Sulfur Out	
kg/hr(lb/hr)		kg/hr(lb/hr)	
NGIN	0 (0)	Elemental Sulfur	0 (0)
		Polishing Sorbent	0 (0)
		Convergence Tolerance	0 (0)
Total	0 (0)	Total	0 (0)

Energy Balance

	HHV	Sensible + Latent	Power	Total
Heat In GJ/hr (MMBtu/hr)				
NG	3,399.41 (3,222.02)	2.3 (2.2)		3,401.7 (3,224.2)
ASU Air		0.0 (0.0)		0.0 (0.0)
Fuel cell Air		42.2 (40.0)		42.2 (40.0)
Auxiliary Power			44.8 (42.5)	44.8 (42.5)
TOTAL	**3,399 (3,222)**	**44.5 (42.2)**	**44.8 (42.5)**	**3,488.7 (3,306.7)**
Heat Out GJ/hr (MMBtu/hr)				
Stack Flue Gas		179.6 (170.2)		179.60 (170.23)
Process Losses*		899.3 (852.4)		899.29 (852.36)
Difference**		24.8 (23.5)		24.76 (23.47)
Power			2,385.1 (2,260.6)	2,385.1 (2,260.6)
TOTAL	**0.0 (0.0)**	**1,103.6 (1,046.1)**	**2,385.1 (2,260.6)**	**3,488.7 (3,306.7)**

* Includes accounting of losses such as inverter, transformer, generator, and motor losses

** Calculated by difference to close the energy balance

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)
Condenser Makeup	**0.1 (14)**	**0.0 (0)**	**0.1 (14)**	**0.0 (0)**	**0.1 (14)**
Reformer Steam	0.0 (0)	0.0 (0)	0.0 (0)		
BFW Makeup	0.1 (14)	0.0 (0)	0.1 (14)		
Cooling Tower	**6.7 (1,774)**	**0.00 (0)**	**6.7 (1,774)**	**1.5 (399)**	**5.2 (1,375)**
0	0.0 (0)	0.00 (0)	0.00 (0)		
Total	**6.8 (1,788)**	**0.00 (0)**	**6.8 (1,788)**	**1.5 (399)**	**5.3 (1,389)**

Emissions

	kg/GJ ($lb/10^6Btu$)	Tonne/year (tons/year)	kg/MWh (lb/MWh)
SO2	0 (0)	0 (0)	0 (0)
NOx	0 (0)	0 (0)	0 (0)
Particulate	0 (0)	0 (0)	0 (0)
Hg	0 (0)	0 (0)	0 (0)
CO2	54214 (126101)	1,162,888 (1,281,865)	236 (520)

Exhibit 4-35. Case ANGFC4A – Advanced Atmospheric NGFC Plant without CCS – Heat and Material Balance Diagram – Power Island

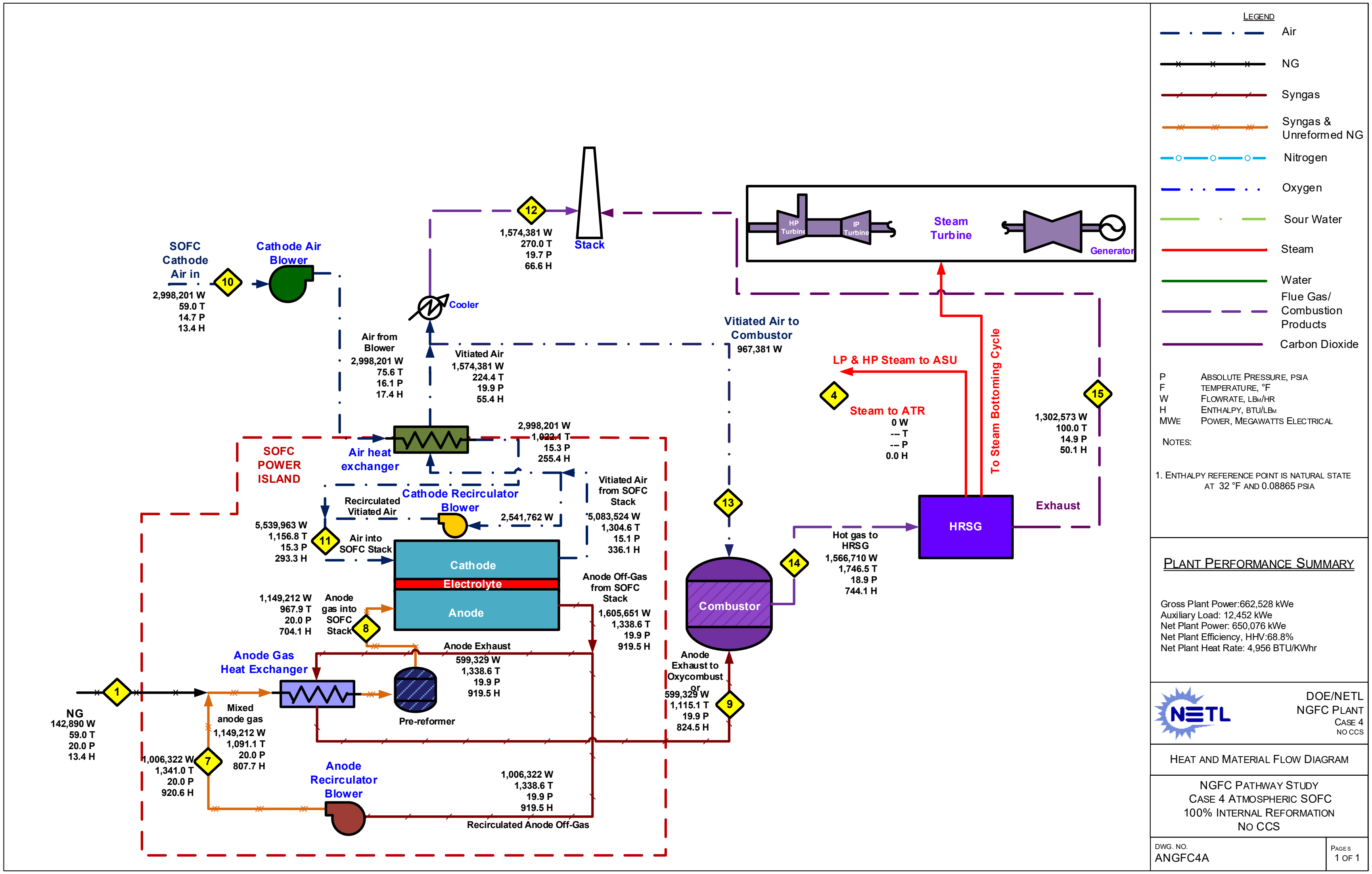


Exhibit 4-36. Case ANGFC4B – Advanced Atmospheric NGFC Plant with CCS – Capital Costs

Cost Component	Cost ($1000)	Specific Cost ($/kWe AC)
	2018$	2018$
SOFC Module		
SOFC Stack	127,166	196
Container	5,645	9
Insulation	2,543	4
Module Assembly	6,358	10
Air Distribution	6,358	10
Fuel Distribution	6,358	10
Pre-reformer	6,358	10
Module Current Collectors	3,179	5
Module I&C	3,179	5
Inverter	43,236	67
Total SOFC Module with 10 % Extra Installed Area	210,382	324
NG EXPANDER	**0**	**0**
SOFC BOP		
Desulfurization System	1,802	3
Cathode Air Compressor	1,961	3
Cathode Gas Recycle Compressor	4,385	7
Cathode Heat Exchanger	19,577	30
Anode Recycle Compressor	1,018	2
Anode Heat Exchanger	195	0
Oxy-Combustor	17,125	26
Air, Exhaust, Fuel Flow Piping system	1,805	3
Section and Overall Assembly	1,805	3
Section I&C	902	1
Total SOFC BOP	50,575	78
TOTAL SOFC POWER ISLAND	260,957	401
ASU	75,232	116
AUTOTHERMAL REFORMER and Natural Gas Preheater	**0**	0
STEAM CYCLE		
HRSG, Ducting, and Stack	39,478	61
Steam Power System	40,376	62
Feedwater and Miscellaneous BOP systems	66,439	102
TOTAL STEAM CYLCE	146,293	225
CO_2 COMPRESSION & PURIFICATION		
CO_2 Purification	81,931	126
TOTAL CO_2 COMPRESSION & PURIFICATION	81,931	126
COOLING WATER SYSTEM	32,260	50
ACCESSORY ELECTRIC PLANT	61,301	94
INSTRUMENTATION & CONTROL	22,013	34
IMPROVEMENTS TO SITE	28,841	44
BUILDING & STRUCTURES	12,651	19
TOTAL PLANT COST (TPC)	721,477	1110
OWNER'S COSTS		
Preproduction Costs		
6 Months All Labor	5,427	
1 Month Maintenance Materials	806	
1 Month Non-fuel Consumables	327	
25% of 1 Months Fuel Cost at 100% CF	2,733	
2% of TPC	14,430	
Total Preproduction Costs	23,723	
Inventory Capital		
60-day supply of fuel and consumables at 100% CF	546	
0.5% of TPC (spare parts)	3,607	
Total Inventory Capital	4,153	
Initial Cost for Catalyst and Chemicals	964	
Land	300	
Other Owner's Costs	108,222	
Financing Costs	19,480	
TOTAL OWNER'S COSTS	156,842	
TOTAL OVERNIGHT COST (TOC)	878,320	1351
TASC Multiplier	1.093	
TOTAL AS-SPENT COST (TASC)	960,003	1477

Exhibit 4-37. Case ANGFC4B – Advanced Atmospheric NGFC Plant with CCS – O&M Costs

Case:	**ANGFC4B**				**Cost Base:**	**Apr 2018**
Plant Size (MW, net):		**650**			**Capacity Factor:**	**85%**
Operating & Maintenance Labor						
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:	1.0	
Operating Labor Burden:		30.00	**% of base**	Operator:	4.3	
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:	1.0	
				Lab Techs, etc.:	1.0	
				Total:	**7.3**	
Fixed Operating Costs						
					Annual Cost	
					($)	**($/kW-net)**
				Annual Operating Labor:	$3,200,597	$4.92
				Maintenance Labor:	$5,483,228	$8.44
				Administrative & Support Labor:	$2,170,956	$3.34
				Property Taxes and Insurance:	$14,429,548	$22.20
				Total:	$25,284,330	$38.90
Variable Operating Costs						
					($)	**($/MWh-net)**
				Maintenance Material:	$8,224,842	$1.70
Stack Replacement						
		Life (y)	**$/kW AC**	**$/y per kW**		
SOFC Stack Replacement Cost		7.3	$205	$22.57	$14,669,537	$3.03
Consumables						
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (gal/1000):	0	937	$1.90	$0	$552,112	$0.11
Makeup and Waste Water Treatment Chemicals (lb):	0	6,565	$0.28	$0	$560,102	$0.12
NG Desulfur TDA Adsorbent (lb):	45,765	1110	$6.03	$275,952	$2,076,301	$0.43
ATR Catalyst (m^3):	1,144	0.8	$601.76	$688,349	$146,871	$0.03
			Subtotal:	$964,301	$3,335,386	$0.69
Waste Disposal						
ATR Catalyst (m^3):	0	0.8	$0.00	$0	$0	$0.00
			Subtotal:	$0	$0	$0.00
			Variable Operating Costs Total:	$964,301	$26,229,765	$5.42
Fuel Cost						
Natural Gas (MMBtu):	0	81,311	$4.42	$0	$111,506,580	$23.04
			Total:	$0	$111,506,580	$23.04

Exhibit 4-38. Case ANGFC4B – Advanced Atmospheric NGFC plant with CCS – Capital Cost Components

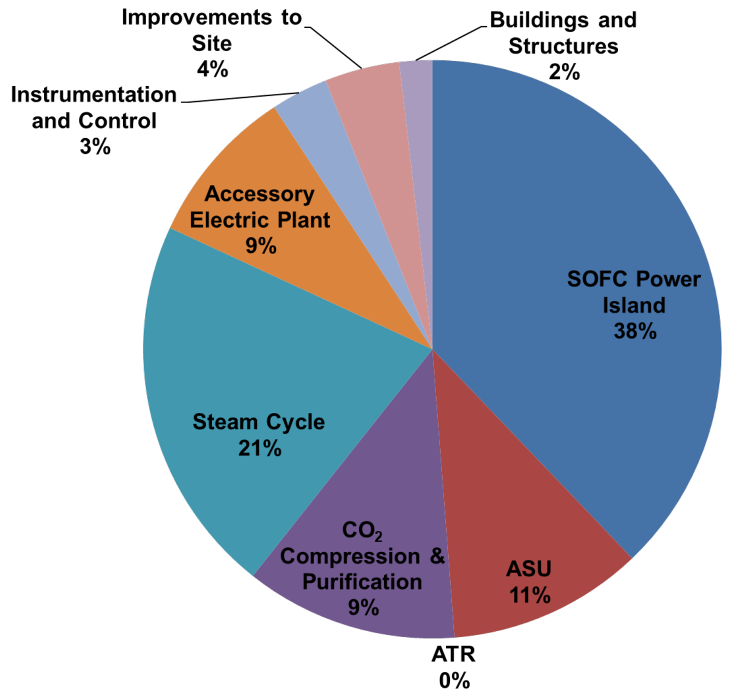


Exhibit 4-39. Case ANGFC4B – Advanced Atmospheric NGFC Plant with CCS – BOP Cost Distribution

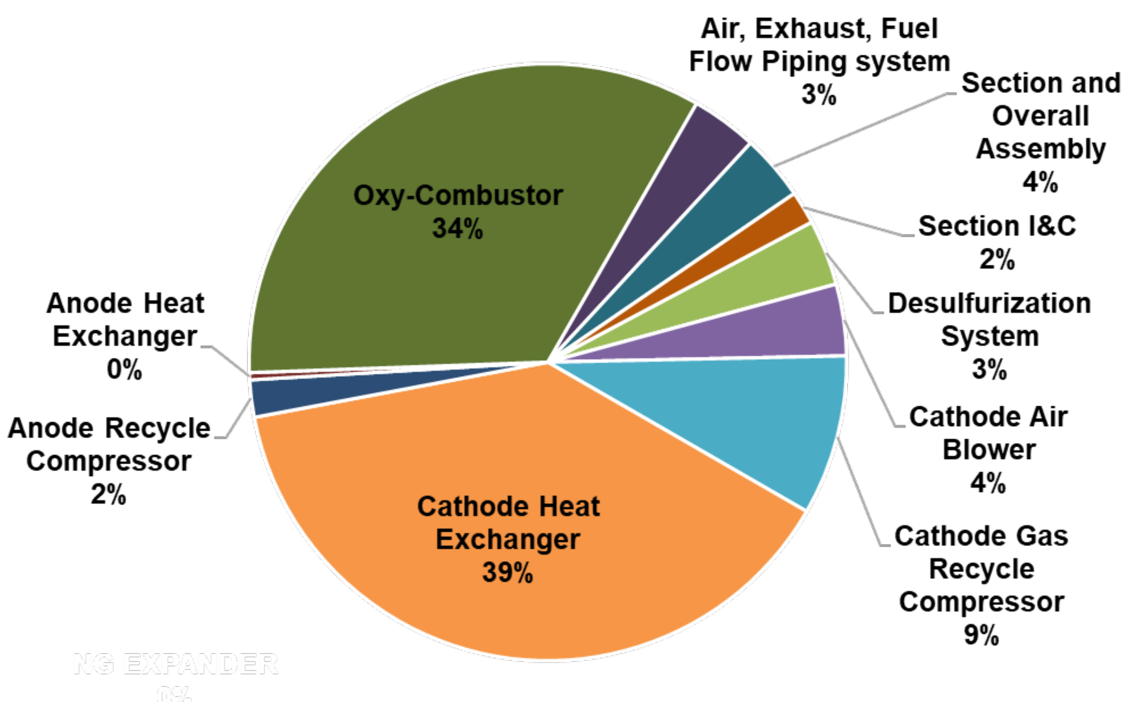


Exhibit 4-40. Case ANGFC4A – Advanced Atmospheric NGFC Plant without CCS – Capital Costs

Cost Component	Cost ($1000)	Specific Cost ($/kWe AC)
	2018$	2018$
SOFC Module		
SOFC Stack	120,101	185
Container	5,331	8
Insulation	2,402	4
Module Assembly	6,005	9
Air Distribution	6,005	9
Fuel Distribution	6,005	9
Pre-reformer	6,005	9
Module Current Collectors	3,003	5
Module I&C	3,003	5
Inverter	40,834	63
Total SOFC Module with 10 % Extra Installed Area	198,694	306
NATURAL GAS EXPANDER	**0**	**0**
SOFC BOP		
Desulfurization System	1,726	3
Cathode Air Compressor	1,861	3
Cathode Gas Recycle Compressor	4,159	6
Cathode Heat Exchanger	19,891	31
Anode Recycle Compressor	963	1
Anode Heat Exchanger	4,910	8
Oxy-Combustor	16,450	25
Air, Exhaust, Fuel Flow Piping system	1,646	3
Section and Overall Assembly	1,646	3
Section I&C	823	1
Total SOFC BOP	54,076	83
TOTAL SOFC POWER ISLAND	252,770	389
ASU	**0**	0
AUTOTHERMAL REFORMER and Natural Gas Preheater	**0**	0
STEAM CYCLE		
HRSG, Ducting, and Stack	32,394	50
Steam Power System	39,316	60
Feedwater and Miscellaneous BOP systems	65,589	101
TOTAL STEAM CYLCE	137,299	211
CO_2 COMPRESSION & PURIFICATION		
CO_2 Purification	0	0
TOTAL CO_2 COMPRESSION & PURIFICATION	**0**	**0**
COOLING WATER SYSTEM	28,813	44
ACCESSORY ELECTRIC PLANT	32,559	50
INSTRUMENTATION & CONTROL	17,377	27
IMPROVEMENTS TO SITE	28,233	43
BUILDING & STRUCTURES	12,485	19
TOTAL PLANT COST (TPC)	509,537	784
OWNER'S COSTS		
Preproduction Costs		
6 Months All Labor	4,064	
1 Month Maintenance Materials	569	
1 Month Non-fuel Consumables	334	
25% of 1 Months Fuel Cost at 100% CF	2,599	
2% of TPC	10,191	
Total Preproduction Costs	17,758	
Inventory Capital		
60-day supply of fuel and consumables at 100% CF	542	
0.5% of TPC (spare parts)	2,548	
Total Inventory Capital	3,090	
Initial Cost for Catalyst and Chemicals	917	
Land	300	
Other Owner's Costs	76,430	
Financing Costs	13,757	
TOTAL OWNER'S COSTS	112,253	
TOTAL OVERNIGHT COST (TOC)	621,790	956
TASC Multiplier	1.093	
TOTAL AS-SPENT COST (TASC)	679,616	1045

Exhibit 4-41. Case ANGFC4A – Advanced Atmospheric NGFC Plant without CCS – O&M Costs

Case:	**ANGFC4A**				**Cost Base:**	**Apr 2018**
Plant Size (MW, net):	**650**				**Capacity Factor:**	**85%**
Operating & Maintenance Labor						
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:	1.0	
Operating Labor Burden:		30.00	**% of base**	Operator:	3.3	
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:	1.0	
				Lab Techs, etc.:	1.0	
				Total:	**6.3**	
Fixed Operating Costs						
					Annual Cost	
					($)	**($/kW-net)**
				Annual Operating Labor:	$2,630,628	$4.05
				Maintenance Labor:	$3,872,477	$5.96
				Administrative & Support Labor:	$1,625,776	$2.50
				Property Taxes and Insurance:	$10,190,730	$15.68
				Total:	$18,319,612	$28.18
Variable Operating Costs						
					($)	**($/MWh-net)**
				Maintenance Material:	$5,808,716	$1.20
Stack Replacement						
		Life (y)	**$/kW AC**	**$/y per kW**		
SOFC Stack Replacement Cost		7.3	$204	$22.52	$14,640,044	$3.02
Consumables						
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (gal/1000):	0	1,091	$1.90	$0	$643,104	$0.13
Makeup and Waste Water Treatment Chemicals (lb):	0	7,647	$0.28	$0	$652,411	$0.13
NG Desulfur TDA Adsorbent (lb):	43,524	1056	$6.03	$262,438	$1,974,620	$0.41
ATR Catalyst (m^3):	1,088	0.7	$601.76	$654,639	$139,679	$0.03
			Subtotal:	$917,077	$3,409,814	$0.70
Waste Disposal						
ATR Catalyst (m^3):	0	0.7	$0.00	$0	$0	$0.00
			Subtotal:	$0	$0	$0.00
			Variable Operating Costs Total:	$917,077	$23,858,574	$4.93
Fuel Cost						
Natural Gas (MMBtu):	0	77,329	$4.42	$0	$106,045,839	$21.91
			Total:	$0	$106,045,839	$21.91

Exhibit 4-42. Case ANGFC4A – Advanced Atmospheric NGFC Plant without CCS – Capital Cost Components

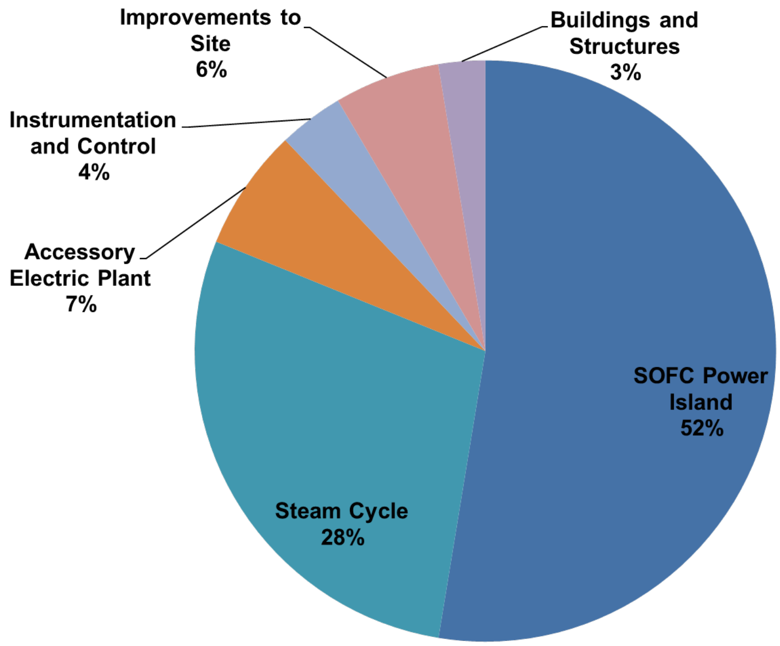


Exhibit 4-43. Case ANGFC4A – Advanced Atmospheric NGFC Plant without CCS – BOP Cost Distribution

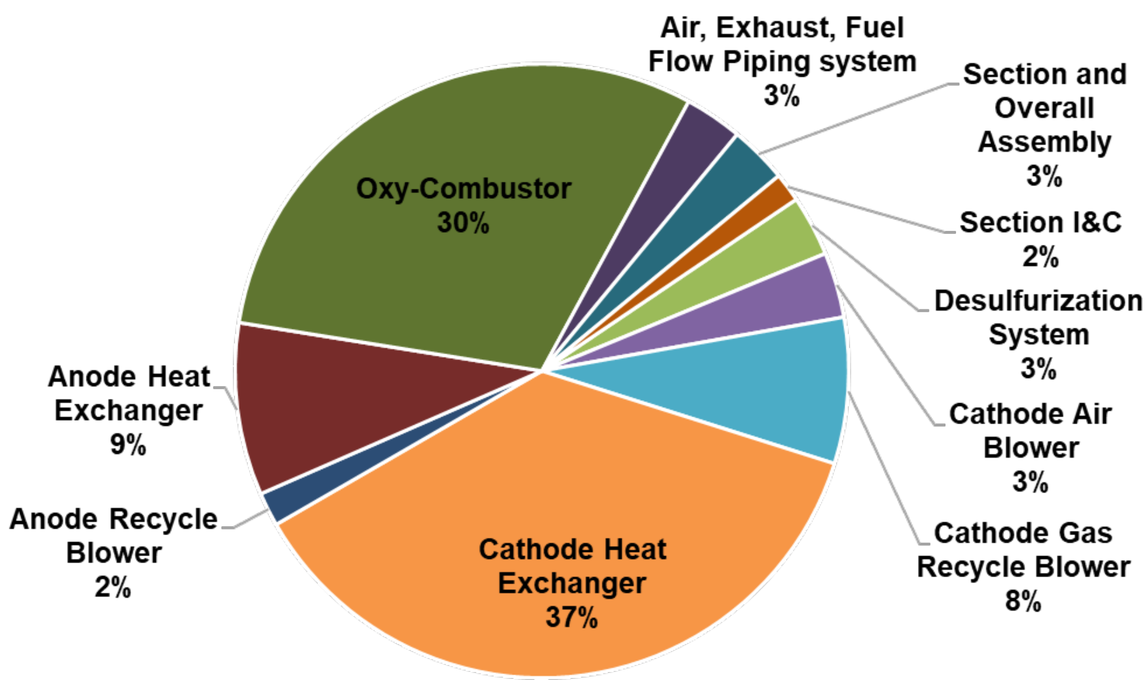


Exhibit 4-44. Case 4 – Advanced Atmospheric NGFC Plant with and without CCS – Levelized Cost of Electricity

Levelized Cost of Electricity (2018$/MWh)		
Carbon Capture	**With CCS**	**No CCS**
Component	**$/MWh**	
Variable Costs	28.5	26.8
Fuel Costs	23.0	21.9
Variable O&M Costs	5.4	4.9
Fixed O&M Costs	5.2	3.8
Capital Costs	14.0	9.9
Total LCOE (excluding T&S)	47.7	40.5
T&S	2.7	0.0
Total LCOE (including T&S)	50.4	40.5

4.3 Case 4BV: Advanced Atmospheric NGFC with VGR Description

Case 4BV assesses a modified configuration of Case 4 with CCS using the high-efficiency VGR system. The SOFC technology parameters are the same as in Case 4, but the VGR configuration allows for 97.5 percent fuel utilization. The SOFC technology parameters for Case 4BV are displayed in Exhibit 4-45.

Exhibit 4-45. SOFC Technology Parameters Used for Case 4BV

Parameter	Value
Reformation	100% Internal
SOFC Operating Pressure	Atmospheric
Cell Technology	Advanced Cell
Fuel Utilization, %	85
Current Density, mA/cm^2	400
Degradation, %/1000 h	0.2
Inverter Efficiency (%)	98
Stack Cost ($/kW)	200

The advanced NGFC plant with VGR is a modified configuration of Case ANGFC4B that allows the removal of the ASU and oxy-combustor. As seen in Exhibit 4-49, desulfurized natural gas (Stream 1) is mixed with recycled anode gas (Stream 3) and recirculated vent gas (Stream 2) before being preheated by the anode heat exchanger. The anode exhaust is cooled by the anode heat exchanger and the HRSG before being dehydrated, purified, and compressed to 2215 psia in the CPU (Stream 9). Unconsumed fuel is recovered from the CPU as a vent gas

(Stream 10) and recirculated back toward the anode after a portion of the vent gas is purged to prevent buildup of impurities. The purge gas is combusted with air (Stream 11) and used for heat recovery before it is vented.

On the cathode side, air (Stream 6) pressurized by the cathode air blower is preheated through the cathode heat exchanger and mixes with the recycled cathode gas to achieve the desired cathode inlet temperature (Stream 7) before being delivered to the SOFC cathode. The cathode air mixture not only provides the O_2 needed for the SOFC oxidation reactions but also acts as a coolant and serves to maintain an acceptable temperature distribution across the SOFC. The cathode off-gas passes through the cathode heat exchanger and is vented (Stream 8) after it exchanges heat in the HRSG.

4.3.1 Case 4BV: Advanced Atmospheric NGFC with VGR Performance

The performance of the advanced atmospheric plant with VGR is summarized in Exhibit 4-46. The HHV efficiency of the VGR plant is 69.24 percent, an increase of 3.7 percentage points over Case 4 with CCS. As seen in Exhibit 4-47, 94 percent of power is generated by the SOFC power island, the most of any case studied thus far. As seen in Exhibit 4-48 the single largest contribution to the auxiliary load is the CPU at 74 percent. The auxiliary load of the VGR plant is nearly 15 percent larger than the advanced plant with CCS primarily due to the higher flow rate of the gas through the CPU. The VGR configuration is not as effective at capturing CO_2 as the standard configuration, capturing ≈93 percent compared to nearly 98 percent in all other atmospheric cases with CCS.

The stream tables for the advanced plant with VGR are listed in Exhibit 4-50. Material and energy balance tables and the heat and material balance diagrams are shown in Exhibit 4-51, Exhibit 4-52, and Exhibit 4-53, respectively.

4.3.2 Case 4BV: Advanced Atmospheric NGFC with VGR Costs

Exhibit 4-54 and Exhibit 4-55 itemize the capital and O&M costs for the VGR baseline plant. The combined costs of the steam cycle and CPU make up ≈27 percent of total capital costs with the SOFC power island being the largest contributor at 45 percent as seen in Exhibit 4-56. The cathode heat exchanger makes up half the total BOP cost as shown in Exhibit 4-57. The LCOE with and without CO_2 T&S is listed in Exhibit 4-58. Compared to Case 4, the VGR configuration reduces the LCOE (including T&S) by $3.9/MWh.

Exhibit 4-46. Case ANGFC4BV – Advanced Atmospheric NGFC Plant with VGR – Performance Summary

Power Summary (Gross Power at Generator Terminals, kWe)	
SOFC Power	657,717
Natural Gas/Syn Gas Expander Power	0
Steam Turbine Power	42,900
Total Gross Power, kW_e	**700,617**
Auxiliary Load Summary, kW_e	
Air Separation Unit Auxiliaries	0
Air Separation Unit Main Air Compressor[A]	0
Oxygen Compressor	0
Nitrogen Compressors	0
CO_2 Compressor	37,094
CO_2 Refrigeration	0
Boiler Feedwater Pumps	788
Condensate Pump	24
Circulating Water Pump	1,740
Cooling Tower Fans	910
Gas Turbine Auxiliaries	-
Steam Turbine Auxiliaries	33
Cathode Air Blower	4,383
Cathode Recycle Blower	1,893
Anode Recycle Blower	959
Miscellaneous Balance of Plant[B]	380
Transformer Losses	2,234
Total Auxiliaries, kW_e	**50,439**
Net Power, kW_e	650,178
Net Plant Efficiency, % (HHV)	69.24
Net Plant Heat Rate, kJ/kWh (Btu/kWh)	5,706 (5,408)
CO_2 Capture Rate, %	91.7
Condenser Cooling Duty, 10^6 kJ/h (10^6 Btu/h)	253 (240)
Natural Gas Feed Rate, kg/h (lb/h)	64,455 (142,100)
Thermal Input[C], kWt	939,061
Raw Water Withdrawal, m^3/min (gpm)	4.6 (1,213.7)
Raw Water Consumption, m^3/min (gpm)	3.08 (812.7)

[A] Reflects power needed to compress air to ATR pressure.
[B] Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads.
[C] HHV of natural gas is 52,449 kJ/kg (22,549 Btu/lb).

Exhibit 4-47. Case ANGFC4BV – Advanced Atmospheric NGFC Plant with VGR – Gross Power Distribution

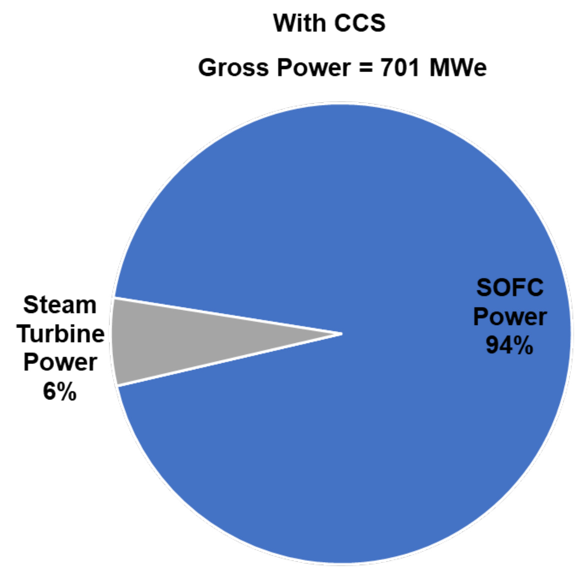


Exhibit 4-48. Case ANGFC4BV – Advanced Atmospheric NGFC Plant with VGR – Auxiliary Load Distribution

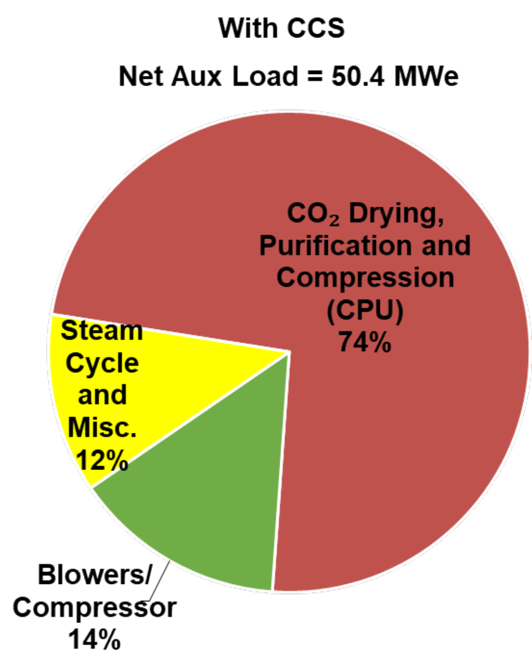


Exhibit 4-49. Case ANGFC4BV – Advanced Atmospheric NGFC Plant with VGR – Block Flow Diagram

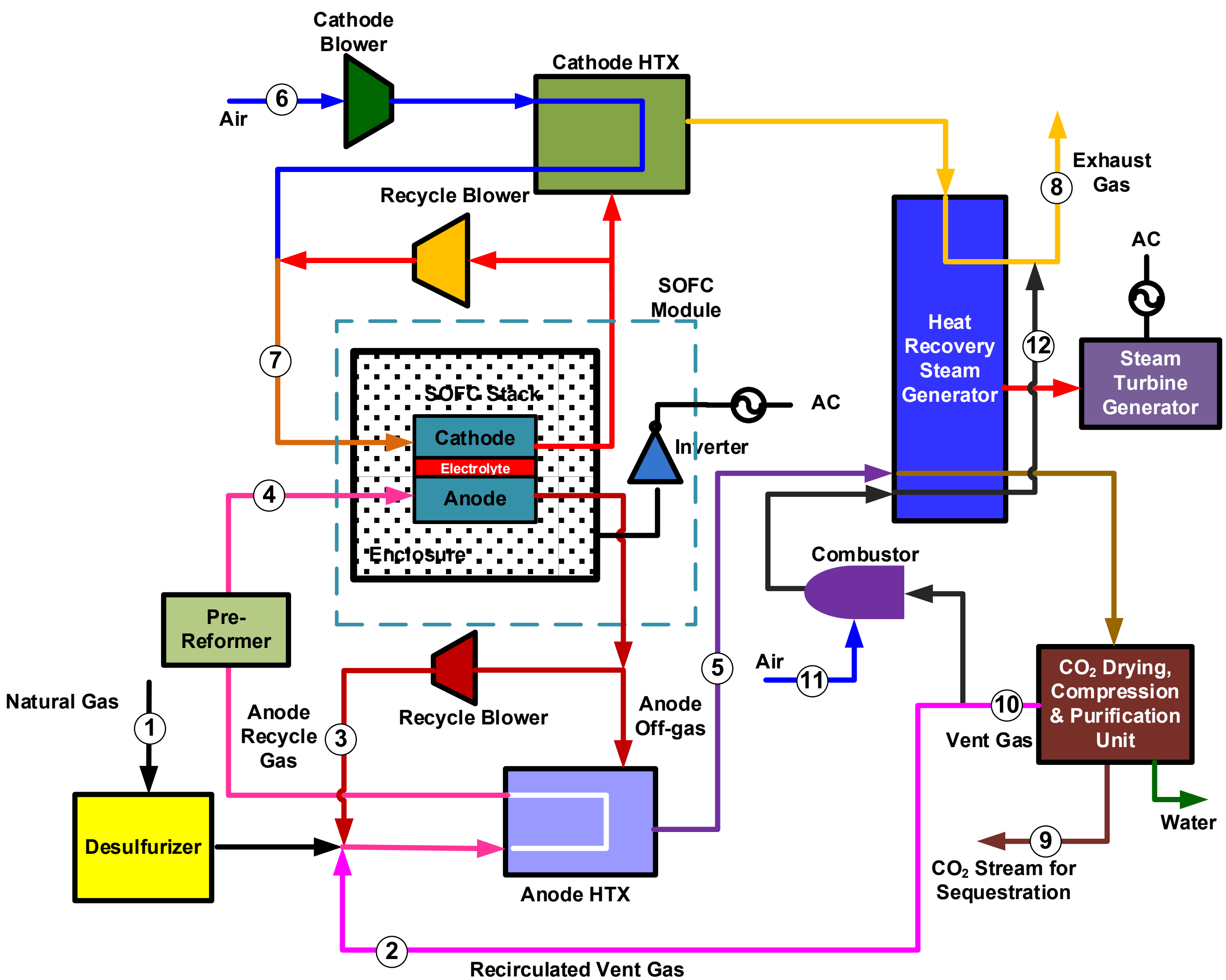


Exhibit 4-50. Case ANGFC4BV – Advanced Atmospheric NGFC Plant with VGR – Stream Table

	1	2	3	4	5	6	7	8	9	10	11	12
V-L Mole Fraction												
Ar	0.0000	0.0000	0.0000	0.0000	0.0000	0.0094	0.0101	0.0109	0.0000	0.0000	0.0094	0.0064
CH_4	0.9310	0.0006	0.0003	0.0406	0.0003	0.0000	0.0000	0.0000	0.0000	0.0006	0.0000	0.0000
CO	0.0000	0.2190	0.1065	0.1106	0.1065	0.0000	0.0000	0.0000	0.0013	0.2190	0.0000	0.0000
CO_2	0.0100	0.2964	0.3135	0.3031	0.3135	0.0003	0.0003	0.0003	0.9981	0.2964	0.0003	0.2369
H_2	0.0000	0.3899	0.1893	0.2602	0.1893	0.0000	0.0000	0.0000	0.0000	0.3899	0.0000	0.0000
H_2O	0.0000	0.0000	0.3446	0.2362	0.3446	0.0104	0.0112	0.0121	0.0000	0.0000	0.0104	0.1865
N_2	0.0160	0.0941	0.0458	0.0494	0.0458	0.7722	0.8291	0.8951	0.0006	0.0941	0.7722	0.5690
C_2H_6	0.0320	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	0.0070	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}	0.0040	0.0000	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	0.2077	0.1493	0.0816	0.0000	0.0000	0.2077	0.0012
Total	1.0000	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)	3,720	9,565	54,250	69,611	20,961	53,764	100,148	46,384	3,563	10,175	907	1,331
V-L Flowrate (kg/h)	64,455	216,270	1,337,771	1,618,496	516,896	1,551,331	2,866,491	1,315,160	156,697	230,074	26,157	39,962
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	15	149	729	580	621	15	628	132	29	29	15	149
Pressure (MPa, abs)	0.14	0.122	0.11	0.11	0.137	0.101	0.11	0.10	15.27	0.12	0.10	0.101
Enthalpy (kJ/kg)[A]	31.11	211.591	1,747.39	1,376.22	1,565.779	31.06	686.38	155.05	-227.66	40.15	31.06	440
Density (kg/m^3)	1.0	0.8	0.3	0.4	0.5	1.2	0.4	0.9	639.9	1.1	1.2	0.9
V-L Molecular Weight	17.328	22.611	24.659	23.251	24.659	28.854	28.622	28.354	43.979	22.611	28.854	30.020
V-L Flowrate (lb_{mol}/h)	8,201	21,087	119,601	153,466	46,212	118,530	220,789	102,259	7,855	22,433	1,999	2,935
V-L Flowrate (lb/h)	142,100	476,793	2,949,280	3,568,172	1,139,560	3,420,099	6,319,530	2,899,431	345,457	507,226	57,667	88,100
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	59	300	1,345	1,075	1,150	59	1,163	270	84	85	59	300
Pressure (psia)	20.1	17.7	16.2	16.2	19.9	14.7	15.3	14.7	2,215.0	17.8	14.7	14.7
Enthalpy (Btu/lb)[A]	13.4	91.0	751.2	591.7	673.2	13.4	295.1	66.7	-97.9	17.3	13.4	189.3
Density (lb/ft^3)	0.063	0.049	0.021	0.023	0.028	0.076	0.025	0.053	39.945	0.069	0.076	0.054

[A] Reference conditions are 32.02°F and 0.089 psia

Exhibit 4-51. Case ANGFC4BV – Advanced Atmospheric NGFC Plant with VGR – Material and Energy Balances

Carbon Balance

Carbon In		Carbon Out	
kg/hr(lb/hr)		kg/hr(lb/hr)	
NG	46,555 (102,637)	Stack Gas	194 (427)
Air (CO2)	197 (434)	CO_2 Product	42,769 (94,291)
		Exhaust	3,787 (8,350)
		ASU Vent	0 (0)
		Water KO	1 (2)
		Convergence Tolerance	1 (2)
Total	46,752 (103,071)	Total	46,752 (103,071)

Sulfur Balance

Sulfur In		Sulfur Out	
kg/hr(lb/hr)		kg/hr(lb/hr)	
NGIN	0 (0)	Elemental Sulfur	0 (0)
		Polishing Sorbent	0 (0)
		Convergence Tolerance	0 (0)
Total	0 (0)	Total	0 (0)

Energy Balance

	HHV	Sensible + Latent	Power	Total
Heat In GJ/hr (MMBtu/hr)				
NG	380.62 (3,204.2	2.3 (2.1)		3,382.9 (3,206.4)
ASU Air		0.8 (0.8)		0.0 (0.0)
Fuel cell Air		48.2 (45.7)		48.2 (45.7)
Raw Water Makeup		0.0 (0.0)		0.0 (0.0)
Auxiliary Power			181.6 (172.1)	181.6 (172.1)
TOTAL	**3,381 (3,204)**	**51.3 (48.6)**	**181.6 (172.1)**	**3,613.4 (3,424.9)**
Heat Out GJ/hr (MMBtu/hr)				
CO_2 Out		-35.7 (-33.8)		-35.7 (-33.8)
Stack Flue Gas		203.9 (193.3)		203.92 (193.28)
Vents		17.6 (16.7)		17.60 (16.68)
Water outlets		20.6 (19.5)		20.58 (19.51)
Process Losses**		893.4 (846.8)		893.38 (846.77)
Difference***		-8.6 (-8.1)		-8.58 (-8.14)
Power			2,522.2 (2,390.6)	2,522.2 (2,390.6)
TOTAL	**0.0 (0.0)**	**1,091.2 (1,034.3)**	**2,522.2 (2,390.6)**	**3,613.4 (3,424.9)**
* Includes ASU compressor intercoolers & CO2 compressor intercoolers				
** Includes accounting of losses such as inverter, transformer, generator, and motor losses				
*** Calculated by difference to close the energy balance				

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)
Condenser Makeup	**0.0 (5)**	**0.0 (0)**	**0.0 (5)**	**0.0 (0)**	**0.0 (05)**
Reformer Steam	0.0 (0)	0.0 (0)	0.0 (0)		
BFW Makeup	0.0 (5)	0.0 (0)	0.0 (5)		
Cooling Tower	**6.7 (1,783)**	**2.17 (574)**	**4.6 (1,209)**	**1.5 (401)**	**3.1 (808)**
CO2 Dehydration	0.0 (0)	2.17 (574)	-2.17 (-574)		
Total	**6.8 (1,787)**	**2.17 (574)**	**4.6 (1,214)**	**1.5 (401)**	**3.1 (813)**

Emissions

	kg/GJ ($lb/10^6Btu$)	Tonne/year (tons/year)	kg/MWh (lb/MWh)
SO2	0 (0)	0 (0)	0 (0)
NOx	0 (0)	0 (0)	0 (0)
Particulate	0 (0)	0 (0)	0 (0)
Hg	0 (0)	0 (0)	0 (0)
CO2	4595 (10687)	98,558 (108,642)	19 (42)

Exhibit 4-52. Case ANGFC4BV – Advanced Atmospheric NGFC Plant with VGR – Heat and Material Balance Diagram – ASU, ATR, and Power Island

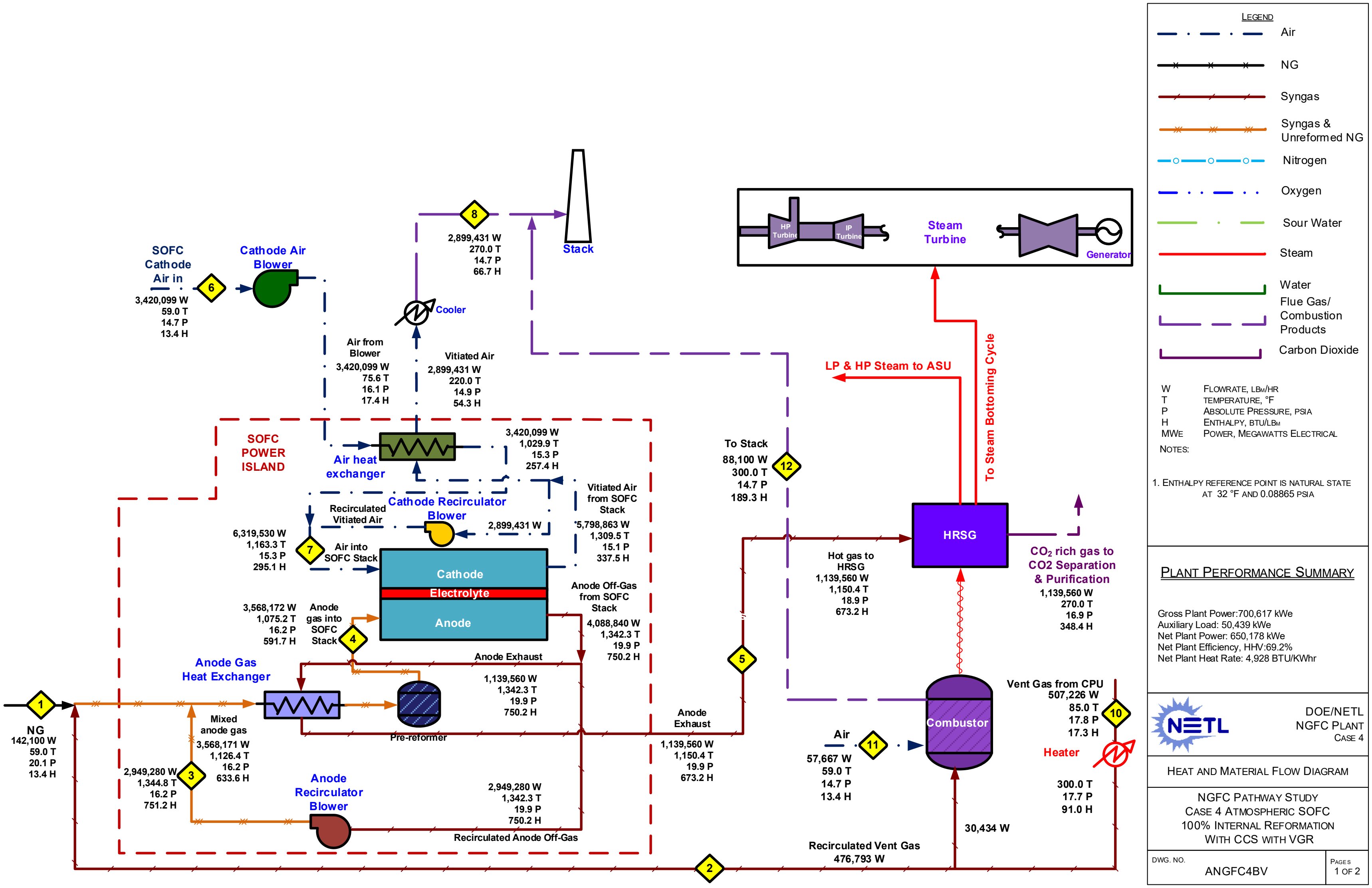


Exhibit 4-53. Case ANGFC4BV – Advanced Atmospheric NGFC Plant with VGR – Heat and Material Balance Diagram – CO_2 Dehydration, Purification, and Compression

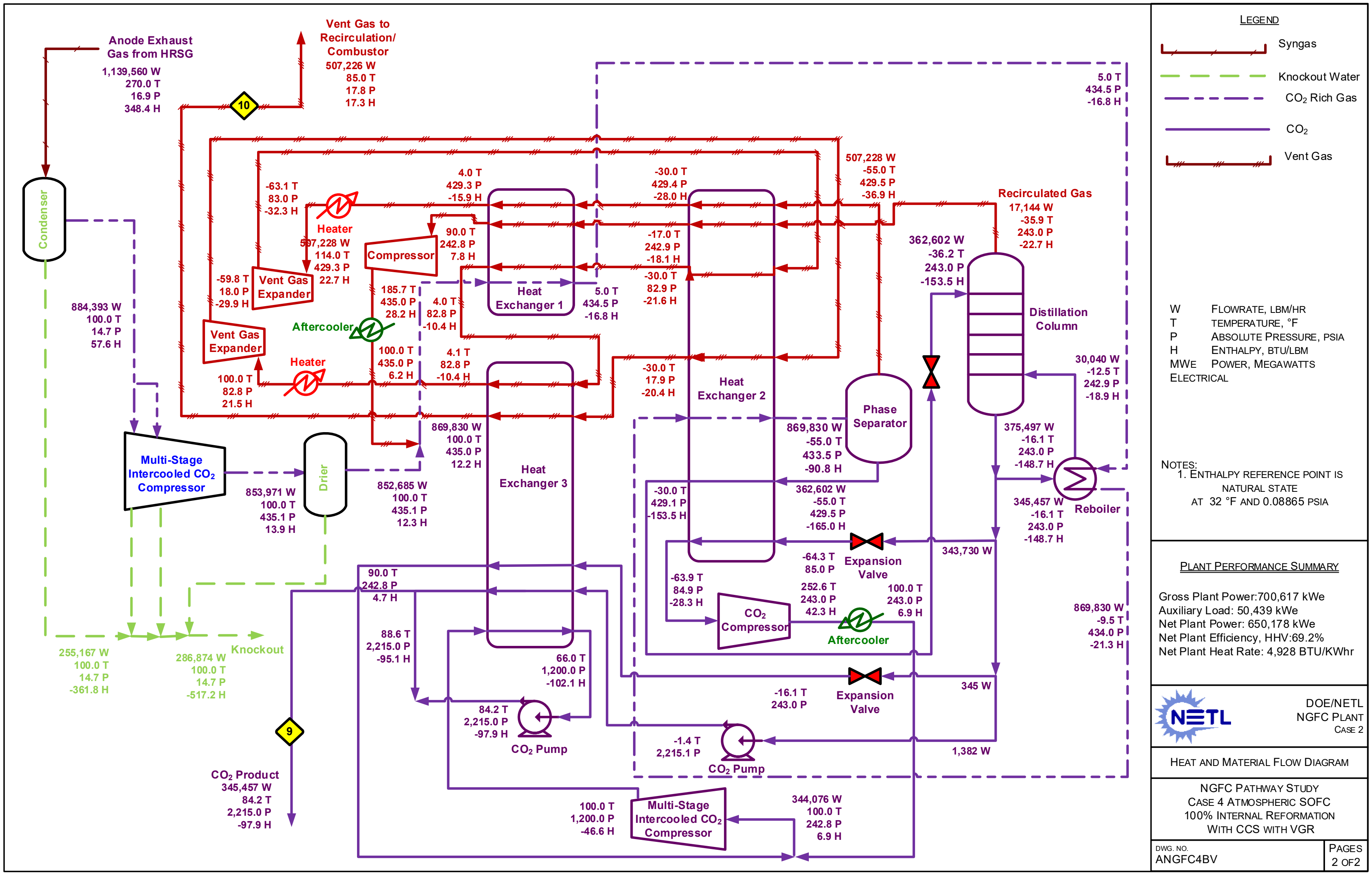


Exhibit 4-54. Case ANGFC4BV – Advanced Atmospheric NGFC Plant with VGR – Capital Costs

Cost Component	Cost ($1000)	Specific Cost ($/kWe AC)
	2018$	2018$
SOFC Module		
SOFC Stack	137,763	212
Container	6,115	9
Insulation	2,755	4
Module Assembly	6,888	11
Air Distribution	6,888	11
Fuel Distribution	6,888	11
Pre-reformer	6,888	11
Module Current Collectors	3,444	5
Module I&C	3,444	5
Inverter	46,839	72
Total SOFC Module with 10 % Extra Installed Area	227,914	351
NATURAL GAS EXPANDER	**0**	**0**
SOFC BOP		
Desulfurization System	1,711	3
Cathode Air Compressor	2,126	3
Cathode Gas Recycle Compressor	4,754	7
Cathode Heat Exchanger	23,664	36
Anode Recycle Compressor	1,782	3
Anode Heat Exchanger	7,207	11
Oxy-Combustor	0	0
Air, Exhaust, Fuel Flow Piping system	2,043	3
Section and Overall Assembly	2,043	3
Section I&C	1,021	2
Total SOFC BOP	46,351	71
TOTAL SOFC POWER ISLAND	274,265	422
ASU	**0**	0
AUTOTHERMAL REFORMER and Natural Gas Preheater	**0**	0
STEAM CYCLE		
HRSG, Ducting, and Stack	26,954	41
Steam Power System	23,891	37
Feedwater and Miscellaneous BOP systems	60,448	93
TOTAL STEAM CYLCE	111,294	171
CO_2 COMPRESSION & PURIFICATION		
CO_2 Purification	96,016	148
TOTAL CO_2 COMPRESSION & PURIFICATION	96,016	148
COOLING WATER SYSTEM	28,778	44
ACCESSORY ELECTRIC PLANT	65,667	101
INSTRUMENTATION & CONTROL	22,514	35
IMPROVEMENTS TO SITE	28,970	45
BUILDING & STRUCTURES	10,765	17
TOTAL PLANT COST (TPC)	638,269	982
OWNER'S COSTS		
Preproduction Costs		
6 Months All Labor	5,032	
1 Month Maintenance Materials	713	
1 Month Non-fuel Consumables	293	
25% of 1 Months Fuel Cost at 100% CF	2,585	
2% of TPC	12,765	
Total Preproduction Costs	21,388	
Inventory Capital		
60-day supply of fuel and consumables at 100% CF	499	
0.5% of TPC (spare parts)	3,191	
Total Inventory Capital	3,691	
Initial Cost for Catalyst and Chemicals	911	
Land	300	
Other Owner's Costs	95,740	
Financing Costs	17,233	
TOTAL OWNER'S COSTS	139,263	
TOTAL OVERNIGHT COST (TOC)	777,532	1196
TASC Multiplier	1.093	
TOTAL AS-SPENT COST (TASC)	849,843	1307

Exhibit 4-55. Case ANGFC4BV – Advanced Atmospheric NGFC Plant with VGR – O&M Costs

Case:	ANGFC4BV				Cost Base:	Apr 2018
Plant Size (MW, net):		650			Capacity Factor:	85%
Operating & Maintenance Labor						
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:	1.0	
Operating Labor Burden:		30.00	**% of base**	Operator:	4.3	
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:	1.0	
				Lab Techs, etc.:	1.0	
				Total:	**7.3**	
Fixed Operating Costs						
					Annual Cost	
					($)	**($/kW-net)**
				Annual Operating Labor:	$3,200,597	$4.92
				Maintenance Labor:	$4,850,844	$7.46
				Administrative & Support Labor:	$2,012,860	$3.10
				Property Taxes and Insurance:	$12,765,380	$19.64
				Total:	$22,829,682	$35.12
Variable Operating Costs						
					($)	**($/MWh-net)**
				Maintenance Material:	$7,276,266	$1.50
Stack Replacement						
		Life (y)	**$/kW AC**	**$/y per kW**		
SOFC Stack Replacement Cost		7.3	$207	$22.75	$14,790,600	$3.06
Consumables						
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (gal/1000):	0	742	$1.90	$0	$437,614	$0.09
Makeup and Waste Water Treatment Chemicals (lb):	0	5,203	$0.28	$0	$443,947	$0.09
NG Desulfur TDA Adsorbent (lb):	43,068	1050	$6.03	$259,688	$1,963,702	$0.41
ATR Catalyst (m^3):	1,082	0.7	$601.76	$651,020	$138,907	$0.03
			Subtotal:	$910,708	$2,984,170	$0.62
Waste Disposal						
ATR Catalyst (m^3):	0	0.7	$0.00	$0	$0	$0.00
			Subtotal:	$0	$0	$0.00
			Variable Operating Costs Total:	$910,708	$25,051,036	$5.18
Fuel Cost						
Natural Gas (MMBtu):	0	76,901	$4.42	$0	$105,459,540	$21.79
			Total:	$0	$105,459,540	$21.79

Exhibit 4-56. Case ANGFC4BV – Advanced Atmospheric NGFC Plant with VGR – Capital Cost Components

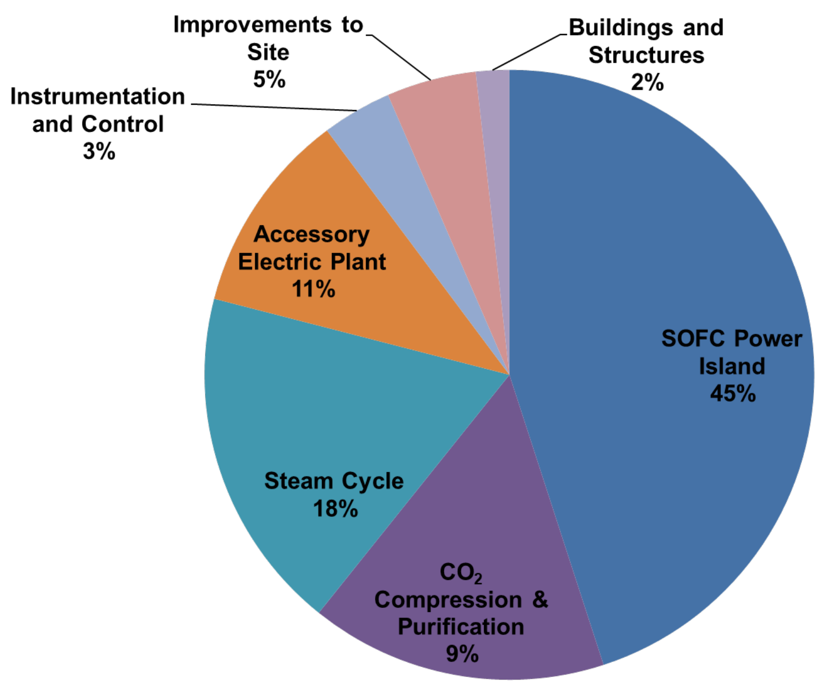


Exhibit 4-57. Case ANGFC4BV – Advanced Atmospheric NGFC Plant with VGR – BOP Cost Distribution

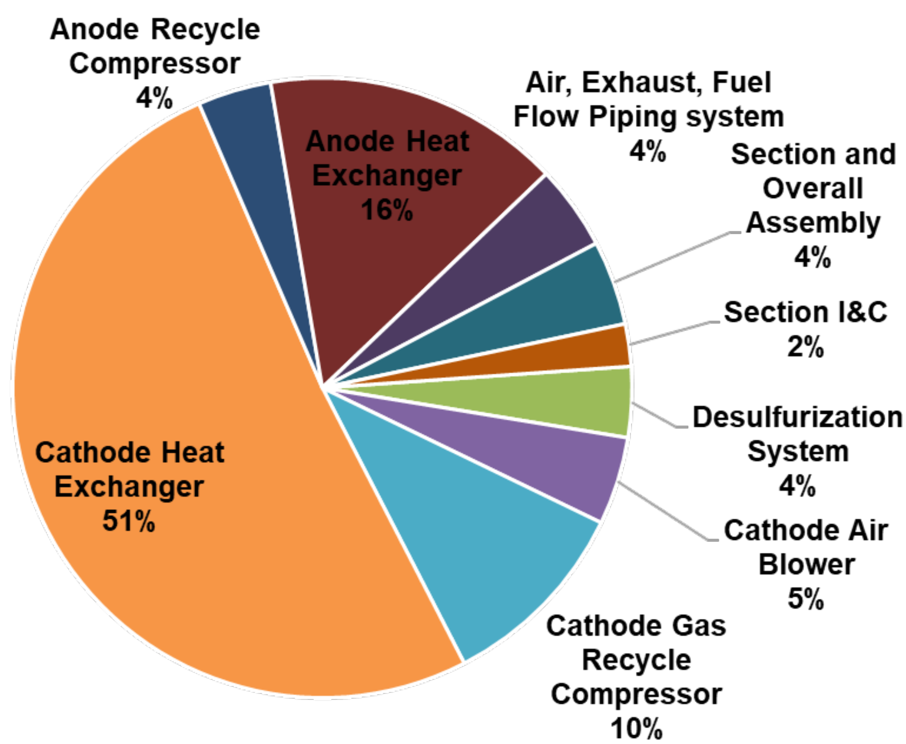


Exhibit 4-58. Case ANGFC4BV – Advanced Atmospheric NGFC Plant with VGR – Levelized Cost of Electricity

Levelized Cost of Electricity (2018$/MWh)	
Component	**$/MWh**
Variable Costs	27.0
Fuel Costs	21.8
Variable O&M Costs	5.2
Fixed O&M Costs	4.7
Capital Costs	12.4
Total LCOE (excluding T&S)	44.1
T&S	2.4
Total LCOE (including T&S)	46.5

4.4 Pathway 1 Results

The atmospheric pathway modifications of increased fuel utilization (Case 1), increased capacity factor (Case 2), 100 percent internal reformation (Case 3), BOP improvements (Case 4), and VGR configurations (Case 2BV, Case 4BV) all contribute to lowering cost.

Exhibit 4-59 displays the major results for all the Pathway 1 steps, all cases having carbon capture. The tabulation shows an increase in the plant efficiency and a reduction in the plant cost as technological advancements and cost reductions are introduced. For the standard atmospheric pathway, the realization of 100 percent internal natural gas reformation (Case 3) reduces the cost by ≈$5.0/MWh, followed by a ≈$1.7/MWh cost benefit attributable to enhanced plant run time (increased capacity factor) Case 2. Both VGR off-shoot pathways, Case 2BV and 4BV, result in LCOE reductions of ≈$3.6/MWh. Across the total pathway (ending with Case 4BV) the LCOE is reduced by ≈23 percent (13.6 $/MWh) relative to the reference plant along with a plant efficiency increase of ≈11 percentage-points. The results for the Pathway 1 NGFC plants without carbon capture are listed in Exhibit 4-60.

Exhibit 4-59. Pathway 1 – Atmospheric NGFC Plants with CCS Results Summary

<table>
<tr><th colspan="2">Case</th><th>Case 0</th><th>Case 1</th><th>Case 2</th><th>Case 2BV</th><th>Case 3</th><th>Case 4</th><th>Case 4BV</th></tr>
<tr><td colspan="2">Internal Reformation (%)</td><td colspan="4">60</td><td colspan="3">100</td></tr>
<tr><td colspan="2">SOFC Degradation Rate (%/1000 h)</td><td colspan="7">0.2</td></tr>
<tr><td colspan="2">Fuel Utilization (%)</td><td>80</td><td colspan="2">85</td><td>97.5</td><td colspan="2">85</td><td>97.5</td></tr>
<tr><td colspan="2">Capacity Factor (%)</td><td colspan="2">80</td><td colspan="5">85</td></tr>
<tr><td colspan="2">Inverter Efficiency (%)</td><td colspan="5">97</td><td colspan="2">98</td></tr>
<tr><td colspan="2">SOFC Stack Cost ($/kW)</td><td colspan="5">225</td><td colspan="2">200</td></tr>
<tr><th colspan="9">Performance</th></tr>
<tr><td rowspan="3">SOFC Parameters</td><td>Current Density (mA/cm²)</td><td>400</td><td>400</td><td>400</td><td>400</td><td>400</td><td>400</td><td>400</td></tr>
<tr><td>Cell Potential (V)</td><td>0.875</td><td>0.866</td><td>0.866</td><td>0.865</td><td>0.855</td><td>0.855</td><td>0.848</td></tr>
<tr><td>Power Density (mW/cm²)</td><td>350</td><td>346</td><td>346</td><td>346</td><td>342</td><td>342</td><td>339</td></tr>
<tr><td colspan="2">Gross Power (kWe)</td><td>713,048</td><td>710,326</td><td>710,326</td><td>712,709</td><td>694,360</td><td>693,950</td><td>700,617</td></tr>
<tr><td colspan="2">Auxiliary Loads (kWe)</td><td>62,922</td><td>60,279</td><td>60,279</td><td>62,732</td><td>46,224</td><td>43,920</td><td>50,439</td></tr>
<tr><td colspan="2">Air Separation Unit (kWe)</td><td>19,955</td><td>16,754</td><td>16,754</td><td>6,889</td><td>9,464</td><td>7,499</td><td>0</td></tr>
<tr><td colspan="2">CO₂ Drying, Purification and Compression (CPU) (kWe)</td><td>25,895</td><td>25,323</td><td>25,323</td><td>39,259</td><td>23,104</td><td>22,883</td><td>37,094</td></tr>
<tr><td colspan="2">Blowers (kWe)</td><td>7,919</td><td>9,862</td><td>9,862</td><td>9,671</td><td>6,197</td><td>6,138</td><td>7,235</td></tr>
<tr><td colspan="2">Steam Cycle and Miscellaneous (kWe)</td><td>9,153</td><td>8,341</td><td>8,341</td><td>6,912</td><td>7,452</td><td>7,400</td><td>6,110</td></tr>
<tr><td colspan="2">Net Power (kWe)</td><td>650,126</td><td>650,047</td><td>650,047</td><td>649,978</td><td>648,136</td><td>650,030</td><td>650,178</td></tr>
<tr><td colspan="2">NG Flowrate (lb/h)</td><td>169,965</td><td>166,190</td><td>166,190</td><td>155,900</td><td>151,700</td><td>150,248</td><td>142,100</td></tr>
<tr><td colspan="2">Net Electric Efficiency, HHV (%)</td><td>57.9</td><td>59.2</td><td>59.2</td><td>63.1</td><td>64.7</td><td>65.5</td><td>69.2</td></tr>
<tr><td colspan="2">Net Plant Heat Rate, HHV (Btu/kWh)</td><td>5,895</td><td>5,765</td><td>5,765</td><td>5,408</td><td>5,278</td><td>5,212</td><td>4,928</td></tr>
<tr><td colspan="2">CO₂ Capture rate (%)</td><td>97.8</td><td>97.8</td><td>97.8</td><td>93.3</td><td>98.1</td><td>98.1</td><td>91.7</td></tr>
<tr><td colspan="2">CO₂ Captured (tonnes per year)</td><td>1,399,003</td><td>1,367,654</td><td>1,453,133</td><td>1,299,505</td><td>1,329,578</td><td>1,316,844</td><td>1,165,365</td></tr>
<tr><td colspan="2">CO₂ Emissions (lb/MWhgross)</td><td>14.8</td><td>15.2</td><td>15.2</td><td>37.9</td><td>12.1</td><td>12.0</td><td>41.7</td></tr>
<tr><td colspan="2">CO₂ Emissions (lb/MWhnet)</td><td>16.2</td><td>16.6</td><td>16.6</td><td>41.5</td><td>12.9</td><td>12.8</td><td>44.9</td></tr>
<tr><td colspan="2">Raw Water Consumption (gpm/MWnet)</td><td>2.34</td><td>2.03</td><td>2.03</td><td>1.63</td><td>1.63</td><td>1.61</td><td>1.25</td></tr>
<tr><th colspan="9">Cost</th></tr>
<tr><td colspan="2">Total Plant Cost (TPC) (1000$)</td><td>868,437</td><td>838,860</td><td>838,860</td><td>770,233</td><td>739,560</td><td>721,477</td><td>638,269</td></tr>
<tr><td colspan="2">Total Overnight Cost (TOC) (1000$)</td><td>1,057,252</td><td>1,021,362</td><td>1,021,308</td><td>938,024</td><td>900,205</td><td>878,320</td><td>777,532</td></tr>
<tr><td colspan="2">Total As-Spent Cost (TASC) (1000$)</td><td>1,155,576</td><td>1,116,349</td><td>1,116,289</td><td>1,025,260</td><td>983,924</td><td>960,003</td><td>849,843</td></tr>
<tr><td colspan="9">Levelized Cost of Electricity ($/MWh)</td></tr>
<tr><td colspan="2">Variable Costs</td><td>32.6</td><td>31.9</td><td>31.6</td><td>29.8</td><td>29.2</td><td>28.5</td><td>27.0</td></tr>
<tr><td colspan="2">Fuel Costs</td><td>26.1</td><td>25.5</td><td>25.5</td><td>23.9</td><td>23.3</td><td>23.0</td><td>21.8</td></tr>
<tr><td colspan="2">Variable O&M Costs</td><td>6.5</td><td>6.5</td><td>6.1</td><td>5.9</td><td>5.8</td><td>5.4</td><td>5.2</td></tr>
<tr><td colspan="2">Fixed O&M Costs</td><td>6.5</td><td>6.3</td><td>5.9</td><td>5.5</td><td>5.3</td><td>5.2</td><td>4.7</td></tr>
<tr><td colspan="2">Capital Costs</td><td>17.9</td><td>17.3</td><td>16.3</td><td>15.0</td><td>14.4</td><td>14.0</td><td>12.4</td></tr>
<tr><td colspan="2">Total LCOE (excluding T&S)</td><td>57.0</td><td>55.6</td><td>53.9</td><td>50.3</td><td>48.9</td><td>47.7</td><td>44.1</td></tr>
<tr><td colspan="2">T&S</td><td>3.1</td><td>3.0</td><td>3.0</td><td>2.7</td><td>2.8</td><td>2.7</td><td>2.4</td></tr>
<tr><td colspan="2">Total LCOE (including T&S)</td><td>60.1</td><td>58.6</td><td>56.9</td><td>53.0</td><td>51.7</td><td>50.4</td><td>46.5</td></tr>
</table>

Exhibit 4-60. Pathway 1 – Atmospheric NGFC Plants without CCS Results Summary

<table>
<tr><th colspan="2">Case</th><th>Case 0</th><th>Case 1</th><th>Case 2</th><th>Case 3</th><th>Case 4</th></tr>
<tr><td colspan="2">Internal Reformation (%)</td><td colspan="3">60</td><td colspan="2">100</td></tr>
<tr><td colspan="2">SOFC Degradation Rate (%/1000 h)</td><td colspan="5">0.2</td></tr>
<tr><td colspan="2">Fuel Utilization (%)</td><td>80</td><td colspan="4">85</td></tr>
<tr><td colspan="2">Capacity Factor (%)</td><td colspan="2">80</td><td colspan="3">85</td></tr>
<tr><td colspan="2">Inverter Efficiency (%)</td><td colspan="4">97</td><td>98</td></tr>
<tr><td colspan="2">SOFC Stack Cost ($/kW)</td><td colspan="4">225</td><td>200</td></tr>
<tr><td colspan="7">Performance</td></tr>
<tr><td rowspan="3">SOFC Parameters</td><td>Current Density (mA/cm^2)</td><td>400</td><td>400</td><td>400</td><td>400</td><td>400</td></tr>
<tr><td>Cell Potential (V)</td><td>0.867</td><td>0.862</td><td>0.862</td><td>0.857</td><td>0.857</td></tr>
<tr><td>Power Density (mW/cm^2)</td><td>347</td><td>345</td><td>345</td><td>343</td><td>343</td></tr>
<tr><td colspan="2">Gross Power (kWe)</td><td>669,409</td><td>670,720</td><td>670,720</td><td>662,670</td><td>662,528</td></tr>
<tr><td colspan="2">Auxiliary Loads (kWe)</td><td>19,346</td><td>20,603</td><td>20,603</td><td>12,545</td><td>12,452</td></tr>
<tr><td colspan="2">Air Separation Unit (kWe)</td><td>3,320</td><td>3,260</td><td>3,260</td><td>0</td><td>0</td></tr>
<tr><td colspan="2">CO_2 Drying, Purification and Compression (CPU) (kWe)</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td colspan="2">Blowers (kWe)</td><td>7,940</td><td>10,011</td><td>10,011</td><td>5,890</td><td>5,837</td></tr>
<tr><td colspan="2">Steam Cycle and Miscellaneous (kWe)</td><td>8,087</td><td>7,332</td><td>7,332</td><td>6,655</td><td>6,615</td></tr>
<tr><td colspan="2">Net Power (kWe)</td><td>650,063</td><td>650,117</td><td>650,117</td><td>650,125</td><td>650,076</td></tr>
<tr><td colspan="2">NG Flowrate (lb/h)</td><td>159,790</td><td>157,070</td><td>157,070</td><td>144,200</td><td>142,890</td></tr>
<tr><td colspan="2">Net Electric Efficiency, HHV (%)</td><td>61.6</td><td>62.6</td><td>62.6</td><td>68.2</td><td>68.8</td></tr>
<tr><td colspan="2">Net Plant Heat Rate, HHV (Btu/kWh)</td><td>5,543</td><td>5,448</td><td>5,448</td><td>5,001</td><td>4,956</td></tr>
<tr><td colspan="2">CO_2 Capture rate (%)</td><td>0.0</td><td>0.0</td><td>0.0</td><td>0.0</td><td>0.0</td></tr>
<tr><td colspan="2">CO_2 Captured (tonnes per year)</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td colspan="2">CO_2 Emissions (lb/MWhgross)</td><td>575.8</td><td>565.6</td><td>565.6</td><td>524.3</td><td>519.7</td></tr>
<tr><td colspan="2">CO_2 Emissions (lb/MWhnet)</td><td>593.0</td><td>583.6</td><td>583.6</td><td>534.5</td><td>529.6</td></tr>
<tr><td colspan="2">Raw Water Consumption (gpm/MWnet)</td><td>3.05</td><td>2.73</td><td>2.73</td><td>2.16</td><td>2.14</td></tr>
<tr><td colspan="7">Cost</td></tr>
<tr><td colspan="2">Total Plant Cost (TPC) (1000$)</td><td>593,305</td><td>584,869</td><td>584,869</td><td>530,446</td><td>509,537</td></tr>
<tr><td colspan="2">Total Overnight Cost (TOC) (1000$)</td><td>725,408</td><td>715,072</td><td>715,036</td><td>647,086</td><td>621,790</td></tr>
<tr><td colspan="2">Total As-Spent Cost (TASC) (1000$)</td><td>792,871</td><td>781,574</td><td>781,534</td><td>707,265</td><td>679,616</td></tr>
<tr><td colspan="7">Levelized Cost of Electricity ($/MWh)</td></tr>
<tr><td colspan="2">Variable Costs</td><td>30.5</td><td>30.0</td><td>29.7</td><td>27.4</td><td>26.8</td></tr>
<tr><td colspan="2">Fuel Costs</td><td>24.5</td><td>24.1</td><td>24.1</td><td>22.1</td><td>21.9</td></tr>
<tr><td colspan="2">Variable O&M Costs</td><td>6.0</td><td>5.9</td><td>5.6</td><td>5.3</td><td>4.9</td></tr>
<tr><td colspan="2">Fixed O&M Costs</td><td>4.6</td><td>4.5</td><td>4.2</td><td>3.9</td><td>3.8</td></tr>
<tr><td colspan="2">Capital Costs</td><td>12.3</td><td>12.1</td><td>11.4</td><td>10.3</td><td>9.9</td></tr>
<tr><td colspan="2">Total LCOE (excluding T&S)</td><td>47.3</td><td>46.6</td><td>45.4</td><td>41.7</td><td>40.5</td></tr>
<tr><td colspan="2">T&S</td><td>0.0</td><td>0.0</td><td>0.0</td><td>0.0</td><td>0.0</td></tr>
<tr><td colspan="2">Total LCOE (including T&S)</td><td>47.3</td><td>46.6</td><td>45.4</td><td>41.7</td><td>40.5</td></tr>
</table>

5 SCENARIO 2: PRESSURIZED-SOFC SYSTEM

Pressurization of the SOFC stack provides the potential for enhanced power plant efficiency. However, pressurization affects adversely the costs of the SOFC stack enclosures, which have to be designed as pressure vessels to operate at design pressures. The Case 0 baseline plant assumes the same plant technology as the start of the atmospheric pathway. Improvements in the pressurized pathway are made in parallel with improvements from the atmospheric pathway. Each pathway has equivalent cases with the exception that there are no VGR cases in the pressurized pathway.

5.1 CASE 0: PRESSURIZED REFERENCE PLANT DESCRIPTION

The reference NGFC plant for pressurized SOFC technology utilizes a high-pressure (≈450 psia) ATR system for external natural gas reformation along with a pressurized-SOFC. The SOFC technology parameters for this case are listed in Exhibit 5-1, and 40 percent external reformation of the incoming natural gas is assumed as in the atmospheric reference. SOFC module configurations operating at elevated pressures (as high as 3 atm [44.1 psia]) are assumed to have been concurrently developed along the atmospheric timeline. Further, 60 percent internal reformation is assumed to be feasible at these elevated pressures despite equilibrium considerations, which predict the need for higher temperatures (relative to atmospheric systems) to achieve the desired reformation in the stack as the pressure is increased.

Exhibit 5-1. SOFC Technology Parameters Used for Reference Case 0

Parameter	Value
Reformation	40% External
SOFC Operating Pressure	≈44.1 psia
Cell Technology	Advanced Cell
Fuel Utilization, %	80
Current Density, mA/cm^2	400
Degradation, %/1000 h	0.2
Inverter Efficiency (%)	97
Stack Cost ($/kW)	225

The block flow diagram for pressurized Case 0 is shown in Exhibit 5-5 for the configuration with CCS. NGFC with pressurized-SOFC can be configured for CCS in two alternative arrangements:

1. The anode off-gas oxy-combustor is followed by hot gas expander power generation. A HRSG produces steam for power generation, and the remaining, low-pressure, wet CO_2 stream is dried and compressed.
2. The anode off-gas oxy-combustor is followed directly by a HRSG for steam bottoming power generation. The remaining, high-pressure, wet CO_2 stream is dehydrated and compressed.

Sensitivity studies have shown that the first approach can result in slightly higher plant efficiencies than the second with lower LCOE, the first configuration requires the development of an advanced, high-temperature, CO_2-cooled turbine expander. In this pathway, the required technology is assumed to exist, and the first approach is utilized for this evaluation. In both cases the steam cycle conversion efficiency was reduced to 30 percent to reflect the reduced temperatures available for heat recovery.

Referring to the block flow diagram for the Case 0 pressurized reference plant with CCS shown in Exhibit 5-5, natural gas (Stream 1), delivered to the plant at 500 psia, is split into two streams, a 40 percent stream to be reformed (Stream 2), and a 60 percent stream to be mixed with the reformer syngas product. The 40 percent stream to be reformed is fed to the ATR mixed with steam (Stream 4) after preheating with the hot syngas stream. Complete reformation (Stream 7) of this stream achieved through partial combustion with the oxidant (Stream 5) accompanied by reaction in a catalytic reactor zone.

A conventional ASU generates oxidant (99.5 percent pure) for the ATR (Stream 5) as well as for the anode off-gas oxy-combustor (Stream 6). The ASU product oxidant streams are pressurized for the ATR (500 psia) and for the oxy-combustor (44 psia). The cooled syngas output from the ATR is mixed with the remaining (unreformed) natural gas and fed to the SOFC unit after expansion to the SOFC inlet pressure (Stream 8, at 44.1 psia). A portion of the pressurized syngas bypasses the expander and is used as motive gas to operate the anode gas recycle jet pump. There are 32 parallel SOFC sections in the plant, each containing a single cathode heat exchanger, anode heat exchanger, cathode air compressor, cathode off-gas expander, and anode gas recycle jet pump.

The SOFC fuel gas stream is mixed with recycled anode gas and preheated through the anode heat exchanger to achieve the anode inlet temperature (Stream 10). A pre-reformer is required to prevent cracking of higher-hydrocarbons and deleterious carbon formation. Air (Stream 12) is boosted in pressure by the cathode air compressor (45 psia) and is preheated through the cathode heat exchanger to achieve the cathode inlet temperature (Stream 13). There is no cathode gas recycle due to the technical challenge of boosting the pressure of hot, pressurized gas. The cathode inlet gas provides the O_2 needed for the SOFC oxidation reactions and provides cooling of the cells to maintain temperatures at an acceptable distribution. The cell cooling is aided by the reforming of methane (based on the fraction of internal reformation) throughout the cells, reducing the required flow of cathode air.

The cathode off-gas passes through the cathode heat exchanger and is then expanded through the cathode gas expander before providing heat to the HRSG and being vented. The anode off-gas (Stream 11) is combusted across the oxy-combustor, generating a hot, pressurized combustion gas (Stream 15, at 44.1 psia) having 1 percent excess O_2 content. The pressurized gas is expanded before giving heat to the HRSG. The HRSG raises high-pressure steam for the steam bottoming cycle, 500 psia steam for the ATR, and low-pressure steam for the auxiliary processing needs.

The cooled combustion gas is dehydrated, purified, and compressed from 44.1 to 2215 psia in the CPU to generate the plant's CO_2 product for sequestration (Stream 17).

Exhibit 5-10 shows the analogous Case 0 NGFC power plant without CCS, which obviates the need for the oxy-combustor, the ASU, and the CO_2 purification unit. The excess fuel gas in the anode off-gas is combusted with the exhaust gas from the cathode. Initial analysis indicated the temperature after expansion of this gas from the exhaust expander was low for any additional heat recovery. Accordingly, natural gas (Stream 12) was additionally injected to the combustor such that the temperature downstream of the expander is still high enough for heat recovery with a bottoming cycle.

5.1.1 Case 0: Pressurized Reference Plant Performance

The stream tables for the NGFC plants with and without the CCS option are listed in Exhibit 5-6 and Exhibit 5-11, respectively and correspond to the state point numbers identified in Exhibit 5-5, and Exhibit 5-10. The pressurized reference plant power summary is shown in Exhibit 5-2. For the NGFC plant with CCS, the dominant power generator in the plant is the SOFC system while the steam bottoming cycle generates about 10 percent of the plant's gross output, as seen in Exhibit 5-3. In this case, the CO_2 capture rate is 97.7 percent and is smaller than in Case 0 for the atmospheric pathway because at high pressure more CO_2 is absorbed in the condensate water streams.

For the pressurized reference plant without CCS, the SOFC generates 57 percent of the total power and the syngas and cathode gas expanders together account for 37 percent of the total power. The increased power output from the expander is a direct result of the additional natural gas injection to the combustor in this case, which enables the cathode gas expander to generate additional power beyond the needs of the air compressor.

For both the case with and without CCS, the dominant auxiliary loads in the plant come from compressors and blowers as seen in Exhibit 5-4. The CPU imposes additional auxiliary load for the plant with CCS with the total plant auxiliary power being ≈19 percent of the gross generating capacity of the plant resulting in an HHV efficiency of ≈61.1 percent. The plant efficiency is only ≈0.3 percentage points higher without carbon capture is mainly due to the additional natural gas that is utilized to generate power at a combination of Brayton and Rankine cycle efficiencies, which are low relative to electrochemical efficiencies.

The stream tables for the pressurized reference plants with and without CCS are listed in Exhibit 4-6 and Exhibit 4-11 for the corresponding points numbered in the process flow diagram shown in Exhibit 4-5 and Exhibit 4-10, respectively. Material and energy balance tables and the heat and material balance diagrams for the reference plant with CCS are shown in Exhibit 4-7, Exhibit 4-8, and Exhibit 4-9, respectively. The corresponding tables for the reference plant without CCS are shown in Exhibit 4-12 and Exhibit 4-13.

5.1.2 Case 0: Pressurized Reference Plant Costs

Breakdown of the capital and O&M costs for the pressurized reference plant with CCS are displayed in Exhibit 5-14 and Exhibit 5-15, respectively. Together, the accessory electric plant, the steam cycle, the CPU, and the ASU make up 53 percent of the total capital cost for the plant with CCS as seen in Exhibit 5-16 while the largest contributor to capital costs is the SOFC power island at 36 percent. The cathode heat exchanger (38 percent) and the oxy-combustor (19 percent) make up the largest portions of the BOP costs as seen in Exhibit 5-17. The corresponding costs for the pressurized reference plant without CCS are shown in Exhibit 5-18 to Exhibit 5-21. The LCOEs for Case 0 are listed in Exhibit 5-22. The addition of CCS increases the LCOE from \$44.4/MWh to \$60.5/MWh (≈36 percent).

Exhibit 5-2. Case 0 – Pressurized Reference NGFC Plant with and without CCS – Performance Summary

Carbon Capture	With CCS	No CCS
Power Summary (Gross Power at Generator Terminals, kWe)		
SOFC Power	570,499	443,408
Natural Gas/Syngas Expander Power	156,190	288,600
Steam Turbine Power	78,400	51,500
Total Gross Power, kW_e	**805,089**	**783,508**
Auxiliary Load Summary, kWe		
Air Separation Unit Auxiliaries	0	0
Air Separation Unit Main Air Compressor[A]	19,036	16,980
Oxygen Compressor	4,300	0
Nitrogen Compressors	0	0
CO_2 Compressor	24,458	0
CO_2 Refrigeration	0	0
Boiler Feedwater Pumps	1,441	947
Condensate Pump	45	29
Circulating Water Pump	2,360	920
Cooling Tower Fans	1,220	470
Gas Turbine Auxiliaries	-	-
Steam Turbine Auxiliaries	60	39
Cathode Air Blower	98,710	110,855
Cathode Recycle Blower	0	0
Anode Recycle Blower	1	1
Miscellaneous Balance of Plant[B]	431	428
Transformer Losses	2,839	2,714
Total Auxiliaries, kW_e	154,900	133,384
Net Power, kW_e	650,189	650,124
Net Plant Efficiency, % (HHV)	61.06	61.40
Net Plant Heat Rate, kJ/kWh (Btu/kWh)	5,896 (5,588)	5,864 (5,558)
CO_2 Capture Rate, %	97.7	0.0
Condenser Cooling Duty, 10^6 kJ/h (10^6 Btu/h)	454 (430)	433 (410)
Natural Gas Feed Rate, kg/h (lb/h)	73,092 (161,140)	72,682 (160,235)
Thermal Input[C], kWt	1,064,886	1,058,908
Raw Water Withdrawal, m^3/min (gpm)	6.7 (1,765.4)	4.0 (1,049.3)
Raw Water Consumption, m^3/min (gpm)	4.62 (1,220.6)	3.18 (840.4)

[A] Reflects power needed to compress air to ATR pressure.

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

[C] HHV of natural gas is 52,449 kJ/kg (22,549 Btu/lb).

Exhibit 5-3. Case 0 – Pressurized Reference NGFC Plant with and without CCS – Gross Power Distribution

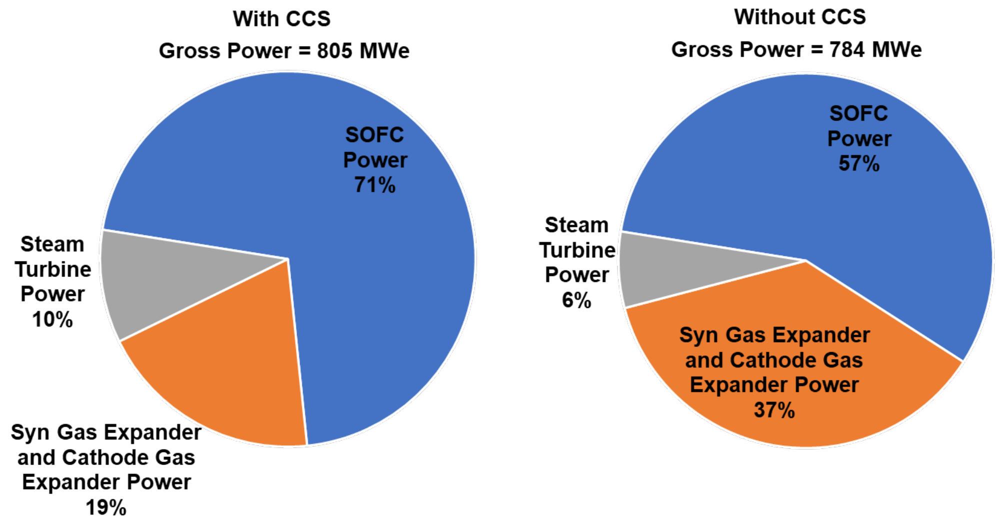


Exhibit 5-4. Case 0 – Pressurized Reference NGFC Plant with and without CCS – Auxiliary Load Distribution

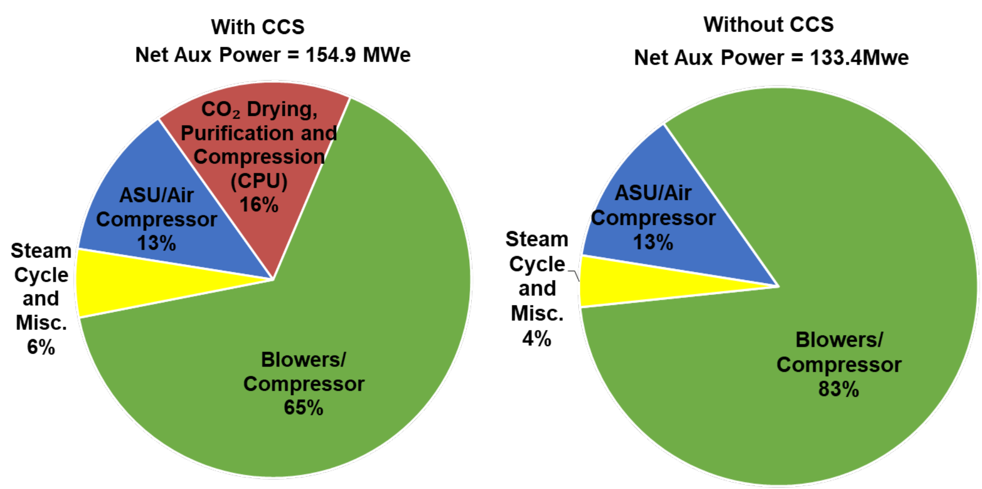


Exhibit 5-5. Case PNGFC0B – Pressurized Reference NGFC Plant with CCS – Block Flow Diagram

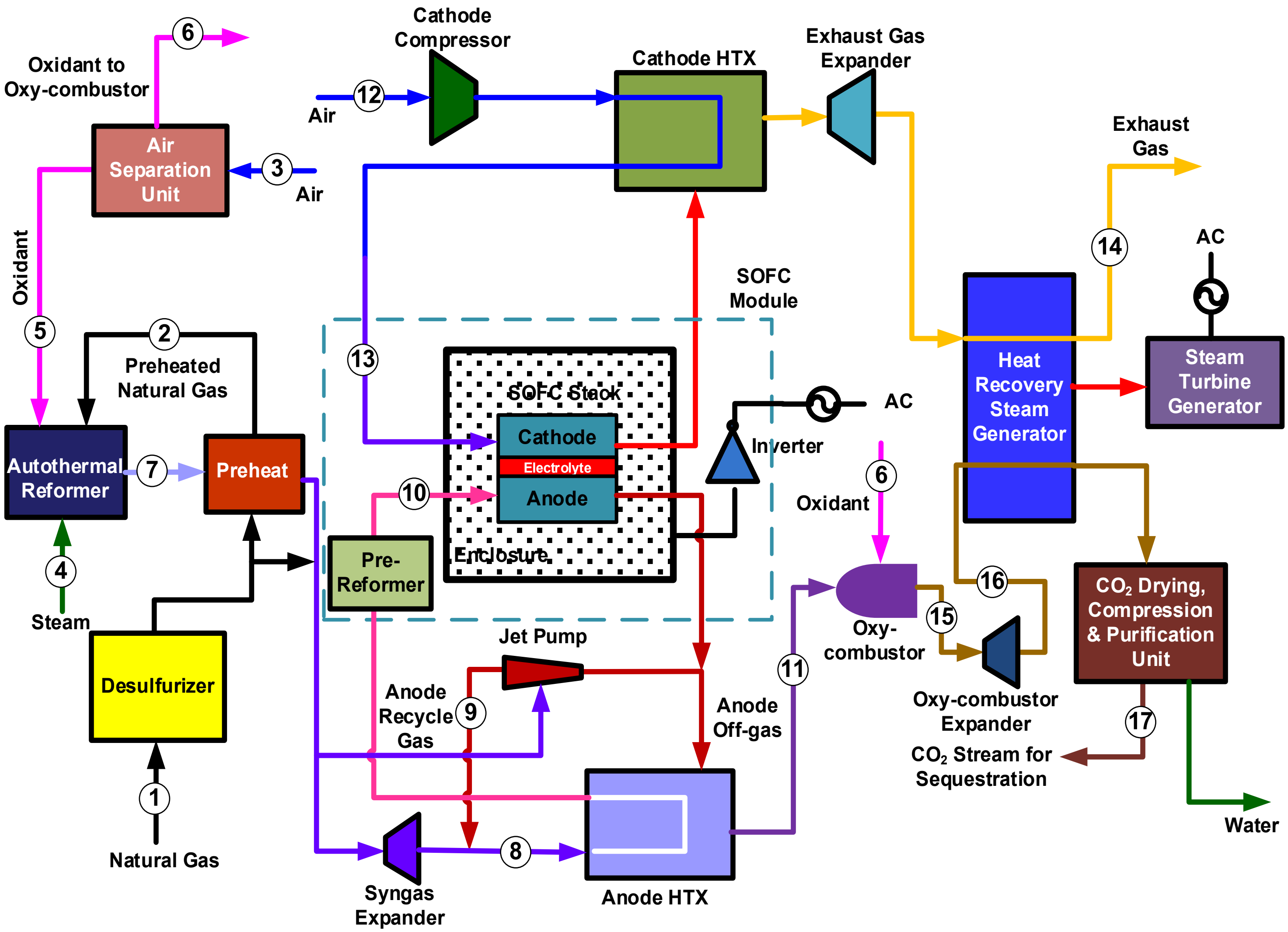


Exhibit 5-6. Case PNGFC0B – Pressurized Reference NGFC Plant with CCS – Stream Table

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
V-L Mole Fraction																	
Ar	0.0000	0.0000	0.0094	0.0000	0.0031	0.0031	0.0005	0.0003	0.0002	0.0003	0.0002	0.0094	0.0094	0.0101	0.0006	0.0006	0.0000
CH_4	0.9310	0.9310	0.0000	0.0000	0.0000	0.0000	0.0235	0.2763	0.0288	0.1121	0.0005	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	0.1771	0.1277	0.0530	0.0658	0.0445	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0100	0.0100	0.0003	0.0000	0.0000	0.0000	0.0677	0.0516	0.2350	0.1902	0.2560	0.0003	0.0003	0.0003	0.2974	0.2974	1.0000
H_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.4718	0.3404	0.1796	0.2996	0.1612	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	0.0000	0.0000	0.0104	1.0000	0.0000	0.0000	0.2551	0.1840	0.4970	0.3262	0.5328	0.0104	0.0104	0.0111	0.6866	0.6866	0.0000
N_2	0.0160	0.0160	0.7722	0.0000	0.0019	0.0019	0.0044	0.0076	0.0050	0.0058	0.0048	0.7722	0.7722	0.8260	0.0049	0.0049	0.0000
C_2H_6	0.0320	0.0320	0.0000	0.0000	0.0000	0.0000	0.0000	0.0089	0.0009	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_3H_8	0.0070	0.0070	0.0000	0.0000	0.0000	0.0000	0.0000	0.0019	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_4H_{10}	0.0040	0.0040	0.0000	0.0000	0.0000	0.0000	0.0000	0.0011	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
O_2	0.0000	0.0000	0.2077	0.0000	0.9950	0.9950	0.0000	0.0000	0.0000	0.0000	0.0000	0.2077	0.2077	0.1525	0.0105	0.0105	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	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)	4,218	1,687	13,274	1,687	1,005	1,681	6,555	7,723	13,273	21,679	14,602	93,193	93,193	87,125	14,781	14,781	4,294
V-L Flowrate (kg/h)	73,092	29,237	382,998	30,397	32,160	53,811	91,794	115,302	289,362	404,667	329,812	2,689,006	2,689,006	2,494,845	383,623	383,623	188,958
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	15	210	15	241	130	94	938	299	696	601	565	15	606	132	1,601	1,352	36
Pressure (MPa, abs)	3.45	3.447	0.10	3.45	3.45	0.30	3.10	0.338	0.34	0.34	0.338	0.101	0.31	0.10	0.34	0.13	15.27
Enthalpy (kJ/kg)[A]	31.11	478.892	31.06	2,867.29	114.27	86.06	3,113.37	1,256.195	2,240.73	1,985.52	1,988.436	31.06	656.52	152.22	3,977.07	3,475.62	-209.44
Density (kg/m^3)	24.9	15.0	1.2	16.7	33.1	3.2	4.3	1.1	0.9	0.9	1.1	1.2	1.2	0.9	0.6	0.3	546.7
V-L Molecular Weight	17.328	17.328	28.854	18.015	32.016	32.016	14.004	14.930	21.800	18.666	22.587	28.854	28.854	28.635	25.954	25.954	44.010
V-L Flowrate (lb_{mol}/h)	9,300	3,720	29,263	3,720	2,215	3,705	14,451	17,026	29,263	47,794	32,192	205,455	205,455	192,078	32,586	32,586	9,466
V-L Flowrate (lb/h)	161,140	64,456	844,366	67,014	70,902	118,632	202,372	254,198	637,935	892,137	727,112	5,928,244	5,928,244	5,500,193	845,744	845,744	416,581
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	59	409	59	466	265	202	1,721	570	1,285	1,115	1,049	59	1,123	270	2,914	2,465	97
Pressure (psia)	500.0	500.0	14.7	500.0	500.0	44.1	450.0	49.1	49.1	49.0	49.0	14.7	44.3	14.7	49.0	19.0	2,215.0
Enthalpy (Btu/lb)[A]	13.4	205.9	13.4	1,232.7	49.1	37.0	1,338.5	540.1	963.3	853.6	854.9	13.4	282.3	65.4	1,709.8	1,494.2	-90.0
Density (lb/ft^3)	1.557	0.937	0.076	1.045	2.067	0.199	0.268	0.066	0.057	0.054	0.068	0.076	0.075	0.054	0.035	0.016	34.128

[A] Reference conditions are 32.02 F and 0.089 psia

Exhibit 5-7. Case PNGFC0B – Pressurized Reference NGFC Plant with CCS – Material and Energy Balances

Carbon Balance

Carbon In		Carbon Out	
kg/hr(lb/hr)		kg/hr(lb/hr)	
NG	52,793 (116,390)	Stack Gas	336 (740)
Air (CO2)	384 (846)	CO_2 Product	51,570 (113,692)
		Exhaust	1,222 (2,695)
		ASU Vent	48 (105)
		Water KO	2 (4)
		Convergence Tolerance	0 (-1)
Total	53,177 (117,235)	Total	53,177 (117,235)

Sulfur Balance

Sulfur In		Sulfur Out	
kg/hr(lb/hr)		kg/hr(lb/hr)	
NGIN	0 (0)	Elemental Sulfur	0 (0)
		Polishing Sorbent	0 (0)
		Convergence Tolerance	0 (0)
Total	0 (0)	Total	0 (0)

Energy Balance

	HHV	Sensible + Latent	Power	Total
Heat In GJ/hr (MMBtu/hr)				
NG	3,833.59 (3,633.54)	2.6 (2.4)		3,836.2 (3,636.0)
Fuel cell Air		83.5 (79.2)		83.5 (79.2)
Auxiliary Power			557.6 (528.5)	557.6 (528.5)
TOTAL	**3,834 (3,634)**	**86.1 (81.6)**	**557.6 (528.5)**	**4,477.3 (4,243.7)**
Heat Out GJ/hr (MMBtu/hr)				
CO_2 Out		-39.6 (-37.5)		-39.6 (-37.5)
Stack Flue Gas		379.8 (360.0)		379.77 (359.95)
Vents		16.4 (15.5)		16.37 (15.51)
Water outlets		28.9 (27.4)		28.95 (27.44)
Process Losses**		1265.4 (1199.4)		1,265.45 (1,199.41)
Difference***		-72.0 (-68.2)		-71.97 (-68.22)
Power			2,898.3 (2,747.1)	2,898.3 (2,747.1)
TOTAL	**0.0 (0.0)**	**1,579.0 (1,496.6)**	**2,898.3 (2,747.1)**	**4,477.3 (4,243.7)**

* Includes ASU compressor intercoolers & CO2 compressor intercoolers

** Includes accounting of losses such as inverter, transformer, generator, and motor losses

*** Calculated by difference to close the energy balance

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)
Condenser Makeup	**0.6 (149)**	**0.0 (0)**	**0.6 (149)**	**0.0 (0)**	**0.6 (149)**
Reformer Steam	0.5 (134)	0.0 (0)	0.5 (134)		
BFW Makeup	0.1 (15)	0.0 (0)	0.1 (15)		
Cooling Tower	**9.2 (2,423)**	**3.05 (806)**	**6.1 (1,617)**	**2.1 (545)**	**4.1 (1,072)**
CO2 Dehydration	0.0 (0)	3.05 (806)	-3.05 (-806)		
Total	**9.7 (2,572)**	**3.05 (806)**	**6.7 (1,765)**	**2.1 (545)**	**4.6 (1,221)**

Emissions

	kg/GJ (lb/10^6Btu)	Tonne/year (tons/year)	kg/MWh (lb/MWh)
SO2	0 (0)	0 (0)	0 (0)
NOx	0 (0)	0 (0)	0 (0)
Particulate	0 (0)	0 (0)	0 (0)
Hg	0 (0)	0 (0)	0 (0)
CO2	1694 (3940)	36,337 (40,054)	6 (14)

Exhibit 5-8. Case PNGFC0B – Pressurized Reference NGFC Plant with CCS – Heat and Material Balance Diagram – ASU, ATR, and Power Island

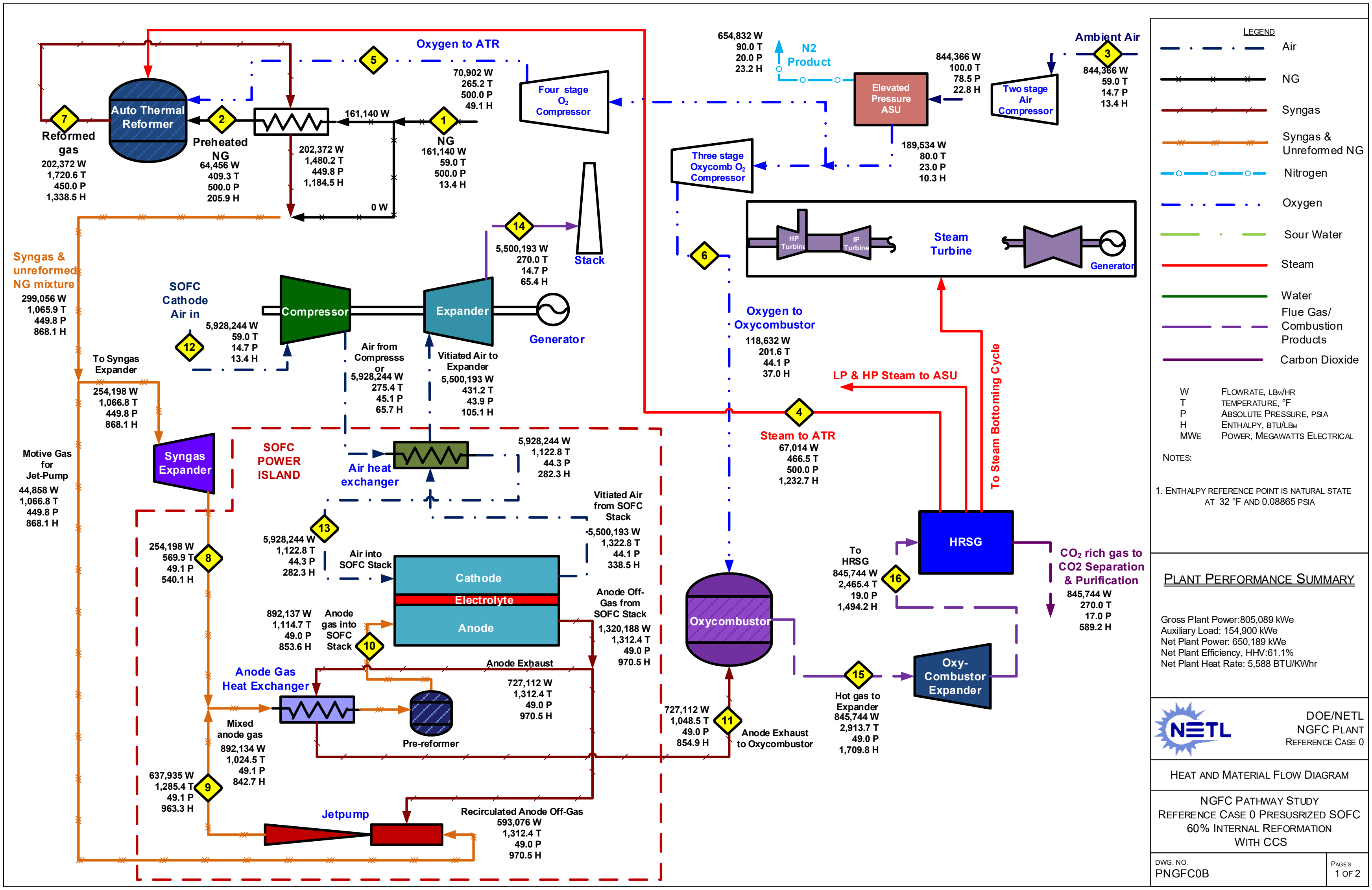


Exhibit 5-9. Case PNGFC0B – Pressurized Reference NGFC Plant with CCS – Heat and Material Balance Diagram – CO_2 Dehydration, Purification, and Compression

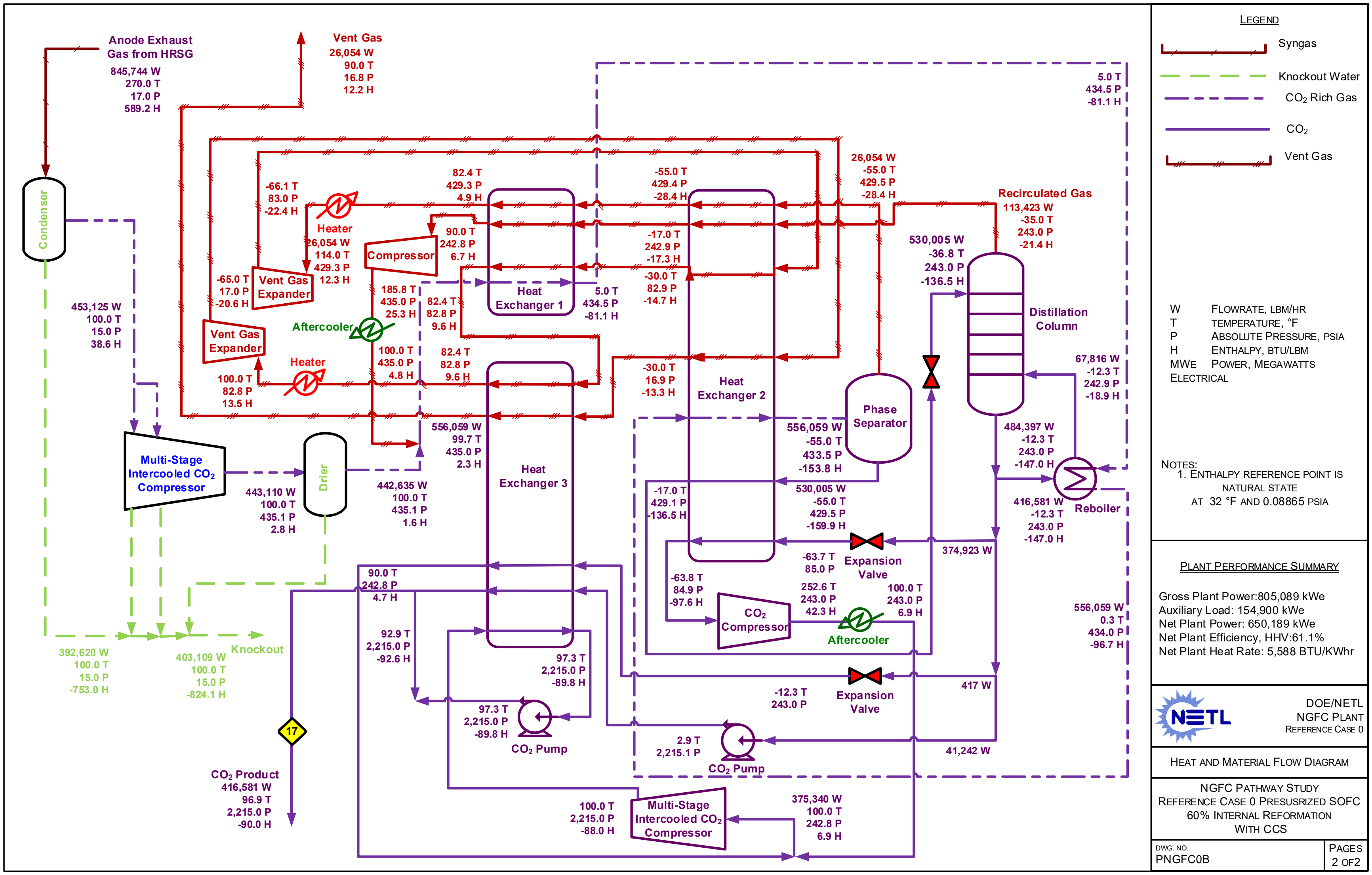


Exhibit 5-10. Case PNGFC0A – Pressurized Reference NGFC Plant without CCS – Block Flow Diagram

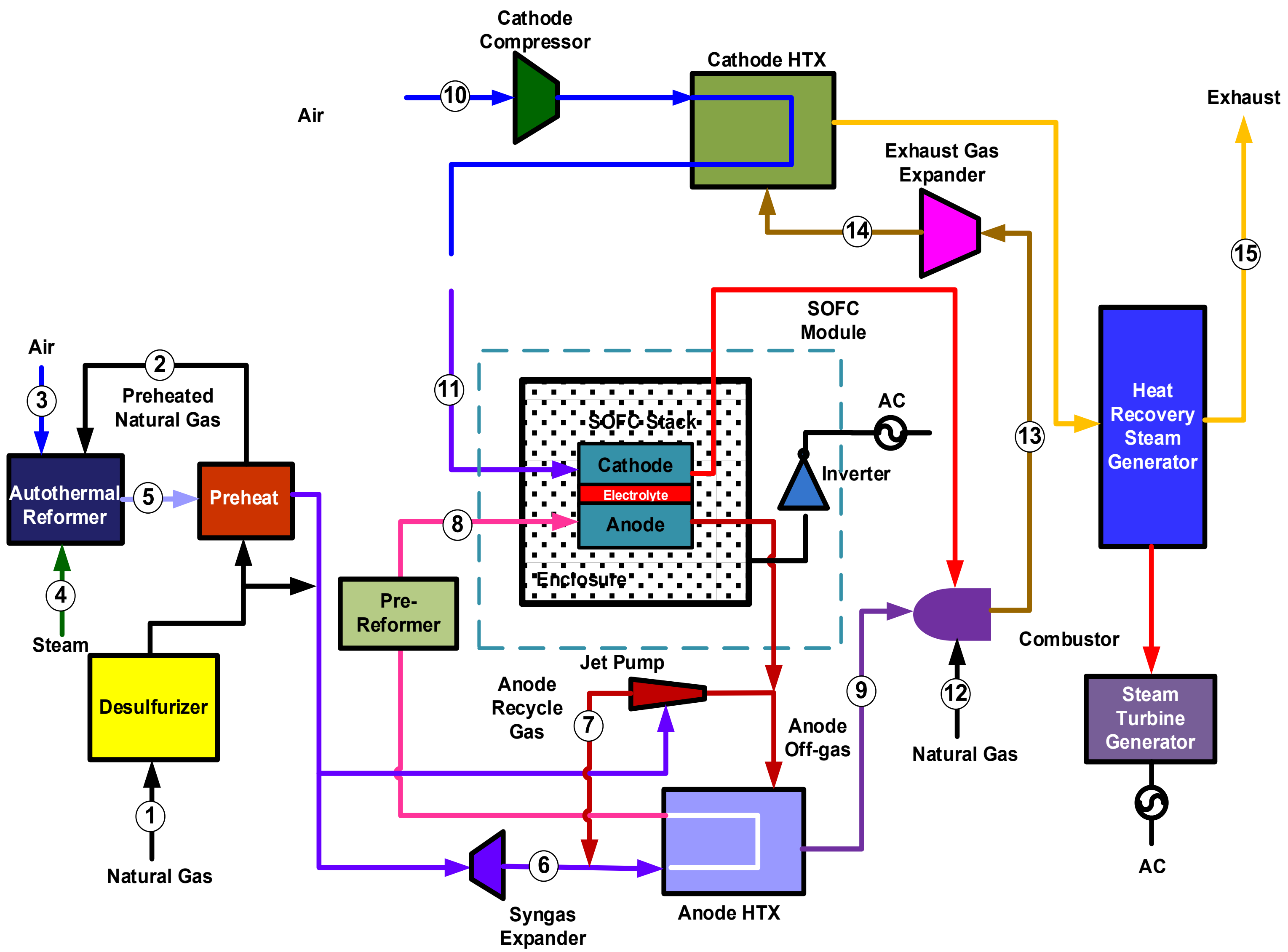


Exhibit 5-11. Case PNGFC0A – Pressurized Reference NGFC Plant without CCS – Stream Table

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
V-L Mole Fraction															
Ar	0.0000	0.0000	0.0094	0.0000	0.0046	0.0037	0.0026	0.0029	0.0025	0.0094	0.0094	0.0000	0.0089	0.0089	0.0089
CH_4	0.9310	0.9310	0.0000	0.0000	0.0440	0.2257	0.0254	0.0929	0.0003	0.0000	0.0000	0.9310	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0725	0.0577	0.0369	0.0403	0.0343	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0100	0.0100	0.0003	0.0000	0.0625	0.0518	0.1869	0.1495	0.2039	0.0003	0.0003	0.0100	0.0387	0.0387	0.0387
H_2	0.0000	0.0000	0.0000	0.0000	0.2457	0.1953	0.1363	0.2154	0.1289	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	0.0000	0.0000	0.0104	1.0000	0.1876	0.1492	0.3932	0.2544	0.4238	0.0104	0.0104	0.0000	0.0961	0.0961	0.0961
N_2	0.0160	0.0160	0.7722	0.0000	0.3830	0.3079	0.2177	0.2446	0.2064	0.7722	0.7722	0.0160	0.7341	0.7341	0.7341
C_2H_6	0.0320	0.0320	0.0000	0.0000	0.0000	0.0066	0.0007	0.0000	0.0000	0.0000	0.0000	0.0320	0.0000	0.0000	0.0000
C_3H_8	0.0070	0.0070	0.0000	0.0000	0.0000	0.0014	0.0002	0.0000	0.0000	0.0000	0.0000	0.0070	0.0000	0.0000	0.0000
C_4H_{10}	0.0040	0.0040	0.0000	0.0000	0.0000	0.0008	0.0001	0.0000	0.0000	0.0000	0.0000	0.0040	0.0000	0.0000	0.0000
O_2	0.0000	0.0000	0.2077	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2077	0.2077	0.0000	0.1223	0.1223	0.1223
Total	1.0000	1.0000	1.0000	1.0000	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)	3,480	1,392	3,992	1,392	8,107	8,666	13,731	23,129	15,208	104,073	104,073	714	113,773	113,773	113,773
V-L Flowrate (kg/h)	60,305	24,122	115,198	25,079	164,400	170,495	319,435	489,931	360,630	3,002,960	3,002,960	12,376	3,215,891	3,215,891	3,215,891
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	15	210	15	241	788	274	686	573	541	15	613	15	976	976	132
Pressure (MPa, abs)	3.45	3.447	0.10	3.45	3.10	0.338	0.34	0.34	0.338	0.101	0.31	0.34	0.34	0.30	0.11
Enthalpy (kJ/kg)[A]	31.11	478.883	31.06	2,867.29	1,731.67	811.234	1,835.53	1,502.65	1,614.615	31.06	664.28	27.06	1,284.61	1,284.61	293.16
Density (kg/m^3)	24.9	15.0	1.2	16.7	7.1	1.5	1.0	1.0	1.2	1.2	1.2	2.5	0.9	0.8	0.9
V-L Molecular Weight	17.328	17.328	28.854	18.015	20.279	19.675	23.263	21.182	23.713	28.854	28.854	17.328	28.266	28.266	28.266
V-L Flowrate (lb_{mol}/h)	7,673	3,069	8,802	3,069	17,873	19,105	30,272	50,991	33,528	229,443	229,443	1,575	250,827	250,827	250,827
V-L Flowrate (lb/h)	132,950	53,180	253,969	55,291	362,440	375,878	704,235	1,080,113	795,053	6,620,395	6,620,395	27,285	7,089,826	7,089,826	7,089,826
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	59	409	59	466	1,451	524	1,267	1,063	1,007	59	1,135	59	1,789	1,789	270
Pressure (psia)	500.0	500.0	14.7	500.0	450.0	49.1	49.1	49.0	49.0	14.7	44.3	49.0	49.0	44.0	15.3
Enthalpy (Btu/lb)[A]	13.4	205.9	13.4	1,232.7	744.5	348.8	789.1	646.0	694.2	13.4	285.6	11.6	552.3	552.3	126.0
Density (lb/ft^3)	1.557	0.937	0.076	1.045	0.442	0.091	0.062	0.064	0.074	0.076	0.075	0.154	0.057	0.052	0.055

[A] Reference conditions are 32.02 F and 0.089 psia

Exhibit 5-12. Case PNGFC0A – Pressurized Reference NGFC Plant without CCS – Material and Energy Balances

Carbon Balance

Carbon In		Carbon Out	
kg/hr(lb/hr)		kg/hr(lb/hr)	
NG	52,497 (115,736)	Stack Gas	52,883 (116,587)
Air (CO2)	389 (858)	CO_2 Product	0 (0)
		Convergence Tolerance	3 (8)
Total	52,886 (116,595)	Total	52,886 (116,595)

Sulfur Balance

Sulfur In		Sulfur Out	
kg/hr(lb/hr)		kg/hr(lb/hr)	
NGIN	0 (0)	Elemental Sulfur	0 (0)
		Polishing Sorbent	0 (0)
		Convergence Tolerance	0 (0)
Total	0 (0)	Total	0 (0)

Energy Balance

	HHV	Sensible + Latent	Power	Total
Heat In GJ/hr (MMBtu/hr)				
NG	3,812.07 (3,613.14)	2.1 (2.0)		3,814.2 (3,615.1)
Fuel cell Air		93.3 (88.4)		93.3 (88.4)
Auxiliary Power			480.6 (455.5)	480.6 (455.5)
TOTAL	**3,812 (3,613)**	**95.4 (90.4)**	**480.6 (455.5)**	**4,388.1 (4,159.1)**
Heat Out GJ/hr (MMBtu/hr)				
Stack Flue Gas		942.8 (893.6)		942.76 (893.56)
Vents		0.0 (0.0)		0.00 (0.00)
Water outlets		0.0 (0.0)		0.00 (0.00)
Process Losses**		552.4 (523.6)		552.41 (523.59)
Difference***		72.3 (68.5)		72.26 (68.49)
Power			2,820.6 (2,673.4)	2,820.6 (2,673.4)
TOTAL	**0.0 (0.0)**	**1,567.4 (1,485.6)**	**2,820.6 (2,673.4)**	**4,388.1 (4,159.1)**

* Includes ASU compressor intercoolers & CO2 compressor intercoolers

** Includes accounting of losses such as inverter, transformer, generator, and motor losses

*** Calculated by difference to close the energy balance

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)
Condenser Makeup	**0.5 (121)**	**0.0 (0)**	**0.5 (121)**	**0.0 (0)**	**0.5 (121)**
Reformer Steam	0.4 (111)	0.0 (0)	0.4 (111)		
BFW Makeup	0.0 (10)	0.0 (0)	0.0 (10)		
Cooling Tower	**3.5 (929)**	**0.00 (0)**	**3.5 (929)**	**0.8 (209)**	**2.7 (720)**
0	0.0 (0)	0.00 (0)	0.00 (0)		
Total	**4.0 (1,049)**	**0.00 (0)**	**4.0 (1,049)**	**0.8 (209)**	**3.2 (840)**

Emissions

	kg/GJ ($lb/10^6 Btu$)	Tonne/year (tons/year)	kg/MWh (lb/MWh)
SO2	0 (0)	0 (0)	0 (0)
NOx	0 (0)	0 (0)	0 (0)
Particulate	0 (0)	0 (0)	0 (0)
Hg	0 (0)	0 (0)	0 (0)
CO2	57431 (133584)	1,231,902 (1,357,939)	224 (495)

Exhibit 5-13. Case PNGFC0A – Pressurized Reference NGFC Plant without CCS – Heat and Material Balance Diagram – ASU, ATR, and Power Island

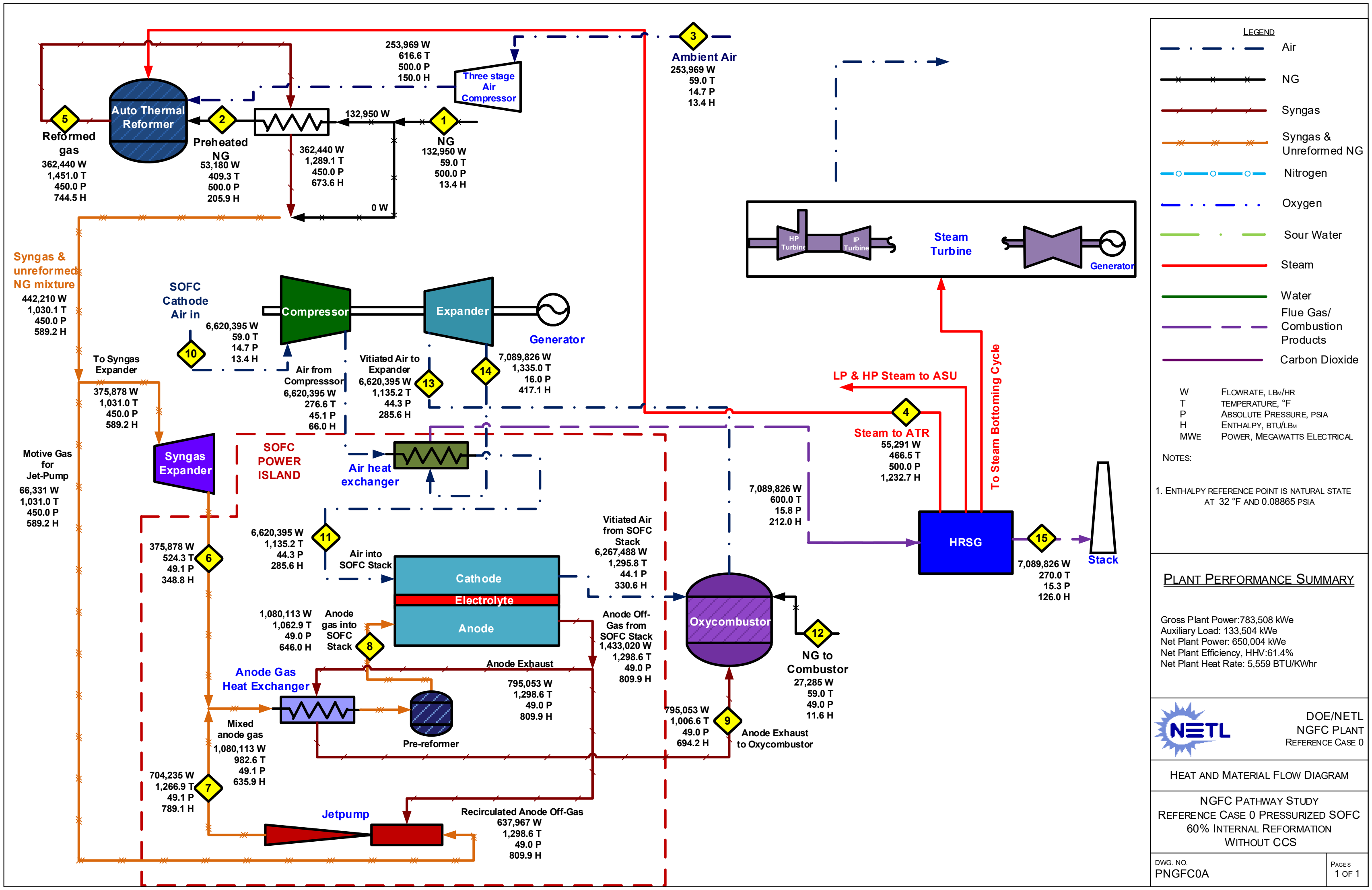


Exhibit 5-14. Case PNGFC0B – Pressurized Reference NGFC Plant with CCS – Capital Costs

Cost Component	Cost ($1000)	Specific Cost ($/kWe AC)
	2018$	2018$
SOFC Power Island		
SOFC Module		
SOFC Stack	125,868	194
Container	15,103	23
Insulation	2,238	3
Module Assembly	5,594	9
Air distribution	5,594	9
Fuel distribution	5,594	9
Pre-reformer	5,594	9
Module Current Collectors	2,797	4
Module I&C	2,797	4
Inverter	38,040	59
Total SOFC Module with 10 % Extra Installed Area	209,220	322
NG EXPANDER	8,414	13
SOFC BOP		
Desulfurization System	1,908	3
Cathode Air Compressor	12,820	20
Cathode Expander	10,439	16
Cathode Heat Exchanger	42,158	65
Anode Recycle Blower	598	1
Anode Heat Exchanger	8,704	13
Oxy-Combustor	20,618	32
Oxy-Combustor Expander	7,352	11
Air, Exhaust, Fuel Flow Piping system	3,080	5
Section and Overall Assembly	1,540	2
Section I&C	770	1
Total SOFC BOP	109,988	169
TOTAL SOFC POWER ISLAND	327,622	504
ASU	124,956	192
AUTOTHERMAL REFORMER and Natural Gas Preheater	19,912	31
STEAM CYCLE		
HRSG, Ducting, and Stack	33,049	51
Steam Power System	42,906	66
Feedwater and Miscellaneous BOP systems	71,868	111
TOTAL STEAM CYLCE	147,823	227
CO_2 COMPRESSION & PURIFICATION		
CO_2 Purification	85,691	132
TOTAL CO_2 COMPRESSION & PURIFICATION	85,691	132
COOLING WATER SYSTEM	34,723	53
ACCESSORY ELECTRIC PLANT	129,365	199
INSTRUMENTATION & CONTROL	26,857	41
IMPROVEMENTS TO SITE	30,881	47
BUILDING & STRUCTURES	12,864	20
TOTAL PLANT COST (TPC)	940,693	1447
OWNER'S COSTS		
Preproduction Costs		
6 Months All Labor	6,469	
1 Month Maintenance Materials	1,117	
1 Month Non-fuel Consumables	365	
25% of 1 Months Fuel Cost at 100% CF	2,931	
2% of TPC	18,814	
Total Preproduction Costs	29,695	
Inventory Capital		
60-day supply of fuel and consumables at 100% CF	612	
0.5% of TPC (spare parts)	4,703	
Total Inventory Capital	5,315	
Initial Cost for Catalyst and Chemicals	1,459	
Land	300	
Other Owner's Costs	141,104	
Financing Costs	25,399	
TOTAL OWNER'S COSTS	203,273	
TOTAL OVERNIGHT COST (TOC)	1,143,966	1759
TASC Multiplier	1.093	
TOTAL AS-SPENT COST (TASC)	1,250,355	1923

Exhibit 5-15. Case PNGFC0B – Pressurized Reference NGFC Plant with CCS – O&M Costs

Case:	**PNGFC0B**				**Cost Base:**	**Apr 2018**
Plant Size (MW, net):		**650**			**Capacity Factor:**	**80%**
Operating & Maintenance Labor						
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:	1.0	
Operating Labor Burden:		30.00	**% of base**	Operator:	4.3	
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:	1.0	
				Lab Techs, etc.:	1.0	
				Total:	**7.3**	
Fixed Operating Costs						
					Annual Cost	
					($)	**($/kW-net)**
				Annual Operating Labor:	$3,200,597	$4.92
				Maintenance Labor:	$7,149,270	$11.00
				Administrative & Support Labor:	$2,587,467	$3.98
				Property Taxes and Insurance:	$18,813,869	$28.94
				Total:	$31,751,203	$48.83
Variable Operating Costs						
					($)	**($/MWh-net)**
				Maintenance Material:	$10,723,905	$2.35
Stack Replacement						
		Life (y)	**$/kW AC**	**$/y per kW**		
SOFC Stack Replacement Cost		7.3	$216	$23.78	$15,462,671	$3.39
Consumables						
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (gal/1000):	0	1,016	$1.90	$0	$563,789	$0.12
Makeup and Waste Water Treatment Chemicals (lb):	0	7,568	$0.28	$0	$607,695	$0.13
NG Desulfur TDA Adsorbent (lb):	48,887	1190	$6.03	$294,773	$2,095,830	$0.46
ATR Catalyst (m^3):	1,935	1.3	$601.76	$1,164,586	$233,868	$0.05
			Subtotal:	$1,459,358	$3,501,183	$0.77
Waste Disposal						
ATR Catalyst (m^3):	0	1.3	$0.00	$0	$0	$0.00
			Subtotal:	$0	$0	$0.00
			Variable Operating Costs Total:	$1,459,358	$29,687,759	$6.65
Fuel Cost						
Natural Gas (MMBtu):	0	87,205	$4.42	$0	$112,555,369	$24.70
			Total:	$0	$112,555,369	$24.70

Exhibit 5-16. Case PNGFC0B – Pressurized Reference NGFC Plant with CCS – Capital Cost Components

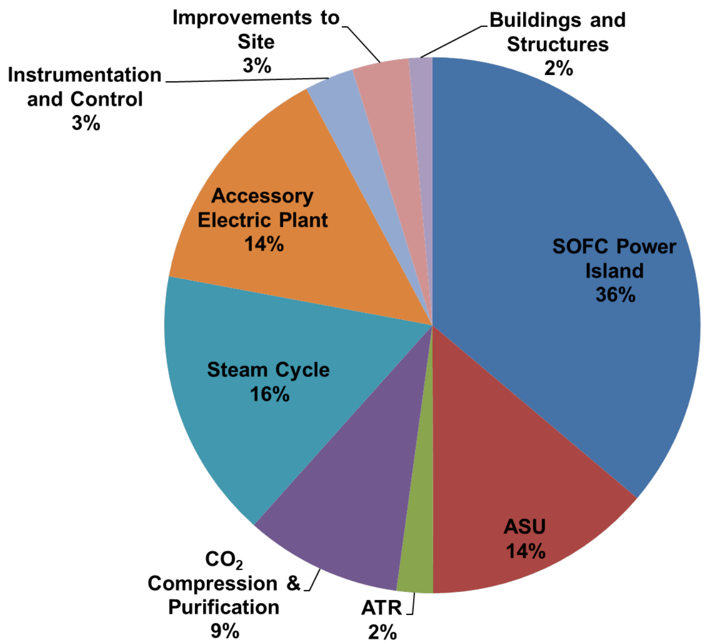


Exhibit 5-17. Case PNGFC0B – Pressurized Reference NGFC Plant with CCS – BOP Cost Distribution

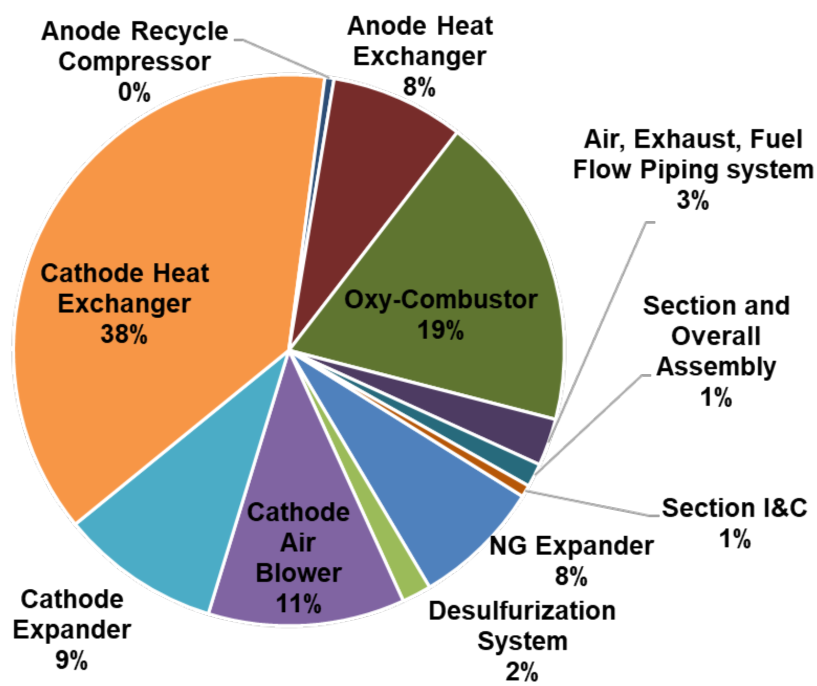


Exhibit 5-18. Case PNGFC0A – Pressurized Reference NGFC Plant without CCS – Capital Costs

Cost Component	Cost ($1000) 2018$	Specific Cost ($/kWe AC) 2018$
SOFC Power Island		
SOFC Module		
SOFC Stack	106,201	163
Container	12,743	20
Insulation	1,888	3
Module Assembly	4,720	7
Air distribution	4,720	7
Fuel distribution	4,720	7
Pre-reformer	4,720	7
Module Current Collectors	2,360	4
Module I&C	2,360	4
Inverter	32,096	49
Total SOFC Module with 10 % Extra Installed Area	176,530	272
NG EXPANDER	9,124	14
SOFC BOP		
Desulfurization System	1,618	2
Cathode Air Blower	13,905	21
Cathode Expander	23,497	36
Cathode Heat Exchanger	32,918	51
Anode Recycle Blower	526	1
Anode Heat Exchanger	8,856	14
Oxy-Combustor	29,845	46
Oxy-Combustor Expander	0	0
Air, Exhaust, Fuel Flow Piping system	2,198	3
Section and Overall Assembly	1,099	2
Section I&C	549	1
Total SOFC BOP	115,011	177
TOTAL SOFC POWER ISLAND	2,127	3
ASU	17,421	27
AUTOTHERMAL REFORMER and Natural Gas Preheater		
STEAM CYCLE	32,782	50
HRSG, Ducting, and Stack	29,978	46
Steam Power System	55,876	86
Feedwater and Misc BOP systems	118,636	182
TOTAL STEAM CYLCE		
CO_2 COMPRESSION & PURIFICATION	0	0
CO_2 Purification	**0**	**0**
TOTAL CO_2 COMPRESSION & PURIFICATION	19,530	30
COOLING WATER SYSTEM	117,334	180
ACCESSORY ELECTRIC PLANT	25,257	39
INSTRUMENTATION & CONTROL	30,497	47
IMPROVEMENTS TO SITE	11,368	17
BUILDING & STRUCTURES	642,834	989
TOTAL PLANT COST (TPC)		
OWNER'S COSTS		
Preproduction Costs		
6 Months All Labor	4,698	
1 Month Maintenance Materials	763	
1 Month Non-fuel Consumables	288	
25% of 1 Months Fuel Cost at 100% CF	2,418	
2% of TPC	12,857	
Total Preproduction Costs	21,024	
Inventory Capital		
60-day supply of fuel and consumables at 100% CF	507	
0.5% of TPC (spare parts)	3,214	
Total Inventory Capital	3,722	
Initial Cost for Catalyst and Chemicals	1,965	
Land	300	
Other Owner's Costs	96,425	
Financing Costs	17,357	
TOTAL OWNER'S COSTS	140,793	
TOTAL OVERNIGHT COST (TOC)	783,627	1205
TASC Multiplier	1.093	
TOTAL AS-SPENT COST (TASC)	856,504	1317

Exhibit 5-19. Case PNGFC0A – Pressurized Reference NGFC Plant without CCS – O&M Costs

Case:	**PNGFC0A**				**Cost Base:**	**Apr 2018**
Plant Size (MW, net):		**650**			**Capacity Factor:**	**80%**
Operating & Maintenance Labor						
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:	1.0	
Operating Labor Burden:		30.00	**% of base**	Operator:	3.3	
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:	1.0	
				Lab Techs, etc.:	1.0	
				Total:	**6.3**	
Fixed Operating Costs						
					Annual Cost	
					($)	**($/kW-net)**
				Annual Operating Labor:	$2,630,628	$4.05
				Maintenance Labor:	$4,885,540	$7.51
				Administrative & Support Labor:	$1,879,042	$2.89
				Property Taxes and Insurance:	$12,856,683	$19.78
				Total:	$22,251,893	$34.23
Variable Operating Costs						
					($)	**($/MWh-net)**
				Maintenance Material:	$7,328,309	$1.61
Stack Replacement						
		Life (y)	**$/kW AC**	**$/y per kW**		
SOFC Stack Replacement Cost		7.3	$229	$25.23	$16,400,495	$3.60
Consumables						
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (gal/1000):	0	602	$1.90	$0	$334,230	$0.07
Makeup and Waste Water Treatment Chemicals (lb):	0	4,486	$0.28	$0	$360,258	$0.08
NG Desulfur TDA Adsorbent (lb):	40,334	982	$6.03	$243,205	$1,729,183	$0.38
ATR Catalyst (m^3):	2,862	2.0	$601.76	$1,722,055	$345,817	$0.08
			Subtotal:	$1,965,260	$2,769,489	$0.61
Waste Disposal						
ATR Catalyst (m^3):	0	2.0	$0.00	$0	$0	$0.00
			Subtotal:	$0	$0	$0.00
			Variable Operating Costs Total:	$1,965,260	$26,498,293	$5.82
Fuel Cost						
Natural Gas (MMBtu):	0	71,949	$4.42	$0	$92,864,815	$20.38
			Total:	$0	$92,864,815	$20.38

Exhibit 5-20. Case PNGFC0A – Pressurized Reference NGFC Plant without CCS – Capital Cost Components

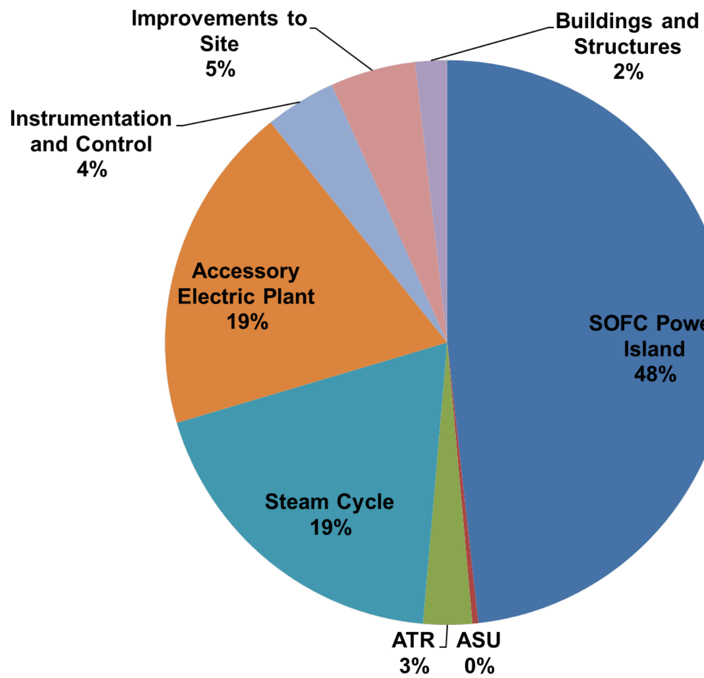


Exhibit 5-21. Case PNGFC0A – Pressurized Reference NGFC Plant without CCS – BOP Cost Distribution

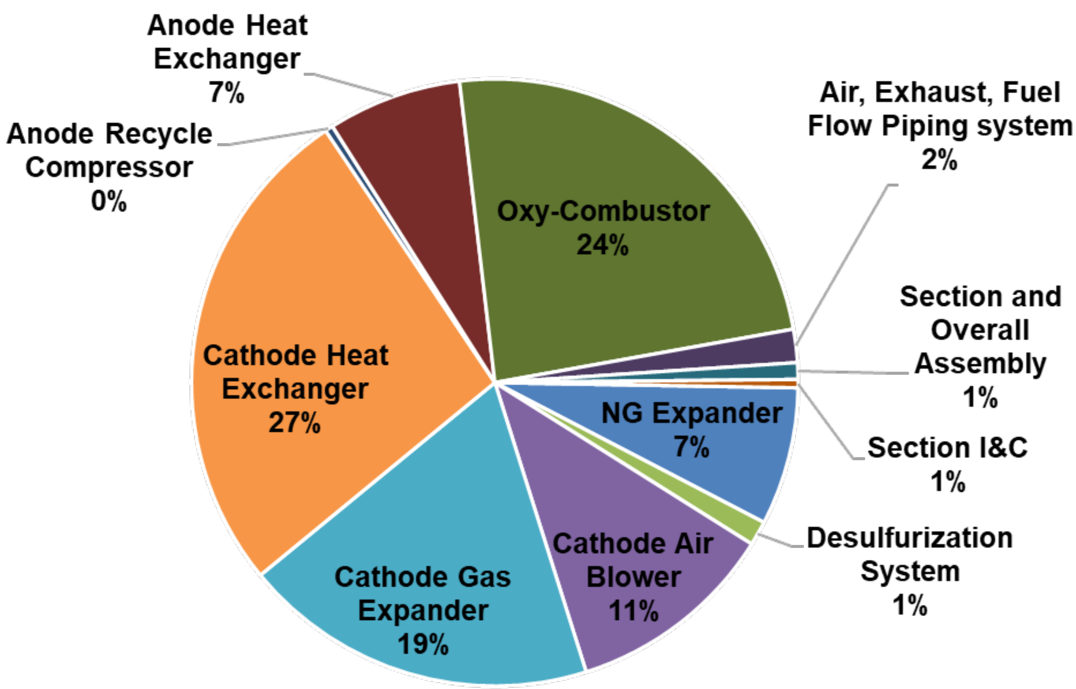


Exhibit 5-22. Case 0 – Pressurized Reference Plant with and without CCS – Levelized Cost of Electricity

Levelized Cost of Electricity (2018$/MWh)		
Carbon Capture	**With CCS**	**No CCS**
Component	**$/MWh**	
Variable Costs	31.2	26.2
Fuel Costs	24.7	20.4
Variable O&M Costs	6.5	5.8
Fixed O&M Costs	7.0	4.9
Capital Costs	19.4	13.3
Total LCOE (excluding T&S)	57.6	44.4
T&S	2.9	0.0
Total LCOE (including T&S)	60.5	44.4

5.2 Case 4: Advanced Pressurized NGFC Plant Description

Case 4 represents the final stage of the pressurized pathway in parallel with the atmospheric pathway. The improvements made prior to Case 4 include increased fuel utilization, an increased capacity factor, and 100 percent internal reformation. Case 4 examines improvements to the BOP such as decreased ASU power consumption, increased inverter efficiency, along with decreased stack costs. The SOFC technology parameters for Case 4 are shown in Exhibit 5-23.

Exhibit 5-23. SOFC technology parameters used for Case 4

Parameter	Value
Reformation	100% Internal
SOFC Operating Pressure	≈44.1 psia
Cell Technology	Advanced Cell
Fuel Utilization, %	85
Current Density, mA/cm^2	400
Degradation, %/1000 hr	0.2
Inverter Efficiency (%)	98
Stack Cost ($/kW)	200

The realization of 100 percent internal reformation removes the need for the ATR and reduces the load of the ASU, as oxidant is only required for the oxy-combustor in the plant with CCS. Natural gas is sent directly to the anode heat exchanger after desulfurization. The remainder of the plant operates the same as in Case 0. In the configuration without CCS, neither the ATR, ASU, nor CPU are required. The analysis show that the additional natural gas injection is not required for the plant without CCS in this case.

5.2.1 Case 4: Advanced Pressurized NGFC Plant Performance

The stream tables for the Case 4 plants with and without the CCS option are listed in Exhibit 5-28 and Exhibit 5-33, respectively and correspond to the state point numbers identified in Exhibit 5-27 and Exhibit 5-32. The Case 4 plant power summary is shown in Exhibit 5-24. For the plant with CCS, the SOFC generates 81 percent of the gross power while the expanders and steam cycle generate the rest as seen in Exhibit 5-25. In the advanced plant without CCS the expanders contribute more to the generation. In the advanced pressurized plant without CCS, 94 percent of the auxiliary load is due to the blowers and compressors as seen in Exhibit 5-26. When CCS is included, the ASU and CPU impose additional auxiliary loads.

The HHV efficiency (68.1 percent) of the advanced plant with CCS is 2.6 percentage points higher than the HHV efficiency of the Pathway 1 end point Case 4 (65.5 percent). The advanced plant without CCS results in the highest HHV efficiency value of 71.4 percent among all the plants in the present study.

The material and energy balances for Case 4 with CCS option are summarized in Exhibit 5-29 while process flow diagrams are shown in Exhibit 5-30 and Exhibit 5-31. Cooling tower makeup is the dominant water demand in the plant. The material and energy balance diagrams and process flow diagrams for the case without CCS are shown in Exhibit 5-34 and Exhibit 5-35.

5.2.2 Case 4: Advanced Pressurized NGFC Plant Costs

Exhibit 5-36 and Exhibit 5-37 itemize the capital and O&M costs for the Case 4 plant with CCS. The capital cost for the pressurized advanced plant with CCS is not significantly different from the capital cost for the atmospheric pathway plant (≈2 percent less). Exhibit 5-39 shows that the oxy-combustor and cathode heat exchanger together account for 56 percent of the BOP costs. The LCOE for the advanced pressurized plant with and without CCS is shown in Exhibit 5-44. Imposing a CCS constraint increases the LCOE by ≈26 percent to $50.2/MWh. The LCOE of the pressurized plant with CCS is ≈$0.2/MWh lower relative to the corresponding atmospheric pathway case.

Exhibit 5-24. Case 4 – Advanced Pressurized NGFC Plant with and without CCS – Performance Summary

Carbon Capture	With CCS	No CCS
Power Summary (Gross Power at Generator Terminals, kWe)		
SOFC Power	596,593	541,288
Natural Gas/Syngas Expander Power	77,020	148,600
Steam Turbine Power	63,800	31,600
Total Gross Power, kW_e	**737,413**	**721,488**
Auxiliary Load Summary, kWe		
Air Separation Unit Auxiliaries	0	0
Air Separation Unit Main Air Compressor	7,282	0[A]
Oxygen Compressor	790	0
Nitrogen Compressors	0	0
CO_2 Compressor	21,918	0
CO_2 Refrigeration	0	0
Boiler Feedwater Pumps	1,173	581
Condensate Pump	36	18
Circulating Water Pump	1,830	590
Cooling Tower Fans	960	300
Gas Turbine Auxiliaries	-	-
Steam Turbine Auxiliaries	49	24
Cathode Air Blower	50,470	66,743
Cathode Recycle Blower	0	0
Anode Recycle Blower	1	1
Miscellaneous Balance of Plant[B]	386	369
Transformer Losses	2,453	2,353
Total Auxiliaries, kW_e	87,342	70,979
Net Power, kW_e	650,071	650,509
Net Plant Efficiency, % (HHV)	68.10	71.35
Net Plant Heat Rate, kJ/kWh (Btu/kWh)	5,287 (5,011)	5,046 (4,782)
CO_2 Capture Rate, %	97.9	0.0
Condenser Cooling Duty, 10^6 kJ/h (10^6 Btu/h)	369 (350)	264 (250)
Natural Gas Feed Rate, kg/h (lb/h)	65,525 (144,458)	62,581 (137,966)
Thermal Input[C], kWt	954,644	911,744
Raw Water Withdrawal, m^3/min (gpm)	4.9 (1,289.7)	2.3 (596.4)
Raw Water Consumption, m^3/min (gpm)	3.28 (866.6)	1.75 (463.5)

[A] Reflects power needed to compress air to ATR pressure.
[B] Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads.
[C] HHV of natural gas is 52,449 kJ/kg (22,549 Btu/lb).

Exhibit 5-25. Case 4 – Advanced Pressurized NGFC Plant with and without CCS – Gross Power Distribution

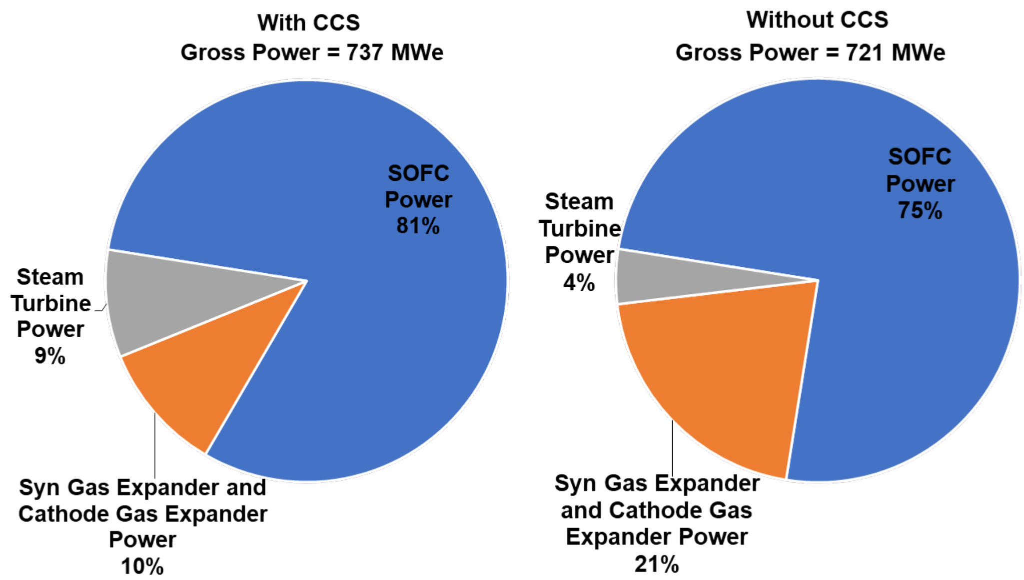


Exhibit 5-26. Case 4 – Advanced Pressurized NGFC Plant with and without CCS – Auxiliary Load Distribution

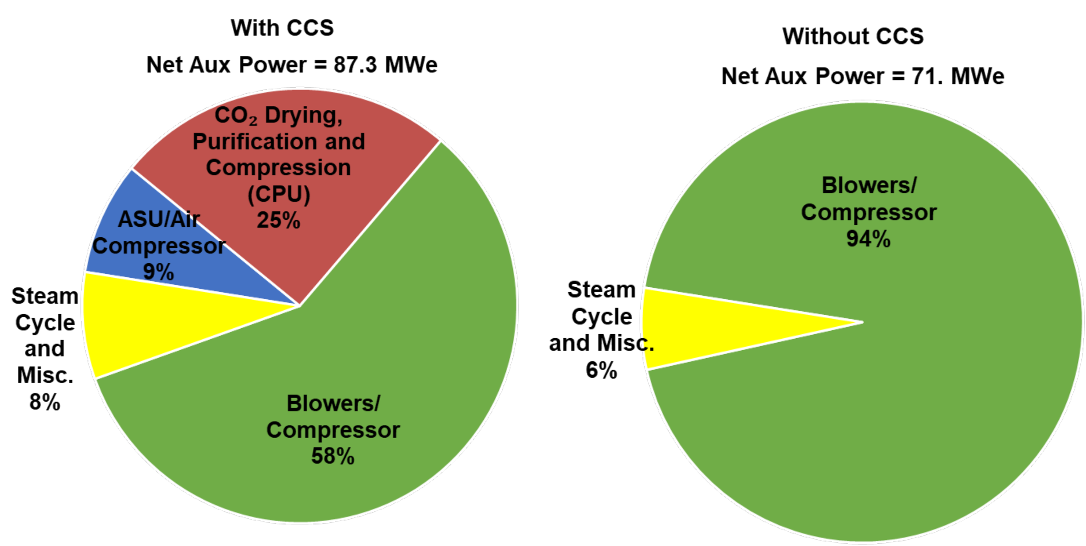


Exhibit 5-27. Case PNGFC4B – Advanced Pressurized NGFC Plant with CCS – Block Flow Diagram

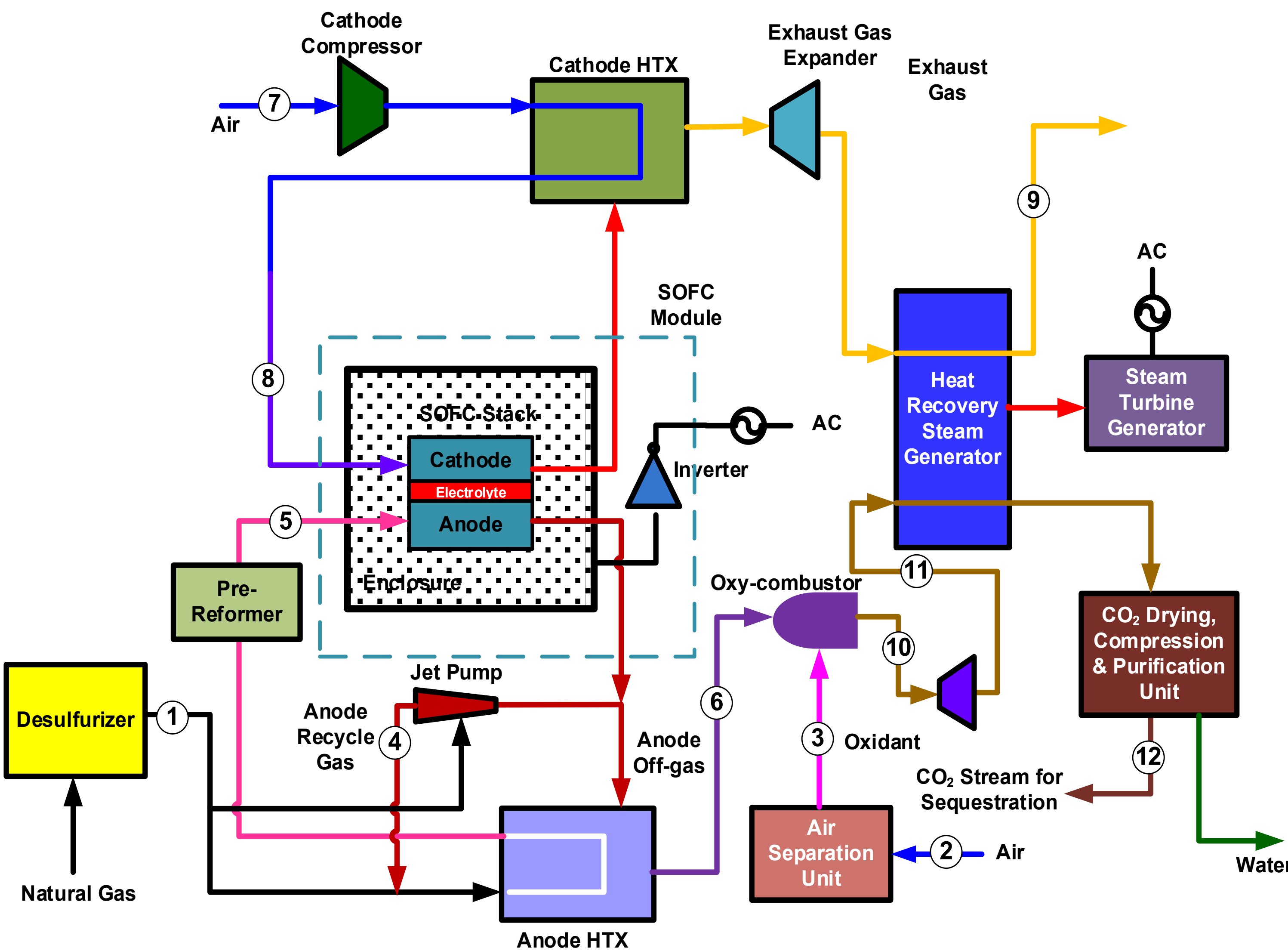


Exhibit 5-28. Case PNGFC4B – Advanced Pressurized NGFC Plant with CCS – Stream Table

	1	2	3	4	5	6	7	8	9	10	11	12
V-L Mole Fraction												
Ar	0.0000	0.0094	0.0031	0.0000	0.0000	0.0000	0.0094	0.0094	0.0109	0.0003	0.0003	0.0000
CH_4	0.9310	0.0000	0.0000	0.0267	0.1346	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000	0.0504	0.0421	0.0519	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0100	0.0003	0.0000	0.2802	0.2549	0.2881	0.0003	0.0003	0.0003	0.3363	0.3363	1.0000
H_2	0.0000	0.0000	0.0000	0.1422	0.2080	0.1464	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	0.0000	0.0104	0.0000	0.4937	0.3537	0.5081	0.0104	0.0104	0.0121	0.6475	0.6475	0.0000
N_2	0.0160	0.7722	0.0019	0.0055	0.0066	0.0052	0.7722	0.7722	0.8951	0.0054	0.0054	0.0000
C_2H_6	0.0320	0.0000	0.0000	0.0009	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_3H_8	0.0070	0.0000	0.0000	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_4H_{10}	0.0040	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
O_2	0.0000	0.2077	0.9950	0.0000	0.0000	0.0000	0.2077	0.2077	0.0816	0.0105	0.0105	0.0000
Total	1.0000	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)	3,782	6,347	1,284	19,963	24,417	11,580	47,649	47,649	41,108	11,716	11,716	3,858
V-L Flowrate (kg/h)	65,525	183,130	41,107	470,137	525,831	274,832	1,374,884	1,374,884	1,165,575	315,939	315,939	169,802
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	15	15	94	704	553	603	15	559	132	1,591	1,345	36
Pressure (MPa, abs)	0.34	0.10	0.30	0.34	0.34	0.338	0.101	0.31	0.10	0.34	0.13	15.27
Enthalpy (kJ/kg)[A]	31.11	31.06	86.06	2,102.75	1,727.66	1,921.626	31.06	604.51	155.05	3,767.52	3,287.30	-209.06
Density (kg/m^3)	2.5	1.2	3.2	1.0	1.1	1.1	1.2	1.3	0.9	0.6	0.3	545.3
V-L Molecular Weight	17.328	28.854	32.016	23.551	21.535	23.733	28.854	28.854	28.354	26.966	26.966	44.010
V-L Flowrate (lb_{mol}/h)	8,337	13,992	2,831	44,010	53,831	25,530	105,049	105,049	90,628	25,830	25,830	8,506
V-L Flowrate (lb/h)	144,458	403,732	90,625	1,036,475	1,159,260	605,901	3,031,101	3,031,101	2,569,654	696,527	696,527	374,349
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	59	59	202	1,299	1,027	1,118	59	1,039	270	2,895	2,452	97
Pressure (psia)	50.0	14.7	44.1	49.1	49.0	49.0	14.7	44.3	14.7	49.0	19.0	2,215.0
Enthalpy (Btu/lb)[A]	13.4	13.4	37.0	904.0	742.8	826.2	13.4	259.9	66.7	1,619.7	1,413.3	-89.9
Density (lb/ft^3)	0.156	0.076	0.199	0.061	0.066	0.069	0.076	0.079	0.053	0.037	0.016	34.043

[A] Reference conditions are 32.02 F and 0.089 psia

Exhibit 5-29. Case PNGFC4B – Advanced Pressurized NGFC Plant with CCS – Material and Energy Balances

Carbon Balance

Carbon In		**Carbon Out**	
kg/hr(lb/hr)		kg/hr(lb/hr)	
NG	47,328 (104,340)	Stack Gas	172 (379)
Air (CO2)	195 (429)	CO_2 Product	46,342 (102,166)
		Exhaust	985 (2,171)
		ASU Vent	23 (50)
		Water KO	1 (3)
		Convergence Tolerance	0 (1)
Total	47,523 (104,769)	Total	47,523 (104,769)

Sulfur Balance

Sulfur In		**Sulfur Out**	
kg/hr(lb/hr)		kg/hr(lb/hr)	
NGIN	0 (0)	Elemental Sulfur	0 (0)
		Polishing Sorbent	0 (0)
		Convergence Tolerance	0 (0)
Total	0 (0)	Total	0 (0)

Energy Balance

	HHV	**Sensible + Latent**	**Power**	**Total**
Heat In GJ/hr (MMBtu/hr)				
NG	3,436.72 (3,257.38)	2.3 (2.2)		3,439.0 (3,259.6)
Fuel cell Air		42.7 (40.5)		42.7 (40.5)
Raw Water Makeup		0.0 (0.0)		0.0 (0.0)
Auxiliary Power			321.0 (304.3)	321.0 (304.3)
TOTAL	**3,437 (3,257)**	**45.0 (42.6)**	**321.0 (304.3)**	**3,802.7 (3,604.3)**
Heat Out GJ/hr (MMBtu/hr)				
CO_2 Out		-35.5 (-33.6)		-35.5 (-33.6)
Stack Flue Gas		180.7 (171.3)		180.73 (171.30)
Vents		7.9 (7.5)		7.94 (7.52)
Water outlets		21.6 (20.5)		21.64 (20.51)
Process Losses**		978.7 (927.7)		978.74 (927.67)
Difference***		-5.5 (-5.2)		-5.51 (-5.23)
Power			2,654.7 (2,516.2)	2,654.7 (2,516.2)
TOTAL	**0.0 (0.0)**	**1,148.0 (1,088.1)**	**2,654.7 (2,516.2)**	**3,802.7 (3,604.3)**

* Includes ASU compressor intercoolers & CO2 compressor intercoolers
** Includes accounting of losses such as inverter, transformer, generator, and motor losses
*** Calculated by difference to close the energy balance

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)
Condenser Makeup	**0.0 (11)**	**0.0 (0)**	**0.0 (11)**	**0.0 (0)**	**0.0 (11)**
Reformer Steam	0.0 (0)	0.0 (0)	0.0 (0)		
BFW Makeup	0.0 (11)	0.0 (0)	0.0 (11)		
Cooling Tower	**7.1 (1,881)**	**2.28 (603)**	**4.8 (1,279)**	**1.6 (423)**	**3.2 (856)**
CO2 Dehydration	0.0 (0)	2.28 (603)	-2.28 (-603)		
Total	**7.2 (1,892)**	**2.28 (603)**	**4.9 (1,290)**	**1.6 (423)**	**3.3 (867)**

Emissions

	kg/GJ ($lb/10^6Btu$)	Tonne/year (tons/year)	kg/MWh (lb/MWh)
SO2	0 (0)	0 (0)	0 (0)
NOx	0 (0)	0 (0)	0 (0)
Particulate	0 (0)	0 (0)	0 (0)
Hg	0 (0)	0 (0)	0 (0)
CO2	1336 (3107)	28,655 (31,586)	5 (12)

Exhibit 5-30. Case PNGFC4B – Advanced Pressurized NGFC Plant with CCS – Heat and Material Balance Diagram – ASU, ATR, and Power Island

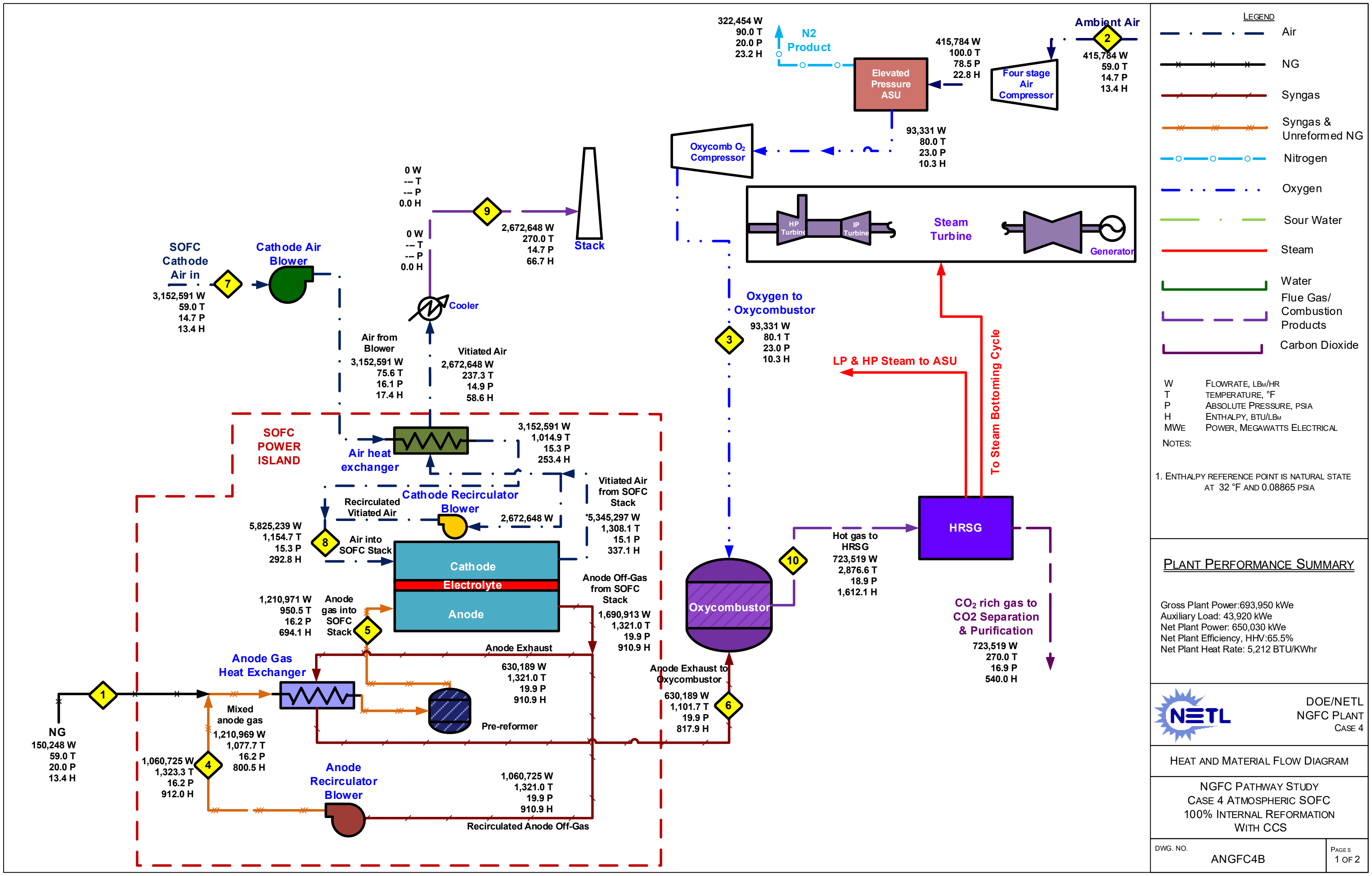


Exhibit 5-31. Case PNGFC4B – Advanced Pressurized NGFC Plant with CCS – Heat and Material Balance Diagram – CO_2 Dehydration, Purification, and Compression

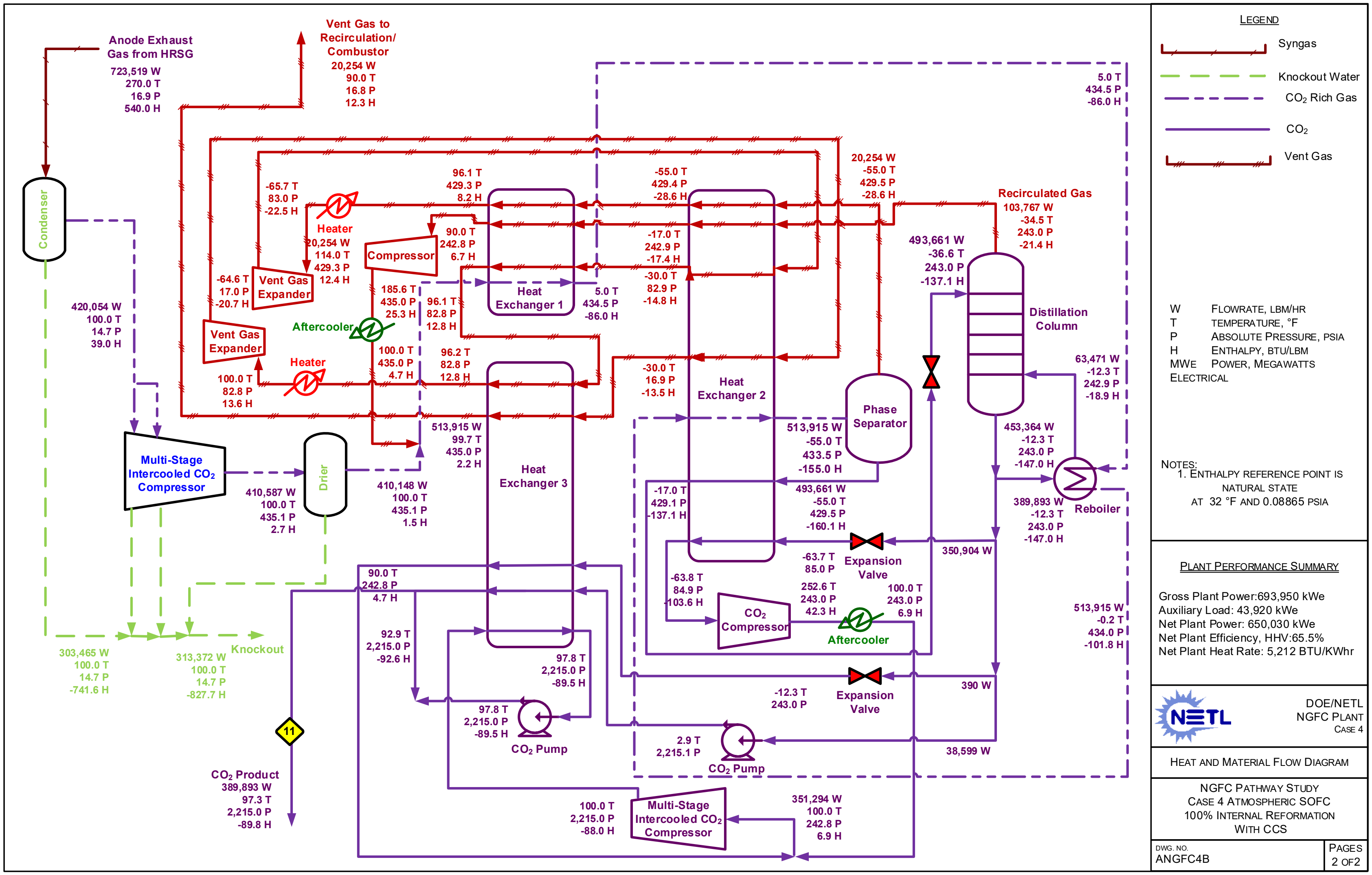


Exhibit 5-32. Case PNGFC4A – Advanced Pressurized NGFC Plant without CCS – Block Flow Diagram

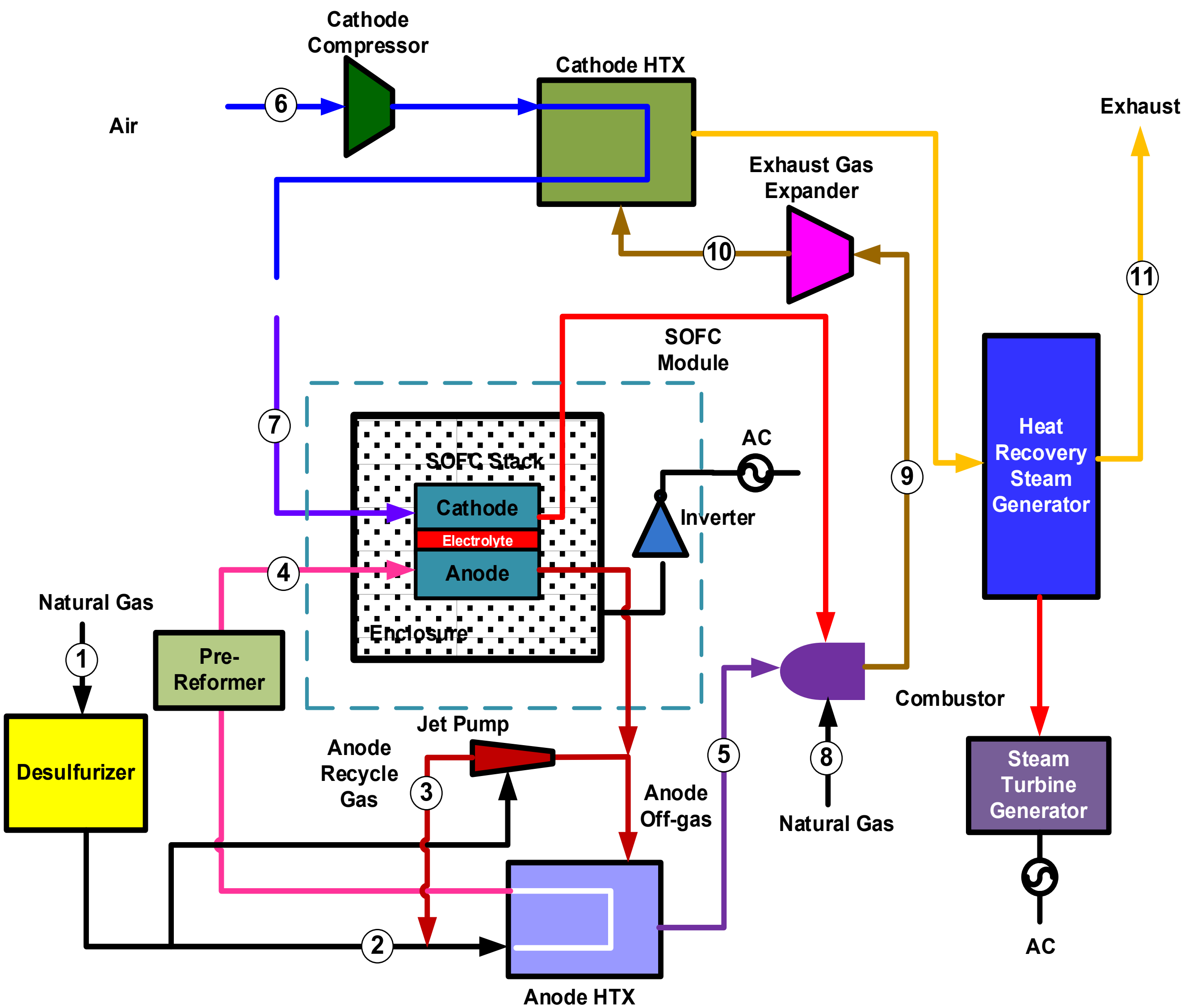


Exhibit 5-33. Case PNGFC4A – Advanced Pressurized NGFC Plant without CCS – Stream Table

	1	2	3	4	5	6	7	8	9	10	11
V-L Mole Fraction											
Ar	0.0000	0.0000	0.0000	0.0000	0.0000	0.0094	0.0094	0.0000	0.0089	0.0089	0.0089
CH_4	0.9310	0.9310	0.0267	0.1352	0.0003	0.0000	0.0000	0.9310	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0496	0.0413	0.0510	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0100	0.0100	0.2811	0.2555	0.2890	0.0003	0.0003	0.0100	0.0570	0.0570	0.0570
H_2	0.0000	0.0000	0.1429	0.2060	0.1471	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	0.0000	0.0000	0.4931	0.3553	0.5074	0.0104	0.0104	0.0000	0.1190	0.1190	0.1190
N_2	0.0160	0.0160	0.0055	0.0066	0.0052	0.7722	0.7722	0.0160	0.7298	0.7298	0.7298
C_2H_6	0.0320	0.0320	0.0009	0.0000	0.0000	0.0000	0.0000	0.0320	0.0000	0.0000	0.0000
C_3H_8	0.0070	0.0070	0.0002	0.0000	0.0000	0.0000	0.0000	0.0070	0.0000	0.0000	0.0000
C_4H_{10}	0.0040	0.0040	0.0001	0.0000	0.0000	0.0000	0.0000	0.0040	0.0000	0.0000	0.0000
O_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.2077	0.2077	0.0000	0.0853	0.0853	0.0853
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)	3,609	3,067	19,115	23,332	11,050	62,660	62,660	3	66,376	66,376	66,376
V-L Flowrate (kg/h)	62,528	53,149	450,224	503,372	262,259	1,808,000	1,808,000	53	1,870,577	1,870,577	1,870,577
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	15	15	698	551	599	15	571	15	936	936	132
Pressure (MPa, abs)	0.34	0.338	0.34	0.34	0.338	0.101	0.31	0.34	0.34	0.30	0.11
Enthalpy (kJ/kg)[A]	31.11	27.676	2,091.49	1,725.68	1,913.135	31.06	616.88	27.06	1,288.40	1,288.40	331.91
Density (kg/m^3)	2.5	2.5	1.0	1.1	1.1	1.2	1.3	2.5	0.9	0.8	0.9
V-L Molecular Weight	17.328	17.328	23.553	21.574	23.735	28.854	28.854	17.328	28.181	28.181	28.181
V-L Flowrate (lb_{mol}/h)	7,956	6,762	42,141	51,439	24,360	138,141	138,141	7	146,334	146,334	146,334
V-L Flowrate (lb/h)	137,850	117,173	992,573	1,109,746	578,182	3,985,959	3,985,959	116	4,123,917	4,123,917	4,123,917
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	59	60	1,289	1,025	1,111	59	1,059	59	1,717	1,717	270
Pressure (psia)	50.0	49.1	49.1	49.0	49.0	14.7	44.3	49.0	49.0	44.0	15.3
Enthalpy (Btu/lb)[A]	13.4	11.9	899.2	741.9	822.5	13.4	265.2	11.6	553.9	553.9	142.7
Density (lb/ft^3)	0.156	0.154	0.062	0.066	0.069	0.076	0.078	0.154	0.059	0.053	0.055

[A] Reference conditions are 32.02 F and 0.089 psia

Exhibit 5-34. Case PNGFC4A – Advanced Pressurized NGFC Plant without CCS – Material and Energy Balances

Carbon Balance

Carbon In		Carbon Out	
kg/hr(lb/hr)		kg/hr(lb/hr)	
NG	45,201 (99,651)	Stack Gas	45,425 (100,145)
Air (CO2)	226 (498)		
		Convergence Tolerance	2 (4)
Total	45,427 (100,149)	Total	45,427 (100,149)

Sulfur Balance

Sulfur In		Sulfur Out	
kg/hr(lb/hr)		kg/hr(lb/hr)	
NGIN	0 (0)	Elemental Sulfur	0 (0)
		Polishing Sorbent	0 (0)
		Convergence Tolerance	0 (0)
Total	0 (0)	Total	0 (0)

Energy Balance

	HHV	Sensible + Latent	Power	Total
Heat In GJ/hr (MMBtu/hr)				
NG	3,282.28 (3,111.00)	2.2 (2.1)		3,284.5 (3,113.1)
Fuel cell Air		56.2 (53.2)		56.2 (53.2)
Auxiliary Power			257.3 (243.9)	257.3 (243.9)
TOTAL	**3,282 (3,111)**	**58.3 (55.3)**	**257.3 (243.9)**	**3,597.9 (3,410.2)**
Heat Out GJ/hr (MMBtu/hr)				
Stack Flue Gas		620.9 (588.5)		620.85 (588.46)
Process Losses**		337.9 (320.2)		337.88 (320.24)
Difference***		41.8 (39.6)		41.83 (39.65)
Power			2,597.4 (2,461.8)	2,597.4 (2,461.8)
TOTAL	**0.0 (0.0)**	**1,000.6 (948.3)**	**2,597.4 (2,461.8)**	**3,597.9 (3,410.2)**

* Includes ASU compressor intercoolers & CO2 compressor intercoolers
** Includes accounting of losses such as inverter, transformer, generator, and motor losses
*** Calculated by difference to close the energy balance

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)
Condenser Makeup	**0.0 (5)**	**0.0 (0)**	**0.0 (5)**	**0.0 (0)**	**0.0 (05)**
Reformer Steam	0.0 (0)	0.0 (0)	0.0 (0)		
BFW Makeup	0.0 (5)	0.0 (0)	0.0 (5)		
Cooling Tower	**2.2 (591)**	**0.00 (0)**	**2.2 (591)**	**0.5 (133)**	**1.7 (458)**
0	0.0 (0)	0.00 (0)	0.00 (0)		
Total	**2.3 (596)**	**0.00 (0)**	**2.3 (596)**	**0.5 (133)**	**1.8 (463)**

Emissions

	kg/GJ (lb/10^6Btu)	Tonne/year (tons/year)	kg/MWh (lb/MWh)
SO2	0 (0)	0 (0)	0 (0)
NOx	0 (0)	0 (0)	0 (0)
Particulate	0 (0)	0 (0)	0 (0)
Hg	0 (0)	0 (0)	0 (0)
CO2	52415 (121917)	1,124,306 (1,239,335)	209 (461)

Exhibit 5-35. Case PNGFC4A – Advanced Pressurized NGFC Plant without CCS – Heat and Material Balance Diagram – ASU, ATR, and Power Island

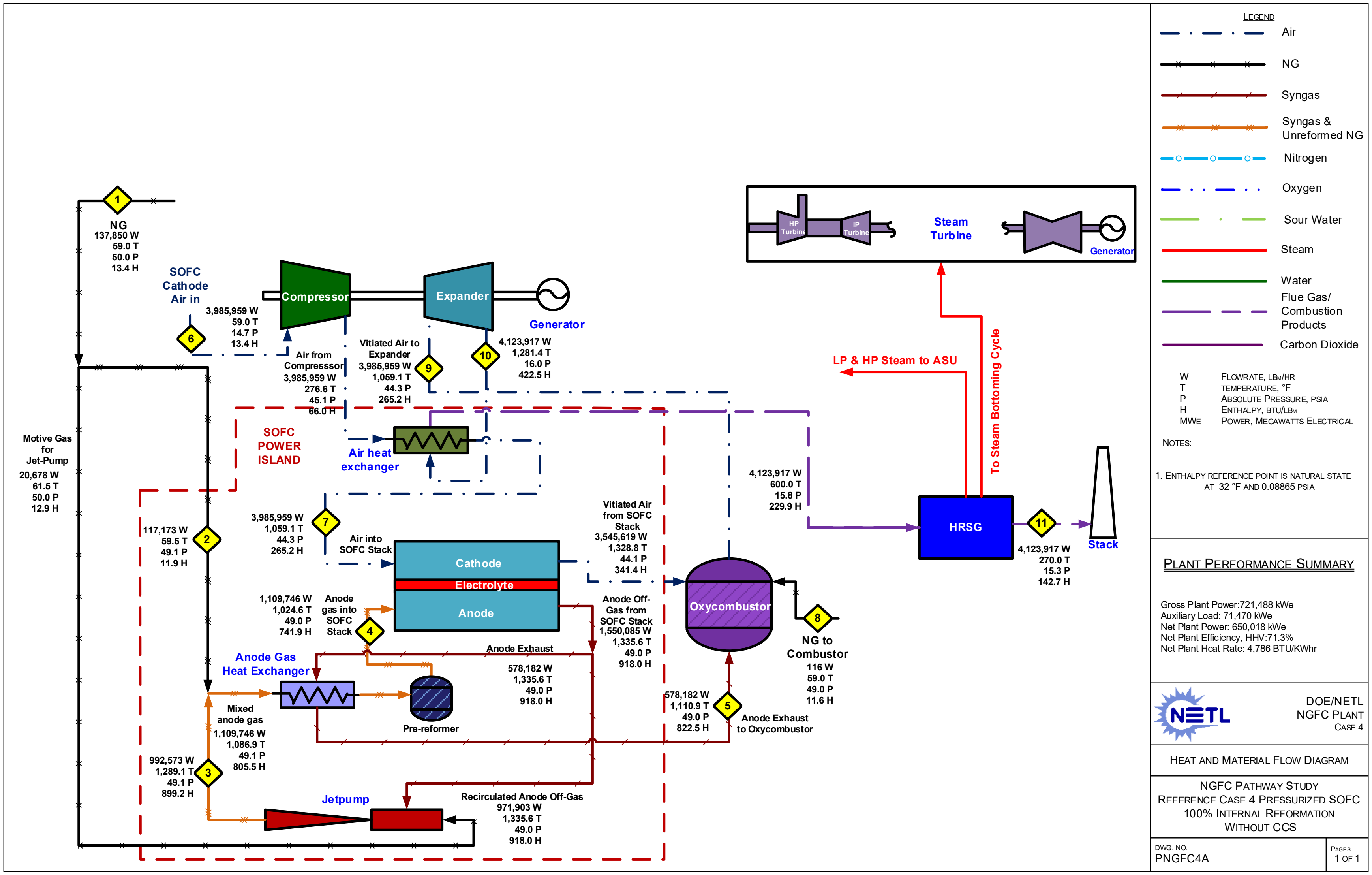


Exhibit 5-36. Case PNGFC4B – Advanced Pressurized NGFC Plant with CCS – Capital Costs

Cost Component	Cost ($1000)	Specific Cost ($/kWe AC)
	2018$	2018$
SOFC Power Island		
SOFC Module		
SOFC Stack	123,634	190
Container	16,689	26
Insulation	2,473	4
Module Assembly	6,182	10
Air distribution	6,182	10
Fuel distribution	6,182	10
Pre-reformer	6,182	10
Module Current Collectors	3,091	5
Module I&C	3,091	5
Inverter	42,035	65
Total SOFC Module with 10 % Extra Installed Area	215,740	332
NG EXPANDER	0	0
SOFC BOP		
Desulfurization System	1,742	3
Cathode Air Blower	8,016	12
Cathode Expander	6,023	9
Cathode Heat Exchanger	19,406	30
Anode Recycle Blower	717	1
Anode Heat Exchanger	5,017	8
Oxy-Combustor	16,592	26
Oxy-Combustor Expander	6,223	10
Air, Exhaust, Fuel Flow Piping system	3,498	5
Section and Overall Assembly	1,749	3
Section I&C	875	1
Total SOFC BOP	69,857	107
TOTAL SOFC POWER ISLAND	285,597	439
ASU	74,135	114
AUTOTHERMAL REFORMER and Natural Gas Preheater	**0**	0
STEAM CYCLE		
HRSG, Ducting, and Stack	26,998	42
Steam Power System	35,480	55
Feedwater and Miscellaneous BOP systems	63,757	98
TOTAL STEAM CYLCE	126,236	194
CO_2 COMPRESSION & PURIFICATION		
CO_2 Purification	79,641	123
TOTAL CO_2 COMPRESSION & PURIFICATION	79,641	123
COOLING WATER SYSTEM	29,743	46
ACCESSORY ELECTRIC PLANT	90,743	140
INSTRUMENTATION & CONTROL	24,535	38
IMPROVEMENTS TO SITE	29,658	46
BUILDING & STRUCTURES	11,909	18
TOTAL PLANT COST (TPC)	752,196	1157
OWNER'S COSTS		
Preproduction Costs		
6 Months All Labor	5,573	
1 Month Maintenance Materials	841	
1 Month Non-fuel Consumables	299	
25% of 1 Months Fuel Cost at 100% CF	2,628	
2% of TPC	15,044	
Total Preproduction Costs	24,385	
Inventory Capital		
60-day supply of fuel and consumables at 100% CF	507	
0.5% of TPC (spare parts)	3,761	
Total Inventory Capital	4,268	
Initial Cost for Catalyst and Chemicals	828	
Land	300	
Other Owner's Costs	112,829	
Financing Costs	20,309	
TOTAL OWNER'S COSTS	162,920	
TOTAL OVERNIGHT COST (TOC)	915,116	1408
TASC Multiplier	1.093	
TOTAL AS-SPENT COST (TASC)	1,000,222	1539

Exhibit 5-37. Case PNGFC4B – Advanced Pressurized NGFC Plant with CCS – O&M Costs

Case:	**PNGFC4B**				**Cost Base:**	**Apr 2018**
Plant Size (MW, net):	**650**				**Capacity Factor:**	**85%**
Operating & Maintenance Labor						
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:	1.0	
Operating Labor Burden:		30.00	**% of base**	Operator:	4.3	
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:	1.0	
				Lab Techs, etc.:	1.0	
				Total:	**7.3**	
Fixed Operating Costs						
					Annual Cost	
					($)	**($/kW-net)**
				Annual Operating Labor:	$3,200,597	$4.92
				Maintenance Labor:	$5,716,693	$8.79
				Administrative & Support Labor:	$2,229,323	$3.43
				Property Taxes and Insurance:	$15,043,930	$23.14
				Total:	$26,190,543	$40.29
Variable Operating Costs						
					($)	**($/MWh-net)**
				Maintenance Material:	$8,575,040	$1.77
Stack Replacement						
		Life (y)	**$/kW AC**	**$/y per kW**		
SOFC Stack Replacement Cost		7.3	$202	$22.23	$14,451,640	$2.99
Consumables						
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (gal/1000):	0	789	$1.90	$0	$464,909	$0.10
Makeup and Waste Water Treatment Chemicals (lb):	0	5,528	$0.28	$0	$471,637	$0.10
NG Desulfur TDA Adsorbent (lb):	44,002	1067	$6.03	$265,318	$1,996,288	$0.41
ATR Catalyst (m^3):	935	0.6	$601.76	$562,549	$120,030	$0.02
			Subtotal:	$827,867	$3,052,865	$0.63
Waste Disposal						
ATR Catalyst (m^3):	0	0.6	$0.00	$0	$0	$0.00
			Subtotal:	$0	$0	$0.00
			Variable Operating Costs Total:	$827,867	$26,079,544	$5.39
Fuel Cost						
Natural Gas (MMBtu):	0	78,177	$4.42	$0	$107,209,530	$22.15
			Total:	$0	$107,209,530	$22.15

Exhibit 5-38. Case PNGFC4B – Advanced Pressurized NGFC Plant with CCS – Capital Cost Components

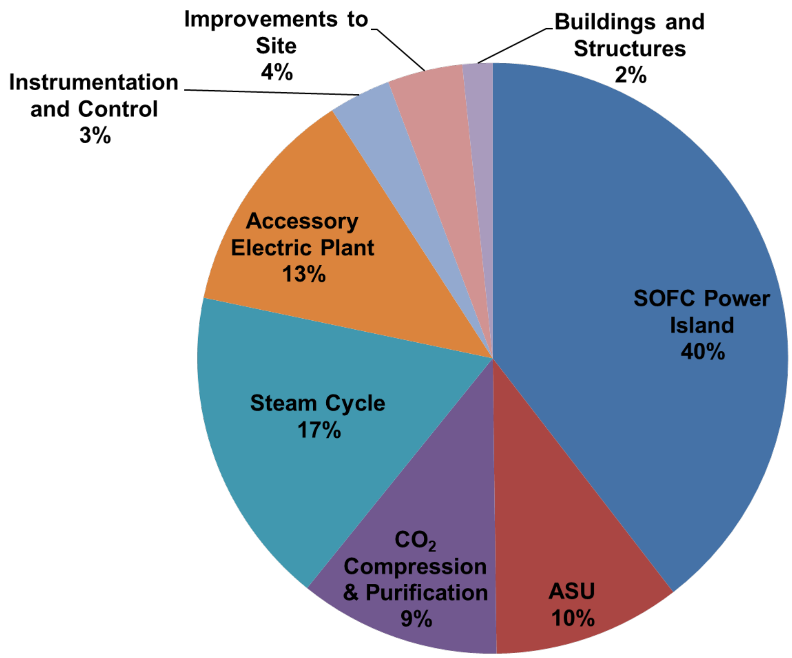


Exhibit 5-39. Case PNGFC4B – Advanced Pressurized NGFC Plant with CCS – BOP Cost Distribution

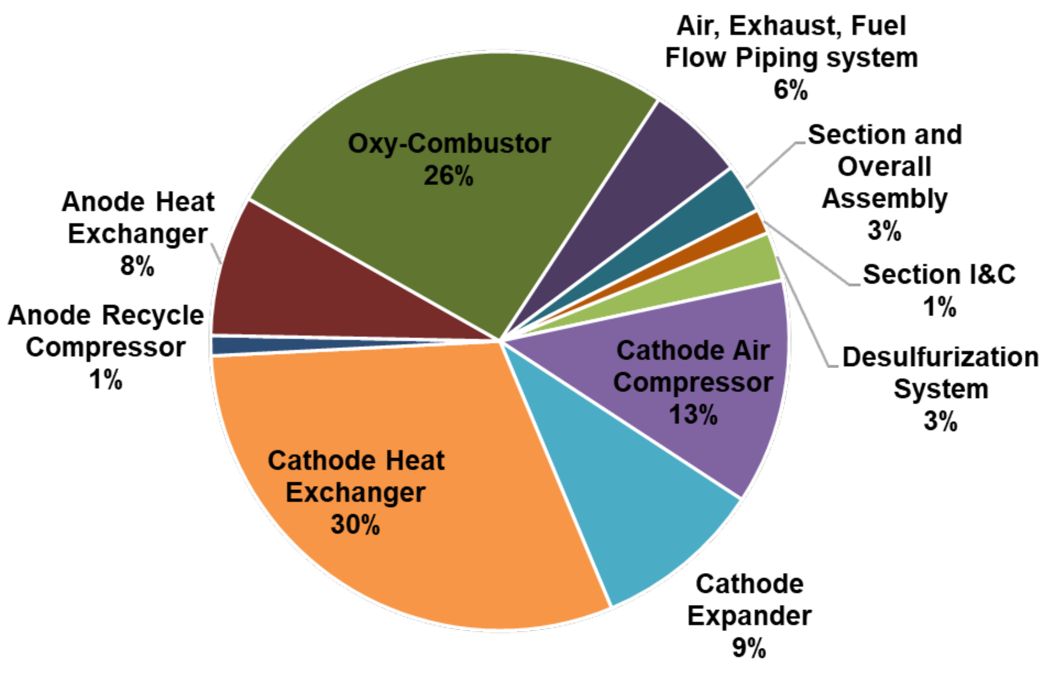


Exhibit 5-40. Case PNGFC4A – Advanced Pressurized NGFC Plant without CCS – Capital Costs

Cost Component	Cost ($1000)	Specific Cost ($/kWe AC)
	2018$	2018$
SOFC Power Island		
SOFC Module		
SOFC Stack	116,569	179
Container	15,736	24
Insulation	2,331	4
Module Assembly	5,828	9
Air distribution	5,828	9
Fuel distribution	5,828	9
Pre-reformer	5,828	9
Module Current Collectors	2,914	4
Module I&C	2,914	4
Inverter	39,633	61
Total SOFC Module with 10 % Extra Installed Area	203,412	313
NG EXPANDER	**0**	**0**
SOFC BOP		
Desulfurization System	1,674	3
Cathode Air Blower	9,748	15
Cathode Expander	15,760	24
Cathode Heat Exchanger	17,109	26
Anode Recycle Blower	678	1
Anode Heat Exchanger	4,749	7
Oxy-Combustor	16,012	25
Air, Exhaust, Fuel Flow Piping system	3,019	5
Section and Overall Assembly	1,510	2
Section I&C	755	1
Total SOFC BOP	71,015	109
TOTAL SOFC POWER ISLAND	274,426	422
ASU	**0**	0
AUTOTHERMAL REFORMER and Natural Gas Preheater	**0**	0
STEAM CYCLE		
HRSG, Ducting, and Stack	22,006	34
Steam Power System	19,611	30
Feedwater and Miscellaneous BOP systems	50,523	78
TOTAL STEAM CYLCE	92,140	142
CO_2 COMPRESSION & PURIFICATION		
CO_2 Purification	0	0
TOTAL CO_2 COMPRESSION & PURIFICATION	**0**	**0**
COOLING WATER SYSTEM	14,892	23
ACCESSORY ELECTRIC PLANT	79,591	122
INSTRUMENTATION & CONTROL	22,864	35
IMPROVEMENTS TO SITE	29,362	45
BUILDING & STRUCTURES	9,971	15
TOTAL PLANT COST (TPC)	523,247	804
OWNER'S COSTS		
Preproduction Costs		
6 Months All Labor	4,130	
1 Month Maintenance Materials	585	
1 Month Non-fuel Consumables	240	
25% of 1 Months Fuel Cost at 100% CF	2,507	
2% of TPC	10,465	
Total Preproduction Costs	17,927	
Inventory Capital		
60-day supply of fuel and consumables at 100% CF	439	
0.5% of TPC (spare parts)	2,616	
Total Inventory Capital	3,055	
Initial Cost for Catalyst and Chemicals	790	
Land	300	
Other Owner's Costs	78,487	
Financing Costs	14,128	
TOTAL OWNER'S COSTS	114,687	
TOTAL OVERNIGHT COST (TOC)	637,933	981
TASC Multiplier	1.093	
TOTAL AS-SPENT COST (TASC)	697,261	1072

Exhibit 5-41. Case PNGFC4A – Advanced Pressurized NGFC Plant without CCS – O&M Costs

Case:	**PNGFC4A**				**Cost Base:**	**Apr 2018**
Plant Size (MW, net):		**650**			**Capacity Factor:**	**85%**
Operating & Maintenance Labor						
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:	1.0	
Operating Labor Burden:		30.00	**% of base**	Operator:	3.3	
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:	1.0	
				Lab Techs, etc.:	1.0	
				Total:	**6.3**	
Fixed Operating Costs						
					Annual Cost	
					($)	**($/kW-net)**
				Annual Operating Labor:	$2,630,628	$4.04
				Maintenance Labor:	$3,976,674	$6.11
				Administrative & Support Labor:	$1,651,826	$2.54
				Property Taxes and Insurance:	$10,464,932	$16.09
				Total:	$18,724,060	$28.78
Variable Operating Costs						
					($)	**($/MWh-net)**
				Maintenance Material:	$5,965,011	$1.23
Stack Replacement						
		Life (y)	**$/kW AC**	**$/y per kW**		
SOFC Stack Replacement Cost		7.3	$212	$23.38	$15,209,844	$3.14
Consumables						
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (gal/1000):	0	364	$1.90	$0	$214,400	$0.04
Makeup and Waste Water Treatment Chemicals (lb):	0	2,549	$0.28	$0	$217,503	$0.04
NG Desulfur TDA Adsorbent (lb):	41,989	1018	$6.03	$253,181	$1,904,971	$0.39
ATR Catalyst (m^3):	892	0.6	$601.76	$536,816	$114,539	$0.02
			Subtotal:	$789,997	$2,451,414	$0.51
Waste Disposal						
ATR Catalyst (m^3):	0	0.6	$0.00	$0	$0	$0.00
			Subtotal:	$0	$0	$0.00
			Variable Operating Costs Total:	$789,997	$23,626,269	$4.88
Fuel Cost						
Natural Gas (MMBtu):	0	74,601	$4.42	$0	$102,305,402	$21.12
			Total:	$0	$102,305,402	$21.12

Exhibit 5-42. Case PNGFC4A – Advanced Pressurized NGFC Plant without CCS – Capital Cost Components

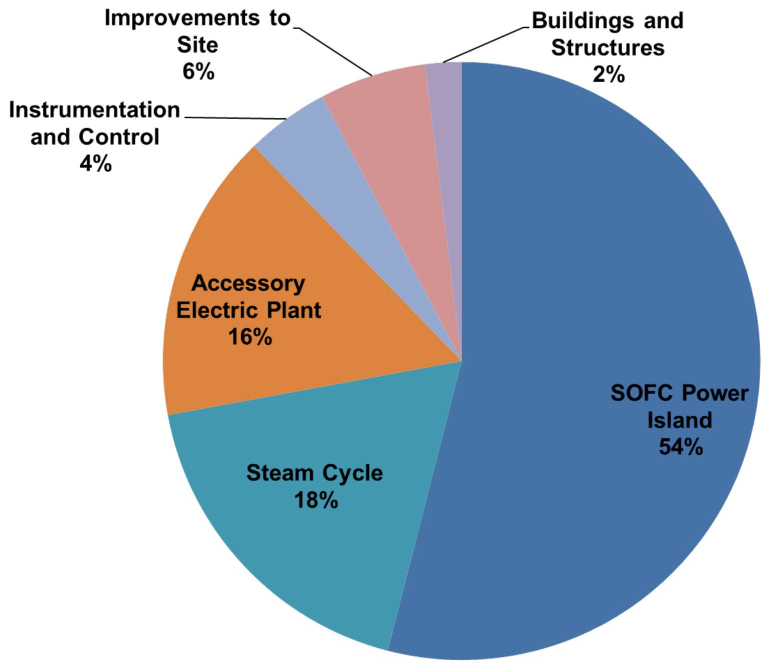


Exhibit 5-43. Case PNGFC4B – Advanced Pressurized NGFC Plant with CCS – BOP Cost Distribution

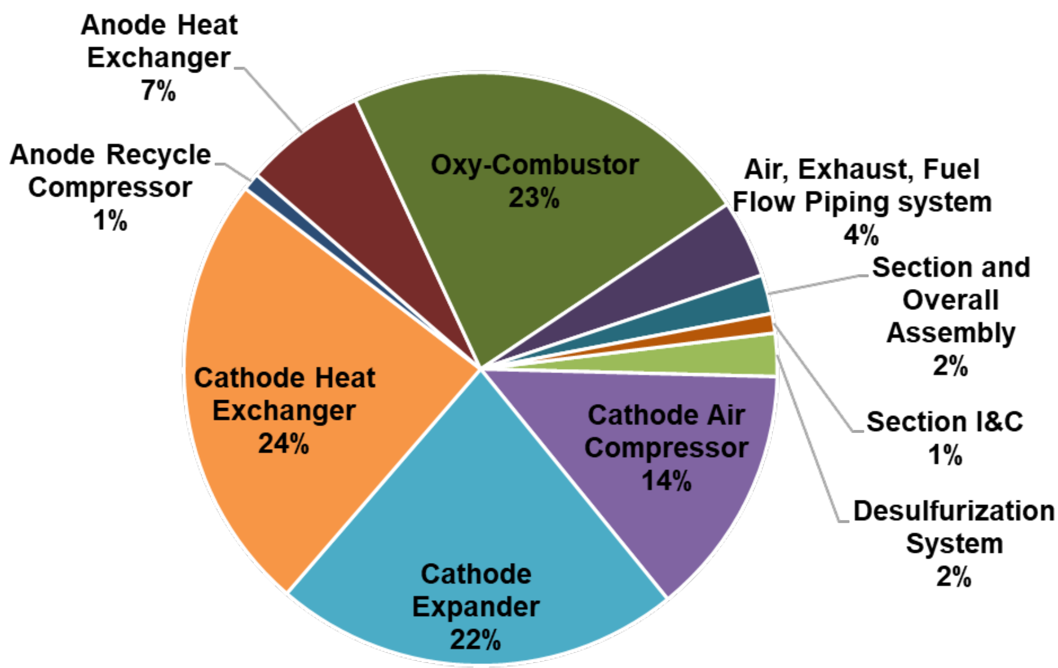


Exhibit 5-44. Case 4 – Advanced Pressurized NGFC Plant with and without CCS – Levelized Cost of Electricity

Levelized Cost of Electricity (2018$/MWh)		
Carbon Capture	**With CCS**	**No CCS**
Component	**$/MWh**	
Variable Costs	27.5	26.0
Fuel Costs	22.1	21.1
Variable O&M Costs	5.4	4.9
Fixed O&M Costs	5.4	3.9
Capital Costs	14.6	10.2
Total LCOE (excluding T&S)	47.6	40.0
T&S	2.6	0.0
Total LCOE (including T&S)	50.2	40.0

5.3 Pathway 2 Results

Over the course of Pathway 2 for the cases with CCS, LCOE decreased by $10.3/MWh and HHV efficiency increased by 7 percentage points as seen in Exhibit 5-45. The results for the Pathway 2 cases without capture are summarized in Exhibit 5-46.

Exhibit 5-45. Pathway 2 – Pressurized NGFC Plants with CCS Results Summary

Case		Case 0	Case 1	Case 2	Case 3	Case 4
Internal Reformation (%)			60		100	
SOFC Degradation Rate (%/1000 h)				0.2		
Fuel Utilization (%)		80		85		
Capacity Factor (%)		80		85		
Inverter Efficiency (%)			97			98
SOFC Stack Cost ($/kW)			225			200
Performance						
SOFC (Parameters)	Current Density (mA/cm^2)	400	400	400	400	400
	Cell Potential (V)	0.904	0.898	0.898	0.868	0.868
	Power Density (mW/cm^2)	362	359	359	347	347
Gross Power (kWe)		**805,089**	**830,082**	**830,082**	**740,186**	**737,413**
Auxiliary Loads (kWe)		**154,900**	**180,096**	**180,096**	**90,225**	**87,342**
Air Separation Unit (kWe)		23,336	20,242	20,242	10,012	7,282
CO_2 Drying, Purification and Compression (CPU) (kWe)		24,458	24,277	24,277	22,183	21,918
Blowers (kWe)		98,711	127,861	127,861	51,081	50,471
Steam Cycle and Miscellaneous (kWe)		8,395	7,715	7,715	6,949	6,887
Net Power (kWe)		**650,189**	**649,987**	**649,987**	**649,962**	**650,071**
NG Flowrate (lb/h)		161,140	159,945	159,945	146,200	144,458
Net Electric Efficiency, HHV (%)		**61.1**	**61.5**	**61.5**	**67.3**	**68.1**
Net Plant Heat Rate, HHV (Btu/kWh)		5,588	5,549	5,549	5,072	5,011
CO_2 Capture rate (%)		**97.7**	**97.7**	**97.7**	**97.9**	**97.9**
CO_2 Captured (tonnes per year)		1,324,217	1,314,654	1,396,819	1,279,612	1,264,343
CO_2 Emissions (lb/MWhgross)		**14.2**	**14.5**	**14.5**	**11.6**	**11.5**
CO_2 Emissions (lb/MWhnet)		17.6	18.5	18.5	13.2	13.1
Raw Water Consumption (gpm/MWnet)		1.88	1.55	1.55	1.35	1.34
Cost						
Total Plant Cost (TPC) (1000$)		922,304	927,010	927,010	757,361	739,234
Total Overnight Cost (TOC) (1000$)		1,125,577	1,131,492	1,131,428	924,124	902,154
Total As-Spent Cost (TASC) (1000$)		1,250,355	1,258,432	1,258,363	1,024,360	1,000,222
Levelized Cost of Electricity ($/MWh)						
Variable Costs		31.2	31.0	30.7	28.2	27.5
Fuel Costs		24.7	24.5	24.5	22.4	22.1
Variable O&M Costs		6.5	6.5	6.2	5.8	5.4
Fixed O&M Costs		7.0	7.0	6.6	5.5	5.4
Capital Costs		19.4	19.5	18.4	15.0	14.6
Total LCOE (excluding T&S)		**57.6**	**57.6**	**55.7**	**48.7**	**47.6**
T&S		2.9	2.9	2.9	2.6	2.6
Total LCOE (including T&S)		**60.5**	**60.5**	**58.6**	**51.3**	**50.2**

Exhibit 5-46. Pathway 2 – Pressurized NGFC Plants without CCS Results Summary

<table>
<tr><th colspan="2">Case</th><th>Case 0</th><th>Case 1</th><th>Case 2</th><th>Case 3</th><th>Case 4</th></tr>
<tr><td colspan="2">Internal Reformation (%)</td><td colspan="3">60</td><td colspan="2">100</td></tr>
<tr><td colspan="2">SOFC Degradation Rate (%/1000 h)</td><td colspan="5">0.2</td></tr>
<tr><td colspan="2">Fuel Utilization (%)</td><td>80</td><td colspan="4">85</td></tr>
<tr><td colspan="2">Capacity Factor (%)</td><td colspan="2">80</td><td colspan="3">85</td></tr>
<tr><td colspan="2">Inverter Efficiency (%)</td><td colspan="4">97</td><td>98</td></tr>
<tr><td colspan="2">SOFC Stack Cost ($/kW)</td><td colspan="4">225</td><td>200</td></tr>
<tr><td colspan="7">Performance</td></tr>
<tr><td rowspan="3">SOFC (Parameters)</td><td>Current Density (mA/cm^2)</td><td>400</td><td>400</td><td>400</td><td>400</td><td>400</td></tr>
<tr><td>Cell Potential (V)</td><td>0.852</td><td>0.845</td><td>0.845</td><td>0.825</td><td>0.825</td></tr>
<tr><td>Power Density (mW/cm^2)</td><td>341</td><td>338</td><td>338</td><td>330</td><td>330</td></tr>
<tr><td colspan="2">Gross Power (kWe)</td><td>**783,508**</td><td>**794,567**</td><td>**794,567**</td><td>**722,228**</td><td>**721,488**</td></tr>
<tr><td colspan="2">Auxiliary Loads (kWe)</td><td>133,384</td><td>144,518</td><td>144,518</td><td>71,573</td><td>70,979</td></tr>
<tr><td colspan="2">*Air Separation Unit (kWe)*</td><td>16,980</td><td>15,330</td><td>15,330</td><td>0</td><td>0</td></tr>
<tr><td colspan="2">*CO_2 Drying, Purification and Compression (CPU) (kWe)*</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td colspan="2">*Blowers (kWe)*</td><td>110,856</td><td>123,320</td><td>123,320</td><td>67,325</td><td>66,744</td></tr>
<tr><td colspan="2">*Steam Cycle and Miscellaneous (kWe)*</td><td>5,548</td><td>5,868</td><td>5,868</td><td>4,248</td><td>4,235</td></tr>
<tr><td colspan="2">Net Power (kWe)</td><td>650,124</td><td>650,049</td><td>650,049</td><td>650,655</td><td>650,509</td></tr>
<tr><td colspan="2">NG Flowrate (lb/h)</td><td>132,950</td><td>120,055</td><td>120,055</td><td>139,050</td><td>137,850</td></tr>
<tr><td colspan="2">Net Electric Efficiency, HHV (%)</td><td>**61.4**</td><td>**59.9**</td><td>**59.9**</td><td>**70.7**</td><td>**71.3**</td></tr>
<tr><td colspan="2">Net Plant Heat Rate, HHV (Btu/kWh)</td><td>5,558</td><td>5,695</td><td>5,695</td><td>4,823</td><td>4,782</td></tr>
<tr><td colspan="2">CO_2 Capture rate (%)</td><td>0.0</td><td>0.0</td><td>0.0</td><td>0.0</td><td>0.0</td></tr>
<tr><td colspan="2">CO_2 Captured (tonnes per year)</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td colspan="2">CO_2 Emissions (lb/MWhgross)</td><td>**494.6**</td><td>**500.1**</td><td>**500.1**</td><td>**464.9**</td><td>**461.4**</td></tr>
<tr><td colspan="2">CO_2 Emissions (lb/MWhnet)</td><td>596.2</td><td>611.3</td><td>611.3</td><td>516.5</td><td>512.1</td></tr>
<tr><td colspan="2">Raw Water Consumption (gpm/MWnet)</td><td>1.29</td><td>1.39</td><td>1.39</td><td>0.72</td><td>0.71</td></tr>
<tr><td colspan="7">Cost</td></tr>
<tr><td colspan="2">Total Plant Cost (TPC) (1000$)</td><td>618,812</td><td>629,499</td><td>629,499</td><td>520,503</td><td>506,808</td></tr>
<tr><td colspan="2">Total Overnight Cost (TOC) (1000$)</td><td>759,605</td><td>772,409</td><td>772,365</td><td>638,092</td><td>621,494</td></tr>
<tr><td colspan="2">Total As-Spent Cost (TASC) (1000$)</td><td>856,504</td><td>872,450</td><td>872,402</td><td>715,509</td><td>697,261</td></tr>
<tr><td colspan="7">Levelized Cost of Electricity ($/MWh)</td></tr>
<tr><td colspan="2">*Variable Costs*</td><td>26.2</td><td>24.3</td><td>23.9</td><td>26.6</td><td>26.0</td></tr>
<tr><td colspan="2">Fuel Costs</td><td>20.4</td><td>18.4</td><td>18.4</td><td>21.3</td><td>21.1</td></tr>
<tr><td colspan="2">Variable O&M Costs</td><td>5.8</td><td>5.8</td><td>5.5</td><td>5.3</td><td>4.9</td></tr>
<tr><td colspan="2">*Fixed O&M Costs*</td><td>4.9</td><td>5.0</td><td>4.7</td><td>3.9</td><td>3.9</td></tr>
<tr><td colspan="2">*Capital Costs*</td><td>13.3</td><td>13.5</td><td>12.7</td><td>10.4</td><td>10.2</td></tr>
<tr><td colspan="2">*Total LCOE*</td><td>44.4</td><td>42.8</td><td>41.4</td><td>41.0</td><td>40.0</td></tr>
</table>

6 DISCUSSION OF PATHWAY RESULTS

The impact of the technological developments and the cost reduction assumptions considered in the present pathway studies on the performance and cost of an NGFC plant are discussed in this section. The results from the various cases are consolidated to provide guidance to the fuel cell R&D program at NETL. Further, the NGFC system performance and costs are compared with conventional heat-engine technologies, specifically, the supercritical (SC) pulverized coal (PC) and F-class NGCC plants from the Baseline study [1], J-class NGCC plants [25], NG-based supercritical CO_2 (sCO_2) systems [26], [27] wherever applicable.

System Performance and Efficiency

The efficiencies of the various NGFC plants considered in the two pathways are shown in Exhibit 6-1. For an atmospheric NGFC plant without CCS, the HHV efficiency varies from a value of 61.6 percent for the reference plant to a value of 68.8 percent for the Case 4 advanced plant with complete internal reformation. Inclusion of CCS imposes an efficiency penalty of ≈3–3.5 percentage points. Pressurization generally results in an increase in efficiency over the atmospheric NGFC cases except for the Reference Case and Case 1 without CCS due to the additional injection of natural gas required to get the desired turbine inlet temperature in these pressurized cases. The atmospheric NGFC plant with VGR (and with CCS) results in an efficiency value of 69.3 percent, which is higher than most of the plants, including the plants without CCS, and is second only to the Case 4 pressurized system without CCS. The VGR concept enables operating at a fuel utilization of 97.5 percent while the in-stack utilization is maintained below 60 percent. The VGR configuration enables an NGFC plant with CCS that is ≈4 percentage points higher than a comparable atmospheric NGFC plant without VGR.

As expected with the underlying SOFC technology advantages, the NGFC efficiencies are significantly higher than the values for comparable conventional technologies including the SC PC and F-class NGCC plants with CCS [1] shown in the Exhibit 6-1. The reference atmospheric NGFC plant without CCS eclipses the system performance of both an advanced H-class NGCC plant and an NG-based Allam-cycle Supercritical CO_2 plant (SCO_2), whose HHV efficiencies are between 53 and 54 percent, [25], [26] by over 7 percentage points. The efficiency advantage relative to the conventional plants increases to over 20 percentage points with the advances in NGFC technology (Case 4).

The technology advancement from 60 percent internal reformation to 100 percent internal reformation has the highest influence on the system efficiency in the case of plants without CCS as indicated by the waterfall plot in Exhibit 6-2. The absence of cathode gas recirculation in the pressurized cases amplifies the beneficial impact of the increase in internal reformation percentage on the system efficiency due a substantial reduction in the process airflow. For atmospheric NGFC plants with CCS, the benefits of VGR significantly outweigh benefits from other technological advancements as shown in Exhibit 6-3. The BOP enhancements resulted only in modest gains since the ASU parasitic is lower for the 100 percent internal reformation cases (Case 4 for all the configurations), which have significantly lower O_2 requirement relative to Case 1 and Case 2 plants due to the elimination of the ATR.

Exhibit 6-1. HHV Efficiency of the NGFC Plant Configurations

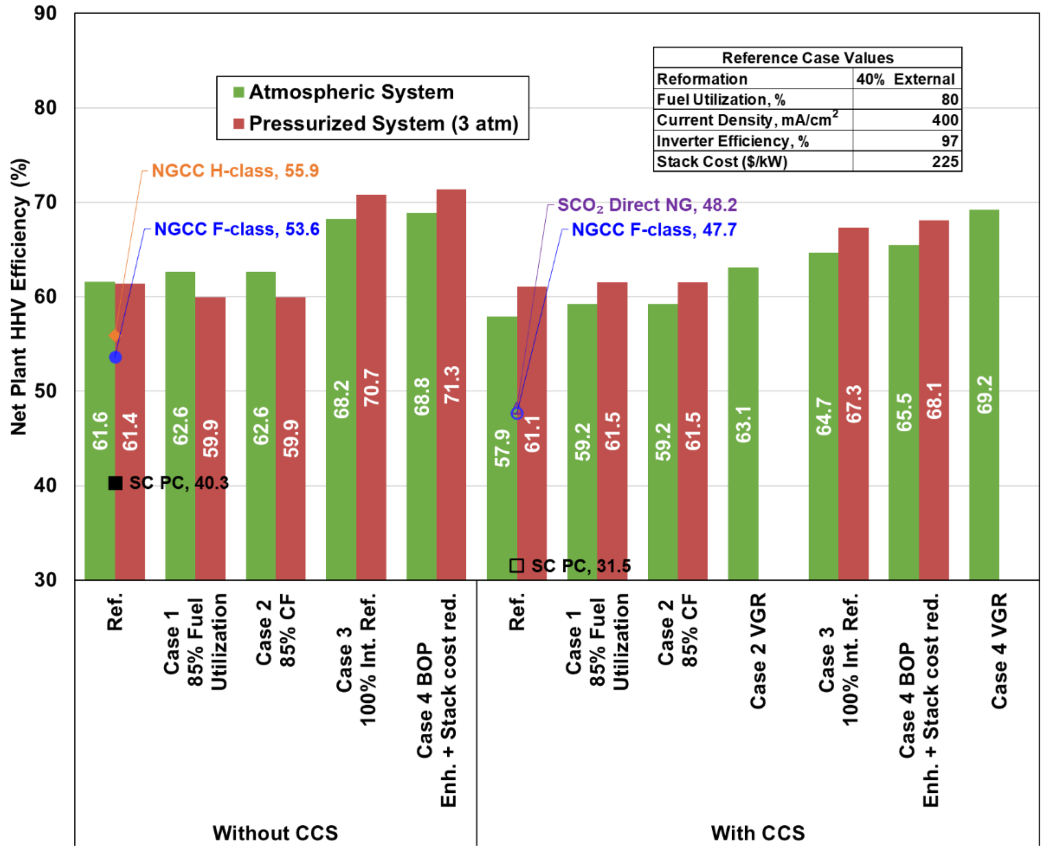


Exhibit 6-2. Technology Developments and Efficiency Improvements for NGFC Plants without CCS

Reference Case Values	
Reformation	40% External
Fuel Utilization, %	80
Current Density, mA/cm^2	400
Inverter Efficiency, %	97
Stack Cost ($/kW)	225

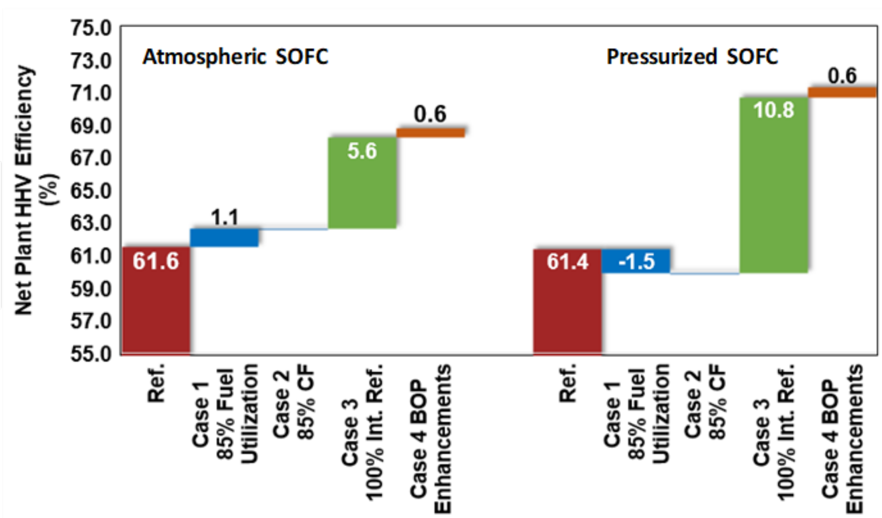
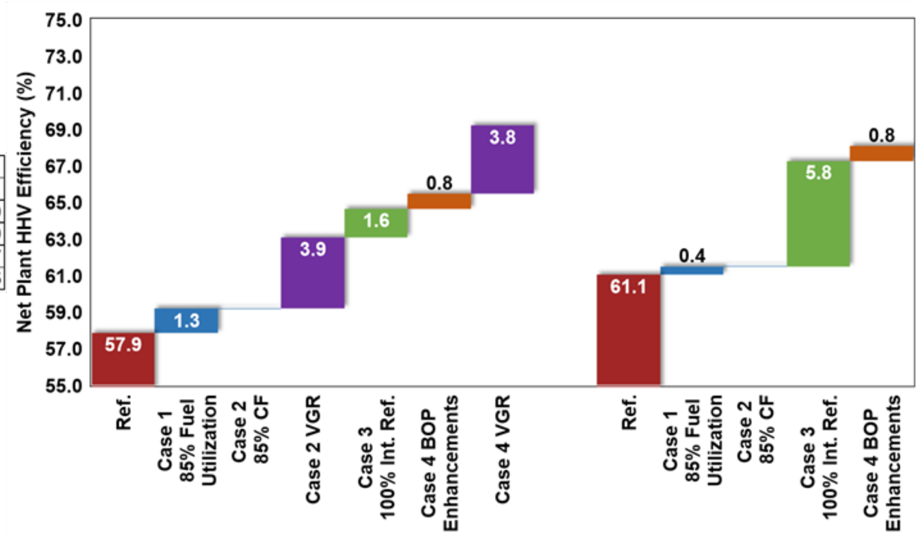


Exhibit 6-3. Technology Developments and Efficiency Improvements for NGFC Plants with CCS

Reference Case Values	
Reformation	40% External
Fuel Utilization, %	80
Current Density, mA/cm^2	400
Inverter Efficiency, %	97
Stack Cost ($/kW)	225



6.1 NGFC Plant Costs

The 100 percent internal reformation case results in the lowest TPC for the NGFC plants without CCS, as shown in Exhibit 6-4, attributable to the high plant efficiency and to the elimination of the external reformer. The pressurized configurations generally result in a higher TPC relative to the atmospheric systems primarily due to the increased enclosure (pressure vessel) costs, which negate any efficiency advantages of pressurization on the capital costs. The TPC of NGFC plants with CCS are considerably lower than the TPC of other technologies with CCS while the NGFC plant costs without CCS are competitive even with F-Class NGCC units.

The LCOE (without T&S) of the reference NGFC plant with CCS is lower by ≈$14/MWh than the LCOE of an F-class NGCC system with CCS as shown in Exhibit 6-5.[i] The advanced NGFC plants with CCS are projected to result in LCOEs that are ≈$23–60/MWh lower than the LCOE of all the other technologies. In the case of systems without CCS, the NGFC systems are economically competitive with the F-class NGCCs. The VGR configuration substantially mitigates the LCOE penalty of CCS (by nearly half). The components of the LCOE of NGFC systems with and without T&S costs are shown in Exhibit 6-6 and Exhibit 6-7 respectively, which show the reduction in capital and variable O&M (fuel) components along the pathways.

The difference in LCOEs between an NGFC plant with and without CCS is significantly smaller than the corresponding penalties for conventional technologies. The SOFC is essentially an oxyfuel reactor, and along with the sealed design generally used to separate the air and fuel, it forms a highly effective inherent carbon separator (that produces power); it produces a concentrated CO_2 effluent that is ready for CCS with minimal incremental costs. This underscores the leading role played by SOFC-based systems in meeting NETL's environmental vision.

[i] The LCOE for H-class have been estimated to be ~$36/MWh in the study by Uysal [25]. However, these were not included on the charts since the costs are based on a 1 GW plant capacity and the financial parameters used are different than the baseline studies.

Exhibit 6-4. Comparison of the Total Plant Cost of the NGFC Plant Configurations

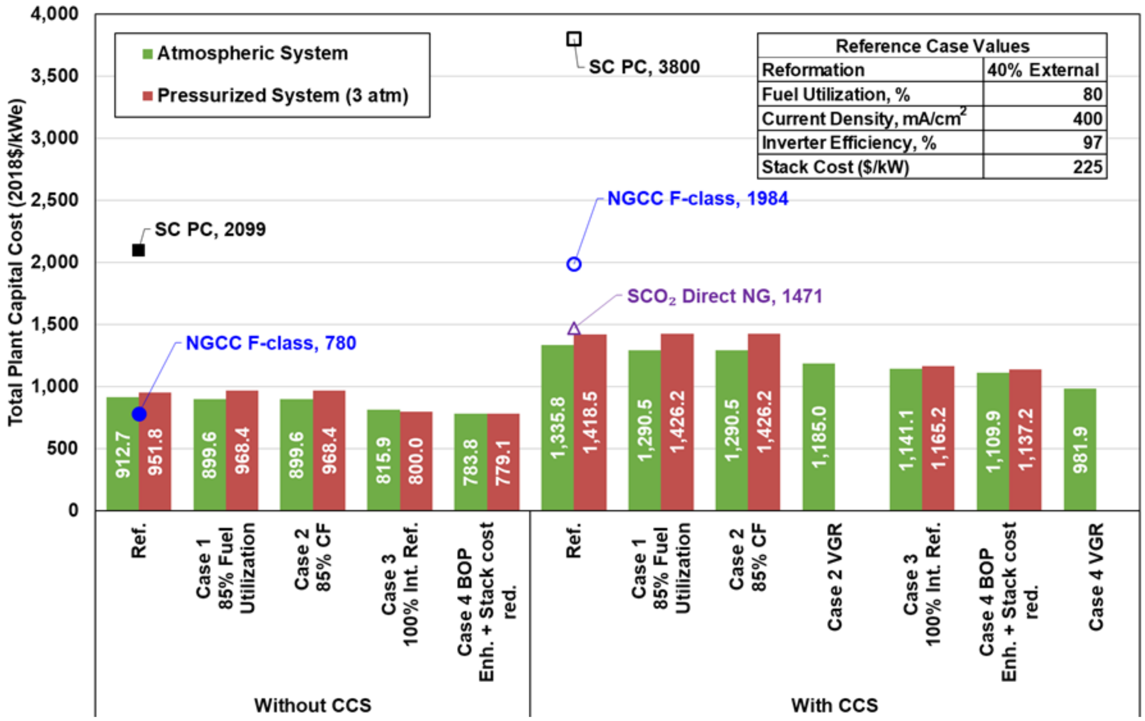


Exhibit 6-5. Comparison of the LCOE (without T&S) of the NGFC Plant Configuration

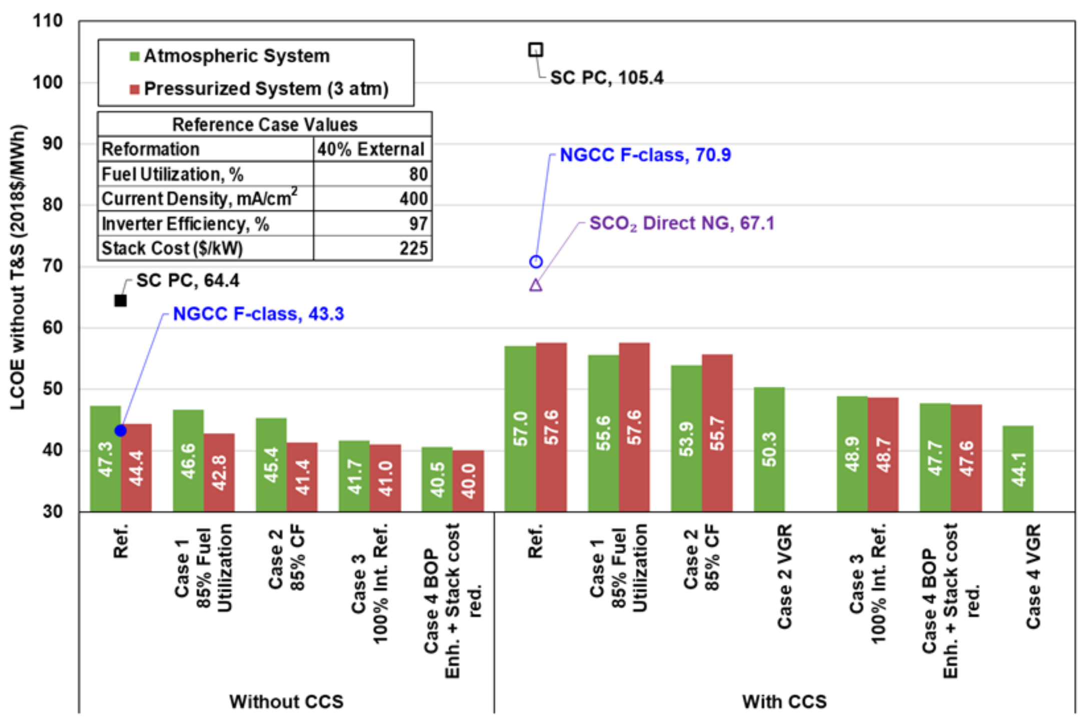


Exhibit 6-6. LCOE Breakdown (with T&S) of the NGFC Plant Configurations

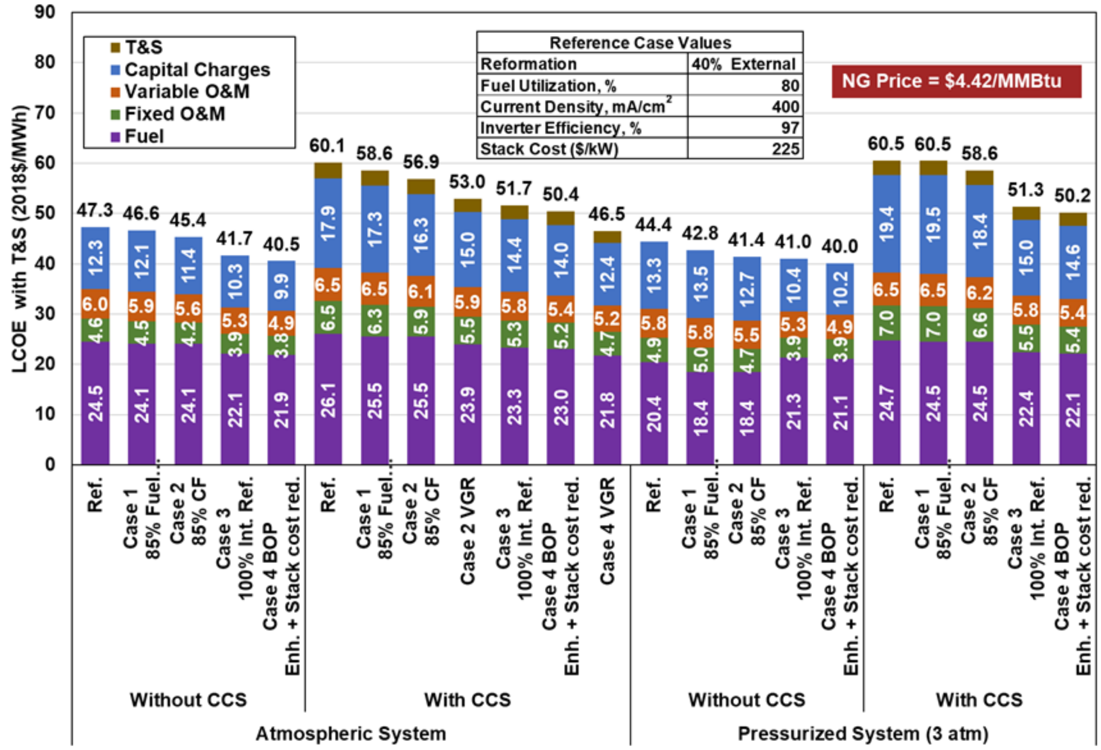
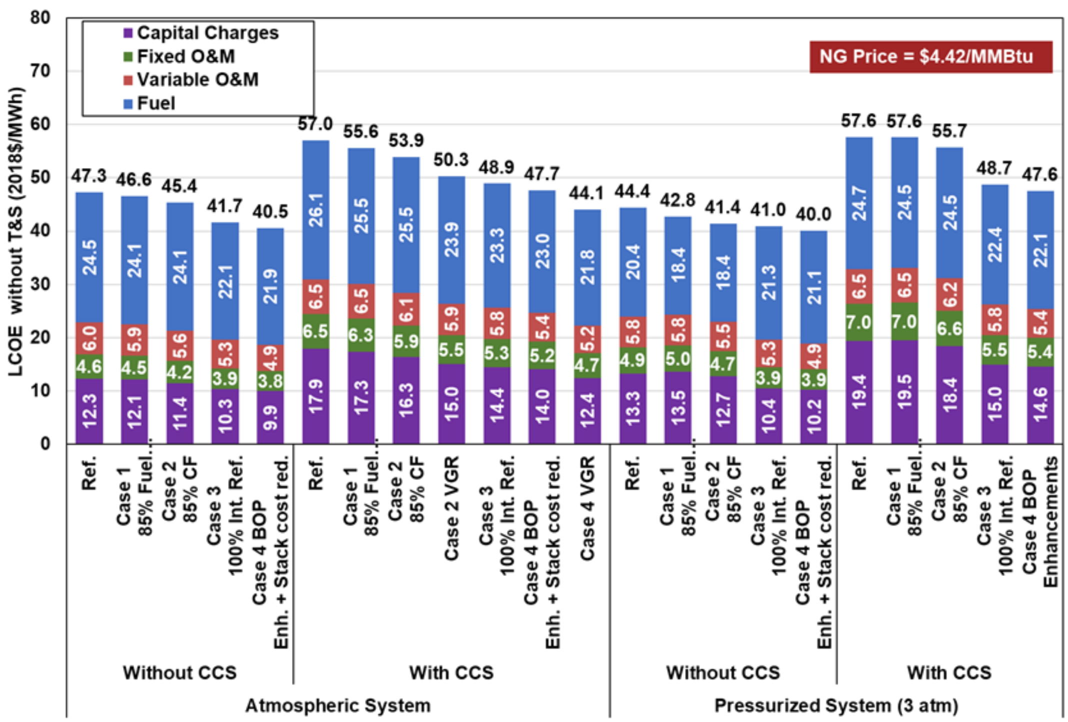


Exhibit 6-7. Comparison of the LCOE (without T&S) of the NGFC Plant Configurations



The progression of LCOE with pathway technology developments, cost reductions, and increased availability are shown in Exhibit 6-8 and Exhibit 6-9 for the NGFC plants without and with CCS respectively. In the case of NGFC plants without CCS, the largest reduction in LCOE, ≈\$3.7/MWh, is associated with the technology advancement to enable 100 percent internal reformation. The VGR configurations yields the largest LCOE reduction (≈\$3.6/MWh) for the NGFC plants with CCS. The pathways, which represent practical and realizable steps consistent with the fuel cell program, lead to a NGFC system with capture that has a significantly low LCOE (at a natural gas price of \$4.42/MMBtu) relative to conventional heat-engine based technologies with CCS. The pathways also lead to NGFC plants without CCS that are economically competitive with F-class and J-class NGCC plants.

Although pressurization does not appear to have a significant advantage in the cases analyzed here, pressurized configurations could be found to be attractive as a hybrid system where operational flexibility aspects may be attractive.

Exhibit 6-8. Progression of Plant LCOE (without T&S) along the NGFC Pathway without CCS

Reference Case Values	
Reformation	40% External
Fuel Utilization, %	80
Current Density, mA/cm^2	400
Inverter Efficiency, %	97
Stack Cost (\$/kW)	225

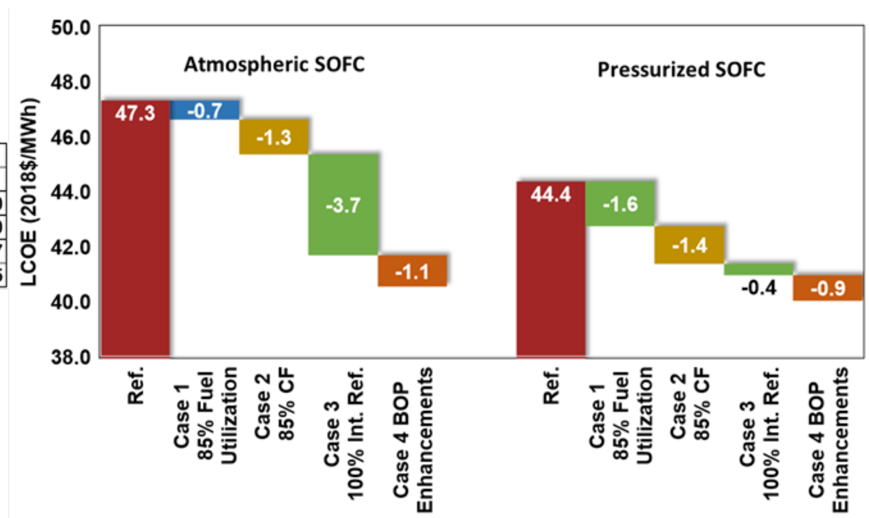
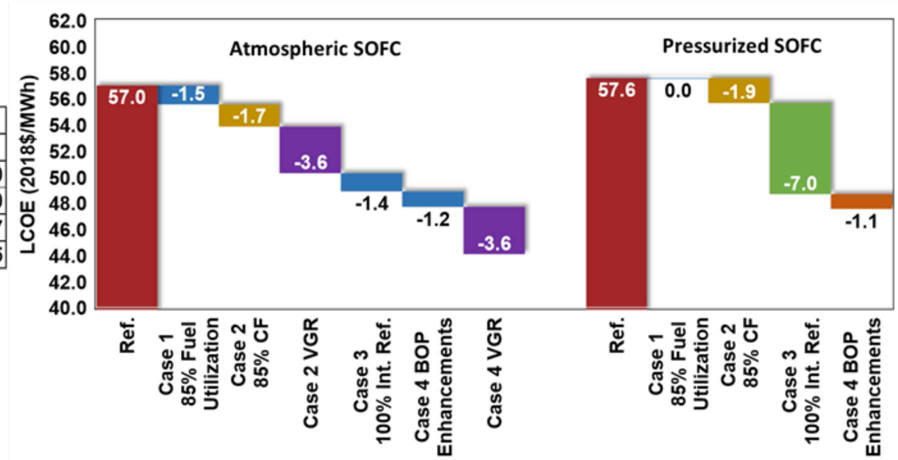


Exhibit 6-9. Progression of Plant LCOE (without T&S) along the NGFC Pathway with CCS

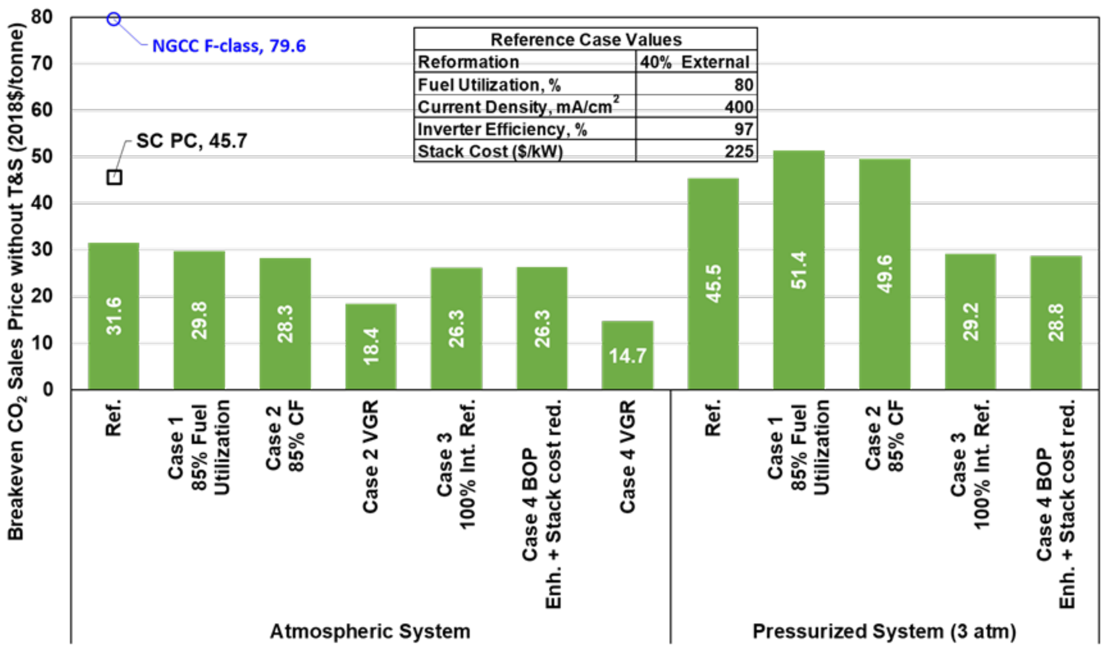
Reference Case Values	
Reformation	40% External
Fuel Utilization, %	80
Current Density, mA/cm^2	400
Inverter Efficiency, %	97
Stack Cost (\$/kW)	225



6.2 Cost of CO_2 Captured

The breakeven CO_2 sales price (the price of CO_2 that is required to pay for the difference in LCOE between a plant with and without CCS) for the pathway NGFC cases are shown in Exhibit 6-10. All the atmospheric NGFC plants and advanced pressurized plants considered herein have a breakeven CO_2 sales price that is well below the $40/tonne of CO_2 generally considered to be an achievable selling price for pure CO_2 for EOR purposes. The NGFC system with the VGR configuration results in a break-even price that is below $15/tonne, which could make this system highly competitive with other CO_2 sources.

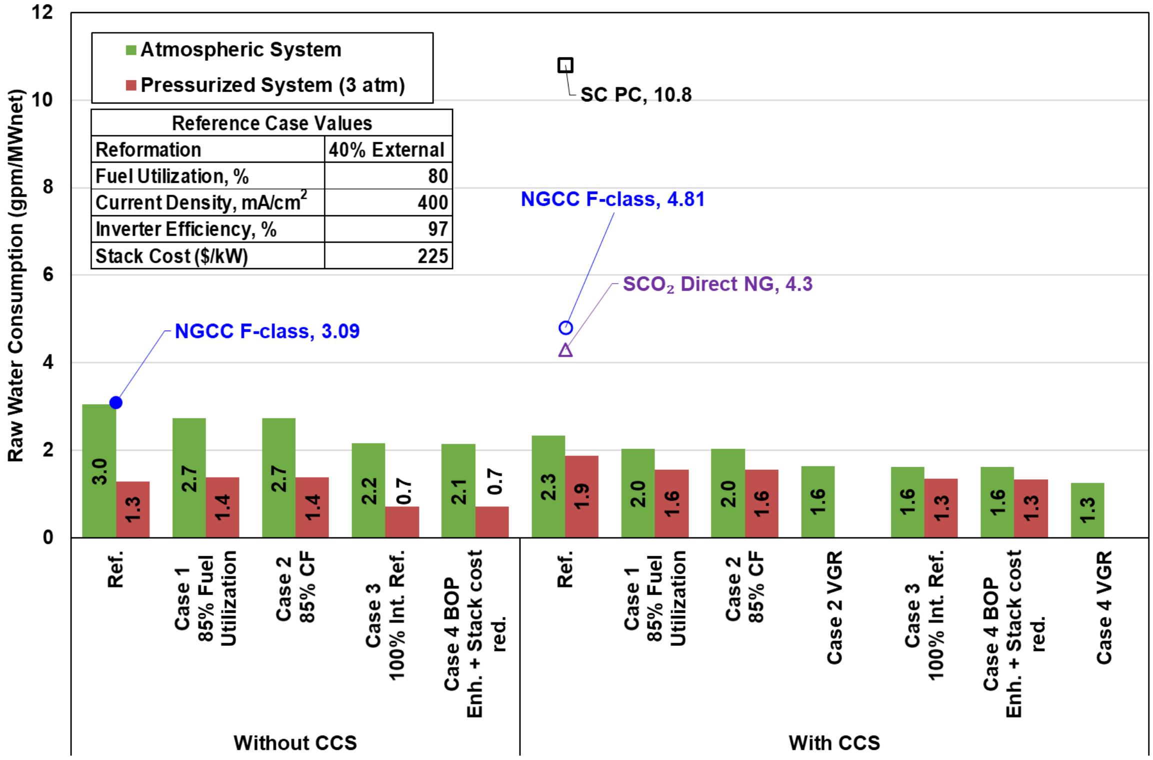
Exhibit 6-10. Break-even Sales Price of CO_2 Captured for the Various NGFC Plant Configurations



6.3 Water Consumption

The NGFC plants result in significantly lower water consumption compared to SC PC and NGCC plants as shown in Exhibit 6-11. The NGFC plant water consumption is dominated by steam-cycle the cooling water make-up requirements. Without the steam bottoming cycle, the advanced NGFC plant Case 3 and Case 4 with 100 percent internal reformation do not require any external steam and can result in a net production of water (not shown in the figure).

Exhibit 6-11. Water Consumption Variation for the Different NGFC Plant Configurations



6.4 Effect of Natural Gas Price

The LCOE of the reference NGFC plant (Case 0) and the best advanced NGFC plant (Case 4 with VGR) with CCS is shown in Exhibit 6-12 as function of natural gas price. The variation of the LCOE of a conventional F-class NGCC plant with CCS is also shown along with the LCOE of an SC PC plant, which does not depend directly on the price of natural gas. While both the NGFC and the NGCC plant LCOEs increase with increase in the price of natural gas, the slope of the dependency is less steep for the for the former (NGFC) relative to the latter (NGCC) due to the higher plant efficiencies. The NGFC plants with CCS show a significant economic advantage relative to other systems at natural gas prices between $2–15/MMBtu. Even at high natural gas prices, the advanced NGFC plant maintain a significant advantage relative to an SC PC plant although IGFC plants may become competitive.

In plants without CCS, there is a natural gas price (≈$8/MMBtu) beyond which the conventional NGFC units overcome the slight LCOE advantage of the NGCC plant at low gas prices as shown in Exhibit 6-13. While the advanced NGFC configuration without CCS is economically advantageous relative to NGCC systems, the SC PC system becomes competitive at natural gas prices > ≈$9/MMBtu.

Exhibit 6-12. Influence of Natural Gas Price on the LCOE (excl. T&S) of NGFC Plants with CCS

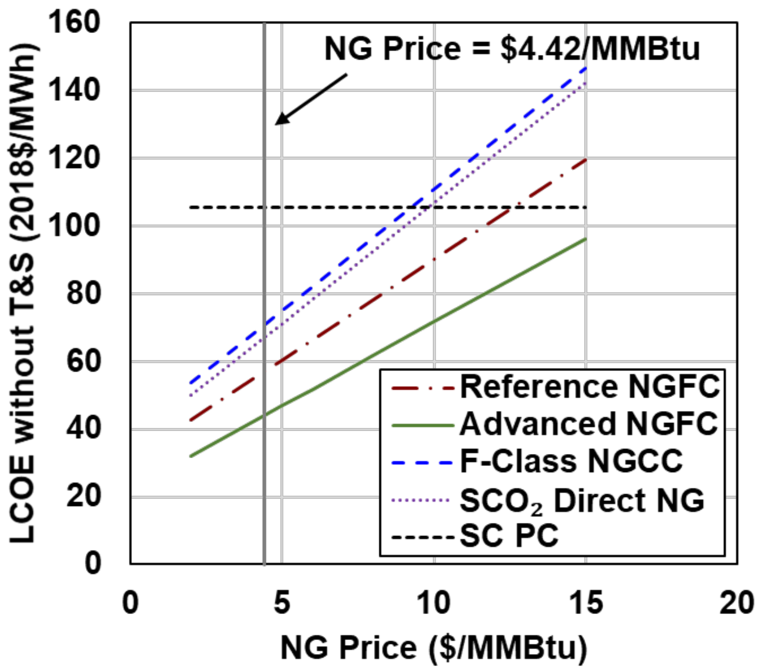
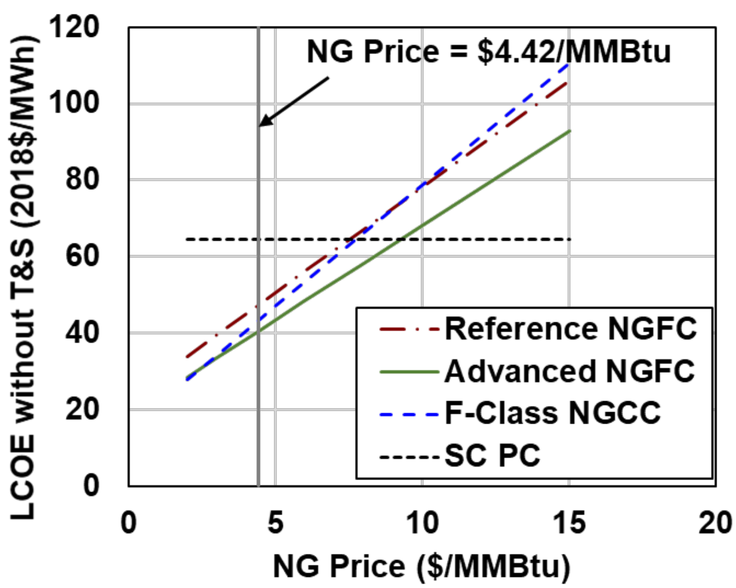


Exhibit 6-13. Influence of Natural Gas Price on the LCOE (excl. T&S) of NGFC Plants without CCS



7 CONCLUSIONS

The performance and costs of potential development pathways for NGFC plant configurations with and without CCS have been investigated. Two pathway scenarios were considered based on the operating pressure of the SOFC. The performance and cost benefits were estimated for a series of projected gains made through the development of advances in the component technologies or improvements in plant costs and availability.

The results for the NGFC pathways were compared with conventional heat-engine based technologies and showcased the potential future benefits of NGFC technology development.

In summary,

- Technology development and cost reduction steps that can cumulatively result in an increase of over 12 percentage points in NGFC plant efficiency accompanied by over 23 percent reduction in the associated LCOE were identified and quantified.
- Development of technologies that enable internal reformation of the natural gas, along with the implementation of the VGR concept for plants with CCS, had the highest impact on the LCOE of the NGFC plant. The advanced NGFC plant based on complete internal reformation of the natural gas and VGR, which has the highest efficiency and lowest LCOE among all the plants considered in this report, fits well within the DOE transformational technology timeframe.
- The advanced NGFC plant with complete internal reformation and VGR has the lowest CO_2 emission footprint and the lowest water consumption relative to any other conventional power generation technology without CCS.
- The LCOE for the NGFC power plant with CCS is attractive compared to the conventional NGCC with CCS. The LCOE of NGFC plants without CCS were also found to be competitive with NGCC technologies. The competitiveness of NGFC without CCS increases as the price of natural gas increases due to the much higher efficiency of the NGFC plants, although higher natural gas prices may tend to favor coal-based plants.
- The results presented in this study are for SOFC systems operating at a nominal current density of 400 mA/cm^2 consistent with today's technology. Operating at higher current densities could potentially reduce the capital costs (since a lower number of SOFCs may be needed to achieve the desired power rating) while increasing production costs due to the concomitant loss of efficiency. The usage of PNNL ROM model enables the evaluation of the trade-off between these costs, which intended to be explored elsewhere as part of sensitivity studies.

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