



# Fuel Cell Power Model for CHP and CHHP Economics and Performance Analysis



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**&**

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# Outline

**Fuel cell  
basics**

**Fuel Cell  
Power Model  
introduction**

**Dairy case  
study/tutorial**

Costs and incentive values shown in this presentation were developed for demonstration purpose only.



# Fuel Cell Basics

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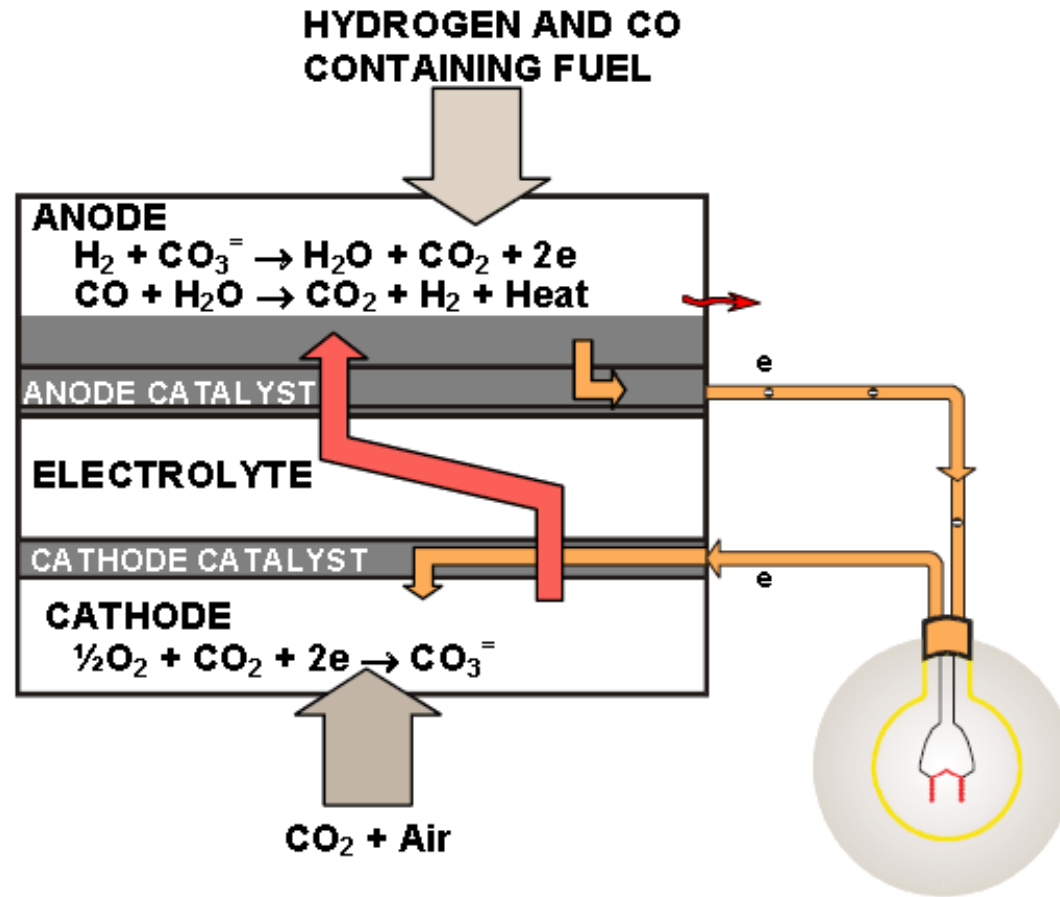


# Fuel Cell General Types

- **Proton Exchange (PEM)**
  - membrane fuel: H<sub>2</sub>
  - system fuel: hydrogen, low CO syngas
- **Phosphoric Acid (PAFC)**
  - membrane fuel: H<sub>2</sub>
  - system fuel: syngas
- **Solid Oxide (SOFC)**
  - membrane fuel: H<sub>2</sub>, CO, CH<sub>4</sub>
- **Molten Carbonate (MCFC)**
  - membrane fuel: H<sub>2</sub>, CO, CH<sub>4</sub>
- **Others:**
  - direct methanol (DMFC)
  - alkaline (AFC)

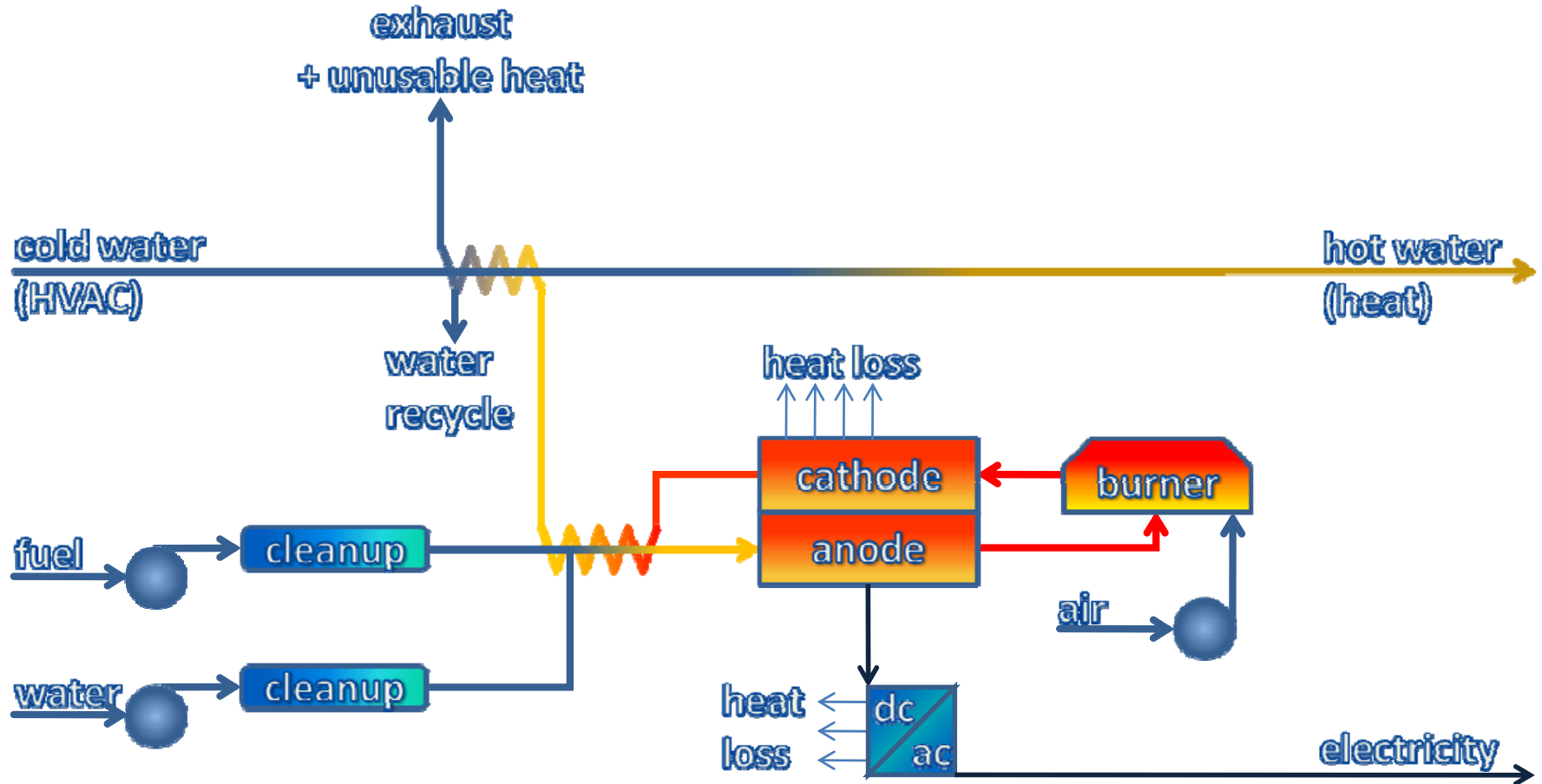


# MCFC Basics

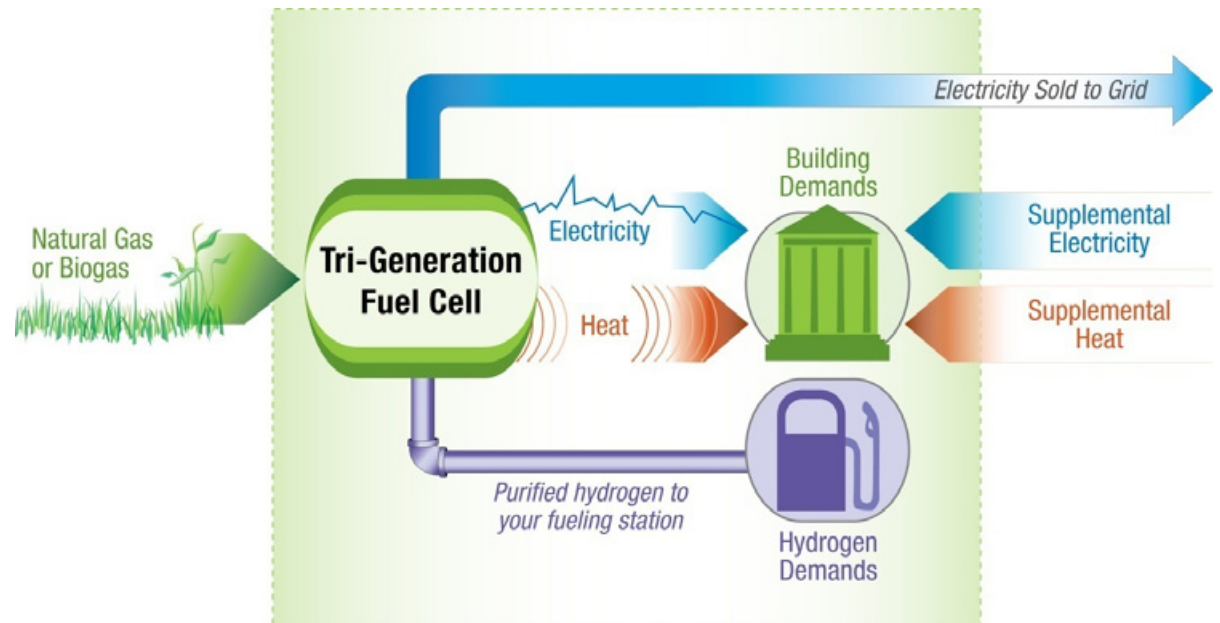


Schematic of MCFC operation (EG&G Technical Services 2004)

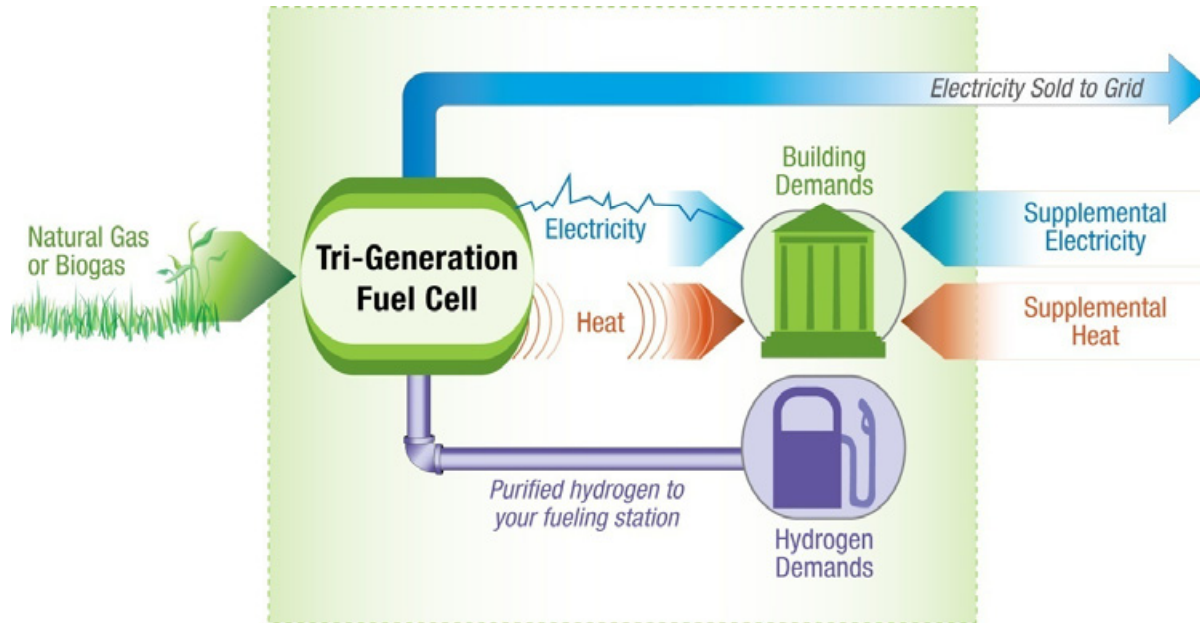
# MCFC System Configuration



# Fuel Cell Power Model Introduction



# FCpower Model



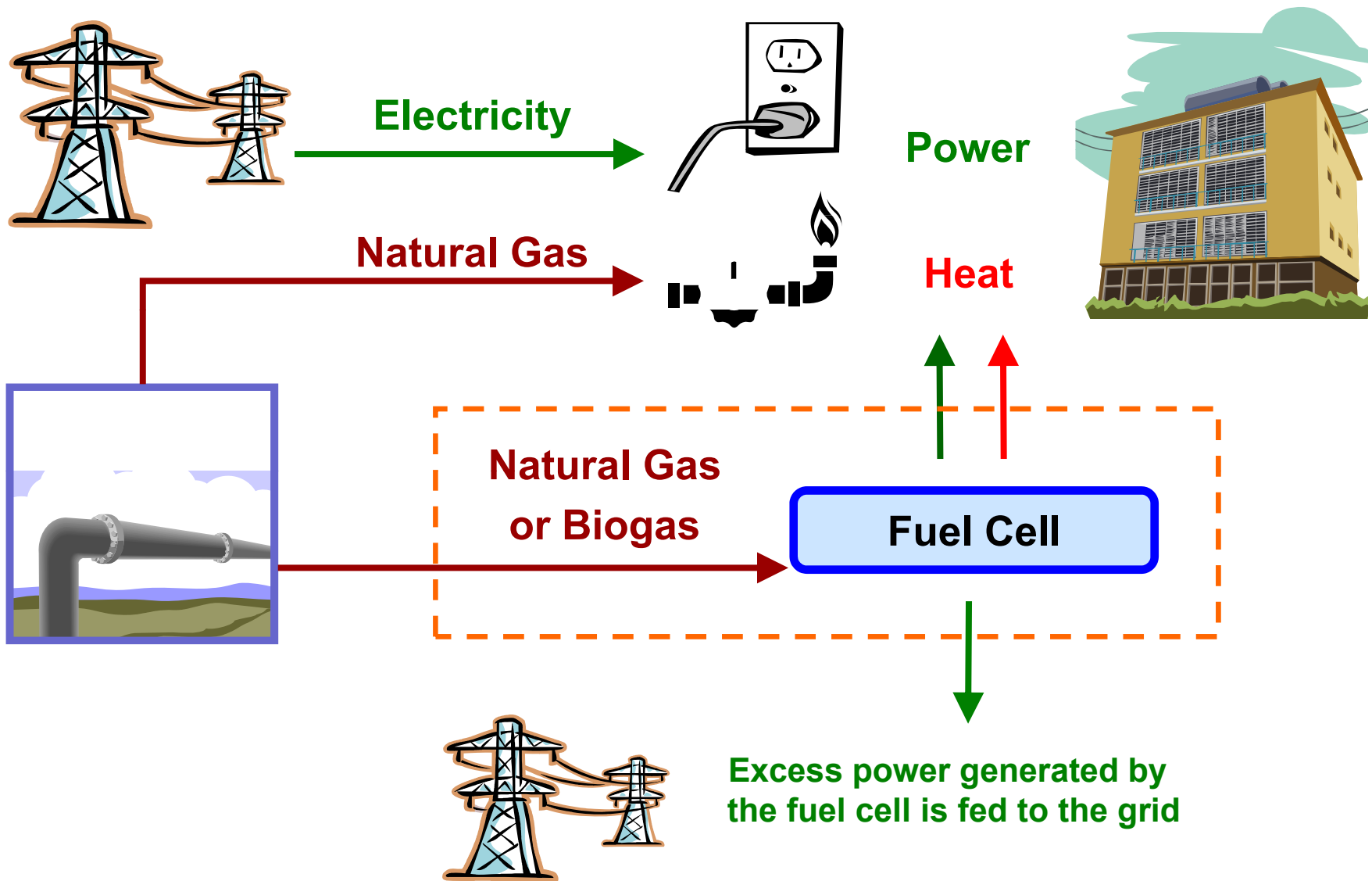
[http://www.hydrogen.energy.gov/fc\\_power\\_analysis.html](http://www.hydrogen.energy.gov/fc_power_analysis.html)

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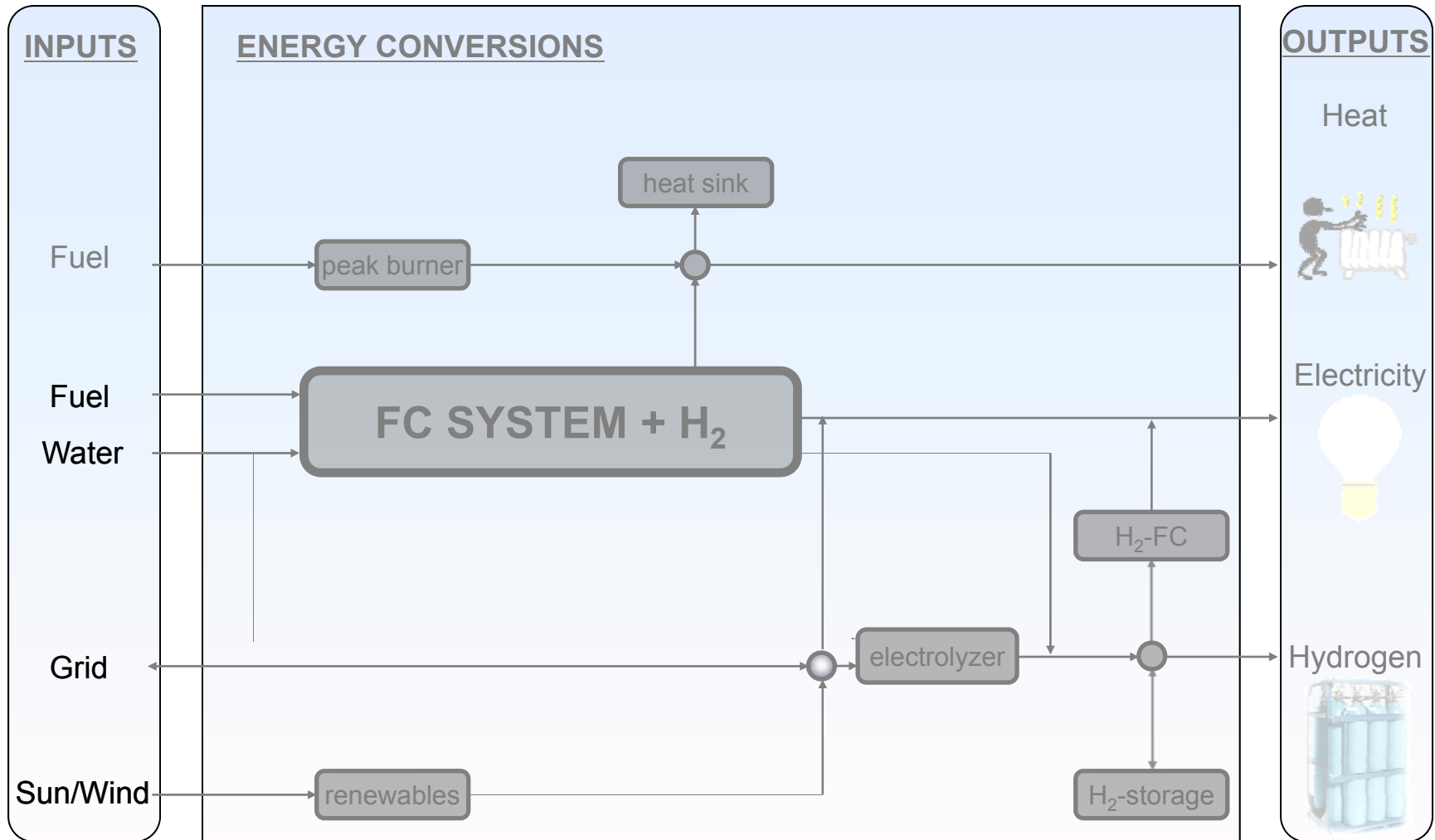
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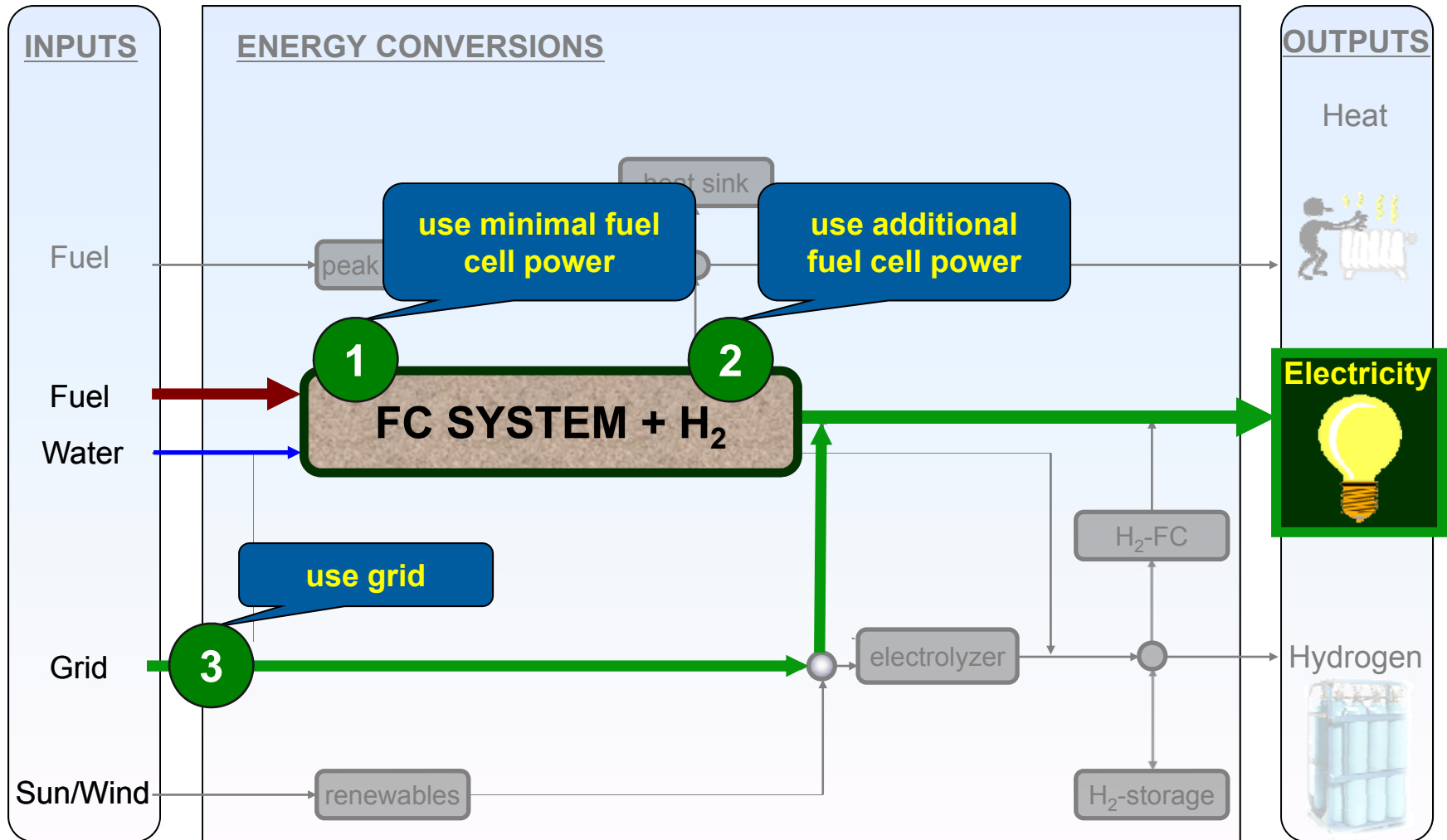
# Overview of Combined Heat & Power Concept



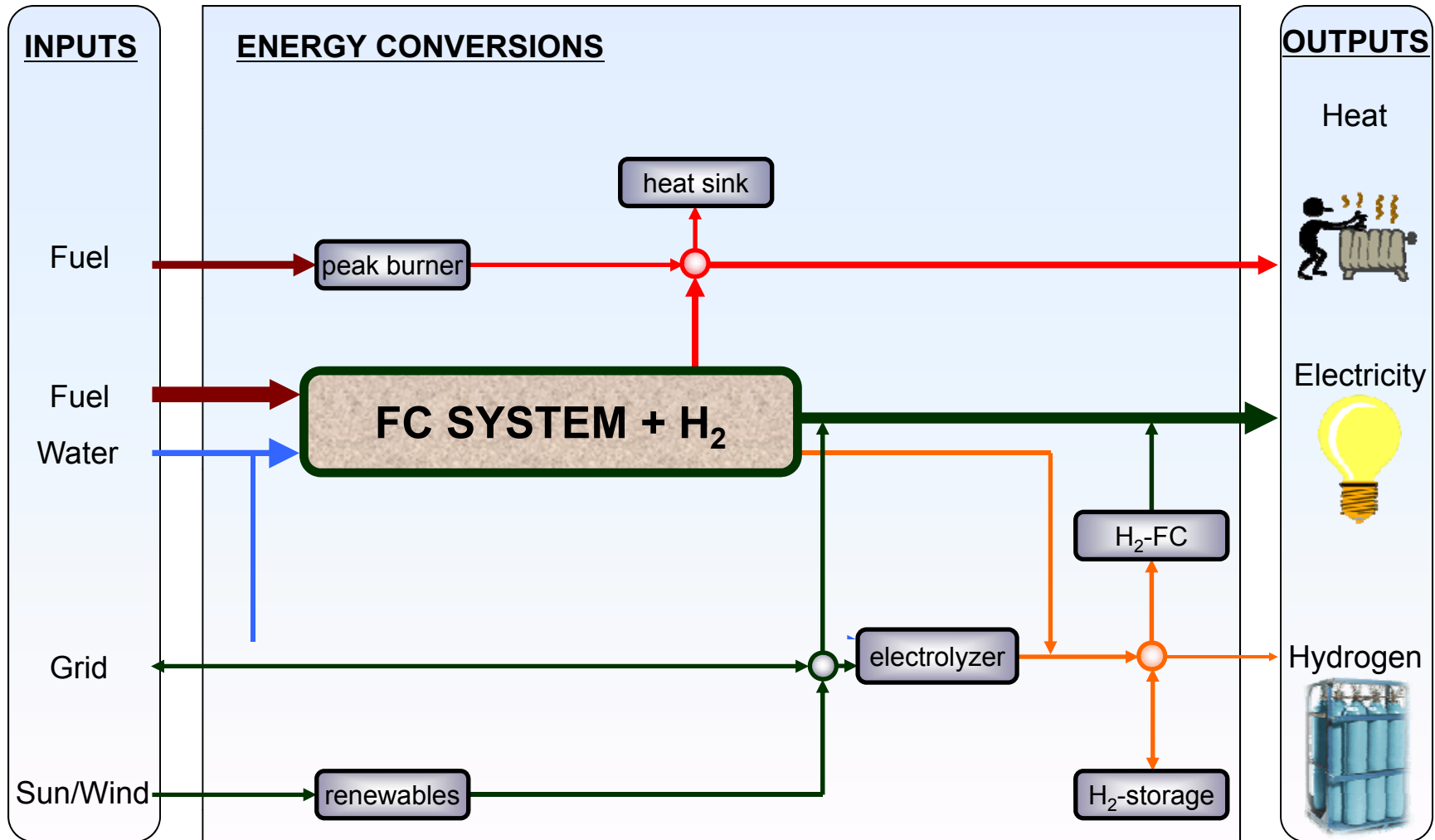
# Dispatch Sequence for Electricity Generation



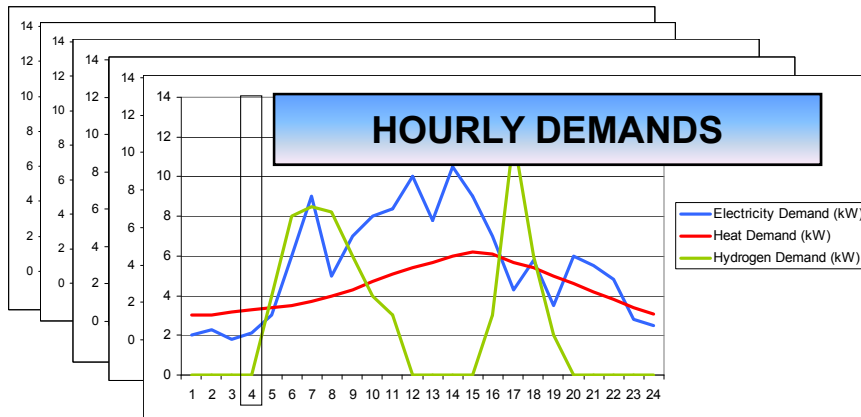
# Dispatch Sequence for Electricity Generation



# Technology Selection for Hourly Energy Analysis



# Integration of Demand Profiles, Renewables Availability, & Grid Cost Structure

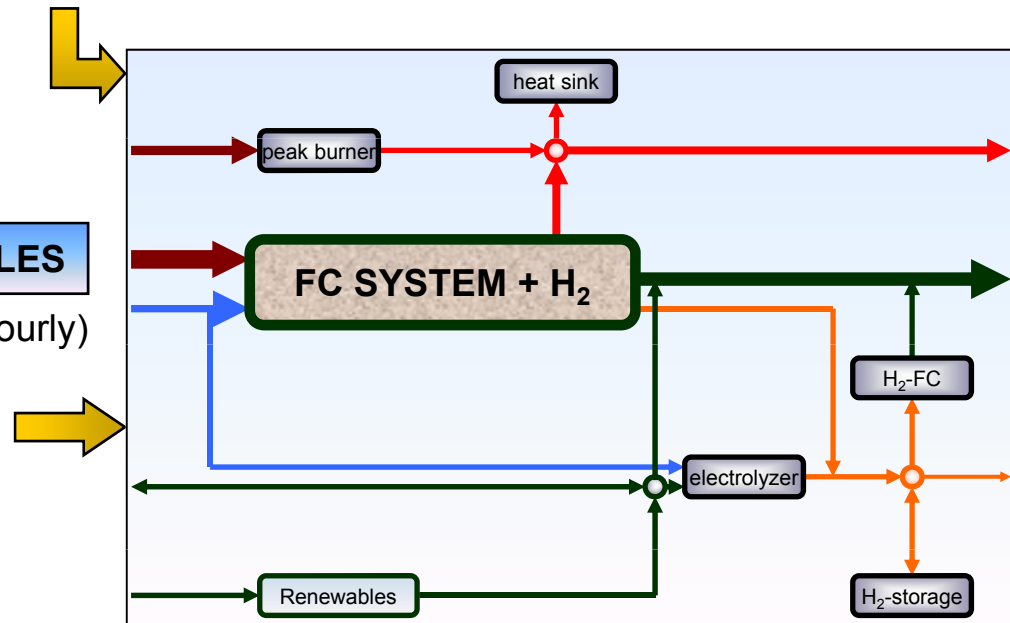


## Enter Process Specifications (default values will be provided)

- Download or enter hourly demand profiles
- Download or enter hourly renewable energy profiles
- Enter grid electricity price profile (peaking price structure)
- Enter equipment capital costs
- Enter equipment capacity, operating parameters, and operating costs

## PRICE SCHEDULES

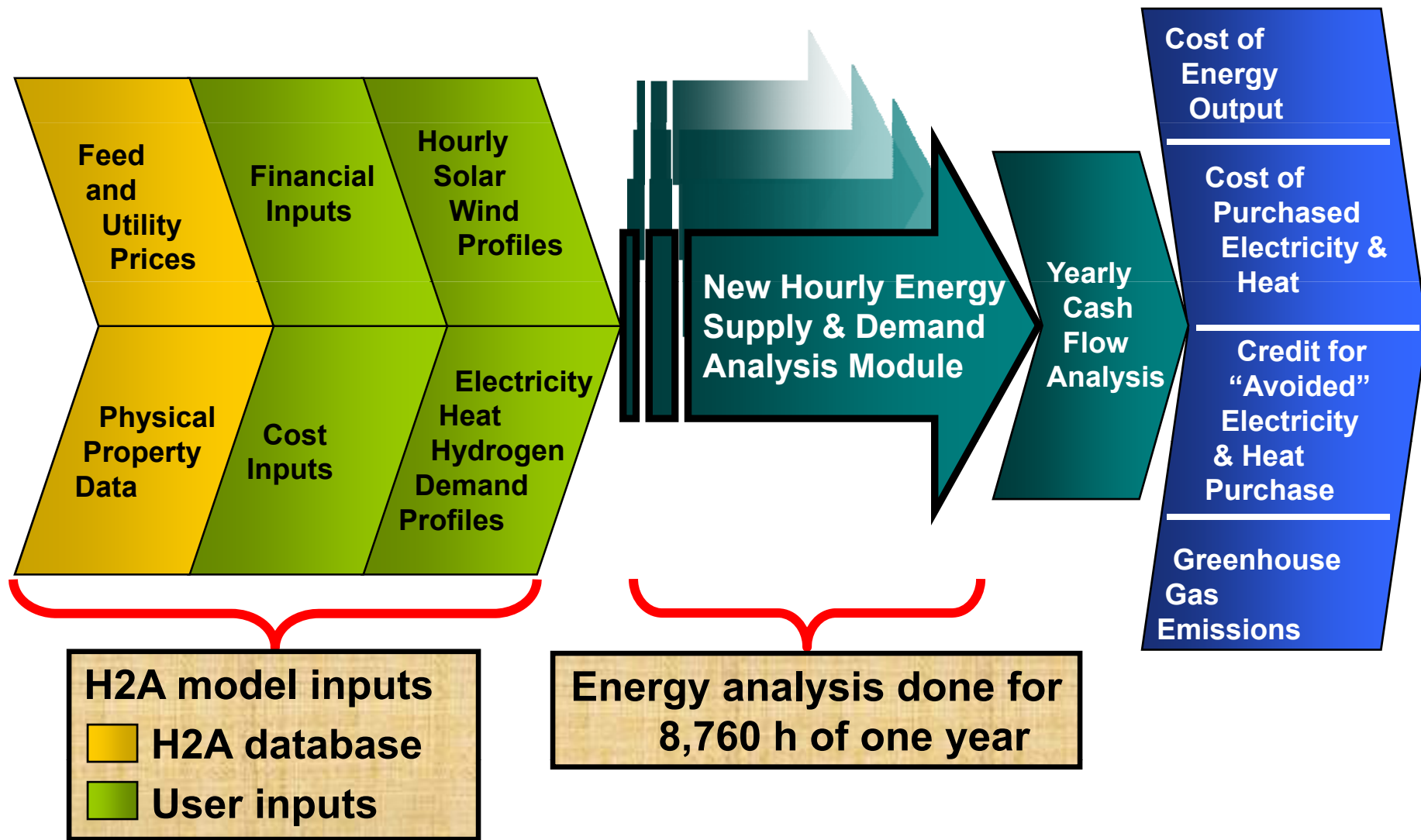
- Grid electricity (hourly)
- Fuel prices
- Water price



## ENERGY FLOWS (\$)

- Delivered electricity
- Delivered heat
- Delivered hydrogen
- Used fuel
- Used grid electricity
- Sales to grid

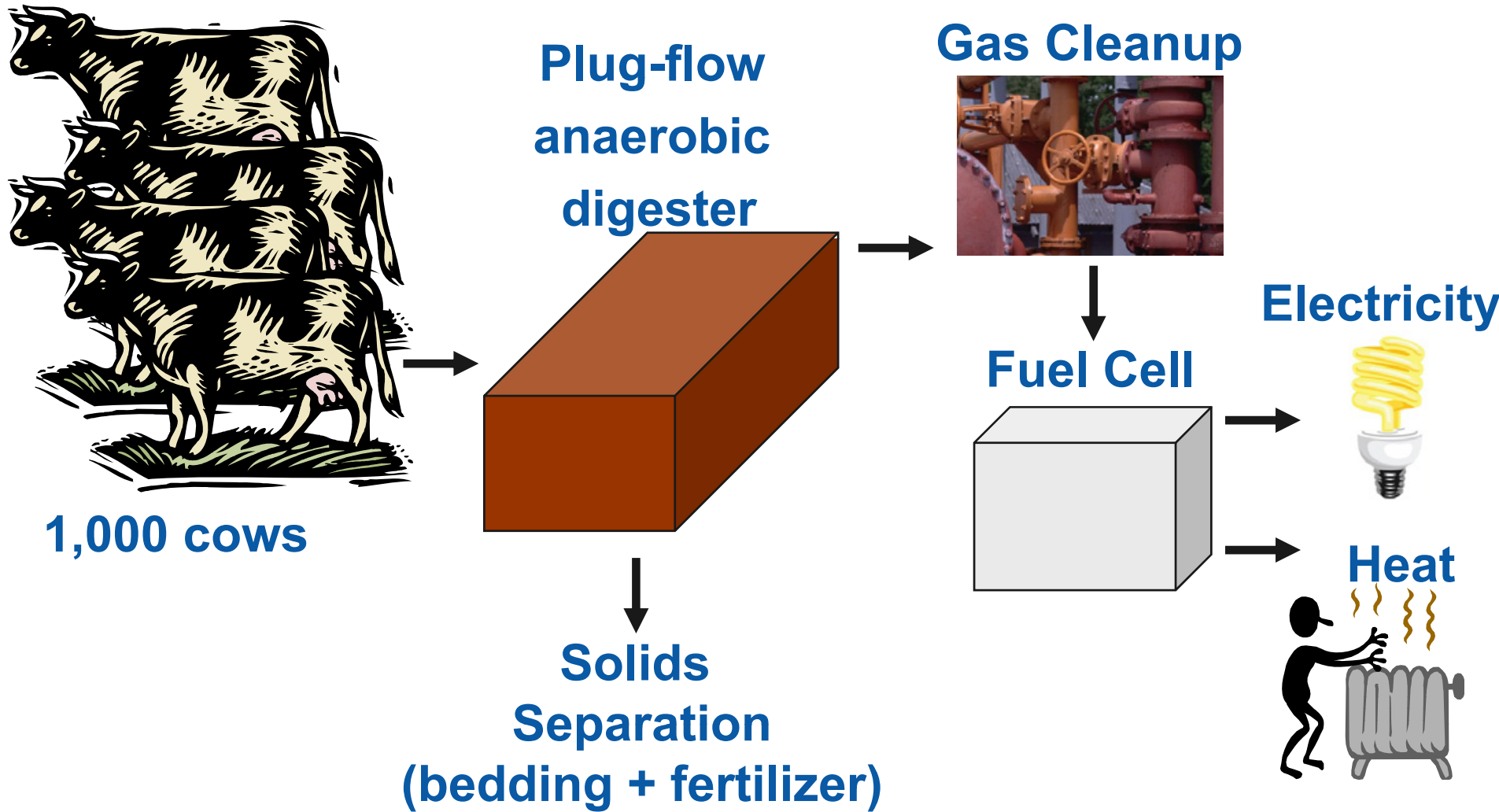
# FCPower Model Hourly Energy Analysis Module



# Biogas Case Study



# System Being Considered







# Quick Start – 4 steps

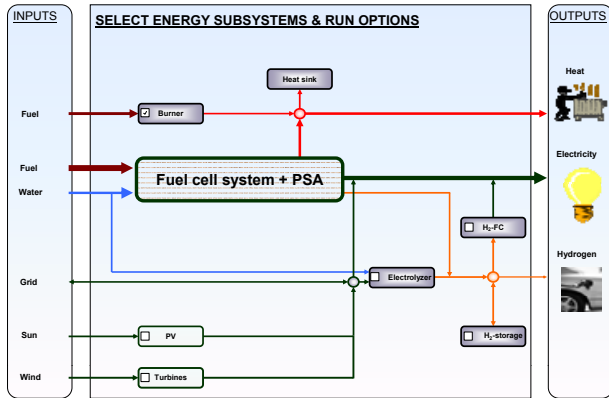
**1** Click Process Flow Diagram

**Title**

Title:	Molten Carbonate Fuel Cell Case Study
Authors:	Darlene Steward, Mike Penev
Contact:	Darlene Steward
Contact phone:	303 275 3837
Contact e-mail:	darlene_steward@nrel.gov
Organization:	NREL
Date:	1-Aug-09
Web site:	

Process Flow Diagram

**2** Configure system  
• Click *Input sheet* button



System Component Selection

Fuel Cell System	TRUE
Electrolyzer	FALSE

Input Sheet

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

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

Analysis Results

**SUMMARY COST RESULTS**

**H2A Power Model Energy Cost Flows**

System Energy to Building (kWh)	Select Value to Save For	\$/kWh	Total Revenue per Year
System Net Electricity to Building	1,564,136	0.100	\$156,414
Fuel Cell System Heat	2,167,229	0.030	\$65,017
Hydrogen	3,834,800	0.020	\$76,696
Annual Total	7,546,301	0.020	\$151,127
Renewable Spill kWh		\$/kWh	Total Revenue per Year
Electricity Heat	6,520	0.120	\$782
Supplementary Heating Electricity, net final (kWh)		\$/kWh	Total Cost per Year
Supplementary Electricity A	217,300	0.100	\$21,730
Supplementary Heat A	1,280,000	0.020	\$25,600
Renewable	1,029	0.020	\$20.6

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.

# Economic Evaluation of a Fuel Cell at a Dairy

## Hypothetical facility profile:

- 1,000 cows housed in a free-stall barn

## Biogas system:

- Manure collection
- Plug-flow anaerobic digester
- Biogas collection and purification
- Digester waste press separator
  - Windrow composting of solids
  - Field application of water

## Fuel cell system:

- Molten carbonate fuel cell (MCFC) produces electricity and heat
- Electricity not used on site is fed to the grid



# Information Needed

## Capital cost, O&M, Life, Performance

- Digester
- Gas cleanup
- Fuel cell system

## Incentives

- Federal incentives
- State incentives

## On-site energy demands

- Electricity hourly
- Heat hourly (including digester)

## Energy costs

- Electricity  $\phi$ /kWh
- Heat \$/MMBTU



# Energy & Material Values

	Units	Value
Methane production	Btu CH <sub>4</sub> /day/ cow (kWh CH <sub>4</sub> /day/cow)	45,218 (13.25)
Electricity production (assuming 45% average electrical efficiency for fuel cell)	kWh/day/cow	~6
Usable heat production (assuming 75% total efficiency for fuel cell)	kWh/day/cow	~4
Finished compost	Cubic yards/year/ cow	3.32
Electricity required for digester operation	kWh/cow/day	~1
Heat required for operation of chillers (for milk) and heating of the digester	kWh/cow/day	~1*
*0.014 tons chilling per cow per day per hour of milking		

**Sources: Martin, John H. Jr. *A Comparison of Dairy Cattle Manure Management With and Without Anaerobic Digestion and Biogas Utilization*, EPA AgSTAR Program, June 2004. EPA AgSTAR Handbook, Second Edition.**

# Cost Values

	Units	Value for 1,000 cow farm
Digester system installed cost	\$K = $[563 * (\text{number of cows}) + 678,064] / 10^3$	1,170
Post-digestion solids separation system	% of total project capital cost (\$K)	6.9 (98)
Hydrogen sulfide removal	% of total project capital cost (\$K)	4.5* (64)
Utility hookup	% of total project capital cost (\$K)	7.9 (112)
MCFC uninstalled cost	\$/kW (\$K), 300 kW system**	2,500 (750)
Federal tax incentive	\$K	324
CA SGIP using renewable fuel	\$K, \$4.50/W for FC > 30kW using renewable fuel	1,350

\*High end of cost range assumed for fuel cell purity requirements

\*\* 250 kW system would be required for 6kWh/day/cow average production.

**Sources: Martin, John H. Jr. *A Comparison of Dairy Cattle Manure Management With and Without Anaerobic Digestion and Biogas Utilization*, EPA AgSTAR Program, June 2004. EPA AgSTAR Handbook, Second Edition.**

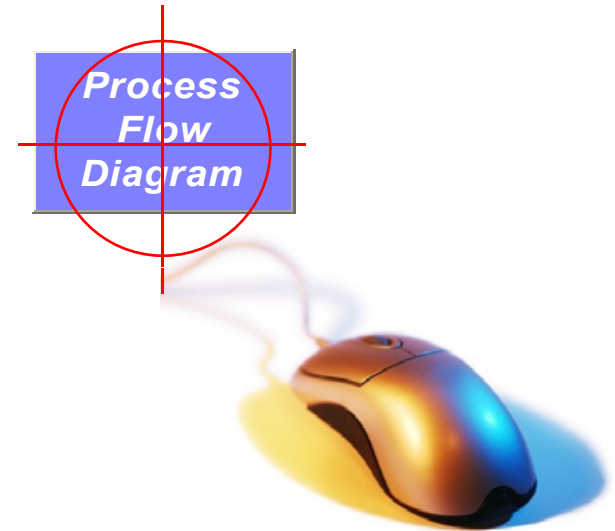
# Step 1

1

Click Process  
Flow Diagram

## Title

<b>Title:</b>	Molten Carbonate Fuel Cell Case Study
<b>Authors:</b>	Darlene Steward, Mike Penev
<b>Contact:</b>	Darlene Steward
<b>Contact phone:</b>	303 275 3837
<b>Contact e-mail:</b>	<a href="mailto:darlene_steward@nrel.gov">darlene_steward@nrel.gov</a>
<b>Organization:</b>	NREL
<b>Date:</b>	1-Aug-09
<b>Web site:</b>	

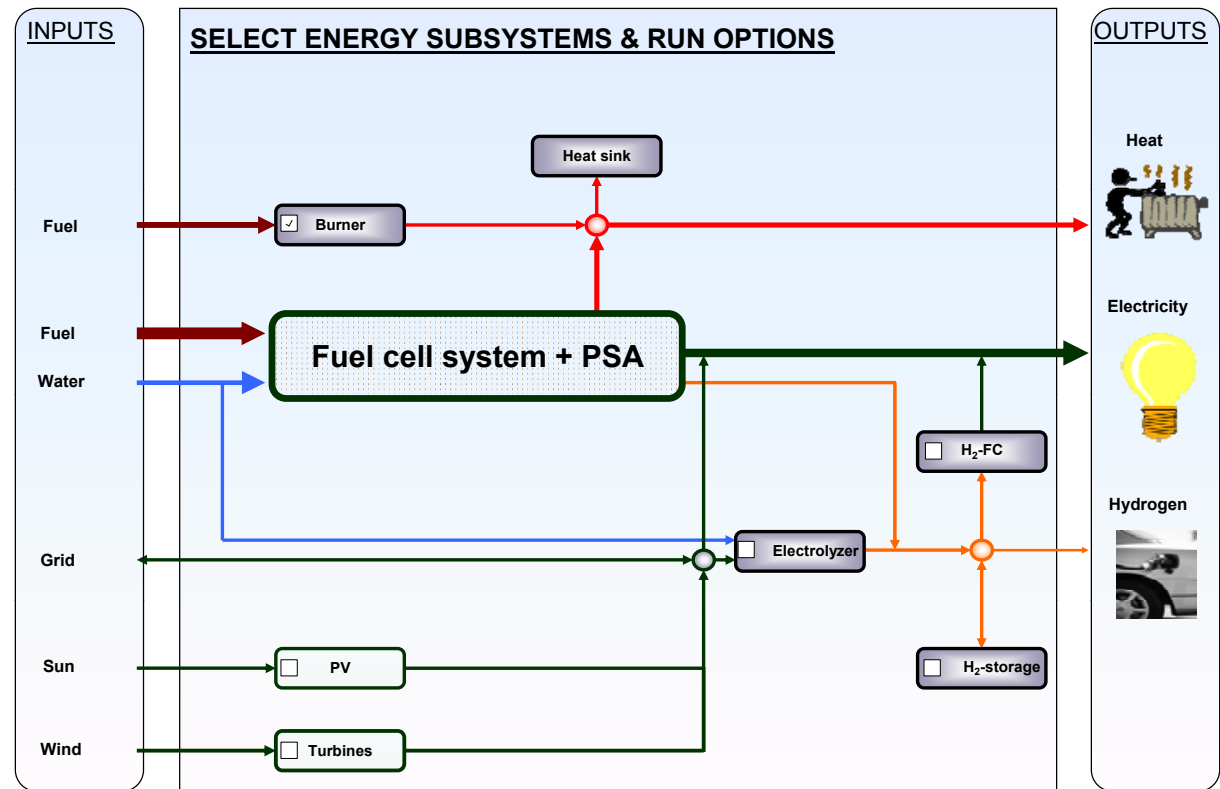


**Simple:** *just click!*

**Model users are first directed to this screen.**

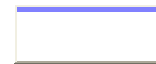
# Step 2: Selecting Hardware

- 2** • Configure system  
• Click *Input sheet* button



System Component Selection

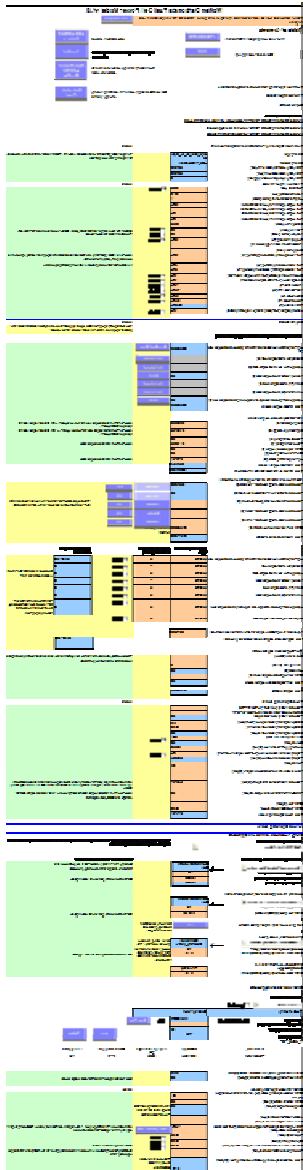
Peak Burner	TRUE
Fuel Cell System	TRUE
Electrolyzer	FALSE



- The Fuel Cell System analysis is active by default
- Burner evaluation should also be selected



# Step 3: Entering Detailed Specifications



- The “Input\_Sheet\_Template” sheet is the main model interface
- The subsequent slides will describe each section of the interface
- Tools and defaults are available for most values
- A lot of customization is possible for special case evaluations

# Step 3A: Entering Specifications

## Molten Carbonate Fuel Cell Power Model v1.0

Molten carbonate fuel cell combined heat, hydrogen, and power installation for a large hotel in Los Angeles [View Description](#)

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### Table of Contents

View and edit project information	<a href="#">Project Info</a>	Use default values	<a href="#">Use Default Values</a>
Cell color coding key	<a href="#">Key</a>	Import and export data and perform analyses	<a href="#">Toolkit</a>
		Run hourly energy calculations and calculate cost	<a href="#">Run Hourly Energy Profile</a>
		Calculate energy cost with existing hourly energy profile	<a href="#">Calculate Cost</a>

---

Technical Operating Parameters and Specifications

Financial Input Values

Capital Costs

Fixed Operating Costs

Variable Operating Costs - Energy Feedstocks, Utilities, and Byproducts

Variable Operating Costs - Other Materials and Byproducts

Variable Operating Costs - Other Variable Operating Costs

---

Technical Operating Parameters and Specifications	Notes
Building type	To import load profiles for a new location, click the "Toolkit" button for importing new load profiles
Building location	
Total yearly electricity load (kWh/year)	
Total yearly heat load (kWh/year)	
Total yearly hydrogen demand (kg/year)	

large_hotel_ca_los_angeles	2,006,040	
LOS ANGELES, CA	2,104,728	
	31,025	

Sheets for electricity and heat demand specification

---

Replacement Costs / Grid Price Structure / Fuel Cell System / Hydrogen Storage / Peak Burner / **AC Demand** / Heat Demand / H2 Demand

- First input is specifying electricity and heat demands.
- Estimates call for 1 kWh /cow-day = 42 kW for heat and electricity



# Step 3C: Economic criteria specification

## Financial Input Values

Reference year	2005	<input checked="" type="checkbox"/> Default
Assumed startup year	2010	
Length of construction period (years)	1	
% of capital spent in 1st year of construction	100%	
% of capital spent in 2nd year of construction		
% of capital spent in 3rd year of construction	0%	
% of capital spent in 4th year of construction	0%	
Startup time (years)	0.038	
Plant life (years)	20	<input checked="" type="checkbox"/> Default
Analysis period (years)	20	<input checked="" type="checkbox"/> Default
% equity financing (%)	100%	<input checked="" type="checkbox"/> Default
Interest rate on debt, if applicable (%)		
Debt period (years)		
% of fixed operating costs during startup (%)	100%	
% of revenues during startup (%)	40%	
% of variable operating costs during startup (%)	50%	
Decommissioning costs (% of initial capital investment)	10%	<input checked="" type="checkbox"/> Default
Salvage value (% of initial capital investment)	10%	<input checked="" type="checkbox"/> Default
Inflation rate (%)	1.9%	<input checked="" type="checkbox"/> Default
After-tax real IRR (%)	10.0%	<input checked="" type="checkbox"/> Default
State taxes (%)	6.0%	<input checked="" type="checkbox"/> Default
Federal taxes (%)	35.0%	<input checked="" type="checkbox"/> Default
Total tax rate (%)	38.90%	
Working capital (% of yearly change in operating costs)	15%	<input checked="" type="checkbox"/> Default



- Verify and update economic assumptions

# Step 3D: Capital Costs

## Direct Capital Cost Specification (“Input\_Sheet\_Template” tab)

Direct capital costs (enter costs on equipment sheet)

High-temperature fuel cell and/or reformer process direct capital cost (\$)	\$2,339,362	<a href="#">Go to Detail Sheet</a>
Electrolyzer direct capital cost (\$)		<a href="#">Not Selected</a>
Hydrogen fuel cell direct capital cost (\$)		<a href="#">Not Selected</a>
Auxiliary heater direct capital cost (\$)	\$0	<a href="#">Unlink</a>
Solar (PV) direct capital cost (\$)		<a href="#">Not Selected</a>
Wind turbine(s) direct capital cost (\$)		<a href="#">Not Selected</a>
Hydrogen compression storage and dispensing direct capital cost (\$)		<a href="#">Not Selected</a>
<b>Total direct capital costs</b>	<b>\$2,339,362</b>	

- This section provides links to the fuel cell system and hydrogen storage tabs

# Step 3E: Remove Hydrogen Co-production

## Hydrogen Demand ("H2 Demand" tab)

Enter zero for  
daily hydrogen  
demand

Average daily hydrogen demand	0 kg/day
Hourly Hydrogen Demand Statistics (% of avg daily demand)	
Maximum	50.00%
Minimum	0.00%
Average	4.17%
Standard deviation	13.82%
Surge: % above the system average demand	0.0000
Friday average above weekly average (%)	0.0000
Adjusted average daily demand	0 kg/day

## Hydrogen Storage Costs ("Hydrogen Storage" tab)

Enter zero for  
all hydrogen  
dispensing  
costs

Major Pieces/Systems of Equipment	Baseline Uninstalled Costs	Installation Cost Factor	Baseline Installed Costs
Low-pressure storage tanks	\$ -	1.30	\$ -
Cascade storage tanks	\$ -	1.30	\$ -
Compressor cost	\$ -	1.20	\$ -
Dispensers	\$ -	1.20	\$ -
Electrical upgrades	\$ -	2.20	\$ -
Control and safety equipment	\$ -	1.20	\$ -
300 ft pipeline to filling station	\$ -	1.00	\$ -
			\$ -
			\$ -
			\$ -
			\$ -
Totals	\$ -		\$ -

- Remove all hydrogen demand by zeroing daily H<sub>2</sub> demand
- Remove all capital cost for hydrogen dispensing

# Step 3F: Fuel Cell Capacity

## Fuel Cell Specifications ("Fuel Cell System" tab)

Enter fuel cell capacity

FUEL CELL SYSTEM SPECIFICATIONS		Descriptions
Maximum electricity output rating kW	300.0	AC average demand.
Minimum electricity output rating kW	249.0	
Efficiency of H <sub>2</sub> production (kW H <sub>2</sub> produced / kW CHP heat reduced)	96%	Coefficient is derived from matching thermodynamic models.
Efficiency of H <sub>2</sub> over-production (kW H <sub>2</sub> produced / additional kW fuel consumed)	80%	Coefficient is derived from matching thermodynamic models.
Maximum fraction of heat convertible to hydrogen	0.65	Coefficient is derived from matching thermodynamic models.
Maximum amount of hydrogen over-production as fraction of H <sub>2</sub> production	0.50	Coefficient is derived from matching thermodynamic models.

- Maximum FC capacity of 300 is a good fit with available digester gas
- 83% of 300 kW allows for utilization factor specification = 249 kW of min. rating
- Remaining coefficients are not important for this analysis as they are for H<sub>2</sub> co-production

# Step 3G: Inputting System Costs

## Fuel Cell Cost Specifications ("Fuel Cell System" tab)

Enter fuel cell,  
digester, gas  
cleanup costs

INVESTMENT (Inputs REQUIRED in			
Major Pieces/Systems of Equipment	Baseline Uninstalled Costs	Installation Cost Factor	Baseline Installed Costs
Fuel cell CHP equipment uninstalled cost	\$ 750,000	1.20	\$ 900,000
<b>Plug Flow Digester System</b>		0.00	\$ -
Digester, engineering, and installation	\$ 1,166,477	1.00	\$ 1,166,477
Total ancillary systems	\$ -		\$ -
Post-digestion solids separation system	\$ 97,560	1.00	\$ 97,560
Hydrogen sulfide treatment	\$ 63,626	1.00	\$ 63,626
Utility hookup	\$ 111,699	1.00	\$ 111,699
			\$ -
			\$ -
			\$ -
<b>Totals</b>	\$ 2,436,796		\$ 2,339,362

2,436,796

2,339,362

- This sheet would contain all hardware capital costs
- If installed costs are used, enter installation cost factors of 1.0



# Step 3H: Input Indirect Capital Costs

## Indirect Capital Costs Specification ("Input\_Sheet\_Template" tab)

### Indirect depreciable capital costs

Site preparation (\$)

Engineering & design (\$)

Process contingency (\$)

Project contingency (\$)

Other (depreciable) capital (\$)

One-time licensing fees (\$)

Up-front permitting costs (\$)

**Total indirect capital costs**

**Total Direct & Indirect Capital Investment**

\$233,936
\$163,755
\$0
\$116,968
\$0
\$0
\$70,181
\$584,840
\$2,924,202

The power model provides default values for each value above, but it can be overridden

# Step 3I: Incentives Specification

## Incentives Specification

(“Input\_Sheet\_Template” tab)

### Incentives and credits (enter as positive numbers)

Federal business energy tax credit - fuel cells (\$)

\$324,000

Federal alternative fuel infrastructure tax credit (\$)

\$0

Federal combined heat and power tax credit (\$)

Federal business energy tax credit - solar (\$)

Federal business energy tax credit - wind (\$)

Other one-time tax incentive credits (\$)

\$1,350,000

**Total incentives and credits**

\$1,674,000

Federal business energy tax credit - fuel cells (\$)	\$324,000	Calculate
Federal alternative fuel infrastructure tax credit (\$)	\$0	Calculate
Federal combined heat and power tax credit (\$)		Calculate
Federal business energy tax credit - solar (\$)		Calculate
Federal business energy tax credit - wind (\$)		Calculate
Other one-time tax incentive credits (\$)	\$1,350,000	Enter as a positive number.
<b>Total incentives and credits</b>	<b>\$1,674,000</b>	

- Federal tax incentive is 30% of capital or 3,000 \$/kW, whichever is less
- Self Generation Incentive Program (SGIP), is a CA program that pays up to 4,500 \$/kW of installed capacity of renewable electric production

# Step 3J: Specifying Fixed Operating Costs

## Fixed Operating Costs Specifications (“Input\_Sheet\_Template” tab)

Fixed Operating Costs		
Production facility plant staff (number of FTEs)		
Burdened labor cost, including overhead (\$/man-hr)		
Production facility labor cost, \$/year	\$0	
Storage/dispensing labor required (hours/year)	0.0	
Storage/dispensing labor cost (\$/man-hr)	\$0.00	
Storage/dispensing labor cost (\$/year)	\$0	
G&A rate (% of labor cost)	20%	<input checked="" type="checkbox"/> Default
G&A (\$/year)	\$0	
Licensing, permits, and fees (\$/year)	\$2,339	
Property tax and insurance rate (% of total capital investment)	2%	<input checked="" type="checkbox"/> Default
Property taxes and insurance (\$/year)	\$25,004	
Rent (\$/year)	\$0	
Material costs for maintenance and repairs (\$/year)		
Production maintenance and repairs (\$/year)	\$46,787	
Forecourt maintenance and repairs (\$/year)	\$0	
Other fees (\$/year)		
Other fixed O&M costs (\$/year)	\$0.00	
<b>Total fixed operating costs</b>	<b>\$74,131</b>	

- Note that some costs for hydrogen production would not apply
- For this analysis we assumed that the fuel cell is installed onsite - so land leasing is not needed.

# Step 3K: Feedstock Cost Specification

## Feedstock Costs

("Input\_Sheet\_Template" tab)

Energy Feedstocks, Utilities, and Byproducts

Select the price table to use

AEO 2005 High A Case

Reforming fuel cell fuel specification

Commercial Natural Gas\_metric

Look up prices for each year?

Enter fuel price (\$(2005)/MMBtu)

Fuel price (\$(2005)/kWh)

Commercial Natural Gas
No
\$0.000
\$0.000

Enter zero for natural gas cost

Auxiliary heater (peak burner) fuel specification

Commercial Natural Gas\_metric

Look up prices for each year?

Enter fuel price (\$(2005)/MMBtu)

Commercial Natural Gas
No
\$10.150

Edit grid electricity import price matrix

Edit

Specify local electricity rates

Grid electricity base prices

Commercial Electricity\_metric

Look up base prices for each year?

Enter base electricity price (\$(2005)/kWh)

Commercial Electricity_metric
No
0.124

Specify local electricity sell-back rates

Byproduct electricity pricing

Select price type

Enter base electricity price (\$(2005)/kWh)

Time of Day
0.124

- Water costs can be specified as well, but they are typically relatively low
- Note: Detailed grid cost structure can be accommodated by this model

# Step 3L: Verify Other Variable Operating Costs

<b>Other Variable Operating Costs</b>	
Other variable operating costs (e.g., environmental surcharges) (\$/year)	\$0
Other material costs (\$/year)	\$0
Grid peak charges (\$/year)	\$0
Waste treatment costs (\$/year)	
Solid waste disposal costs (\$/year)	
Total unplanned replacement capital cost factor (% of total direct depreciable costs/year)	1.50%
Royalties (\$/year)	\$0.00
Operator profit (\$/year)	\$0.00
Subsidies and tax incentives based on production (\$/year)	\$0.00
Refueling station O&M costs (\$/year)	
<b>Total variable operating costs excluding fuel (\$/year)</b>	<b>\$172</b>



- Note that this is the place to define maintenance costs (1.5% of cap is default)
- Detailed capital cost replacements can be specified within the “Replacement Costs” sheet
- At this point, the model specifications are complete!

# Step 4: Running and Results

## “Input\_Sheet\_Template” tab:

### Table of Contents

View and edit project information

*Project Info*

Cell color coding key

*Key*

Technical Operating Parameters and Specifications

Financial Input Values

Capital Costs

Use default values

*Use Default Values*

Import and export data and perform analyses

*Toolkit*

Run hourly energy calculations and calculate cost

*Run Hourly Energy Profile*

Calculate energy cost with existing hourly energy profile

*Calculate Cost*

Once all inputs are complete, click here

- Running the model performs an hourly energy analysis
- After energy analysis is complete, economic analysis and emissions are evaluated
- Completed running will place you on the results tab

# Reviewing Results

---

# Analysis Results for 1,000 Cow Dairy

1,000 cow dairy	Electricity (kWh/y)	Heat (kWh/y)
Used onsite	367,920	367,920
Sold	1,810,190	
Total	2,178,110	367,920

Overall system efficiency is 54% based on heat used.  
Utilization of available heat is only 26%.



# Analysis Results for 1,000 Cow Dairy

Baseline system energy costs (without to installation of fuel cell)	
<b>Electricity</b>	(\$/year)
Usage and Demand charges	\$
<b>Commercial Natural Gas</b>	(\$/year)
	\$
<b>Hydrogen (supplied by forecourt SMR system)</b>	\$ 55,461
Hydrogen price = \$0/kg	
<b>Total baseline system energy cost per year</b>	\$ 14,157

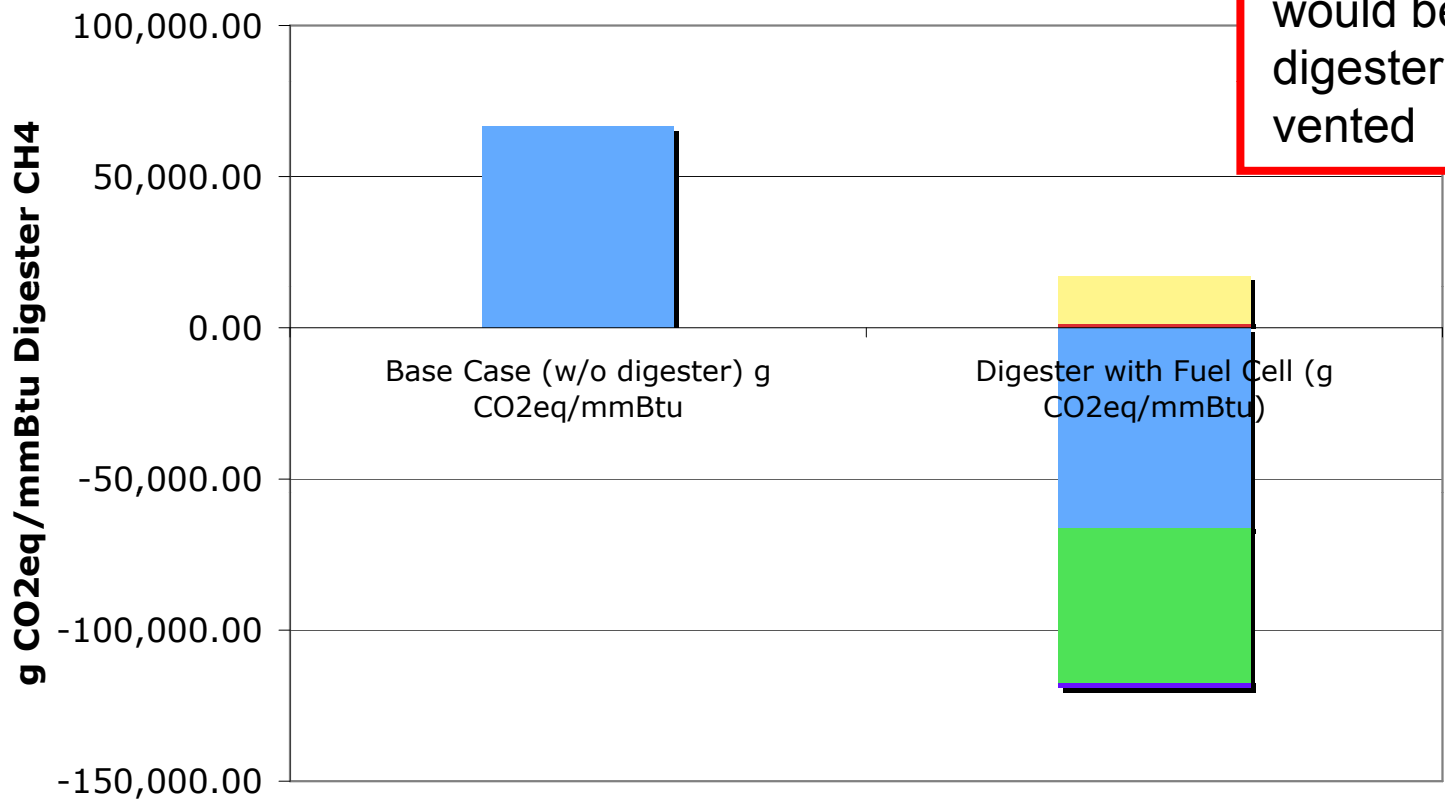
Cost of natural gas for chillers would be \$14,157/year.

<b>CHHP System Annualized Costs</b>	-
<b>Annualized costs</b>	<b>69,618</b>
Capital costs	\$92,806
Decommissioning costs	\$1,176
Fixed O&M	\$14,422
Feedstock costs	\$0
Other raw material costs	\$0
Byproduct credits	-\$43,590
Other variable costs	\$8
Supplementary electricity	\$2,702
Supplementary heat	\$0
<b>Total</b>	<b>\$67,525</b>

Fuel cell combined heat and power system with an 8.5% internal rate of return

# GHG Emissions Comparison

GHG Emissions Comparison



~515,000 g of CO2eq would be emitted if the digester methane were vented

- GHG Emissions from manure management
- GHG Emissions from biogas recovery
- GHG Emissions from biogas processing
- avoided emissions - electricity generation
- avoided emissions - heat utilization

Data Source: CARB, Detailed California-Modified GREET Pathway for Liquefied Natural Gas (NG) from Dairy Digester BioGas, CARB Stationary Source Division, Version 2.0, September 23, 2009.

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# Thank You

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