Fuel Cell Power Model Version 2: Startup Guide, System Designs, and Case Studies

Modeling Electricity, Heat, and Hydrogen Generation from Fuel Cell–Based Distributed Energy Systems

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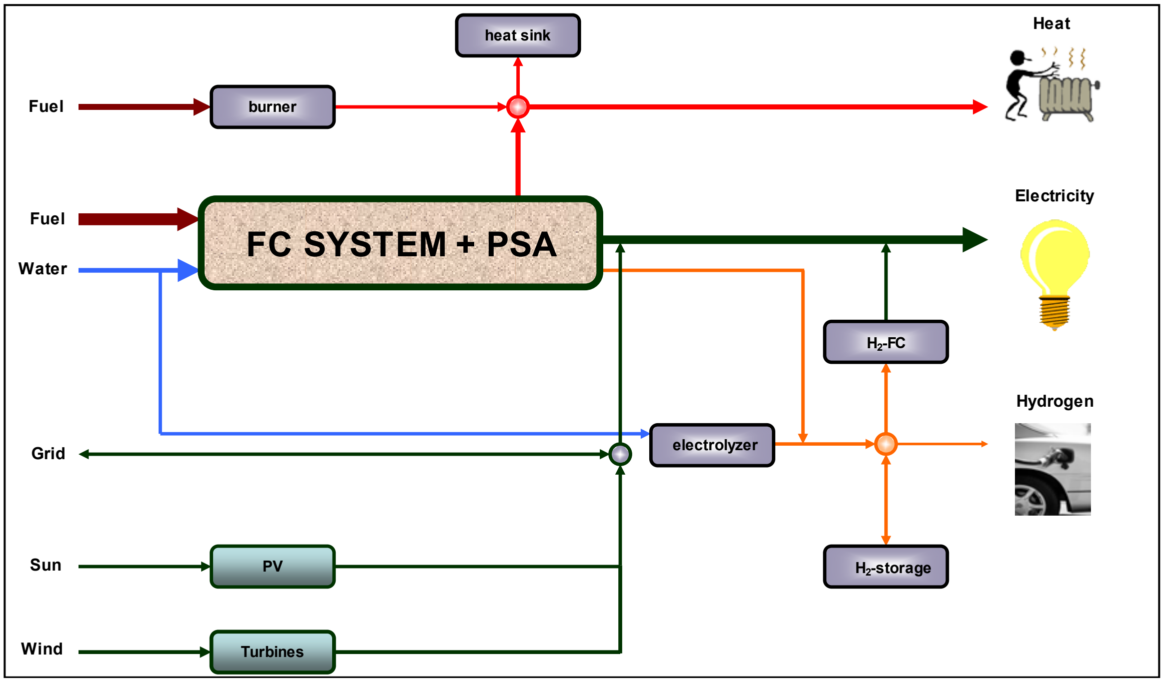
1 Startup Guide

1.1 *Introduction*

The Fuel Cell Power (FCPower) Model is a Microsoft Excel workbook that analyzes the technical and economic aspects of high-temperature fuel cell–based distributed energy systems with the aim of providing consistent, transparent, comparable results. This type of energy system would provide onsite-generated heat and electricity to large end users such as hospitals and office complexes. The hydrogen produced could be used for fueling vehicles or stored for later conversion to electricity.

Schematic of a Fuel Cell–Based Distributed Energy System

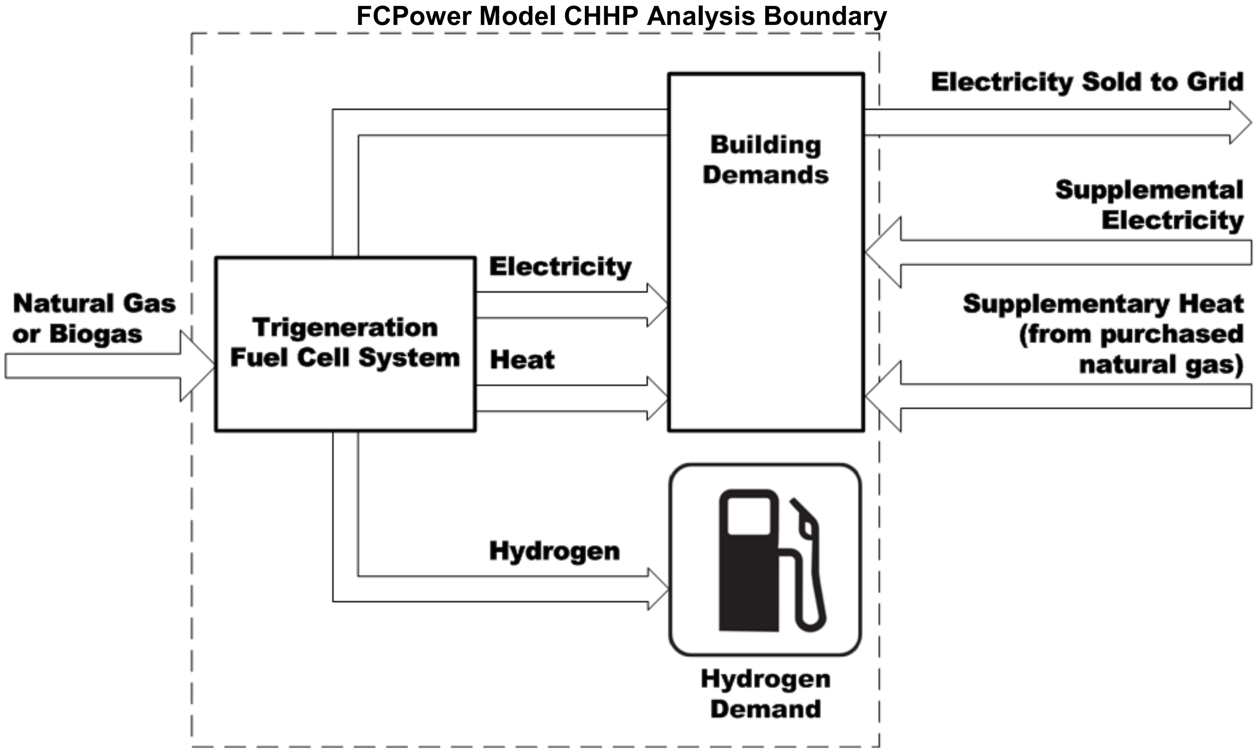


In the FCPower Model, users select which technologies are used in the system—such as hydrogen fuel cells, photovoltaic (PV) panels, and electrolyzers—and define each technology's cost and performance parameters. Users also select fuel costs and demand priority (i.e., whether the system follows electricity or heat demand) and can accept default FCPower Model financial parameters or enter custom parameters. Hourly electricity, heat, and hydrogen demand profiles and renewable energy supply profiles can be entered or selected from databases.

The model uses the inputs, default values and calculations, and a standard discounted cash flow rate of return methodology to determine the cost of delivered energy, with reference to a specified after-tax internal rate of return. It also determines the amount and type of energy input and output and the associated greenhouse gas emissions.

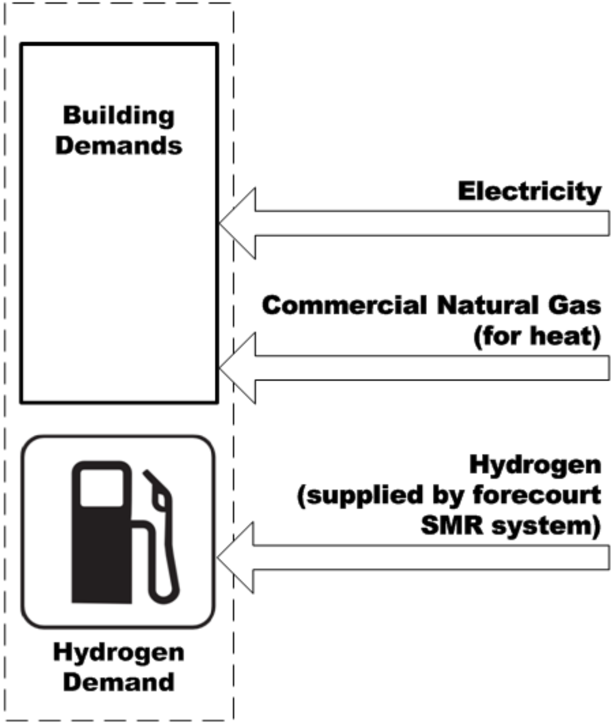
In the model, the fuel cell system is integrated with the building heat and electrical demand, and hydrogen is assumed to be produced for onsite use (e.g., in forklifts) or sale (see diagram below). Arrows that cross the analysis boundary are explicitly accounted for in the discounted cash flow analysis. Internal arrows represent the avoided costs (revenue) for supplying electricity, heat, and hydrogen via the fuel cell system. The model solves for the total revenue derived for these energy services that is equal to the annualized profited cost for the fuel cell installation.

The model solves for a total cost of energy in dollars per kWh and does not distinguish between the types of energy (electricity, heat, and hydrogen). The user sets the costs for two of the energy types; these values are subtracted from the total energy cost to calculate the cost of the third energy type. In the default case, electricity supplied by the fuel cell is assigned the same value as electricity purchased from the grid, and heat from the fuel cell is assigned the same value as would have been paid for heating from a natural gas heating system. Hydrogen is the third (free) variable, and its value is calculated as the remaining cost. If the user selects heat or electricity as the free variable, the hydrogen value is set at the profited cost of producing hydrogen from a standalone steam methane reforming (SMR) system.



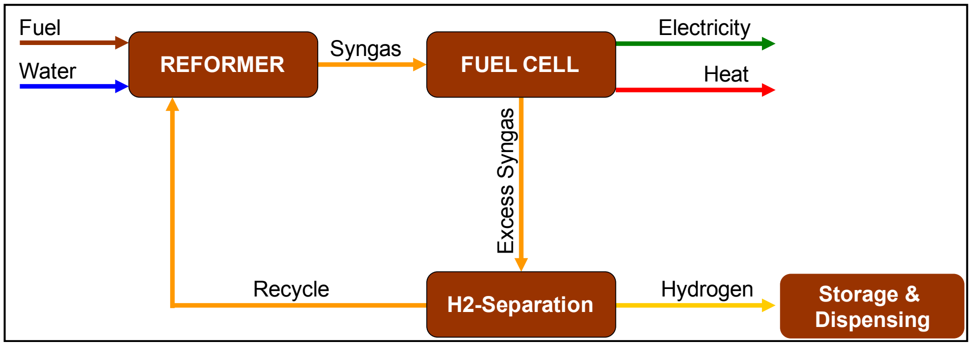
The output of the model is compared with a baseline system in which electricity is supplied by the electric grid, heat is supplied by a natural gas heating system, and hydrogen is supplied by a standalone SMR system (see diagram below).

Baseline System Analysis Boundary

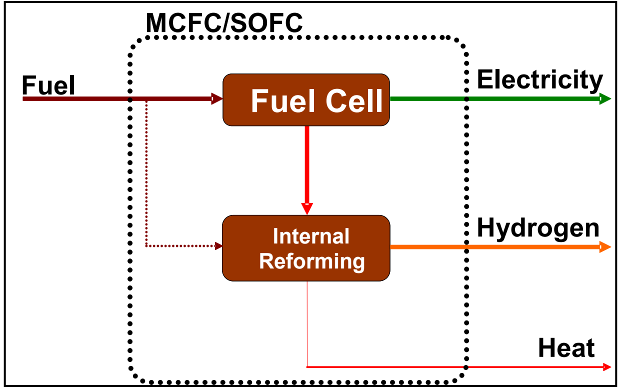


The FCPower Model comes in three different versions (i.e., three different Excel workbooks): one version based on a molten carbonate fuel cell (MCFC) system, one based on a phosphoric acid fuel cell (PAFC) system, and one based on a solid oxide fuel cell (SOFC) system. One of the major differences between the systems is that the PAFC system has a separate reformer; hydrogen is produced by diverting some of the reformed syngas to a hydrogen separator, allowing the production of additional hydrogen via oversizing the reformer relative to the fuel cell. In contrast, the MCFC and SOFC systems have internal reformers, and heat from electricity-production efficiency losses is used to produce hydrogen. A consequence of the different technologies is that the model can be set to follow heat or electricity demand for the PAFC system, whereas the model can only follow electricity demand for the MCFC and SOFC systems. This function is discussed later in this guide.

Schematic of a PAFC System



Schematic of MCFC and SOFC Systems



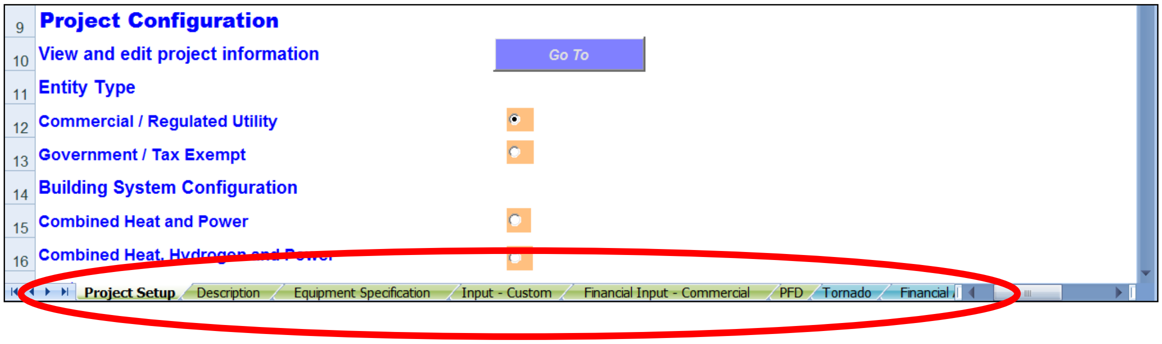
The first section of this guide helps users get started with the FCPower Model. Note that screen captures and values shown in this guide are for illustration only and will not necessarily match what appears in the version of the model or case study you are using. More detailed instructional materials and model documentation are being developed and will be posted on the following Web site as they become publicly available: www.hydrogen.energy.gov/fc_power_analysis.html. Also visit this Web site to download the most updated version of the model. Section 2 of this guide describes the technical characteristics of the fuel cell systems on which the FCPower Model is based, and Section 3 describes FCPower Model case studies.

1.2 Getting Around

The FCPower Model workbook is organized into a series of worksheets, which are linked by tabs as shown below. Some of the worksheets are used for all analyses and are always visible, whereas others become visible or invisible based on whether or not they are being used for a specific analysis.

Worksheets with green tabs are for user input and information. Worksheets with blue tabs are for model results. Worksheets with yellow tabs are for data and properties such as feedstock prices and heating values. Worksheets with gray tabs show standard calculations and variables and are not meant to be modified directly by users. Darker-shaded tabs indicate worksheets accessed frequently by users. Lighter-shaded tabs indicate infrequently accessed or calculation worksheets.

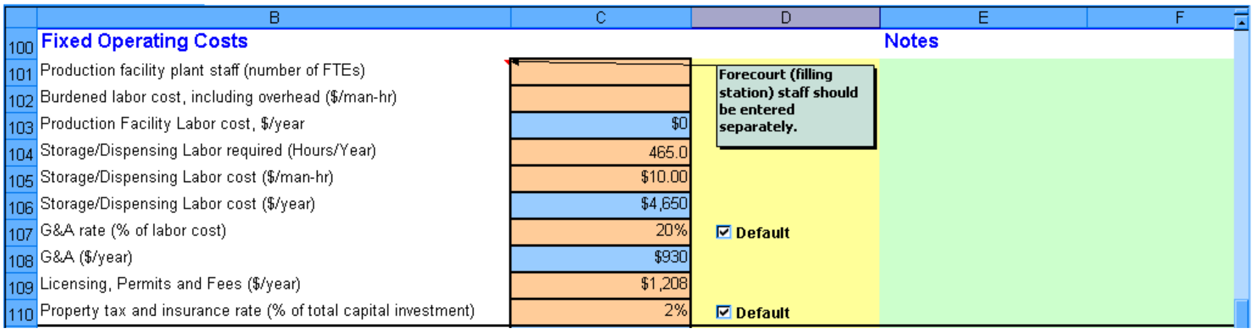
FCPower Model Worksheet Tabs



9 **Project Configuration**
10 View and edit project information
11 Entity Type
12 Commercial / Regulated Utility ●
13 Government / Tax Exempt ○
14 Building System Configuration
15 Combined Heat and Power ○
16 Combined Heat, Hydrogen and Power ○

1.3 Tips & Troubleshooting

- Before you start modifying the model, save the file under a new name. This will make it simple to go back to the unmodified model later if necessary.
- If the file you are working with accumulates numerous errors, you delete information that you later find you need, etc., it might be easier to discard the file and start afresh with the original version of the model. If you have not kept an original version, download the model again from the following Web site: www.hydrogen.energy.gov/fc_power_analysis.html.
- Throughout the model, orange cells are meant to accept static user-input values or user-defined equations, and blue cells are calculated automatically by the model. Use care if you overwrite the blue calculation cells with static values or your own equations; once overwritten, the original equation information is permanently deleted. Green cells are for notes that do not participate in calculations.
- Do not type values into cells with drop-down menus. Select only from values in the menu.
- If it is not obvious how to close or move on past a pop-up window, you can close it by clicking the ☒ in the upper right corner.
- Mouse over small red triangles for useful notes as shown below.



	B	C	D	E	F
100	**Fixed Operating Costs**			**Notes**	
101	Production facility plant staff (number of FTEs)		**Forecourt (filling station) staff should be entered separately.**		
102	Burdened labor cost, including overhead ($/man-hr)				
103	Production Facility Labor cost, $/year	$0			
104	Storage/Dispensing Labor required (Hours/Year)	465.0			
105	Storage/Dispensing Labor cost ($/man-hr)	$10.00			
106	Storage/Dispensing Labor cost ($/year)	$4,650			
107	G&A rate (% of labor cost)	20%	☑ **Default**		
108	G&A ($/year)	$930			
109	Licensing, Permits and Fees ($/year)	$1,208			
110	Property tax and insurance rate (% of total capital investment)	2%	☑ **Default**		

- The model works best (i.e., has the least likelihood of errors) when you fill out the *Project Setup* worksheet and all linked worksheets as completely as possible, starting with the top and working down. After filling out all relevant worksheets completely, run the model using the button in the *Project Setup* worksheet.

1.4 Configuring Your Simulated Distributed Energy System

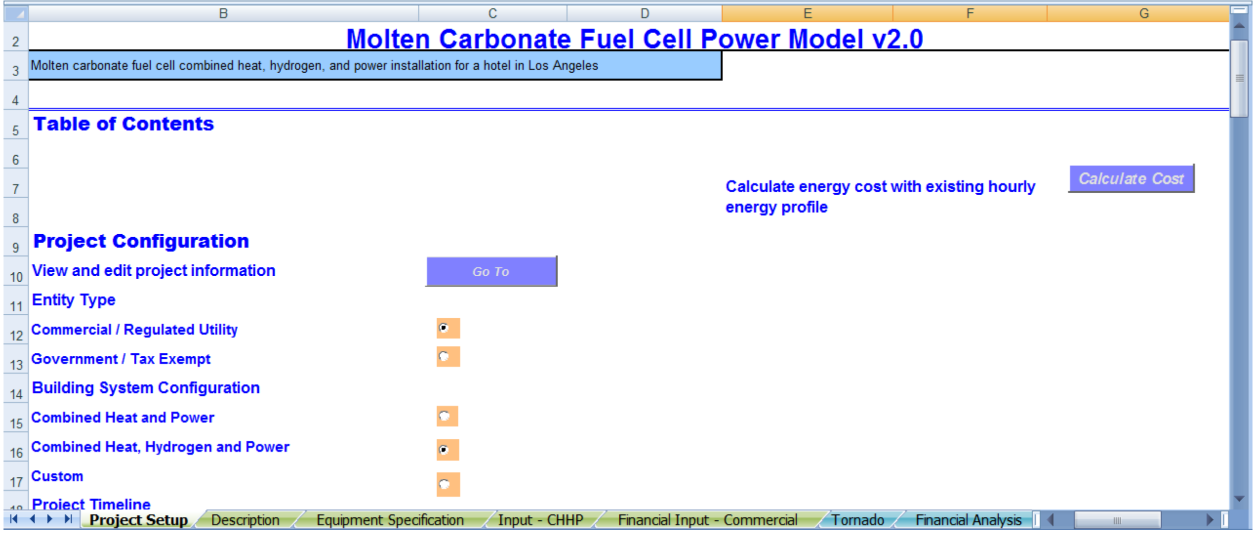
When you open the model, you will start in the *Description* worksheet, which contains basic information about the model and the case study you are working on. The FCPower Model's default case study is a large hotel in Los Angeles.

From the *Description* worksheet, clicking the *Project Setup* button sends you to the *Project Setup* worksheet. The *Project Setup* worksheet will be your "home base" for configuring your simulated distributed energy system. You will complete the worksheet from top to bottom—linking to other worksheets to enter information as necessary—and returning to the *Project Setup* worksheet to run the hourly energy profile and calculate costs. The following information describes how to complete each section of the *Project Setup* worksheet and related worksheets.

1.4.1 Project Configuration

The *Project Configuration* section is the first part of the *Project Setup* worksheet. In this section, the first choice you make is the type of entity that will be using the distributed energy system: commercial/regulated utility or government/tax exempt. This choice determines some of the model's financial inputs and calculations, related to taxation and depreciation.

***Project Setup* Worksheet**



Molten Carbonate Fuel Cell Power Model v2.0

Molten carbonate fuel cell combined heat, hydrogen, and power installation for a hotel in Los Angeles

Table of Contents

Calculate energy cost with existing hourly energy profile

Project Configuration

View and edit project information

Entity Type

Commercial / Regulated Utility ●

Government / Tax Exempt ○

Building System Configuration

Combined Heat and Power ○

Combined Heat, Hydrogen and Power ●

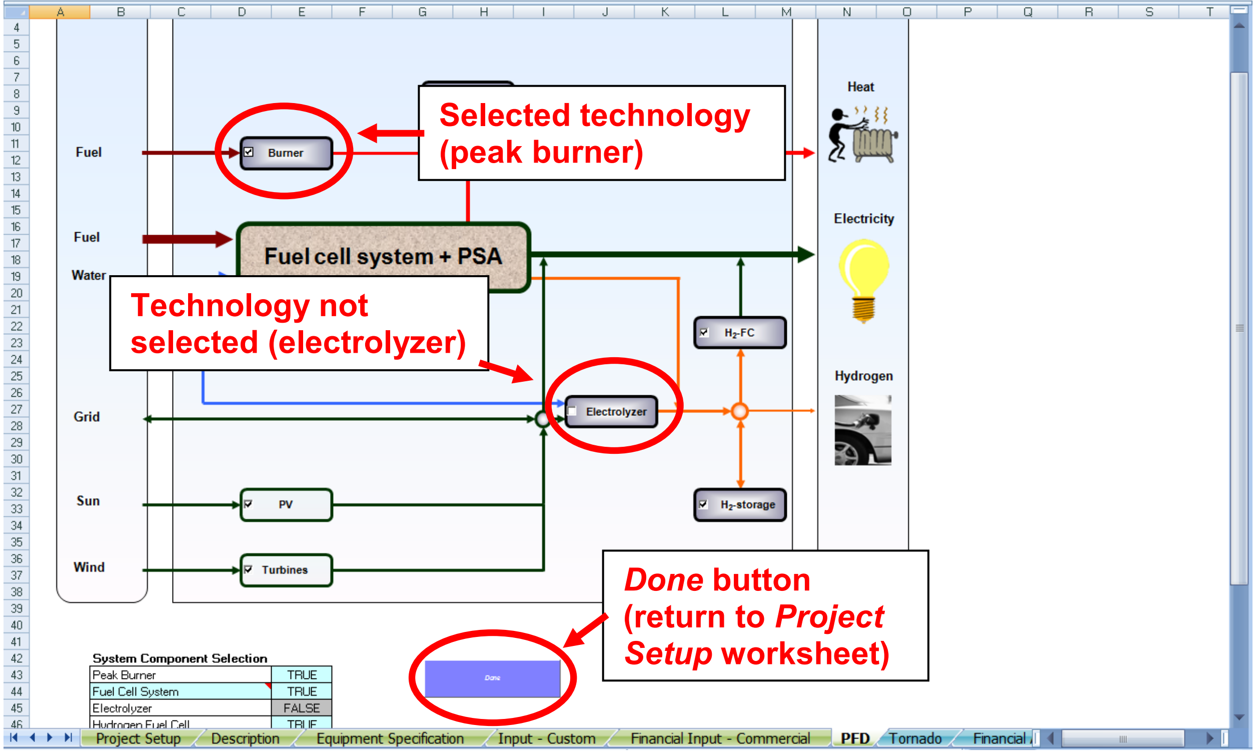
Custom ○

Project Timeline

Next, you choose the building system configuration from among three choices: combined heat and power (CHP); combined heat, hydrogen, and power (CHHP); and custom. The model will adjust automatically to collect the relevant information based on the type of system you choose.

The CHP system is the simplest of the three systems. The fuel cell system provides electricity and heat to meet building demands, buying supplemental grid electricity and natural gas heating as necessary and selling electricity to the grid when the fuel cell's output is greater than the building's demand. No hydrogen is produced with this system. The CHHP system performs the same functions as the CHP system and adds the ability to produce hydrogen. The custom system allows you to add components to the CHHP system. Choices include solar and wind electricity production, electrolytic hydrogen production, hydrogen storage, hydrogen fuel cells, and a natural gas burner. If you select the custom system, you will be sent to the *PFD* worksheet, where you will select the components of your system and then click the *Done* button to return to the *Project Setup* worksheet.

PFD Worksheet (for the Custom Configuration)



Selected technology (peak burner)

Technology not selected (electrolyzer)

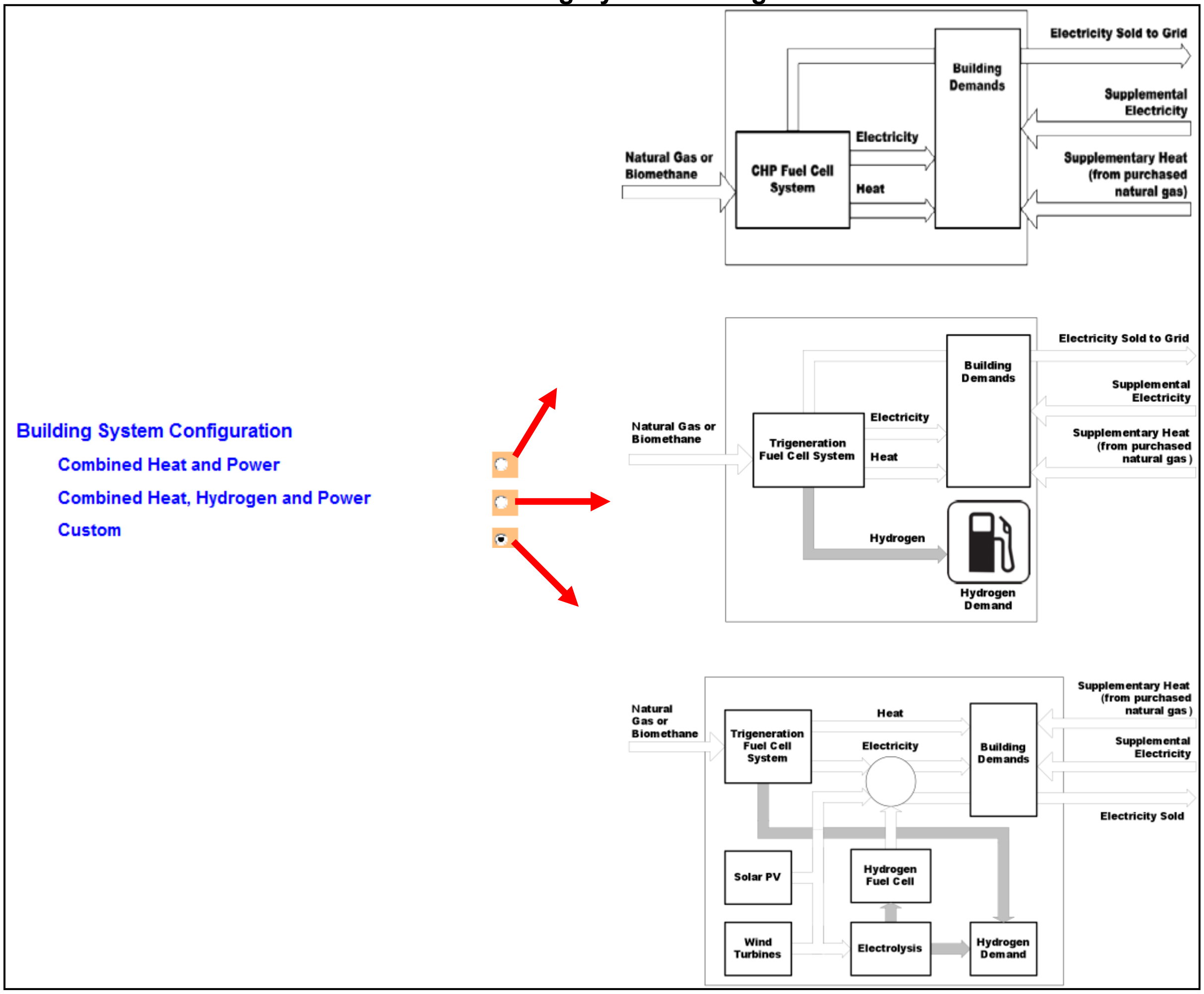
Done button (return to *Project Setup* worksheet)

System Component Selection

Peak Burner	TRUE
Fuel Cell System	TRUE
Electrolyzer	FALSE
Hydrogen Fuel Cell	TRUE

After you select the building system configuration, you enter or accept the default values for project timeline information, including reference year for costs, anticipated start-up year, length of construction period, equipment start-up duration, and total equipment life. Then you proceed to the *Building Characteristics* section.

Schematics of Building System Configuration Choices



Building System Configuration

○ Combined Heat and Power

○ Combined Heat, Hydrogen and Power

● Custom

1.4.2 Building Characteristics

The *Building Characteristics* section of the *Project Setup* worksheet prompts you to import building electricity and heat load profiles and a hydrogen demand profile for your system. The FCPower Model calculates the types and amounts of energy used and produced primarily based on electricity and heat demand profiles. The *AC Demand* (electricity) and *Heat Demand* (heat) worksheets contain energy demand values for each of the 8,760 hours in a year. The model's standard case study location for the purposes of the demand profiles is a large hotel in Los Angeles. If the model is set to follow the electrical load, the system will make meeting electricity demand its top priority. If the model is set to follow the heat load (only available in the PAFC system model), the system will make meeting heat demand its top priority.

The model also uses a hydrogen demand profile, contained in the *H2 Demand* worksheet. However, the model cannot be set to follow hydrogen load, i.e., meeting hydrogen demand cannot be set as the top priority. Hydrogen demand is only applicable to CHHP and custom system configurations, not to the CHP configuration.

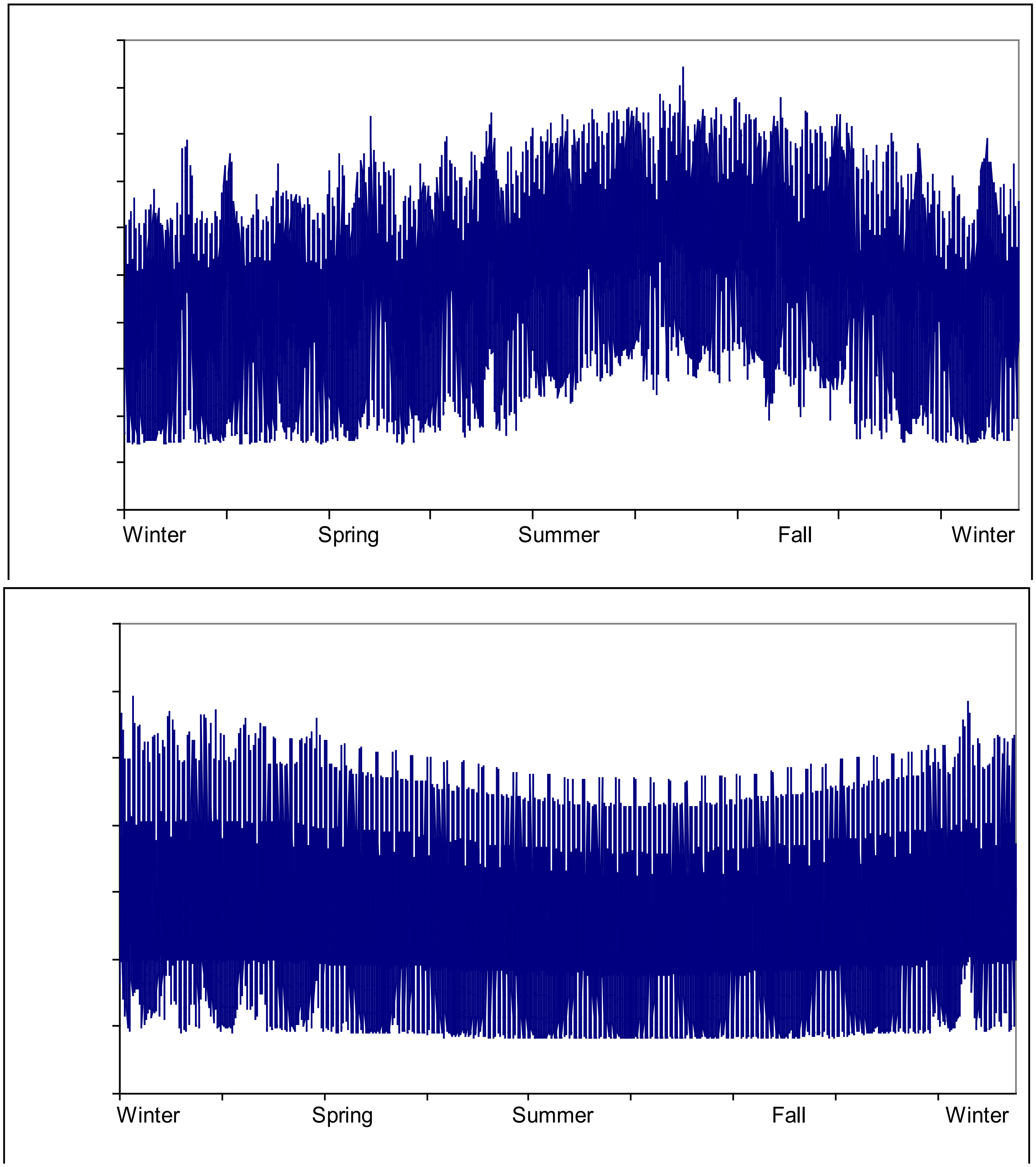
You can accept the default electricity, heat, and hydrogen demand profiles or modify them by modifying the values in their respective worksheets. However, because there are 8,760 data points, this approach is usually impractical. Instead, you can import profiles (except for hydrogen profiles).

Click the *Go To* button adjacent to *Enter or Import Building Load Profiles*. A popup window asks if you want to import a new building profile or use the existing/default profile. Click *Yes* to import a new profile. A browser window opens allowing you to locate and select an appropriately formatted electricity/heat demand file (which can be downloaded at www.hydrogen.energy.gov/fc_power_analysis.html). Follow the prompts to select the desired file. The electricity and heat profiles from the file you selected automatically replace the profiles in the *AC Demand* and *Heat Demand* worksheets. Enter or accept the default year for the demand profile on the *AC Demand* worksheet; this value is used to determine the day of the week for January 1 of that year.

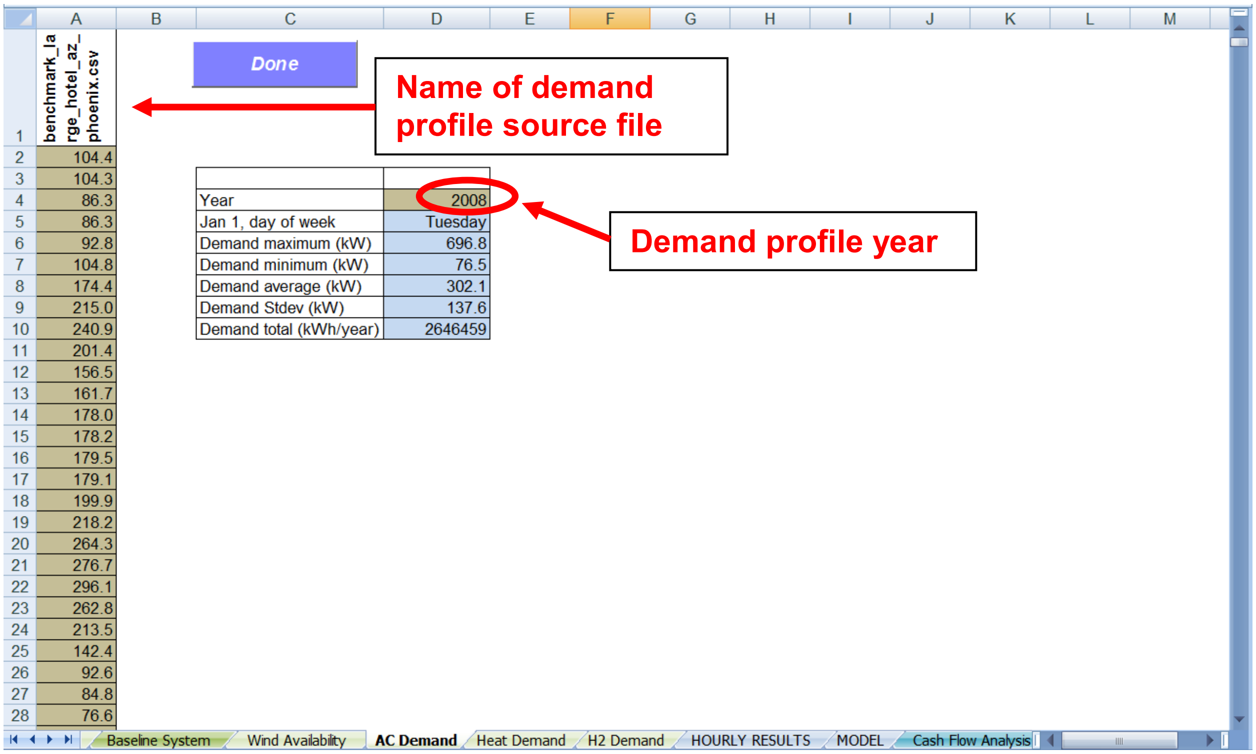
If you chose a custom building configuration and selected PV and/or wind as part of your system, after you select an electricity/heat profile you will be prompted to select solar and wind profiles (which can be downloaded at www.hydrogen.energy.gov/fc_power_analysis.html). If the solar/wind profile file is stored in the same folder as the electricity/heat profile file that you imported, the model will automatically import the solar/wind file from that location. If the solar/wind file is in another location, you will have the opportunity to navigate to the file and select it (if no solar/wind profile is available, it is best to deselect PV and/or wind turbines in the *PFD* worksheet). If PV is part of your system, you will be asked to input the latitude of your building's location during this process. The availability profiles will be entered into the *Solar Availability* and *Wind Availability* worksheets. Click the *Done* button to return to the *Project Setup* worksheet.

Next, click the *Go To* button adjacent to *Enter Hydrogen Demand Profile*. This sends you to the *H2 Demand* worksheet, where you can specify average daily hydrogen demand and demand-surge characteristics. Click the *Done* button to return to the *Project Setup* worksheet.

Graphs of Default Electricity (top) and Heat (bottom) Demand Profiles (Large Hotel in Los Angeles)



AC Demand Worksheet



	A
1	benchmark_large_hotel_az_phoenix.csv
2	104.4
3	104.3
4	86.3
5	86.3
6	92.8
7	104.8
8	174.4
9	215.0
10	240.9
11	201.4
12	156.5
13	161.7
14	178.0
15	178.2
16	179.5
17	179.1
18	199.9
19	218.2
20	264.3
21	276.7
22	296.1
23	262.8
24	213.5
25	142.4
26	92.6
27	84.8
28	76.6

Year	2008
Jan 1, day of week	Tuesday
Demand maximum (kW)	696.8
Demand minimum (kW)	76.5
Demand average (kW)	302.1
Demand Stdev (kW)	137.6
Demand total (kWh/year)	2646459

Name of demand profile source file

Demand profile year

1.4.3 Equipment Configuration

The *Equipment Configuration* section of the *Project Setup* worksheet prompts you to configure your CHP/CHHP and baseline systems. Click the *Go To* button adjacent to *Equipment Configuration*. This sends you to the *Equipment Specification* worksheet. Here, you enter the technical specifications for the primary fuel cell system and—if you selected them as part of your system—supplementary heat supply, hydrogen storage, PV, wind turbines, electrolyzer, and hydrogen fuel cell. Some of the calculated values in this worksheet depend on profiles that you may already have created/imported (hydrogen demand, solar and wind availability); if you have not yet established these profiles, you have another opportunity to do so here.

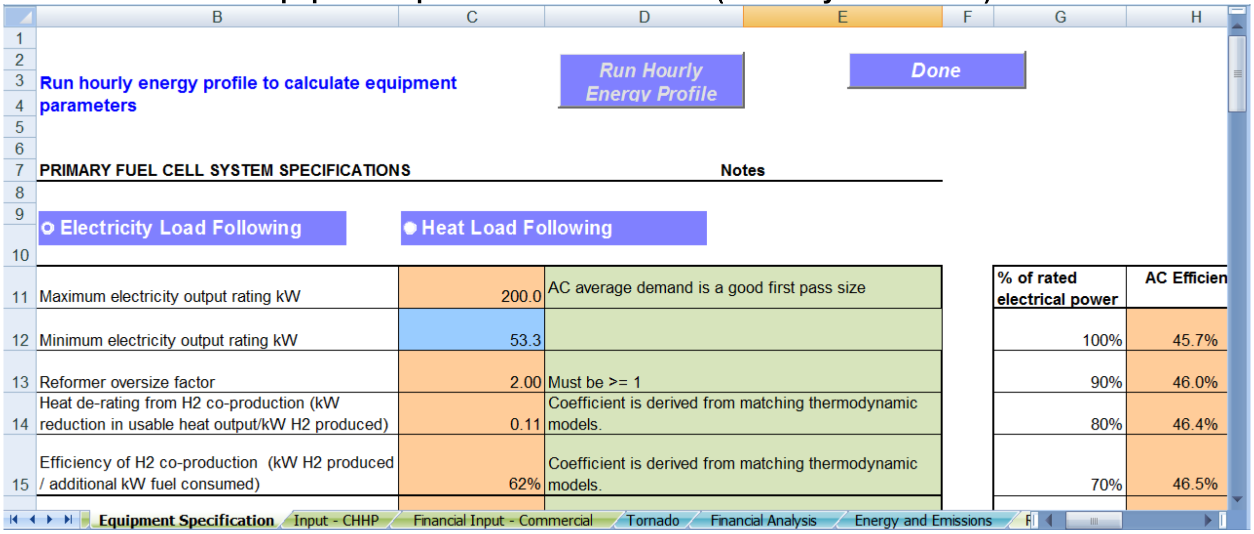
The high-temperature fuel cell system is sized by specifying the maximum AC power output of the system; for the standard FCPower Model case studies, the maximum AC power output is set approximately to the average electricity demand. In general, it is advantageous to size the fuel cell for as high an output as possible while running the fuel cell close to its maximum power output as much of the time as possible. The model can be used to experiment with different fuel cell sizes to achieve the lowest cost. The reforming portion of the PAFC system also can be oversized to produce additional hydrogen by adjusting the reformer oversize factor.

For PAFC systems, select *Electricity Load Following* or *Heat Load Following* using the radio buttons. This determines the energy priority of your system. If you select *Electricity Load Following*, the system will make meeting electricity demand its top priority. If you select *Heat Load Following*, the system will make meeting heat demand its top priority. Note: this function is only available for the model based on the PAFC system. The MCFC and SOFC systems always make meeting electricity demand their top priority.

If the applicable technologies are activated, ensure values are present for the supplementary heat supply's *Maximum power*, the electrolyzer's *Electrolyzer size*, the hydrogen fuel cell's *Fuel cell capacity*, the hydrogen storage system's *Total storage volume*, the PV system's *PV array area*, and the wind turbine's *Installed capacity*. Note that you can select 350 or 700 bar (5,000 or 10,000 psi) refueling pressure for the hydrogen storage system.

After entering or accepting the default specifications for each of the pieces of equipment in your system, it is recommended that you have the model analyze the system's energy performance by clicking the *Run Hourly Energy Profile* button at the top of the worksheet. This will identify any equipment specifications that are not adequate for meeting your system's energy needs and will ready the model for analyzing the financial performance of your system. When you have finished, click the *Done* button to return to the *Project Setup* worksheet.

Equipment Specification Worksheet (PAFC System Model)



Run hourly energy profile to calculate equipment parameters

PRIMARY FUEL CELL SYSTEM SPECIFICATIONS

Notes

○ Electricity Load Following
● Heat Load Following

				% of rated electrical power	AC Efficien
11	Maximum electricity output rating kW	200.0	AC average demand is a good first pass size		
12	Minimum electricity output rating kW	53.3		100%	45.7%
13	Reformer oversize factor	2.00	Must be >= 1	90%	46.0%
14	Heat de-rating from H2 co-production (kW reduction in usable heat output/kW H2 produced)	0.11	Coefficient is derived from matching thermodynamic models.	80%	46.4%
15	Efficiency of H2 co-production (kW H2 produced / additional kW fuel consumed)	62%	Coefficient is derived from matching thermodynamic models.	70%	46.5%

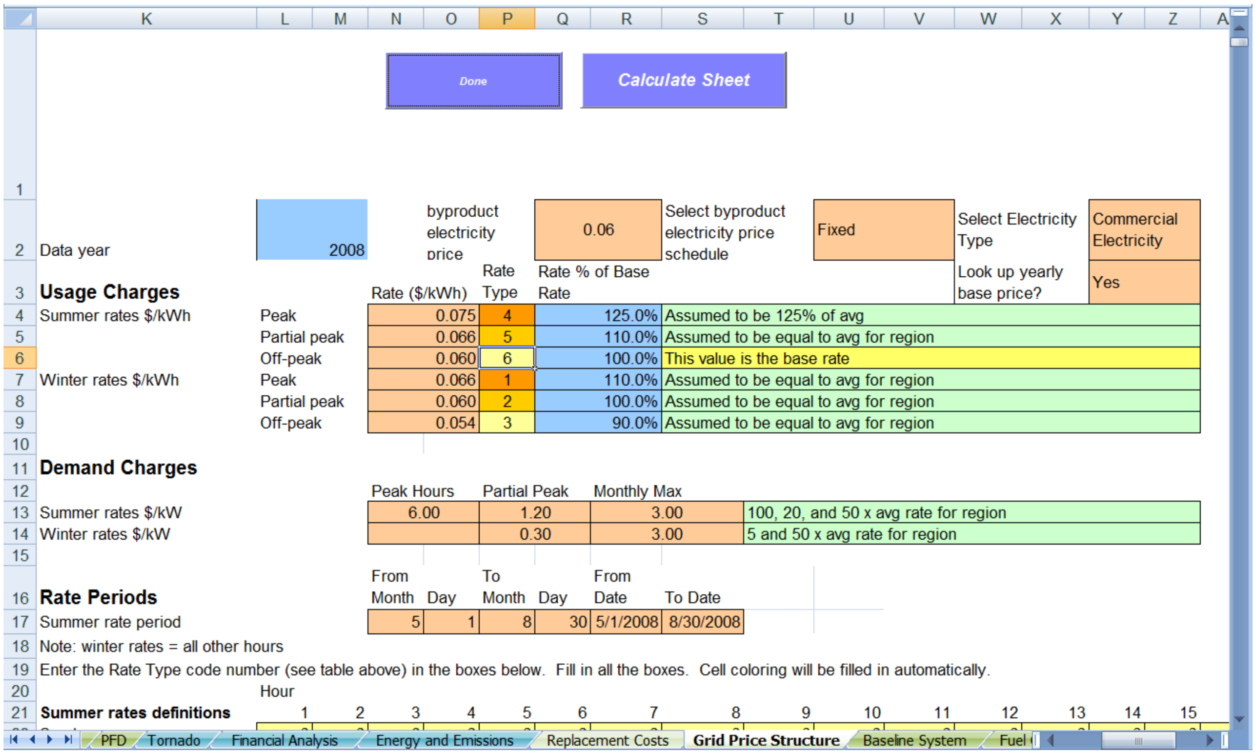
Next, from the *Project Setup* worksheet, click the *Go To* button adjacent to *Specify Baseline System*. The baseline system provides energy for the building (and in the case of CHHP, hydrogen) from conventional sources assuming no onsite electricity production. The baseline system is used for energy supply cost comparison with the CHP/CHHP system and provides a baseline value for calculations of greenhouse gas and overall energy use reduction calculations. Electricity for the building is supplied from the grid using the same electricity source and price structure that is used for supply of supplementary electricity for the CHP/CHHP system. Heat is supplied using a conventional boiler or furnace using the same fuel as is used for the fuel cell system. Hydrogen, if applicable, is supplied using the technology you select from the *Select Hydrogen Production System* drop-down menu (e.g., distributed natural gas reforming).

Note that you can select 350 or 700 bar (5,000 or 10,000 psi) hydrogen refueling for the baseline system.

1.4.4 Purchased Electricity Price

From the *Project Setup* worksheet, click the *Go To* button adjacent to *Purchased Electricity Price*, which sends you to the *Grid Price Structure* worksheet. This worksheet accounts for hourly electricity price variations (e.g., higher prices during peak-demand times such as 7:00 AM to 6:00 PM on workdays), seasonal rates, and demand charges. Accept the default values or enter new values for *Usage Charges*, *Demand Charges*, and *Rate Periods*. When finished, click the *Calculate Sheet* button to calculate grid prices based on your inputs. Note that the numbers in the columns at left are model calculations/results, not inputs, and are updated when the model is run. You only need to enter values at the top of the worksheet in the *Usage Charges*, *Demand Charges*, and *Rate Periods* sections. You can update the worksheet calculations by clicking the *Calculate Sheet* button, but this is not necessary; all calculations are run when the model is run. When finished with the *Grid Price Structure* worksheet, click the *Done* button to return to the *Project Setup* worksheet.

Grid Price Structure Worksheet



2	Data year	2008	byproduct electricity price	0.06	Select byproduct electricity price schedule	Fixed

Select Electricity Type: Commercial Electricity

Look up yearly base price?: Yes

			Rate ($/kWh)	Rate Type	Rate % of Base Rate	
3	**Usage Charges**					
4	Summer rates $/kWh	Peak	0.075	4	125.0%	Assumed to be 125% of avg
5		Partial peak	0.066	5	110.0%	Assumed to be equal to avg for region
6		Off-peak	0.060	6	100.0%	This value is the base rate
7	Winter rates $/kWh	Peak	0.066	1	110.0%	Assumed to be equal to avg for region
8		Partial peak	0.060	2	100.0%	Assumed to be equal to avg for region
9		Off-peak	0.054	3	90.0%	Assumed to be equal to avg for region
10						

		Peak Hours	Partial Peak	Monthly Max	
11	**Demand Charges**				
12					
13	Summer rates $/kW	6.00	1.20	3.00	100, 20, and 50 x avg rate for region
14	Winter rates $/kW		0.30	3.00	5 and 50 x avg rate for region
15					

		From Month	Day	To Month	Day	From Date	To Date
16	**Rate Periods**						
17	Summer rate period	5	1	8	30	5/1/2008	8/30/2008

18 Note: winter rates = all other hours

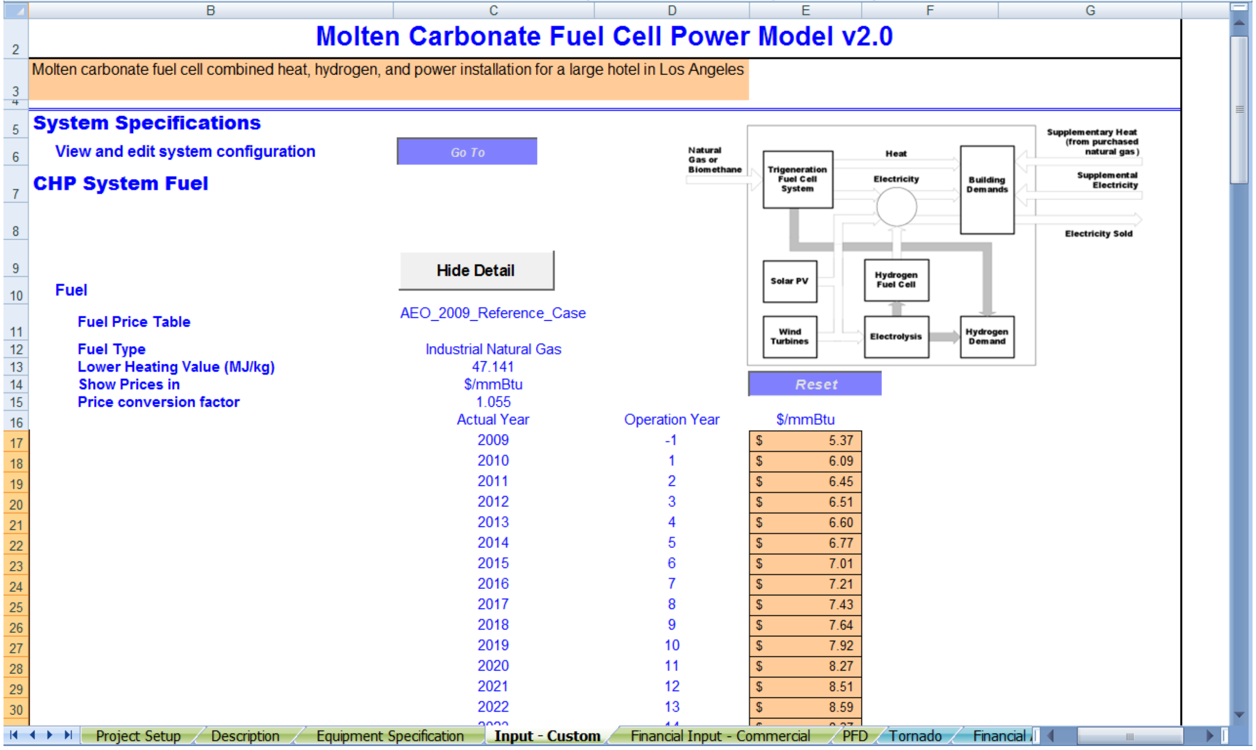
19 Enter the Rate Type code number (see table above) in the boxes below. Fill in all the boxes. Cell coloring will be filled in automatically.

		Hour														
21	**Summer rates definitions**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

1.4.5 Capital and Operating Costs

From the *Project Setup* worksheet, click the *Go To* button adjacent to *Capital and Operating Costs*, which sends you to the *Input* worksheet. The information you enter into the *Input* worksheet varies based on the configuration you selected. However, for all configurations, you are first prompted to enter fuel type and price information. Use the drop-down menus to select the fuel price table that the model will use, the fuel type, and the price units. The worksheet automatically generates fuel prices for each year of your system's operation; view the yearly breakdown by clicking the *Show Detail* button. If you overwrite any of these yearly values with your own values and want to return to the model's default calculations, click the *Reset* button.

Input Worksheet (Custom Configuration)



Molten Carbonate Fuel Cell Power Model v2.0

Molten carbonate fuel cell combined heat, hydrogen, and power installation for a large hotel in Los Angeles

System Specifications

View and edit system configuration

CHP System Fuel

Fuel

Fuel Price Table: AEO_2009_Reference_Case

Fuel Type: Industrial Natural Gas

Lower Heating Value (MJ/kg): 47.141

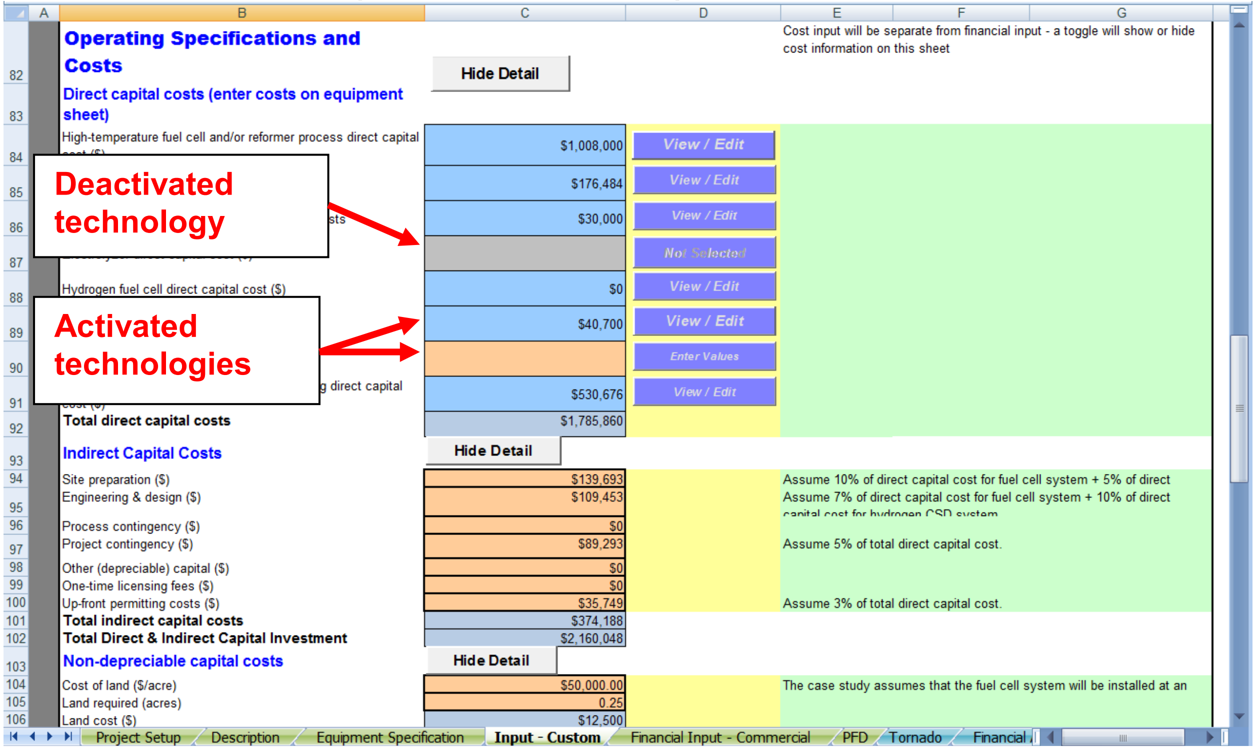
Show Prices in: $/mmBtu

Price conversion factor: 1.055

Actual Year	Operation Year	$/mmBtu
2009	-1	$ 5.37
2010	1	$ 6.09
2011	2	$ 6.45
2012	3	$ 6.51
2013	4	$ 6.60
2014	5	$ 6.77
2015	6	$ 7.01
2016	7	$ 7.21
2017	8	$ 7.43
2018	9	$ 7.64
2019	10	$ 7.92
2020	11	$ 8.27
2021	12	$ 8.51
2022	13	$ 8.59

If you previously selected the custom configuration, after entering the fuel type and price information on the *Input* worksheet you are given another opportunity to import solar and wind availability profiles. The next step for all configurations is to enter information into the *Operating Specifications and Costs* section of the *Input* worksheet. The input sections are similar for each configuration, although there are more input fields as the system increases in complexity (from CHP to CHHP to custom). Accept the default values or enter new values into the orange cells. The contents of the blue cells are calculated automatically. In the *Direct Capital Costs* section of the *Input* worksheet, you will see *Enter Values*, *View/Edit*, or *Not Selected* buttons next to the technologies that make up your system.

Input Worksheet, Direct Capital Costs Section



Cost input will be separate from financial input - a toggle will show or hide cost information on this sheet

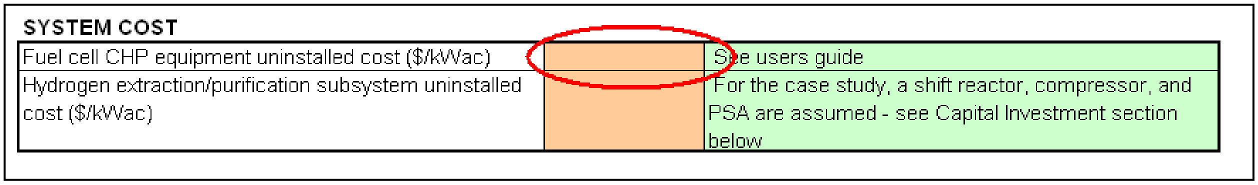
	B	C	D	E–G
82	**Operating Specifications and Costs**	Hide Detail		
83	**Direct capital costs (enter costs on equipment sheet)**			
84	High-temperature fuel cell and/or reformer process direct capital cost ($)	$1,008,000	View / Edit	
85		$176,484	View / Edit	
86	sts	$30,000	View / Edit	
87			Not Selected	
88	Hydrogen fuel cell direct capital cost ($)	$0	View / Edit	
89		$40,700	View / Edit	
90			Enter Values	
91	g direct capital cost ($)	$530,676	View / Edit	
92	**Total direct capital costs**	$1,785,860		
93	**Indirect Capital Costs**	Hide Detail		
94	Site preparation ($)	$139,693		Assume 10% of direct capital cost for fuel cell system + 5% of direct
95	Engineering & design ($)	$109,453		Assume 7% of direct capital cost for fuel cell system + 10% of direct capital cost for hydrogen CSD system
96	Process contingency ($)	$0		
97	Project contingency ($)	$89,293		Assume 5% of total direct capital cost.
98	Other (depreciable) capital ($)	$0		
99	One-time licensing fees ($)	$0		
100	Up-front permitting costs ($)	$35,749		Assume 3% of total direct capital cost.
101	**Total indirect capital costs**	$374,188		
102	**Total Direct & Indirect Capital Investment**	$2,160,048		
103	**Non-depreciable capital costs**	Hide Detail		
104	Cost of land ($/acre)	$50,000.00		The case study assumes that the fuel cell system will be installed at an
105	Land required (acres)	0.25		
106	Land cost ($)	$12,500		

Deactivated technology

Activated technologies

Click the first button, which is adjacent to the field *High-temperature fuel cell and/or reformer process direct capital cost*, to go to the *Fuel Cell System* worksheet. The most important value on this worksheet is the *Fuel cell CHP equipment uninstalled cost* at the top. For help choosing this value, click the adjacent *Cost guidance* button. A window titled "Reference Material and Guidance for Fuel Cell System Cost Estimates" pops up (see screen capture below). Once you have read the information in the pop-up window and decided on a cost, close the window and fill in the mandatory field. Continue to make other changes on the *Fuel Cell System* worksheet as necessary. Once you are done making changes to this technology, return to the *Input* worksheet using the *Input Sheet* button. Repeat this process for all activated technologies. Later, you can modify values on the detail worksheets using the *View/Edit* button if necessary.

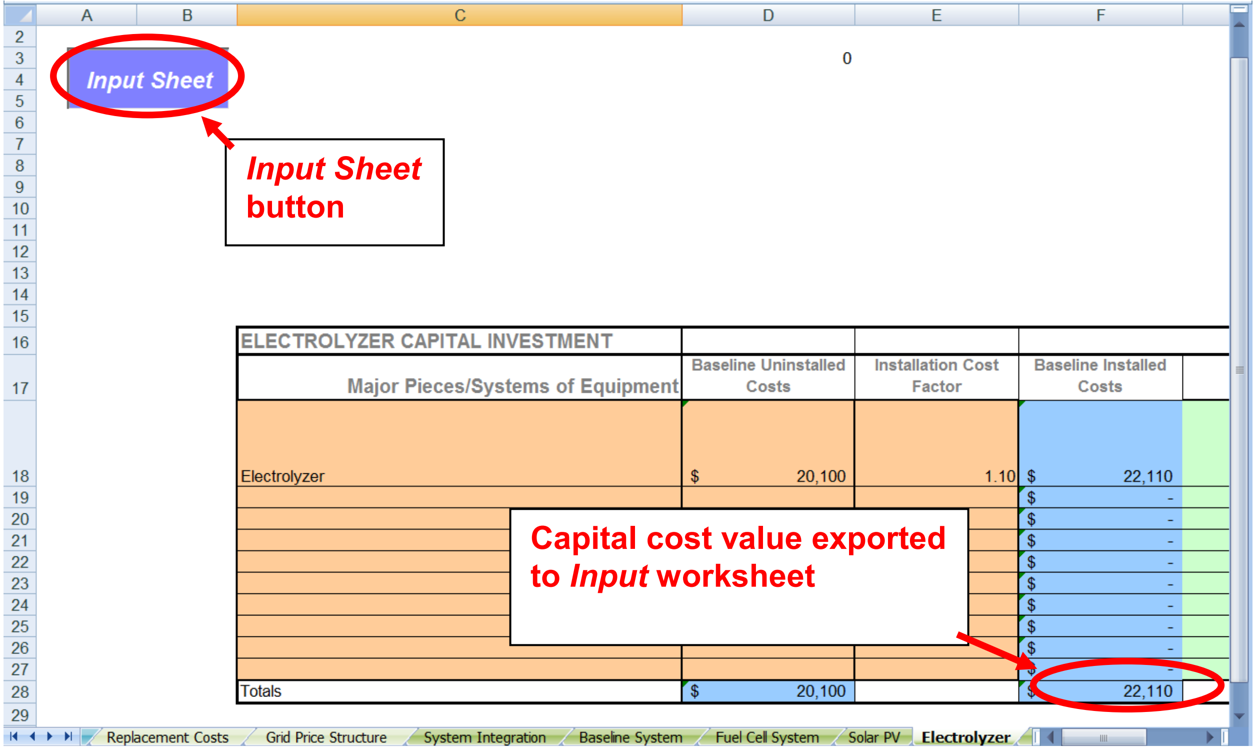
Fuel Cell System Worksheet, Mandatory Fuel Cell Uninstalled Cost Field



SYSTEM COST

Fuel cell CHP equipment uninstalled cost ($/kWac)		See users guide
Hydrogen extraction/purification subsystem uninstalled cost ($/kWac)		For the case study, a shift reactor, compressor, and PSA are assumed - see Capital Investment section below

Example Technology Detail Worksheet (Electrolyzer)



ELECTROLYZER CAPITAL INVESTMENT			
Major Pieces/Systems of Equipment	Baseline Uninstalled Costs	Installation Cost Factor	Baseline Installed Costs
Electrolyzer	$ 20,100	1.10	$ 22,110
			$ -
			$ -
			$ -
			$ -
			$ -
			$ -
			$ -
			$ -
			$ -
Totals	$ 20,100		$ 22,110

Input Sheet button

Capital cost value exported to *Input* worksheet

As you continue to complete the *Input* worksheet, you will find fields for indirect capital costs, non-depreciable capital costs, fixed operating costs, and variable operating costs. In the *Other Variable Operating Costs* section, the factor you enter in the field *Total unplanned replacement capital cost factor* is transferred to the *Replacement Costs* worksheet, which calculates replacement costs based on this factor and the value for total depreciable capital costs. Go to the *Replacement Costs* worksheet if you want to specify additional replacement costs. Enter replacement costs for all selected technologies here. Specified replacement costs are depreciated on the same schedule as the original equipment. Unplanned replacement costs are depreciated on a 5-year Modified Accelerated Cost Recovery System (MACRS) schedule. The depreciation types and schedules can be changed in the *Financial Input* worksheet as described in the next section.

Accept the default values/calculations for all other fields or enter your own values, then click the *Done* button at the bottom of the worksheet to return to the *Project Setup* worksheet.

1.4.6 Energy Analysis

After working down to the *Run Energy Analysis* section of the *Project Setup* worksheet, click the adjacent *Run* button (if you already ran the energy analysis as part of a previous step, you do not need to run it again here—you can proceed directly to the *Financial Assumptions* described in the next section). This prompts the model to run hourly energy calculations based on the system characteristics you have chosen and the energy demand and supply profiles in the *AC Demand*, *Heat Demand*, *H2 Demand*, and *Solar* and *Wind Availability* worksheets.

The hourly energy calculations can require a substantial amount of time to complete depending on the speed of your computer. A counter at the bottom of the worksheet shows the estimated modeling runtime. As the energy analysis is running, the model is completing each cell within the *MODEL* worksheet process flow diagram (invisibly) for each of 8,760 hours. It prioritizes the type of energy demand (electricity or heat) to meet, then prioritizes the energy sources used to meet the demand. For example, the high-temperature fuel cell system must always remain on and thus is always producing a minimum amount of electricity. If the model is set to follow electrical demand, it will meet the demand with this minimum fuel cell system electricity first plus PV or wind-generated electricity (if available). If there is still unmet electrical demand, the model will attempt to meet it by increasing the output of the fuel cell system and then using the low-temperature hydrogen fuel cell. (Note: the electrolyzer and hydrogen fuel cell cannot both operate at the same time.) Finally, grid electricity is used to satisfy any demand that is still unmet.

1.4.7 Financial Assumptions

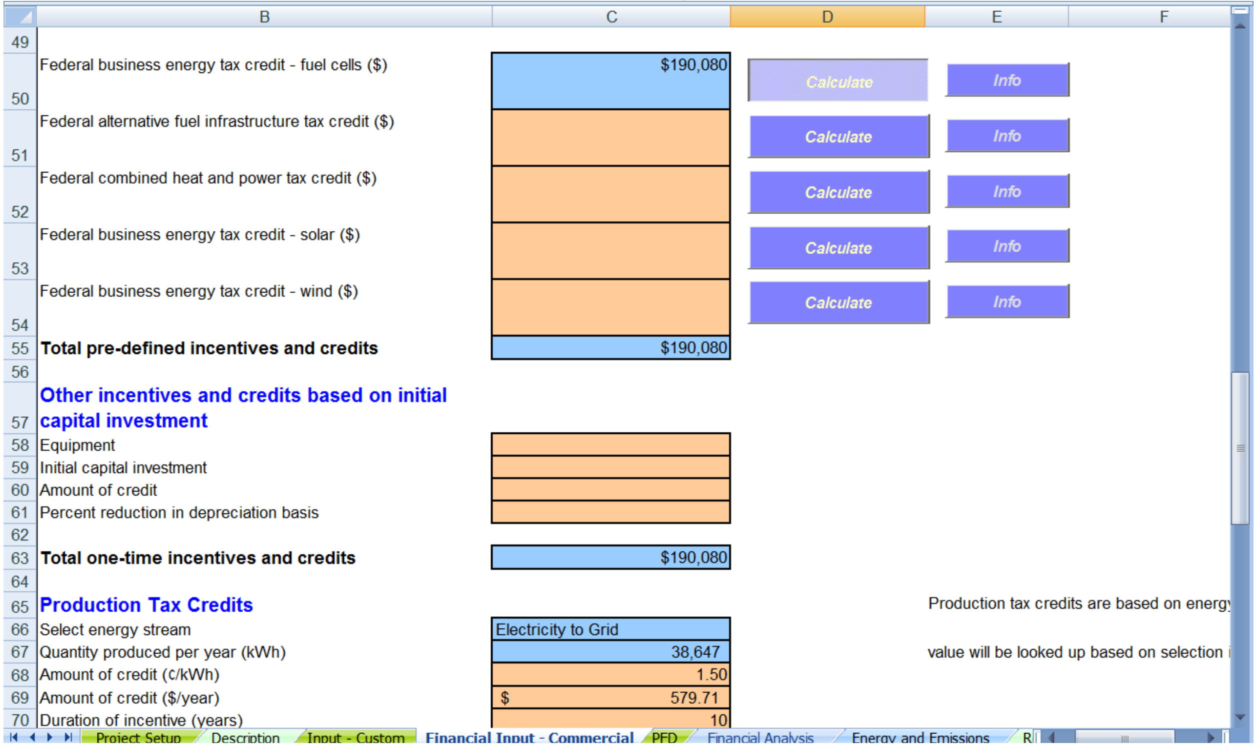
After the energy analysis has completed, click the *Go To* button adjacent to the *Project Setup* worksheet's last section—*Financial Assumptions*. This sends you to the *Financial Input* worksheet.

The information you enter into the *Financial Input* worksheet varies based on the entity type you selected previously (commercial/regulated utility or government/tax exempt). The commercial/regulated input includes tax incentive and depreciation fields, whereas the government/tax-exempt input does not include these fields.

For all entity types, the project timeline is displayed at the top of the *Financial Input* worksheet. You do not need to modify the project timeline—it is imported here from the values you entered on the *Project Setup* worksheet. Next, for all entity types, enter or accept the default values in the *Financial Basis Inputs*, *Fixed Operating Costs*, and *Other Variable Operating Costs* sections. If you selected the government/tax-exempt entity type, you are now finished with the *Financial Input* worksheet. Click the *Done* button (at the bottom) to return to the *Project Setup* worksheet.

If you selected the commercial/regulated entity type, continue to the tax incentive and depreciation sections of the *Financial Input* worksheet. Several specific incentives are already listed (e.g., *Federal business energy tax credit - fuel cells*); click the *Info* buttons to learn about these incentives. Click the *Calculate* buttons to calculate the incentives automatically for your system. If you overwrite these calculations with your own values, you can bring the original default calculations back by clicking the *Calculate* button twice. Continue entering values in the *Other Incentives*, *Production Tax Credits*, and *Production Tax Credits Based on Emissions Reduction* fields as applicable.

Tax Incentive Fields in the Financial Input – Commercial Worksheet



	B	C	D	E	F
49					
50	Federal business energy tax credit - fuel cells ($)	$190,080	Calculate	Info	
51	Federal alternative fuel infrastructure tax credit ($)		Calculate	Info	
52	Federal combined heat and power tax credit ($)		Calculate	Info	
53	Federal business energy tax credit - solar ($)		Calculate	Info	
54	Federal business energy tax credit - wind ($)		Calculate	Info	
55	**Total pre-defined incentives and credits**	$190,080			
56					
57	**Other incentives and credits based on initial capital investment**				
58	Equipment				
59	Initial capital investment				
60	Amount of credit				
61	Percent reduction in depreciation basis				
62					
63	**Total one-time incentives and credits**	$190,080			
64					
65	**Production Tax Credits**			Production tax credits are based on energy	
66	Select energy stream	Electricity to Grid			
67	Quantity produced per year (kWh)	38,647		value will be looked up based on selection i	
68	Amount of credit (¢/kWh)	1.50			
69	Amount of credit ($/year)	$ 579.71			
70	Duration of incentive (years)	10			

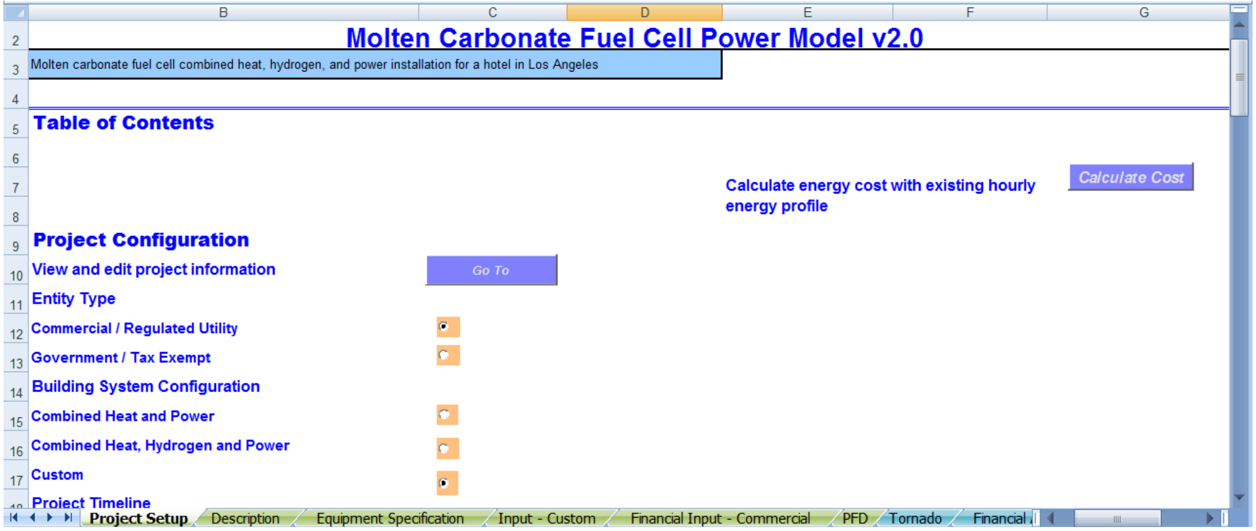
The tax incentive sections are followed by a section for setting depreciation types and schedules for your capital equipment. Depreciation type options include straight line, MACRS, and none. Selecting "none" sets the depreciable capital cost basis to zero; this is applicable to nonprofit organizations. If you overwrite the default values, you can bring them back by unchecking and rechecking the *Default* check boxes. If you enter a value in the last field in this section, *Adjustment to depreciable capital for other one-time tax incentives*, the value is subtracted from the total depreciable capital cost basis. Once you have completed all applicable fields in the *Financial Input* worksheet, click the *Done* button (at the bottom) to return to the *Project Setup* worksheet.

You are now done configuring your distributed energy system and are ready to calculate financial, energy, and emissions results.

1.5 Calculating Financial, Energy, and Emissions Results

Return to the top of the *Project Setup* worksheet and click the *Calculate Cost* button. The model runs financial, energy, and emissions calculations based on the hourly energy results and the system and financial parameters you have chosen. You can change financial parameters and calculate new costs using the *Calculate Cost* button without running the energy analysis again, which minimizes processing time. However, if you want to change characteristics of your hourly energy calculations, you will need to click the *Run* button next to *Run Energy Analysis* again and allow the model to process the hourly calculations again before calculating new costs.

Project Setup Worksheet (Calculate Cost Button at Top Right)



Molten Carbonate Fuel Cell Power Model v2.0

Molten carbonate fuel cell combined heat, hydrogen, and power installation for a hotel in Los Angeles

Table of Contents

Calculate energy cost with existing hourly energy profile

Project Configuration

View and edit project information

Entity Type

● Commercial / Regulated Utility

○ Government / Tax Exempt

Building System Configuration

○ Combined Heat and Power

○ Combined Heat, Hydrogen and Power

● Custom

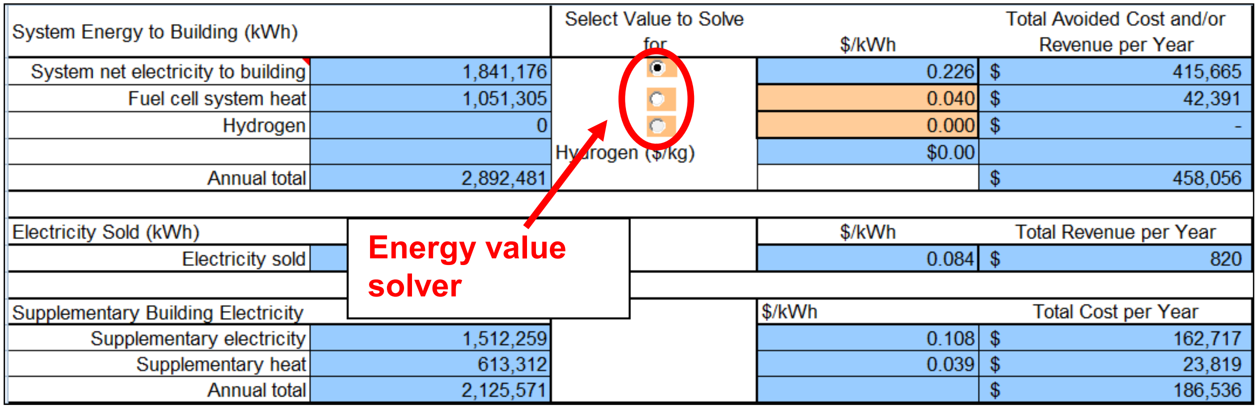
Project Timeline

When the model is done performing the cost calculations, it sends you to the *Financial Analysis* worksheet. This worksheet contains a variety of financial summary information and results, including breakdowns of annual energy costs, levelized costs, lifecycle system costs, and payback periods. An energy value solver enables you to allocate the value of your system's total energy among the different energy types: electricity, heat, and hydrogen. Click the radio button corresponding to the energy type for which you want to calculate a value. Then, enter or accept the default values[1] for the two orange fields. The blue field corresponding to the radio button is calculated automatically, thus completing the allocation of values (in $/kWh) for each energy type. Also calculated are the value of hydrogen in $/kg and the total yearly value of each energy type. You can perform sensitivity analyses from the *Financial Analysis* worksheet. Click the tab for the *Energy and Emissions* worksheet to view summary energy and emissions results. Detailed results can be found in the *HOURLY RESULTS* worksheet.

---

[1] The default value for electricity is the average electricity cost for your system if you had purchased all electricity from the grid. The default heat value is based on the cost of heating with natural gas (this is the same value as the cost of supplementary heating in the table below). The default hydrogen cost is based on the cost of hydrogen from a standalone SMR system, assuming the same cost of natural gas feedstock as for the high-temperature fuel cell.

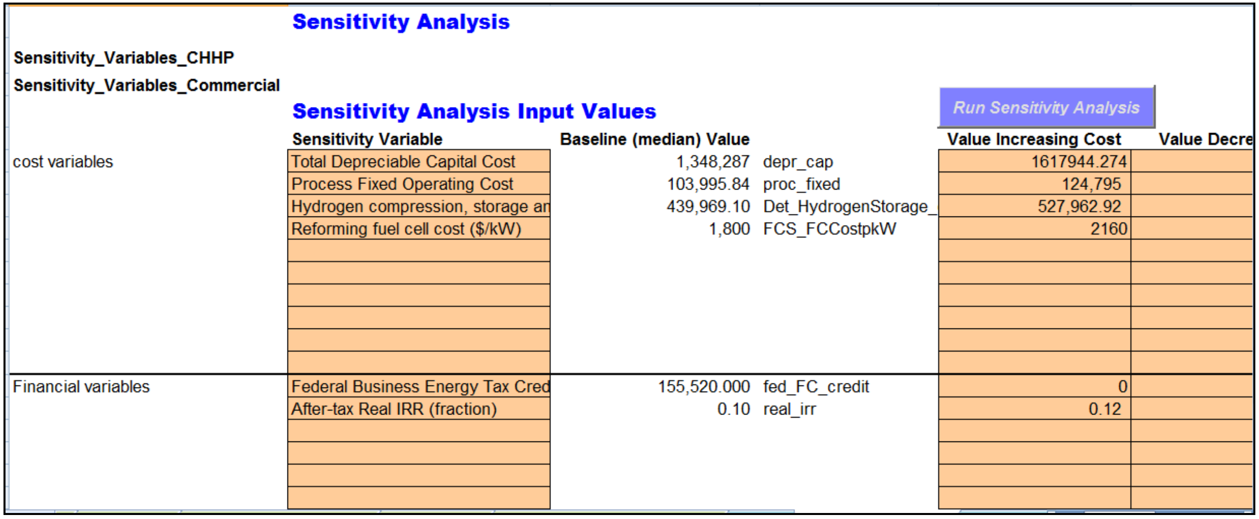
Financial Analysis Worksheet, Energy Value Solver



System Energy to Building (kWh)		Select Value to Solve for	$/kWh	Total Avoided Cost and/or Revenue per Year
System net electricity to building	1,841,176	●	0.226	$ 415,665
Fuel cell system heat	1,051,305	○	0.040	$ 42,391
Hydrogen	0	○	0.000	$ -
		Hydrogen ($/kg)	$0.00	
Annual total	2,892,481			$ 458,056
Electricity Sold (kWh)			$/kWh	Total Revenue per Year
Electricity sold			0.084	$ 820
Supplementary Building Electricity			$/kWh	Total Cost per Year
Supplementary electricity	1,512,259		0.108	$ 162,717
Supplementary heat	613,312		0.039	$ 23,819
Annual total	2,125,571			$ 186,536

Energy value solver

Financial Analysis Worksheet, Sensitivity Analysis



Sensitivity Analysis

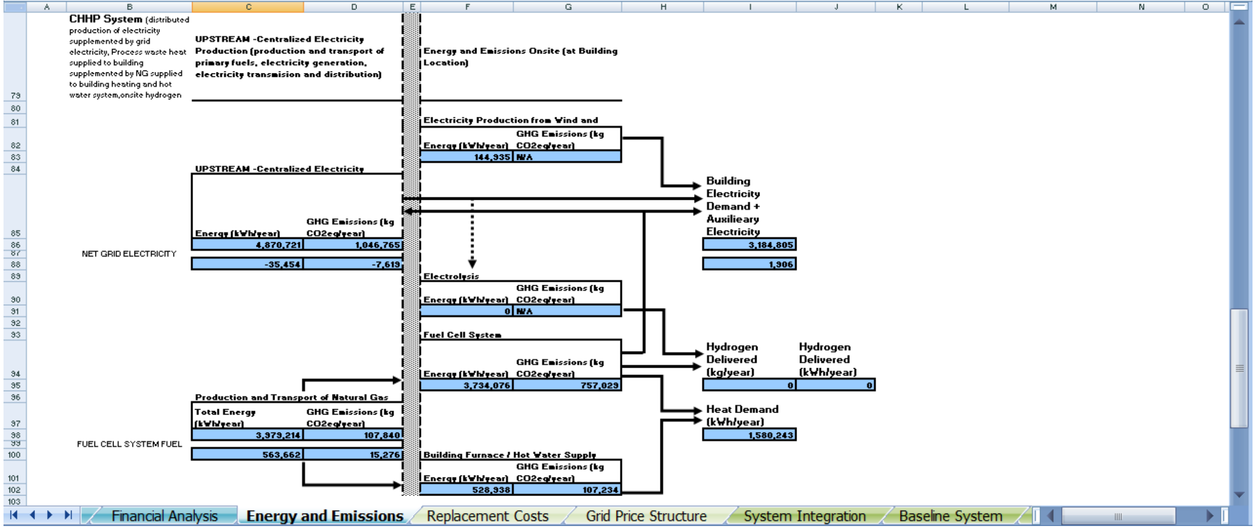
Sensitivity_Variables_CHHP

Sensitivity_Variables_Commercial

Sensitivity Analysis Input Values

	Sensitivity Variable	**Baseline (median) Value**		**Value Increasing Cost**	**Value Decre**
cost variables	Total Depreciable Capital Cost	1,348,287	depr_cap	1617944.274	
	Process Fixed Operating Cost	103,995.84	proc_fixed	124,795	
	Hydrogen compression, storage an	439,969.10	Det_HydrogenStorage_	527,962.92	
	Reforming fuel cell cost ($/kW)	1,800	FCS_FCCostpkW	2160	
Financial variables	Federal Business Energy Tax Cred	155,520.000	fed_FC_credit	0	
	After-tax Real IRR (fraction)	0.10	real_irr	0.12	

Energy and Emissions Worksheet, Energy and GHG Flows



CHHP System (distributed production of electricity supplemented by grid electricity, Process waste heat supplied to building supplemented by NG supplied to building heating and hot water system,onsite hydrogen

UPSTREAM -Centralized Electricity Production (production and transport of primary fuels, electricity generation, electricity transmision and distribution)

Energy and Emissions Onsite (at Building Location)

UPSTREAM -Centralized Electricity

Energy (kWh/year)	GHG Emissions (kg CO2eq/year)
4,870,721	1,046,765
-35,454	-7,619

NET GRID ELECTRICITY

Production and Transport of Natural Gas

Total Energy (kWh/year)	GHG Emissions (kg CO2eq/year)
3,979,214	107,840
563,662	15,276

FUEL CELL SYSTEM FUEL

Electricity Production from Wind and

Energy (kWh/year)	GHG Emissions (kg CO2eq/year)
144,935	N/A

Electrolysis

Energy (kWh/year)	GHG Emissions (kg CO2eq/year)
0	N/A

Fuel Cell System

Energy (kWh/year)	GHG Emissions (kg CO2eq/year)
3,734,076	757,029

Building Furnace / Hot Water Supply

Energy (kWh/year)	GHG Emissions (kg CO2eq/year)
528,938	107,234

Building Electricity Demand + Auxilieary Electricity
3,184,805
1,906

Hydrogen Delivered (kg/year)	Hydrogen Delivered (kWh/year)
0	0

Heat Demand (kWh/year)
1,580,243

In the FCPower Model results, the modeled system is compared to a “baseline” case for which building electricity is supplied by the grid, heat is supplied by a natural gas space heating and hot water system, and hydrogen is supplied by a standalone forecourt SMR and dispensing system.

Costs for the baseline hydrogen production and dispensing system are derived from the H2A current timeframe distributed natural gas hydrogen production case study (Current Forecourt Hydrogen Production from Natural Gas [1,500 kg per day] version 3.0) published at www.hydrogen.energy.gov/h2a_prod_studies.html. The H2A case study was scaled to various sizes to derive the cost correlation equations used in the FCPower Model. The user can select either 350 bar refueling or 700 bar refueling for the baseline station.

1.6 Technical Support

Information related to the FCPower Model will be posted at www.hydrogen.energy.gov/fc_power_analysis.html as it becomes publicly available. Also visit the Web site to download the most updated version of the model. For technical questions not answered by this guide or the Web site, contact:

Darlene Steward, National Renewable Energy Laboratory
303-275-3837, darlene.steward@nrel.gov

2 Designs of the FCPower Model Fuel Cell Systems

2.1 Introduction

The FCPower Model simulates the performance of three types of CHP systems: one based on MCFCs, one based on PAFCs, and one based on SOFCs. Each type of fuel cell can be integrated with other components to operate as a CHP system alone or as a CHHP system that co-produces hydrogen. The CHHP system design has been developed for multiple platforms, but currently only a MCFC system has been built as a large-scale demonstration unit.

The MCFC, PAFC, and SOFC system concepts were modeled using ASPEN Plus, a steady-state thermodynamics simulation software. ASPEN is an industry-standard software for modeling and designing chemical plants. It performs detailed mass and energy balances on various unit operations such as reactors, compressors, and condensers. The CHHP systems models use conventional industrial unit operations integrated into a novel system. The analysis assumes that near-term technology improvements currently under development are in place, the systems are fully integrated, and moderate production volumes have reduced costs from current stationary fuel cell installations.

The FCPower Model simulations were created using a two-step process. First, detailed and thermodynamically correct CHP/CHHP systems were designed using ASPEN Plus. Then, these detailed models were used to create simplified linear models of system performance within the FCPower Model framework so that FCPower results approximate the ASPEN results within a reasonable range of system performance.

This section describes the basic operation of MCFCs, PAFCs, and SOFCs and details the CHP/CHHP systems that were designed and modeled using ASPEN. It also discusses modeling of the fuel cell systems using the FCPower Model and the correlation of FCPower results with ASPEN model results.

2.2 Molten Carbonate Fuel Cell System

Molten carbonate fuel cells use an electrolyte composed of a molten carbonate salt mixture suspended in a porous, chemically inert ceramic lithium aluminum oxide matrix [1]. Because they operate at extremely high temperatures (650°C and above), non-precious metals can be used as catalysts at the anode and cathode, which reduces costs.

Molten carbonate fuel cells can be more efficient than PAFCs, with efficiencies approaching 50%, compared with 37%–42% for PAFCs. For MCFC configurations in which waste heat is used for additional electricity generation, electrical efficiencies greater than 60% are possible, and overall fuel efficiencies can be as high as 85%.

Unlike alkaline, phosphoric acid, and polymer electrolyte membrane fuel cells, MCFCs do not require an external reformer to convert fuels to hydrogen. Owing to the high operating temperature, fuels are converted to hydrogen within the fuel cell itself via SMR, which reduces system complexity. In addition, MCFCs are not prone to carbon monoxide (CO) poisoning; in fact, CO is used as fuel along with hydrogen (H_2).

The primary disadvantage of current MCFC technology is durability. The high temperatures at which these cells operate and the corrosive electrolyte used accelerate component breakdown and corrosion, decreasing cell life. Corrosion-resistant component materials are being developed along with fuel cell designs that increase cell life without decreasing performance. Another disadvantage of MCFCs is their dynamic performance. Because the system must balance the fuel cell temperature while maintaining an even temperature distribution, long times are required for the temperature to distribute from one power level to another.

2.2.1 Molten Carbonate Fuel Cell Operation

The following description of MCFC operation is taken from the *Fuel Cell Handbook*, 7th edition [1]. See that reference for additional details. Figure 1 is a schematic of an MCFC's operating configuration. The following are the half-cell electrochemical reactions:

Equation 1. $H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$ **(at the anode)**

Equation 2. $\frac{1}{2}O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$ **(at the cathode)**

The following is the overall cell reaction:

Equation 3. $H_2 + \frac{1}{2}O_2 + CO_2\ (\text{cathode}) \rightarrow H_2O + CO_2\ (\text{anode})$

Besides the reaction involving H_2 and O_2 to produce H_2O, this equation shows a transfer of CO_2 from the cathode gas stream to the anode gas stream via the CO_3^{2-} ion. The need for CO_2 at the cathode requires that either CO_2 is transferred from the anode exit gas to the cathode inlet gas, CO_2 is produced by combusting the anode exhaust gas (which is mixed directly with the cathode inlet gas), or CO_2 is supplied from an alternate source. It is usual practice in an MCFC system that the CO_2 generated at the anode (right side of Equation 1) be routed (external to the cell) to the cathode (left side of Equation 2).

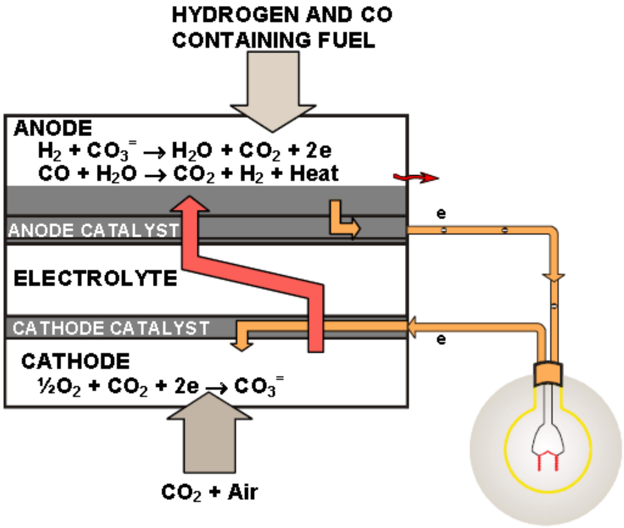


Figure 1. Schematic of MCFC operation [1]

2.2.2 ASPEN Model of MCFC-CHP System

The MCFC-CHP system developed in ASPEN uses fuel, air, and water inputs to produce electricity and heat. Figure 2 is a generalized schematic of the system. Figure 23 and Table 1 at the end of this section show the detailed ASPEN process flow diagram and accompanying energy and material flows. Some of the key process steps are described below, numbered to correspond with the numbers in Figure 2.

1. **Water and fuel inputs:** Water and fuel (e.g., natural gas) enter the system. The model uses a steam-to-carbon ratio of 1.5, which is typical of current industry applications. The feedstock is cleaned of contaminants that can degrade the system, such as sulfur (from the fuel) and chlorides (from the water). The cleanup subsystems were not modeled in ASPEN, because multiple technologies could be used, and many of them do not affect the mass and energy balance of the system significantly. The purified water and fuel are vaporized before entering the fuel cell, where internal reforming produces a mixture containing H_2 and CO. Heat for vaporizing the fuel and water is taken from the cathode exhaust stream.

2. **MCFC electricity production:** Seventy percent of the caloric content of the fuel entering the anode is used to make electricity via the reactions described in Equations 1–3. This is a typical percentage used in current MCFC designs; it provides high performance while accounting for flow distribution and mass transport limitations in the anode. The fuel mixture not used to make electricity passes through the fuel cell to the burner.

3. **Burner and cathode air supply:** Air supplied to the cathode has multiple functions. It oxidizes the anode exhaust to eliminate emissions. The burner exhaust contains the CO_2 and O_2 required for the cathode reaction. The burner

air regulates the temperature of the fuel cell, carrying heat away from the fuel cell reaction (650°C). Heat from the cathode exhaust is then used for steam generation and providing heat output.

4. **Building heating system:** Excess heat from the fuel cell is used to heat the building. In the ASPEN model, water enters the exhaust heat exchanger at 60°C, is heated to 80°C, and then is circulated to heat the building. Excess fuel cell heat not needed to heat the building is vented. This range of heat-recovery temperatures is most commonly seen in large building installations.

5. **Power electronics:** The inverter transforms DC electricity produced in the fuel cell to AC electricity. The 93% efficiency is typical of standard inverters available today. In addition, the power electronics typically supply the power required by the fuel cell blowers, pumps, and valves.

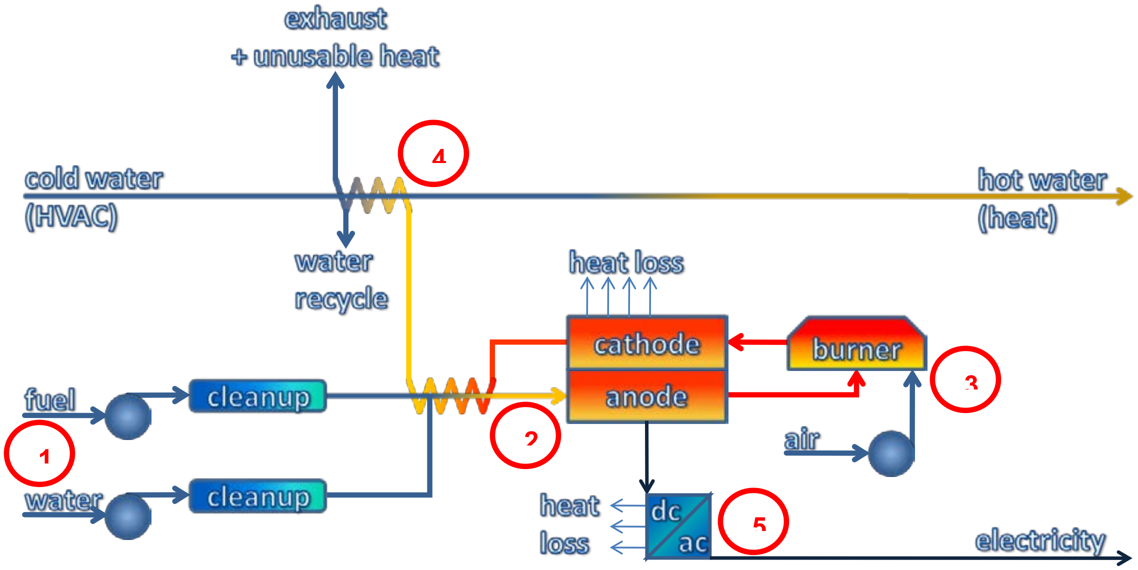


Figure 2. Schematic of modeled MCFC-CHP system

2.2.3 ASPEN Model of MCFC-CHHP System

The MCFC-CHHP system developed in ASPEN uses fuel, air, and water inputs to produce electricity, heat, and hydrogen. It operates much like the CHP system discussed above, with the exception that hydrogen from the anode exhaust gas is enriched, separated, and compressed for storage and dispensing. The system operates in two modes. In the hydrogen production mode, 70% of the caloric content of the fuel mixture entering the anode is used to make electricity (as in the CHP system), and 70% of the hydrogen in the anode exhaust gas is recovered and stored. In the hydrogen over-production mode, 60% of the caloric content of the fuel mixture entering the anode is used to make electricity, and 75% of the hydrogen in the anode exhaust gas is recovered and stored. Both modes reduce the amount of energy available for heating the building. Figure 3 is a generalized schematic of the system. Figure 23, Table 2, and Table 3 at the end of this section show the detailed ASPEN process flow diagram and accompanying energy and material flows. Some of the key process steps are described below, numbered to correspond with the numbers in Figure 3.

6. **Anode exhaust shift reaction:** Hydrogen produced via internal reforming in the fuel cell and not used to produce electricity exits the anode in the exhaust stream. This stream contains CO, H_2, and H_2O. The stream is cooled to ~300°C by using PSA exhaust. The gas then enters the shift catalyst, which converts CO and H_2O to H_2 via the following reaction:

   Equation 4. $CO + H_2O \rightarrow CO_2 + H_2$

7. **Gas compression:** Most of the water is removed from the gas stream by chilling to ambient temperatures, and the gas stream is compressed to 150 psig as per standard industry practice for PSA. A multi-stage compressor is used with a maximum compression ratio of 2:1 per stage and intercoolers to 25°C. In the ASPEN model, water is removed once again after the compression stage.

8. **Pressure swing adsorption (PSA):** Hydrogen is recovered via PSA before being compressed to 6,250 psig for storage and dispensing. The remaining gas stream (including unrecovered H_2) is returned to the burner. Although other hydrogen separation technologies, such as electrochemical hydrogen pumping, might eventually prove to be better suited to CHHP applications, PSA was selected for the model because of its market availability and expected use in the first commercial CHHP systems.

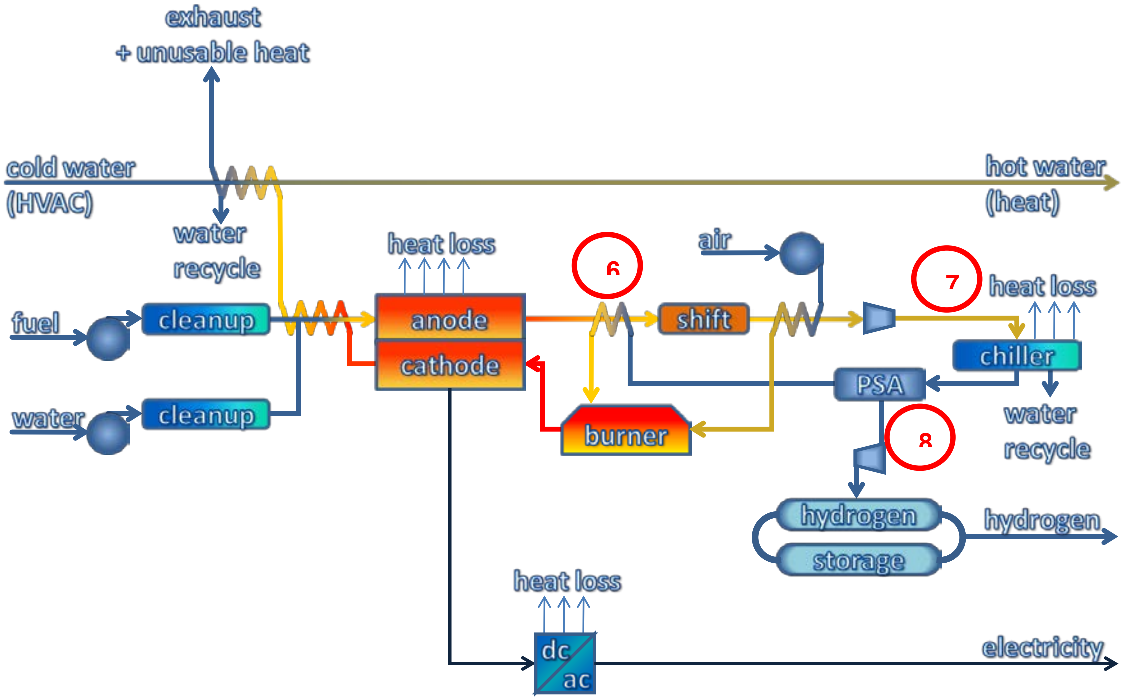
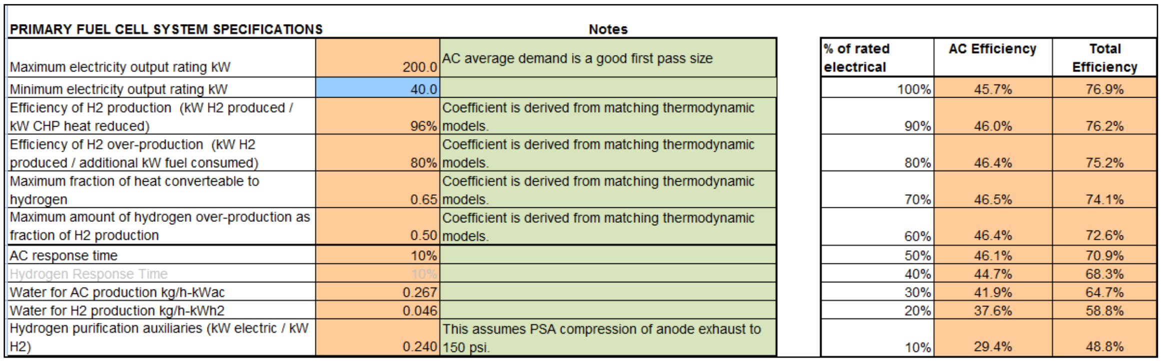


Figure 3. Schematic of modeled MCFC-CHHP system

2.2.4 Modeling MCFC Systems with the FCPower Model

The FCPower Model was designed with a linear model that mimics the performance of the ASPEN-modeled MCFC CHP/CHHP systems described above. The system tracks electricity demand, with heat and hydrogen as co-products. Hydrogen is the primary co-product and has production priority over heat.

Most of the fuel cell system parameters—found in the *Equipment Specification* worksheet—are set automatically in the FCPower Model to match the system parameters established in the ASPEN models and to meet the FCPower energy demand profiles. Many users will not need to change any of the values on this worksheet. The technical values that can be changed by users are shown in orange in Figure 4 and described briefly below.



PRIMARY FUEL CELL SYSTEM SPECIFICATIONS		Notes
Maximum electricity output rating kW	200.0	AC average demand is a good first pass size
Minimum electricity output rating kW	40.0	
Efficiency of H2 production (kW H2 produced / kW CHP heat reduced)	96%	Coefficient is derived from matching thermodynamic models.
Efficiency of H2 over-production (kW H2 produced / additional kW fuel consumed)	80%	Coefficient is derived from matching thermodynamic models.
Maximum fraction of heat converteable to hydrogen	0.65	Coefficient is derived from matching thermodynamic models.
Maximum amount of hydrogen over-production as fraction of H2 production	0.50	Coefficient is derived from matching thermodynamic models.
AC response time	10%	
Hydrogen Response Time	10%	
Water for AC production kg/h-kWac	0.267	
Water for H2 production kg/h-kWh2	0.046	
Hydrogen purification auxiliaries (kW electric / kW H2)	0.240	This assumes PSA compression of anode exhaust to 150 psi.

% of rated electrical	AC Efficiency	Total Efficiency
100%	45.7%	76.9%
90%	46.0%	76.2%
80%	46.4%	75.2%
70%	46.5%	74.1%
60%	46.4%	72.6%
50%	46.1%	70.9%
40%	44.7%	68.3%
30%	41.9%	64.7%
20%	37.6%	58.8%
10%	29.4%	48.8%

Figure 4. FCPower Model MCFC Equipment Specification worksheet

Maximum electricity output rating—The default value for this field is set to the average electricity demand from the *AC Demand* worksheet. This is a reasonable first estimate for the fuel cell system's maximum electrical output. However, commercial MCFC systems are available in a limited range of sizes, so users might want to research currently available products and replace the default value with a value from one of these products. Optimal economic results are obtained when the fuel cell is sized to operate at nearly full power all the time. Note that system performance is scalable. For example, doubling the size of the fuel cell doubles the potential hydrogen production. This assumption is reasonable because the modeled fuel cell systems are large; thus their heat-loss effects are relatively small.

Efficiency of H2 production—The efficiency of hydrogen production is defined as the kW of hydrogen produced from the fuel cell anode exhaust gas divided by the kW reduction in the available CHP (usable) heat [fuel used × (total efficiency – electrical efficiency)]. The default value is derived from the system modeled in ASPEN and accounts for the recovery of the PSA system and heat-quality reduction in the anode exhaust. Exhaust heat recovery is assumed with a 60°–80°C cooling loop. Note that this definition of efficiency does not include auxiliaries required for running the PSA unit or compressing the hydrogen. Those inputs are accounted for within the *MODEL* worksheet.

Efficiency of H2 over-production—The efficiency of hydrogen over-production is defined as the kW of hydrogen produced from addition of excess fuel divided by the kW of additional fuel consumed. The default value is derived from the system modeled in ASPEN. Note that this definition of efficiency does not include auxiliaries required for running the PSA unit or compressing the hydrogen. Those inputs are accounted for within the *MODEL* worksheet.

Maximum fraction of heat convertible to hydrogen—The maximum fraction of heat convertible to hydrogen is defined as the fraction of CHP heat that can be converted to hydrogen. The default value is derived from the system modeled in ASPEN.

Maximum amount of hydrogen over-production as fraction of H2 production—The maximum hydrogen over-production potential is defined as the fractional increase in the total amount of hydrogen that can be produced if more fuel is supplied to the fuel cell than is needed for electricity production at rated power. For example, a value of 0.5 means that for every kg/h of hydrogen produced an additional 0.5 kg/h of hydrogen can be over-produced by increasing fuel consumption of the system. Thus, a total of 1.5 kg/h of hydrogen would be produced while increasing the fuel consumption rate. The default value is derived from the system modeled in ASPEN.

AC Efficiency—The default values for these fields are set based on the MCFC system modeled in ASPEN, but users can change the values (e.g., based on the specifications of a currently available system). Note that total efficiency always must be higher than electrical efficiency.

Total efficiency—Values for total efficiency at part load are generated using the ASPEN model. Total efficiency is typically lower at low-power operation because fuel is consumed to maintain the operating temperature. Total efficiency depends largely on fuel cell exhaust temperature. For this ASPEN analysis, a heating loop of 60°–80°C (140°–176°F) is assumed: heat-recovery water enters from the building at 60°C and returns to the building at 80°C. This is a very common range for heating, but if, for example, a building requires 40°–60°C (104°–140°F) operation, this would result in better total efficiency because more heat would be captured from the exhaust.

AC Response Time—This is the amount that the fuel cell electrical output can change per hour, e.g., a value of 10% means the AC output can change by a maximum of 10% per hour.

Water for AC Production—The default value for this field is based on the MCFC system modeled in ASPEN, but users can change it to any positive number, e.g., to match specifications of currently available systems. Note that, in general, less water is required for systems that operate in condensing conditions. If the exhaust is cooled sufficiently, condensed water can be used for fuel cell operation.

Water for H2 Production—The default value for this field is based on the MCFC system modeled in ASPEN, but users can change it to any positive number, e.g., to match specifications of currently available systems. In the model, PSA is used for hydrogen purification. Water is extracted from the syngas before entering the PSA; therefore, less makeup water is typically required in CHHP mode.

Hydrogen Purification Auxiliaries—This defines the electrical power requirements for the compressor component of the PSA system.

2.2.5 Correlation of MCFC ASPEN Model and FCPower Model

Sensitivity analyses were performed to determine the correlation between results from the detailed MCFC system ASPEN model and the simplified model of system performance created for the FCPower Model. Figure 5 (CHP), Figure 6 (CHHP), and Figure 7 (CHHP with hydrogen over-production) contain ASPEN and FCPower Model results showing the electricity, heat, and hydrogen produced and fuel used at different fuel cell system power levels. The size of the system modeled is 1.4 MW.

For each analysis, the correlation generally decreases as the system utilization decreases owing to the linear nature of the FCPower Model and the non-linear performance of fuel cells. FCPower Model results at system utilization levels below 20% do not correlate well with ASPEN results; therefore, system utilization rates below this level are not used in the FCPower Model. If energy demand drops below this level, the model continues to operate at 20%, and excess electricity is sold to the grid. Future versions of the FCPower Model may increase fit complexity to accommodate better system performance fit.

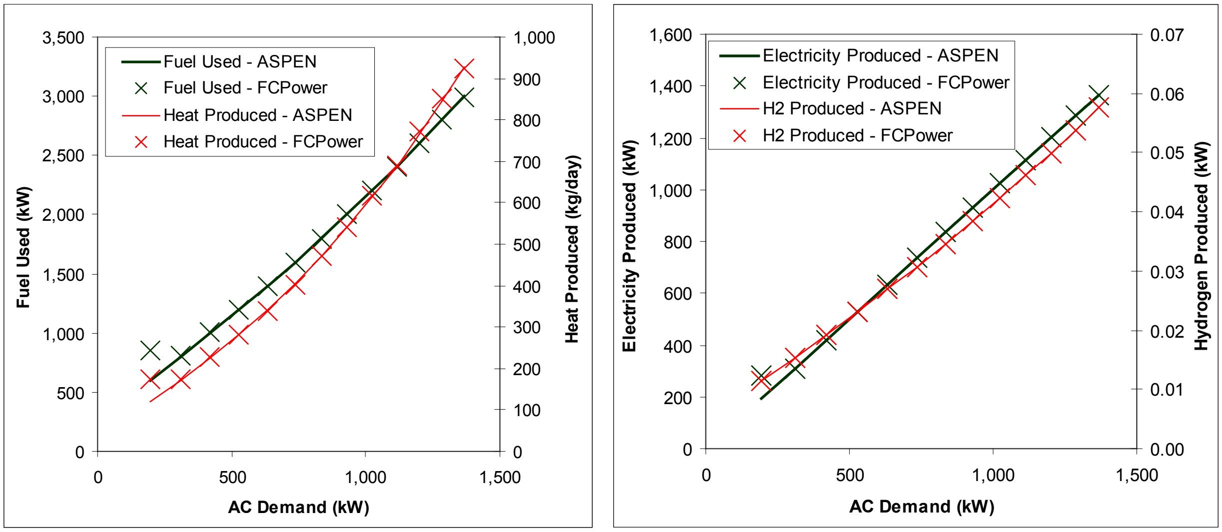


Figure 5. Correlation of ASPEN and FCPower Model results for MCFC-CHP system

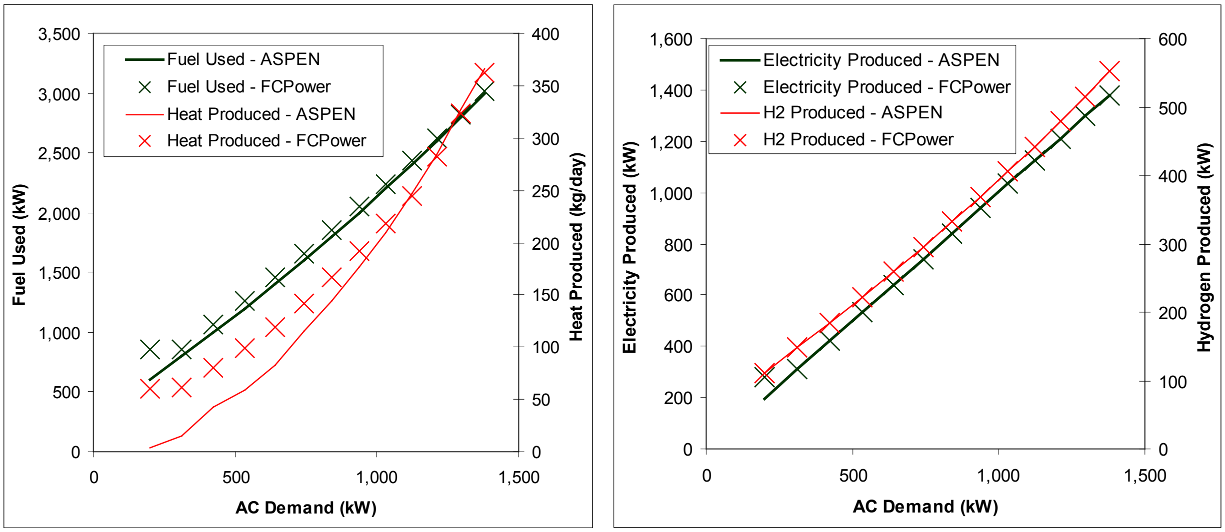


Figure 6. Correlation of ASPEN and FCPower Model results for MCFC-CHHP system

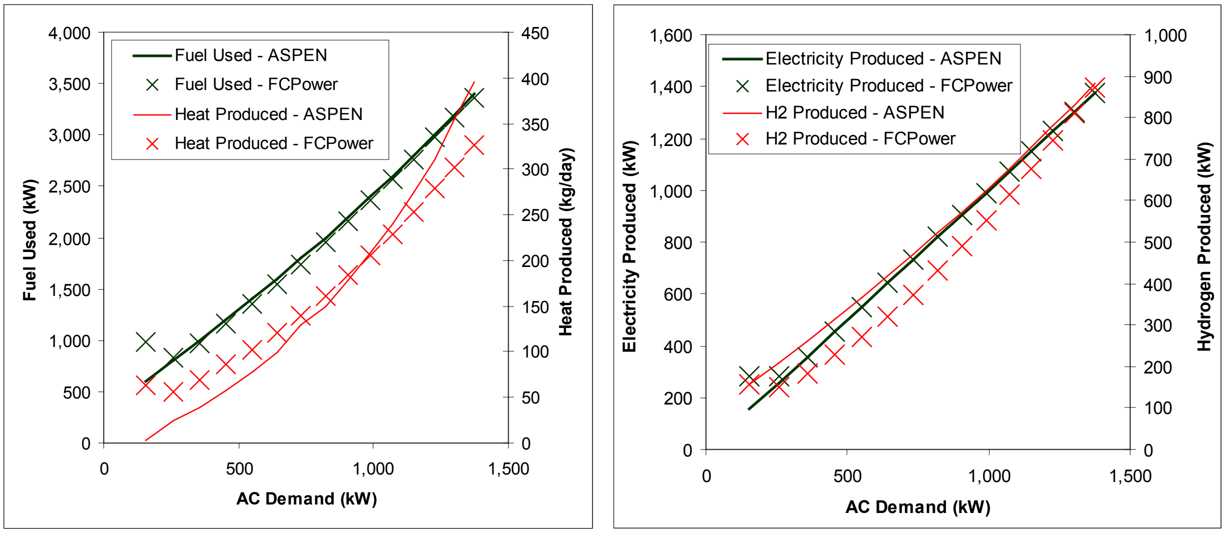


Figure 7. Correlation of ASPEN and FCPower Model results for MCFC-CHHP system, H_2 over-production

2.3 Phosphoric Acid Fuel Cell System

Phosphoric acid fuel cells use liquid phosphoric acid as an electrolyte—the acid is contained in a Teflon-bonded silicon carbide matrix—and porous carbon electrodes containing a platinum catalyst [1]. The PAFC is considered the "first generation" of modern fuel cells. It is one of the most mature cell types and the first to be used commercially. This type of fuel cell is typically used for stationary power generation, but some PAFCs have been used to power large vehicles such as city buses.

Phosphoric acid fuel cells are more tolerant of impurities in reformed fossil fuels than are PEM fuel cells, which are easily "poisoned" by CO and hydrogen sulfide (H_2S). At lower temperatures, CO and H_2S bind to catalyst surfaces, masking the catalyst from use for hydrogen dissociation. This problem is reduced in PAFCs because they operate at approximately 200°C. PAFCs have a lower power density than most other fuel cell types; however, they have significantly longer lifetimes, about 10 years for state-of-the-art stacks. The electrical efficiency of PAFC systems is typically about 40% at the beginning of their lives and at rated power. This is only slightly more efficient than combustion-based power plants, which typically operate at 33%–35% efficiency, but the distributed nature of CHP systems avoids electrical transmission losses. Depending on heat recovery, the total efficiency of PAFC systems can reach 85% in CHP mode.

2.3.1 Phosphoric Acid Fuel Cell Operation

The following description of PAFC operation is taken from the *Fuel Cell Handbook*, 7th edition [1]. See that reference for additional details. Figure 8 is a schematic of a PAFC's operating configuration. The following are the half-cell electrochemical reactions:

Equation 5. $H_2 \rightarrow 2H^+ + 2e^-$ **(at the anode)**

Equation 6. $\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$ **(at the cathode)**

The following is the overall cell reaction:

Equation 7. $\frac{1}{2}O_2 + H_2 \rightarrow H_2O$

The electrochemical reactions occur on highly dispersed electro-catalyst particles supported on carbon black. Platinum or platinum alloys are used as the catalyst at both electrodes.

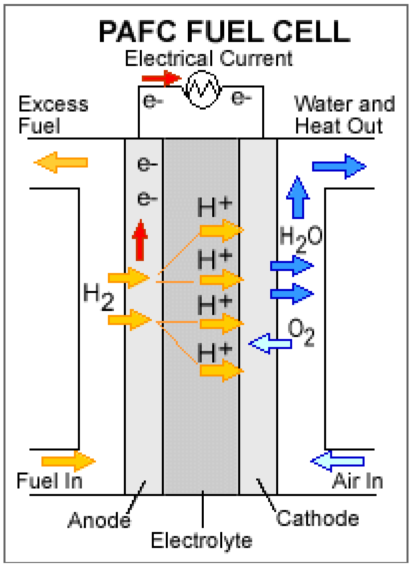


Figure 8. Schematic of PAFC operation [2]

Natural gas (CH_4) is the most commonly used fuel for PAFC systems. It is converted to hydrogen and used to produce electricity via the following reactions:

Equation 8. $CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$ **(reforming reaction)**

Equation 9. $4H_2 \rightarrow 8H^+ + 8e^-$ **(anode reaction)**

Equation 10. $2O_2 + 8H^+ + 8e^- \rightarrow 4H_2O$ **(cathode reaction)**

Combining these equations gives the overall reaction of methane combustion:

Equation 11. $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ **(overall reaction)**

2.3.2 ASPEN Model of PAFC-CHP System

The PAFC-CHP system developed in ASPEN uses fuel, air, and water inputs to produce electricity and heat. Figure 9 is a generalized schematic of a PAFC system. Figure 24 and Table 4 at the end of this section show the detailed ASPEN process flow diagram and accompanying stream table. Some of the key process steps are described below, numbered to correspond with the numbers in Figure 9.

1. **Water and fuel inputs:** Water and fuel (e.g., natural gas) enter the system. The model uses a H_2O-to-CH_4 ratio of 3.0, which is typical of current industry practices. The feedstock is cleaned of contaminants that can degrade the system, such as sulfur (from the fuel) and salts (from the water). The cleanup subsystems were not modeled in ASPEN because multiple technologies could be used, and many of them do not affect the mass and energy balance of the system significantly. Water is vaporized in the fuel cell stack's coolers, which serves to cool the fuel cell stack in addition to producing the steam needed for the reformer.

2. **Steam-methane reforming:** The SMR is a heat exchanger with two reactions occurring on each side. On the reforming side, fuel and steam are reformed to produce CO and H_2. The reforming reaction temperature in the model is 700°C. Because this reaction is endothermic, the opposing side of the heat exchanger combusts depleted and fresh fuel at 750°C to provide sufficient heat for the reforming. It is assumed that reformate exhaust is also used to preheat the steam and fuel mixture before the mixture enters the reformer, and burner exhaust is used to preheat the burner air.

3. **Shift reaction:** The stream exiting the reformer contains H_2, CO, CO_2, and H_2O. This stream enters the shift catalyst, which operates at 270°C (at low power) or 310°C (at high power) and converts CO and H_2O to H_2 via the following reaction:

   Equation 12. $CO + H_2O \rightarrow CO_2 + H_2$

4. **PAFC electricity production:** Hydrogen is supplied to the anode at a stoichiometric ratio of 1.15 (i.e., 15% more H_2 is present than can react with the amount of O_2 present). Of the fuel entering the anode, 87% is used to make electricity via the reactions described in Equations 5–7. The polarization curve is defined by a linear relationship with cell voltage of 0.77 V at minimum power (100

kW) and 0.675 V at maximum power (400 kW). The depleted reformate from the anode exhaust is fed to the burner.

5. **Cathode air supply and water recovery:** Air is supplied to the cathode at a stoichiometric ratio of 2.0 (i.e., twice as much O_2 is fed than stoichiometrically needed to react with the amount of H_2 consumed). Water created via the cathode reaction is recovered if the fuel cell exhaust is cooled to a sufficiently low temperature (~50°C). If the exhaust is not cooled sufficiently, product vapor escapes, and makeup water is fed into the system.

6. **Building heating system:** Excess heat from the fuel cell is used for heat cogeneration. In the ASPEN model, water enters the fuel cell heat recovery subsystem at 60°C and is heated to 80°C before returning to the facility. Heat is captured first from the exhaust to ensure the maximum possible condensation and overall heat recovery. Excess heat from the stack is then captured by cooling excess steam and water exiting the fuel cell coolers.

7. **Power electronics:** The inverter transforms DC electricity produced in the fuel cell into AC electricity. An efficiency of 93% is assumed for this conversion; higher efficiencies are possible for large applications. In addition, the power electronics typically supply the power required by the fuel cell blowers, pumps, and valves. Within the ASPEN model, some power is used for fixed electrical draws such as control systems, cabinet ventilation, solenoids, and fixed-speed auxiliaries.

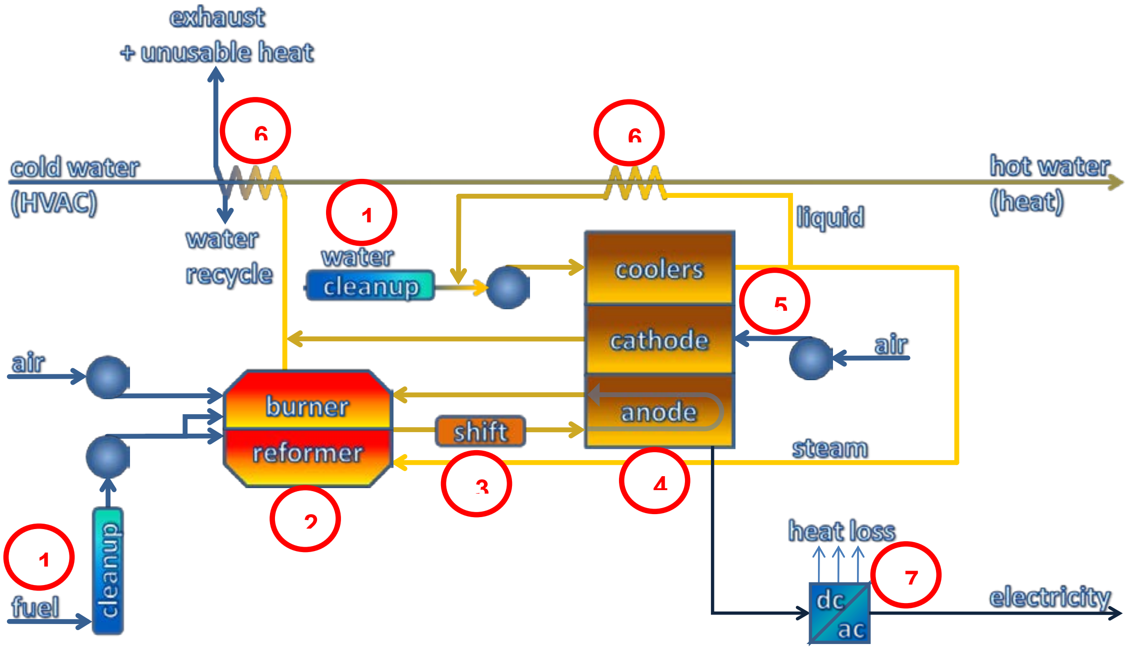


Figure 9. Schematic of modeled PAFC-CHP system

2.3.3 ASPEN Model of PAFC-CHHP System

The PAFC-CHHP system developed in ASPEN uses fuel, air, and water inputs to produce electricity, heat, and hydrogen. It operates much like the CHP system discussed above, with the exception that some of the reformate output from the shift reaction is diverted for purification and storage. In addition, a supplementary burner is added to supplement the heat needed for steam generation. This reduces the amount of energy available for producing electricity and heating the building. Figure 10 is a generalized schematic of the system. Figure 24 and Table 5 at the end of this section show the detailed ASPEN process flow diagram and accompanying energy and material flows. Some of the key process steps are described below, numbered to correspond with the numbers in Figure 10.

8. **Gas diversion and compression:** Some of the reformate stream exiting the shift reaction is diverted away from the fuel cell stack. Most of the water is removed from the stream by chilling to ambient temperatures, and the stream is compressed to 150 psig as per standard industry practice for PSA. A multi-stage compressor is used with a maximum compression ratio of 2:1 per stage and intercoolers to 25°C. In the ASPEN model, water is removed once again after the compression stage.

9. **Pressure swing adsorption (PSA):** About 75% of the hydrogen in the gas stream is recovered via PSA before being compressed to 6,250 psig for storage and dispensing. The remaining gas stream (including unrecovered H_2) is fed to the burner. Although other hydrogen separation technologies, such as electrochemical hydrogen pumping, might eventually prove to be better suited to CHHP applications, PSA was selected for the model because of its market availability.

10. **Supplementary heat:** When steam is produced for normal fuel cell applications, it is generated mostly using heat from the fuel cell stack. However, if H_2 production is high and electricity production is low, additional steam heat must be generated.

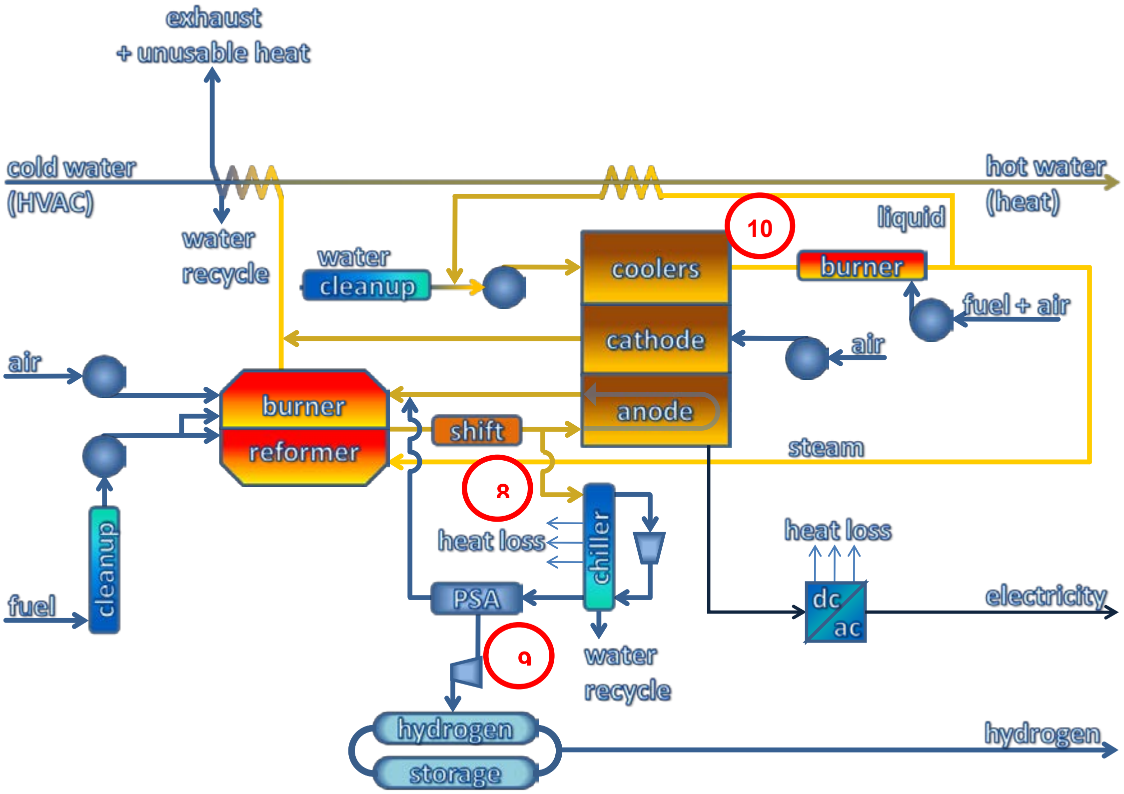
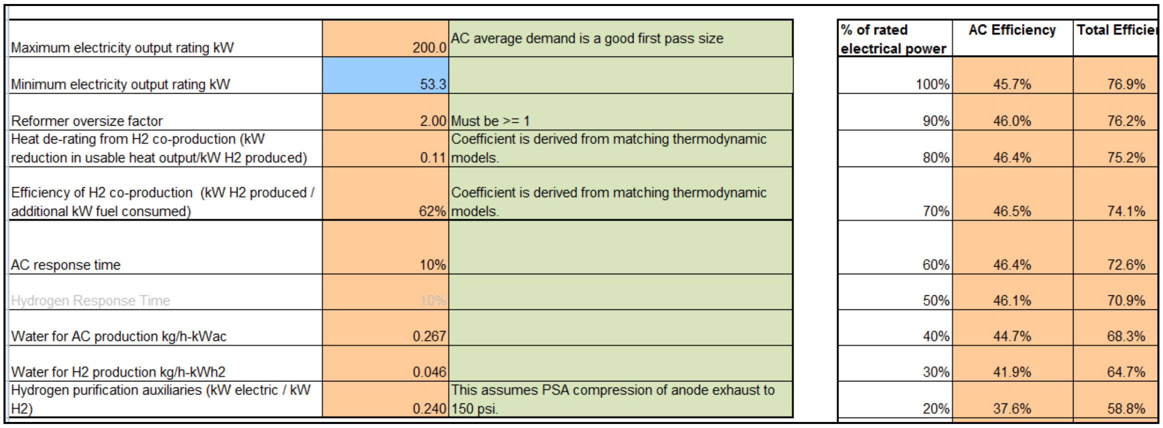


Figure 10. Schematic of modeled PAFC-CHHP system

2.3.4 Modeling PAFC Systems with the FCPower Model

The FCPower Model was designed with a linear model that mimics the performance of the ASPEN-modeled PAFC CHP/CHHP systems described above. The model can make meeting electricity demand (input via the *AC Demand* worksheet) or heat demand (*Heat Demand* worksheet) the highest priority; this is selected via the radio buttons in the *Equipment Specification* worksheet.

Most of the fuel cell system parameters—found in the *Equipment Specification* worksheet—are set to default values in the FCPower Model to match the system parameters established in the ASPEN models. Most users will not need to change any of the values on this worksheet other than the fuel cell capacity. The technical values that can be changed by users are shown in orange in Figure 11 and described briefly below.



Maximum electricity output rating kW	200.0	AC average demand is a good first pass size
Minimum electricity output rating kW	53.3	
Reformer oversize factor	2.00	Must be >= 1
Heat de-rating from H2 co-production (kW reduction in usable heat output/kW H2 produced)	0.11	Coefficient is derived from matching thermodynamic models.
Efficiency of H2 co-production (kW H2 produced / additional kW fuel consumed)	62%	Coefficient is derived from matching thermodynamic models.
AC response time	10%	
Hydrogen Response Time	10%	
Water for AC production kg/h-kWac	0.267	
Water for H2 production kg/h-kWh2	0.046	
Hydrogen purification auxiliaries (kW electric / kW H2)	0.240	This assumes PSA compression of anode exhaust to 150 psi.

% of rated electrical power	AC Efficiency	Total Efficie
100%	45.7%	76.9%
90%	46.0%	76.2%
80%	46.4%	75.2%
70%	46.5%	74.1%
60%	46.4%	72.6%
50%	46.1%	70.9%
40%	44.7%	68.3%
30%	41.9%	64.7%
20%	37.6%	58.8%

Figure 11. FCPower Model PAFC Equipment Specification worksheet

Maximum electric output rating—The default value for this field is set to the average electricity demand from the *AC Demand* worksheet. This is a reasonable first estimate for the fuel cell system's maximum electrical output. However, commercial PAFC systems are available in a limited range of sizes, so users might want to research currently available products and replace the default value with a value from one of these products. Optimal economic results are obtained when the fuel cell is sized to operate at nearly full power all the time. Note that system performance is scalable. For example, doubling the size of the fuel cell doubles the potential hydrogen production. This assumption is reasonable because the modeled fuel cell systems are large; thus their heat-loss effects are relatively small.

Minimum electric output rating—The FCPower Model provides a close match to the ASPEN-modeled fuel cell system down to a minimum system utilization of 40%; thus the default minimum electric output rating is set to 40% of the maximum electric output rating. This value can be changed, but it should only be increased, not decreased, because the model may not return accurate results below the 40% value.

Reformer oversize factor—This value is a multiplier of the amount of reforming required for maximum electrical output. A reformer oversize factor of 1.0 means the exact amount of fuel is reformed as is needed to enable maximum electrical output only. A reformer oversize factor of 2.0 means twice the amount of fuel is reformed as is needed for maximum electrical output and so forth.

Efficiency of hydrogen co-production—The efficiency of hydrogen co-production is defined as the kW of hydrogen produced from addition of excess fuel divided by the kW of additional fuel consumed. The default value is derived from the system modeled in ASPEN.

Heat de-rating from H2 co-production—The PAFC reforming process requires heat for reforming and steam generation. In typical operation, excess heat is available after the reforming process has been satisfied. This heat is available as a co-product. However, if additional hydrogen is co-produced, steam generation requires some of the excess heat to be diverted for the additional reforming requirement. Thus, heat output is reduced when the fuel cell co-produces hydrogen. This effect is proportional; for example, doubling the hydrogen co-production doubles the heat requirement. This effect is captured in the model by the coefficient (kW reduction in usable heat output per kW of hydrogen produced) in the *Heat de-rating from H2 co-production* field. The effect was modeled using ASPEN, and the results were used to determine the value for this coefficient.

Electrical efficiency—The default values for these fields are set based on the PAFC system modeled in ASPEN, but users can change the values (e.g., based on the specifications of a currently available system). Note that total efficiency always must be higher than electrical efficiency.

Total efficiency—Values for total efficiency at part load are generated using the ASPEN model. Total efficiency is typically lower at low-power operation because fuel is consumed to maintain the operating temperature. Total efficiency depends largely on fuel cell exhaust temperature. For this ASPEN analysis, a heating loop of 60°–80°C (140°–176°F) is assumed: heat-recovery water enters from the building at 60°C and returns to the building at 80°C. This is a very common range for heating, but if, for example, a building requires 40°–60°C (104°–140°F) operation, this would result in better total efficiency because more heat would be captured from the exhaust. The usable heat fraction for the MCFC system is higher than for the PAFC system because the PAFC system operates at a lower temperature.

AC response time—This is the amount that the fuel cell electrical output can change per hour, e.g., a value of 10% means the AC output can change by a maximum of 10% per hour. The default value is 100%. Unlike the MCFC system, the default PAFC system can change instantaneously to any electrical output level between the minimum and maximum output ratings.

Water for AC production—The default value for this field is based on the PAFC system modeled in ASPEN, but users can change it to any positive number, e.g., to match specifications of currently available systems. Note that, in general, less water is required for systems that operate in condensing conditions. If the exhaust is cooled sufficiently, condensed water can be used for fuel cell operation.

Water for H2 production—The default value for this field is based on the PAFC system modeled in ASPEN, but users can change it to any positive number, e.g., to match specifications of currently available systems. In the model, PSA is used for hydrogen purification. Water is extracted from the syngas before entering the PSA; therefore, less makeup water is typically required in CHHP mode.

2.3.5 Correlation of PAFC ASPEN Model and FCPower Model

Sensitivity analyses were performed to determine the correlation between results from the detailed PAFC system ASPEN model and the simplified model of system performance created for the FCPower Model. Figure 12 (CHP) and Figure 13 (CHHP) contain ASPEN and FCPower Model results showing the fuel, electricity, hydrogen, and high-quality heat flows and efficiencies at different fuel cell system utilization levels. FCPower Model results at system utilization levels below 40% do not correlate well with ASPEN results; therefore, system utilization rates below this level are not used in the FCPower Model. If energy demand drops below this level, the model continues to operate at 40%, and excess electricity is sold to the grid.

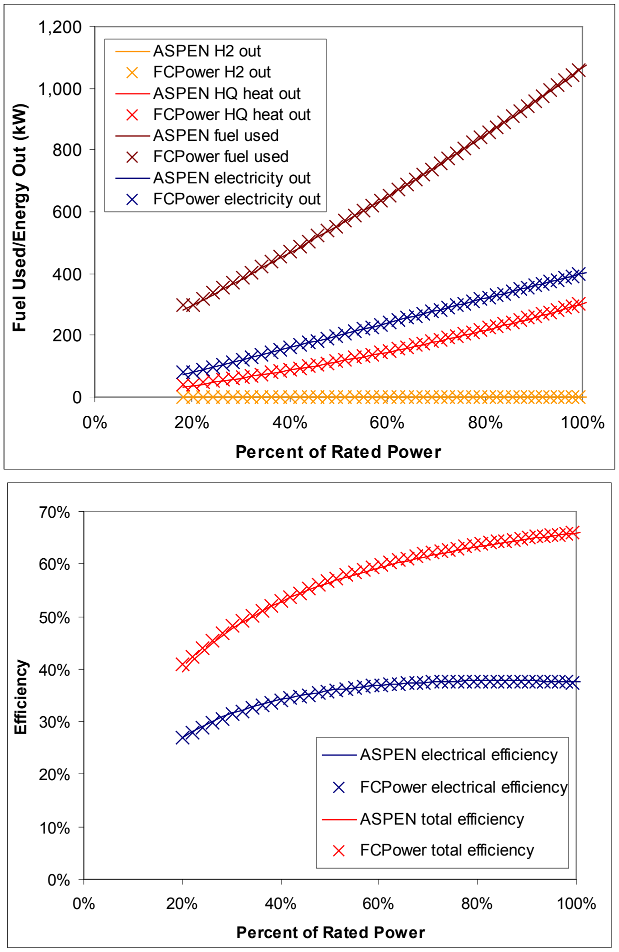


Figure 12. Correlation of ASPEN and FCPower Model results for PAFC-CHP system

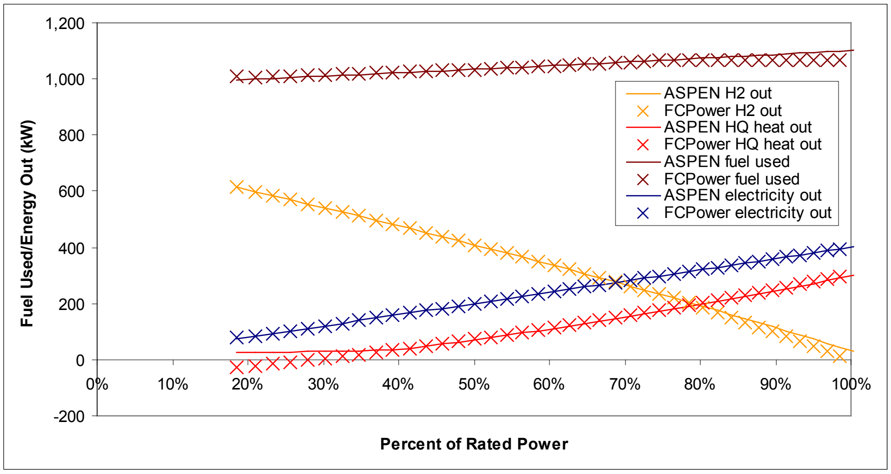


Figure 13. Correlation of ASPEN and FCPower Model results for PAFC-CHHP system

2.4 Solid Oxide Fuel Cell System

Solid oxide fuel cells use an electrolyte composed of a solid, non-porous metal oxide, usually Y_2O_3-stablilized ZrO_2 [1]. They operate at 600°–1,000°C, at which temperatures ionic conduction by oxygen ions takes place. Typically, the anode is a Ni-ZrO_2 cermet, and the cathode is Sr-doped $LaMnO_3$. Because the SOFC electrolyte is solid, there are no material-corrosion or electrolyte-management problems associated with liquid electrolytes. However, the high operating temperatures place stringent requirements on the materials.

A wide range of fuels, including various hydrocarbon fuels, can be converted by SOFCs. The high operating temperatures allow for high-efficiency power conversion, internal reforming, and high-quality byproduct heat for cogeneration or use in a bottoming cycle. Simple-cycle and hybrid SOFC systems have demonstrated efficiencies that are among the highest of any power-generation system in addition to minimal air pollutant emissions and low greenhouse gas emissions. These capabilities make SOFCs an attractive emerging technology for stationary power generation ranging from 2 kW to 100s of megawatts of capacity.

More recently, planar SOFC systems with high power densities operating at lower temperatures (700°–850°C instead of the previous norm of 900°–1,000°C) have been developed, which enables the use of less-expensive materials. This could improve the economics of SOFC applications ranging from small-scale stationary power (down to ~2 kW) to auxiliary power units for vehicles and mobile generators. SOFCs could eventually be used to supply part of the prime power in vehicles. The key technical challenge is to produce robust, high-performance SOFC stack technologies using suitable low-cost materials and fabrication methods. Derivatives from SOFC technology, such as automobile oxygen sensors, are already in widespread commercial use.

2.4.1 Solid Oxide Fuel Cell Operation

The following description of SOFC operation is taken from the *Fuel Cell Handbook*, 7th edition [1]. See that reference for additional details. Figure 14 is a schematic of an SOFC operating configuration. The following are the half-cell electrochemical reactions:

Equation 13. $H_2 \rightarrow 2H^+ + 2e^-$ (at the anode)

Equation 14. $\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$ (at the cathode)

The following is the overall cell reaction:

Equation 15. $\frac{1}{2}O_2 + H_2 \rightarrow H_2O$

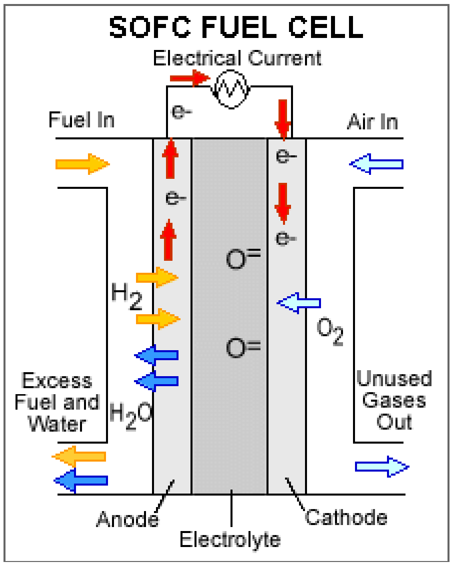


Figure 14. Schematic of SOFC operation [2]

Natural gas (CH_4) is the most commonly used fuel for SOFC systems. It is converted to hydrogen and used to produce electricity via the following reactions:

Equation 16. $CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$ (reforming reaction)

Equation 17. $4H_2 \rightarrow 8H^+ + 8e^-$ (anode reaction)

Equation 18. $2O_2 + 8H^+ + 8e^- \rightarrow 4H_2O$ (cathode reaction)

Combining these equations gives the overall reaction of methane combustion:

Equation 19. $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ (overall reaction)

2.4.2 ASPEN Model of SOFC-CHP System

The SOFC-CHP system developed in ASPEN uses fuel and air inputs to produce electricity and heat. Figure 15 is a generalized schematic of a SOFC system. Figure 25 and Table 6 at the end of this section show the detailed ASPEN process flow diagram and accompanying stream table. Some of the key process steps are described below, numbered to correspond with the numbers in Figure 15.

1. **Fuel input and water content:** Fuel (e.g., natural gas) enters the system. Anode exhaust recycle of 65% achieves an H_2O-to-CH_4 ratio of 2.5–3.0, which is typical of current industry practices. The feedstock is cleaned of contaminants that can degrade the system, such as sulfur (from the fuel) and salts (from the water). The cleanup subsystems were not modeled in ASPEN because multiple technologies could be used, and many of them do not affect the mass and energy balance of the system significantly.

2. **Steam-methane reforming:** The SMR partially (20%) reforms the fuel (CH_4) to produce CO and H_2. The reforming reaction temperature in the model is 700°C. Because this reaction is endothermic, the anode exhaust gas is used to preheat the steam and fuel mixture up to a sufficient temperature for the catalytic reactor. Partial pre-reform is done to limit the temperature gradient in the fuel cell from the endothermic reforming of CH_4 and the exothermic electrochemical reactions.

3. **Cathode air supply:** Air is supplied to the cathode at a stoichiometric ratio of 3.2 (i.e., ~3 times as much O_2 is fed than stoichiometrically needed to react with the amount of H_2 consumed). The extra air is used to cool the fuel cell and limit the temperature rise in the fuel cell stack to about 150°C. The air is preheated to a favorable catalytic reaction temperature by recuperation with the cathode exhaust (depleted-O_2 air). The cathode exhaust is then used as an oxidant for the tail gas combustion.

4. **SOFC electricity production:** Hydrogen is supplied to the anode at a stoichiometric ratio of 1.77 (i.e., 77% more H_2 is present than can react with the amount of O_2 present). The anode exhaust recycle of 65% brings the total fuel cell fuel utilization up to 78% (i.e., the total percentage of fuel converted to electricity by the fuel cell is 78% via the reactions described in Equations 13–15). The polarization curve is defined by a linear relationship with cell voltage of 0.78 V at maximum power (1,000 kW) and 0.84 V at minimum power (250 kW). The depleted reformate from the anode exhaust is fed to the burner after heat recuperation.

5. **Building heating system:** Excess heat—from the fuel cell and from combustion of unused fuel in the anode tail gas with the air from the cathode exhaust—is used for heat cogeneration. In the ASPEN model, water enters the fuel cell heat recovery subsystem at 60°C and is heated to 80°C before returning to the facility.

6. **Power electronics:** The inverter transforms DC electricity produced in the fuel cell into AC electricity. An efficiency of 93% is assumed for this conversion; higher efficiencies are possible for large applications. In addition, the power electronics typically supply the power required by the fuel cell blowers, pumps,

and valves. Within the ASPEN model, some power is used for fixed electrical draws such as control systems, cabinet ventilation, solenoids, and fixed speed auxiliaries. These extra factors are accounted for by an additional 5% power loss.

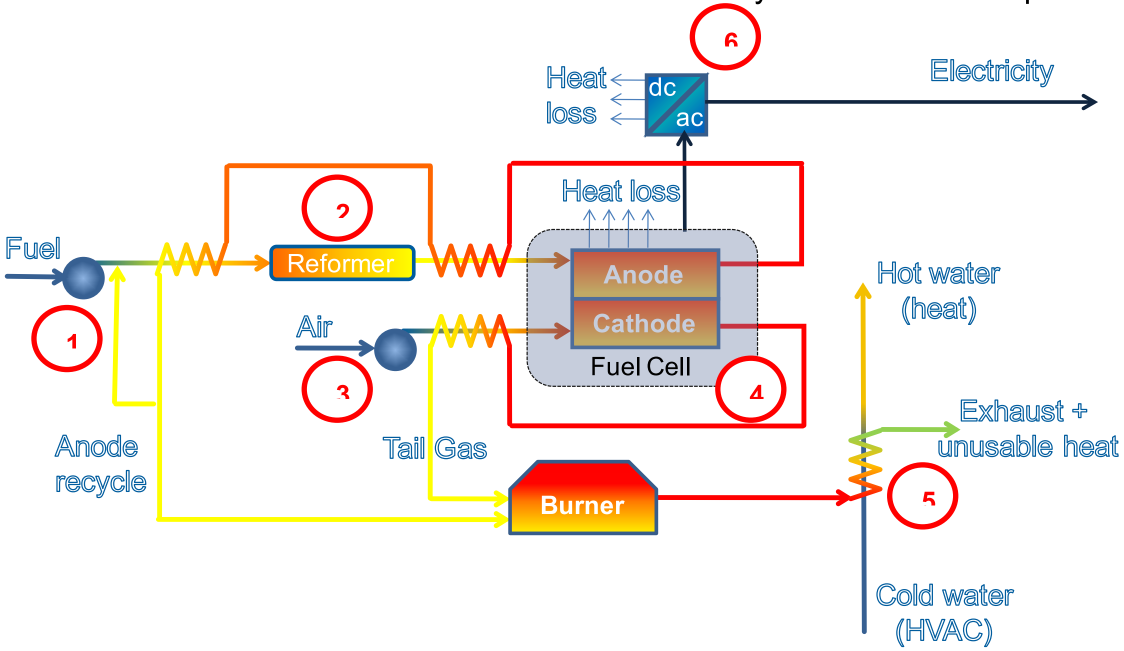


Figure 15. Schematic of modeled SOFC-CHP system

2.4.3 ASPEN Model of SOFC-CHHP System

The SOFC-CHHP system developed in ASPEN uses fuel and air inputs to produce electricity, heat, and hydrogen. It operates much like the CHP system discussed above with the exception that some of the anode exhaust gas goes through a shift reaction and is diverted for purification and storage of hydrogen. This reduces the amount of energy available for producing heat to the building, but the electricity production from the SOFC is independent of the heat recovery and hydrogen-capture processes, so it is not affected. Figure 16 is a generalized schematic of the system. Figure 25 and Table 7 at the end of this section show the detailed ASPEN process flow diagram and accompanying energy and material flows. Some of the key process steps are described below, numbered to correspond with the numbers in Figure 16.

7. **Shift reaction:** The anode exhaust stream contains H_2, CO, CO_2, and H_2O. This stream enters the shift catalyst, which operates at around 300°C and converts CO and H_2O to H_2 and CO_2 via the following reaction:

   Equation 20. $CO + H_2O \rightarrow CO_2 + H_2$

8. **Gas diversion and compression:** A controlled amount of shifted anode exhaust gas gets diverted before the burner, and the stream is compressed to 150 psig as per standard industry practice for PSA. A multi-stage compressor is used with a maximum compression ratio of 2:1 per stage and intercoolers to 25°C. In the ASPEN model, water is removed once again after the compression stage.

9. **Pressure swing adsorption (PSA):** About 85% of the hydrogen in the gas stream is recovered via PSA before being compressed to 6,250 psig for storage and dispensing. The remaining gas stream (including unrecovered hydrogen) is fed to the burner. Although other hydrogen-separation technologies, such as electrochemical hydrogen pumping, might eventually prove to be better suited to CHHP applications, PSA was selected for the model because of its market availability.

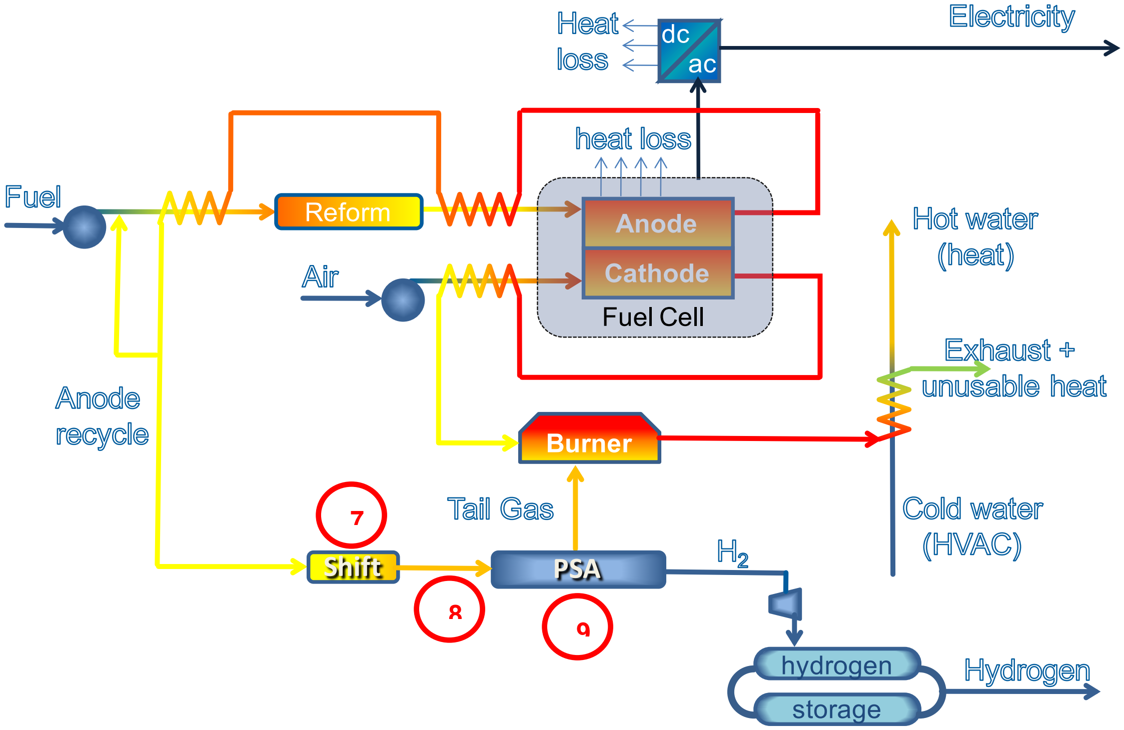
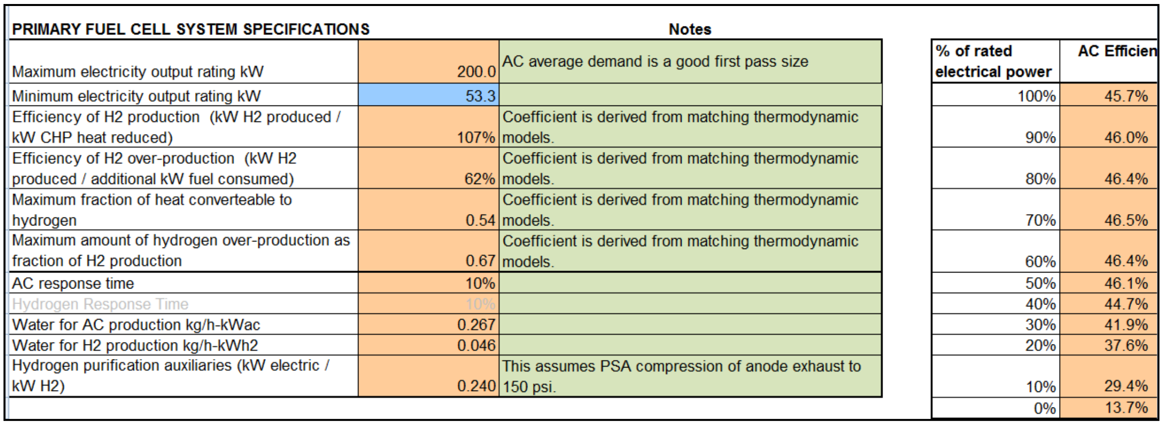


Figure 16. Schematic of modeled SOFC-CHHP system

2.4.4 Modeling SOFC Systems with the FCPower Model

The FCPower Model was designed with a linear model that mimics the performance of the ASPEN-modeled SOFC CHP/CHHP systems described above. The system tracks electricity demand, with heat and hydrogen as co-products. Hydrogen is the primary co-product and has production priority over heat.

Most of the fuel cell system parameters—found in the *Equipment Specification* worksheet—are set automatically in the FCPower Model to match the system parameters established in the ASPEN models and to meet the FCPower energy demand profiles. Many users will not need to change any of the values on this worksheet. The technical values that can be changed by users are shown in orange in Figure 17 and described briefly below.



PRIMARY FUEL CELL SYSTEM SPECIFICATIONS		Notes
Maximum electricity output rating kW	200.0	AC average demand is a good first pass size
Minimum electricity output rating kW	53.3	
Efficiency of H2 production (kW H2 produced / kW CHP heat reduced)	107%	Coefficient is derived from matching thermodynamic models.
Efficiency of H2 over-production (kW H2 produced / additional kW fuel consumed)	62%	Coefficient is derived from matching thermodynamic models.
Maximum fraction of heat converteable to hydrogen	0.54	Coefficient is derived from matching thermodynamic models.
Maximum amount of hydrogen over-production as fraction of H2 production	0.67	Coefficient is derived from matching thermodynamic models.
AC response time	10%	
Hydrogen Response Time	10%	
Water for AC production kg/h-kWac	0.267	
Water for H2 production kg/h-kWh2	0.046	
Hydrogen purification auxiliaries (kW electric / kW H2)	0.240	This assumes PSA compression of anode exhaust to 150 psi.

% of rated electrical power	AC Efficien
100%	45.7%
90%	46.0%
80%	46.4%
70%	46.5%
60%	46.4%
50%	46.1%
40%	44.7%
30%	41.9%
20%	37.6%
10%	29.4%
0%	13.7%

Figure 17. FCPower Model SOFC Equipment Specification worksheet

Maximum electricity output rating—The default value for this field is set to the average electricity demand from the *AC Demand* worksheet. This is a reasonable first estimate for the fuel cell system's maximum electrical output. However, commercial SOFC systems are available in a limited range of sizes, so users might want to research currently available products and replace the default value with a value from one of these products. Optimal economic results are obtained when the fuel cell is sized to operate at nearly full power all the time. Note that system performance is scalable. For example, doubling the size of the fuel cell doubles the potential hydrogen production. This assumption is reasonable because the modeled fuel cell systems are large; thus their heat-loss effects are relatively small.

Efficiency of H2 production—The efficiency of hydrogen production is defined as the kW of hydrogen produced from the fuel cell anode exhaust gas divided by the kW reduction in the available CHP (usable) heat [fuel used × (total efficiency – electrical efficiency)]. The default value is derived from the system modeled in ASPEN and accounts for the recovery of the PSA system and heat-quality reduction in the anode exhaust. Exhaust heat recovery is assumed with a 60°–80°C cooling loop. Note that this definition of efficiency does not include auxiliaries required for running the PSA unit or compressing the hydrogen. Those inputs are accounted for within the *MODEL* worksheet.

Efficiency of H2 over-production—The efficiency of hydrogen over-production is defined as the kW of hydrogen produced from addition of excess fuel divided by the kW of additional fuel consumed. The default value is derived from the system modeled in ASPEN. Note that this definition of efficiency does not include auxiliaries required for running the PSA unit or compressing the hydrogen. Those inputs are accounted for within the *MODEL* worksheet.

Maximum fraction of heat convertible to hydrogen—The maximum fraction of heat convertible to hydrogen is defined as the fraction of CHP heat that can be converted to hydrogen. The default value is derived from the system modeled in ASPEN.

Maximum amount of hydrogen over-production as fraction of H2 production—The maximum hydrogen over-production potential is defined as the fractional increase in the total amount of hydrogen that can be produced if more fuel is supplied to the fuel cell than is needed for electricity production at rated power. For example, a value of 0.5 means that for every kg/h of hydrogen produced an additional 0.5 kg/h of hydrogen can be over-produced by increasing fuel consumption of the system. Thus, a total of 1.5 kg/h of hydrogen would be produced while increasing the fuel consumption rate. The default value is derived from the system modeled in ASPEN.

AC Efficiency—The default values for these fields are set based on the SOFC system modeled in ASPEN, but users can change the values (e.g., based on the specifications of a currently available system). Note that total efficiency always must be higher than electrical efficiency.

Total Efficiency—Values for total efficiency at part load are generated using the ASPEN model. Total efficiency is typically lower at low-power operation because fuel is consumed to maintain the operating temperature. Total efficiency depends largely on fuel cell exhaust temperature. For this ASPEN analysis, a heating loop of 60°–80°C (140°–176°F) is assumed: heat-recovery water enters from the building at 60°C and returns to the building at 80°C. This is a very common range for heating, but if, for example, a building requires 40°–60°C (104°–140°F) operation, this would result in better total efficiency because more heat would be captured from the exhaust.

AC response time—This is the amount that the fuel cell electrical output can change per hour, e.g., a value of 10% means the AC output can change by a maximum of 10% per hour.

Water for AC production—The default value for this field is based on the SOFC system modeled in ASPEN, but users can change it to any positive number, e.g., to match specifications of currently available systems. Note that, in general, less water is required for systems that operate in condensing conditions. If the exhaust is cooled sufficiently, condensed water can be used for fuel cell operation.

Water for H2 production—The default value for this field is based on the SOFC system modeled in ASPEN, but users can change it to any positive number, e.g., to match specifications of currently available systems. In the model, PSA is used for hydrogen purification. Water is extracted from the syngas before entering the PSA; therefore, less makeup water is typically required in CHHP mode.

Hydrogen purification auxiliaries—This defines the electrical power requirements for the compressor component of the PSA system.

2.4.5 Correlation of SOFC ASPEN Model and FCPower Model

Sensitivity analyses were performed to determine the correlation between results from the detailed SOFC system ASPEN model and the simplified model of system performance created for the FCPower Model. Figure 18 (CHP), Figure 19 (CHHP), and Figure 20 (CHHP with hydrogen over-production) contain ASPEN and FCPower Model results showing the electricity, heat, and hydrogen produced and fuel used at different fuel cell system power levels. The size of the system modeled is 1 MW.

For each analysis, the correlation generally decreases as the system utilization decreases owing to the linear nature of the FCPower Model and the non-linear performance of fuel cells. FCPower Model results at system utilization levels below 20% do not correlate well with ASPEN results; therefore, system utilization rates below this level are not used in the FCPower Model. If energy demand drops below this level, the model continues to operate at 20%, and excess electricity is sold to the grid. Future versions of the FCPower Model may increase fit complexity to accommodate better system performance fit.

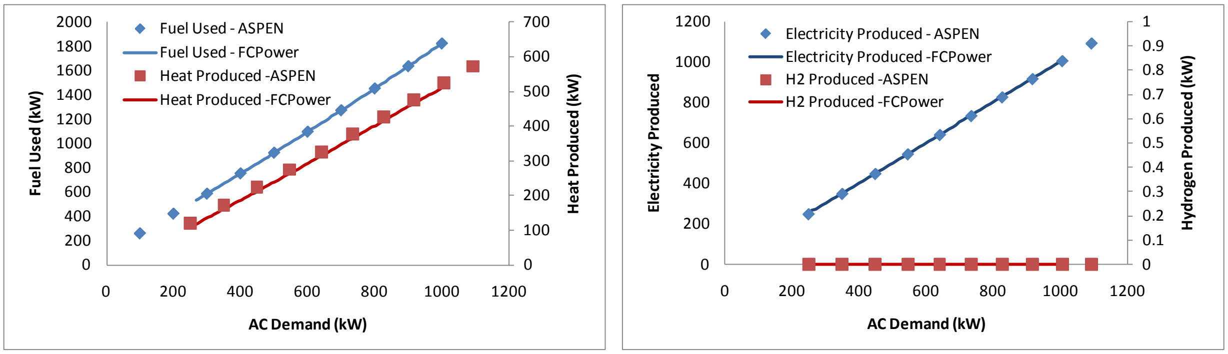


Figure 18. Correlation of ASPEN and FCPower Model results for SOFC-CHP system

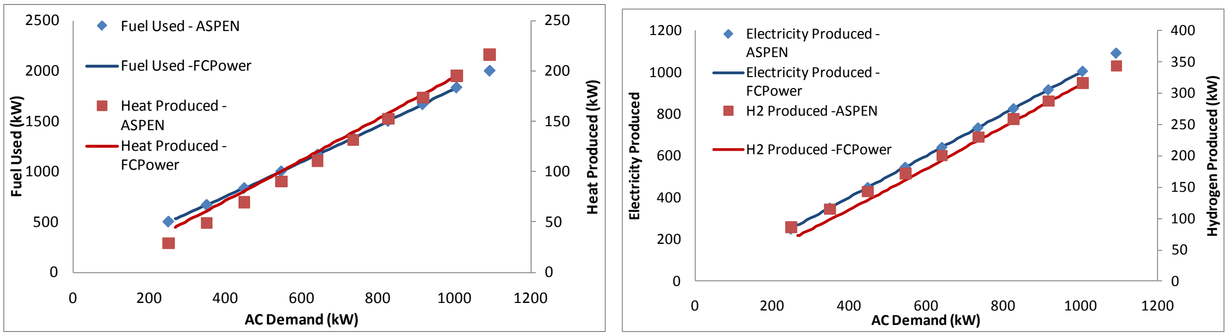


Figure 19. Correlation of ASPEN and FCPower Model results for SOFC-CHHP system

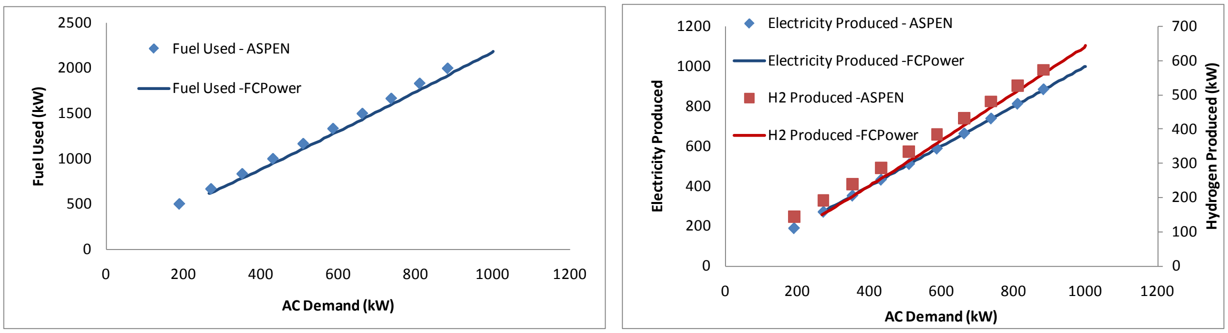


Figure 20. Correlation of ASPEN and FCPower Model results for SOFC-CHHP system, H_2 over-production

2.5 FCPower Model Energy Balance

Like the detailed ASPEN models, the FCPower Model meets system energy balance requirements. Figure 21 shows the working portion of the FCPower Model hourly energy model, a linear, numerically solved representation of the system performance modeled in ASPEN. Energy balance is established for each hour, and subsystems are dispatched depending on demand. Because the fuel cell system has the most complex calculations, the energy balance of this subsystem is described below.

The fuel cell system uses fuel (e.g., natural gas) as an energy feedstock. The chemical energy of the fuel is converted within the fuel cell system to three product streams: electricity, heat, and hydrogen.

The fuel cell generates its own auxiliary power (e.g., blowers and pumps); thus, no auxiliaries are monitored outside the fuel cell. Fuel cell systems are not 100% efficient. The energetic sum of all the products is always lower than the energy inputs. Within this simplified model of fuel cell system performance, three waste energy streams are accounted for:

- Fixed heat loss (fixed amount of unrecoverable energy)
- Unusable heat (unrecoverable energy proportional to thermal input)
- Inverter loss (energy loss associated with power electronics)

In this example, the energy balance of the fuel cell is the sum of all energy flows through the dotted line system boundary:

Net energy flow = (fuel in) – (electricity out) – (usable heat out) – (hydrogen out) – (unusable heat)

The following are the example model values (in kW):

Fuel in	=	+491
Electricity out	=	-200
Usable heat out	=	-48
Hydrogen out	=	-128
Unusable heat	=	-115
Net energy flow	=	0.00

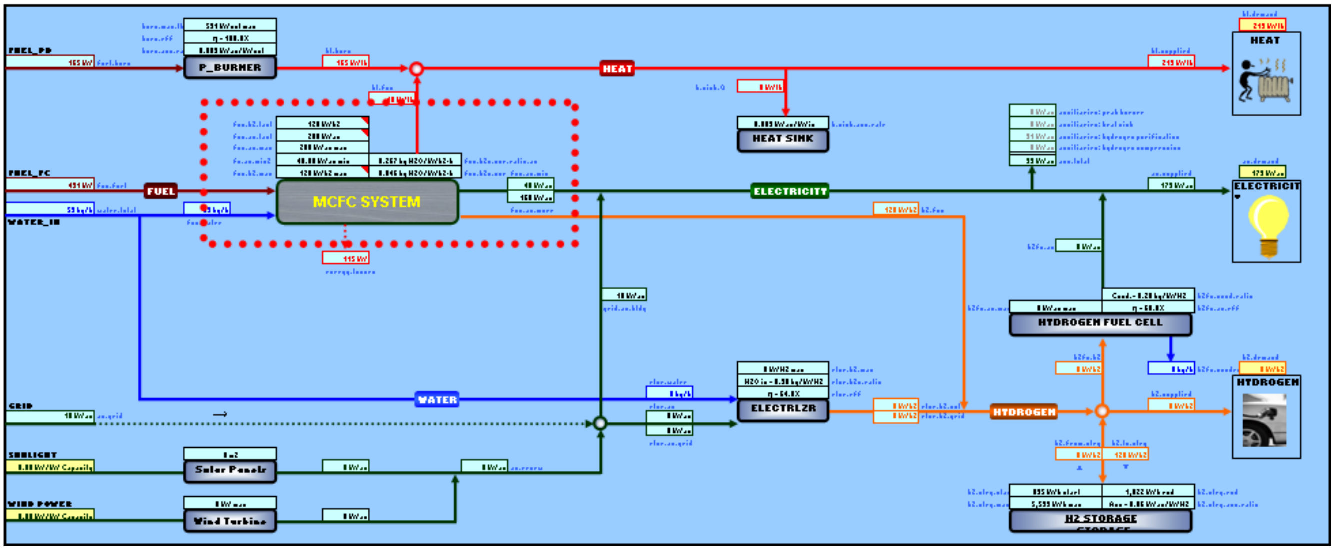


Figure 21. FCPower Model hourly energy model, for fuel cell energy balance example

An energy balance calculation also can be performed for the entire system (Figure 22). In this example, wind, solar, and grid power are used, and hydrogen is stored. Note that auxiliary power going back to operating components is not considered to contribute to the thermal value of the process streams. For example, the burner auxiliaries such as blowers may heat the process stream, but this effect is minimal and was not modeled. Therefore, auxiliary energy is counted as an output of the system, which is internally consumed.

Note that, because the model uses 1-hour time steps, power values of kW have equivalent numeric value as the energy flow of kWh for each time step.

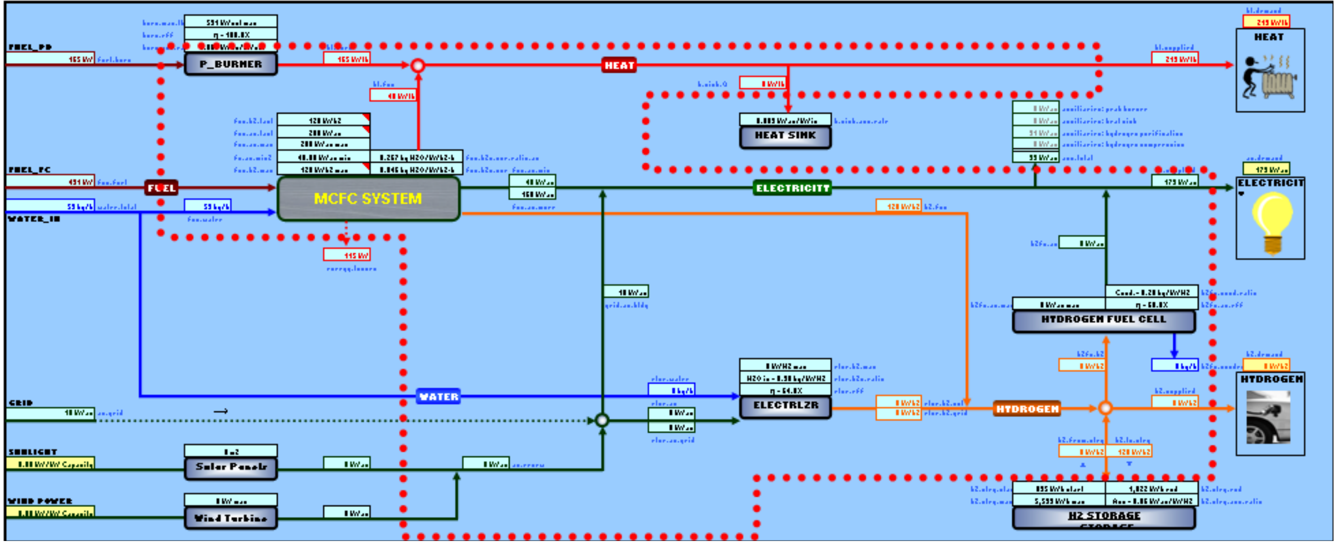


Figure 22. FCPower Model hourly energy model, for fuel cell system energy balance example

2.6 *ASPEN System Process Flow Diagrams and Energy/Material Stream Tables*

This section shows the process flow diagrams and energy/material stream tables for the fuel cell systems modeled in ASPEN Plus. Each diagram is followed by tables with columns corresponding to the labels on the diagram. The diagram labels are very small; to read them, use the zoom function on your computer.

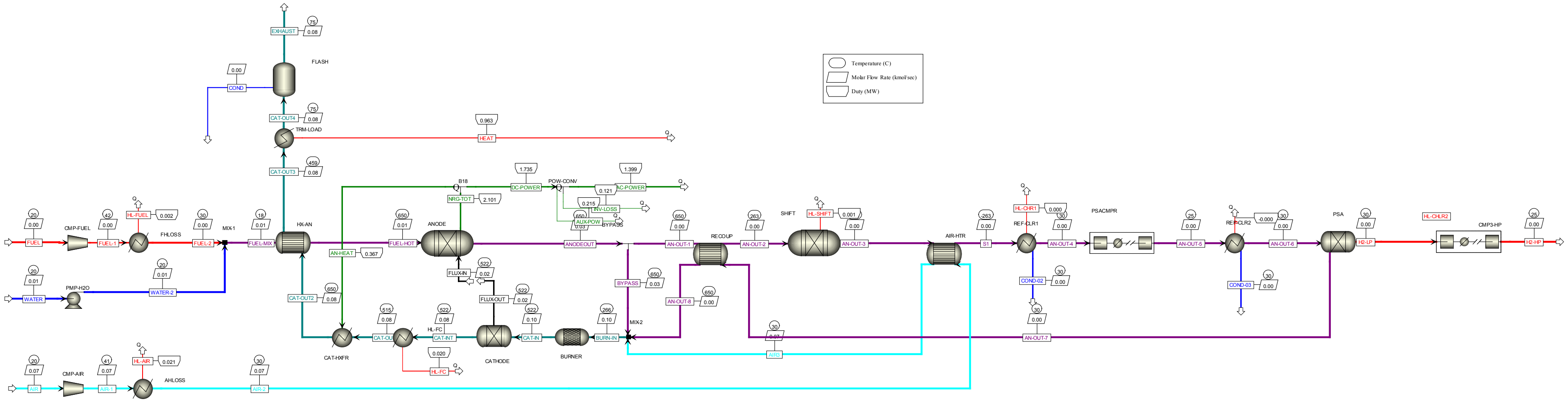


Figure 23. MCFC ASPEN process flow diagram

Table 1. MCFC-CHP stream table

	AIR	AIR-1	AIR-2	AIR3	AN-OUT-1	AN-OUT-2	AN-OUT-3	AN-OUT-4	AN-OUT-5	AN-OUT-6	AN-OUT-7	AN-OUT-8
Mole Flow kmol/sec												
CO2	0	0	0	0	1.46E-06	1.46E-06	1.59E-06	1.59E-06	1.59E-06	1.59E-06	1.59E-06	1.59E-06
CO	0	0	0	0	1.28E-07	1.28E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0	0
CH4	0	0	0	0	4.94E-11	4.94E-11	4.94E-11	4.94E-11	4.94E-11	4.94E-11	4.94E-11	4.94E-11
H2	0	0	0	0	2.04E-07	2.04E-07	3.32E-07	3.32E-07	3.32E-07	3.32E-07	1.16E-07	1.16E-07
O2	0.0145313	0.0145313	0.0145313	0.0145313	4.34E-27	4.34E-27	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0	0
N2	0.0546655	0.0546655	0.0546655	0.0546655	0	0	0	0	0	0	0	0
H2O	0	0	0	0	1.14E-06	1.14E-06	1.01E-06	1.04E-09	1.04E-09	1.14E-10	1.14E-10	1.14E-10
Mole Frac												
CO2	0	0	0	0	0.4980502	0.4980502	0.5415985	0.8266444	0.8266444	0.8270434	0.9317396	0.9317396
CO	0	0	0	0	0.0435482	0.0435482	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0	0
CH4	0	0	0	0	1.69E-05	1.69E-05	1.69E-05	2.57E-05	2.57E-05	2.58E-05	2.90E-05	2.90E-05
H2	0	0	0	0	0.0696584	0.0696584	0.1132067	0.1727879	0.1727879	0.1728713	0.0681643	0.0681643
O2	0.21	0.21	0.21	0.21	1.48E-21	1.48E-21	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0	0
N2	0.79	0.79	0.79	0.79	0	0	0	0	0	0	0	0
H2O	0	0	0	0	0.3887262	0.3887262	0.3451779	5.42E-04	5.42E-04	5.95E-05	6.70E-05	6.70E-05
Total Flow kg/sec	1.996358	1.996358	1.996358	1.996358	8.87E-05	8.87E-05	8.87E-05	7.05E-05	7.05E-05	7.05E-05	7.01E-05	7.01E-05
Temperature C	20	40.55239	30	30	650	262.579	-263.15	30	25	30	30	650
Pressure psia	14.7	16.2	16.2	16.2	16.2	16.2	16.2	16.2	164.7	164.7	164.7	164.7
Vapor Frac	1	1	1	1	1	1	1	1	1	1	1	1
Enthalpy J/kmol	-1.53E+05	4.47E+05	1.39E+05	1.39E+05	-2.69E+08	-2.86E+08	-3.06E+08	-3.25E+08	-3.26E+08	-3.26E+08	-3.67E+08	-3.38E+08
Enthalpy J/kg	-5299.787	15498.39	4805.04	4805.04	-8.89E+06	-9.44E+06	-1.01E+07	-8.85E+06	-8.87E+06	-8.86E+06	-8.92E+06	-8.22E+06
Enthalpy MW	-0.0105802	0.0309403	9.59E-03	9.59E-03	-7.89E-04	-8.38E-04	-8.96E-04	-6.24E-04	-6.25E-04	-6.25E-04	-6.25E-04	-5.76E-04
Entropy J/kmol-K	3757.812	4928.597	3928.237	3928.237	40994.46	17768.04	2.76E+06	5952.465	-14517.9	-13901.25	-15490.56	34611.99
Entropy J/kg-K	130.2517	170.8329	136.1589	136.1589	1353.73	586.741	91138.08	162.0206	-395.1638	-378.2859	-376.4892	841.2247
Density kmol/cum	0.0416047	0.04284	0.0443354	0.0443354	0.0145542	0.0251086	0.0239404	0.0444716	0.4763239	0.4675054	0.4727921	0.14785
Density kg/cum	1.200312	1.235953	1.279095	1.279095	0.4407393	0.7603552	0.7249797	1.633842	17.49964	17.17988	19.45292	6.083252
Average MW	28.8504	28.8504	28.8504	28.8504	30.2826	30.2826	30.2826	36.73895	36.73895	36.74799	41.14476	41.14476
***** ALL PHASES *****												
TDEW C	-191.0213	-190.1785	-190.1785	-190.1785	77.97679	77.97679	75.12089	30	3.248492	30	-18.57765	-18.57765

Table 1 (cont.)

	ANODEOUT	BURN-IN	BYPASS	CAT-IN	CAT-INT	CAT-OUT1	CAT-OUT2	CAT-OUT3	CAT-OUT4	COND	COND-02	COND-03
Mole Flow kmol/sec												
CO2	0.0145943	0.0145944	0.0145928	0.0158709	3.84E-03	3.84E-03	3.84E-03	3.84E-03	3.84E-03	0	0	0
CO	1.28E-03	1.28E-03	1.28E-03	0	0	0	0	0	0	0	0	0
CH4	4.94E-07	4.94E-07	4.94E-07	0	0	0	0	0	0	0	0	0
H2	2.04E-03	2.04E-03	2.04E-03	0	0	0	0	0	0	0	0	0
O2	4.34E-23	0.0145313	4.34E-23	0.0128718	6.86E-03	6.86E-03	6.86E-03	6.86E-03	6.86E-03	0	0	0
N2	0	0.0546655	0	0.0546655	0.0546655	0.0546655	0.0546655	0.0546655	0.0546655	0	0	0
H2O	0.0113908	0.0113897	0.0113897	0.0134317	0.0134317	0.0134317	0.0134317	0.0134317	0.0134317	0	1.01E-06	9.26E-10
Mole Frac												
CO2	0.4980502	0.1481693	0.4980502	0.1638881	0.0487113	0.0487113	0.0487113	0.0487113	0.0487113	0	0	0
CO	0.0435482	0.0129541	0.0435482	0	0	0	0	0	0	0	0	0
CH4	1.69E-05	5.02E-06	1.69E-05	0	0	0	0	0	0	0	0	0
H2	0.0696584	0.0207222	0.0696584	0	0	0	0	0	0	0	0	0
O2	1.48E-21	0.1475284	1.48E-21	0.1329183	0.0870082	0.0870082	0.0870082	0.0870082	0.0870082	0	0	0
N2	0	0.5549879	0	0.5644929	0.6938063	0.6938063	0.6938063	0.6938063	0.6938063	0	0	0
H2O	0.3887262	0.115633	0.3887262	0.1387007	0.1704741	0.1704741	0.1704741	0.1704741	0.1704741	0	1	1
Total Flow kg/sec	0.8873703	2.88371	0.8872815	2.88371	2.161626	2.161626	2.161626	2.161626	2.161626	0	1.82E-05	1.67E-08
Temperature C	650	266.066	650	522.1475	522.1475	514.6315	650.3007	459.4951	75		30	30
Pressure psia	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	164.7
Vapor Frac	1	1	1	1	1	1	1	1	1		0	0
Enthalpy J/kmol	-2.69E+08	-8.00E+07	-2.69E+08	-8.14E+07	-4.46E+07	-4.48E+07	-4.02E+07	-4.67E+07	-5.89E+07		-2.85E+08	-2.85E+08
Enthalpy J/kg	-8.89E+06	-2.73E+06	-8.89E+06	-2.73E+06	-1.62E+06	-1.63E+06	-1.46E+06	-1.70E+06	-2.15E+06		-1.58E+07	-1.58E+07
Enthalpy MW	-7.889775	-7.879969	-7.888986	-7.879969	-3.510625	-3.530625	-3.164077	-3.676214	-4.639528		-2.88E-04	-2.64E-07
Entropy J/kmol-K	40994.46	25136.3	40994.46	35664.4	30348.64	30027.95	35474.32	27596.46	4062.048		-1.62E+05	-1.62E+05
Entropy J/kg-K	1353.73	858.5786	1353.73	1197.674	1106.201	1094.512	1293.031	1005.885	148.0608		-8986.351	-8986.878
Density kmol/cum	0.0145542	0.0249158	0.0145542	0.0168895	0.0168892	0.0170504	0.014545	0.018334	0.0386331		55.27336	55.29857
Density kg/cum	0.4407393	0.7294514	0.4407393	0.5029376	0.4633562	0.4677781	0.3990428	0.5029933	1.0599		995.7651	996.2192
Average MW	30.2826	29.27664	30.2826	29.77805	27.435	27.435	27.435	27.435	27.435		18.01528	18.01528
***** ALL PHASES *****												
TDEW C	77.97679	50.8618	77.97679	54.60628	58.92372	58.92372	58.92372	58.92372	58.92372		102.7428	185.4826

Table 1 (cont.)

	EXHAUST	FLUX-IN	FLUX-OUT	FUEL	FUEL-1	FUEL-2	FUEL-HOT	FUEL-MIX	H2-HP	H2-LP	S1	WATER	WATER-2
Mole Flow kmol/sec													
CO2	3.84E-03	0.0120329	0.0120329	0	0	0	0	0	0	0	1.59E-06	0	0
CO	0	0	0	0	0	0	0	0	0	0	0.00E+00	0	0
CH4	0	0	0	3.84E-03	3.84E-03	3.84E-03	3.84E-03	3.84E-03	0	0	4.94E-11	0	0
H2	0	0	0	0	0	0	0	0	2.16E-07	2.16E-07	3.32E-07	0	0
O2	6.86E-03	6.02E-03	6.02E-03	0	0	0	0	0	0	0	0.00E+00	0	0
N2	0.0546655	0	0	0	0	0	0	0	0	0	0	0	0
H2O	0.0134317	0	0	0	0	0	5.76E-03	5.76E-03	0	0	1.01E-06	5.76E-03	5.76E-03
Mole Frac													
CO2	0.0487113	0.66667	0.66667	0	0	0	0	0	0	0	0.5415985	0	0
CO	0	0	0	0	0	0	0	0	0	0	0.00E+00	0	0
CH4	0	0	0	1	1	1	0.4	0.4	0	0	1.69E-05	0	0
H2	0	0	0	0	0	0	0	0	1	1	0.1132067	0	0
O2	0.0870082	0.33333	0.33333	0	0	0	0	0	0	0	0.00E+00	0	0
N2	0.6938063	0	0	0	0	0	0	0	0	0	0	0	0
H2O	0.1704741	0	0	0	0	0	0.6	0.6	0	0	0.3451779	1	1
Total Flow kg/sec	2.161626	0.7220839	0.7220839	0.0615722	0.0615722	0.0615722	0.1652863	0.1652863	4.35E-07	4.35E-07	8.87E-05	0.1037141	0.1037141
Temperature C	75	522.1475	522.1475	20	41.92543	30	650.3005	18.46574	25	30	-263.15	20	20.21997
Pressure psia	16.2	16.2	16.2	14.7	16.7	16.7	16.7	16.7	6250	164.7	16.2	14.7	64.7
Vapor Frac	1	1	1	1	1	1	1	0.3956657	1	1	1	0	0
Enthalpy J/kmol	-5.89E+07	-2.42E+08	-2.42E+08	-7.47E+07	-7.39E+07	-7.44E+07	-1.48E+08	-2.01E+08	5.68E+05	1.56E+05	-3.06E+08	-2.86E+08	-2.86E+08
Enthalpy J/kg	-2.15E+06	-6.05E+06	-6.05E+06	-4.66E+06	-4.61E+06	-4.64E+06	-8.59E+06	-1.17E+07	2.82E+05	77156.4	-1.01E+07	-1.59E+07	-1.59E+07
Enthalpy MW	-4.639528	-4.369348	-4.369348	-0.2867546	-0.2837325	-0.2853897	-1.419769	-1.931943	1.22E-07	3.35E-08	-8.96E-04	-1.646672	-1.646553
Entropy J/kmol-K	4062.048	45556.72	45556.72	-81241.23	-79709.86	-81106.81	-7527.105	-1.31E+05	-50721.69	-19631.15	2.76E+06	-1.64E+05	-1.64E+05
Entropy J/kg-K	148.0608	1138.742	1138.742	-5064.043	-4968.588	-5055.665	-436.955	-7577.787	-25161.06	-9738.254	91138.08	-9094.916	-9092.205
Density kmol/cum	0.0386331	0.016891	0.016891	0.0416652	0.0440297	0.0457735	0.0149997	0.120156	13.48305	0.4475042	0.0239404	55.44	55.42829
Density kg/cum	1.0599	0.6757468	0.6757468	0.6684259	0.7063578	0.7343338	0.258389	2.06984	27.18021	0.9021147	0.7249797	998.7672	998.5561
Average MW	27.435	40.00617	40.00617	16.04276	16.04276	16.04276	17.22627	17.22627	2.01588	2.01588	30.2826	18.01528	18.01528
***** ALL PHASES *****													
TDEW C	58.92372	-93.4242	-93.4242	-161.4806	-159.9087	-159.9087	89.60892	89.60892		-240.9779	75.12089	100.0252	147.6647

Table 2. MCFC-CHHP stream table

	AIR	AIR-1	AIR-2	AIR3	AN-OUT-1	AN-OUT-2	AN-OUT-3	AN-OUT-4	AN-OUT-5	AN-OUT-6	AN-OUT-7	AN-OUT-8
Mole Flow kmol/sec												
CO2	0	0	0	0	0.0145928	0.0145928	0.0157243	0.0157243	0.0157243	0.0157243	0.0157243	0.0157243
CO	0	0	0	0	1.28E-03	1.28E-03	1.45E-04	1.45E-04	1.45E-04	1.45E-04	1.45E-04	1.45E-04
CH4	0	0	0	0	4.94E-07	4.94E-07	4.94E-07	4.94E-07	4.94E-07	4.94E-07	4.94E-07	4.94E-07
H2	0	0	0	0	2.04E-03	2.04E-03	3.17E-03	3.17E-03	3.17E-03	3.17E-03	8.72E-04	8.72E-04
O2	0.0107645	0.0107645	0.0107645	0.0107645	4.34E-23	4.34E-23	0	0	0	0	0	0
N2	0.0404952	0.0404952	0.0404952	0.0404952	0	0	0	0	0	0	0	0
H2O	0	0	0	0	0.0113897	0.0113897	0.0102582	1.03E-05	1.03E-05	1.13E-06	1.13E-06	1.13E-06
Mole Frac												
CO2	0	0	0	0	0.4980502	0.4980502	0.5366653	0.8253326	0.8253326	0.825731	0.9391632	0.9391632
CO	0	0	0	0	0.0435482	0.0435482	4.93E-03	7.59E-03	7.59E-03	7.59E-03	8.63E-03	8.63E-03
CH4	0	0	0	0	1.69E-05	1.69E-05	1.69E-05	2.59E-05	2.59E-05	2.60E-05	2.95E-05	2.95E-05
H2	0	0	0	0	0.0696584	0.0696584	0.1082735	0.1665128	0.1665128	0.1665932	0.0521065	0.0521065
O2	0.21	0.21	0.21	0.21	1.48E-21	1.48E-21	0	0	0	0	0	0
N2	0.79	0.79	0.79	0.79	0	0	0	0	0	0	0	0
H2O	0	0	0	0	0.3887262	0.3887262	0.3501111	5.42E-04	5.42E-04	5.95E-05	6.77E-05	6.77E-05
Total Flow kg/sec	1.478866	1.478866	1.478866	1.478866	0.8872815	0.8872815	0.8872815	0.7026619	0.7026619	0.7024963	0.6978598	0.6978598
Temperature C	20	40.55239	30	214.5115	650	276.8076	313.9461	30	25	30	30	638.4248
Pressure psia	14.7	16.2	16.2	16.2	16.2	16.2	16.2	16.2	164.7	164.7	164.7	164.7
Vapor Frac	1	1	1	1	1	1	1	1	1	1	1	1
Enthalpy J/kmol	-1.53E+05	4.47E+05	1.39E+05	5.58E+06	-2.69E+08	-2.85E+08	-2.85E+08	-3.26E+08	-3.26E+08	-3.26E+08	-3.71E+08	-3.43E+08
Enthalpy J/kg	-5299.787	15498.39	4805.04	1.93E+05	-8.89E+06	-9.42E+06	-9.42E+06	-8.83E+06	-8.84E+06	-8.83E+06	-8.89E+06	-8.22E+06
Enthalpy MW	-7.84E-03	0.02292	7.11E-03	0.2858254	-7.888986	-8.359316	-8.359644	-6.203283	-6.211701	-6.205893	-6.206882	-5.736178
Entropy J/kmol-K	3757.812	4928.597	3928.237	17926.31	40994.46	18819.19	19468.33	6902.016	-13570.67	-12953.57	-14672.78	34935.33
Entropy J/kg-K	130.2517	170.8329	136.1589	621.354	1353.73	621.4522	642.8882	187.1425	-367.9575	-351.1388	-352.0262	838.1608
Density kmol/cum	0.0416047	0.04284	0.0443354	0.0275418	0.0145542	0.0244564	0.0229019	0.0444723	0.4764139	0.4675893	0.4733929	0.1497441
Density kg/cum	1.200312	1.235953	1.279095	0.7945924	0.4407393	0.7406045	0.6935311	1.64019	17.57066	17.24945	19.73146	6.241475
Average MW	28.8504	28.8504	28.8504	28.8504	30.2826	30.2826	30.2826	36.88108	36.88108	36.89018	41.68093	41.68093
***** ALL PHASES *****												
TDEW C	-191.0213	-190.1785	-190.1785	-190.1785	77.97679	77.97679	75.45921	30	3.2435	30	-18.39963	-18.39963

Table 2 (cont.)

	ANODEOUT	BURN-IN	BYPASS	CAT-IN	CAT-INT	CAT-OUT1	CAT-OUT2	CAT-OUT3	CAT-OUT4	COND	COND-02	COND-03
Mole Flow kmol/sec												
CO2	0.0145943	0.0157257	1.46E-06	0.0158709	3.84E-03	3.84E-03	3.84E-03	3.84E-03	3.84E-03	0	0	0
CO	1.28E-03	1.45E-04	1.28E-07	0	0	0	0	0	0	0	0	0
CH4	4.94E-07	4.94E-07	4.94E-11	0	0	0	0	0	0	0	0	0
H2	2.04E-03	8.73E-04	2.04E-07	0	0	0	0	0	0	0	0	0
O2	4.34E-23	0.0107645	4.34E-27	0.0102549	4.24E-03	4.24E-03	4.24E-03	4.24E-03	4.24E-03	0	0	0
N2	0	0.0404952	0	0.0404952	0.0404952	0.0404952	0.0404952	0.0404952	0.0404952	0	0	0
H2O	0.0113908	2.27E-06	1.14E-06	8.76E-04	8.76E-04	8.76E-04	8.76E-04	8.76E-04	8.76E-04	0	0.0102479	9.19E-06
Mole Frac												
CO2	0.4980502	0.2312422	0.4980502	0.2351355	0.0776174	0.0776174	0.0776174	0.0776174	0.0776174	0	0	0
CO	0.0435482	2.13E-03	0.0435482	0	0	0	0	0	0	0	0	0
CH4	1.69E-05	7.27E-06	1.69E-05	0	0	0	0	0	0	0	0	0
H2	0.0696584	0.0128315	0.0696584	0	0	0	0	0	0	0	0	0
O2	1.48E-21	0.1582892	1.48E-21	0.1519316	0.0857178	0.0857178	0.0857178	0.0857178	0.0857178	0	0	0
N2	0	0.595469	0	0.5999564	0.8189514	0.8189514	0.8189514	0.8189514	0.8189514	0	0	0
H2O	0.3887262	3.34E-05	0.3887262	0.0129765	0.0177132	0.0177132	0.0177132	0.0177132	0.0177132	0	1	1
Total Flow kg/sec	0.8873703	2.176815	8.87E-05	2.176815	1.454731	1.454731	1.454731	1.454731	1.454731	0	0.1846196	1.66E-04
Temperature C	650	361.5354	650	468.3004	468.3004	455.9646	650.2271	336.5957	75		30	30
Pressure psia	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	164.7
Vapor Frac	1	1	1	1	1	1	1	1	1		0	0
Enthalpy J/kmol	-2.69E+08	-8.02E+07	-2.69E+08	-8.08E+07	-2.10E+07	-2.14E+07	-1.49E+07	-2.53E+07	-3.33E+07		-2.85E+08	-2.85E+08
Enthalpy J/kg	-8.89E+06	-2.50E+06	-8.89E+06	-2.50E+06	-7.14E+05	-7.27E+05	-5.06E+05	-8.58E+05	-1.13E+06		-1.58E+07	-1.58E+07
Enthalpy MW	-7.889775	-5.451142	-7.89E-04	-5.451142	-1.038153	-1.058153	-0.7365072	-1.248607	-1.648332		-2.925242	-2.62E-03
Entropy J/kmol-K	40994.46	33138.7	40994.46	37822.32	32203.49	31653.39	39555.85	25886.98	8612.065		-1.62E+05	-1.62E+05
Entropy J/kg-K	1353.73	1035.283	1353.73	1172.766	1094.628	1075.929	1344.541	879.9234	292.7324		-8986.351	-8986.878
Density kmol/cum	0.0145542	0.0211626	0.0145542	0.0181148	0.0181137	0.0184202	0.0145449	0.0220269	0.0386013		55.27336	55.29857
Density kg/cum	0.4407393	0.6774008	0.4407393	0.5842127	0.5328985	0.541915	0.4279075	0.6480233	1.135636		995.7651	996.2192
Average MW	30.2826	32.00932	30.2826	32.25054	29.41959	29.41959	29.41959	29.41959	29.41959		18.01528	18.01528
***** ALL PHASES *****												
TDEW C	77.97679	-55.32611	77.97679	12.51084	17.26529	17.26529	17.26529	17.26529	17.26529		102.7428	185.4826

Table 2 (cont.)

	EXHAUST	FLUX-IN	FLUX-OUT	FUEL	FUEL-1	FUEL-2	FUEL-HOT	FUEL-MIX	H2-HP	H2-LP	S1	WATER	WATER-2
Mole Flow kmol/sec													
CO2	3.84E-03	0.0120329	0.0120329	0	0	0	0	0	0	0	0.0157243	0	0
CO	0	0	0	0	0	0	0	0	0	0	1.45E-04	0	0
CH4	0	0	0	3.84E-03	3.84E-03	3.84E-03	3.84E-03	3.84E-03	0	0	4.94E-07	0	0
H2	0	0	0	0	0	0	0	0	2.30E-03	2.30E-03	3.17E-03	0	0
O2	4.24E-03	6.02E-03	6.02E-03	0	0	0	0	0	0	0	0	0	0
N2	0.0404952	0	0	0	0	0	0	0	0	0	0	0	0
H2O	8.76E-04	0	0	0	0	0	5.76E-03	5.76E-03	0	0	0.0102582	5.76E-03	5.76E-03
Mole Frac													
CO2	0.0776174	0.66667	0.66667	0	0	0	0	0	0	0	0.5366653	0	0
CO	0	0	0	0	0	0	0	0	0	0	4.93E-03	0	0
CH4	0	0	0	1	1	1	0.4	0.4	0	0	1.69E-05	0	0
H2	0	0	0	0	0	0	0	0	1	1	0.1082735	0	0
O2	0.0857178	0.33333	0.33333	0	0	0	0	0	0	0	0	0	0
N2	0.8189514	0	0	0	0	0	0	0	0	0	0	0	0
H2O	0.0177132	0	0	0	0	0	0.6	0.6	0	0	0.3501111	1	1
Total Flow kg/sec	1.454731	0.7220839	0.7220839	0.0615722	0.0615722	0.0615722	0.1652863	0.1652863	4.64E-03	4.64E-03	0.8872815	0.1037141	0.1037141
Temperature C	74.99993	468.3004	468.3004	20	41.92543	30	650.2265	18.46574	25	30	75.25558	20	20.21997
Pressure psia	16.2	16.2	16.2	14.7	16.7	16.7	16.7	16.7	6250	164.7	16.2	14.7	64.7
Vapor Frac	1	1	1	1	1	1	1	0.3956657	1	1	0.9953691	0	0
Enthalpy J/kmol	-3.33E+07	-2.45E+08	-2.45E+08	-7.47E+07	-7.39E+07	-7.44E+07	-1.48E+08	-2.01E+08	5.68E+05	1.56E+05	-2.95E+08	-2.86E+08	-2.86E+08
Enthalpy J/kg	-1.13E+06	-6.11E+06	-6.11E+06	-4.66E+06	-4.61E+06	-4.64E+06	-8.59E+06	-1.17E+07	2.82E+05	77156.4	-9.74E+06	-1.59E+07	-1.59E+07
Enthalpy MW	-1.648332	-4.413001	-4.413001	-0.2867546	-0.2837325	-0.2853897	-1.419933	-1.931943	1.31E-03	3.58E-04	-8.638364	-1.646672	-1.646553
Entropy J/kmol-K	8612.059	42408.14	42408.14	-81241.23	-79709.86	-81106.81	-7531.268	-1.31E+05	-50721.69	-19631.15	-1355.441	-1.64E+05	-1.64E+05
Entropy J/kg-K	292.7322	1060.04	1060.04	-5064.043	-4968.588	-5055.665	-437.1966	-7577.787	-25161.06	-9738.254	-44.75974	-9094.916	-9092.205
Density kmol/cum	0.0386013	0.0181185	0.0181185	0.0416652	0.0440297	0.0457735	0.0150009	0.120156	13.48305	0.4475042	0.0389068	55.44	55.42829
Density kg/cum	1.135636	0.7248553	0.7248553	0.6684259	0.7063578	0.7343338	0.2584097	2.06984	27.18021	0.9021147	1.178201	998.7672	998.5561
Average MW	29.41959	40.00617	40.00617	16.04276	16.04276	16.04276	17.22627	17.22627	2.01588	2.01588	30.2826	18.01528	18.01528
***** ALL PHASES *****													
TDEW C	17.26529	-93.4242	-93.4242	-161.4806	-159.9087	-159.9087	89.60892	89.60892		-240.9779	75.45921	100.0252	147.6647

Table 3. MCFC-CHHP with hydrogen overproduction stream table

	AIR	AIR-1	AIR-2	AIR3	AN-OUT-1	AN-OUT-2	AN-OUT-3	AN-OUT-4	AN-OUT-5	AN-OUT-6	AN-OUT-7	AN-OUT-8
Mole Flow kmol/sec												
CO2	0	0	0	0	0.0139835	0.0139835	0.0156367	0.0156367	0.0156367	0.0156367	0.0156367	0.0156367
CO	0	0	0	0	1.95E-03	1.95E-03	2.94E-04	2.94E-04	2.94E-04	2.94E-04	2.94E-04	2.94E-04
CH4	0	0	0	0	2.83E-06	2.83E-06	2.83E-06	2.83E-06	2.83E-06	2.83E-06	2.83E-06	2.83E-06
H2	0	0	0	0	3.29E-03	3.29E-03	4.94E-03	4.94E-03	4.94E-03	4.94E-03	1.31E-03	1.31E-03
O2	0.0111705	0.0111705	0.0111705	0.0111705	1.80E-23	1.80E-23	2.52E-14	2.52E-14	2.52E-14	2.52E-14	2.52E-14	2.52E-14
N2	0.0420226	0.0420226	0.0420226	0.0420226	0	0	0	0	0	0	0	0
H2O	0	0	0	0	0.0115311	0.0115311	9.88E-03	1.13E-05	1.13E-05	1.23E-06	1.23E-06	1.23E-06
Mole Frac												
CO2	0	0	0	0	0.4546778	0.4546778	0.5084341	0.7485933	0.7485933	0.7489547	0.9067662	0.9067662
CO	0	0	0	0	0.0633041	0.0633041	9.55E-03	0.0140577	0.0140577	0.0140645	0.0170281	0.0170281
CH4	0	0	0	0	9.21E-05	9.21E-05	9.21E-05	1.36E-04	1.36E-04	1.36E-04	1.64E-04	1.64E-04
H2	0	0	0	0	0.1069878	0.1069878	0.1607441	0.2366717	0.2366717	0.2367859	0.0759698	0.0759698
O2	0.21	0.21	0.21	0.21	5.85E-22	5.85E-22	8.18E-13	1.20E-12	1.20E-12	1.21E-12	1.46E-12	1.46E-12
N2	0.79	0.79	0.79	0.79	0	0	0	0	0	0	0	0
H2O	0	0	0	0	0.3749381	0.3749381	0.3211818	5.42E-04	5.42E-04	5.91E-05	7.16E-05	7.16E-05
Total Flow kg/sec	1.534644	1.534644	1.534644	1.534644	0.8843597	0.8843597	0.8843597	0.706611	0.706611	0.7064294	0.6991046	0.6991046
Temperature C	20	40.55239	30	224.3202	650	280.5265	331.6598	30	25	30	30	638.1663
Pressure psia	14.7	16.2	16.2	16.2	16.2	16.2	16.2	16.2	164.7	164.7	164.7	164.7
Vapor Frac	1	1	1	1	1	1	1	1	1	1	1	1
Enthalpy J/kmol	-1.53E+05	4.47E+05	1.39E+05	5.87E+06	-2.52E+08	-2.67E+08	-2.67E+08	-2.96E+08	-2.97E+08	-2.96E+08	-3.59E+08	-3.31E+08
Enthalpy J/kg	-5299.787	15498.39	4805.04	2.03E+05	-8.75E+06	-9.29E+06	-9.29E+06	-8.75E+06	-8.77E+06	-8.76E+06	-8.85E+06	-8.17E+06
Enthalpy MW	-8.13E-03	0.0237845	7.37E-03	0.3121905	-7.736414	-8.215334	-8.216334	-6.185425	-6.193703	-6.187432	-6.188863	-5.710338
Entropy J/kmol-K	3757.812	4928.597	3928.237	18521.14	43240.31	21822.43	22591.51	8284.26	-12088.16	-11485.76	-13148.35	35844.46
Entropy J/kg-K	130.2517	170.8329	136.1589	641.9717	1503.738	758.903	785.649	244.8918	-357.3394	-339.4552	-324.3251	884.1614
Density kmol/cum	0.0416047	0.04284	0.0443354	0.0269985	0.0145536	0.024288	0.0222261	0.0444437	0.4728927	0.464296	0.471832	0.1497646
Density kg/cum	1.200312	1.235953	1.279095	0.7789177	0.4184941	0.698409	0.6391186	1.503453	15.99713	15.70986	19.12837	6.07155
Average MW	28.8504	28.8504	28.8504	28.8504	28.75522	28.75522	28.75522	33.82824	33.82824	33.83587	40.54063	40.54063
***** ALL PHASES *****												
TDEW C	-191.0213	-190.1785	-190.1785	-190.1785	77.07923	77.07923	73.3909	30	2.816143	30	-18.24226	-18.24226

Table 3 (cont.)

	ANODEOUT	BURN-IN	BYPASS	CAT-IN	CAT-INT	CAT-OUT1	CAT-OUT2	CAT-OUT3	CAT-OUT4	COND	COND-02	COND-03
Mole Flow kmol/sec												
CO2	0.0139849	0.0156381	1.40E-06	0.0159348	4.24E-03	4.24E-03	4.24E-03	4.24E-03	4.24E-03	0	0	0
CO	1.95E-03	2.94E-04	1.95E-07	0	0	0	0	0	0	0	0	0
CH4	2.83E-06	2.83E-06	2.83E-10	0	0	0	0	0	0	0	0	0
H2	3.29E-03	1.31E-03	3.29E-07	0	0	0	0	0	0	0	0	0
O2	1.80E-23	0.0111705	1.80E-27	0.0103627	4.51E-03	4.51E-03	4.51E-03	4.51E-03	4.51E-03	0	0	0
N2	0	0.0420226	0	0.0420226	0.0420226	0.0420226	0.0420226	0.0420226	0.0420226	0	0	0
H2O	0.0115322	2.39E-06	1.15E-06	1.32E-03	1.32E-03	1.32E-03	1.32E-03	1.32E-03	1.32E-03	0	9.87E-03	1.01E-05
Mole Frac												
CO2	0.4546778	0.2220044	0.4546778	0.2288216	0.0813328	0.0813328	0.0813328	0.0813328	0.0813328	0	0	0
CO	0.0633041	4.17E-03	0.0633041	0	0	0	0	0	0	0	0	0
CH4	9.21E-05	4.02E-05	9.21E-05	0	0	0	0	0	0	0	0	0
H2	0.1069878	0.0186027	0.1069878	0	0	0	0	0	0	0	0	0
O2	5.85E-22	0.1585809	5.85E-22	0.1488079	0.0866518	0.0866518	0.0866518	0.0866518	0.0866518	0	0	0
N2	0	0.5965664	0	0.6034378	0.8067052	0.8067052	0.8067052	0.8067052	0.8067052	0	0	0
H2O	0.3749381	3.39E-05	0.3749381	0.0189327	0.0253101	0.0253101	0.0253101	0.0253101	0.0253101	0	1	1
Total Flow kg/sec	0.8844482	2.233837	8.84E-05	2.233837	1.531848	1.531848	1.531848	1.531848	1.531848	0	0.1777487	1.82E-04
Temperature C	650	365.8406	650	529.6255	529.6255	518.1307	649.7005	321.9014	75		30	30
Pressure psia	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	164.7
Vapor Frac	1	1	1	1	1	1	1	1	1		0	0
Enthalpy J/kmol	-2.52E+08	-7.66E+07	-2.52E+08	-7.75E+07	-2.22E+07	-2.26E+07	-1.81E+07	-2.90E+07	-3.66E+07		-2.85E+08	-2.85E+08
Enthalpy J/kg	-8.75E+06	-2.42E+06	-8.75E+06	-2.42E+06	-7.55E+05	-7.68E+05	-6.17E+05	-9.86E+05	-1.25E+06		-1.58E+07	-1.58E+07
Enthalpy MW	-7.737188	-5.398921	-7.74E-04	-5.398921	-1.157128	-1.177128	-0.9451046	-1.510119	-1.908158		-2.816374	-2.88E-03
Entropy J/kmol-K	43240.31	33628.7	43240.31	40452.9	34921.84	34440.12	39645.39	25166.31	8614.979		-1.62E+05	-1.62E+05
Entropy J/kg-K	1503.738	1060.432	1503.738	1261.097	1187.544	1171.162	1348.172	855.7995	292.9589		-8986.351	-8986.878
Density kmol/cum	0.0145536	0.0210198	0.0145536	0.0167308	0.01673	0.0169731	0.0145533	0.0225713	0.0386033		55.27336	55.29857
Density kg/cum	0.4184941	0.6665866	0.4184941	0.5366842	0.4919781	0.4991251	0.4279674	0.6637505	1.135199		995.7651	996.2192
Average MW	28.75522	31.71227	28.75522	32.07754	29.40678	29.40678	29.40678	29.40678	29.40678		18.01528	18.01528
***** ALL PHASES *****												
TDEW C	77.07923	-55.21833	77.07923	18.37931	23.02893	23.02893	23.02893	23.02893	23.02893		102.7428	185.4826

Table 3 (cont.)

	EXHAUST	FLUX-IN	FLUX-OUT	FUEL	FUEL-1	FUEL-2	FUEL-HOT	FUEL-MIX	H2-HP	H2-LP	S1	WATER	WATER-2
Mole Flow kmol/sec													
CO2	4.24E-03	0.011698	0.011698	0	0	0	0	0	0	0	0.0156367	0	0
CO	0	0	0	0	0	0	0	0	0	0	2.94E-04	0	0
CH4	0	0	0	4.24E-03	4.24E-03	4.24E-03	4.24E-03	4.24E-03	0	0	2.83E-06	0	0
H2	0	0	0	0	0	0	0	0	3.63E-03	3.63E-03	4.94E-03	0	0
O2	4.51E-03	5.85E-03	5.85E-03	0	0	0	0	0	0	0	2.52E-14	0	0
N2	0.0420226	0	0	0	0	0	0	0	0	0	0	0	0
H2O	1.32E-03	0	0	0	0	0	6.36E-03	6.36E-03	0	0	9.88E-03	6.36E-03	6.36E-03
Mole Frac													
CO2	0.0813328	0.66667	0.66667	0	0	0	0	0	0	0	0.5084341	0	0
CO	0	0	0	0	0	0	0	0	0	0	9.55E-03	0	0
CH4	0	0	0	1	1	1	0.4	0.4	0	0	9.21E-05	0	0
H2	0	0	0	0	0	0	0	0	1	1	0.1607441	0	0
O2	0.0866518	0.33333	0.33333	0	0	0	0	0	0	0	8.18E-13	0	0
N2	0.8067052	0	0	0	0	0	0	0	0	0	0	0	0
H2O	0.0253101	0	0	0	0	0	0.6	0.6	0	0	0.3211818	1	1
Total Flow kg/sec	1.531848	0.7019892	0.7019892	0.0679693	0.0679693	0.0679693	0.182459	0.182459	7.32E-03	7.32E-03	0.8843597	0.1144896	0.1144896
Temperature C	74.99996	529.6255	529.6255	20	41.92543	30	649.698	18.46574	25	30	75.01835	20	20.21997
Pressure psia	16.2	16.2	16.2	14.7	16.7	16.7	16.7	16.7	6250	164.7	16.2	14.7	64.7
Vapor Frac	1	1	1	1	1	1	1	0.3956657	1	1	1	0	0
Enthalpy J/kmol	-3.66E+07	-2.42E+08	-2.42E+08	-7.47E+07	-7.39E+07	-7.44E+07	-1.48E+08	-2.01E+08	5.68E+05	1.56E+05	-2.77E+08	-2.86E+08	-2.86E+08
Enthalpy J/kg	-1.25E+06	-6.04E+06	-6.04E+06	-4.66E+06	-4.61E+06	-4.64E+06	-8.59E+06	-1.17E+07	2.82E+05	77156.4	-9.64E+06	-1.59E+07	-1.59E+07
Enthalpy MW	-1.908158	-4.241803	-4.241803	-0.3165473	-0.3132112	-0.3150405	-1.567723	-2.132664	2.06E-03	5.65E-04	-8.52115	-1.817755	-1.817624
Entropy J/kmol-K	8614.975	45981.17	45981.17	-81241.23	-79709.86	-81106.81	-7561.016	-1.31E+05	-50721.69	-19631.15	1382.087	-1.64E+05	-1.64E+05
Entropy J/kg-K	292.9588	1149.352	1149.352	-5064.043	-4968.588	-5055.665	-438.9235	-7577.787	-25161.06	-9738.254	48.06386	-9094.916	-9092.205
Density kmol/cum	0.0386033	0.0167336	0.0167336	0.0416652	0.0440297	0.0457735	0.0150095	0.120156	13.48305	0.4475042	0.0387317	55.44	55.42829
Density kg/cum	1.135199	0.6694486	0.6694486	0.6684259	0.7063578	0.7343338	0.2585579	2.06984	27.18021	0.9021147	1.113741	998.7672	998.5561
Average MW	29.40678	40.00617	40.00617	16.04276	16.04276	16.04276	17.22627	17.22627	2.01588	2.01588	28.75522	18.01528	18.01528
***** ALL PHASES *****													
TDEW C	23.02893	-93.4242	-93.4242	-161.4806	-159.9087	-159.9087	89.60892	89.60892		-240.9779	73.3909	100.0252	147.6647

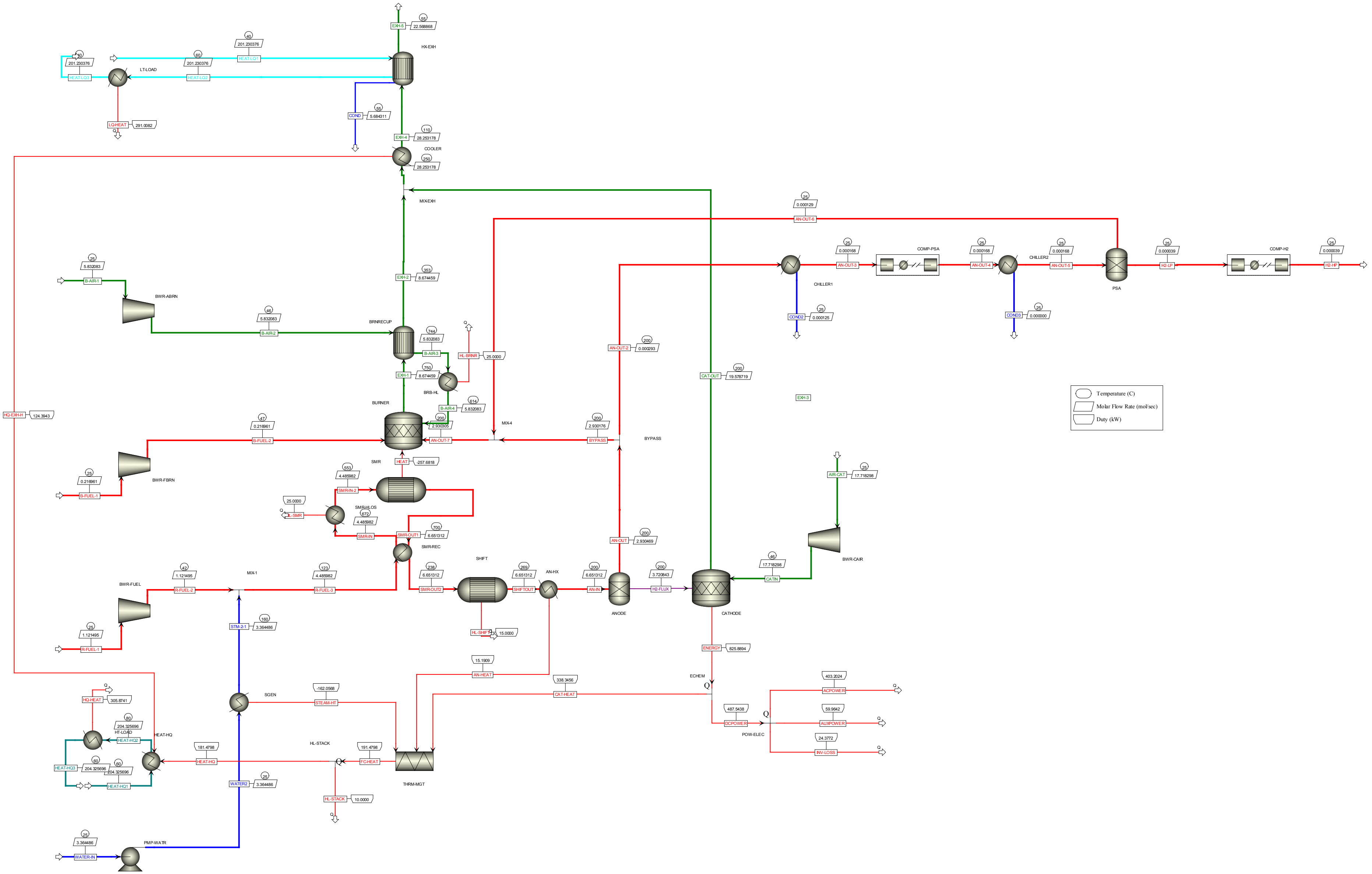


Figure 24. PAFC ASPEN process flow diagram

Table 4. PAFC-CHP stream table

	AIR-CAT	**AN-IN**	**AN-OUT**	**AN-OUT-2**	**AN-OUT-3**	**AN-OUT-4**	**AN-OUT-5**	**AN-OUT-6**	**AN-OUT-7**	**B-AIR-1**	**B-AIR-2**
	BWR-CAIR	**ANODE**	**BYPASS**	**CHILLER1**	**COMP-PSA**	**CHILLER2**	**PSA**	**MIX-4**	**BURNER**	**BWR-ABRN**	**BRNRECUP**
		AN-HX	**ANODE**	**BYPASS**	**CHILLER1**	**COMP-PSA**	**CHILLER2**	**PSA**	**MIX-4**		**BWR-ABRN**
	VAPOR	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**
Substream: MIXED											
Mole Flow mol/sec											
CO2	0	1.028835	1.028835	1.03E-04	1.03E-04	1.03E-04	1.03E-04	1.03E-04	1.028835	0	0
CO	0	0.05383	0.05383	5.38E-06	5.38E-06	5.38E-06	5.38E-06	5.38E-06	0.05383	0	0
CH4	0	0.03883	0.03883	3.88E-06	3.88E-06	3.88E-06	3.88E-06	3.88E-06	0.03883	0	0
H2	0	4.27683	0.555988	5.56E-05	5.56E-05	5.56E-05	5.56E-05	1.67E-05	0.555949	0	0
O2	3.720842	0	0	0	0	0	0	0	0	1.224737	1.224737
N2	13.99745	0	0	0	0	0	0	0	0	4.607345	4.607345
H2O	0	1.252986	1.252986	1.25E-04	6.67E-08	6.67E-08	4.19E-09	4.19E-09	1.252861	0	0
Mole Frac											
CO2	0	0.154682	0.351082	0.351082	0.613077	0.613077	0.613305	0.798578	0.351102	0	0
CO	0	8.09E-03	0.018369	0.018369	0.032077	0.032077	0.032089	0.041783	0.01837	0	0
CH4	0	5.84E-03	0.013251	0.013251	0.023139	0.023139	0.023147	0.03014	0.013251	0	0
H2	0	0.643006	0.189727	0.189727	0.33131	0.33131	0.331433	0.129467	0.189724	0	0
O2	0.21	0	0	0	0	0	0	0	0	0.21	0.21
N2	0.79	0	0	0	0	0	0	0	0	0.79	0.79
H2O	0	0.188382	0.427572	0.427572	3.97E-04	3.97E-04	2.50E-05	3.26E-05	0.427553	0	0
Total Flow mol/sec	17.7183	6.651312	2.930469	2.93E-04	1.68E-04	1.68E-04	1.68E-04	1.29E-04	2.930305	5.832082	5.832082
Total Flow kg/sec	0.51118	0.078604	0.071103	7.11E-06	4.85E-06	4.85E-06	4.85E-06	4.77E-06	0.071101	0.168258	0.168258
Total Flow cum/sec	0.433157	0.234253	0.103045	1.03E-05	3.72E-06	1.84E-07	1.84E-07	1.36E-07	0.103038	0.142576	0.138462
Temperature C	25	200	200	200	25	25	25	24.99996	199.9913	25	45.89837
Pressure psi	14.7	16.2	16.2	16.2	16.2	314.7	314.7	314.7	16.2	14.7	16.2
Vapor Frac	1	1	1	1	1	1	1	1	1	1	1
Liquid Frac	0	0	0	0	0	0	0	0	0	0	0
Solid Frac	0	0	0	0	0	0	0	0	0	0	0
Enthalpy J/kmol	-6813.77	-1.02E+08	-2.38E+08	-2.38E+08	-2.47E+08	-2.47E+08	-2.47E+08	-3.22E+08	-2.38E+08	-6813.77	6.03E+05
Enthalpy J/kg	-236.176	-8.64E+06	-9.82E+06	-9.82E+06	-8.53E+06	-8.54E+06	-8.54E+06	-8.68E+06	-9.82E+06	-236.176	20917.68
Enthalpy kW	-0.12073	-679.502	-698.5	-0.06985	-0.04139	-0.04144	-0.04143	-0.04145	-698.472	-0.03974	3.519564
Entropy J/kmol-K	4251.946	14208.87	7942.791	7942.791	9103.305	-16341.7	-16347.4	-17509	7943.157	4251.946	5422.795
Entropy J/kg-K	147.3791	1202.326	327.3564	327.3564	314.7087	-564.944	-565.065	-472.442	327.3638	147.3791	187.9626
Density kmol/cum	0.040905	0.028394	0.028439	0.028439	0.045154	0.912756	0.9127	0.947095	0.028439	0.040905	0.04212
Density kg/cum	1.180126	0.335552	0.69002	0.69002	1.306135	26.4025	26.40458	35.1	0.690049	1.180126	1.215191
Average MW	28.8504	11.81783	24.26344	24.26344	28.92613	28.92613	28.93019	37.06071	24.264	28.8504	28.8504
Liq Vol 60F cum/sec	9.49E-04	3.12E-04	1.12E-04	1.12E-08	8.99E-09	8.99E-09	8.98E-09	6.90E-09	1.12E-04	3.12E-04	3.12E-04

Table 4 (cont.)

	B-AIR-3	**B-AIR-4**	**B-FUEL-1**	**B-FUEL-2**	**BYPASS**	**CAT-OUT**	**CATIN**	**COND**	**COND2**	**COND3**	**EXH-1**
	BRB-HL	**BURNER**	**BWR-FBRN**	**BURNER**	**MIX-4**	**MIX-EXH**	**CATHODE**				**BRNRECUP**
	BRNRECUP	**BRB-HL**		**BWR-FBRN**	**BYPASS**	**CATHODE**	**BWR-CAIR**	**HX-EXH**	**CHILLER1**	**CHILLER2**	**BURNER**
	VAPOR	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**LIQUID**	**LIQUID**	**LIQUID**	**VAPOR**
Substream: MIXED											
Mole Flow mol/sec											
CO2	0	0	0	0	1.028732	0	0	0	0	0	1.338456
CO	0	0	0	0	0.053825	0	0	0	0	0	0
CH4	0	0	0.216961	0.216961	0.038826	0	0	0	0	0	0
H2	0	0	0	0	0.555932	0	0	0	0	0	0
O2	1.224737	1.224737	0	0	0	1.860421	3.720842	0	0	0	0.408265
N2	4.607345	4.607345	0	0	0	13.99745	13.99745	0	0	0	4.607345
H2O	0	0	0	0	1.252861	3.720842	0	5.68431	1.25E-04	6.25E-08	2.320392
Mole Frac											
CO2	0	0	0	0	0.351082	0	0	0	0	0	0.154299
CO	0	0	0	0	0.018369	0	0	0	0	0	0
CH4	0	0	1	1	0.013251	0	0	0	0	0	0
H2	0	0	0	0	0.189727	0	0	0	0	0	0
O2	0.21	0.21	0	0	0	0.095023	0.21	0	0	0	0.047065
N2	0.79	0.79	0	0	0	0.714932	0.79	0	0	0	0.531139
H2O	0	0	0	0	0.427572	0.190045	0	1	1	1	0.267497
Total Flow mol/sec	5.832082	5.832082	0.216961	0.216961	2.930176	19.57872	17.7183	5.68431	1.25E-04	6.25E-08	8.674459
Total Flow kg/sec	0.168258	0.168258	3.48E-03	3.48E-03	0.071096	0.518681	0.51118	0.102404	2.26E-06	1.13E-09	0.24284
Total Flow cum/sec	0.44181	0.3852	5.30E-03	5.01E-03	0.103035	0.689373	0.420658	1.04E-04	2.26E-09	1.13E-12	0.660492
Temperature C	744.2808	613.8982	25	47.17453	200	200	45.89837	54.71243	25	25	749.628
Pressure psi	16.2	16.2	14.7	16.7	16.2	16.2	16.2	16.2	16.2	314.7	16.2
Vapor Frac	1	1	1	1	1	1	1	0	0	0	1
Liquid Frac	0	0	0	0	0	0	0	1	1	1	0
Solid Frac	0	0	0	0	0	0	0	0	0	0	0
Enthalpy J/kmol	2.23E+07	1.80E+07	-7.45E+07	-7.37E+07	-2.38E+08	-4.07E+07	6.03E+05	-2.84E+08	-2.86E+08	-2.86E+08	-1.00E+08
Enthalpy J/kg	7.73E+05	6.24E+05	-4.65E+06	-4.60E+06	-9.82E+06	-1.54E+06	20917.68	-1.57E+07	-1.59E+07	-1.59E+07	-3.57E+06
Enthalpy kW	130.0613	105.0613	-16.1714	-15.9977	-698.43	-796.226	10.6927	-1612.01	-0.03579	-1.79E-05	-867.088
Entropy J/kmol-K	40986.27	36478.78	-80637.7	-79105.9	7942.791	11187.22	5422.795	-1.56E+05	-1.63E+05	-1.63E+05	39491.01
Entropy J/kg-K	1420.648	1264.412	-5026.42	-4930.94	327.3564	422.2855	187.9626	-8659.32	-9055.76	-9056.56	1410.657
Density kmol/cum	0.0132	0.01514	0.040962	0.043304	0.028439	0.028401	0.04212	54.72333	55.35149	55.40261	0.013133
Density kg/cum	0.380838	0.436807	0.657143	0.694712	0.69002	0.752395	1.215191	985.8561	997.1726	998.0935	0.367665
Average MW	28.8504	28.8504	16.04276	16.04276	24.26344	26.49207	28.8504	18.01528	18.01528	18.01528	27.99477
Liq Vol 60F cum/sec	3.12E-04	3.12E-04	1.16E-05	1.16E-05	1.12E-04	9.16E-04	9.49E-04	1.03E-04	2.26E-09	1.13E-12	3.82E-04

Table 4 (cont.)

	EXH-2	**EXH-3**	**EXH-4**	**EXH-5**	**H2-FLUX**	**H2-HP**	**H2-LP**	**HEAT-HQ1**	**HEAT-HQ2**	**HEAT-HQ3**	**HEAT-LQ1**	**HEAT-LQ2**
	MIX-EXH	**COOLER**	**HX-EXH**		**CATHODE**		**COMP-H2**	**HEAT-HQ**	**HT-LOAD**		**HX-EXH**	**LT-LOAD**
	BRNRECUP	**MIX-EXH**	**COOLER**	**HX-EXH**	**ANODE**	**COMP-H2**	**PSA**		**HEAT-HQ**	**HT-LOAD**		**HX-EXH**
	VAPOR	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**LIQUID**	**LIQUID**	**LIQUID**	**LIQUID**	**LIQUID**
Substream: MIXED												
Mole Flow mol/sec												
CO2	1.338456	1.338456	1.338456	1.338456	0	0	0	0	0	0	0	0
CO	0	0	0	0	0	0	0	0	0	0	0	0
CH4	0	0	0	0	0	0	0	0	0	0	0	0
H2	0	0	0	0	3.72E+00	3.89E-05	3.89E-05	0	0	0	0	0
O2	0.408265	2.268686	2.268686	2.268686	0	0	0	0	0	0	0	0
N2	4.607345	18.6048	18.6048	18.6048	0	0	0	0	0	0	0	0
H2O	2.320392	6.041234	6.041234	0.356924	0	0	0	204.3257	204.3257	204.3257	201.2304	201.2304
Mole Frac												
CO2	0.154299	0.047374	0.047374	0.059305	0	0	0	0	0	0	0	0
CO	0	0	0	0	0	0	0	0	0	0	0	0
CH4	0	0	0	0	0	0	0	0	0	0	0	0
H2	0	0	0	0	1	1	1	0	0	0	0	0
O2	0.047065	0.080298	0.080298	0.100523	0	0	0	0	0	0	0	0
N2	0.531139	0.658503	0.658503	0.824357	0	0	0	0	0	0	0	0
H2O	0.267497	0.213825	0.213825	0.015815	0	0	0	1	1	1	1	1
Total Flow mol/sec	8.674459	28.25318	28.25318	22.56887	3.72E+00	3.89E-05	3.89E-05	204.3257	204.3257	204.3257	201.2304	201.2304
Total Flow kg/sec	0.24284	0.76152	0.76152	6.59E-01	7.50E-03	7.85E-08	7.85E-08	3.680984	3.680984	3.680984	3.625221	3.625221
Total Flow cum/sec	0.404057	1.100848	0.804961	0.550538	1.31E-01	2.88E-09	4.50E-08	3.84E-03	3.92E-03	3.84E-03	3.70E-03	3.78E-03
Temperature C	352.7332	250.4135	110	54.71243	200	25	24.99996	60	80.00055	60	40	60.00641
Pressure psi	16.2	16.2	16.2	16.2	16.2	6264.7	314.7	14.7	14.7	14.7	14.7	14.7
Vapor Frac	1	1	1	1	1	1	1	0	0	0	0	0
Liquid Frac	0	0	0	0	0	0	0	1	1	1	1	1
Solid Frac	0	0	0	0	0	0	0	0	0	0	0	0
Enthalpy J/kmol	-1.15E+08	-6.34E+07	-6.78E+07	-2.63E+07	5.10E+06	5.69E+05	2.19E+04	-2.83E+08	-2.82E+08	-2.83E+08	-2.85E+08	-2.83E+08
Enthalpy J/kg	-4.09E+06	-2.35E+06	-2.51E+06	-9.00E+05	2.53E+06	2.82E+05	1.09E+04	-1.57E+07	-1.56E+07	-1.57E+07	-1.58E+07	-1.57E+07
Enthalpy kW	-993.63	-1789.86	-1914.25	-593.222	1.90E+01	2.21E-05	8.54E-07	-57862.1	-57556.2	-57862.1	-57276.4	-56985.4
Entropy J/kmol-K	21517.58	15207.59	5424.356	6649.315	12630.5	-50741.7	-2.55E+04	-1.55E+05	-1.50E+05	-1.55E+05	-1.59E+05	-1.55E+05
Entropy J/kg-K	768.6285	564.2171	201.2491	227.6801	6265.502	-25171	-12654.9	-8593.23	-8351.62	-8593.23	-8840.82	-8593.16
Density kmol/cum	0.021468	0.025665	0.035099	0.040994	0.028379	13.50721	0.863937	53.26158	52.13249	53.26158	54.36319	53.26122
Density kg/cum	0.601003	0.691758	0.946034	1.197222	0.05721	27.22891	1.741594	959.5222	939.1815	959.5222	979.3681	959.5158
Average MW	27.99477	26.95343	26.95343	29.20464	2.01588	2.01588	2.01588	18.01528	18.01528	18.01528	18.01528	18.01528
Liq Vol 60F cum/sec	3.82E-04	1.30E-03	1.30E-03	1.20E-03	1.99E-04	2.08E-09	2.08E-09	3.69E-03	3.69E-03	3.69E-03	3.63E-03	3.63E-03

Table 4 (cont.)

	HEAT-LQ3	**R-FUEL-1**	**R-FUEL-2**	**R-FUEL-3**	**SHIFTOUT**	**SMR-IN**	**SMR-IN-2**	**SMR-OUT1**	**SMR-OUT2**	**STM-2-1**	**WATER-IN**	**WATER2**
		BWR-FUEL	**MIX-1**	**SMR-REC**	**AN-HX**	**SMR-HLOS**	**SMR**	**SMR-REC**	**SHIFT**	**MIX-1**	**PMP-WATR**	**SGEN**
	LT-LOAD		**BWR-FUEL**	**MIX-1**	**SHIFT**	**SMR-REC**	**SMR-HLOS**	**SMR**	**SMR-REC**	**SGEN**		**PMP-WATR**
	LIQUID	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**LIQUID**	**LIQUID**
Substream: MIXED												
Mole Flow mol/sec												
CO2	0	0	0	0	1.028835	0	0	0.47602	0.47602	0	0	0
CO	0	0	0	0	0.05383	0	0	0.606645	0.606645	0	0	0
CH4	0	1.121495	1.121495	1.121495	0.03883	1.121495	1.121495	0.03883	0.03883	0	0	0
H2	0	0	0	0	4.27683	0	0	3.724015	3.724015	0	0	0
O2	0	0	0	0	0	0	0.00E+00	2.05E-21	2.05E-21	0	0	0
N2	0	0	0	0	0	0	0	0	0	0	0	0
H2O	201.2304	0	0	3.364486	1.252986	3.364486	3.364486	1.805801	1.805801	3.364486	3.364486	3.364486
Mole Frac												
CO2	0	0	0	0	0.154682	0	0	0.071568	0.071568	0	0	0
CO	0	0	0	0.00E+00	8.09E-03	0	0	0.091207	0.091207	0	0	0
CH4	0	1	1	2.50E-01	5.84E-03	0.25	2.50E-01	5.84E-03	5.84E-03	0	0	0
H2	0	0	0	0	0.643006	0	0	0.559892	0.559892	0	0	0
O2	0	0	0	0	0	0	0.00E+00	3.08E-22	3.08E-22	0	0	0
N2	0	0	0	0	0	0	0	0	0	0	0	0
H2O	1	0	0	0.75	0.188382	0.75	0.75	0.271496	0.271496	1	1	1
Total Flow mol/sec	201.2304	1.121495	1.121495	4.485981	6.651312	4.485981	4.485981	6.651312	6.651312	3.364486	3.364486	3.364486
Total Flow kg/sec	3.625221	0.017992	0.017992	0.078604	0.078604	0.078604	0.078604	0.078604	0.078604	0.060612	0.060612	0.060612
Total Flow cum/sec	3.70E-03	0.027379	0.026255	0.131705	0.268569	0.315634	0.275818	0.48189	0.25295	1.90E-02	6.10E-05	6.10E-05
Temperature C	40	25	41.88113	123.1612	269.2567	672.3553	553.2543	700	237.8054	160.2358	25	25.04886
Pressure psi	14.7	14.7	16.2	16.2	16.2	16.2	16.2	16.2	16.2	90	14.7	90
Vapor Frac	0	1	1	1	1	1	1	1	1	1	0	0
Liquid Frac	1	0	0	0	0	0	0	0	0	0	1	1
Solid Frac	0	0	0	0	0	0	0	0	0	0	0	0
Enthalpy J/kmol	-2.85E+08	-7.45E+07	-7.39E+07	-1.97E+08	-9.99E+07	-1.74E+08	-1.79E+08	-8.21E+07	-9.76E+07	-2.38E+08	-2.86E+08	-2.86E+08
Enthalpy J/kg	-1.58E+07	-4.65E+06	-4.61E+06	-1.12E+07	-8.45E+06	-9.90E+06	-1.02E+07	-6.94E+06	-8.26E+06	-1.32E+07	-1.59E+07	-1.59E+07
Enthalpy kW	-57276.4	-83.5918	-82.9101	-881.993	-664.311	-778.475	-803.475	-545.793	-649.311	-799.083	-961.179	-961.14
Entropy J/kmol-K	-1.59E+05	-80637.7	-79461.1	-39705.8	18712.98	-3935.13	-10231.1	42847.03	21255.5	-4.71E+04	-1.63E+05	-1.63E+05
Entropy J/kg-K	-8840.82	-5026.42	-4953.08	-2266.04	1583.454	-224.581	-583.895	3625.628	1798.596	-2616.52	-9030.75	-9030.32
Density kmol/cum	54.36319	0.040962	0.042715	0.034061	0.024766	0.014213	0.016264	0.013803	0.026295	0.177513	55.173	55.17038
Density kg/cum	979.3681	0.657143	0.685271	0.596821	0.292677	0.249035	0.284985	0.163116	0.310749	3.19794	993.957	993.9099
Average MW	18.01528	16.04276	16.04276	17.52215	11.81783	17.52215	17.52215	11.81783	11.81783	18.01528	18.01528	18.01528
Liq Vol 60F cum/sec	3.63E-03	6.01E-05	6.01E-05	1.21E-04	3.12E-04	1.21E-04	1.21E-04	2.92E-04	2.92E-04	6.07E-05	6.07E-05	6.07E-05

Table 5. PAFC-CHHP stream table

	AFMIX2	**AIR+FUEL**	**AIR-CAT**	**AN-IN**	**AN-OUT**	**B-AIR-1**	**B-AIR-2**	**B-AIR-3**	**B-AIR-4**	**B-FUEL-1**	**B-FUEL-2**	**CAT-OUT**
	BRNR2	**CMP-BRN2**	**BWR-CAIR**	**ANODE**	**MIX-4**	**BWR-ABRN**	**BRNRECUP**	**BURNER**	**BRB-HL**	**BWR-FBRN**	**BURNER**	**MIX-EXH**
	CMP-BRN2			**BYPASS**	**ANODE**		**BWR-ABRN**	**BRNRECUP**	**BURNER**		**BWR-FBRN**	**CATHODE**
	VAPOR	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**
Substream: MIXED												
Mole Flow mol/sec												
CO2	0	0	0	0.106051	0.106051	0	0	0	1.220009	0	0	0
CO	0	0	0	5.82E-03	5.82E-03	0	0	0	0	0	0	0
CH4	0.130541	0.130541	0	4.01E-03	4.01E-03	0	0	0	0	0.061131	0.061131	0
H2	0	0	0	0.441678	0.057418	0	0	0	0	0	0	0
O2	0.287178	0.287178	0.38426	0	0	1.135841	1.135841	1.135841	0.378614	0	0	0.19213
N2	1.080339	1.080339	1.445548	0	0	4.272924	4.272924	4.272924	4.272924	0	0	1.445548
H2O	0	0	0	0.129737	0.129737	0	0	0	1.383646	0	0	0.38426
Mole Frac												
CO2	0	0	0	0.154301	0.349955	0	0	0	0.168157	0	0	0
CO	0	0	0	8.47E-03	0.019218	0	0	0	0	0	0	0
CH4	0.08714	0.08714	0	5.84E-03	0.013241	0	0	0	0	1	1	0
H2	0	0	0	0.642625	0.189472	0	0	0	0	0	0	0
O2	0.1917	0.1917	0.21	0	0	0.21	0.21	0.21	0.052185	0	0	0.095023
N2	0.72116	0.72116	0.79	0	0	0.79	0.79	0.79	0.588947	0	0	0.714932
H2O	0	0	0	0.188762	0.428114	0	0	0	0.190711	0	0	0.190045
Total Flow mol/sec	1.498057	1.498057	1.829807	0.687302	0.303043	5.408765	5.408765	5.408765	7.255193	0.061131	0.061131	2.021937
Total Flow kg/sec	0.041548	0.041548	0.052791	8.12E-03	7.35E-03	0.156045	0.156045	0.156045	0.210434	9.81E-04	9.81E-04	0.053565
Total Flow cum/sec	0.034536	0.036619	0.044733	0.024206	0.010656	0.132227	0.128412	0.409119	0.600582	1.49E-03	1.41E-03	0.071193
Temperature C	36.716	25	25	200	200	25	45.89837	742.734	838.7326	25	47.17113	200
Pressure psi	16.2	14.7	14.7	16.2	16.2	14.7	16.2	16.2	16.2	14.7	16.7	16.2
Vapor Frac	1	1	1	1	1	1	1	1	1	1	1	1
Liquid Frac	0	0	0	0	0	0	0	0	0	0	0	0
Solid Frac	0	0	0	0	0	0	0	0	0	0	0	0
Enthalpy J/kmol	-6.15E+06	-6.50E+06	-6813.77	-1.02E+08	-2.38E+08	-6813.77	6.03E+05	2.22E+07	-8.36E+07	-7.45E+07	-7.37E+07	-4.07E+07
Enthalpy J/kg	-2.22E+05	-2.34E+05	-236.176	-8.64E+06	-9.82E+06	-236.176	20917.68	7.71E+05	-2.88E+06	-4.65E+06	-4.60E+06	-1.54E+06
Enthalpy kW	-9.21686	-9.7391	-0.01247	-70.2048	-72.1667	-0.03685	3.264099	120.3335	-606.459	-4.55646	-4.5075	-82.228
Entropy J/kmol-K	-345.674	-685.11	4251.946	14236.88	8005.565	4251.946	5422.795	40935.68	45534.83	-80637.7	-79106.3	11187.22
Entropy J/kg-K	-12.4638	-24.7026	147.3791	1204.695	330.1708	147.3791	187.9626	1418.895	1569.919	-5026.42	-4930.96	422.2855
Density kmol/cum	0.043376	0.040909	0.040905	0.028394	0.028439	0.040905	0.04212	0.013221	0.01208	0.040962	0.043304	0.028401
Density kg/cum	1.203008	1.134587	1.180126	0.335553	0.689546	1.180126	1.215191	0.381417	0.350383	0.657143	0.69472	0.752395
Average MW	27.73434	27.73434	28.8504	11.81783	24.24674	28.8504	28.8504	28.8504	29.00458	16.04276	16.04276	26.49207
Liq Vol 60F cum/sec	8.02E-05	8.02E-05	9.80E-05	3.22E-05	1.16E-05	2.90E-04	2.90E-04	2.90E-04	3.39E-04	3.27E-06	3.27E-06	9.46E-05

Table 5 (cont.)

	CATIN	**COND1**	**COND2**	**COND3**	**EXH**	**EXH-1**	**EXH-2**	**EXH-3**	**EXH-4**	**EXH-5**	**EXH-6**	**EXH-7**
	CATHODE					**BRNRECUP**	**SGENBRNR**	**MIX-EXH**	**COOLER**	**HX-EXH**	**B4**	
	BWR-CAIR	**B4**	**CHILLER1**	**CHILLER2**	**BRNR2**	**BRB-HL**	**BRNRECUP**	**SGENBRNR**	**MIX-EXH**	**COOLER**	**HX-EXH**	**B4**
	VAPOR	**LIQUID**	**LIQUID**	**LIQUID**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**MIXED**	**VAPOR**
Substream: MIXED												
Mole Flow mol/sec												
CO2	0	7.76E-03	0	0	0.130541	1.220009	1.220009	1.220009	1.220009	1.220009	1.220009	1.212249
CO	0	0	0	0	0	0	0	0	0	0	0	0
CH4	0	0	0	0	0	0	0	0	0	0	0	0
H2	0	0	0	0	0	0	0	0	0	0	0	0
O2	0.38426	8.07E-04	0	0	0.026096	0.378614	0.378614	0.378614	0.570743	0.570743	0.570743	0.569936
N2	1.445548	3.08E-03	0	0	1.080339	4.272924	4.272924	4.272924	5.718472	5.718472	5.718472	5.715392
H2O	0	1.59497	1.165645	1.78E-03	0.261081	1.383646	1.383646	1.383646	1.767905	1.767905	1.767905	0.172936
Mole Frac												
CO2	0	4.83E-03	0	0	0.08714	0.168157	0.168157	0.168157	0.131507	0.131507	0.131507	0.15804
CO	0	0	0	0	0	0	0	0	0	0	0	0
CH4	0	0	0	0	0	0	0	0	0	0	0	0
H2	0	0	0	0	0	0	0	0	0	0	0	0
O2	0.21	5.02E-04	0	0	0.01742	0.052185	0.052185	0.052185	0.061522	0.061522	0.061522	0.074302
N2	0.79	1.92E-03	0	0	0.72116	0.588947	0.588947	0.588947	0.616405	0.616405	0.616405	0.745112
H2O	0	0.99275	1	1	0.17428	0.190711	0.190711	0.190711	0.190566	0.190566	0.190566	0.022546
Total Flow mol/sec	1.829807	1.606618	1.165645	1.78E-03	1.498057	7.255193	7.255193	7.255193	9.27713	9.27713	9.27713	7.670512
Total Flow kg/sec	0.052791	0.029188	0.020999	3.21E-05	0.041548	0.210434	0.210434	0.210434	0.263999	0.263999	0.263999	0.234812
Total Flow cum/sec	0.043442	2.92E-05	2.11E-05	3.21E-08	0.046512	0.552355	0.311657	0.233747	0.30463	0.264292	0.175597	0.16783
Temperature C	45.89837	21.15891	25	25	144.2173	749.4543	304.0224	160	168.2637	110	40.43257	21.15891
Pressure psi	16.2	16.2	16.2	164.7	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2
Vapor Frac	1	0	0	0	1	1	1	1	1	1	0.811423	1
Liquid Frac	0	1	1	1	0	0	0	0	0	0	0.188577	0
Solid Frac	0	0	0	0	0	0	0	0	0	0	0	0
Enthalpy J/kmol	6.03E+05	-2.86E+08	-2.86E+08	-2.86E+08	-7.28E+07	-8.70E+07	-1.03E+08	-1.08E+08	-9.33E+07	-9.52E+07	-1.06E+08	-6.78E+07
Enthalpy J/kg	20917.68	-1.57E+07	-1.59E+07	-1.59E+07	-2.62E+06	-3.00E+06	-3.56E+06	-3.72E+06	-3.28E+06	-3.34E+06	-3.71E+06	-2.21E+06
Enthalpy kW	1.104258	-459.236	-333.168	-0.50869	-108.987	-631.459	-748.538	-783.405	-865.633	-882.952	-979.079	-519.843
Entropy J/kmol-K	5422.795	-1.62E+05	-1.63E+05	-1.63E+05	8947.442	42304.65	21698.2	12128.89	12250.03	7715.175	-24368.1	4782.811
Entropy J/kg-K	187.9626	-8942.05	-9055.76	-9056.23	322.6124	1458.551	748.0956	418.1714	430.4754	271.1172	-856.315	156.2385
Density kmol/cum	0.04212	54.988	55.35149	55.37695	0.032208	0.013135	0.023279	0.031039	0.030454	0.035102	0.052832	0.045704
Density kg/cum	1.215191	998.9694	997.1726	997.6312	0.893271	0.380976	0.67521	0.900263	0.866623	0.998893	1.50344	1.399105
Average MW	28.8504	18.16704	18.01528	18.01528	27.73434	29.00458	29.00458	29.00458	28.45698	28.45698	28.45698	30.61224
Liq Vol 60F cum/sec	9.80E-05	2.94E-05	2.10E-05	3.21E-08	7.10E-05	3.39E-04	3.39E-04	3.39E-04	4.34E-04	4.34E-04	4.34E-04	4.05E-04

Table 5 (cont.)

	H2-FLUX	**H2-HP**	**H2-LP**	**HEAT-LQ1**	**HEAT-LQ2**	**HEAT-LQ3**	**R-FUEL-1**	**R-FUEL-2**	**R-FUEL-3**	**SHIFTOUT**	**SMR-IN**	**SMR-IN-2**
	CATHODE		**COMP-H2**	**HX-EXH**	**LT-LOAD**		**BWR-FUEL**	**MIX-1**	**SMR-REC**	**AN-HX**	**SMR-HLOS**	**SMR**
	ANODE	**COMP-H2**	**PSA**		**HX-EXH**	**LT-LOAD**		**BWR-FUEL**	**MIX-1**	**SHIFT**	**SMR-REC**	**SMR-HLOS**
	VAPOR	**VAPOR**	**VAPOR**	**LIQUID**	**LIQUID**	**LIQUID**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**
Substream: MIXED												
Mole Flow mol/sec												
CO2	0	0	0	0	0	0	0	0	0	1.060514	0	0
CO	0	0	0	0	0	0	0	0	0	0.05824	0	0
CH4	0	0	0	0	0	0	1.158878	1.158878	1.158878	0.040125	1.158878	1.158878
H2	0.38426	2.981324	2.981324	0	0	0	0	0	0	4.416776	0	0
O2	0	0	0	0	0	0	0	0	0	0	0	0
N2	0	0	0	0	0	0	0	0	0	0	0	0
H2O	0	0	0	66.49669	66.49669	66.49669	0	0	3.476636	1.297367	3.476636	3.476636
Mole Frac												
CO2	0	0	0	0	0	0	0	0	0	0.154301	0	0
CO	0	0	0	0	0	0	0	0	0	8.47E-03	0	0
CH4	0	0	0	0	0	0	1	1	0.25	5.84E-03	0.25	0.25
H2	1	1	1	0	0	0	0	0	0	0.642625	0	0
O2	0	0	0	0	0	0	0	0	0	0	0	0
N2	0	0	0	0	0	0	0	0	0	0	0	0
H2O	0	0	0	1	1	1	0	0	0.75	0.188762	0.75	0.75
Total Flow mol/sec	0.38426	2.981324	2.981324	66.49669	66.49669	66.49669	1.158878	1.158878	4.635514	6.873022	4.635514	4.635514
Total Flow kg/sec	7.75E-04	6.01E-03	6.01E-03	1.197956	1.197956	1.197956	0.018592	0.018592	0.081224	0.081224	0.081224	0.081224
Total Flow cum/sec	0.01354	2.21E-04	6.55E-03	1.22E-03	1.25E-03	1.22E-03	0.028292	0.02713	0.136095	0.279154	0.325642	0.285835
Temperature C	200	25	25.00004	40	59.99897	40	25	41.88113	123.1612	272.446	670.8693	555.6345
Pressure psi	16.2	6264.7	164.7	14.7	14.7	14.7	14.7	16.2	16.2	16.2	16.2	16.2
Vapor Frac	1	1	1	0	0	0	1	1	1	1	1	1
Liquid Frac	0	0	0	1	1	1	0	0	0	0	0	0
Solid Frac	0	0	0	0	0	0	0	0	0	0	0	0
Enthalpy J/kmol	5.10E+06	5.69E+05	11355.15	-2.85E+08	-2.83E+08	-2.85E+08	-7.45E+07	-7.39E+07	-1.97E+08	-9.98E+07	-1.74E+08	-1.79E+08
Enthalpy J/kg	2.53E+06	2.82E+05	5632.848	-1.58E+07	-1.57E+07	-1.58E+07	-4.65E+06	-4.61E+06	-1.12E+07	-8.44E+06	-9.91E+06	-1.02E+07
Enthalpy kW	1.959141	1.696543	0.033853	-18927	-18830.9	-18927	-86.3782	-85.6738	-911.393	-685.624	-804.755	-829.755
Entropy J/kmol-K	12630.5	-50741.7	-20110.7	-1.59E+05	-1.55E+05	-1.59E+05	-80637.7	-79461.1	-39705.8	18935.2	-4010.69	-10100.1
Entropy J/kg-K	6265.502	-25171	-9976.16	-8840.82	-8593.25	-8840.82	-5026.42	-4953.08	-2266.04	1602.258	-228.892	-576.42
Density kmol/cum	0.028379	13.50721	0.454974	54.36319	53.26163	54.36319	0.040962	0.042715	0.034061	0.024621	0.014235	0.016217
Density kg/cum	0.05721	27.22891	0.917173	979.3681	959.5232	979.3681	0.657143	0.685271	0.596821	0.290965	0.249428	0.284165
Average MW	2.01588	2.01588	2.01588	18.01528	18.01528	18.01528	16.04276	16.04276	17.52215	11.81783	17.52215	17.52215
Liq Vol 60F cum/sec	2.06E-05	1.60E-04	1.60E-04	1.20E-03	1.20E-03	1.20E-03	6.21E-05	6.21E-05	1.25E-04	3.22E-04	1.25E-04	1.25E-04

Table 5 (cont.)

	SMR-OUT1	**SMR-OUT2**	**STM-2-1**	**SYNGAS1**	**SYNGAS2**	**SYNGAS3**	**SYNGAS4**	**SYNGAS5**	**SYNGAS6**	**SYNGAS7**	**WATER-IN**	**WATER2**
	SMR-REC	**SHIFT**	**MIX-1**	**BYPASS**	**CHILLER1**	**COMP-PSA**	**CHILLER2**	**PSA**	**MIX-4**	**BURNER**	**PMP-WATR**	**SGEN**
	SMR	**SMR-REC**	**SGEN**	**AN-HX**	**BYPASS**	**CHILLER1**	**COMP-PSA**	**CHILLER2**	**PSA**	**MIX-4**		**PMP-WATR**
	VAPOR	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**VAPOR**	**LIQUID**	**LIQUID**
Substream: MIXED												
Mole Flow mol/sec												
CO2	0.491887	0.491887	0	1.060514	0.954463	0.954463	0.954463	0.954463	0.954463	1.060514	0	0
CO	0.626867	0.626867	0	0.05824	0.052416	0.052416	0.052416	0.052416	0.052416	0.05824	0	0
CH4	0.040125	0.040125	0	0.040125	0.036112	0.036112	0.036112	0.036112	0.036112	0.040125	0	0
H2	3.848149	3.848149	0	4.416776	3.975099	3.975099	3.975099	3.975099	0.993775	1.051193	0	0
O2	2.12E-21	2.12E-21	0	0	0	0	0	0	0	0	0	0
N2	0	0	0	0	0	0	0	0	0	0	0	0
H2O	1.865994	1.865994	3.476636	1.297367	1.167631	1.99E-03	1.99E-03	2.05E-04	2.05E-04	0.129942	3.476636	3.476636
Mole Frac												
CO2	0.071568	0.071568	0	0.154301	0.154301	0.190129	0.190129	0.190197	0.46857	0.453209	0	0
CO	0.091207	0.091207	0	8.47E-03	8.47E-03	0.010441	0.010441	0.010445	0.025732	0.024889	0	0
CH4	5.84E-03	5.84E-03	0	5.84E-03	5.84E-03	7.19E-03	7.19E-03	7.20E-03	0.017728	0.017147	0	0
H2	0.559892	0.559892	0	0.642625	0.642625	0.791841	0.791841	0.792121	0.487869	0.449225	0	0
O2	3.08E-22	3.08E-22	0	0	0	0	0	0	0	0	0	0
N2	0	0	0	0	0	0	0	0	0	0	0	0
H2O	0.271496	0.271496	1	0.188762	0.188762	3.95E-04	3.95E-04	4.09E-05	1.01E-04	0.055531	1	1
Total Flow mol/sec	6.873022	6.873022	3.476636	6.873022	6.18572	5.020074	5.020074	5.018295	2.036971	2.340013	3.476636	3.476636
Total Flow kg/sec	0.081224	0.081224	0.062633	0.081224	0.073102	0.052102	0.052102	0.05207	0.04606	0.053408	0.062633	0.062633
Total Flow cum/sec	0.497953	0.262146	0.019585	0.242061	0.217855	0.11144	0.010987	0.010983	4.40E-03	0.05563	6.30E-05	6.30E-05
Temperature C	700	239.298	160.2358	200	200	25	25	25	25.00004	46.61996	25	25.04886
Pressure psi	16.2	16.2	90	16.2	16.2	16.2	164.7	164.7	164.7	16.2	14.7	90
Vapor Frac	1	1	1	1	1	1	1	1	1	1	0	0
Liquid Frac	0	0	0	0	0	0	0	0	0	0	1	1
Solid Frac	0	0	0	0	0	0	0	0	0	0	0	0
Enthalpy J/kmol	-8.21E+07	-9.76E+07	-2.38E+08	-1.02E+08	-1.02E+08	-7.66E+07	-7.66E+07	-7.66E+07	-1.89E+08	-1.95E+08	-2.86E+08	-2.86E+08
Enthalpy J/kg	-6.94E+06	-8.26E+06	-1.32E+07	-8.64E+06	-8.64E+06	-7.38E+06	-7.38E+06	-7.38E+06	-8.34E+06	-8.55E+06	-1.59E+07	-1.59E+07
Enthalpy kW	-563.986	-670.624	-825.719	-702.048	-631.843	-384.565	-384.654	-384.223	-384.35	-456.516	-993.219	-993.178
Entropy J/kmol-K	42847.03	21349.58	-47137.3	14236.88	14236.88	4942.298	-14417.4	-14424.7	-10904.3	9826.388	-1.63E+05	-1.63E+05
Entropy J/kg-K	3625.628	1806.557	-2616.52	1204.695	1204.695	476.1918	-1389.12	-1390.19	-482.234	430.5319	-9030.75	-9030.32
Density kmol/cum	0.013803	0.026218	0.177513	0.028394	0.028394	0.045047	0.456929	0.456921	0.463175	0.042064	55.173	55.17038
Density kg/cum	0.163116	0.309843	3.19794	0.335553	0.335553	0.467537	4.742377	4.741055	10.47337	0.960054	993.957	993.9099
Average MW	11.81783	11.81783	18.01528	11.81783	11.81783	10.3788	10.3788	10.37609	22.61214	22.82383	18.01528	18.01528
Liq Vol 60F cum/sec	3.02E-04	3.02E-04	6.28E-05	3.22E-04	2.90E-04	2.69E-04	2.69E-04	2.69E-04	1.09E-04	1.21E-04	6.28E-05	6.28E-05

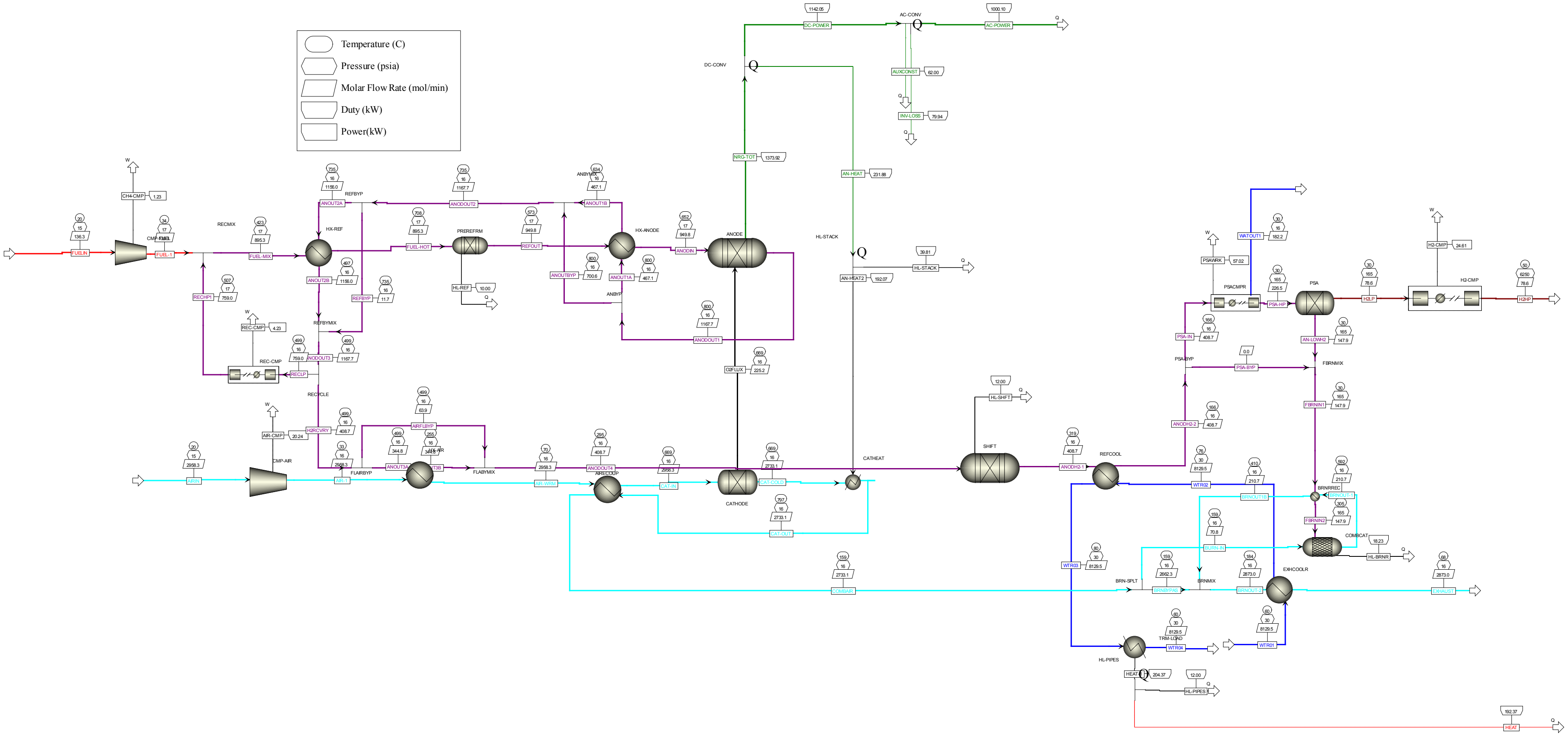


Figure 25. SOFC ASPEN process flow diagram

Table 6. SOFC-CHP stream table

	AIR-1	AIR-WRM	AIRFLBYP	AIRIN	AN-LOWH2	ANODH2-1	ANODH2-2	ANODIN	ANODOUT1	ANODOUT2	ANODOUT3
Mole Flow mol/min											
CH4	0	0	2.69E-04	0	1.63E-09	1.64E-03	1.64E-03	109.0179	4.92E-03	4.92E-03	4.92E-03
N2	2337.046	2337.046	0	2337.046	0	0	0	0	0	0	0
CO	0	0	4.723909	0	2.18E-06	2.187676	2.187676	51.71445	86.36537	86.36537	86.36475
CO2	0	0	16.56564	0	1.31E-04	134.0414	134.0414	228.5366	302.8631	302.8631	302.8609
H2	0	0	10.07224	0	1.39E-05	92.49124	92.49124	233.135	184.1467	184.1467	184.1454
H2O	0	0	32.50686	0	7.70E-07	179.9669	179.9669	327.3671	594.3101	594.3101	594.3059
O2	621.2402	621.2402	2.64E-16	621.2402	0	1.11E-34	1.11E-34	2.43E-22	4.82E-15	4.82E-15	4.82E-15
C	0	0	3.59E-28	0	0	8.98E-36	8.98E-36	2.11E-34	6.57E-27	6.57E-27	6.57E-27
Mole Frac											
CH4	0	0	4.21E-06	0	1.10E-05	4.00E-06	4.00E-06	0.1147833	4.21E-06	4.21E-06	4.21E-06
N2	0.79	0.79	0	0.79	0	0	0	0	0	0	0
CO	0	0	0.0739625	0	0.0147685	5.35E-03	5.35E-03	0.0544493	0.0739625	0.0739625	0.0739625
CO2	0	0	0.2593694	0	0.8862063	0.3279791	0.3279791	0.2406228	0.2593694	0.2593694	0.2593694
H2	0	0	0.1577017	0	0.0938087	0.2263121	0.2263121	0.2454644	0.1577017	0.1577017	0.1577017
H2O	0	0	0.5089622	0	5.21E-03	0.4403519	0.4403519	0.3446801	0.5089622	0.5089622	0.5089622
O2	0.21	0.21	4.13E-18	0.21	0	2.72E-37	2.72E-37	2.56E-25	4.13E-18	4.13E-18	4.13E-18
C	0	0	5.63E-30	0	0	2.20E-38	2.20E-38	2.22E-37	5.63E-30	5.63E-30	5.63E-30
Total Flowmol/min	2958.286	2958.286	63.86891	2958.286	1.48E-04	408.6889	408.6889	949.7711	1167.69	1167.69	1167.682
Total Flowkg/sec	1.422462	1.422462	0.0244549	1.422462	9.78E-08	0.1564841	0.1564841	0.3270487	0.4471005	0.4471005	0.4470974
Total Flowl/min	67342.52	75521.75	3671.093	71141.18	3.27E-04	18015.12	13381.06	63466.39	93278.45	87591.12	67116.67
Temperature C	32.66295	69.80611	499.0194	20	30	319.0265	166.6999	652.2575	800	734.5684	499.0194
Pressurepsia	16.2	16.2	16.2	14.7	164.6959	16.2	16.2	16.7	16.2	16.2	16.2
Vapor Frac	1	1	1	1	0.9976798	1	1	1	1	1	1
Liquid Frac	0	0	0	0	2.32E-03	0	0	0	0	0	0
Solid Frac	0	0	0	0	0	0	0	0	0	0	0
EnthalpyJ/kmol	2.24E+05	1.31E+06	-2.16E+08	-1.46E+05	-3.52E+08	-2.26E+08	-2.31E+08	-1.68E+08	-2.03E+08	-2.06E+08	-2.16E+08
EnthalpyJ/kg	7749.924	45364.87	-9.40E+06	-5055.209	-8.86E+06	-9.82E+06	-1.01E+07	-8.14E+06	-8.86E+06	-8.98E+06	-9.40E+06
EnthalpykW	11.02398	64.52982	-229.8271	-7.190845	-8.66E-04	-1536.139	-1574.707	-2663.438	-3959.363	-4013.741	-4201.81
Entropy J/kmol-K	4203.506	7552.521	28247.81	3777.6	-12647.01	14756.25	3717.578	34968.23	41842.66	39156.42	28247.81
Entropy J/kg-K	145.7001	261.7822	1229.578	130.9375	-318.5765	642.3141	161.8197	1692.501	1821.338	1704.411	1229.578
Density kmol/cum	0.0439289	0.0391713	0.0173977	0.0415833	0.451561	0.0226858	0.0305423	0.0149649	0.0125183	0.0133311	0.0173977
Density kg/cum	1.267368	1.130108	0.3996897	1.199695	17.92629	0.5211757	0.7016667	0.3091861	0.2875909	0.3062643	0.3996897
Average MW	28.8504	28.8504	22.97359	28.8504	39.69849	22.97358	22.97358	20.66069	22.97359	22.97359	22.97359
Liq Vol 60F l/min	158.4393	158.4393	2.266431	158.4393	7.89E-06	15.49825	15.49825	39.24356	41.43628	41.43628	41.43598
*** ALL PHASES ***											
TDEWC	-190.1721	-190.1721	84.61444	-191.015	38.16618	80.98133	80.98133	75.73295	84.61444	84.61444	84.61444
Substream: $TOTAL											
Total Flowkg/sec	1.422462	1.422462	0.0244549	1.422462	9.78E-08	0.1564841	0.1564841	0.3270487	0.4471005	0.4471005	0.4470974
EnthalpykW	11.02398	64.52982	-229.8271	-7.190845	-8.66E-04	-1536.139	-1574.707	-2663.438	-3959.363	-4013.741	-4201.81

Table 6 (cont.)

	ANODOUT4	ANOUT1A	ANOUT1B	ANOUT2A	ANOUT2B	ANOUT3A	ANOUT3B	ANOUTBYP	BRNBYPAS	BRNOUT-1	BRNOUT-2
Mole Flow mol/min											
CH4	1.72E-03	1.97E-03	1.97E-03	4.87E-03	4.87E-03	1.45E-03	1.45E-03	2.95E-03	0	0	0
N2	0	0	0	0	0	0	0	0	1232.888	1104.158	2337.046
CO	30.22766	34.54615	34.54615	85.5011	85.5011	25.50376	25.50376	51.81922	0	0	0
CO2	106.0013	121.1452	121.1452	299.8323	299.8323	89.43569	89.43569	181.7178	0	136.2307	136.2307
H2	64.4509	73.6587	73.6587	182.304	182.304	54.37867	54.37867	110.488	0	0	0
H2O	208.0071	237.7241	237.7241	588.3628	588.3628	175.5002	175.5002	356.5861	0	272.4612	272.4612
O2	1.69E-15	1.93E-15	1.93E-15	4.78E-15	4.78E-15	1.42E-15	1.42E-15	2.89E-15	208.9369	139.7784	348.7152
C	2.30E-27	2.63E-27	2.63E-27	6.50E-27	6.50E-27	1.94E-27	1.94E-27	3.94E-27	0	0	0
Mole Frac											
CH4	4.21E-06	4.21E-06	4.21E-06	4.21E-06	4.21E-06	4.21E-06	4.21E-06	4.21E-06	0	0	0
N2	0	0	0	0	0	0	0	0	0.8550886	0.6681225	0.7552372
CO	0.0739625	0.0739625	0.0739625	0.0739625	0.0739625	0.0739625	0.0739625	0.0739625	0	0	0
CO2	0.2593694	0.2593694	0.2593694	0.2593694	0.2593694	0.2593694	0.2593694	0.2593694	0	0.0824327	0.0440241
H2	0.1577017	0.1577017	0.1577017	0.1577017	0.1577017	0.1577017	0.1577017	0.1577017	0	0	0
H2O	0.5089622	0.5089622	0.5089622	0.5089622	0.5089622	0.5089622	0.5089622	0.5089622	0	0.1648653	0.0880482
O2	4.13E-18	4.13E-18	4.13E-18	4.13E-18	4.13E-18	4.13E-18	4.13E-18	4.13E-18	0.1449114	0.0845794	0.1126904
C	5.63E-30	5.63E-30	5.63E-30	5.63E-30	5.63E-30	5.63E-30	5.63E-30	5.63E-30	0	0	0
Total Flowmol/min	408.6887	467.0761	467.0761	1156.005	1156.005	344.8198	344.8198	700.6141	1441.825	1652.628	3094.453
Total Flowkg/sec	0.1564841	0.1788402	0.1788402	0.4426264	0.4426264	0.1320291	0.1320291	0.2682603	0.6870536	0.7718001	1.458854
Total Flowl/min	17275.67	37311.38	31550.39	86714.59	66233.67	19819.74	13565.46	55967.07	46395.47	1.07E+05	1.52E+05
Temperature C	294.7202	800	634.3024	734.5684	496.5577	499.0194	255.3551	800	159.1346	595.6236	387.9136
Pressurepsia	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2
Vapor Frac	1	1	1	1	1	1	1	1	1	1	1
Liquid Frac	0	0	0	0	0	0	0	0	0	0	0
Solid Frac	0	0	0	0	0	0	0	0	0	0	0
EnthalpyJ/kmol	-2.24E+08	-2.03E+08	-2.10E+08	-2.06E+08	-2.16E+08	-2.16E+08	-2.25E+08	-2.03E+08	3.93E+06	-5.37E+07	-2.74E+07
EnthalpyJ/kg	-9.74E+06	-8.86E+06	-9.16E+06	-8.98E+06	-9.40E+06	-9.40E+06	-9.80E+06	-8.86E+06	1.37E+05	-1.92E+06	-9.69E+05
EnthalpykW	-1524.139	-1583.745	-1638.124	-3973.572	-4161.672	-1240.806	-1294.312	-2375.618	94.41278	-1478.451	-1413.964
Entropy J/kmol-K	16451.17	41842.66	34776.55	39156.42	28121.18	28247.81	13796.08	41842.66	13507.56	34763.92	26599
Entropy J/kg-K	716.0907	1821.338	1513.762	1704.411	1224.066	1229.578	600.5191	1821.338	472.441	1240.646	940.3428
Density kmol/cum	0.0236568	0.0125183	0.0148041	0.0133311	0.0174534	0.0173977	0.0254189	0.0125183	0.0310768	0.0154632	0.0203218
Density kg/cum	0.5434836	0.2875909	0.3401039	0.3062643	0.400968	0.3996897	0.5839644	0.2875909	0.8885181	0.4332923	0.5748341
Average MW	22.97359	22.97359	22.97359	22.97359	22.97359	22.97359	22.97359	22.97359	28.591	28.02082	28.28649
Liq Vol 60F l/min	14.50259	16.57451	16.57451	41.02162	41.02162	12.23616	12.23616	24.86176	77.22097	78.83665	156.0576
*** ALL PHASES ***											
TDEWC	84.61444	84.61444	84.61444	84.61444	84.61444	84.61444	84.61444	84.61444	-191.3545	58.31881	45.50493
Substream: $TOTAL											
Total Flowkg/sec	0.1564841	0.1788402	0.1788402	0.4426264	0.4426264	0.1320291	0.1320291	0.2682603	0.6870536	0.7718001	1.458854
EnthalpykW	-1524.139	-1583.745	-1638.124	-3973.572	-4161.672	-1240.806	-1294.312	-2375.618	94.41278	-1478.451	-1413.964

Table 6 (cont.)

	BRNOUT1B	BURN-IN	CAT-COLD	CAT-IN	CAT-OUT	COMBAIR	EXHAUST	FBRNIN1	FBRNIN2	FUEL-1	FUEL-HOT
Mole Flow mol/min											
CH4	0	0	0	0	0	0	0	1.64E-03	1.64E-03	136.2692	136.2724
N2	1104.158	1104.158	2337.046	2337.046	2337.046	2337.046	2337.046	0	0	0	0
CO	0	0	0	0	0	0	0	2.187676	2.187676	0	56.13707
CO2	136.2307	0	0	0	0	0	136.2307	134.0414	134.0414	0	196.8595
H2	0	0	0	0	0	0	0	92.49116	92.49116	0	119.6945
H2O	272.4612	0	0	0	0	0	272.4612	179.9667	179.9667	0	386.2987
O2	139.7784	187.1211	396.0579	621.2402	396.0579	396.0579	348.7152	1.11E-34	1.11E-34	0	3.14E-15
C	0	0	0	0	0	0	0	8.98E-36	8.98E-36	0	4.27E-27
Mole Frac											
CH4	0	0	0	0	0	0	0	4.00E-06	4.00E-06	1	0.152215
N2	0.6681225	0.8550886	0.8550886	0.79	0.8550886	0.8550886	0.7552372	0	0	0	0
CO	0	0	0	0	0	0	0	5.35E-03	5.35E-03	0	0.0627046
CO2	0.0824327	0	0	0	0	0	0.0440241	0.3279793	0.3279793	0	0.2198904
H2	0	0	0	0	0	0	0	0.2263121	0.2263121	0	0.1336977
H2O	0.1648653	0	0	0	0	0	0.0880482	0.4403517	0.4403517	0	0.4314923
O2	0.0845794	0.1449114	0.1449114	0.21	0.1449114	0.1449114	0.1126904	2.72E-37	2.72E-37	0	3.50E-18
C	0	0	0	0	0	0	0	2.20E-38	2.20E-38	0	4.77E-30
Total Flowmol/min	1652.628	1291.279	2733.104	2958.286	2733.104	2733.104	3094.453	408.6886	408.6886	136.2692	895.2621
Total Flowkg/sec	0.7718001	0.6153161	1.30237	1.422462	1.30237	1.30237	1.458854	0.156484	0.156484	0.0364355	0.3270487
Total Flowl/min	1.03E+05	41551.17	1.92E+05	2.07E+05	2.18E+05	87946.63	82630.37	13381.05	16998.41	3018.199	63453.67
Temperature C	564.4932	159.1346	668.9406	668.9406	796.5607	159.1346	85.57567	166.6998	285.6063	33.58157	708.4053
Pressurepsia	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.7	16.7
Vapor Frac	1	1	1	1	1	1	1	1	1	1	1
Liquid Frac	0	0	0	0	0	0	0	0	0	0	0
Solid Frac	0	0	0	0	0	0	0	0	0	0	0
EnthalpyJ/kmol	-5.48E+07	3.93E+06	1.97E+07	1.98E+07	2.40E+07	3.93E+06	-3.68E+07	-2.31E+08	-2.27E+08	-7.42E+07	-1.81E+08
EnthalpyJ/kg	-1.95E+06	1.37E+05	6.90E+05	6.87E+05	8.38E+05	1.37E+05	-1.30E+06	-1.01E+07	-9.87E+06	-4.63E+06	-8.28E+06
EnthalpykW	-1508.377	84.55483	899.1297	976.7658	1091.204	178.9676	-1897.779	-1574.707	-1544.779	-168.5477	-2707.818
Entropy J/kmol-K	33490.34	13507.56	37500.69	38445.78	41697.21	13507.56	7692.727	3717.582	12551.34	-80642.84	32340.35
Entropy J/kg-K	1195.195	472.441	1311.626	1332.591	1458.404	472.441	271.9576	161.8199	546.3378	-5026.743	1475.473
Density kmol/cum	0.0160379	0.0310768	0.0142598	0.0142598	0.0125585	0.0310768	0.0374493	0.0305423	0.0240427	0.0451491	0.0141089
Density kg/cum	0.4493953	0.8885181	0.4077025	0.4114015	0.3590622	0.8885181	1.059311	0.701667	0.5523483	0.7243172	0.309248
Average MW	28.02082	28.591	28.591	28.8504	28.591	28.591	28.28649	22.97358	22.97358	16.04276	21.91863
Liq Vol 60F l/min	78.83665	69.15808	146.3791	158.4393	146.3791	146.3791	156.0576	15.49824	15.49824	7.298276	34.23165
*** ALL PHASES ***											
TDEWC	58.31881	-191.3545	-191.3545	-190.1721	-191.3545	-191.3545	45.50493	80.98132	80.98132	-159.9087	81.22483
Substream: $TOTAL											
Total Flowkg/sec	0.7718001	0.6153161	1.30237	1.422462	1.30237	1.30237	1.458854	0.156484	0.156484	0.0364355	0.3270487
EnthalpykW	-1508.377	84.55483	899.1297	976.7658	1091.204	178.9676	-1897.779	-1574.707	-1544.779	-168.5477	-2707.818

Table 6 (cont.)

	FUEL-MIX	FUELIN	H2HP	H2LP	H2RCVRY	O2FLUX	PSA-BYP	PSA-HP	PSA-IN	RECHP1	RECLP
Mole Flow mol/min											
CH4	136.2724	136.2692	0	0	1.72E-03	0	1.64E-03	1.63E-09	1.64E-09	3.20E-03	3.20E-03
N2	0	0	0	0	0	0	0	0	0	0	0
CO	56.13707	0	0	0	30.22766	0	2.187674	2.18E-06	2.19E-06	56.13707	56.13707
CO2	196.8595	0	0	0	106.0013	0	134.0413	1.31E-04	1.34E-04	196.8595	196.8595
H2	119.6945	0	7.86E-05	7.86E-05	64.4509	0	92.49114	9.25E-05	9.25E-05	119.6945	119.6945
H2O	386.2987	0	0	0	208.0071	0	179.9667	7.70E-07	1.80E-04	386.2987	386.2987
O2	3.14E-15	0	0	0	1.69E-15	225.1822	1.11E-34	1.11E-40	1.11E-40	3.14E-15	3.14E-15
C	4.27E-27	0	0	0	2.30E-27	0	8.98E-36	8.98E-42	8.98E-42	4.27E-27	4.27E-27
Mole Frac											
CH4	0.152215	1	0	0	4.21E-06	0	4.00E-06	7.19E-06	4.00E-06	4.21E-06	4.21E-06
N2	0	0	0	0	0	0	0	0	0	0	0
CO	0.0627046	0	0	0	0.0739625	0	5.35E-03	9.64E-03	5.35E-03	0.0739625	0.0739625
CO2	0.2198904	0	0	0	0.2593694	0	0.3279791	0.5786211	0.3279791	0.2593694	0.2593694
H2	0.1336977	0	1	1	0.1577017	0	0.2263121	0.4083304	0.2263121	0.1577017	0.1577017
H2O	0.4314923	0	0	0	0.5089622	0	0.4403519	3.40E-03	0.4403519	0.5089622	0.5089622
O2	3.50E-18	0	0	0	4.13E-18	1	2.72E-37	4.90E-37	2.72E-37	4.13E-18	4.13E-18
C	4.77E-30	0	0	0	5.63E-30	0	2.20E-38	3.96E-38	2.20E-38	5.63E-30	5.63E-30
Total Flowmol/min	895.2621	136.2692	7.86E-05	7.86E-05	408.6887	225.1822	408.6885	2.26E-04	4.09E-04	758.993	758.993
Total Flowkg/sec	0.3270487	0.0364355	2.64E-09	2.64E-09	0.1564841	0.1200927	0.1564839	1.00E-07	1.56E-07	0.2906132	0.2906132
Total Flowl/min	45026.36	3277.015	4.90E-06	1.74E-04	23490.84	15791.38	13381.05	5.03E-04	0.013381	42734.71	43625.82
Temperature C	423.356	20	50	30	499.0194	668.9406	166.6999	30	166.6999	506.5924	499.0194
Pressurepsia	16.7	14.7	6250	164.6959	16.2	16.2	16.2	164.6959	16.2	16.7	16.2
Vapor Frac	1	1	1	1	1	1	1	1	1	1	1
Liquid Frac	0	0	0	0	0	0	0	0	0	0	0
Solid Frac	0	0	0	0	0	0	0	0	0	0	0
EnthalpyJ/kmol	-1.94E+08	-7.47E+07	7.21E+05	1.44E+05	-2.16E+08	2.07E+07	-2.31E+08	-2.29E+08	-2.31E+08	-2.16E+08	-2.16E+08
EnthalpyJ/kg	-8.85E+06	-4.66E+06	3.58E+05	71411.16	-9.40E+06	6.46E+05	-1.01E+07	-8.62E+06	-1.01E+07	-9.38E+06	-9.40E+06
EnthalpykW	-2895.918	-169.6504	9.45E-07	1.89E-07	-1470.633	77.63496	-1574.706	-8.66E-04	-1.57E-03	-2727.37	-2731.18
Entropy J/kmol-K	17216.78	-81201.15	-48001.69	-19612.99	28247.81	35534.22	3717.578	-10945.15	3717.578	28382.72	28247.81
Entropy J/kg-K	785.4859	-5061.545	-23811.78	-9729.247	1229.578	1110.486	161.8197	-411.1691	161.8197	1235.45	1229.578
Density kmol/cum	0.019883	0.0415833	16.03864	0.4505231	0.0173977	0.0142598	0.0305423	0.4505231	0.0305423	0.0177605	0.0173977
Density kg/cum	0.4358097	0.6671112	32.33198	0.9082005	0.3996897	0.4562971	0.7016667	11.99274	0.7016667	0.4080241	0.3996897
Average MW	21.91863	16.04276	2.01588	2.01588	22.97359	31.9988	22.97358	26.61958	22.97358	22.97359	22.97359
Liq Vol 60F l/min	34.23165	7.298276	4.21E-06	4.21E-06	14.50259	12.06026	15.49823	1.21E-05	1.55E-05	26.93338	26.93338
*** ALL PHASES ***											
TDEWC	81.22483	-161.4806		-240.9781	84.61444	-182.0033	80.98133	30.00004	80.98133	85.39109	84.61444
Substream: $TOTAL											
Total Flowkg/sec	0.3270487	0.0364355	2.64E-09	2.64E-09	0.1564841	0.1200927	0.1564839	1.00E-07	1.56E-07	0.2906132	0.2906132
EnthalpykW	-2895.918	-169.6504	9.45E-07	1.89E-07	-1470.633	77.63496	-1574.706	-8.66E-04	-1.57E-03	-2727.37	-2731.18

Table 6 (cont.)

	REFBYP	**REFOUT**	**WATOUT1**	**WTR01**	**WTR02**	**WTR03**	**WTR04**
Mole Flow mol/min							
CH4	4.92E-05	109.0179	0	0	0	0	0
N2	0	0	0	0	0	0	0
CO	0.8636537	51.71445	3.76E-09	0	0	0	0
CO2	3.028631	228.5366	2.99E-06	0	0	0	0
H2	1.841467	233.135	1.06E-08	0	0	0	0
H2O	5.943101	327.3671	1.79E-04	20779.94	20779.94	20779.94	20779.94
O2	4.82E-17	2.43E-22	0	0	0	0	0
C	6.57E-29	2.11E-34	0	0	0	0	0
Mole Frac							
CH4	4.21E-06	0.1147833	0	0	0	0	0
N2	0	0	0	0	0	0	0
CO	0.0739625	0.0544493	2.06E-05	0	0	0	0
CO2	0.2593694	0.2406228	0.0164234	0	0	0	0
H2	0.1577017	0.2454644	5.79E-05	0	0	0	0
H2O	0.5089622	0.3446801	0.9834979	1	1	1	1
O2	4.13E-18	2.56E-25	0	0	0	0	0
C	5.63E-30	2.22E-37	0	0	0	0	0
Total Flowmol/min	11.6769	949.7711	1.82E-04	20779.94	20779.94	20779.94	20779.94
Total Flowkg/sec	4.47E-03	0.3270487	5.60E-08	6.239274	6.239274	6.239274	6.239274
Total Flowl/min	875.9112	58015.06	1.23E-05	390.1488	397.9672	398.5983	390.1488
Temperature C	734.5684	572.7713	29.89082	60	78.55294	80	60
Pressurepsia	16.2	16.7	16.2	30	30	30	30
Vapor Frac	1	1	2.17E-03	0	0	0	0
Liquid Frac	0	0	0.997833	1	1	1	1
Solid Frac	0	0	0	0	0	0	0
EnthalpyJ/kmol	-2.06E+08	-1.72E+08	-2.87E+08	-2.83E+08	-2.82E+08	-2.82E+08	-2.83E+08
EnthalpyJ/kg	-8.98E+06	-8.31E+06	-1.56E+07	-1.57E+07	-1.56E+07	-1.56E+07	-1.57E+07
EnthalpykW	-40.13741	-2717.817	-8.72E-04	-98073.96	-97590.14	-97551.57	-98073.96
Entropy J/kmol-K	39156.42	31087.66	-1.59E+05	-1.55E+05	-1.51E+05	-1.50E+05	-1.55E+05
Entropy J/kg-K	1704.411	1504.677	-8612.076	-8592.745	-8367.796	-8350.408	-8592.745
Density kmol/cum	0.0133311	0.0163711	14.85758	53.26158	52.2152	52.13253	53.26158
Density kg/cum	0.3062643	0.3382385	273.9958	959.5222	940.6715	939.1821	959.5222
Average MW	22.97359	20.66069	18.44148	18.01528	18.01528	18.01528	18.01528
Liq Vol 60F l/min	0.4143628	39.24356	3.40E-06	375.0779	375.0779	375.0779	375.0779
*** ALL PHASES ***							
TDEWC	84.61444	75.73295	102.3016	121.3395	121.3395	121.3395	121.3395
Substream: $TOTAL							
Total Flowkg/sec	4.47E-03	0.3270487	5.60E-08	6.239274	6.239274	6.239274	6.239274
EnthalpykW	-40.13741	-2717.817	-8.72E-04	-98073.96	-97590.14	-97551.57	-98073.96

Table 7. SOFC-CHHP stream table

	AIR-1	AIR-WRM	AIRFLBYP	AIRIN	AN-LOWH2	ANODH2-1	ANODH2-2	ANODIN	ANODOUT1	ANODOUT2	ANODOUT3
Mole Flow mol/min											
CH4	0	0	2.69E-04	0	1.63E-03	1.64E-03	1.64E-03	109.0179	4.92E-03	4.92E-03	4.92E-03
N2	2337.046	2337.046	0	2337.046	0	0	0	0	0	0	0
CO	0	0	4.723909	0	2.183914	2.187676	2.187676	51.71445	86.36537	86.36537	86.36475
CO2	0	0	16.56564	0	131.049	134.0414	134.0414	228.5366	302.8631	302.8631	302.8609
H2	0	0	10.07224	0	13.8721	92.49124	92.49124	233.135	184.1467	184.1467	184.1454
H2O	0	0	32.50686	0	0.7697566	179.9669	179.9669	327.3671	594.3101	594.3101	594.3059
O2	621.2402	621.2402	2.64E-16	621.2402	0	1.11E-34	1.11E-34	2.43E-22	4.82E-15	4.82E-15	4.82E-15
C	0	0	3.59E-28	0	0	8.98E-36	8.98E-36	2.11E-34	6.57E-27	6.57E-27	6.57E-27
Mole Frac											
CH4	0	0	4.21E-06	0	1.10E-05	4.00E-06	4.00E-06	0.1147833	4.21E-06	4.21E-06	4.21E-06
N2	0.79	0.79	0	0.79	0	0	0	0	0	0	0
CO	0	0	0.0739625	0	0.0147685	5.35E-03	5.35E-03	0.0544493	0.0739625	0.0739625	0.0739625
CO2	0	0	0.2593694	0	0.8862063	0.3279791	0.3279791	0.2406228	0.2593694	0.2593694	0.2593694
H2	0	0	0.1577017	0	0.0938087	0.2263121	0.2263121	0.2454644	0.1577017	0.1577017	0.1577017
H2O	0	0	0.5089622	0	5.21E-03	0.4403519	0.4403519	0.3446801	0.5089622	0.5089622	0.5089622
O2	0.21	0.21	4.13E-18	0.21	0	2.72E-37	2.72E-37	2.56E-25	4.13E-18	4.13E-18	4.13E-18
C	0	0	5.63E-30	0	0	2.20E-38	2.20E-38	2.22E-37	5.63E-30	5.63E-30	5.63E-30
Total Flowmol/min	2958.286	2958.286	63.86891	2958.286	147.8764	408.6889	408.6889	949.7711	1167.69	1167.69	1167.682
Total Flowkg/sec	1.422462	1.422462	0.0244549	1.422462	0.0978411	0.1564841	0.1564841	0.3270487	0.4471005	0.4471005	0.4470974
Total Flowl/min	67342.52	75521.75	3671.093	71141.18	327.4782	18015.12	13351.47	63466.39	93278.45	87591.12	67116.67
Temperature C	32.66295	69.80611	499.0194	20	30	319.0265	165.7274	652.2575	800	734.5684	499.0194
Pressurepsia	16.2	16.2	16.2	14.7	164.6959	16.2	16.2	16.7	16.2	16.2	16.2
Vapor Frac	1	1	1	1	0.9976798	1	1	1	1	1	1
Liquid Frac	0	0	0	0	2.32E-03	0	0	0	0	0	0
Solid Frac	0	0	0	0	0	0	0	0	0	0	0
EnthalpyJ/kmol	2.24E+05	1.31E+06	-2.16E+08	-1.46E+05	-3.52E+08	-2.26E+08	-2.31E+08	-1.68E+08	-2.03E+08	-2.06E+08	-2.16E+08
EnthalpyJ/kg	7749.924	45364.87	-9.40E+06	-5055.209	-8.86E+06	-9.82E+06	-1.01E+07	-8.14E+06	-8.86E+06	-8.98E+06	-9.40E+06
EnthalpykW	11.02398	64.52982	-229.8271	-7.190845	-866.3803	-1536.139	-1574.946	-2663.438	-3959.363	-4013.741	-4201.81
Entropy J/kmol-K	4203.506	7552.521	28247.81	3777.6	-12647.01	14756.25	3637.646	34968.23	41842.66	39156.42	28247.81
Entropy J/kg-K	145.7001	261.7822	1229.578	130.9375	-318.5765	642.3141	158.3404	1692.501	1821.338	1704.411	1229.578
Density kmol/cum	0.0439289	0.0391713	0.0173977	0.0415833	0.451561	0.0226858	0.03061	0.0149649	0.0125183	0.0133311	0.0173977
Density kg/cum	1.267368	1.130108	0.3996897	1.199695	17.92629	0.5211757	0.7032215	0.3091861	0.2875909	0.3062643	0.3996897
Average MW	28.8504	28.8504	22.97359	28.8504	39.69849	22.97358	22.97358	20.66069	22.97359	22.97359	22.97359
Liq Vol 60F l/min	158.4393	158.4393	2.266431	158.4393	7.892601	15.49825	15.49825	39.24356	41.43628	41.43628	41.43598
*** ALL PHASES ***											
TDEWC	-190.1721	-190.1721	84.61444	-191.015	38.16618	80.98133	80.98133	75.73295	84.61444	84.61444	84.61444
Substream: $TOTAL											
Total Flowkg/sec	1.422462	1.422462	0.0244549	1.422462	0.0978411	0.1564841	0.1564841	0.3270487	0.4471005	0.4471005	0.4470974
EnthalpykW	11.02398	64.52982	-229.8271	-7.190845	-866.3803	-1536.139	-1574.946	-2663.438	-3959.363	-4013.741	-4201.81

Table 7 (cont.)

	ANODOUT4	ANOUT1A	ANOUT1B	ANOUT2A	ANOUT2B	ANOUT3A	ANOUT3B	ANOUTBYP	BRNBYPAS	BRNOUT-1	BRNOUT-2
Mole Flow mol/min											
CH4	1.72E-03	1.97E-03	1.97E-03	4.87E-03	4.87E-03	1.45E-03	1.45E-03	2.95E-03	0	0	0
N2	0	0	0	0	0	0	0	0	2276.466	60.58065	2337.046
CO	30.22766	34.54615	34.54615	85.5011	85.5011	25.50376	25.50376	51.81922	0	0	0
CO2	106.0013	121.1452	121.1452	299.8323	299.8323	89.43569	89.43569	181.7178	0	133.2345	133.2345
H2	64.4509	73.6587	73.6587	182.304	182.304	54.37867	54.37867	110.488	0	0	0
H2O	208.0071	237.7241	237.7241	588.3628	588.3628	175.5002	175.5002	356.5861	0	14.64512	14.64512
O2	1.69E-15	1.93E-15	1.93E-15	4.78E-15	4.78E-15	1.42E-15	1.42E-15	2.89E-15	385.7914	2.235304	388.0267
C	2.30E-27	2.63E-27	2.63E-27	6.50E-27	6.50E-27	1.94E-27	1.94E-27	3.94E-27	0	0	0
Mole Frac											
CH4	4.21E-06	4.21E-06	4.21E-06	4.21E-06	4.21E-06	4.21E-06	4.21E-06	4.21E-06	0	0	0
N2	0	0	0	0	0	0	0	0	0.8550886	0.2875269	0.813465
CO	0.0739625	0.0739625	0.0739625	0.0739625	0.0739625	0.0739625	0.0739625	0.0739625	0	0	0
CO2	0.2593694	0.2593694	0.2593694	0.2593694	0.2593694	0.2593694	0.2593694	0.2593694	0	0.6323555	0.0463754
H2	0.1577017	0.1577017	0.1577017	0.1577017	0.1577017	0.1577017	0.1577017	0.1577017	0	0	0
H2O	0.5089622	0.5089622	0.5089622	0.5089622	0.5089622	0.5089622	0.5089622	0.5089622	0	0.0695084	5.10E-03
O2	4.13E-18	4.13E-18	4.13E-18	4.13E-18	4.13E-18	4.13E-18	4.13E-18	4.13E-18	0.1449114	0.0106091	0.135062
C	5.63E-30	5.63E-30	5.63E-30	5.63E-30	5.63E-30	5.63E-30	5.63E-30	5.63E-30	0	0	0
Total Flowmol/min	408.6887	467.0761	467.0761	1156.005	1156.005	344.8198	344.8198	700.6141	2662.257	210.6956	2872.953
Total Flowkg/sec	0.1564841	0.1788402	0.1788402	0.4426264	0.4426264	0.1320291	0.1320291	0.2682603	1.26861	0.131601	1.400211
Total Flowl/min	17275.67	37311.38	31550.39	86714.59	66233.67	19819.74	13565.46	55967.07	85666.89	13565.77	97726.38
Temperature C	294.7202	800	634.3024	734.5684	496.5577	499.0194	255.3551	800	159.1346	591.8091	183.8225
Pressurepsia	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2	16.2
Vapor Frac	1	1	1	1	1	1	1	1	1	1	1
Liquid Frac	0	0	0	0	0	0	0	0	0	0	0
Solid Frac	0	0	0	0	0	0	0	0	0	0	0
EnthalpyJ/kmol	-2.24E+08	-2.03E+08	-2.10E+08	-2.06E+08	-2.16E+08	-2.16E+08	-2.25E+08	-2.03E+08	3.93E+06	-2.43E+08	-1.47E+07
EnthalpyJ/kg	-9.74E+06	-8.86E+06	-9.16E+06	-8.98E+06	-9.40E+06	-9.40E+06	-9.80E+06	-8.86E+06	1.37E+05	-6.47E+06	-5.04E+05
EnthalpykW	-1524.139	-1583.745	-1638.124	-3973.572	-4161.672	-1240.806	-1294.312	-2375.618	174.3284	-851.7898	-705.6283
Entropy J/kmol-K	16451.17	41842.66	34776.55	39156.42	28121.18	28247.81	13796.08	41842.66	13507.56	47648.84	16897.85
Entropy J/kg-K	716.0907	1821.338	1513.762	1704.411	1224.066	1229.578	600.5191	1821.338	472.441	1271.444	577.8501
Density kmol/cum	0.0236568	0.0125183	0.0148041	0.0133311	0.0174534	0.0173977	0.0254189	0.0125183	0.0310768	0.0155314	0.0293979
Density kg/cum	0.5434836	0.2875909	0.3401039	0.3062643	0.400968	0.3996897	0.5839644	0.2875909	0.8885181	0.582058	0.8596722
Average MW	22.97359	22.97359	22.97359	22.97359	22.97359	22.97359	22.97359	22.97359	28.591	37.47616	29.24262
Liq Vol 60F l/min	14.50259	16.57451	16.57451	41.02162	41.02162	12.23616	12.23616	24.86176	142.5846	10.76438	153.349
*** ALL PHASES ***											
TDEWC	84.61444	84.61444	84.61444	84.61444	84.61444	84.61444	84.61444	84.61444	-191.3545	41.09008	-0.9057125
Substream: $TOTAL											
Total Flowkg/sec	0.1564841	0.1788402	0.1788402	0.4426264	0.4426264	0.1320291	0.1320291	0.2682603	1.26861	0.131601	1.400211
EnthalpykW	-1524.139	-1583.745	-1638.124	-3973.572	-4161.672	-1240.806	-1294.312	-2375.618	174.3284	-851.7898	-705.6283

Table 7 (cont.)

	BRNOUT1B	**BURN-IN**	**CAT-COLD**	**CAT-IN**	**CAT-OUT**	**COMBAIR**	**EXHAUST**	**FBRNIN1**	**FBRNIN2**	**FUEL-1**	**FUEL-HOT**
Mole Flow mol/min											
CH4	0	0	0	0	0	0	0	1.63E-03	1.63E-03	136.2692	136.2724
N2	60.58065	60.58065	2337.046	2337.046	2337.046	2337.046	2337.046	0	0	0	0
CO	0	0	0	0	0	0	0	2.183914	2.183914	0	56.13707
CO2	133.2345	0	0	0	0	0	133.2345	131.049	131.049	0	196.8595
H2	0	0	0	0	0	0	0	13.8721	13.8721	0	119.6945
H2O	14.64512	0	0	0	0	0	14.64512	0.7697566	0.7697566	0	386.2987
O2	2.235304	10.26657	396.0579	621.2402	396.0579	396.0579	388.0267	0	0	0	3.14E-15
C	0	0	0	0	0	0	0	0	0	0	4.27E-27
Mole Frac											
CH4	0	0	0	0	0	0	0	1.10E-05	1.10E-05	1	0.152215
N2	0.2875269	0.8550886	0.8550886	0.79	0.8550886	0.8550886	0.813465	0	0	0	0
CO	0	0	0	0	0	0	0	0.0147685	0.0147685	0	0.0627046
CO2	0.6323555	0	0	0	0	0	0.0463754	0.8862063	0.8862063	0	0.2198904
H2	0	0	0	0	0	0	0	0.0938087	0.0938087	0	0.1336977
H2O	0.0695084	0	0	0	0	0	5.10E-03	5.21E-03	5.21E-03	0	0.4314923
O2	0.0106091	0.1449114	0.1449114	0.21	0.1449114	0.1449114	0.135062	0	0	0	3.50E-18
C	0	0	0	0	0	0	0	0	0	0	4.77E-30
Total Flowmol/min	210.6956	70.84722	2733.104	2958.286	2733.104	2733.104	2872.953	147.8764	147.8764	136.2692	895.2621
Total Flowkg/sec	0.131601	0.0337598	1.30237	1.422462	1.30237	1.30237	1.400211	0.0978411	0.0978411	0.0364355	0.3270487
Total Flowl/min	10708.8	2279.743	1.92E+05	2.07E+05	2.18E+05	87946.63	73052.93	327.4782	626.3595	3018.199	63453.67
Temperature C	409.6477	159.1346	668.9406	668.9406	796.5607	159.1346	68.44846	30	305.3448	33.58157	708.4053
Pressurepsia	16.2	16.2	16.2	16.2	16.2	16.2	16.2	164.6959	164.6959	16.7	16.7
Vapor Frac	1	1	1	1	1	1	1	0.9976798	1	1	1
Liquid Frac	0	0	0	0	0	0	0	2.32E-03	0	0	0
Solid Frac	0	0	0	0	0	0	0	0	0	0	0
EnthalpyJ/kmol	-2.51E+08	3.93E+06	1.97E+07	1.98E+07	2.40E+07	3.93E+06	-1.82E+07	-3.52E+08	-3.40E+08	-7.42E+07	-1.81E+08
EnthalpyJ/kg	-6.69E+06	1.37E+05	6.90E+05	6.87E+05	8.38E+05	1.37E+05	-6.22E+05	-8.86E+06	-8.57E+06	-4.63E+06	-8.28E+06
EnthalpykW	-879.9568	4.639179	899.1297	976.7658	1091.204	178.9676	-871.1925	-866.3803	-838.203	-168.5477	-2707.818
Entropy J/kmol-K	37244.07	13507.56	37500.69	38445.78	41697.21	13507.56	8180.888	-12647.01	13982.57	-80642.84	32340.35
Entropy J/kg-K	993.8069	472.441	1311.626	1332.591	1458.404	472.441	279.7591	-318.5765	352.2192	-5026.743	1475.473
Density kmol/cum	0.019675	0.0310768	0.0142598	0.0142598	0.0125585	0.0310768	0.039327	0.451561	0.2360887	0.0451491	0.0141089
Density kg/cum	0.7373434	0.8885181	0.4077025	0.4114015	0.3590622	0.8885181	1.150024	17.92629	9.372365	0.7243172	0.309248
Average MW	37.47616	28.591	28.591	28.8504	28.591	28.591	29.24262	39.69849	39.69849	16.04276	21.91863
Liq Vol 60F l/min	10.76438	3.794421	146.3791	158.4393	146.3791	146.3791	153.349	7.892601	7.892601	7.298276	34.23165
*** ALL PHASES ***											
TDEWC	41.09008	-191.3545	-191.3545	-190.1721	-191.3545	-191.3545	-0.9057125	38.16618	38.16618	-159.9087	81.22483
Substream: $TOTAL											
Total Flowkg/sec	0.131601	0.0337598	1.30237	1.422462	1.30237	1.30237	1.400211	0.0978411	0.0978411	0.0364355	0.3270487
EnthalpykW	-879.9568	4.639179	899.1297	976.7658	1091.204	178.9676	-871.1925	-866.3803	-838.203	-168.5477	-2707.818

Table 7 (cont.)

	FUEL-MIX	**FUELIN**	**H2HP**	**H2LP**	**H2RCVRY**	**O2FLUX**	**PSA-BYP**	**PSA-HP**	**PSA-IN**	**RECHP1**	**RECLP**
Mole Flow mol/min											
CH4	136.2724	136.2692	0	0	1.72E-03	0	0	1.63E-03	1.64E-03	3.20E-03	3.20E-03
N2	0	0	0	0	0	0	0	0	0	0	0
CO	56.13707	0	0	0	30.22766	0	0	2.183914	2.187676	56.13707	56.13707
CO2	196.8595	0	0	0	106.0013	0	0	131.049	134.0414	196.8595	196.8595
H2	119.6945	0	78.60858	78.60858	64.4509	0	0	92.48068	92.49124	119.6945	119.6945
H2O	386.2987	0	0	0	208.0071	0	0	0.7697566	179.9669	386.2987	386.2987
O2	3.14E-15	0	0	0	1.69E-15	225.1822	0	1.11E-34	1.11E-34	3.14E-15	3.14E-15
C	4.27E-27	0	0	0	2.30E-27	0	0	8.98E-36	8.98E-36	4.27E-27	4.27E-27
Mole Frac											
CH4	0.152215	1	0	0	4.21E-06	0	0	7.19E-06	4.00E-06	4.21E-06	4.21E-06
N2	0	0	0	0	0	0	0	0	0	0	0
CO	0.0627046	0	0	0	0.0739625	0	0	9.64E-03	5.35E-03	0.0739625	0.0739625
CO2	0.2198904	0	0	0	0.2593694	0	0	0.5786211	0.3279791	0.2593694	0.2593694
H2	0.1336977	0	1	1	0.1577017	0	0	0.4083304	0.2263121	0.1577017	0.1577017
H2O	0.4314923	0	0	0	0.5089622	0	0	3.40E-03	0.4403519	0.5089622	0.5089622
O2	3.50E-18	0	0	0	4.13E-18	1	0	4.90E-37	2.72E-37	4.13E-18	4.13E-18
C	4.77E-30	0	0	0	5.63E-30	0	0	3.96E-38	2.20E-38	5.63E-30	5.63E-30
Total Flowmol/min	895.2621	136.2692	78.60858	78.60858	408.6887	225.1822	0	226.485	408.6889	758.993	758.993
Total Flowkg/sec	0.3270487	0.0364355	2.64E-03	2.64E-03	0.1564841	0.1200927	0	0.1004823	0.1564841	0.2906132	0.2906132
Total Flowl/min	45026.36	3277.015	4.901199	174.4829	23490.84	15791.38	0	502.7155	13351.47	42734.71	43625.82
Temperature C	423.356	20	50	30	499.0194	668.9406		30	165.7274	506.5924	499.0194
Pressurepsia	16.7	14.7	6250	164.6959	16.2	16.2		164.6959	16.2	16.7	16.2
Vapor Frac	1	1	1	1	1	1		1	1	1	1
Liquid Frac	0	0	0	0	0	0		0	0	0	0
Solid Frac	0	0	0	0	0	0		0	0	0	0
EnthalpyJ/kmol	-1.94E+08	-7.47E+07	7.21E+05	1.44E+05	-2.16E+08	2.07E+07		-2.29E+08	-2.31E+08	-2.16E+08	-2.16E+08
EnthalpyJ/kg	-8.85E+06	-4.66E+06	3.58E+05	71411.16	-9.40E+06	6.46E+05		-8.62E+06	-1.01E+07	-9.38E+06	-9.40E+06
EnthalpykW	-2895.918	-169.6504	0.9449698	0.1886034	-1470.633	77.63496		-865.9747	-1574.946	-2727.37	-2731.18
Entropy J/kmol-K	17216.78	-81201.15	-48001.69	-19612.99	28247.81	35534.22		-10945.15	3637.646	28382.72	28247.81
Entropy J/kg-K	785.4859	-5061.545	-23811.78	-9729.247	1229.578	1110.486		-411.1691	158.3404	1235.45	1229.578
Density kmol/cum	0.019883	0.0415833	16.03864	0.4505231	0.0173977	0.0142598		0.4505231	0.03061	0.0177605	0.0173977
Density kg/cum	0.4358097	0.6671112	32.33198	0.9082005	0.3996897	0.4562971		11.99274	0.7032215	0.4080241	0.3996897
Average MW	21.91863	16.04276	2.01588	2.01588	22.97359	31.9988		26.61958	22.97358	22.97359	22.97359
Liq Vol 60F l/min	34.23165	7.298276	4.210103	4.210103	14.50259	12.06026	0	12.1027	15.49825	26.93338	26.93338
*** ALL PHASES ***											
TDEWC	81.22483	-161.4806		-240.9781	84.61444	-182.0033		30.00004	80.98133	85.39109	84.61444
Substream: $TOTAL											
Total Flowkg/sec	0.3270487	0.0364355	2.64E-03	2.64E-03	0.1564841	0.1200927	0	0.1004823	0.1564841	0.2906132	0.2906132
EnthalpykW	-2895.918	-169.6504	0.9449698	0.1886034	-1470.633	77.63496	0	-865.9747	-1574.946	-2727.37	-2731.18

Table 7 (cont.)

	REFBYP	REFOUT	WATOUT1	WTR01	WTR02	WTR03	WTR04
Mole Flow mol/min							
CH4	4.92E-05	109.0179	6.86E-06	0	0	0	0
N2	0	0	0	0	0	0	0
CO	0.8636537	51.71445	3.76E-03	0	0	0	0
CO2	3.028631	228.5366	2.992424	0	0	0	0
H2	1.841467	233.135	0.010551	0	0	0	0
H2O	5.943101	327.3671	179.1972	8129.539	8129.539	8129.539	8129.539
O2	4.82E-17	2.43E-22	0	0	0	0	0
C	6.57E-29	2.11E-34	0	0	0	0	0
Mole Frac							
CH4	4.21E-06	0.1147833	3.77E-08	0	0	0	0
N2	0	0	0	0	0	0	0
CO	0.0739625	0.0544493	2.06E-05	0	0	0	0
CO2	0.2593694	0.2406228	0.0164234	0	0	0	0
H2	0.1577017	0.2454644	5.79E-05	0	0	0	0
H2O	0.5089622	0.3446801	0.9834979	1	1	1	1
O2	4.13E-18	2.56E-25	0	0	0	0	0
C	5.63E-30	2.22E-37	0	0	0	0	0
Total Flowmol/min	11.6769	949.7711	182.2039	8129.539	8129.539	8129.539	8129.539
Total Flowkg/sec	4.47E-03	0.3270487	0.0560018	2.440932	2.440932	2.440932	2.440932
Total Flowl/min	875.9112	58015.06	12.26386	152.6342	155.3058	155.9399	152.6342
Temperature C	734.5684	572.7713	29.89085	60	76.26915	80.00043	60
Pressurepsia	16.2	16.7	16.2	30	30	30	30
Vapor Frac	1	1	2.17E-03	0	0	0	0
Liquid Frac	0	0	0.9978329	1	1	1	1
Solid Frac	0	0	0	0	0	0	0
EnthalpyJ/kmol	-2.06E+08	-1.72E+08	-2.87E+08	-2.83E+08	-2.82E+08	-2.82E+08	-2.83E+08
EnthalpyJ/kg	-8.98E+06	-8.31E+06	-1.56E+07	-1.57E+07	-1.57E+07	-1.56E+07	-1.57E+07
EnthalpykW	-40.13741	-2717.817	-871.9243	-38368.55	-38202.98	-38164.17	-38368.55
Entropy J/kmol-K	39156.42	31087.66	-1.59E+05	-1.55E+05	-1.51E+05	-1.50E+05	-1.55E+05
Entropy J/kg-K	1704.411	1504.677	-8612.076	-8592.745	-8395.281	-8350.403	-8592.745
Density kmol/cum	0.0133311	0.0163711	14.85698	53.26158	52.34536	52.1325	53.26158
Density kg/cum	0.3062643	0.3382385	273.9847	959.5222	943.0163	939.1816	959.5222
Average MW	22.97359	20.66069	18.44148	18.01528	18.01528	18.01528	18.01528
Liq Vol 60F l/min	0.4143628	39.24356	3.395543	146.7382	146.7382	146.7382	146.7382
*** ALL PHASES ***							
TDEWC	84.61444	75.73295	102.3016	121.3395	121.3395	121.3395	121.3395
Substream: $TOTAL							
Total Flowkg/sec	4.47E-03	0.3270487	0.0560018	2.440932	2.440932	2.440932	2.440932
EnthalpykW	-40.13741	-2717.817	-871.9243	-38368.55	-38202.98	-38164.17	-38368.55

3 FCPower Model Case Studies

3.1 Molten Carbonate Fuel Cell Case Study Description

The case study models installation of a fuel cell CHHP system at a large hotel in Los Angeles. The system is assumed to start operation in 2013 and will operate for 20 years. Dollar amounts are shown in 2007 dollars. The FCPower Model escalates these using the inflation rate (1.9% for this analysis) and performs all calculations in current dollars. The system is assumed to be a combined heat, hydrogen, and power system. The fuel cell is sized to meet the average AC demand of the hotel. Electricity and heat from the fuel cell are used at the hotel, and hydrogen produced by the system is piped to a nearby fueling station. Additional electricity needed for high-demand periods is purchased from the utility, and excess electricity produced by the fuel cell during periods of especially low demand is sold back to the utility under a net-metering agreement. Hydrogen CSD are assumed to closely resemble the CSD portion for standalone forecourt SMR hydrogen production at a comparable hydrogen production rate. The business is assumed to take advantage of the federal fuel cell tax credit. Note that the cost values used in this case study are for illustration purposes only and are not validated or endorsed by DOE.

An MCFC system nominally includes a fuel processor integrated with the MCFCs and power-conditioning equipment. A standard CHP fuel cell system used in CHP applications also includes a water purification system, nitrogen-purging equipment, piping, valves, plumbing, and heat exchanger [3]. Owing to the high operating temperature, internal fuel reforming is possible; however, systems generally include at least some form of external fuel reformer as well [4,5]. The MCFC operates at about 650°C, which necessitates special design considerations owing to the high temperature and potential for corrosion.

The CHHP application modeled includes additional equipment for integrating the hydrogen co-production with a standard CHP application. In addition to the fuel cell plant—which includes a fuel-reforming system, fuel cell stacks, and power-conditioning equipment—a shift reactor converts additional CO to hydrogen, and a PSA unit extracts hydrogen from the fuel cell exhaust stream. A CSD unit is installed for vehicle refueling. The CSD costs do not include costs for a convenience store or building.

The CHHP power model includes several additional components that can be included within the model analysis. These include a burner for additional heat, an electrolyzer for additional hydrogen production, and an additional, usually smaller fuel cell for meeting peak electricity demand. Hydrogen storage can be used for electricity or vehicle fueling. However, it is assumed that the fuel cell system will tie into existing building electricity, heating, cooling, and domestic hot water production. Equipment such as additional thermal storage is not used; existing thermal water storage is used instead.

3.1.1 Financial Inputs

Fuel Cell System
MCFC systems are slightly behind PAFC systems in market entry; however, estimates of their potential for cost reduction are better. Costs were collected from a number of sources (Figure 26) [4,6–9]. References are shown in brackets. The capital costs in most cases are based on demonstration and pre-commercial estimates for low-volume costs. Current costs assume commercial, low-volume productions, while high-volume costs are predictions for cost reduction of at least 100 MW/yr.

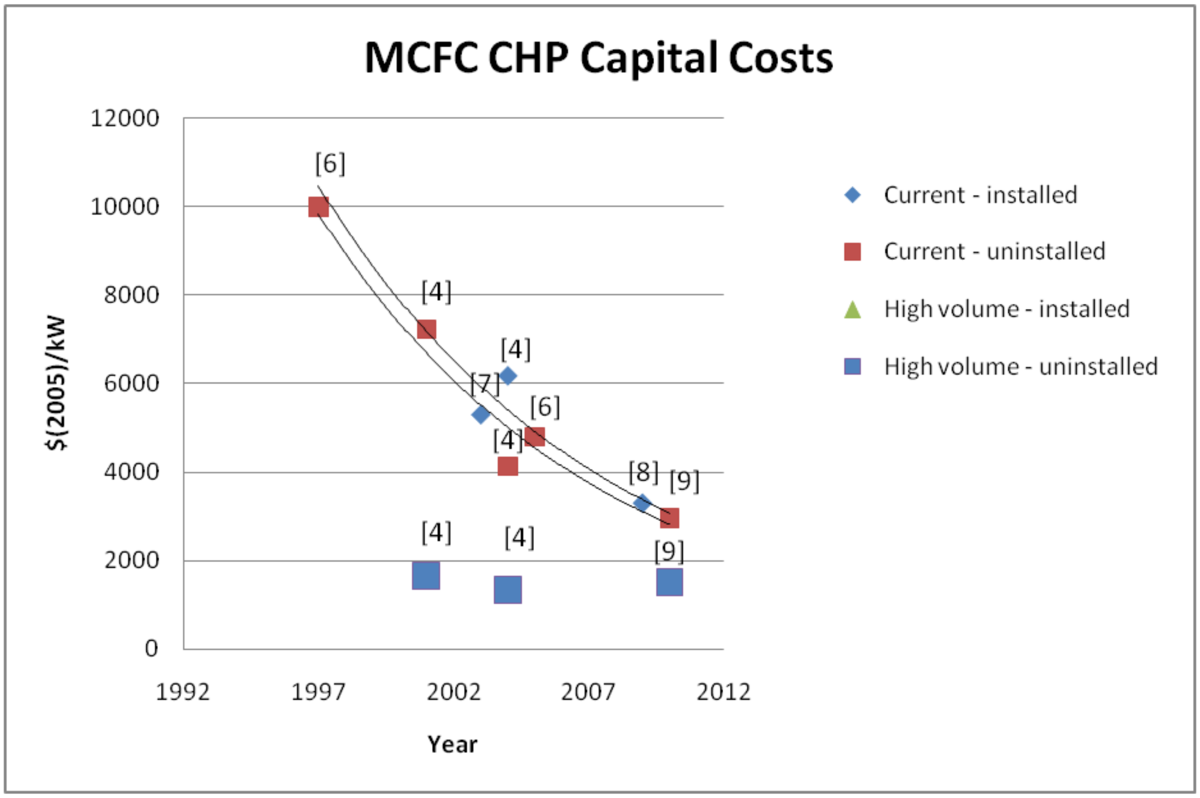


Figure 26. Collected cost information for MCFC CHP plants

Equation 21. $y = 15{,}908e^{-0.096x}$

Equation 22. $x = \text{year} - 1992$

Equation 21 is the curve represented by current uninstalled low-volume production levels where y is the total uninstalled cost in $(2005)/kW and x is calculated as per Equation 22. It has an r-squared fit to the data of 0.95. The costs for the case study represent relatively high-volume production. The costs were adjusted from 2005 to 2007 dollars using the Chemical Engineering Plant Cost Index (CEPCI). A shift reactor and PSA system were added for hydrogen production and purification from the fuel cell. The shift reactor and PSA system were sized for the more dilute hydrogen stream from the MCFC. Direct uninstalled costs for the fuel cell plant including internal reforming were estimated to be $(2007)1,800/kW fuel cell rated AC power.[2] The combined uninstalled cost of the shift reactor and fuel compressor was estimated to be $(2007)116/kW, and the uninstalled PSA cost was estimated to be $(2007)312/kW. Total CHHP system uninstalled direct capital cost is approximately $(2007)2,228/kW. Installation was estimated to be 20% of the equipment cost for the fuel cell plant and PSA. Indirect costs are 25% of the installed equipment cost. Installation and indirect costs are approximately $(2007)1,085/kW for a total installed capital cost of the fuel cell and hydrogen purification system (not including CSD) of $3,313/kW.

Indirect capital costs are difficult to enumerate separately because researched costs typically included the entire chain. Indirect costs for project contingency and permitting were generally not included in literature values for costs. The values used in the FCPower Model for project contingency and permitting (5% and 3% of installed equipment costs, respectively) are derived from previous H2A hydrogen production models [10]. The separation of direct and indirect capital cost was estimated and then split into 10% of installed equipment cost for site preparation and 7% for engineering and design.

Operating and maintenance costs are as follows. Replacement costs are estimated to be 25% of the total fuel cell system capital cost every 10 years. Fixed maintenance and repairs were estimated at 2%, and variable unplanned replacement 1.5%, of direct fuel cell system capital cost yearly, both estimated using figures from an EPRI report [3].

Hydrogen Storage and Dispensing
The hydrogen CSD system operating assumptions and costs are derived from the H2A production forecourt model. It is assumed that the hydrogen produced by the system will be used in vehicles used on public streets. The scenario envisions a very small hydrogen demand in an emerging market. Therefore, the hydrogen is piped a short distance to an existing conventional fueling station where storage tanks for about 1 day of production and a single dispenser are located.

3.1.2 Load Profile and Fuel Cell Specification

The hotel is assumed to have 176 rooms, a laundry, and a restaurant. The modeled building is six stories tall. The electricity and heat load profiles for the building are calculated using building simulation output from the NREL building systems model [12]. The building is assumed to be an existing building that was constructed using typical building techniques and materials. The electricity load includes electricity use for air conditioning, and the heat load is fuel demand for both space heating and hot water. Because the heating demand profile already accounts for the efficiency of the furnace or boiler, the efficiency of the burner for supplementary heat in the CHHP system is set at 100%.

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[2] Note that, although DOE supports fuel cell cost-estimation analysis, the $1,800/kW value is not derived from those efforts and should not be interpreted as a DOE-endorsed cost estimate. It is merely an example cost.

The average building electrical demand is 229 kW with peaks in demand up to 471 kW and a minimum value of 71 kW. The fuel cell was assumed to be 200 kW, which is a commercially available size, with a maximum rated AC output just under the building's average demand.

3.1.3 Utilities

The fuel cell CHHP system is assumed to be grid parallel, with electrical connections that can be islanded from the grid during a power outage. Electricity demand that cannot be met by the fuel cell is provided by the grid. Both time-of-day and seasonal usage charges are assumed to apply. The base price for electricity purchased from the grid is $0.087/kWh in the startup year (2013), which is the EIA projected national average electricity rate for 2013. Peak rates and off-peak rates are 25% above and 10% below the base rate, respectively. Electricity can also be sold to the grid if more electricity is produced by the system than is required by the hotel at that time. Electricity sold to the utility is assumed to be priced at the same price as electricity would cost if purchased during that hour (net metering).

The fuel cell system and auxiliary space and hot water heating systems are assumed to be fueled with natural gas. The natural gas rate is assumed to be the projected average national commercial natural gas rate, which is $10.71/MMBtu in 2013.

3.2 Molten Carbonate Fuel Cell Case Study Results

3.2.1 Baseline System

The FCPower Model calculates costs for supplying electricity and heat to the building and purchasing an equivalent amount of hydrogen for the refueling station in the absence of the fuel cell system. This baseline system assumes electricity purchased from the grid, heat for hot water and space heating supplied by a natural gas furnace or boiler, and hydrogen production using a small (forecourt) natural gas SMR. Electricity for the building is purchased using the same price schedule as is used for the CHHP supplementary electricity supply. Natural gas for heating and fueling the SMR unit is purchased at the same rate as fuel for the CHHP system. Yearly costs for energy for the baseline system are shown in Table 8. In a real-world application, a small-volume hydrogen station like this one likely would be part of an existing conventional fuel station (instead of being a standalone station as assumed here) and possibly supplied with off-site-generated hydrogen via truck, which might reduce the hydrogen cost below the $11.66/kg shown here.

Table 8. Baseline system levelized energy costs (prior to installation of fuel cell)

Electricity (use and demand charges)	$238,392/year
Commercial natural gas (for heat)	$89,946/year
Hydrogen (from forecourt SMR, $11.66/kg)	$347,674/year
Total baseline system energy cost per year	**$676,012/year**

3.2.2 CHHP System Energy Supply

The MCFC CHHP system supplies a yearly total of 2,670 MWh of energy to the building in the form of electricity, heat, and hydrogen, in addition to 20 MWh of electricity that is sold to the utility. Of this, 1,300 MWh (49%) are in the form of electricity, 380 MWh (14%) are in the form of useful heat, and the remaining 994 MWh (29,819 kg, 37%) are in the form of hydrogen. The total system efficiency is 76%. Table 9 shows the energy supplied by the fuel cell at full operation and supplementary electricity and heat purchased for the building. The analysis assumes that, during construction and startup (about 1 year), all of the electricity and heating fuel to supply the building will be purchased.

Table 9. MCFC System Building Energy Supply at Full Operation

	System Energy to Building (kWh)	Percent of Energy Type Supplied by the CHHP System
System net electricity to building	1,299,578	65
Fuel cell system heat	379,968	18
Hydrogen	993,857	100
	Supplementary Building Electricity and Heat (kWh)	**Percent of Energy Type Supplied by Supplementary System**
Supplementary electricity	813,392	35
Supplementary heat	1,831,935	82

Approximately 19% (307 MWh/year) of the fuel cell total electrical output of 1,626 MWh per year at full operation, is required for auxiliary power, primarily for the hydrogen purification system and compression of hydrogen to the dispensing pressure of 5,000 psi (350 bar).

3.2.3 CHHP System Capital Costs and Credits

For the case study, it is assumed that a commercial entity (the hotel owner) purchases the fuel cell system and owns and operates the refueling station equipment but rents the land for the refueling station, which is co-located with a gasoline refueling station adjacent to the hotel. A 300-ft pipeline connects the CHHP system to the storage tanks and compressors at the filling station. Equity financing, a 10% internal rate of return, and a 20-year life are assumed for the CHHP installation.

Table 10 shows the initial capital investment and federal tax credits taken for the installation. Indirect capital investment (site preparation, engineering, contingency, and permitting) totals $177,472.

Table 10. MCFC System Initial Investment and Credits

Direct capital investment (reference year, (2007)$)						
Major pieces/ systems of equipment	**Baseline installed costs ($) (with indirect capital)**	**Depreciation type**	**Depreciation schedule (years)**	**Federal credit or incentive**	**Credit amount ($)**	**Total adjusted depreciable capital cost basis ($)[1]**
MCFC System (including hydrogen purification)	530,092	MACRS	5	Federal business energy tax credit	155,520	532,683
Auxiliary heater	170,754	MACRS	7			196,637
System integration and control	30,000	MACRS	7			34,547
Hydrogen compression, storage, and dispensing	439,969	MACRS	5			506,660
Total	1,170,815 ($1,348,28)				155,520	1,270,527

1. Total depreciation basis includes indirect capital costs.

3.2.4 MCFC CHHP System Cash Flow

Figure 27 shows key expenditures and cash flow for the MCFC CHHP installation throughout its lifetime. Yearly replacement costs include an allowance of 1.5% of the initial depreciable capital investment for unplanned replacement of capital equipment as well as planned restacking of the fuel cell every 10 years. It is assumed that the compressors and dispensers will be replaced after 10 years at 35% of the initial cost for the entire CSD system. A replacement cost of 25% of building system integration direct capital cost is also incurred after 10 years. Figure 27 indicates that the project will break even after approximately 7 years.

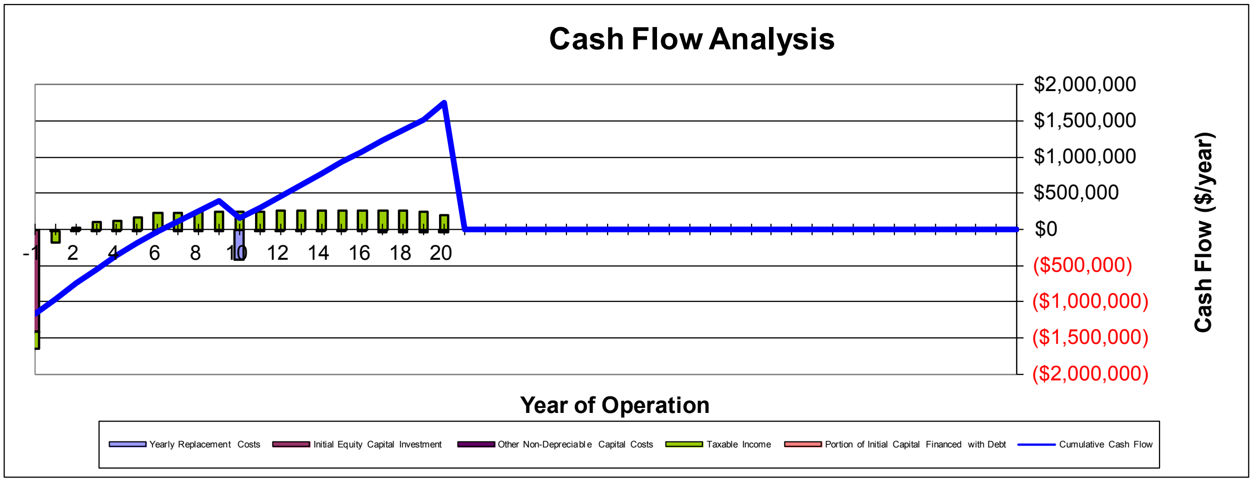

Figure 27. MCFC CHHP Key Yearly Expenditures and Revenue

3.2.5 Cost of Hydrogen and Total Annualized Costs

The FCPower Model solves for the levelized revenue for energy supplied by the CHHP system (electricity, heat, and hydrogen) that will result in a net present value (including inflation and an internal rate of return specified by the user) of zero for the project. The user may distribute the required revenue between the three energy streams in any way desired. However, the default distribution assumes that electricity supplied by the fuel cell is “sold” at the same price as would have been paid for grid electricity. Similarly, heat is assumed to be supplied at the same rate as purchased natural gas. The levelized profited cost of hydrogen is derived by difference. For this installation, the cost of hydrogen is $12.18/kg as dispensed. This is comparable to the cost of hydrogen supplied by a forecourt SMR unit ($11.66/kg) for the baseline system. Table 11 shows the total annualized costs for the MCFC CHHP system.

Table 11. Total Annualized Costs for the MCFC CHHP Installation

Annualized costs	
Capital costs	$231,769
Decommissioning costs	$2,259
Fixed O&M	$132,061
Feedstock costs	$152,132
Other raw material costs	$0
Byproduct credits	–$1,755
Other variable costs (excluding supplementary electricity and heat)	$4,183
Supplementary electricity	$99,132
Supplementary heat	$83,367
Total	**$703,148**

The total annualized cost for the CHHP system is slightly more than the energy costs for the baseline system of $676,012 shown in Table 8. This analysis indicates that the CHHP system could be a cost-effective alternative to conventional energy supply for the hotel.

3.2.6 Sensitivity Analysis

Sensitivity analyses were performed for six key cost elements for the CHHP system: internal rate of return, federal business energy tax credit, reforming fuel cell cost, CSD cost, process fixed operating cost, and total depreciable capital cost. The results, presented in terms of levelized energy cost, are shown in Figure 28.

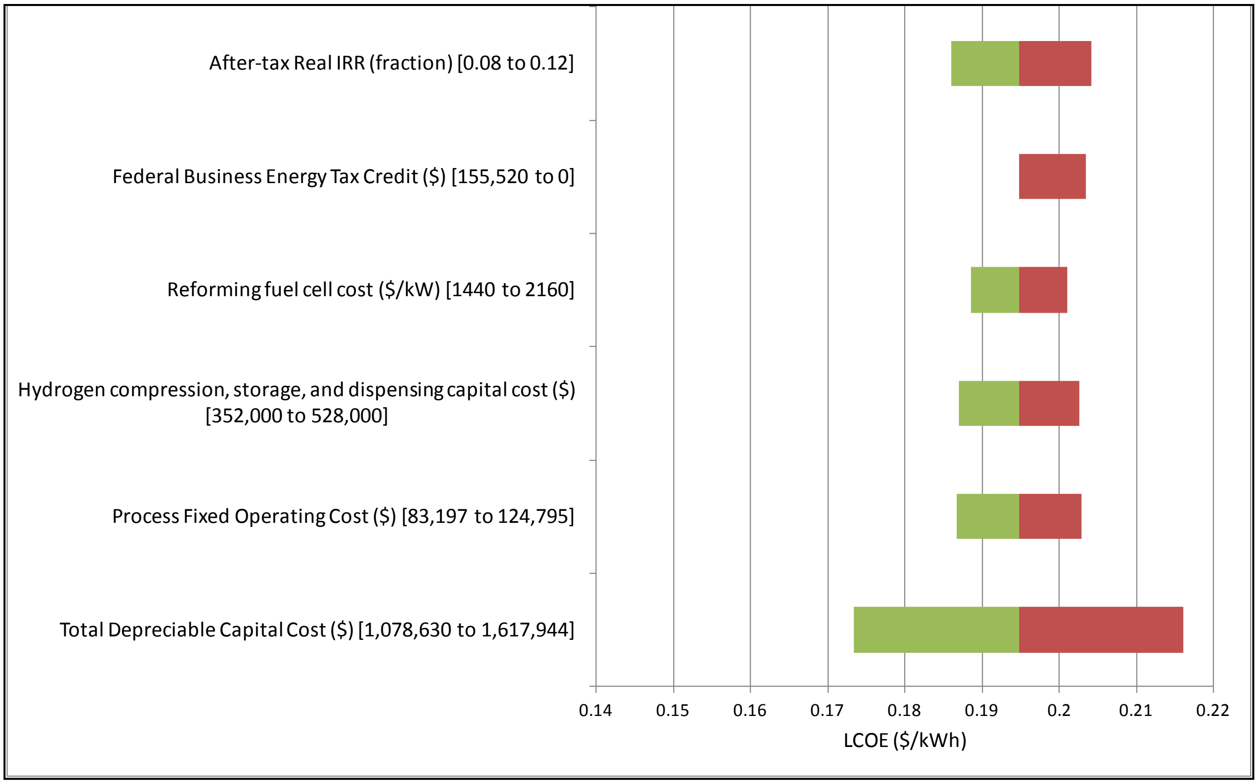

Figure 28. Sensitivity analysis for the MCFC CHHP system key costs (LCOE in $/kWh)

3.3 Phosphoric Acid Fuel Cell Case Study Description

The system is assumed to be a combined heat, hydrogen, and power system. The fuel cell is sized to meet the average AC demand. Hydrogen CSD are assumed to closely resemble the CSD portion for standalone forecourt SMR hydrogen production at a comparable hydrogen production rate. The business is assumed to take advantage of the federal fuel cell tax credit.

A standard CHP fuel cell system used in CHP applications includes the PAFC(s), water purification system, nitrogen-purging equipment, power-conversion equipment, piping, valves, plumbing, and heat exchanger [3,13]. There may be a low-grade heat exchanger, delivering hot water in the 160°F range, and/or a high-grade heat exchanger for delivering water at 250°F depending on the installation thermal requirements [13]. A thermal storage unit might be used for following domestic hot water. The fuel cell will also have an air-cooling system (heat sink) to shed excess heat that cannot be used by the building. The fuel reformer is generally a standard fuel cell component for reforming natural gas, but options are available for using propane, or the fuel cell may use pure hydrogen without a fuel processor. The PAFC system modeled for the case study is fueled with commercial natural gas. Note that the cost values used in this case study are for illustration purposes only and are not validated or endorsed by DOE.

The CHHP application modeled here includes several additional options for integrating the hydrogen co-production with a standard CHP application. In addition to the fuel cell plant—which would include a fuel reforming system, fuel cell stacks, and power conditioning equipment—a PSA unit is used to extract hydrogen from the reformer syngas stream, and a CSD unit is installed for vehicle refueling.

The CHHP power model includes several additional components that can be included within the model analysis. These include a burner for additional heat, an electrolyzer for additional hydrogen production, and an additional, usually smaller, fuel cell for peak electricity demand. Hydrogen storage can be used for either electricity or vehicle fueling. However it is assumed that the fuel cell system will tie into existing building electricity, heating, cooling, and domestic hot water production. Equipment such as additional thermal storage will not be used; existing thermal water storage will be used instead.

3.3.1 Financial Inputs

Fuel Cell System

Costs for PAFC CHP plants were collected from a variety of sources, which included both actual projects as well as estimates and projections. The CHP plants vary from this case study in that they do not include the PSA for separation of hydrogen or the CSD unit for hydrogen vehicle filling. The data were normalized to 2005 dollars and analyzed over a period from 1993 to 2008. Figure 29 shows cost data collected from a number of sources [4,6,7,13–18]. An average installation factor of 1.15 was found between uninstalled and installed plant costs. Using several sources, equipment costs were estimated to be about 70% of the total capital investment, leaving 30% for installation and indirect capital costs [3,4,6,17]. The installation factor was estimated to be 15% of the uninstalled equipment cost and indirect costs (site preparation, engineering design, project contingency, and permit licensing fees), accounting for 24% of the installed cost.

As shown in Figure 29, current costs represent actual plant costs or estimated low-volume production that is not taking advantage of mass-production economies of scale. References for the data points are shown in brackets. High-volume data points are predictions for mass production generally at the 100 MW/year or more level. As can be seen, the costs have decreased, and the yearly trend for current costs fits an exponential curve with an r-squared fit of 0.82 for installed and 0.81 for uninstalled. The crossing of the installed and uninstalled trend lines is due to inconsistent cost estimates in the 2003–2008 range. One explanation is that the main supplier of PAFC fuel cells exited the market for several years, so while earlier data points are based on actual projects, some of the later data points are estimates based on past evidence. This inconsistency may be due to the nascent commercial status of the technology and uncertainties associated with the small number of data points. Trend lines for high-volume estimates were not fit to a curve due to few data points but they are shown for comparison.

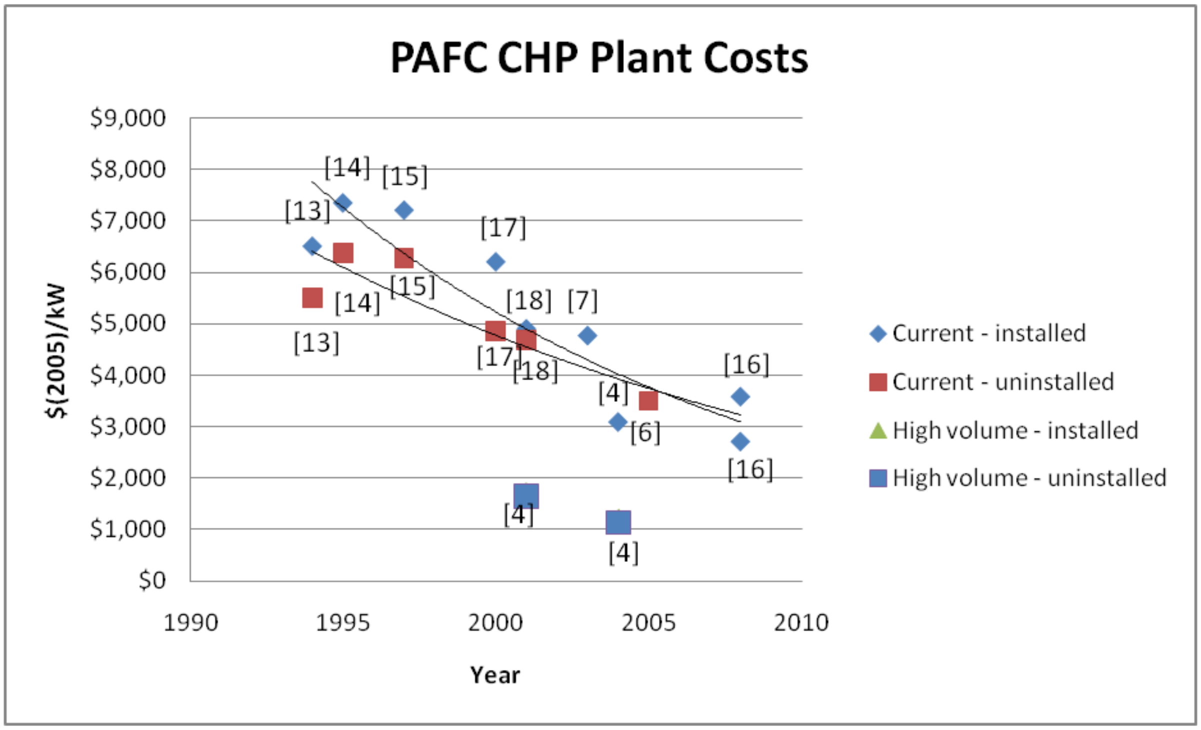

Figure 29. Collected cost information for PAFC CHP plants

Equation 23. $y = 8{,}841e^{-0.066x}$

Equation 24. $x = \text{year} - 1992$

Equation 23 is the curve represented by current uninstalled low-volume production levels: y is the total direct and indirect capital cost in $(2005)/kW, and x is calculated as per Equation 24. The costs for the case study represent relatively high-volume production. The costs were adjusted from 2005 to 2007 dollars using the Chemical Engineering Plant Cost Index (CEPCI). Uninstalled costs for the fuel cell plant were estimated to be $(2007)800/kW, and the natural gas reformer cost was estimated to be $(2007)660/kW of fuel cell AC output. [3] The uninstalled PSA unit cost of $(2007)140/kW for the case study is based on the costs developed for the H2A Hydrogen Production forecourt SMR system (see www.hydrogen.energy.gov/h2a_production.html). The uninstalled cost of the shift reactor was estimated to be $(2007)500/kW, and the system assembly and balance of plant was estimated to be $(2007)1,550. Total CHHP system uninstalled direct capital cost is approximately $(2007)3,650/kW. Installation costs average 12% for all the fuel cell system components, and indirect costs are 25% of the installed equipment cost. Installation and indirect costs are approximately $(2007)1,468/kW for a total installed capital cost of the fuel cell and hydrogen purification system (not including CSD) of $5,118/kW.

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[3] Note that, although DOE supports fuel cell cost-estimation analysis, the $800/kW and $660/kW values are not derived from those efforts and should not be interpreted as a DOE-endorsed cost estimates. They are merely example costs.

Literature values typically include the entire chain. Therefore, the separation of direct capital and indirect was estimated and then split into 10% of installed equipment cost for site preparation, 7% for engineering and design, 5% for project contingency, and 3% for permitting fees on the fuel cell system facility. The values for project contingency and permitting fees were derived from other H2A case studies [10].

Operating and maintenance costs are as follows. Replacement costs are estimated to be 8% after the first 5 years, 39% after the first 10 years, and 8% 5 years after that. Fixed maintenance and repairs were estimated at 2%, and variable unplanned replacement 1.5%, of direct fuel cell system capital cost yearly, both estimated using figures from an EPRI report [3].

Hydrogen Storage and Dispensing

The hydrogen CSD system operating assumptions and costs are derived from the H2A production forecourt model. It is assumed that the hydrogen produced by the system will be used in vehicles used on public streets. The scenario envisions a very small hydrogen demand in an emerging market. Therefore, the hydrogen is piped a short distance to an existing conventional fueling station where storage tanks for about 1 day of production and a single dispenser are located.

3.3.2 Load Profile and Fuel Cell Specification

The hotel is assumed to have 176 rooms, a laundry, and a restaurant. The modeled building was six stories tall. The electricity and heat load profiles for the building are calculated building simulation output from the NREL building systems model [12]. The building is assumed to be an existing building that was constructed using typical building techniques and materials. The electricity load includes electricity use for air conditioning, and the heat load is fuel demand for both space heating and hot water. Because the heating demand profile already accounts for the efficiency of the furnace or boiler, the efficiency of the burner for supplementary heat in the CHHP system is set at 100%.

The average building electrical demand is 229 kW with peaks in demand up to 471 kW and a minimum value of 71 kW. The fuel cell was assumed to be 200 kW, which is a commercially available size, and has a maximum rated AC output just under the building's average demand. For the PAFC system, the reformer can be specified separately from the fuel cell. For the case study, the reformer was oversized by a factor of 2 to produce additional hydrogen.

3.3.3 Utilities

The fuel cell CHHP system is assumed to be grid parallel, with electrical connections that can be islanded from the grid during a power outage. Electricity demand that cannot be met by the fuel cell is provided by the grid. Both time-of-day and seasonal usage charges are assumed to apply. The base price for electricity purchased from the grid is \$0.087/kWh in the startup year (2013), which is the EIA projected national average electricity rate for 2013. Peak rates and off-peak rates are 25% above and 10% below the base rate, respectively. Electricity can also be sold to the grid if more electricity is produced by the system than is required by the hotel at that time. Electricity sold to the utility is assumed to be priced at the same price as electricity would cost if purchased during that hour (net metering).

The fuel cell system and auxiliary space and hot water heating systems are assumed to be fueled with natural gas. The natural gas rate is assumed to be the projected average national commercial natural gas rate, which is $10.71/MMBtu in 2013.

3.4 Phosphoric Acid Fuel Cell Case Study Results

3.4.1 Baseline System

The FCPower Model calculates costs for supplying electricity and heat to the building and purchase of an equivalent amount of hydrogen for the refueling station in the absence of the fuel cell system. This baseline system assumes electricity purchased from the grid, heat for hot water and space heating supplied by a natural gas furnace or boiler, and hydrogen production using a small (forecourt) natural gas SMR. Electricity for the building is purchased using the same price schedule as is used for the CHHP supplementary electricity supply. Natural gas for heating and fueling the SMR unit is purchased at the same rate as fuel for the CHHP system. Yearly costs for energy for the baseline system are shown in Table 12.

Table 12. Baseline system levelized energy costs (prior to installation of fuel cell)

Electricity (use and demand charges)	$238,392/year
Commercial natural gas	$89,946/year
Hydrogen (from forecourt SMR system, $5.23/kg)	$648,804/year
Total baseline system energy cost per year	**$977,142/year**

3.4.2 CHHP System Energy Supply

The PAFC CHHP system supplies a yearly total of 6,142 MWh of energy in the form of electricity, heat, and hydrogen; no electricity is sold to the utility. Of this, 1,184 MWh (19%) are in the form of electricity, 826 MWh (13%) are in the form of useful heat, and the remaining 4,133 MWh (123,993 kg, 67%) are in the form of hydrogen. The total system efficiency is 71%. Table 13 shows the energy supplied by the fuel cell at full operation and supplementary electricity and heat purchased for the building. The analysis assumes that, during construction and startup (about 1 year), all of the electricity and heating fuel to supply the building will be purchased.

Table 13. PAFC System Building Energy Supply

	System Energy to Building (kWh)	Percent of Energy Type Supplied by the CHHP System
System net electricity to building	1,183,907	59
Fuel cell system heat	825,602	39
Hydrogen	4,132,595 (123,993 kg)	100
	Supplementary Building Electricity and Heat (kWh)	**Percent of Energy Type Supplied by Supplementary Systems**
Supplementary electricity	928,473	41
Supplementary heat	1,388,573	61

3.4.3 CHHP System Capital Costs and Credits

For the case study, it is assumed that a commercial entity (the hotel owner) purchases the fuel cell system and owns and operates the refueling station equipment but rents the land for the refueling station, which is co-located with a gasoline refueling station adjacent to the hotel. A 300-ft pipeline connects the CHHP system to the storage tanks and compressors at the filling station. Equity financing, a 10% internal rate of return, and a 20-year life are assumed for the CHHP installation.

Table 14 shows the initial capital investment and federal tax credits taken for the installation. Indirect capital investment (site preparation, engineering, contingency, and permitting) totals $329,525.

Table 14. PAFC System Initial Investment and Credits

Direct capital investment (reference year, (2007)$)						
Major pieces/ systems of equipment	**Baseline installed costs ($) (total initial capital investment)**	**Depreciation type**	**Depreciation schedule (years)**	**Federal credit or incentive**	**Credit amount ($)**	**Total adjusted depreciable capital cost basis ($)[1]**
PAFC System (including hydrogen purification)	818,817	MACRS	5	Federal business energy tax credit	69,120	911,127
Auxiliary heater	170,754	MACRS	7			197,211
System integration and control	30,000	MACRS	7			34,648
Hydrogen compression, storage, and dispensing	1,107,185	MACRS	5			1,278,735
Total	2,126,757 (2,456,28)				69,120	2,421,722

1. Total depreciation basis includes indirect capital costs.

3.4.4 PAFC CHHP System Cash Flow

Figure 30 shows key expenditures and cash flow for the PAFC CHHP installation throughout its lifetime. Replacement costs include an allowance of 1.5% per year of the initial depreciable capital investment for unplanned replacement of capital equipment as well as planned restacking/refurbishment of the fuel cell and reformer every 5 years (8% of fuel cell capital investment at year 5 and 15, 39% at year 10). It is assumed that the compressors and dispensers will be replaced after 10 years at 35% of the initial cost for the entire CSD system. A replacement cost of 25% of building system integration direct capital cost is also incurred after 10 years. Figure 30 indicates that the project will break even after approximately 7 years.

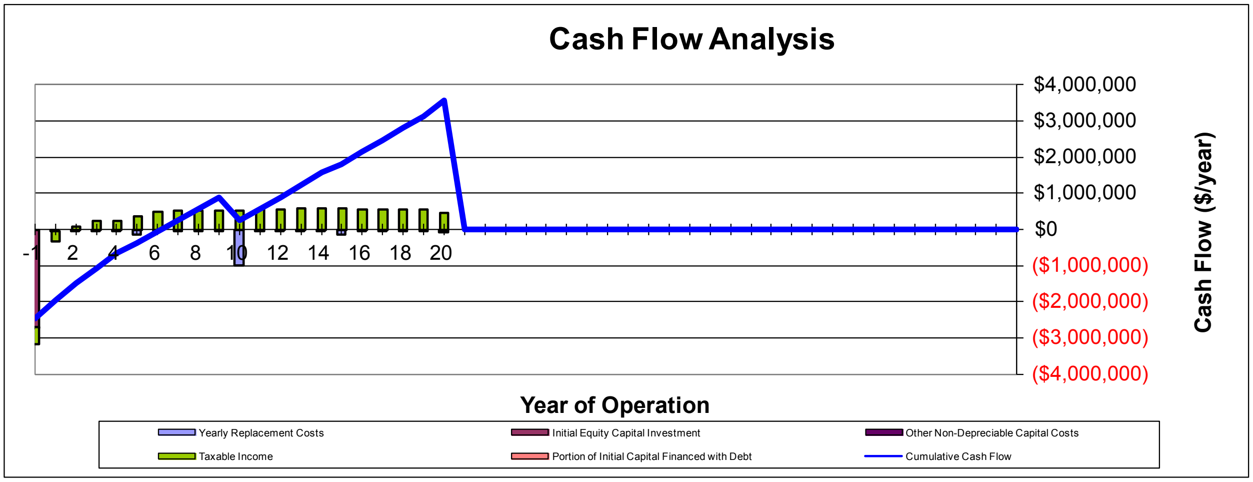

Figure 30. PAFC CHHP Key Yearly Expenditures and Revenue

3.4.5 Cost of Hydrogen and Total Annualized Costs

The FCPower Model solves for the levelized revenue for energy supplied by the CHHP system (electricity, heat, and hydrogen) that will result in a net present value (including inflation and an internal rate of return specified by the user) of zero for the project. The user may distribute the required revenue between the three energy streams in any way desired. However, the default distribution assumes that electricity supplied by the fuel cell is “sold” at the same price as would have been paid for grid electricity. Similarly, heat is assumed to be supplied at the same rate as purchased natural gas. The levelized profited cost of hydrogen is derived by difference. For this installation, the cost of hydrogen is $5.92/kg as dispensed. This is comparable to the cost of hydrogen supplied by a forecourt SMR unit ($5.23/kg) for the baseline system. Table 15 shows the total annualized costs for the PAFC CHHP system

Table 15. Total Annualized Costs for the PAFC CHHP Installation

Annualized costs	
Capital costs	$451,583
Decommissioning costs	$4,277
Fixed O&M	$172,828
Feedstock costs	$247,424
Other raw material costs	$0
Byproduct credits	$0
Other variable costs (not including supplementary electricity and heat)	$10,941
Supplementary electricity	$112,008
Supplementary heat	$41,958
Total	**$1,041,020**

The total annualized cost for the CHHP system is similar to the energy costs for the baseline system of $977,142 shown in Table 12. This analysis indicates that the CHHP system could be a cost-effective alternative to conventional energy supply for the hotel.

3.4.6 Sensitivity Analysis

Sensitivity analyses were performed for key cost elements for the CHHP system: inflation rate, internal rate of return, federal tax credit, CSD capital cost, fuel cell cost, process fixed operating cost, and total depreciable capital cost. The results, presented in terms of the levelized hydrogen cost, are shown in Figure 31.

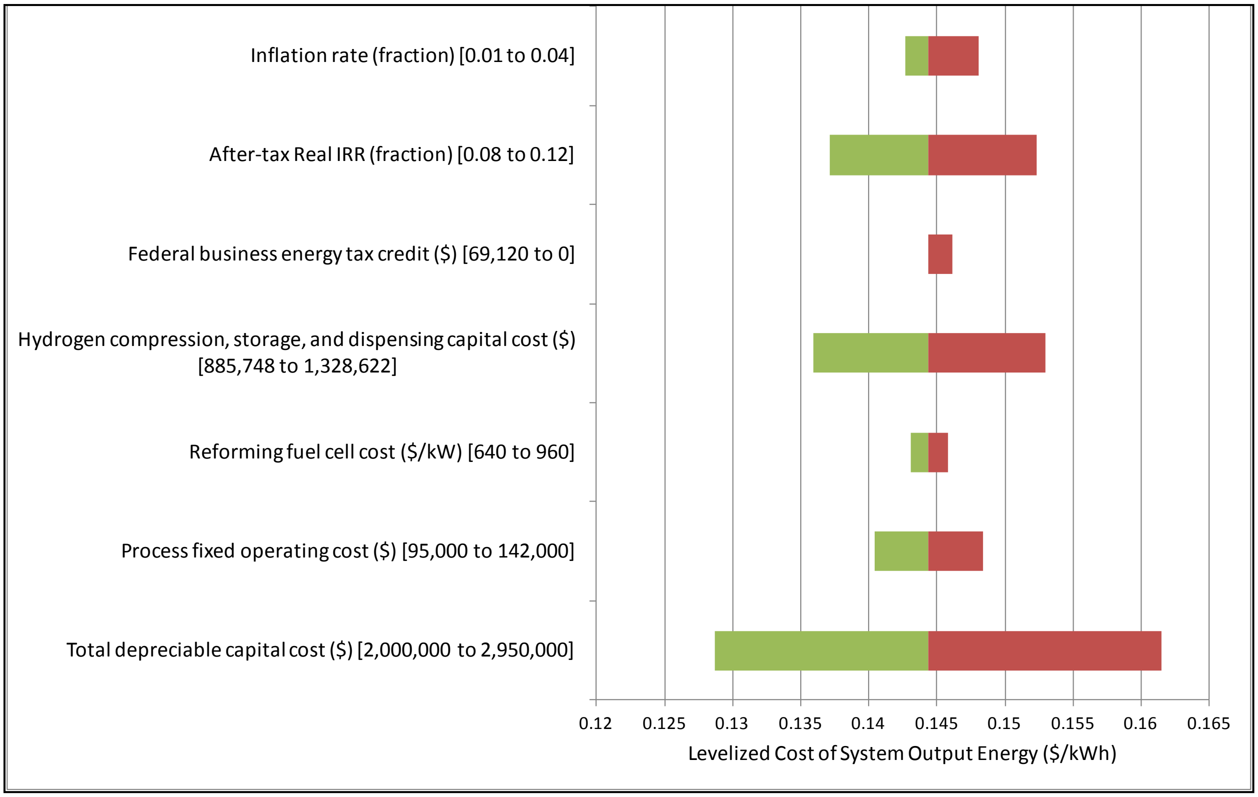

Figure 31. Sensitivity analysis for the PAFC CHHP system key costs

3.5 Solid Oxide Fuel Cell Case Study Description

The system is assumed to be a combined heat, hydrogen, and power system. The fuel cell is sized to meet the average AC demand. Hydrogen CSD are assumed to closely resemble the CSD portion for standalone forecourt SMR hydrogen production at a comparable hydrogen production rate. The business is assumed to take advantage of the federal fuel cell tax credit.

The CHHP application modeled includes additional equipment for integrating the hydrogen co-production with a standard CHP application. In addition to the fuel cell plant—which includes a fuel-reforming system, fuel cell stacks, and power-conditioning equipment—a shift reactor converts additional CO to hydrogen, and a PSA unit extracts hydrogen from the fuel cell exhaust stream. A CSD unit is installed for vehicle refueling. The CSD costs do not include costs for a convenience store or building.

The CHHP power model includes several additional components that can be included within the model analysis. These include a burner for additional heat, an electrolyzer for additional hydrogen production, and an additional, usually smaller fuel cell for meeting peak electricity demand. Hydrogen storage can be used for electricity or vehicle fueling. However, it is assumed that the fuel cell system will tie into existing building electricity, heating, cooling, and domestic hot water production. Equipment such as additional thermal storage is not used; existing thermal water storage is used instead. Note that the cost values used in this case study are for illustration purposes only and are not validated or endorsed by DOE.

3.5.1 Financial Inputs

Fuel Cell System

The Solid State Energy Conversion Alliance (SECA)[4] has set a target of $700/kW[5] fuel cell rated AC power for SOFC systems (direct uninstalled cost for the fuel cell plant including internal reforming), and the case study uses this value. A shift reactor and PSA system were added for hydrogen production and purification from the fuel cell. The shift reactor and PSA system were sized for the more dilute hydrogen stream from the SOFC. The combined uninstalled cost of the shift reactor and fuel compressor was estimated to be $117/kW, and the uninstalled PSA cost was estimated to be $315/kW. Total CHHP system uninstalled direct capital cost is approximately $1,131/kW. Installation was estimated to be 20% of the equipment cost for the fuel cell plant and PSA. Indirect costs are 25% of the installed equipment cost. Installation and indirect costs are approximately $537/kW for a total installed capital cost of the fuel cell and hydrogen purification system (not including CSD) of $1,668/kW.

Indirect capital costs are difficult to enumerate separately because researched costs typically included the entire chain. Indirect costs for project contingency and permitting

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[4] For information about SECA, visit http://www.netl.doe.gov/technologies/coalpower/fuelcells/seca/.

[5] Note that, although DOE supports fuel cell cost-estimation analysis, the $700/kW value is not derived from those efforts and should not be interpreted as a DOE-endorsed cost estimate. It is merely an example cost.

were generally not included in literature values for costs. The values used in the FCPower Model for project contingency and permitting (5% and 3% of installed equipment costs, respectively) are derived from previous H2A hydrogen production models [10]. The separation of direct and indirect capital cost was estimated and then split into 10% of installed equipment cost for site preparation and 7% for engineering and design.

Operating and maintenance costs are as follows. Replacement costs are estimated to be 25% of the total fuel cell system capital cost every 10 years. Fixed maintenance and repairs were estimated at 2%, and variable unplanned replacement 1.5%, of direct fuel cell system capital cost yearly, both estimated using figures from an EPRI report [3].

Hydrogen Storage and Dispensing

The hydrogen CSD system operating assumptions and costs are derived from the H2A production forecourt model. It is assumed that the hydrogen produced by the system will be used in vehicles used on public streets. The scenario envisions a very small hydrogen demand in an emerging market. Therefore, the hydrogen is piped a short distance to an existing conventional fueling station where storage tanks for about 1 day of production and a single dispenser are located.

3.5.2 Load Profile and Fuel Cell Specification

The hotel is assumed to have 176 rooms, a laundry, and a restaurant. The modeled building is six stories tall. The electricity and heat load profiles for the building are calculated using building simulation output from the NREL building systems model [12]. The building is assumed to be an existing building that was constructed using typical building techniques and materials. The electricity load includes electricity use for air conditioning, and the heat load is fuel demand for both space heating and hot water. Because the heating demand profile already accounts for the efficiency of the furnace or boiler, the efficiency of the burner for supplementary heat in the CHHP system is set at 100%.

The average building electrical demand is 229 kW with peaks in demand up to 471 kW and a minimum value of 71 kW. The fuel cell was assumed to be 200 kW, which is a commercially available size, with a maximum rated AC output just under the building's average demand.

3.5.3 Utilities

The fuel cell CHHP system is assumed to be grid parallel, with electrical connections that can be islanded from the grid during a power outage. Electricity demand that cannot be met by the fuel cell is provided by the grid. Both time-of-day and seasonal usage charges are assumed to apply. The base price for electricity purchased from the grid is \$0.087/kWh in the startup year (2013), which is the EIA projected national average electricity rate for 2013. Peak rates and off-peak rates are 25% above and 10% below the base rate, respectively. Electricity can also be sold to the grid if more electricity is produced by the system than is required by the hotel at that time. Electricity sold to the utility is assumed to be priced at the same price as electricity would cost if purchased during that hour (net metering).

The fuel cell system and auxiliary space and hot water heating systems are assumed to be fueled with natural gas. The natural gas rate is assumed to be the projected average national commercial natural gas rate, which is \$10.71/MMBtu in 2013.

3.6 Solid Oxide Fuel Cell Case Study Results

3.6.1 Baseline System

The FCPower Model calculates costs for supplying electricity and heat to the building and purchasing an equivalent amount of hydrogen for the refueling station in the absence of the fuel cell system. This baseline system assumes electricity purchased from the grid, heat for hot water and space heating supplied by a natural gas furnace or boiler, and hydrogen production using a small (forecourt) natural gas SMR. Electricity for the building is purchased using the same price schedule as is used for the CHHP supplementary electricity supply. Natural gas for heating and fueling the SMR unit is purchased at the same rate as fuel for the CHHP system. Yearly costs for energy for the baseline system are shown in Table 16. In a real-world application, a small-volume hydrogen station like this one likely would be part of an existing conventional fuel station (instead of being a standalone station as assumed here) and possibly supplied with off-site-generated hydrogen via truck, which might reduce the hydrogen cost below the \$12.04/kg shown here.

Table 16. Baseline system levelized energy costs (prior to installation of fuel cell)

Electricity (use and demand charges)	\$238,392/year
Commercial natural gas (for heat)	\$89,946/year
Hydrogen (from forecourt SMR, \$12.04/kg)	\$365,975/year
Total baseline system energy cost per year	**\$694,313/year**

3.6.2 CHHP System Energy Supply

The SOFC CHHP system supplies a yearly total of 2,810 MWh of energy to the building in the form of electricity, heat, and hydrogen, in addition to 20 MWh of electricity that is sold to the utility. Of this, 1,300 MWh (46%) are in the form of electricity, 500 MWh (18%) are in the form of useful heat, and the remaining 1,000 MWh (30,400 kg, 36%) are in the form of hydrogen. The total system efficiency is 75%. Table 17 shows the energy supplied by the fuel cell at full operation and supplementary electricity and heat purchased for the building. The analysis assumes that, during construction and startup (about 1 year), all of the electricity and heating fuel to supply the building will be purchased.

Table 17. SOFC System Building Energy Supply at Full Operation

	System Energy to Building (kWh)	Percent of Energy Type Supplied by the CHHP System
System net electricity to building	1,296,444	65
Fuel cell system heat	500,110	24
Hydrogen	1,013,213	100
	Supplementary Building Electricity and Heat (kWh)	**Percent of Energy Type Supplied by Supplementary System**
Supplementary electricity	816,510	35
Supplementary heat	1,712,405	76

Approximately 19% (312 MWh/year) of the fuel cell total electrical output of 1,628 MWh per year at full operation, is required for auxiliary power, primarily for the hydrogen purification system and compression of hydrogen to the dispensing pressure of 5,000 psi (350 bar).

3.6.3 CHHP System Capital Costs and Credits

For the case study, it is assumed that a commercial entity (the hotel owner) purchases the fuel cell system and owns and operates the refueling station equipment but rents the land for the refueling station, which is co-located with a gasoline refueling station adjacent to the hotel. A 300-ft pipeline connects the CHHP system to the storage tanks and compressors at the filling station. Equity financing, a 10% internal rate of return, and a 20-year life are assumed for the CHHP installation.

Table 18 shows the initial capital investment and federal tax credits taken for the installation. Indirect capital investment (site preparation, engineering, contingency, and permitting) totals $132,253.

Table 18. SOFC System Initial Investment and Credits

Direct capital investment (reference year, (2007)$)						
Major pieces/ systems of equipment	**Baseline installed costs ($) (with indirect capital)**	**Depreciation type**	**Depreciation schedule (years)**	**Federal credit or incentive**	**Credit amount ($)**	**Total adjusted depreciable capital cost basis ($)[1]**
MCFC System (including hydrogen purification)	266,864	MACRS	5	Federal business energy tax credit	60,480	274,903
Auxiliary heater	170,754	MACRS	7			195,247
System integration and control	30,000	MACRS	7			34,303
Hydrogen compression, storage, and dispensing	454,381	MACRS	5			519,558
Total	921,999 (1,054,252)				60,480	1,024,012

1. Total depreciation basis includes indirect capital costs.

3.6.4 SOFC CHHP System Cash Flow

Figure 32 shows key expenditures and cash flow for the SOFC CHHP installation throughout its lifetime. Yearly replacement costs include an allowance of 1.5% of the initial depreciable capital investment for unplanned replacement of capital equipment as well as planned restacking of the fuel cell every 10 years. It is assumed that the compressors and dispensers will be replaced after 10 years at 35% of the initial cost for the entire CSD system. A replacement cost of 25% of building system integration direct capital cost is also incurred after 10 years. Figure 32 indicates that the project will break even after approximately 7 years.

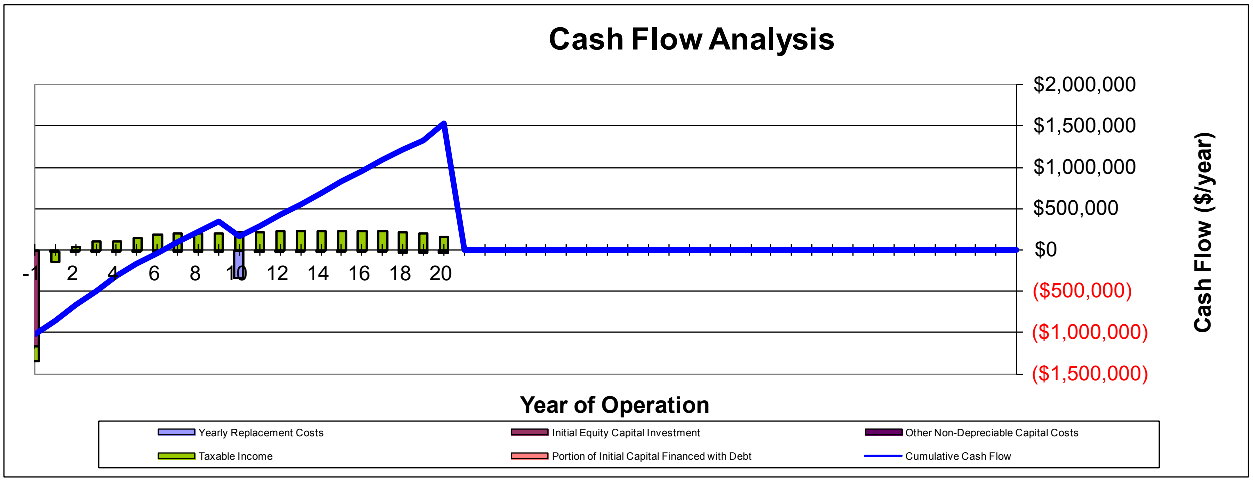

Figure 32. SOFC CHHP Key Yearly Expenditures and Revenue

3.6.5 Cost of Hydrogen and Total Annualized Costs

The FCPower Model solves for the levelized revenue for energy supplied by the CHHP system (electricity, heat, and hydrogen) that will result in a net present value (including inflation and an internal rate of return specified by the user) of zero for the project. The user may distribute the required revenue between the three energy streams in any way desired. However, the default distribution assumes that electricity supplied by the fuel cell is “sold” at the same price as would have been paid for grid electricity. Similarly, heat is assumed to be supplied at the same rate as purchased natural gas. The levelized profited cost of hydrogen is derived by difference. For this installation, the cost of hydrogen is $10.54/kg as dispensed. This compares favorably to the cost of hydrogen supplied by a forecourt SMR unit ($12.04/kg) for the baseline system. Table 19 shows the total annualized costs for the SOFC CHHP system.

Table 19. Total Annualized Costs for the SOFC CHHP Installation

Annualized costs	
Capital costs	$187,462
Decommissioning costs	$1,819
Fixed O&M	$125,542
Feedstock costs	$165,829
Other raw material costs	$0
Byproduct credits	–$1,776
Other variable costs (excluding supplementary electricity and heat)	$4,450
Supplementary electricity	$99,523
Supplementary heat	$77,880
Total	**$660,729**

The total annualized cost for the CHHP system is less than the energy costs for the baseline system of $694,313 shown in Table 16. This analysis indicates that the CHHP system could be a cost-effective alternative to conventional energy supply for the hotel.

3.6.6 Sensitivity Analysis

Sensitivity analyses were performed for six key cost elements for the CHHP system: internal rate of return, federal business energy tax credit, reforming fuel cell cost, CSD cost, process fixed operating cost, and total depreciable capital cost. The results, presented in terms of levelized energy cost, are shown in Figure 33.

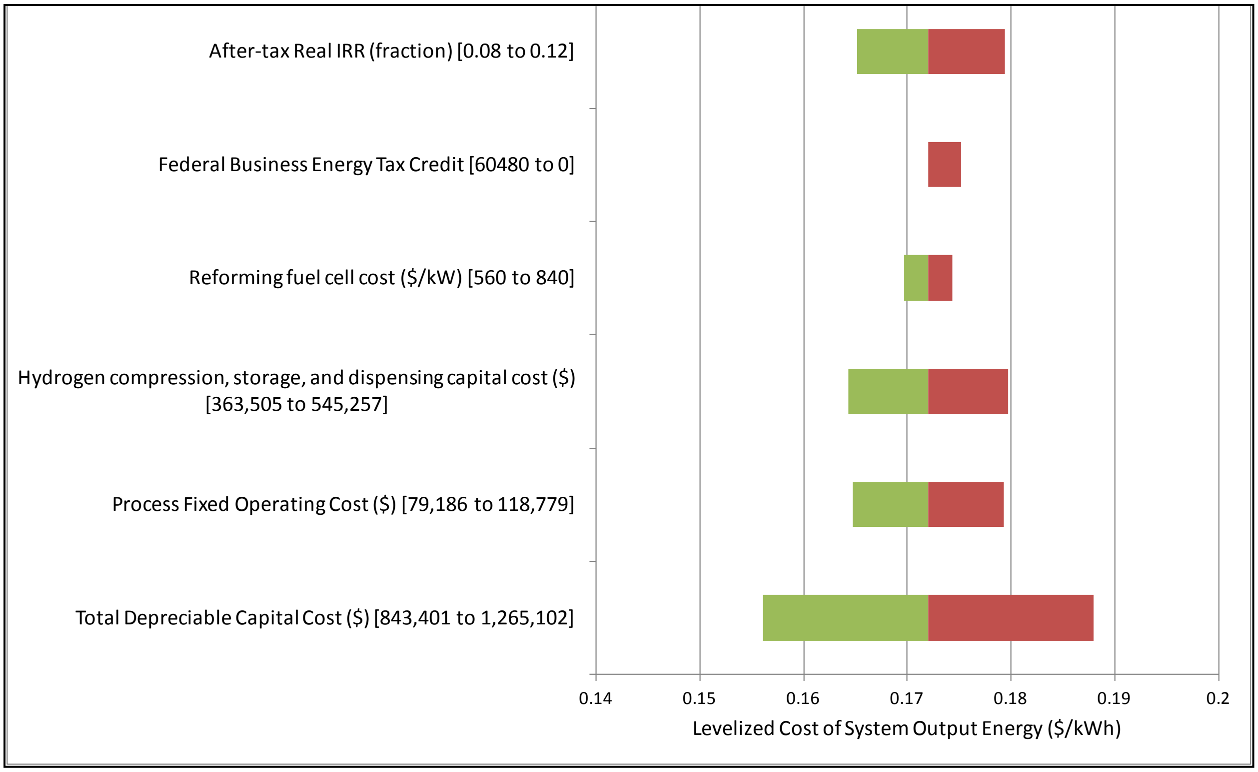

Figure 33. Sensitivity analysis for the SOFC CHHP system key costs (LCOE in $/kWh)

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