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

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

Draft

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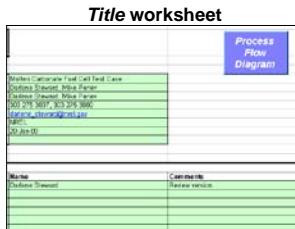
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Quick Start

1 **Click *Process Flow Diagram* button**

Title worksheet

The model opens in the *Title* worksheet. Click the button to proceed to the *Process Flow Diagram (PFD)* worksheet.

2
- **Configure system**
- **Click *Input Sheet* button**
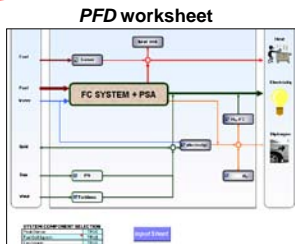
PFD worksheet

In the *PFD* worksheet, check and uncheck boxes to define your energy system then click the button.

3
- **Fill out Input Sheet completely**
- **Click *Run Hourly Energy Profile* button**

Input_Sheet_Template worksheet

Click to run model after completing entire worksheet

Click to link to detailed capital cost worksheets

Click to enter specific replacement costs

Complete the *Input_Sheet_Template* worksheet from top to bottom. Some values in the *Capital Costs* and *Variable Operating Costs* sections can link to other worksheets; after entering values on those worksheets, click the *Input Sheet* button to return to the *Input_Sheet_Template* worksheet. In the *Other Materials and Byproducts* section, you must click the *Add* button to add materials.

4 **View results**

Results worksheet

After clicking the *Run Hourly Energy Profile* button in the *Input_Sheet_Template* worksheet, the model runs energy and cost calculations, and you are sent to the *Results* worksheet, where you can view the cost, energy, and emissions results of your system. Also see the *Financial Summary* and *Key Figures* worksheets, the tabs for which are adjacent to the *Results* tab.

Table of Contents

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
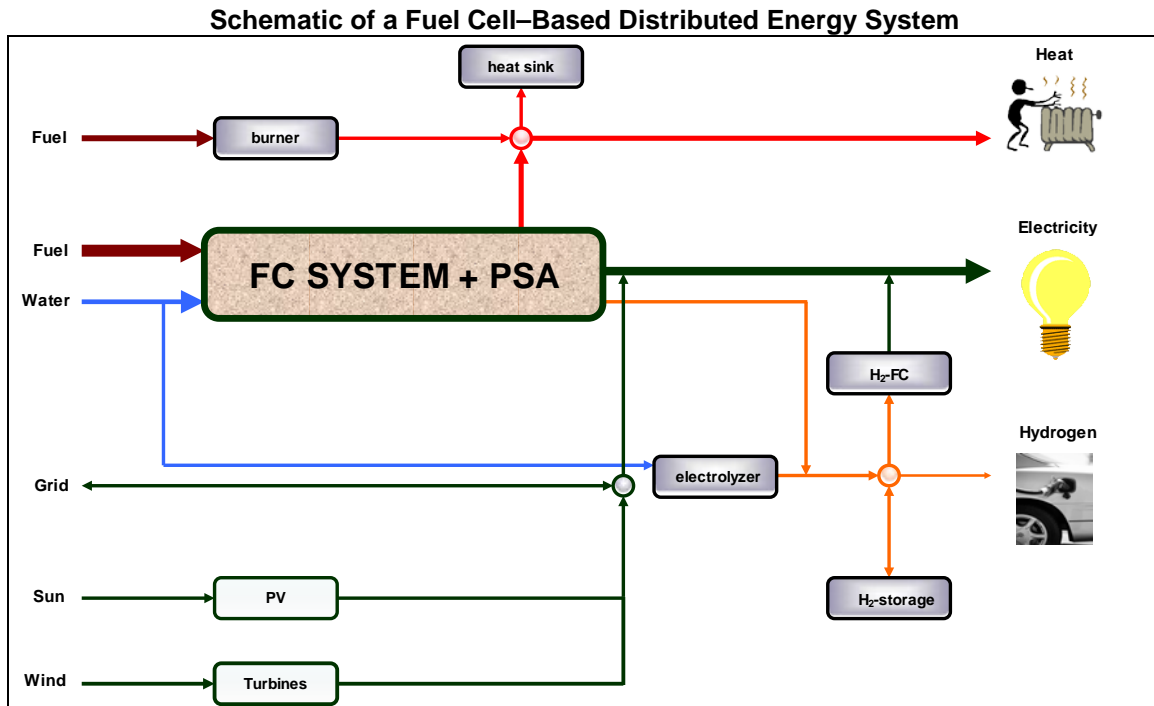
In the FCPower Model, users select which technologies are used in the system—such as hydrogen fuel cells, photovoltaic (PV) panels, and electrolyzers—and define each technology's cost and performance parameters. Users also select fuel costs and demand priority (i.e., whether the system follows electricity 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.
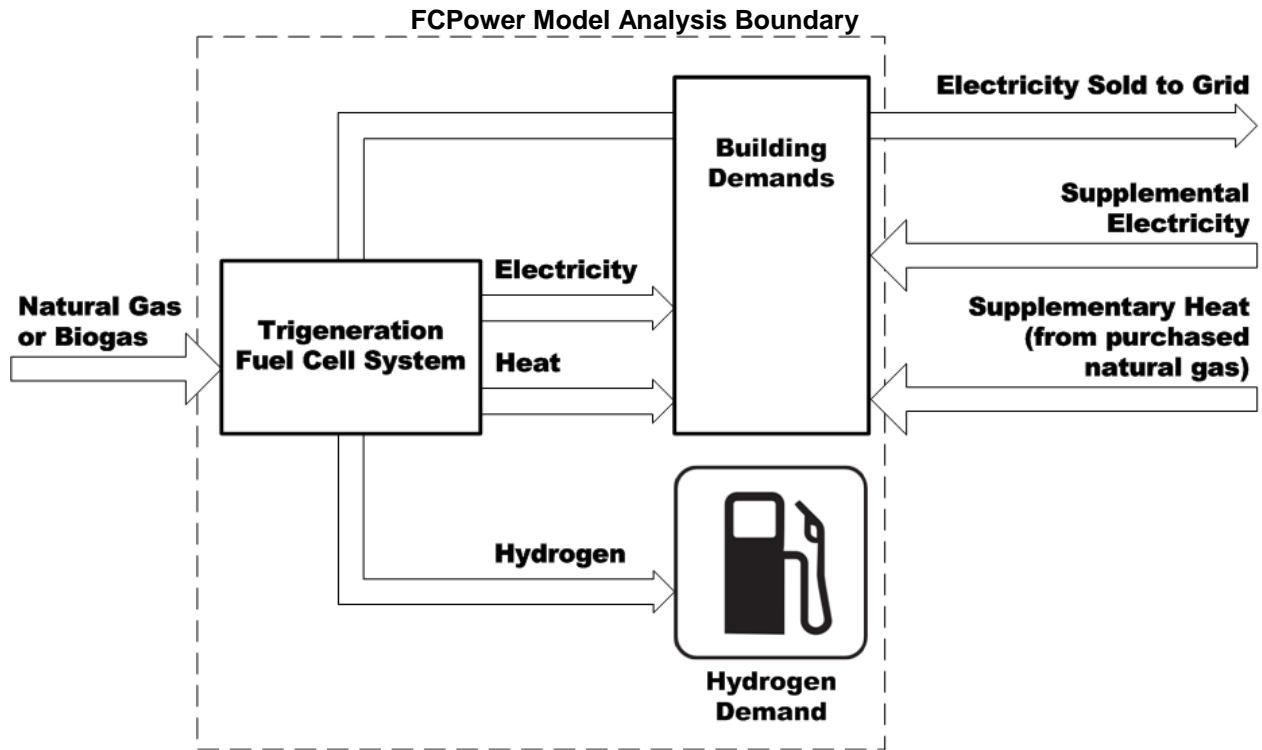
The output of the model is compared with a baseline system in which electricity is supplied by the electric grid, heat is supplied by a natural gas heating system, and hydrogen is supplied by a standalone SMR system (see diagram below).

Baseline System Analysis Boundary
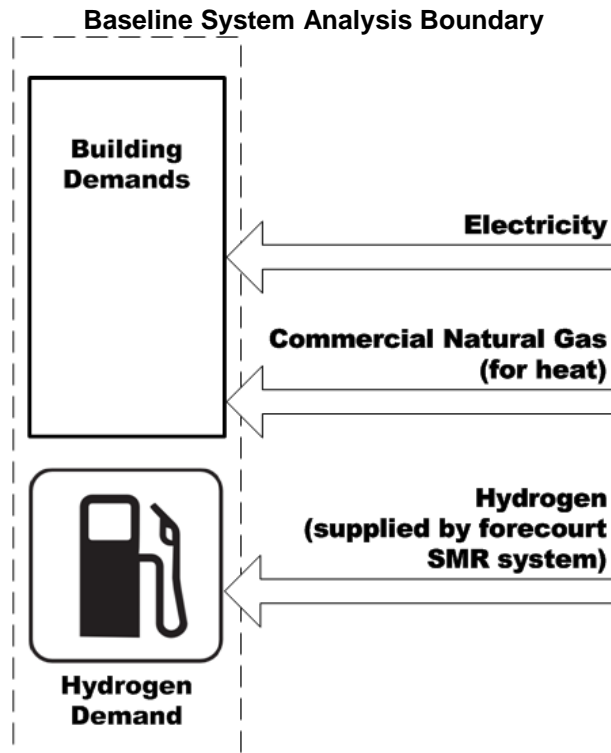
The FCPower Model comes in two different versions (i.e., two different Excel workbooks): one version based on a molten carbonate fuel cell (MCFC) system and one based on a phosphoric acid fuel cell (PAFC) system. One of the major differences between the systems is that the PAFC system has a separate 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 system has an internal reformer, 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 system. This function is discussed later in this guide.

Schematic of a PAFC System

Schematic of a MCFC System
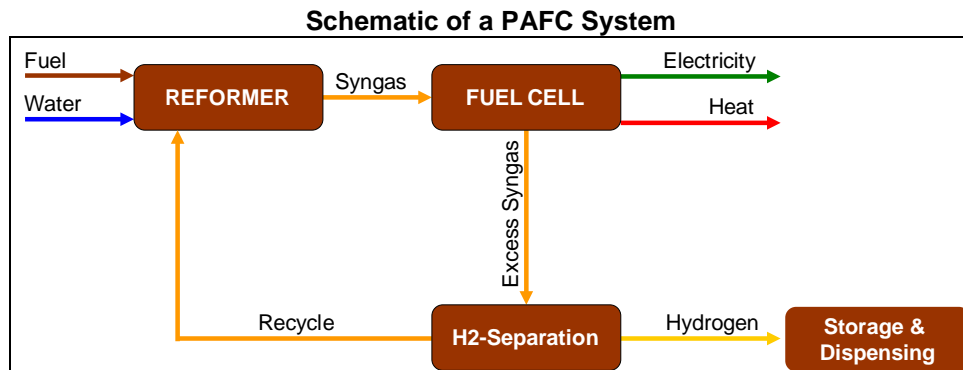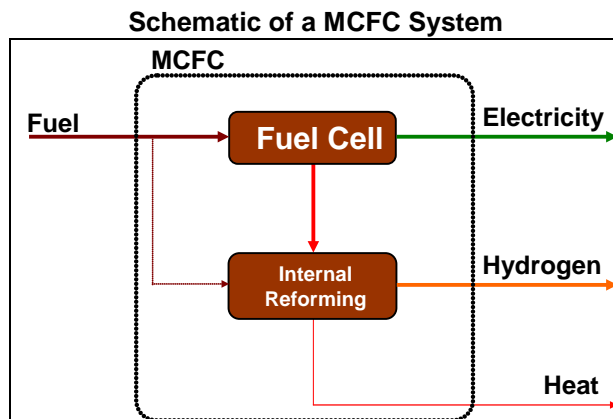
This guide helps users get started with the FCPower Model. Note that screen captures and values shown in this guide are for illustration only and will not necessarily match what appears in the version of the model or case study you are using. More detailed instructional materials and model documentation 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.

Getting Around

The FCPower Model workbook is organized into as many as 34 worksheets (depending on the number of energy technologies selected), which have tabs color coded according to their function, as shown below. The schematic on the following page shows a generalized data flow among the worksheets.

FCPower Model Worksheets
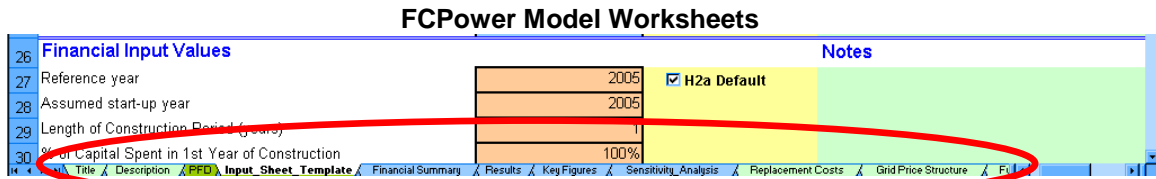
| Title |
| Description |
| PFD |
| Input_Sheet_Template |
| Financial Summary |
| Results |
| Key Figures |
| Tornado Chart |
| Sensitivity_Analysis |
| Replacement Costs |
| Grid Price Structure |
| Fuel Cell System |
| Solar PV |
| Wind Turbines |
| Electrolyzer |
| Hydrogen Fuel Cell |
| Hydrogen Storage |
| Peak Burner |
| Solar Availability |
| Wind Availability |
| AC Demand |
| Heat Demand |
| H2 Demand |
| HOURLY RESULTS |
| MODEL |
| Cash Flow Analysis |
| Energy Feed & Utility Prices |
| Non-Energy Material Prices |
| AEO Data |
| HyARC Physical Property Data |
| Debt Financing Calculations |
| Depreciation |
| Constants and Conversions |
| Lists |

Worksheet Color Key

- Inputs & information*
- Results*
- Data & properties
- Standard calculations & variables

*Darker color indicates worksheets accessed frequently by user. Lighter color indicates infrequently accessed or calculation worksheets.

Schematic of Primary Data Flow among FCPower Model Worksheets
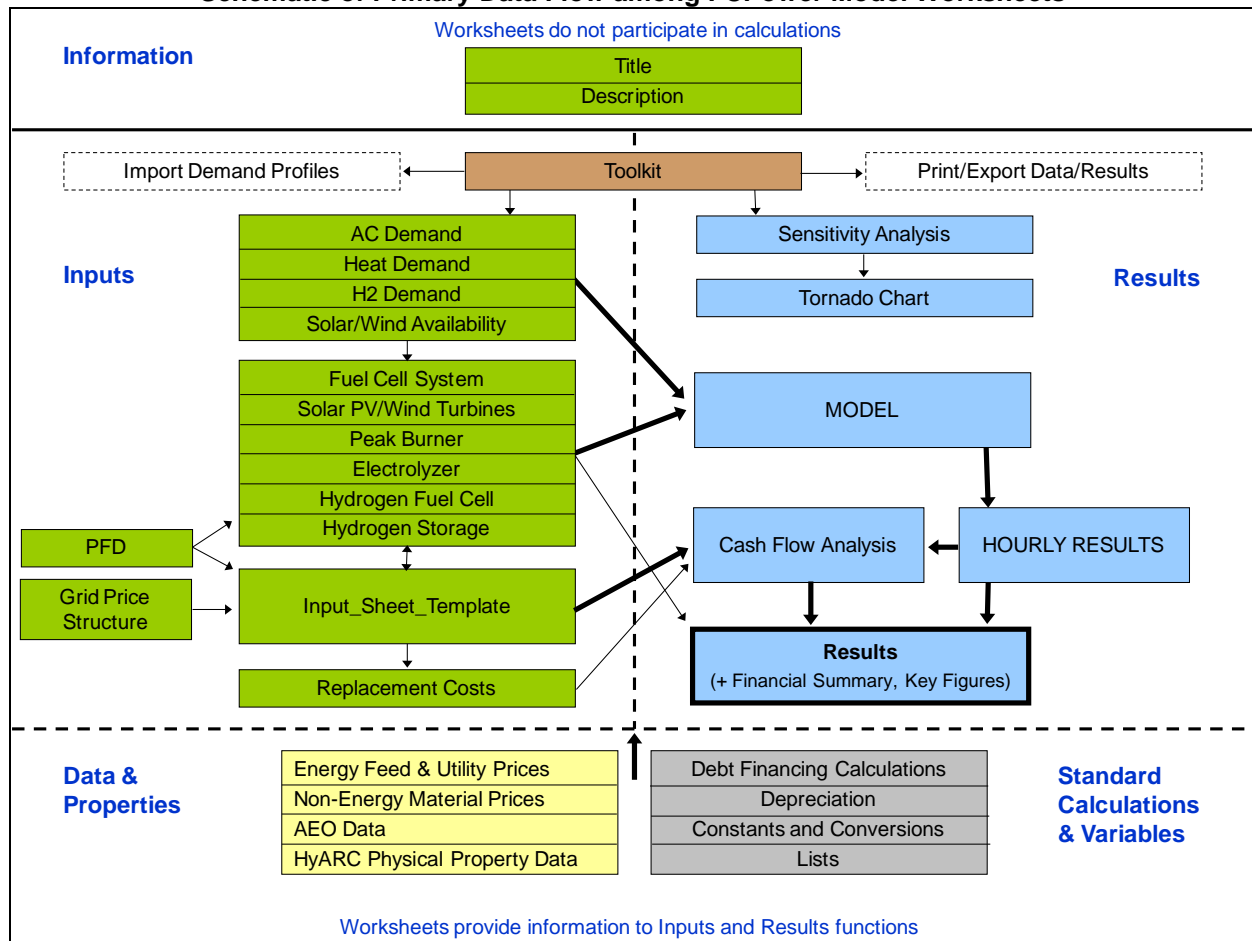
Tips & Troubleshooting

- 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 user-input information and notes. Yellow cells contain information and default values.

- 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 *Input_Sheet_Template* worksheet works best (i.e., has the least likelihood of errors) when you fill it out as completely as possible, starting with the top and working down. After filling out the worksheet completely, run the model using the buttons at the top of the *Input_Sheet_Template* worksheet.

Performing Simple Analyses

Configuring Your Simulated Distributed Energy System

To perform a simple analysis, first select the *PFD* (Process Flow Diagram) worksheet. Use the check boxes within the diagram to select technologies you want to include in your distributed energy system and de-select technologies you do not want to include. The choices are a peak burner (for providing supplementary heat), PV and wind turbines (for providing renewable electricity), electrolyzer (for producing hydrogen with electricity), hydrogen fuel cell (for converting hydrogen to electricity), and hydrogen storage. The primary high-temperature fuel cell system with pressure swing adsorption (PSA)—which reforms fuel and produces electricity, hydrogen, and heat—is always activated, as is the heat sink.
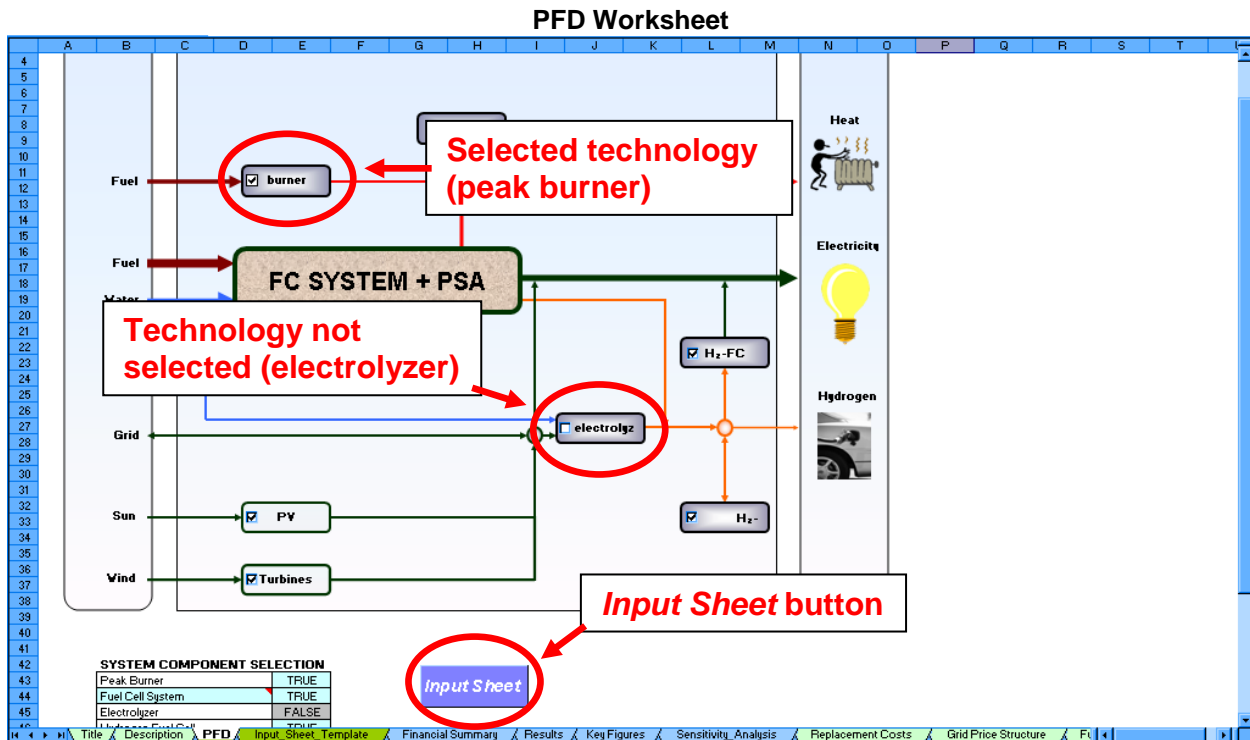
PFD Worksheet

Next, click the *Input Sheet* button to go to the *Input_Sheet_Template* worksheet. Disregard the buttons at the top for now, and scroll down to the data-entry fields. Accept the default values or enter new values into the orange cells. The contents of the blue cells are calculated automatically.

When you reach the *Capital Costs* section of the *Input_Sheet_Template* worksheet, you will see that the fields corresponding to each technology selected in the *PFD* worksheet are orange or blue with adjacent *Enter Values* or *Unlink* buttons. Fields corresponding to technologies not selected in the *PFD* worksheet are grayed out and have deactivated (*Not Selected*) buttons.

Input_Sheet_Template Worksheet, Capital Costs Section

Click the first *Enter Values* button, which is adjacent to the field *High-temperature fuel cell and/or reformer process direct capital cost*. Clicking the button sends you to the *Fuel Cell System* worksheet. Immediately, a window titled "Reference Material and Guidance for Fuel Cell System Cost Estimates" pops up. This window helps you select a value for the field *Fuel cell CHP equipment uninstalled cost* (see screen capture below), which must be filled in before the model is run. 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. Click the *Cost guidance* button if you want to see the pop-up window again after you have closed it.

Fuel Cell System Worksheet, Mandatory Fuel Cell Uninstalled Cost Field

Continue to make other changes on the *Fuel Cell System* worksheet as necessary. 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. Once you are done making changes

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to this technology, return to the *Input_Sheet_Template* worksheet using the *Input Sheet* button.

Repeat this process for all activated technologies. Ensure values are present for *Maximum Power* (*Peak Burner* worksheet), *Electrolyzer Size* (*Electrolyzer* worksheet), *Fuel Cell Capacity* (*Hydrogen Fuel Cell* worksheet), *Storage Volume* (*Hydrogen Storage* worksheet), *PV Array Area* (*Solar PV* worksheet), and Installed Capacity (*Wind Turbine*s worksheet). Later, you can unlink values from their detail worksheets using the *Unlink* button (and re-link using the *Link to Detail Sheet* button), but you must link to them initially.

The *High-temperature fuel cell and/or reformer process direct capital cost* field is always linked to its corresponding *Fuel Cell System* worksheet. Also, as part of the model's standard case study, the *Auxiliary heater* and *Hydrogen compression, storage, and dispensing direct capital cost* fields are automatically linked to their corresponding detail worksheets, which contain default technology and cost values. To enter your own values for these fields, click the appropriate *Unlink* button and enter a value in the orange field. To re-link to the detail worksheet, click the *Link to Detail Sheet* button.

Example Technology Detail Worksheet (Electrolyzer)

As you continue to complete the *Capital Costs* section of the *Input_Sheet_Template* worksheet, you will find fields for entering incentives and credits. 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.

Also in this section are fields with drop-down menus for entering depreciation type and schedule for your capital equipment. Note that in the depreciation type drop-down menus, you can select "Straight line," "MACRS," or "none." Selecting "none" sets the depreciable capital cost basis to zero; this is applicable to nonprofit organizations. If you are modeling a system for a tax-exempt organization, also set the state and federal taxes to zero.

Continue working your way down the *Input_Sheet_Template* worksheet, entering or accepting values, until you reach the *Variable Operating Costs* section. In the *Energy Feedstocks, Utilities, and Byproducts* sub-section, specify the type and price of fuel inputs and electricity. Select a price table using the first drop-down menu. These price tables are drawn from U.S. Energy Information Administration (EIA) data/projections and are located in the *Energy Feed & Utility Prices* worksheet. The default table is the *AEO 2005 High A Case*.

Using the next drop-down menu, specify the type of fuel that will be used by the high-temperature fuel cell system. If the *Look up prices for each year?* field says "Yes," the model looks up the price for each year of the analysis in the selected price table and inflates that value using the inflation rate entered in the *Financial Input Values* section of the *Input_Sheet_Template* worksheet. If you select "No"—by clicking on the field and using the drop-down menu—and enter your own price in the *Fuel price in startup year* field, the model inflates that price over the analysis period. Use this same process to define the energy source and price for the auxiliary heater (peak burner), if present, and grid electricity.

The *Edit Grid Electricity Import Price Matrix* function allows you to change values in 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. To view and modify the price matrix, click the *Edit* button, which sends you to the *Grid Price Structure* worksheet. Accept the default values or enter new values for *Usage Charges*, *Demand Charges*, and *Rate Periods*. The base price is the national average price looked up from the EIA tables or entered on the *Input_Sheet_Template* worksheet. When finished, click the *Calculate Sheet* button to calculate grid prices based on your inputs. Then, click the *Input Sheet* button to return to the *Input_Sheet_Template* worksheet. 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.

Input_Sheet_Template Worksheet: Energy Feedstocks, Utilities, and Byproducts Sub-Section

	B	C	D	E	F
96	**Energy Feedstocks, Utilities, and Byproducts**				
	Select the Price Table to Use		the fuel cell system and the peak		
	AEO 2005 High A Case		culated by the model.		
97					
98					
99	**Reforming Fuel Cell Fuel Specification**		**Purchases of Renewable Electricity**		
100	Commercial Natural Gas_metric	Commercial Natural Gas_metric	sumed to be purchased electricity produced.		
101	Look up prices for each year?	Yes			
102	Fuel Price in Startup Year (\$(2005)/ Nm3 @ 0°C)	\$0.340			
103					
104					
105	**Auxillary Heater (Peak Burner) Fuel Specification**				
106	Commercial Natural Gas_metric	Commercial Natural Gas_metric			
107	Look up prices for each year?	Yes			
108	Fuel Price in Startup Year (\$(2005)/ Nm3 @ 0°C)	\$0.340			
109					
110	Edit Grid Electricity Import Price Matrix	Edit	es as a percen		
111					
112	**Grid Electricity Base Prices**				
113	Commercial Electricity_metric	Commercial Electricity_metric	Set or look up the base price for electricity. The look from the EIA nationwide average electricity price proj		
114	Look up base prices for each year?	Yes			
115	Base Grid Electricity Price in Startup Year (\$(2005)/ kWh)	0.081598698			

Price table drop-down menu

Fields define energy sources and prices

***Edit* button links to *Grid Price Structure* worksheet**

Tabs: Input_Sheet_Template / Replacement Costs / Capital Costs / Fuel Cell System / Solar PV / Peak Burner / Electrolyzer / Hydrogen Storage / AC Demand / Heat Demand

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Grid Price Structure Worksheet

Buttons: **Input Sheet**   **Calculate Sheet**

	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC
2	Data Year		2008																
3	**Usage Charges**				Rate (\$/kWh)	Rate Type	Rate % of Base Rate												
4	Summer Rates \$/kWh	Peak			0.12	4	147.1%												
5		Partial Peak			0.1	5	122.6%												
6		Off-Peak			0.06	6	73.5%												
7	Winter Rates \$/kWh	Peak				1	100.0%												
8		Partial Peak			0.07	2	85.8%												
9		Off-Peak			0.05	3	61.3%												
10																			
11	**Demand Charges**																		
12					Peak Hours		Partial Peak		Monthly Max										
13	Summer Rates \$/kW				11.43		2.63		5.85										
14	Winter Rates \$/kW						0.64		5.85										
15																			
16	**Rate Periods**				From		To		From D	To Day									
17	Summer Rate Period				5/30/2008		10/31/2008		151	305									
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.																		
20				Hour															
21	**Summer Rates Definitions**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
22	Sunday	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
23	Monday	6	6	6	6	6	6	6	6	5	5	5	5	4	4	4	4	4	4

Tabs: Input_Sheet_Template / Financial Summary / Results / Key Figures / Sensitivity_Analysis / Replacement Costs / **Grid Price Structure** / Fuel Cell System / Solar PV

The *Other Materials and Byproducts* sub-section allows you to define up to three non-energy input materials and three byproducts. Each element is added by first defining it using the drop-down menu and data entry fields, then clicking the *Add* button. Prices are automatically drawn from the lists on the *Non-Energy Material Prices* worksheet, or you can enter your own price by clicking the *Enter Price* button.

The *Byproduct* check box allows you to switch between materials consumed as process inputs (which incur costs) and materials produced as byproducts (which produce income/credits). When the box is unchecked, the material in the drop-down menu (cooling water, demineralized water, etc.) is labeled as a feed or utility, and the number you input is usage per kilowatt-hour total energy (combined electricity, heat, and hydrogen) generated by the technology configuration selected. When the box is checked, the material in the drop-down menu is labeled as a byproduct, and the number you input is production per kilowatt-hour generated.

You can add materials to the drop-down menu simply by going to the *Non-Energy Material Prices* worksheet and adding information for the new material in the rows underneath the existing information. This is also where you can modify the material prices if desired.

When deleting entries, it is critical to use the *Delete* button. Do not delete the rows using Excel's delete functionality. Also, be careful to choose the correct item from the *Delete* drop-down menu within the *Toolkit*.

Input_Sheet_Template Worksheet: Other Materials and Byproducts Sub-Section

When you have completed the *Other Materials and Byproducts* sub-section, continue down the *Input_Sheet_Template* worksheet and fill in the appropriate input (orange) cells in the *Other Variable Operating Costs* sub-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. Clicking the *Enter Specific Costs* button takes you to the *Replacement Costs* worksheet, where you can 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 MACRS schedule. The depreciation

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types and schedules can be changed in the *Capital Costs* section of the *Input_Sheet_Template* worksheet as described previously.

Defining Demand and Supply Profiles

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. See *Running the Model and Viewing Results* (page 17) to learn how to set the demand priority.

The model also uses a hydrogen demand profile—contained in the *H2 Demand* worksheet—based on the hourly hydrogen demand of a refueling station with an average daily demand of 85 kg per day. However, the model cannot be set to follow hydrogen load, i.e., meeting hydrogen demand cannot be set as the top priority. If PV is selected as part of the energy system, the model uses a solar availability profile to determine the amount of sun striking the specified PV surface each hour. If wind turbines are selected as part of the energy system, the model uses a wind speed profile to determine the power generated by the wind turbines each hour.

You can accept the default electricity, heat, and hydrogen demand profiles and the solar and wind availability 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) using the *Toolkit*.

Click the *Toolkit* button at the top of the *Input_Sheet_Template* worksheet, then click the *Import Demand Profiles* button within the *Toolkit*. 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). Select the desired file then click *OK*. The electricity and heat profiles from the file you selected automatically replace the profiles in the *AC Demand* and *Heat Demand* worksheets. The top left cell on each worksheet contains the name and path of the source file. 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 selected PV or wind turbines in the *PFD* worksheet, the model will automatically search for location-matching solar/wind availability profiles when you import an electricity/heat demand profile. If the paired demand and availability profiles are stored in the same folder on your computer or network, the model will import the availability profiles automatically when you select the demand profile, and there is nothing additional you must do. If they are not stored in the same folder, you will have the option

to search for them. If you do not have the paired profiles, you can download them at www.hydrogen.energy.gov/fc_power_analysis.html. If solar and/or wind profiles are already in the model, you will have the option to keep those profiles or import new ones. If no matching solar and/or wind profile is available, it is best to deselect PV and/or wind turbines in the *PFD* worksheet. See *Technical Support* on page 20 if you have questions about this function.

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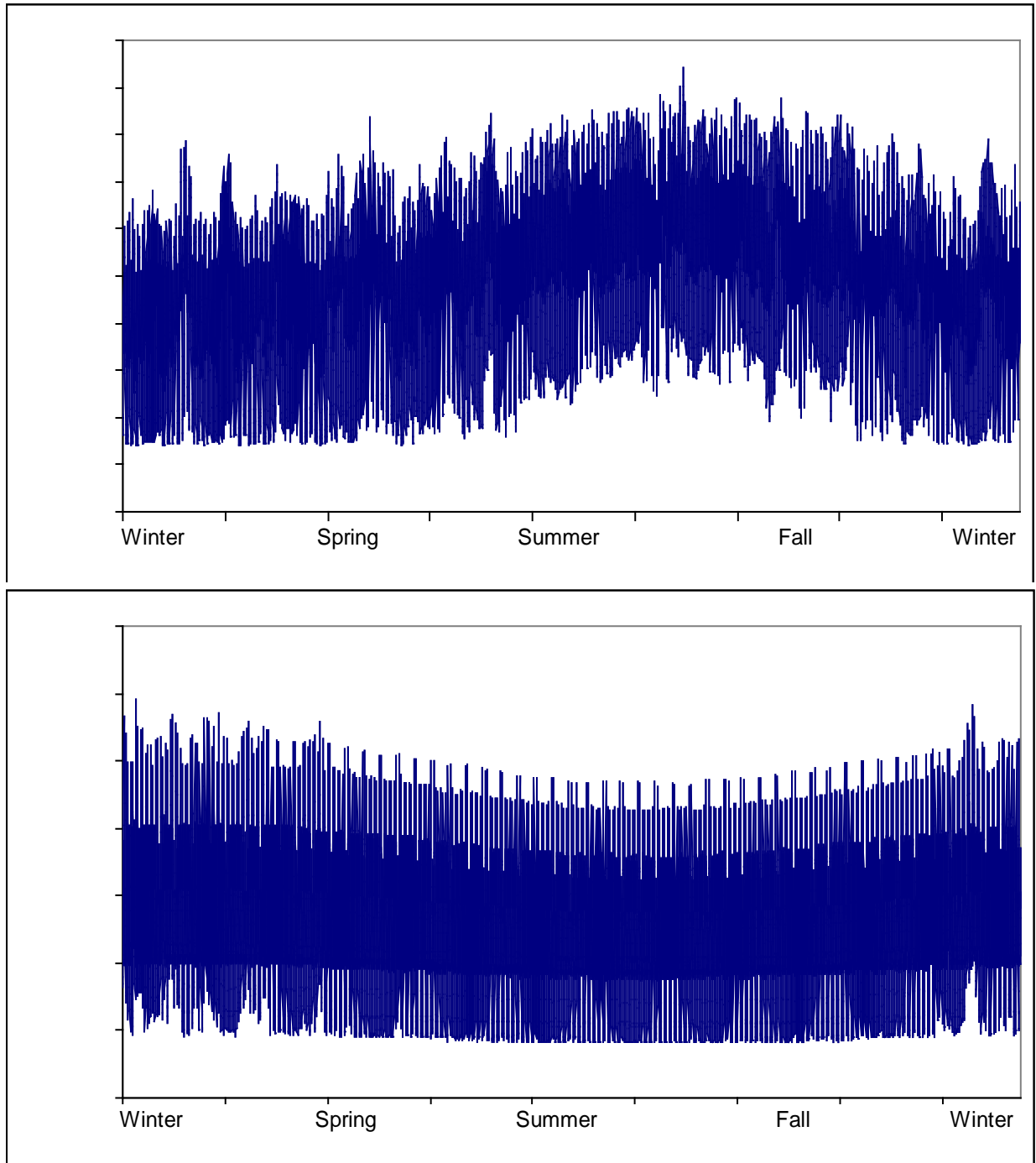
Toolkit

AC Demand Worksheet

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Running the Model and Viewing Results

Once you have entered all necessary information and defined your demand and supply profiles as described above, go to the buttons at the top of the *Input_Sheet_Template* worksheet. Select *Electricity* or *Heat* using the radio buttons. This determines the energy priority of your system. If you select *Electricity*, the system will make meeting electricity demand its top priority. If you select *Heat*, 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 system always makes meeting electricity demand its top priority.

Finally, click the *Run Hourly Energy Profile* button. 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. Once it has completed its hourly energy calculations, the model runs financial, energy, and emissions calculations based on the hourly energy results and the system and financial parameters you have chosen.

The hourly energy calculations can require a substantial amount of time to complete depending on the speed of your computer. After you have run the hourly energy calculations once, you can calculate different costs by using the *Calculate Cost* button at the top of the *Input_Sheet_Template* worksheet. This calculates costs based on the hourly energy calculations you have already run and requires no processing time. If you want to change characteristics of your hourly energy calculations, you will need to click the *Run Hourly Energy Profile* button again and allow the model to process the hourly calculations again.

Energy Profile and Cost Buttons in Input_Sheet_Template Worksheet

Assuming you used the *Run Hourly Energy Profile* button, the model will send you to the *MODEL* worksheet while it performs the hourly energy profile calculations. You do not need to do anything at this stage. 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 as described above, then prioritizes the energy sources used to meet the demand. A counter at the bottom of the worksheet shows the estimated modeling runtime.

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.

When the model is done calculating the hourly energy profile, it calculates financial, energy, and emissions results (again, no input is required from you at this stage) then sends you to the *Results* worksheet to view them. The *Results* worksheet includes an energy value solver, which 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.

Results Worksheet

Detailed results can be found in the *HOURLY RESULTS* worksheet. See the *Key Figures* and *Financial Summary* worksheets for tabular and graphical result summaries.

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[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.

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Example Chart from Key Figures Worksheet

Financial Summary Worksheet

On the *Financial Summary* worksheet, 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. The text, equation, and graph below explain the baseline hydrogen cost calculation.

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 2.1.1) published at www.hydrogen.energy.gov/h2a_prod_studies.html. The H2A case study was scaled to various sizes to derive the cost correlation equation used in the FCPower Model. The figure below shows the cost of hydrogen production and compression, storage, and dispensing (CSD) for various hydrogen production capacities. The feedstock cost contribution to the total has been omitted because this value depends on the price of the feedstock as well as the production capacity.

The feedstock price contribution to the total cost of hydrogen is a constant ratio related to the process efficiency (assumed to be 68.5% on a LHV basis). The resulting correlation for the total cost of hydrogen for the SMR system is the following:

$$\text{Hydrogen cost (\$/kg)} = 60.458 \times (\text{kg/day } H_2)^{-0.4526} + \text{fuel price (\$/kWh)} \times 45.64$$

Cost correlation for baseline system hydrogen production and CSD without feedstock cost contribution
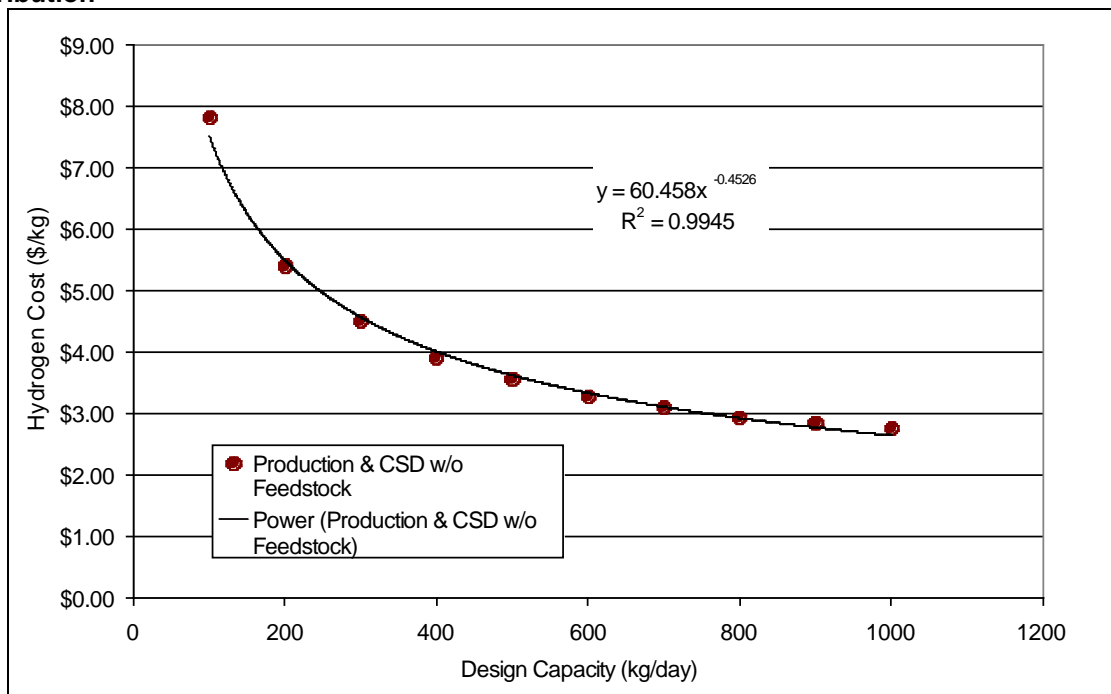
Technical Support

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

Appendix A: Designs of the FCPower Model Fuel Cell Systems

Introduction

The FCPower Model simulates the performance of two types of combined heat and power (CHP) systems: one based on molten carbonate fuel cells (MCFCs) and one based on phosphoric acid fuel cells (PAFCs). Each type of fuel cell can be integrated with other components to operate as a CHP system alone or as a combined heat, hydrogen, and power (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.

Both the MCFC and PAFC 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 appendix describes the basic operation of MCFCs and PAFCs 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.

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. 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.

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. $H_2 + \frac{1}{2}O_2 + CO_2$ (cathode) $\rightarrow H_2O + CO_2$ (anode)
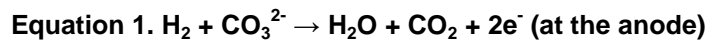
Besides the reaction involving H_2 and O_2 to produce H_2O, this equation shows a transfer of CO_2 from the cathode gas stream to the anode gas stream via the CO_3^{2-} ion. The need for CO_2 at the cathode requires that either CO_2 is transferred from the anode exit gas to the cathode inlet gas, CO_2 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).
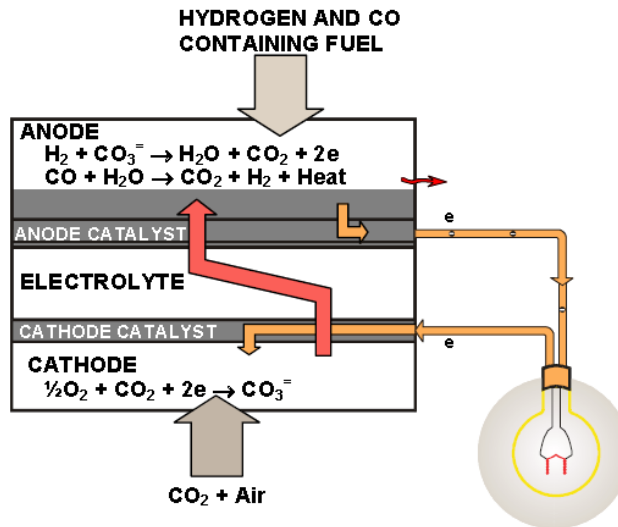
Figure 1. Schematic of MCFC operation [1]

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 16 and Table 1 at the end of this appendix 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

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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.
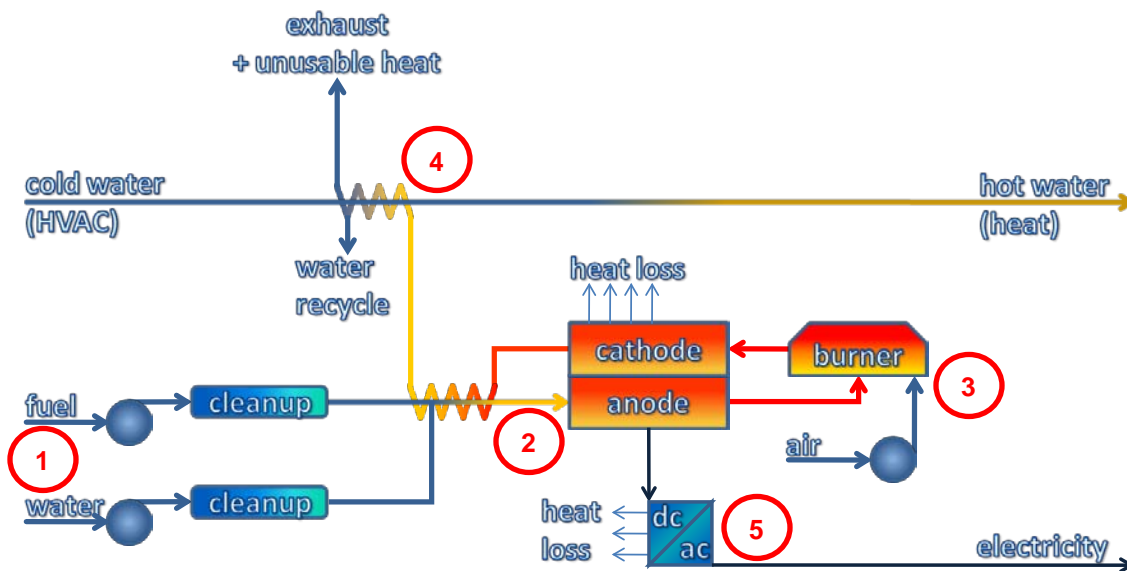
Figure 2. Schematic of modeled MCFC-CHP system

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 16, Table 2, and Table 3 at the end of this appendix 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 → CO_2 + H_2
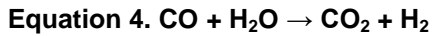
7. **Gas compression:** Most of the water is removed from the gas stream by chilling to ambient temperatures, and the gas stream is compressed to 150 psig as per standard industry practice for PSA. A multi-stage compressor is used with a maximum compression ratio of 2:1 per stage and intercoolers to 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.
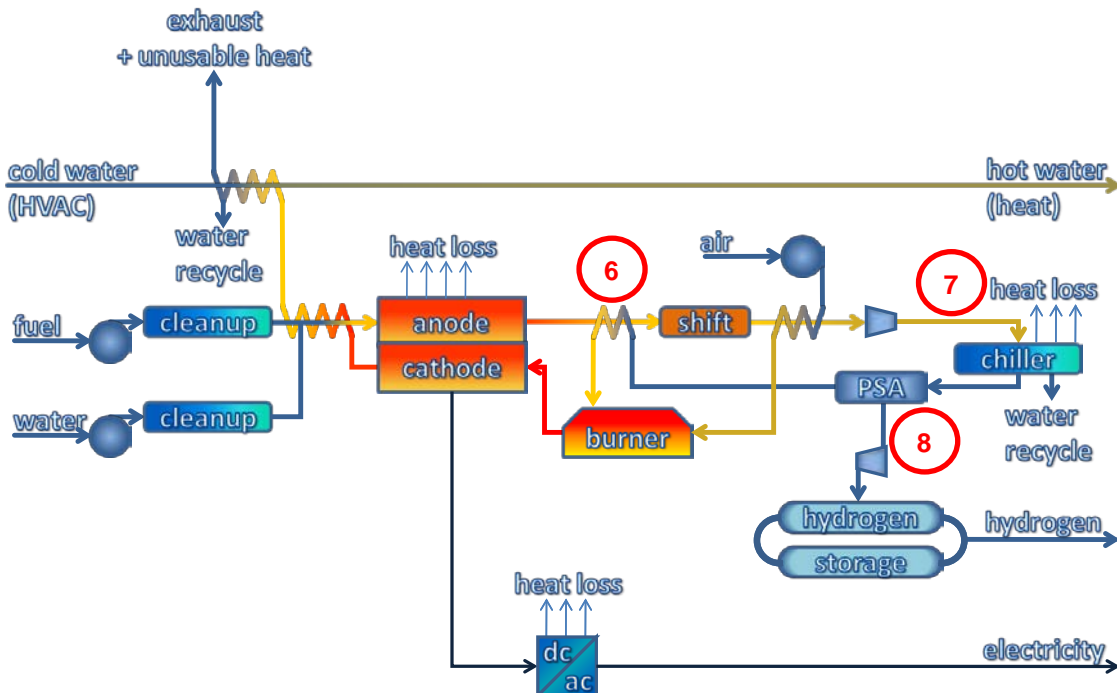
Figure 3. Schematic of modeled MCFC-CHHP system

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 mode of operation depends on the energy demands specified within the FCPower Model. If there is no hydrogen demand, the model's MCFC system operates in CHP mode. If there is hydrogen demand, the system operates in CHHP mode (and in CHHP hydrogen over-production mode if the hydrogen demand is above a certain threshold). 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 *Fuel Cell System* 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.

FUEL CELL SYSTEM SPECIFICATIONS		Descriptions		% of rated electrical	AC Efficiency	Total Efficiency
Maximum electricity output rating kW	200.0	AC average demand.		100%	45.7%	76.9%
Minimum electricity output rating kW	40.0			90%	46.0%	76.2%
Efficiency of H2 production (kW H2 produced / kW CHP heat reduced)	96%	Coefficient is derived from matching thermodynamic models.		80%	46.4%	75.2%
Efficiency of H2 over-production (kW H2 produced / additional kW fuel consumed	80%	Coefficient is derived from matching thermodynamic models.		70%	46.5%	74.1%
Maximum fraction of heat converteable to hydrogen	0.65	Coefficient is derived from matching thermodynamic models.		60%	46.4%	72.6%
Maximum amount of hydrogen over-production as fraction of H2 production	0.50	Coefficient is derived from matching thermodynamic models.		50%	46.1%	70.9%
				40%	44.7%	68.3%
OTHER VALUES				30%	41.9%	64.7%
AC response time	10%			20%	37.6%	58.8%
Hydrogen Response Time	10%			10%	29.4%	48.8%
Water for AC production kg/h-kWac	0.267			0%	13.7%	32.0%
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				

Figure 4. FCPower Model MCFC Fuel Cell System 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.

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.
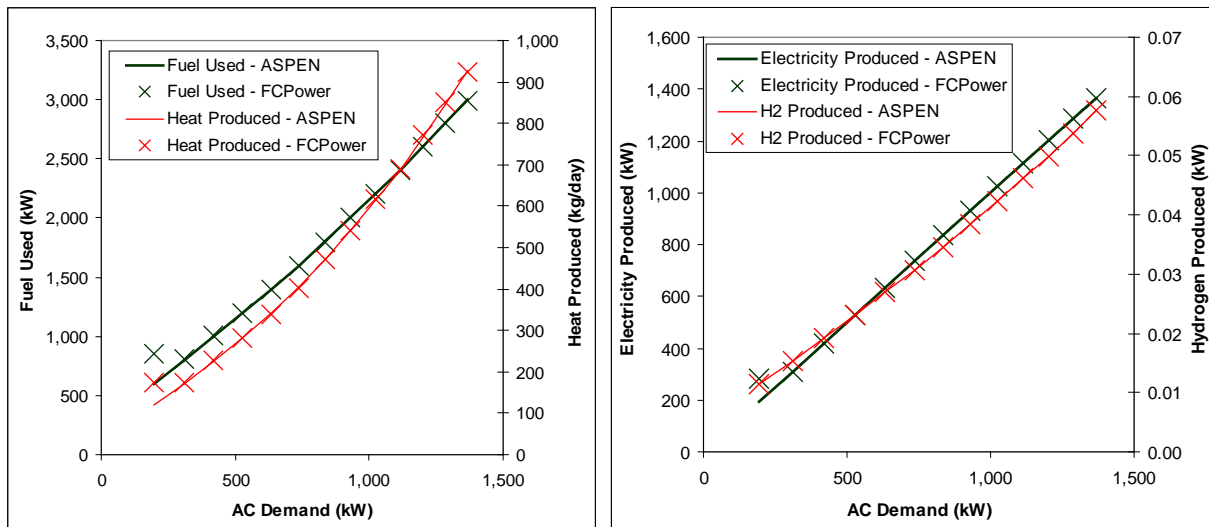
Figure 5. Correlation of ASPEN and FCPower Model results for MCFC-CHP system
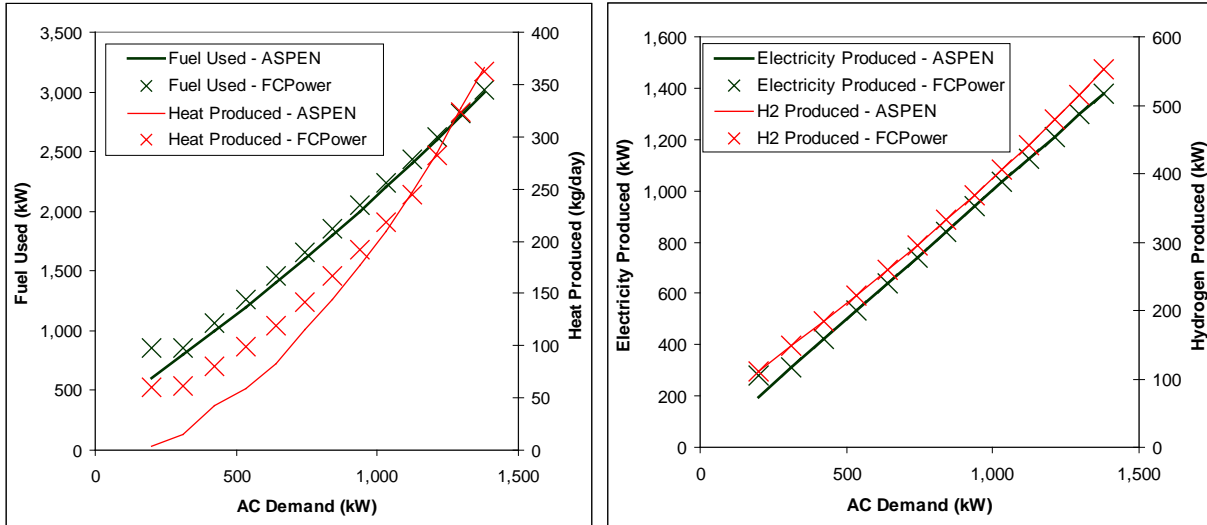
Figure 6. Correlation of ASPEN and FCPower Model results for MCFC-CHHP system

Figure 7. Correlation of ASPEN and FCPower Model results for MCFC-CHHP system, H$_2$ over-production

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. 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$_2$S). At lower temperatures, CO and H$_2$S bind to catalyst surfaces, masking the catalyst from use for hydrogen dissociation. This problem is reduced in PAFCs because they operate

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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.

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. $\frac{1}{2}O_2 + H_2 \rightarrow H_2O$
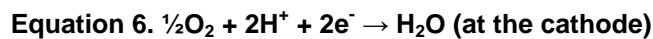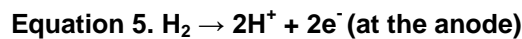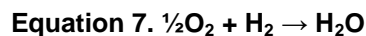
The electrochemical reactions occur on highly dispersed electro-catalyst particles supported on carbon black. Platinum or platinum alloys are used as the catalyst at both electrodes.
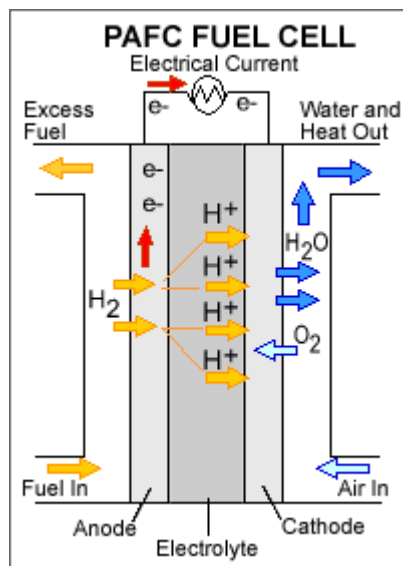
Figure 8. Schematic of PAFC operation [2]

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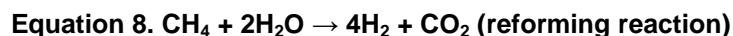
Equation 9. $4H_2 \rightarrow 8H^+ + 8e^-$ (anode reaction)

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)

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 17 and Table 4 at the end of this appendix 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 co-generation. 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.
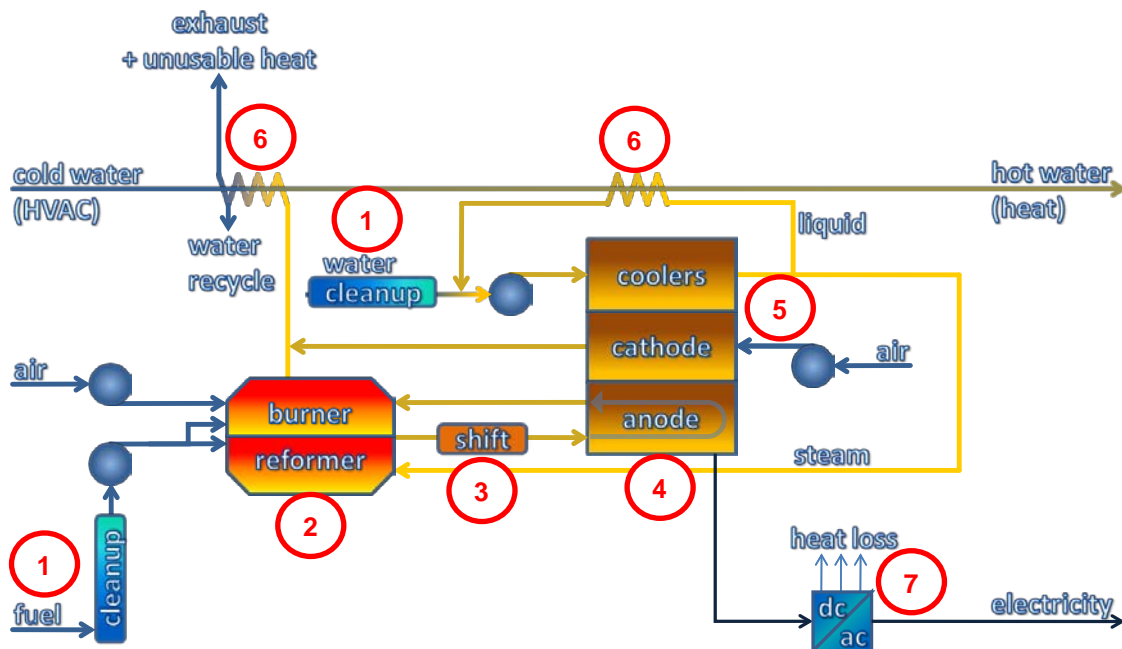
Figure 9. Schematic of modeled PAFC-CHP system

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 17 and Table 5 at the end of this appendix 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.
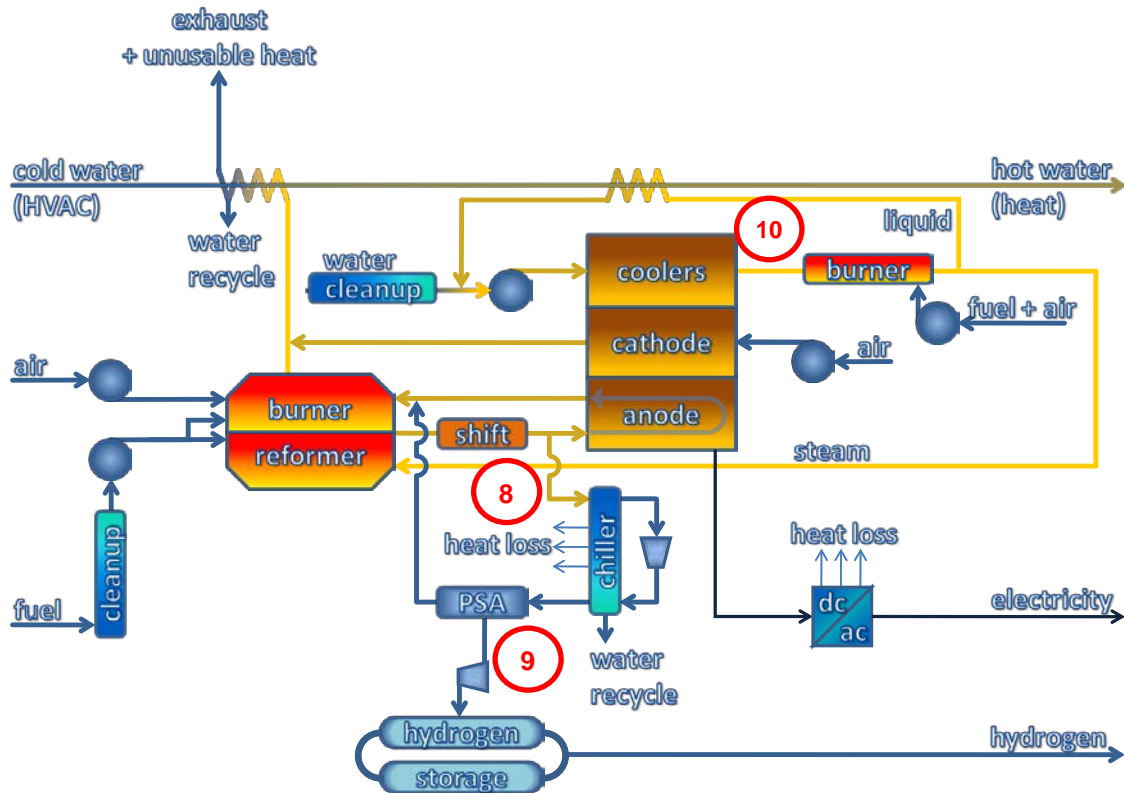
Figure 10. Schematic of modeled PAFC-CHHP system

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 mode of operation depends on the energy demands specified within the FCPower Model. If there is no hydrogen demand, the model's PAFC system operates in CHP mode. If there is hydrogen demand, the system operates in CHHP mode. 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 at the top of the *Input_Sheet_Template* worksheet.

Most of the fuel cell system parameters—found in the *Fuel Cell System* 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.

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FUEL CELL SYSTEM SPECIFICATIONS	Descriptions		System Performance Inputs		
				Electrical	Total Efficiency
Maximum electric output rating (kW)	200	Rated power output of the fuel cell system	% Rated Power	Efficiency LHV	LHV
			100%	37.44%	65.98%
Minimum electric output rating (kW)	80		90%	37.67%	64.98%
Reformer oversize factor	1.20	Must be >= 1.0	80%	37.69%	63.70%
Efficiency of hydrogen co-production (kW H2 output / kW additional fuel used)	0.86	Default value based on Aspen modeling			
Heat de-rating from H2 co-production (kW reduction in usable heat output/kW H2 produced)	0.11	Default value based on Aspen modeling	70%	37.50%	62.04%
Hydrogen purification auxiliaries (kWac/kWh2)	0.0620		60%	36.93%	59.85%
			50%	35.89%	56.93%
			40%	34.05%	52.92%
OTHER VALUES			30%	31.40%	48.00%
AC response time	100%		20%	26.90%	40.90%
Hydrogen response time	100%		10%	20.30%	31.00%
Water for AC production (kg/h-kWac)	0.540	Assuming no exhaust condensing.	0%	10.50%	17.50%
Water for H2 production (kg/h-kWh2)	0.059	Assuming no exhaust condensing.			

Figure 11. FCPower Model PAFC Fuel Cell System 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.

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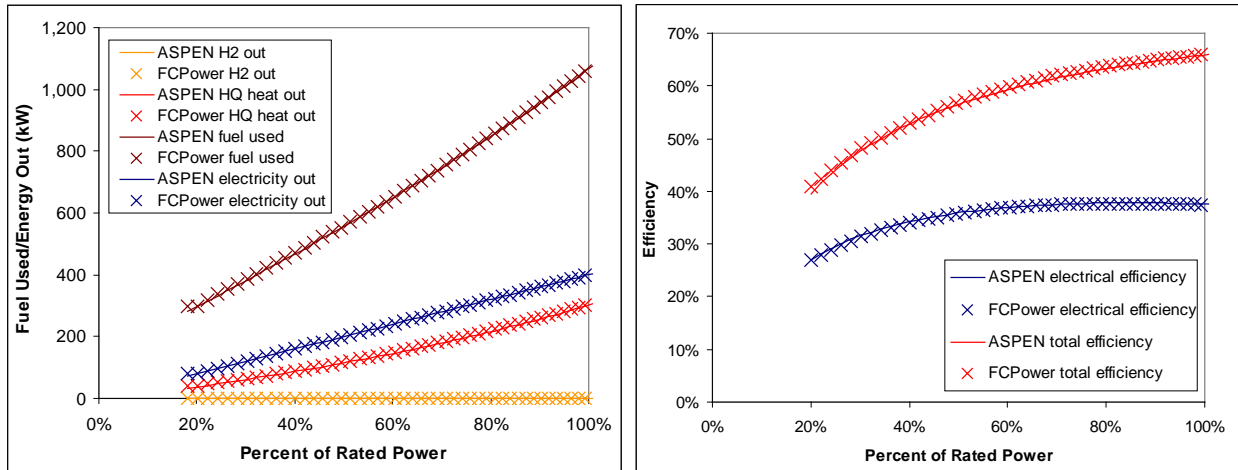
Figure 12. Correlation of ASPEN and FCPower Model results for PAFC-CHP system

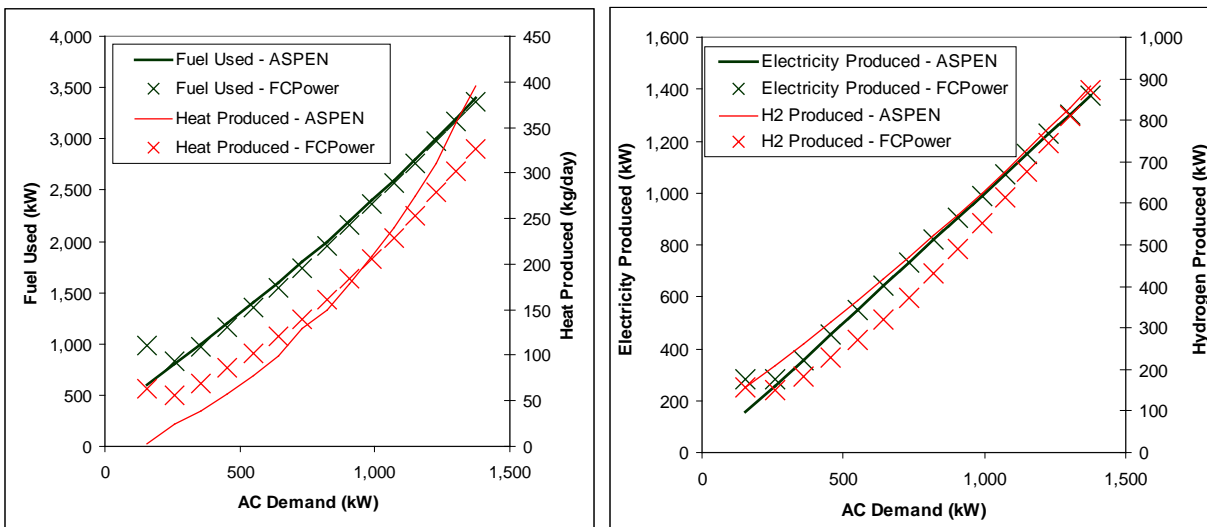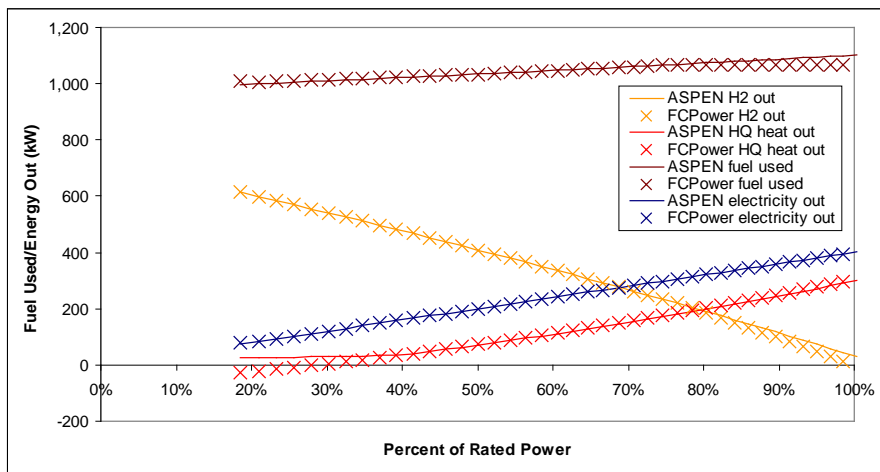**Figure 13. Correlation of ASPEN and FCPower Model results for PAFC-CHHP system**

FCPower Model Energy Balance

Like the detailed ASPEN models, the FCPower Model meets system energy balance requirements. Figure 14 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
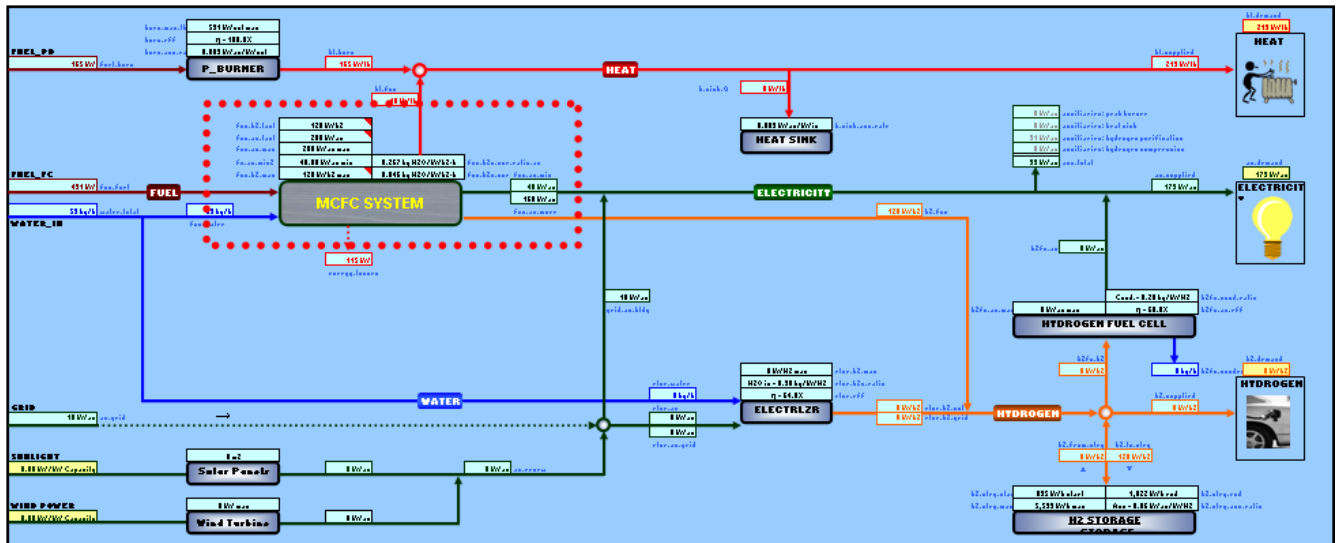
Figure 14. FCPower Model hourly energy model, for fuel cell energy balance example

An energy balance calculation also can be performed for the entire system (Figure 15). 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

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

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.
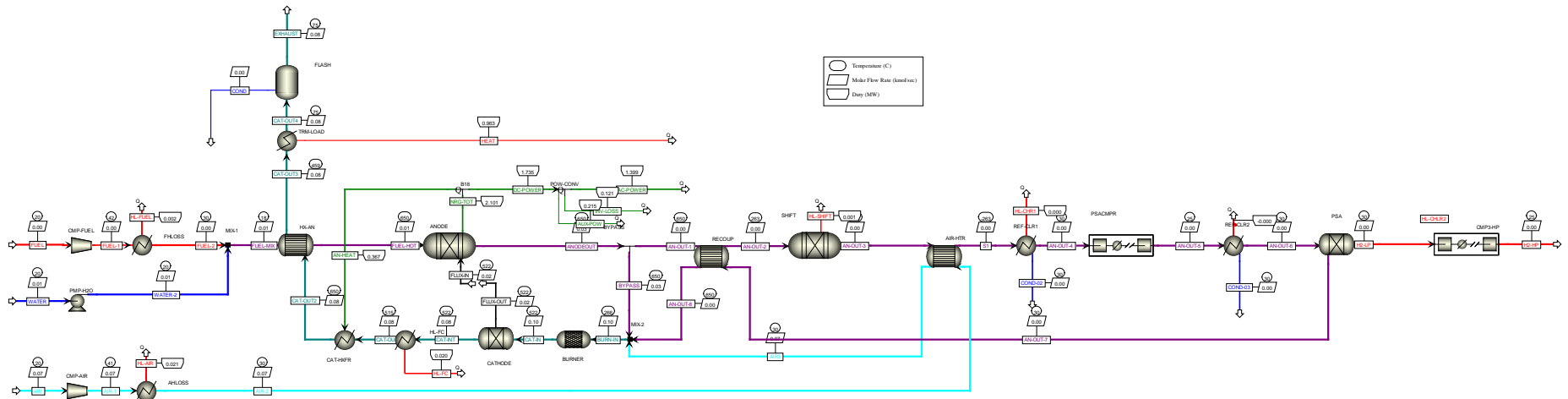
Figure 16. MCFC ASPEN process flow diagram

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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	O2
CO	0	0	0	0	0	0	0	0	0	0	0.00E+00	0	O
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	N2
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	O
CO	0	0	0	0	0	0	0	0	0	0	0.00E+00	0	O
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	N2
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
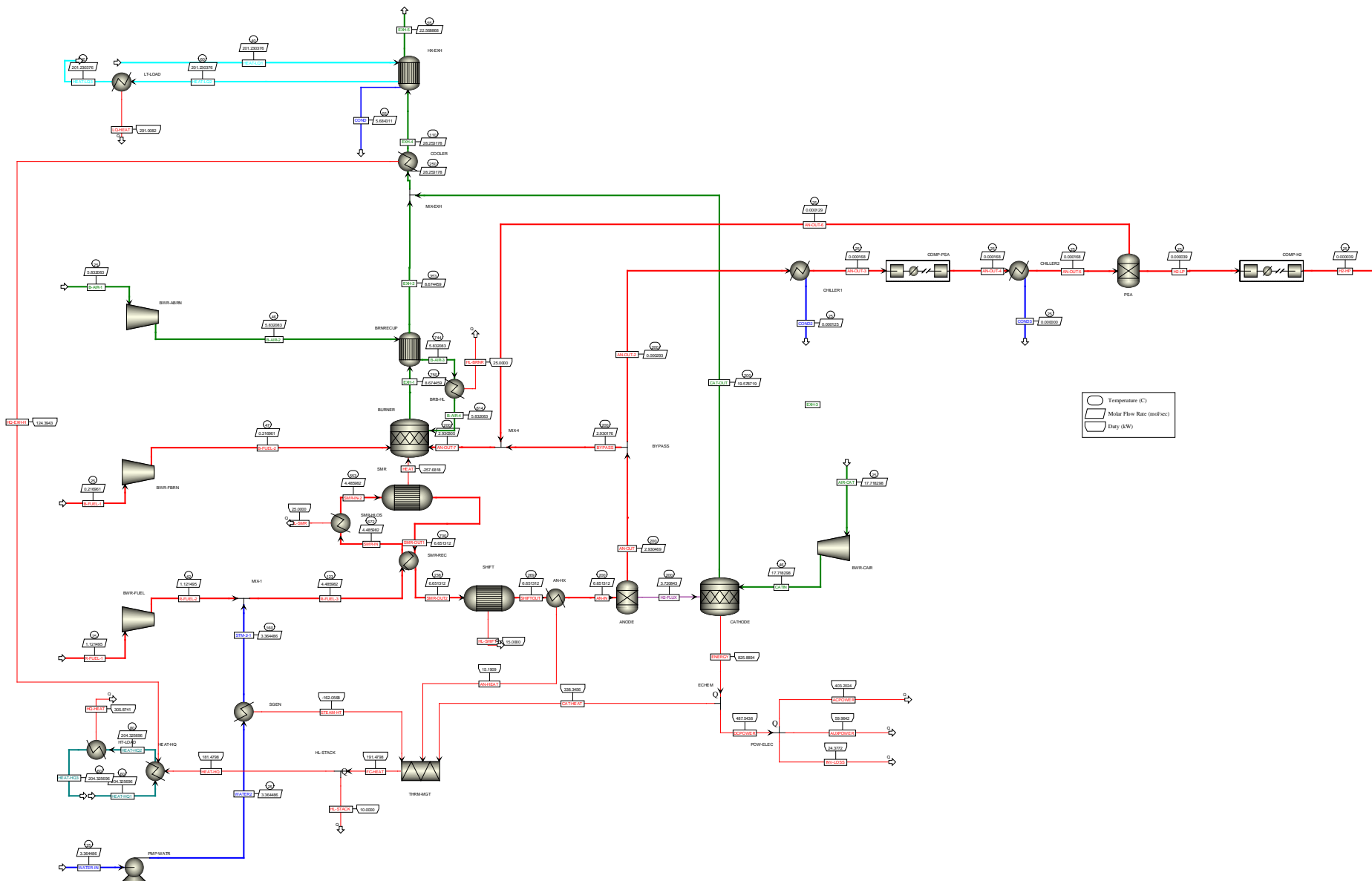
Figure 17. PAFC ASPEN process flow diagram

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

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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

References

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2. U.S. Department of Energy. 2009. Hydrogen, Fuel Cells and Infrastructure Technologies Program Web site: Types of Fuel Cells, Phosphoric Acid Fuel Cells. www.eere.energy.gov/hydrogenandfuelcells/fuelcells/fc_types.html#phosphoric. Accessed August 2009.

Appendix B: FCPower Model Case Studies

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 be installed in 2010 and will operate for 20 years. Dollar amounts are shown in 2005 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 and the alternative refueling infrastructure tax credit.

A 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 [1]. 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 [2,3]. 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.

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 18) [2,4–7]. 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.
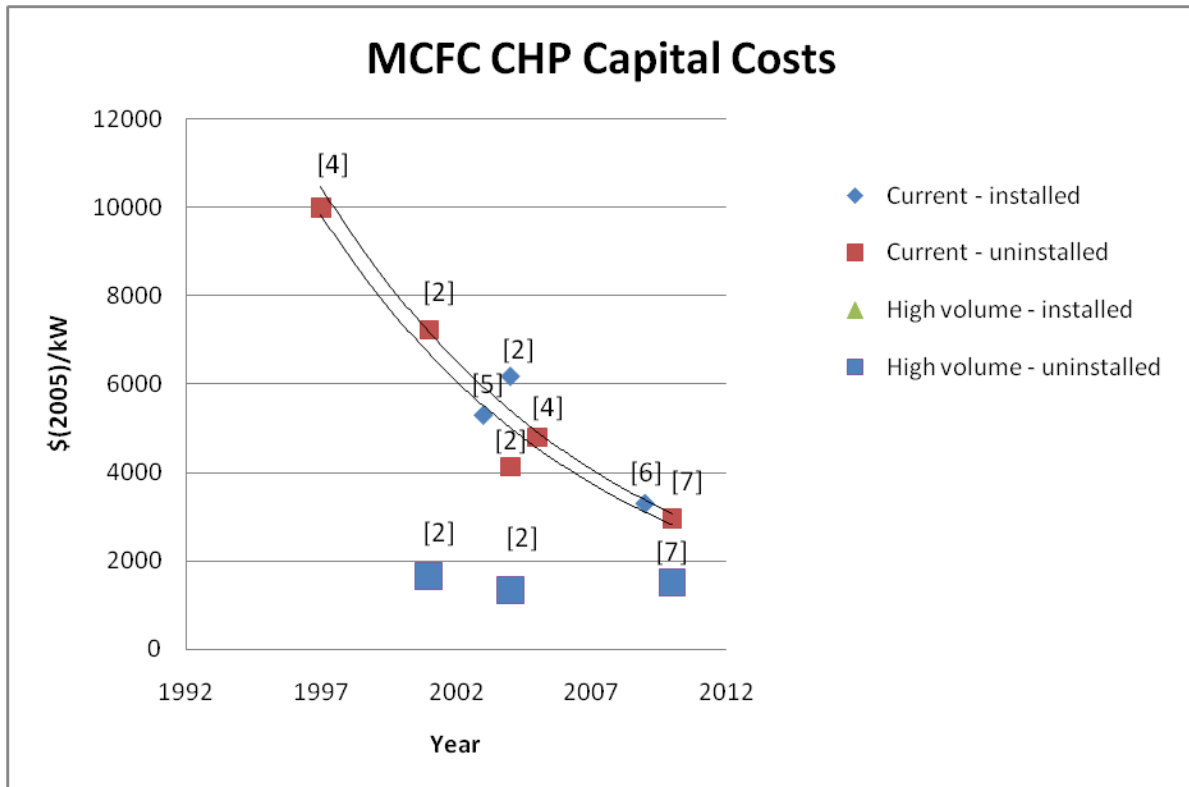

Figure 18. Collected cost information for MCFC CHP plants

Equation 13. y = 15,908e$^{-0.096x}$

Equation 14. x = year - 1992

Equation 13 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 14. It has an r-squared fit to the data of 0.95. The costs for the case study represent how costs might develop but prior to true economy of scale from high levels of production. With that in mind, an average value between the 2010 current uninstalled cost and a predicted 2010 mass-production cost was used for the CHP portion of the fuel cell system to represent a slightly more mature technology. 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 $(2005)2,200/kW fuel cell rated AC power. Hydrogen production and purification equipment uninstalled costs were estimated at approximately $(2005)603/kW fuel cell rated AC power. Total CHHP system uninstalled direct capital cost was approximately $(2005)2,800/kW. Installation was estimated to be 20% of the equipment cost. The installation factor of 1.2 is slightly higher than the PAFC system due to higher-temperature balance-of-plant equipment needed and a slightly more complicated system [2,4]. Indirect costs are 25% of the installed equipment cost. Installation and indirect costs are approximately $(2005)1,400/kW for a total installed capital cost of the fuel cell and hydrogen purification system (not including CSD) of $4,200/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 [8]. 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 8% of the total fuel cell system capital cost every 2 years due to a short stack life [2,9]. 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 [1].

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. Thus, the alternative refueling infrastructure tax credit can be taken for the CSD installation. 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.

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 building simulation output from the NREL building systems model [10]. 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.

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 $0.097/kWh in the reference year (2005), which was the commercial electricity average rate for Los Angeles in 2008 (EIA Class of Ownership, Number of Consumers, Sales, Revenue, and Average Retail Price by State and Utility Table 7 for commercial electricity in the city of Los Angeles in 2008 de-escalated to 2005 dollars using the consumer price index.). 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 commercial natural gas rate for Los Angeles: $10.15/MMBtu.

Molten Carbonate Fuel Cell Case Study Results

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 6.

Table 6. Baseline system levelized energy costs (prior to installation of fuel cell)

Electricity (use and demand charges)	$258,929/year
Commercial natural gas	$80,989/year
Hydrogen (from forecourt SMR, $9.86/kg)	$291,254/year
Total baseline system energy cost per year	**$631,171/year**

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 and an additional 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 985 MWh (29,680 kg, 37%) are in the form of hydrogen. The total system efficiency is 68.3%. Table 7 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 7. 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	1,302,484	65
Fuel cell system heat	379,968	18
Hydrogen	984,957	100
	Supplementary Building Electricity and Heat (kWh)	Percent of Energy Type Supplied by Supplementary System
Supplementary electricity	703,555	35
Supplementary heat	1,724,760	82

Approximately 19% (304 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 6,250 psi.

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.

The hotel owner is eligible for the federal business energy tax credit as well as the California Self Generation Incentive Program (SGIP). However, for this case study, it is assumed that funding for the SGIP is not available in the construction year. Sensitivity analyses were performed with and without the SGIP to assess the potential advantage of waiting for funding to become available.

Table 8 shows the initial capital investment and federal tax credits taken for the installation. Indirect capital investment (site preparation, engineering, contingency, and permitting) totals $287,403.

Table 8. MCFC System Initial Investment and Credits

Direct capital investment (reference year, (2005)$)						
Major pieces/ systems of equipment	Baseline installed costs ($) (with indirect capital)	Depreciation type	Depreciation schedule (years)	Federal credit or incentive	Credit amount ($)	Total depreciable capital cost basis[1]
MCFC System (including hydrogen purification)	670,359	MACRS	5	Federal business energy tax credit	190,080	737,045
Auxiliary heater	0	MACRS	N/A			
Hydrogen compression, storage, and dispensing	520,929	MACRS	5	Federal alternative fuel refueling infrastructure credit	30,000	616,606
Total	1,191,288 (1,478,691)				220,080	1,353,651

1. Total depreciation basis includes indirect capital costs.

MCFC CHHP System Cash Flow

Figure 19 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 partial restacking of the fuel cell every 2 years. It is assumed that the compressors and dispensers will be replaced after 10 years at 30% of the initial cost for the entire CSD system. Figure 19 indicates that the project will break even after approximately 7 years.
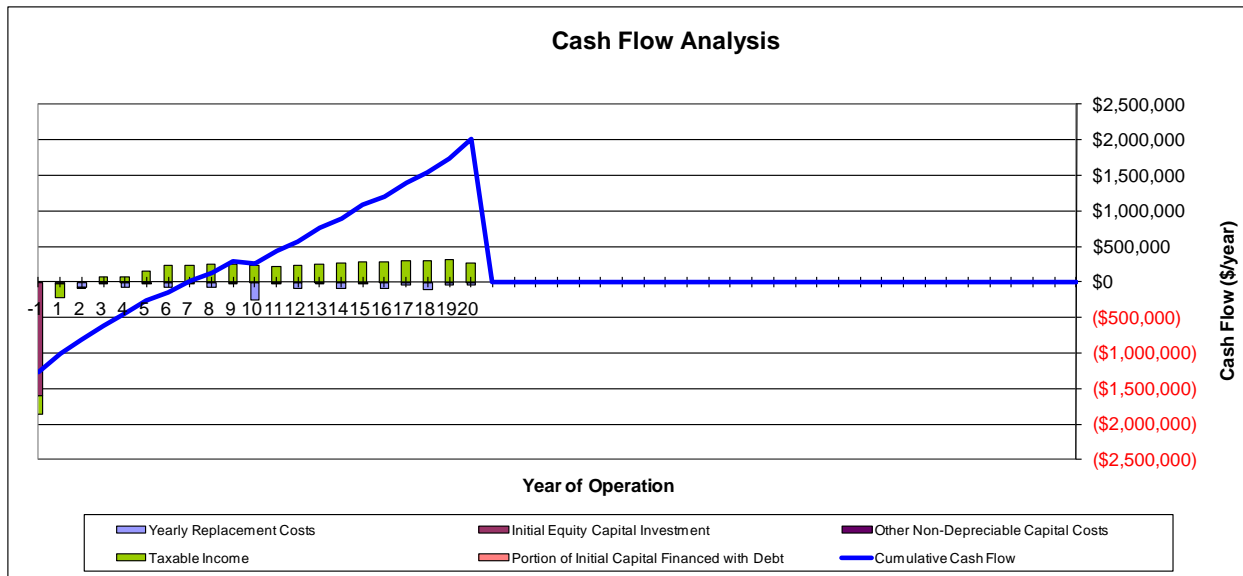
Figure 19. MCFC CHHP Key Yearly Expenditures and Revenue

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 $9.58/kg as dispensed. This compares favorably to the cost of hydrogen supplied by a forecourt SMR unit ($9.86/kg) for the baseline system. Table 9 shows the total annualized costs for the MCFC CHHP system.

Table 9. Total Annualized Costs for the MCFC CHHP Installation

Annualized costs	
Capital costs	$246,226
Decommissioning costs	$2,384
Fixed O&M	$87,234
Feedstock costs	$125,537
Other raw material costs	$0
Byproduct credits	-$1,635
Other variable costs (excluding supplementary electricity and heat)	$143
Supplementary electricity	$96,812
Supplementary heat	$63,207
Total	$619,910

The total annualized cost for the CHHP system is less than the energy costs for the baseline system of $631,171 shown in Table 6. This analysis indicates that the CHHP system could be a cost-effective alternative to conventional energy supply for the hotel.

Sensitivity Analysis

Sensitivity analyses were performed for three key cost elements for the CHHP system: the internal rate of return, depreciable capital cost, and fuel cost. The results, presented in terms of the levelized hydrogen cost, are shown in Figure 20.
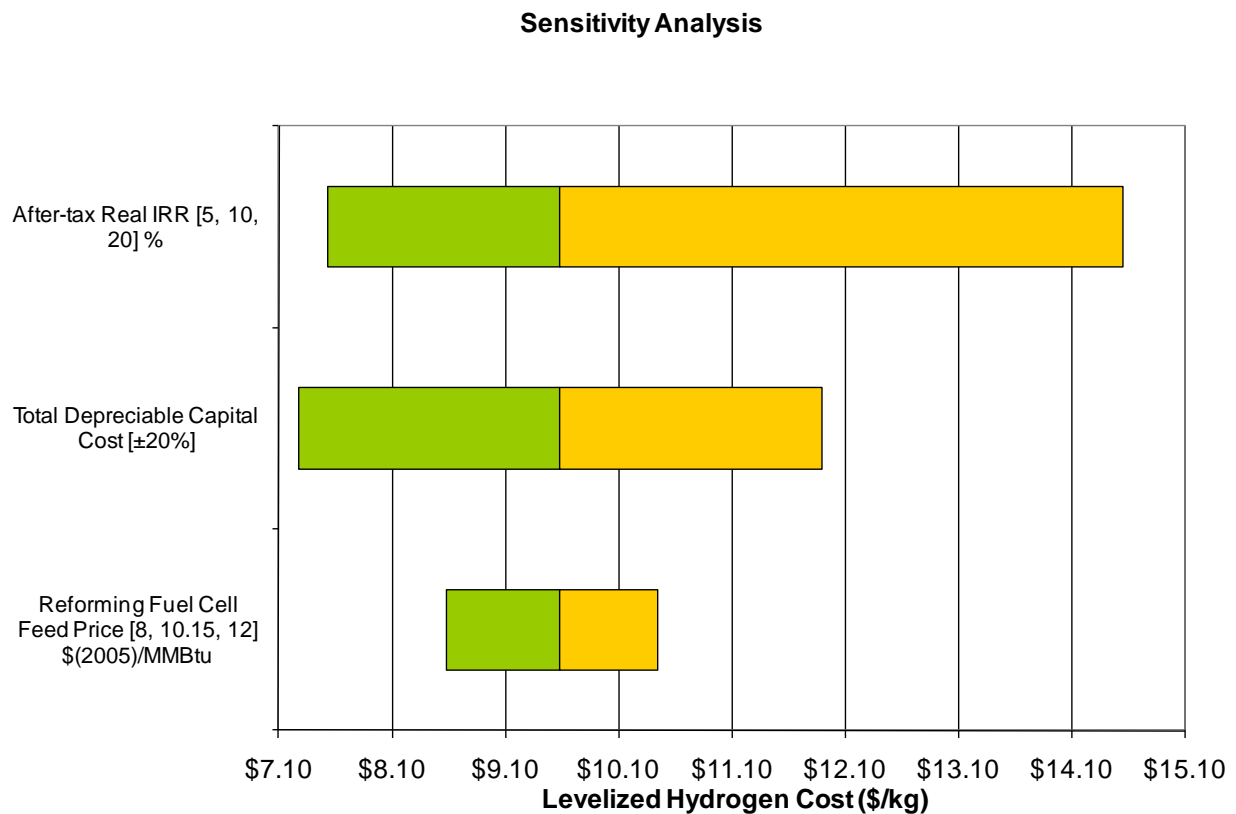
Sensitivity Analysis

Figure 20. Sensitivity analysis for the MCFC CHHP system key costs

The SGIP would amount to $500,000 for the proposed fuel cell system ($2.50/W x 200 kW), which is approximately 80% of the installed cost for the fuel cell and hydrogen purification system. Capital costs account for approximately 40% of the total annualized cost for the installation. Applying the SGIP credit would reduce the hydrogen cost to $7.04/kg (about 27%).

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 and the alternative refueling infrastructure 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 [1,11]. 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 [11]. 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. The EIA's commercial natural gas rate for California was used for the analysis. A full description of the PAFC system modeled for the FCPower Model is given in Appendix A.

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.

A fuel cell–based CHP system with co-production of hydrogen is modeled in the case study. The system, shown in the PFD tab of the FCPower Model spreadsheet, includes the fuel cell plant, PSA, additional burner, heat sink, and hydrogen storage for vehicle fueling. The fuel cell plant includes fuel cell stacks, natural gas fuel reformer, high-grade heat exchanger, water purification system, nitrogen purge system, cooling system for excess heat, and power conversion equipment for tie-in to the building, which would include an electrical transformer for grid-parallel design. The burner is assumed to be the existing facility's space heating and hot water system. Therefore, no additional costs are associated with the burner. The hydrogen storage unit includes CSD using low-pressure storage and high-pressure cascade storage with a dispenser unit. It is assumed that the hydrogen will be used to fuel passenger vehicles for use on public roads; thus, the alternative refueling infrastructure tax credit may be taken.

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 21 shows cost data collected from a number of sources [2,4,5,11–16]. 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 [1,2,4,15]. 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 21, 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.
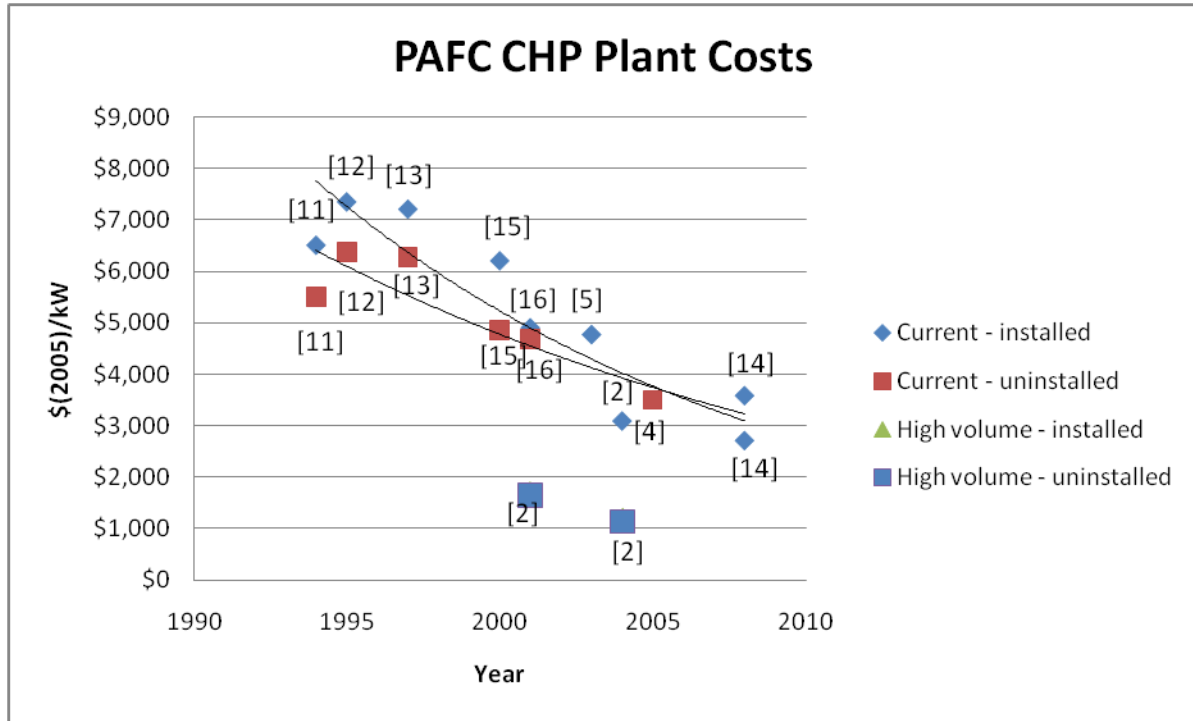
Figure 21. Collected cost information for PAFC CHP plants

For the case study, costs for a PAFC CHP plant were estimated for 2010 using a prediction of the current installed plant cost (Equation 15). The CHP equipment costs (excluding fuel reformer and PSA) were assumed to be 60% of the installed cost found in Equation 15. This was done to portray a slightly better established technology that has not reached mass-production levels.

Equation 15. y = 8,841e$^{-0.066x}$

Equation 16. x = year - 1992

In Equation 15, y is the total direct and indirect capital cost in $(2005)/kW and x is calculated as per Equation 16. The costs for the case study represent how costs might develop but prior to true economy of scale from high levels of production. Uninstalled costs for the fuel cell plant were estimated to be $(2005)1,700/kW and the natural gas reformer cost was estimated $525/kW of fuel cell AC output [14]. The PSA unit 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). Installation and indirect costs represented 43% of the uninstalled costs.

Literature values typically include the entire chain. Therefore, the separation of direct capital and indirect was estimated and then split into 9% for site preparation, 7% engineering and design, 5% project contingency, and 3% permitting fees on the fuel cell system facility. The values for project contingency and permitting fees were derived from other H2A case studies [8]. Values for the separate hydrogen storage and dispensing unit are discussed below.

Operating and maintenance values have been estimated as follows: replacement time and costs are based at 5 years [1,2,4,5,14] and 21%, estimated, of PAFC installed capital cost [1]. Fixed maintenance and repairs were estimated at 4% yearly, and variable unplanned replacement 1.5% yearly, of the total installed fuel cell system capital cost, estimated using figures from an EPRI report and U.S. Department of Defense project [1,13]. Other materials costs—such as nitrogen, resin, and charcoal—are expected to be low, 0%–1% of direct capital cost; 1% was used in the case study.

Hydrogen Storage and Dispensing

Despite the scatter in the plot, the following equation can be used to calculate the required dispensers, based on the daily capacity of the refueling station. Table 10 shows dispenser calculations.

Equation 17. Dispensers = Daily Capacity ÷ (305.85 × Daily Capacity$^{0.0763}$)

Table 10. Refueling Station Dispenser Calculations

Daily Average Demand (kg/day)	Demand Multiplier	Daily Demand (kg/day)	H2 per Fill (kg)	Daily Cars	Fill Hoses	Dispensers	Mult.	Hose Flow Rate (kg/min)	Fill Time (min)	Linger Time	Occupied Time (min)	Peak Hour Fraction	Peak Flow (kg/hr)	Peak Fills (fills/hr)	Occupied Fraction	Predicted Dispensers
300	1.19	357	4.5	79	2	1	300	1.67	2.7	3.0	5.7	7.80%	27.8	6.2	29.4%	1
400	1.19	476	4.5	106	2	1	400	1.67	2.7	3.0	5.7	7.80%	37.1	8.3	39.2%	1
600	1.19	714	4.5	159	2	1	600	1.67	2.7	3.0	5.7	7.80%	55.7	12.4	58.7%	1
800	1.19	952	4.5	212	4	2	400	1.67	2.7	3.0	5.7	7.80%	74.3	16.5	39.2%	2
1000	1.19	1190	4.5	264	4	2	500	1.67	2.7	3.0	5.7	7.80%	92.8	20.6	48.9%	2
1200	1.19	1428	4.5	317	4	2	600	1.67	2.7	3.0	5.7	7.80%	111.4	24.8	58.7%	2
1400	1.19	1666	4.5	370	6	3	467	1.67	2.7	3.0	5.7	7.80%	129.9	28.9	45.7%	3
1600	1.19	1904	4.5	423	6	3	533	1.67	2.7	3.0	5.7	7.80%	148.5	33.0	52.2%	3
1800	1.19	2142	4.5	476	6	3	600	1.67	2.7	3.0	5.7	7.80%	167.1	37.1	58.7%	3
2000	1.19	2380	4.5	529	8	4	500	1.67	2.7	3.0	5.7	7.80%	185.6	41.3	48.9%	4
2200	1.19	2618	4.5	582	8	4	550	1.67	2.7	3.0	5.7	7.80%	204.2	45.4	53.8%	4
2400	1.19	2856	4.5	635	8	4	600	1.67	2.7	3.0	5.7	7.80%	222.8	49.5	58.7%	4
2600	1.19	3094	4.5	688	10	5	520	1.67	2.7	3.0	5.7	7.80%	241.3	53.6	50.9%	5
2800	1.19	3332	4.5	740	10	5	560	1.67	2.7	3.0	5.7	7.80%	259.9	57.8	54.8%	5
3000	1.19	3570	4.5	793	10	5	600	1.67	2.7	3.0	5.7	7.80%	278.5	61.9	58.7%	5
3200	1.19	3808	4.5	846	12	6	533	1.67	2.7	3.0	5.7	7.80%	297.0	66.0	52.2%	6
3400	1.19	4046	4.5	899	12	6	567	1.67	2.7	3.0	5.7	7.80%	315.6	70.1	55.5%	6
3600	1.19	4284	4.5	952	12	6	600	1.67	2.7	3.0	5.7	7.80%	334.2	74.3	58.7%	6
3800	1.19	4522	4.5	1005	14	7	543	1.67	2.7	3.0	5.7	7.80%	352.7	78.4	53.1%	7
4000	1.19	4760	4.5	1058	14	7	571	1.67	2.7	3.0	5.7	7.80%	371.3	82.5	55.9%	7
4200	1.19	4998	4.5	1111	14	7	600	1.67	2.7	3.0	5.7	7.80%	389.8	86.6	58.7%	7
4400	1.19	5236	4.5	1164	16	8	550	1.67	2.7	3.0	5.7	7.80%	408.4	90.8	53.8%	8
4600	1.19	5474	4.5	1216	16	8	575	1.67	2.7	3.0	5.7	7.80%	427.0	94.9	56.3%	8
4800	1.19	5712	4.5	1269	16	8	600	1.67	2.7	3.0	5.7	7.80%	445.5	99.0	58.7%	8

Load Profile and Fuel Cell Specification

The case study models a large hotel in Los Angeles. 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 [10]. 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 226 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.

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 $0.097/kWh in the reference year (2005), which was the commercial electricity average rate for Los Angeles in 2008 (EIA Class of Ownership, Number of Consumers, Sales, Revenue, and Average Retail Price by State and Utility Table 7 for commercial electricity in the city of Los Angeles in 2008 de-escalated to 2005 dollars using the consumer price index.). 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 commercial natural gas rate for Los Angeles: $10.15/MMBtu.

Phosphoric Acid Fuel Cell Case Study Results

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 11.

Table 11. Baseline system levelized energy costs (prior to installation of fuel cell)

Electricity (use and demand charges)	$258,929/year
Commercial natural gas	$80,989/year
Hydrogen (from forecourt SMR system, $5.91/kg)	$729,940/year
Total baseline system energy cost per year	**$1,069,857/year**

CHHP System Energy Supply

The PAFC CHHP system supplies a yearly total of 6,126 MWh of energy to the building in the form of electricity, heat, and hydrogen. No electricity is sold to the utility. Of the total energy, 1,185 MWh (19%) are in the form of electricity, 827 MWh (13%) are in the form of useful heat, and the remaining 4,114 MWh (123,437 kg, 67%) are in the form of hydrogen. The total system efficiency is 65.7% Table 12 shows the energy supplied by the fuel cell and supplementary electricity and heat.

Table 12. PAFC System Building Energy Supply

	System Energy to Building (kWh)	Percent of Energy Type Supplied by the CHHP System
System net electricity to building	1,185,437	59
Fuel cell system heat	826,939	39
Hydrogen	4,114,076 (123,437 kg)	100
	Supplementary Building Electricity and Heat (kWh)	Percent of Energy Type Supplied by Supplementary Systems
Supplementary electricity	820,603	41
Supplementary heat	1,277,789	61
Building energy supply annual total	8,224,844	

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.

The hotel owner is eligible for the federal business energy tax credit as well as the California SGIP. However, for this case study, it is assumed that funding for the SGIP is not available in the construction year. Sensitivity analyses were performed with and without the SGIP to assess the potential advantage of waiting for funding to become available. Table 13 shows the initial capital investment and federal tax credits taken for the installation. Indirect capital investment (site preparation, engineering, contingency, and permitting) totals $446,535

Table 13. PAFC System Initial Investment and Credits

Direct capital investment (reference year, (2005)\$)						
Major pieces/ systems of equipment	**Baseline installed costs (\$) (total initial capital investment)**	**Depreciation type**	**Depreciation schedule (years)**	**Federal credit or incentive**	**Credit amount (\$)**	**Total depreciable capital cost basis[1]**
PAFC System (including hydrogen purification)	929,560	MACRS	5	Federal business energy tax credit	139,587	1,078,111
Auxiliary heater	0	MACRS	N/A			
Hydrogen compression, storage, and dispensing	971,481	MACRS	5	Federal alternative fuel refueling infrastructure credit	30,000	1,169,672
Total	1,901,041 (2,347,576)				169,587	2,247,782

1. Total depreciation basis includes indirect capital costs.

PAFC CHHP System Cash Flow

Figure 22 shows key expenditures and cash flow for the PAFC 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 partial restacking of the fuel cell every 5 years. It is assumed that the reformer will require replacement of the catalyst every 5 years and refurbishment every 10 years. Compressors and dispensers will be replaced after 10 years at 30% of the initial cost for the entire CSD system. Figure 22 indicates that the project will break even after approximately 7 years.
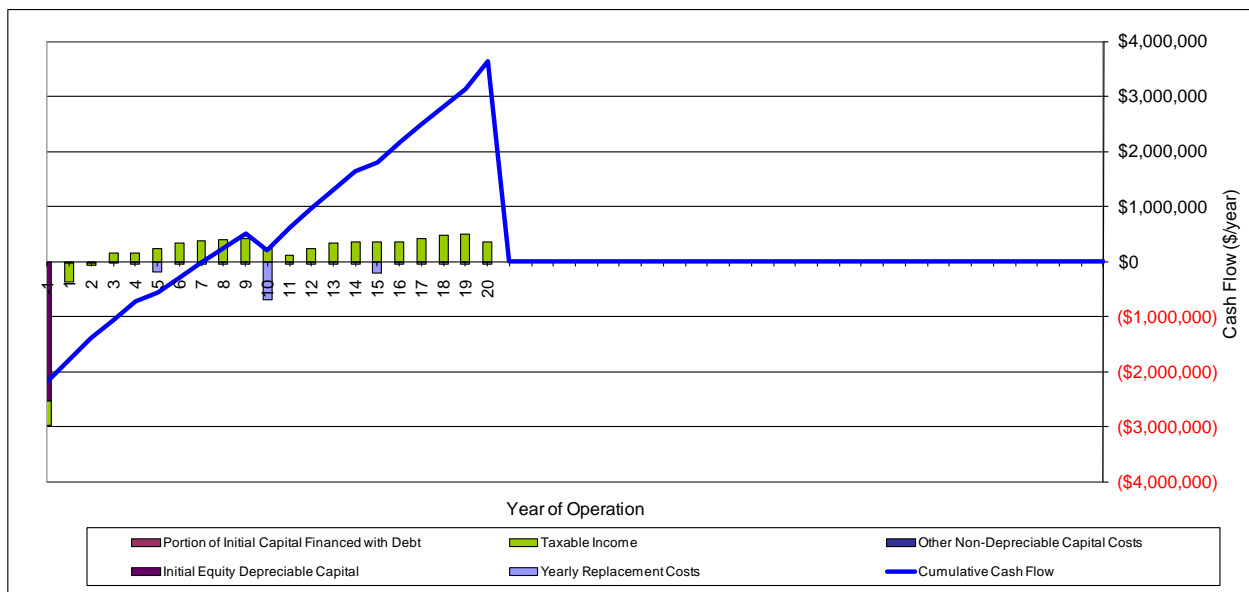

Figure 22. PAFC CHHP Key Yearly Expenditures and Revenue

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 $5.49/kg as dispensed. This compares favorably to the cost of hydrogen supplied by a forecourt SMR unit ($5.91/kg) for the baseline system. Table 14 shows the total annualized costs for the PAFC CHHP system

Table 14. Total Annualized Costs for the PAFC CHHP Installation

Annualized costs	
Capital costs	$383,731
Decommissioning costs	$3,965
Fixed O&M	$134,758
Feedstock costs	$312,279
Other raw material costs	$8,974
Byproduct credits	$0
Other variable costs (not including supplementary electricity and heat)	$443
Supplementary electricity	$111,039
Supplementary heat	$0
Total	**$955,189**

The total annualized cost for the CHHP system is less than the energy costs for the baseline system of $1,069,857 shown in Table 11. This analysis indicates that the CHHP system could be a cost-effective alternative to conventional energy supply for the hotel.

Sensitivity Analysis

Sensitivity analyses were performed for three key cost elements for the CHHP system: the internal rate of return, depreciable capital cost, and fuel cost. The results, presented in terms of the levelized hydrogen cost, are shown in Figure 23.
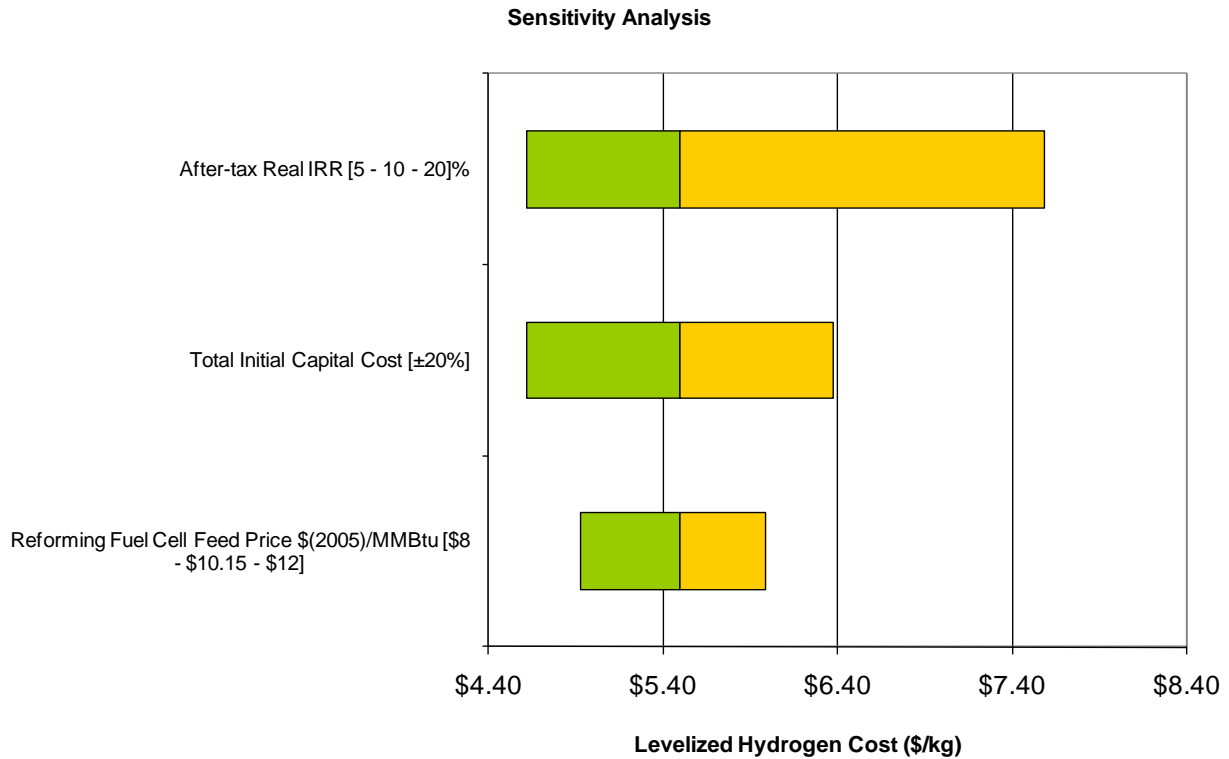
Sensitivity Analysis

Figure 23. Sensitivity analysis for the PAFC CHHP system key costs

The SGIP would amount to $500,000 for the proposed fuel cell system ($2.50/W x 200 kW), which is approximately 54% of the installed cost for the fuel cell and hydrogen purification system. Capital costs account for approximately 46% of the total annualized cost for the installation. Applying the SGIP credit would reduce the hydrogen cost to $4.89/kg (about 17%).

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