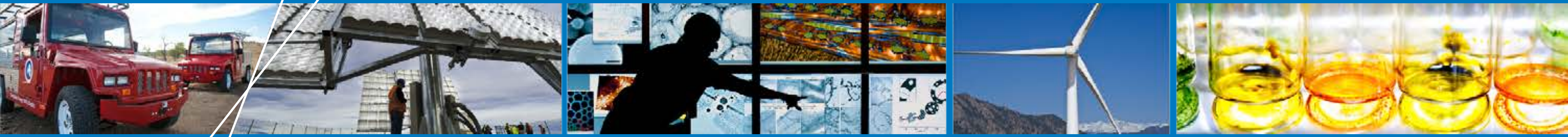
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

AN040

Analysis of Fuel Cell Integration with Biofuels Production



DOE Annual Merit Review
Crystal City, VA

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NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Overview

Timeline

- Start: May 2012
- Finish: May 2013
- 95% Complete

Budget

- Total Funding: $70K
  - 100% DOE funded
- FY12 Funding: $70K

DOE BioEnergy Technology Office (BETO)

- Ad hoc funding for related FY13 analysis*

Barriers Addressed

- Stove-piped/siloed analytical capability (B)
- Insufficient suite of models and tools (D)
- Unplanned studies and analysis (E)

Partners

- DOE BETO & NREL analysts
- NREL Fuel Cell Power Modeling Team

* Not reported in this presentation

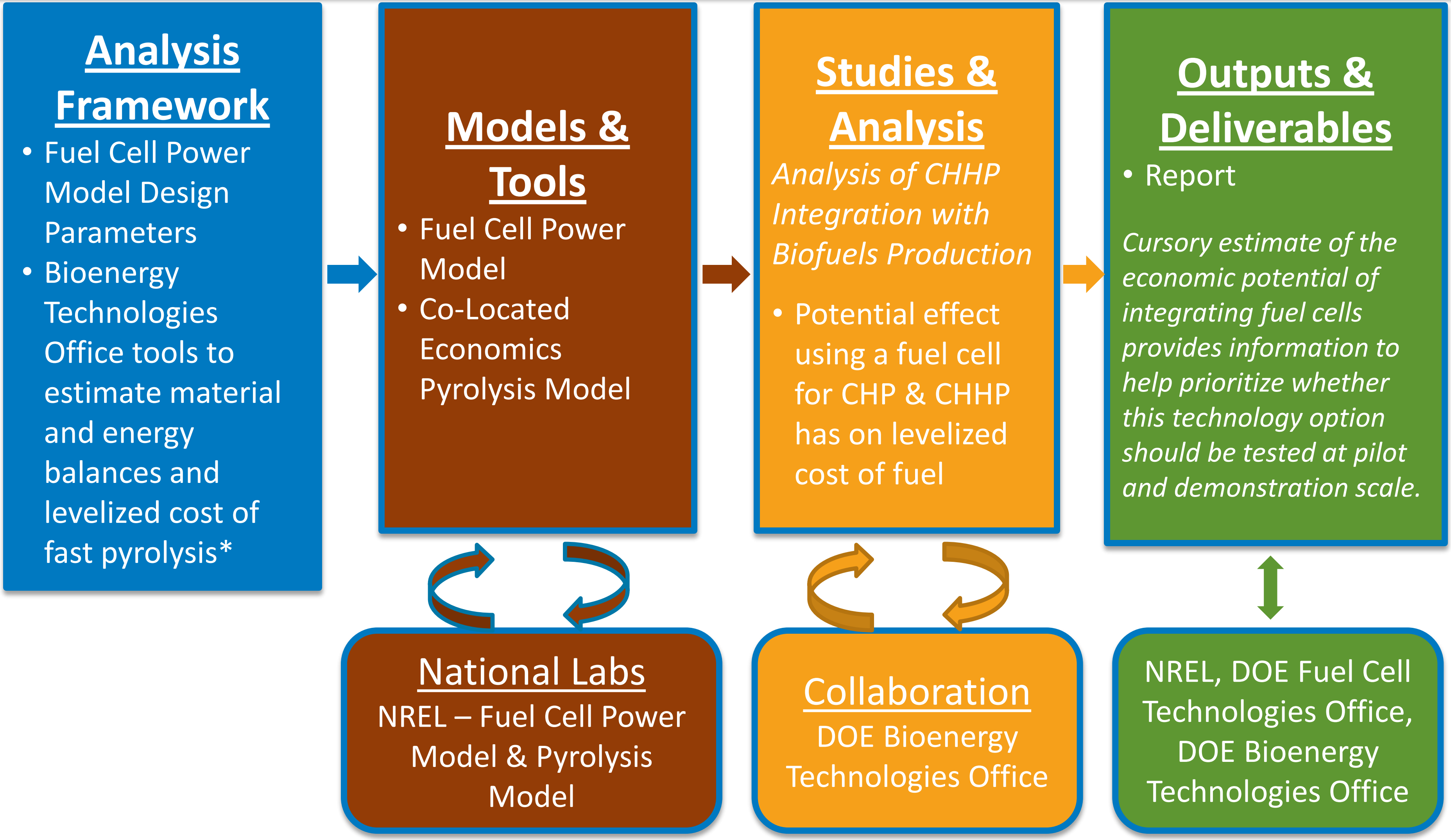
Project Objectives

Fuel Cell CHHP Integration with Biofuel Production Project Objectives	
Identify opportunities for using fuel cells (FC) in biorefineries	Review biomass processing options being developed and identify opportunities for fuel cell integration with a focus on combined heat, hydrogen (H_2) , and power (CHHP) options.
Analyze potential benefits	Initially, estimate how integration of FCs into biorefineries may affect levelized biofuel cost in both CHHP and combined heat and power (CHP) configurations. Future work may involve other benefits such as reductions in greenhouse gas emissions, hedging against market volatility, reliability, and resilience
Reporting	Report the effects of integration of FCs on • Levelized cost • Capital cost • Operating costs

Relevance	
Support Fuel Cell Technology Office Goals and Activities	• Evaluate potential options for fuel cells in industrial CHHP applications to identify new markets for fuel cells • Leverage Fuel Cell Technologies Office funds by working with other Energy Efficiency and Renewable Energy (EERE) Offices

Project Overview

Analysis of CHHP Integration with Biofuels Production fits the Analysis subprogram's strategy



Analysis Framework

- Fuel Cell Power Model Design Parameters
- Bioenergy Technologies Office tools to estimate material and energy balances and levelized cost of fast pyrolysis*

Models & Tools

- Fuel Cell Power Model
- Co-Located Economics Pyrolysis Model

Studies & Analysis

Analysis of CHHP Integration with Biofuels Production

- Potential effect using a fuel cell for CHP & CHHP has on levelized cost of fuel

Outputs & Deliverables

- Report

Cursory estimate of the economic potential of integrating fuel cells provides information to help prioritize whether this technology option should be tested at pilot and demonstration scale.

National Labs

NREL – Fuel Cell Power Model & Pyrolysis Model

Collaboration

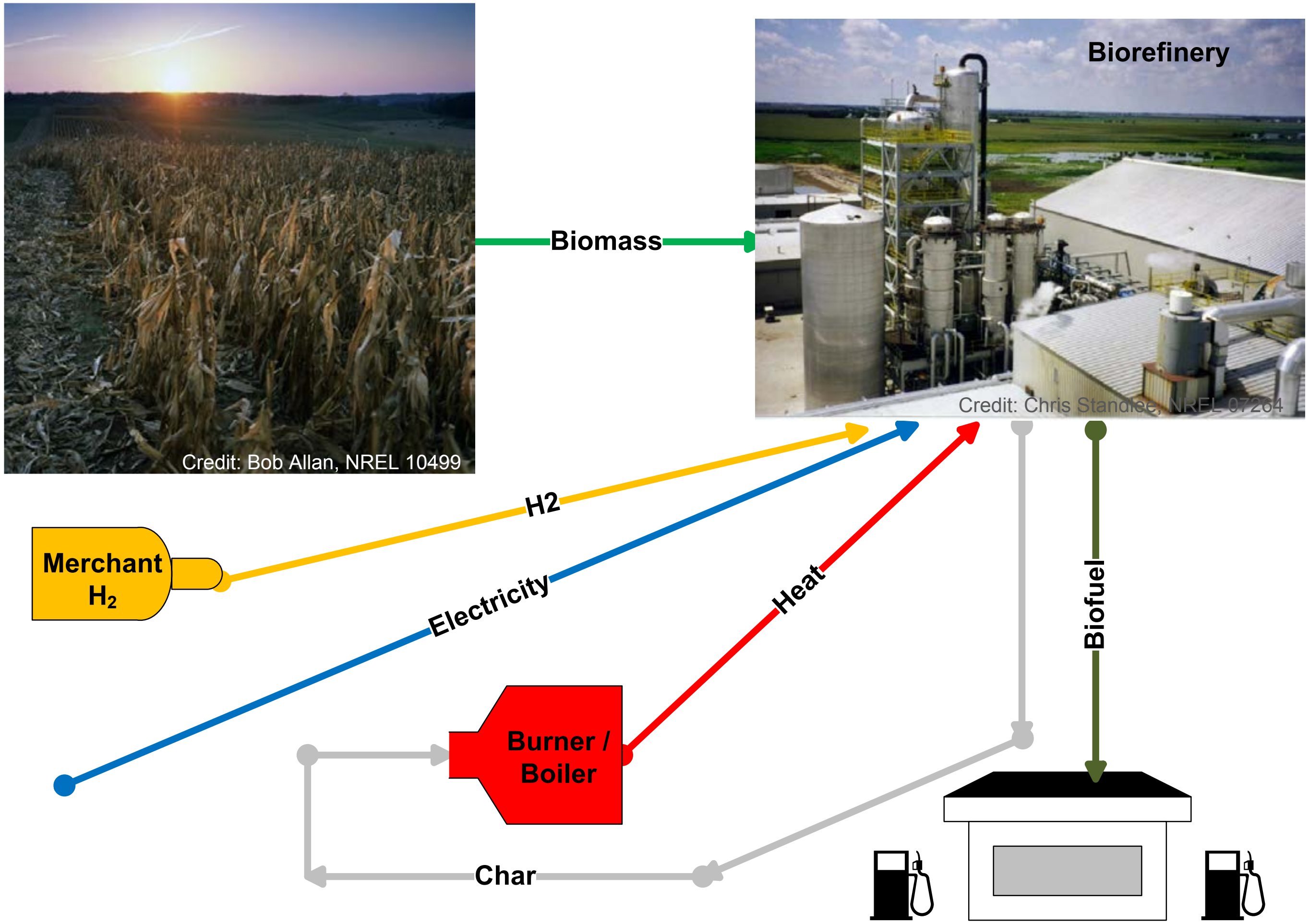
DOE Bioenergy Technologies Office

NREL, DOE Fuel Cell Technologies Office, DOE Bioenergy Technologies Office

* Data reported in Wright, M.M., Satrio, J.A., Brown, R.C., Daugaard, D.E., and Hsu, D.D. (Nov 2010). *Techno-Economic Analysis of Biomass Fast Pyrolysis to Transportation Fuels*. NREL/TP-6A20-46586. Golden, CO: National Renewable Energy Laboratory

Biomass Processing

A fast pyrolysis of biomass process was analyzed because it requires heat, H_2, and electricity



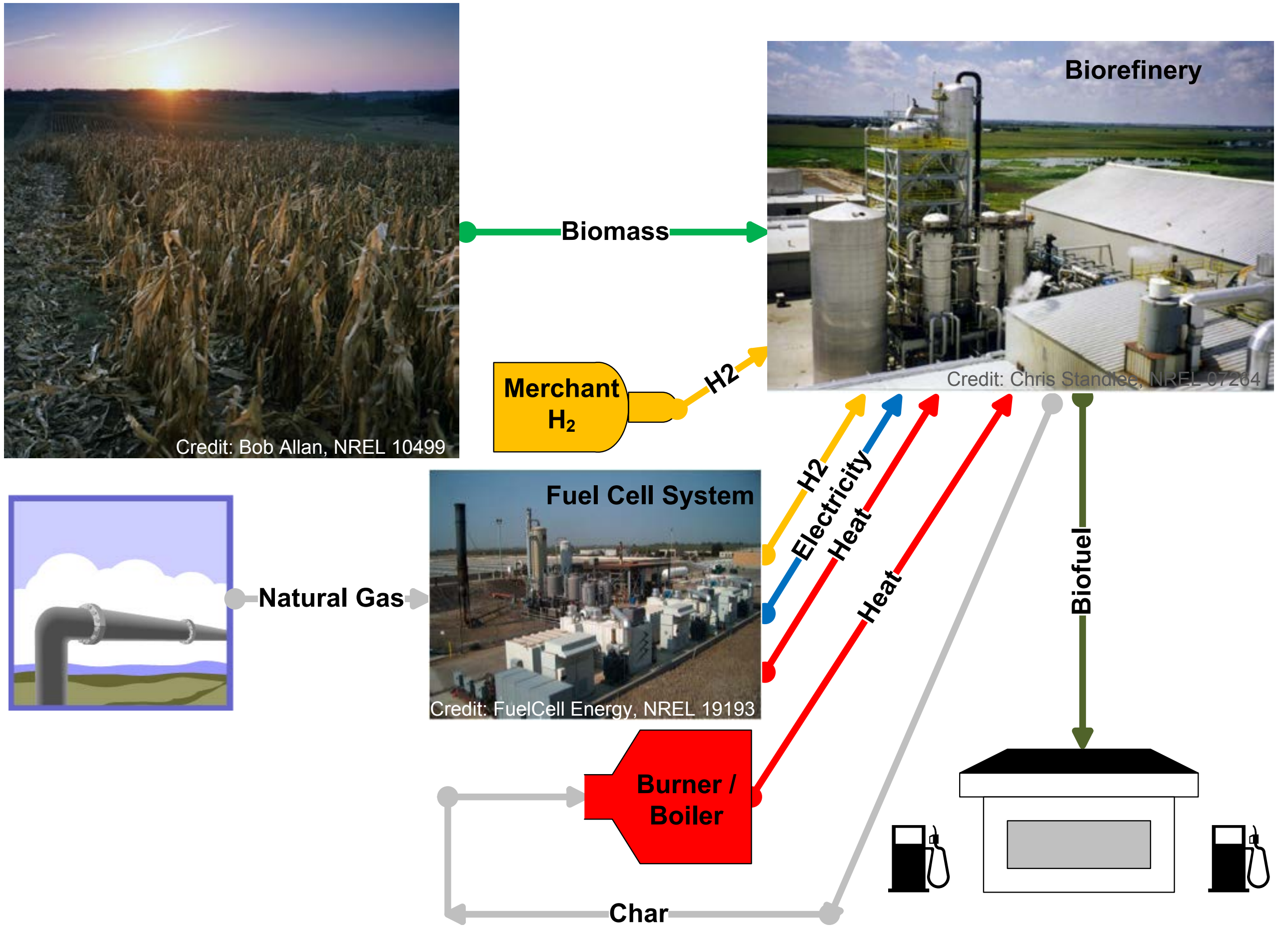
Credit: Bob Allan, NREL 10499

Credit: Chris Standlee, NREL 07264

- Many biomass processing options are being studied but only several require hydrogen in addition to heat and electricity.
- Those include torrefaction, gasification, and fast pyrolysis.
- Fast pyrolysis was chosen because it requires H_2 and an available analysis could be used as a basis.

Fast Pyrolysis with Integrated FC System

MCFC & PAFC options were considered with both CHP & CHHP process options



Credit: Bob Allan, NREL 10499

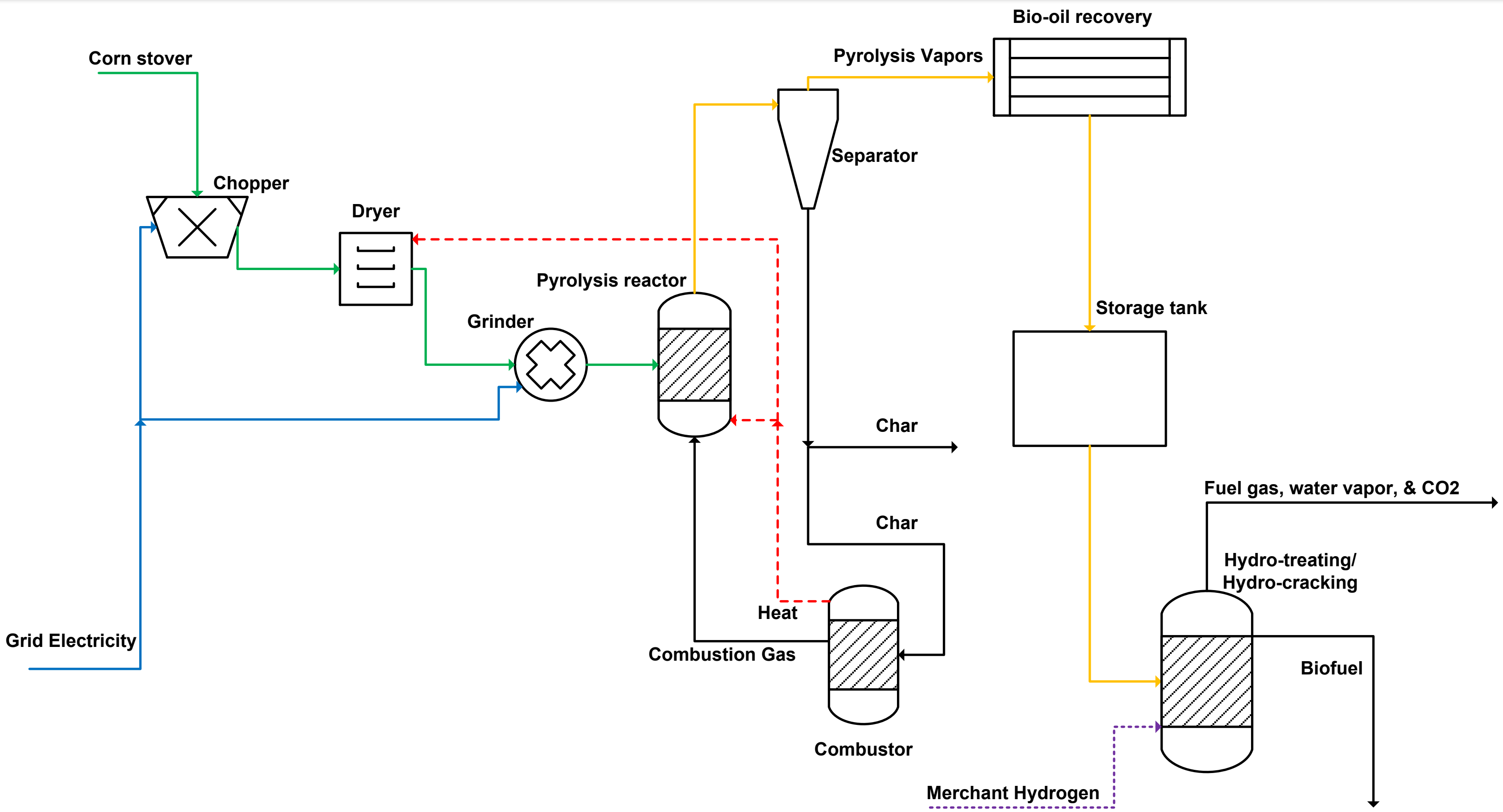
Credit: Chris Standlee, NREL 07264

Credit: FuelCell Energy, NREL 19193

- Two fuel cell systems were analyzed:
  - Molten carbonate fuel cell (MCFC) system with internal reforming
  - Phosphoric acid fuel cell (PAFC) proceeded by a natural gas (NG) reformer
- CHP & CHHP options were analyzed with both fuel cell systems

Fast Pyrolysis Process

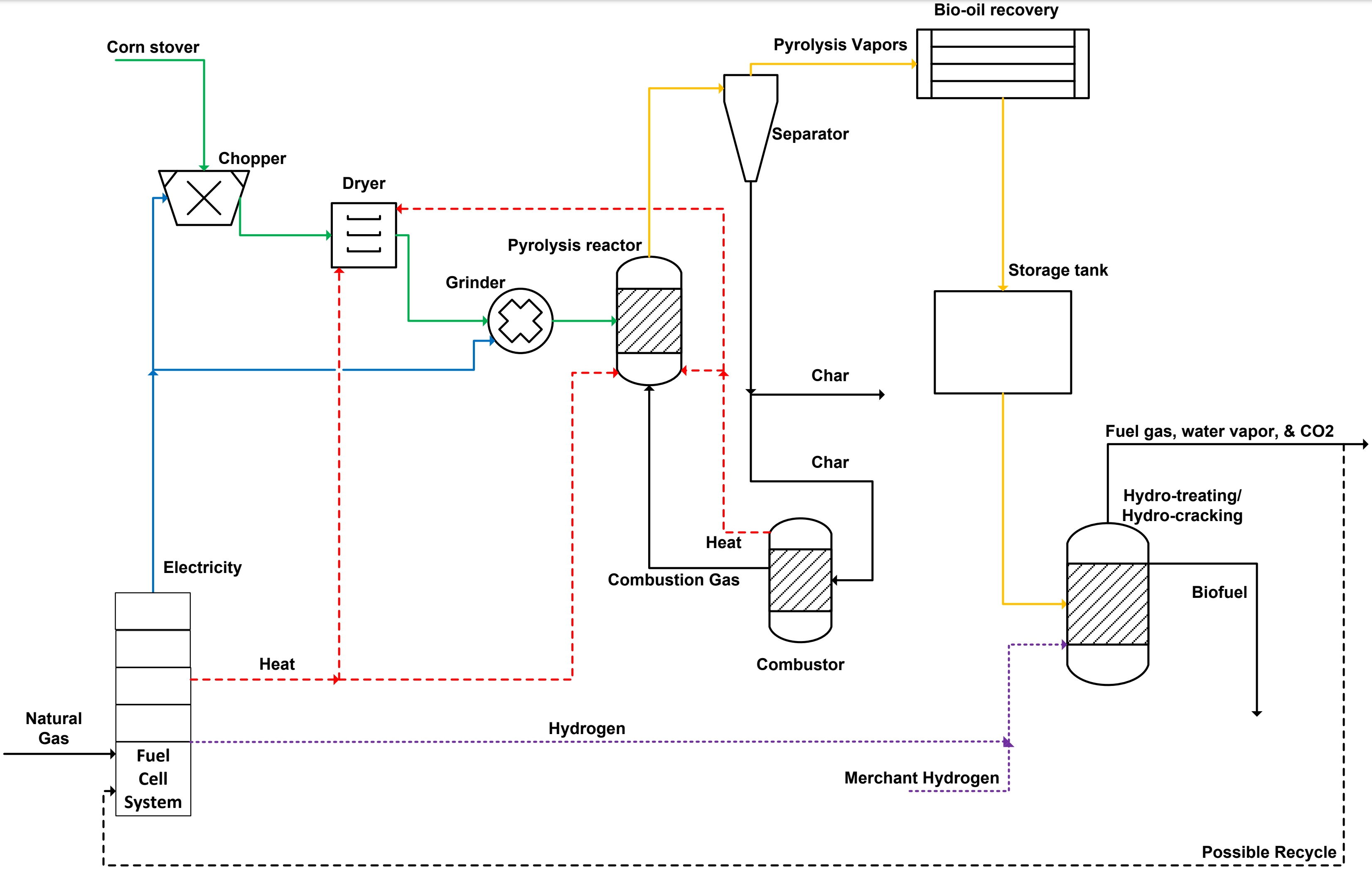
The fast pyrolysis process requires a number of energy feeds: corn stover, electricity from the grid, and heat from combusting char that could be sold as a byproduct. It produces fuel, char, and fuel gas products.



Biofuel product is naptha-diesel weight
Fixed capital investment = $172MM
Levelized cost of biofuel = $2.11 / gal

Fuel Cell System Integration

The FC system integration is designed to provide all power needs. Heat it produces can be used for the dryer and possibly the pyrolysis reactor; thus, increasing char byproduct sales. If used for CHHP, the FC system's hydrogen is used for hydrotreating and hydrocracking



Key Input Parameters & Assumptions

Fast Pyrolysis Biorefinery*

- 2000 dry tonne / day of corn stover feed
- Produces 58.2 million gal fuel / yr
- Power requirement is 11.49 MW
- Heat requirement is 34 MW and is satisfied by combustion of 4440 kg/ hr of char (total char production of 13,660 kg / hr
- Byproduct char sold at $20 / dry ton)
- Fuel upgrading requires 2040 kg / hr H_2

MCFC System

- 45.7% electrical efficiency and 76.9% total efficiency
- Hydrogen yield of 65% of available efficiency (i.e., 20.2% of initial NG energy converted to H_2)

PAFC System

- 37.4% electrical efficiency and 66.0% total efficiency
- External reformer efficiency of 75%

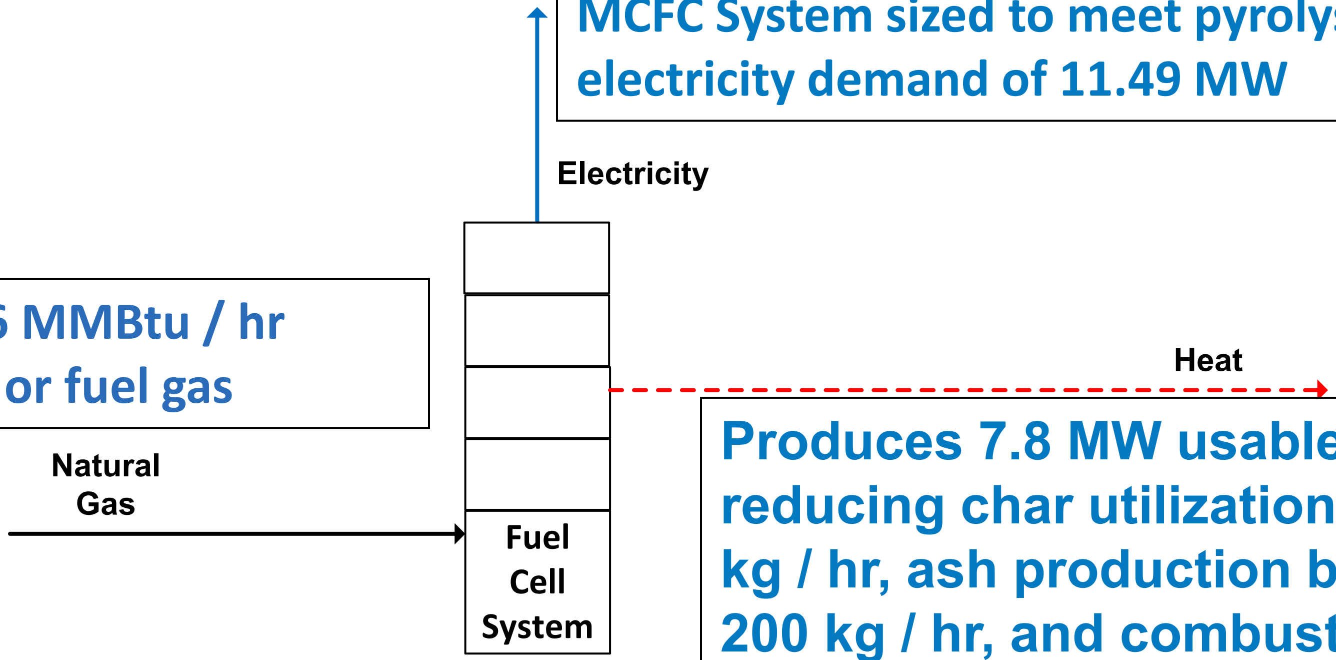
Financial

- 2017 startup of a greenfield plant
- nth plant cost and performance
- 10% internal rate of return (IRR)
- 7900 hours on-stream per year (90.2% capacity factor)
- Natural gas cost is $5.00 / MMBtu (fuel gas has same value)
- Electricity cost is $0.054/kWh
- Hydrogen cost is $1.50/gge

* Data reported in Wright, M.M., Satrio, J.A., Brown, R.C., Daugaard, D.E., and Hsu, D.D. (Nov 2010). *Techno-Economic Analysis of Biomass Fast Pyrolysis to Transportation Fuels*. NREL/TP-6A20-46586. Golden, CO: National Renewable Energy Laboratory

MCFC System Integrated to Provide CHP

Adding a MCFC system with internal reforming increases the levelized cost of the biofuel from \$2.11/gal to \$2.19/gal



MCFC System sized to meet pyrolysis electricity demand of 11.49 MW

Requires 86 MMBtu / hr natural gas or fuel gas

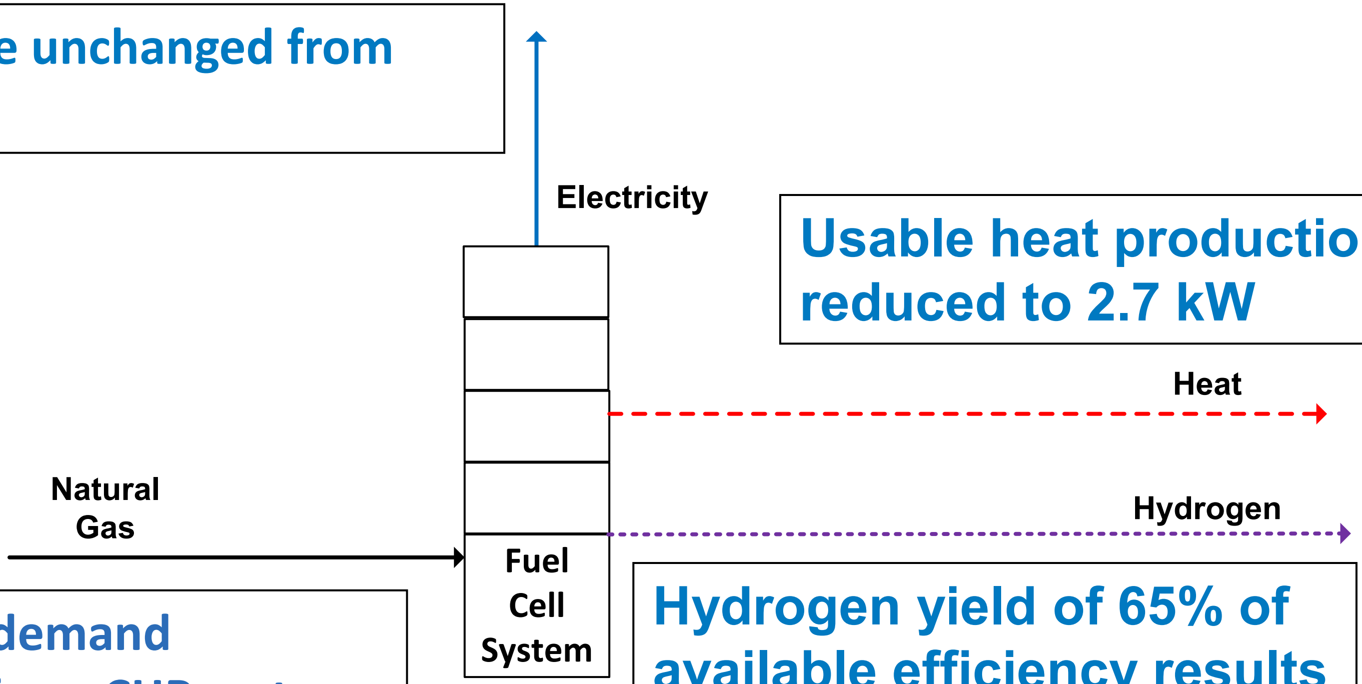
Produces 7.8 MW usable heat reducing char utilization by 1030 kg / hr, ash production by almost 200 kg / hr, and combustion system purchase cost by \$0.8MM

MCFC Cost = \$15,908$e^{-0.096*(2017-1992)}$ / kW = \$1443/kW = \$16.5MM
Installed cost = \$20.2MM
Resultant fixed capital investment (FCI) = \$203MM

MCFC System Integrated to Provide CHHP

Using the MCFC system with internal reforming for CHHP results in a levelized cost of $2.17/gal

MCFC System size unchanged from CHP design



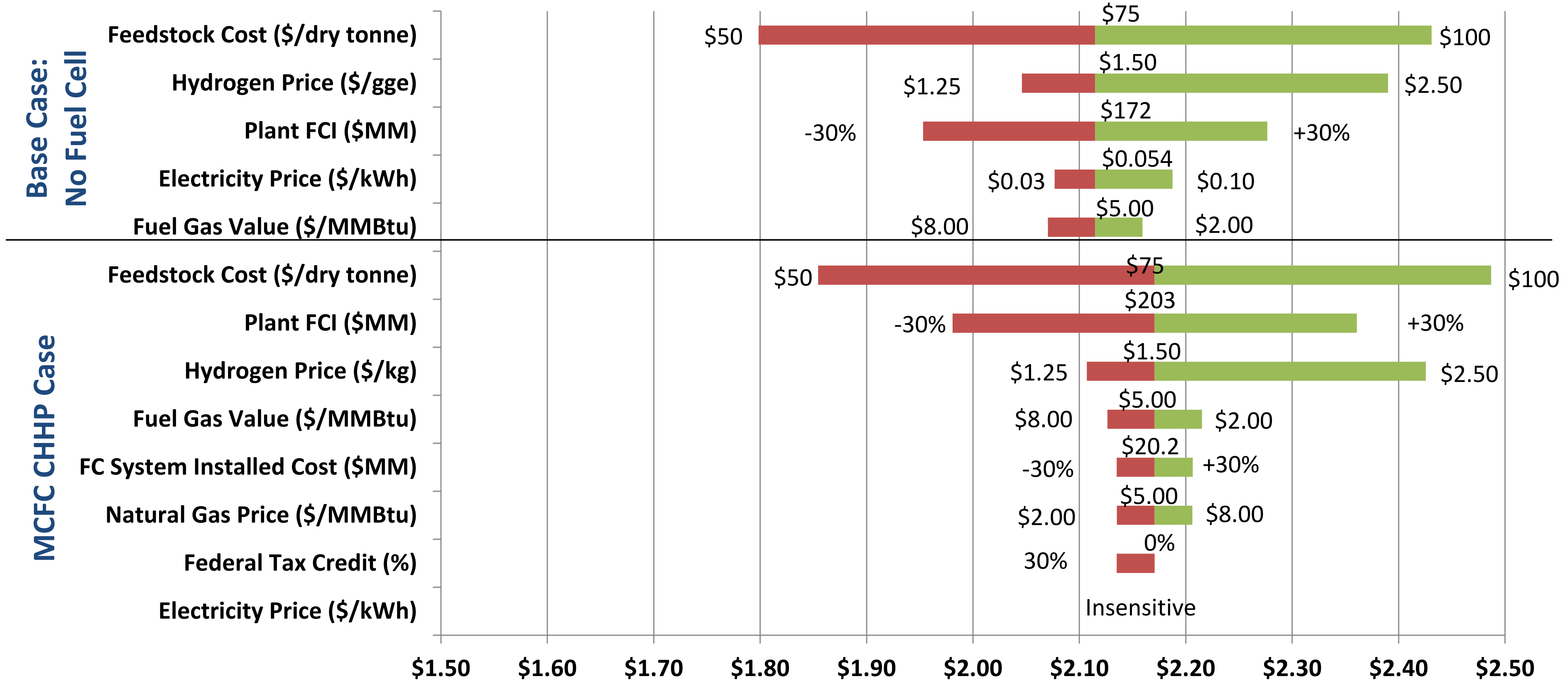
Usable heat production reduced to 2.7 kW

Natural gas demand unchanged from CHP system

Hydrogen yield of 65% of available efficiency results in 152 kg/hr H_2 production (7.5% of total hydrogen demand)

Sensitivities on MCFC CHHP System

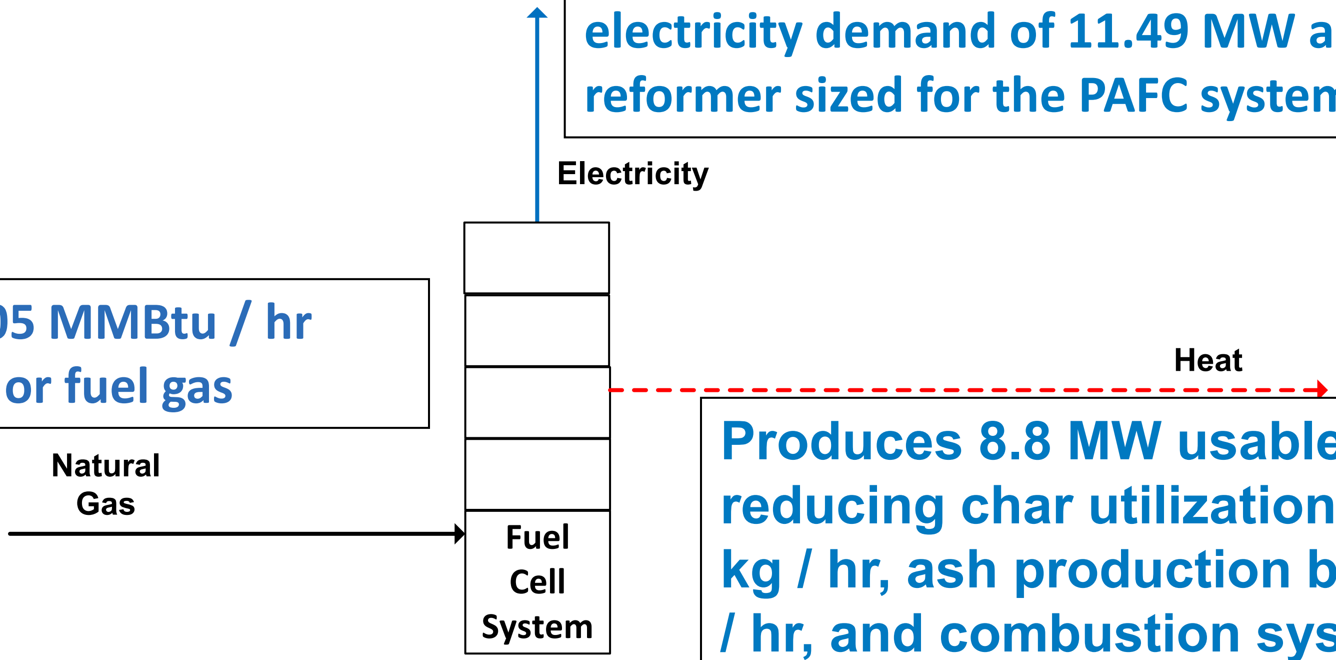
The MCFC CHHP case is cost-competitive when the electricity to natural gas cost ratio is high or there are concerns about electricity or hydrogen price volatility



- **Single-point sensitivity analyses for the base case (without a fuel cell) and the MCFC CHHP cases are shown above**

PAFC System Integrated to Provide CHP

A PAFC system with reformer sized for the FC increases the levelized cost of the biofuel from \$2.11/gal to \$2.29/gal



PAFC System sized to meet pyrolysis electricity demand of 11.49 MW and reformer sized for the PAFC system only

Requires 105 MMBtu / hr natural gas or fuel gas

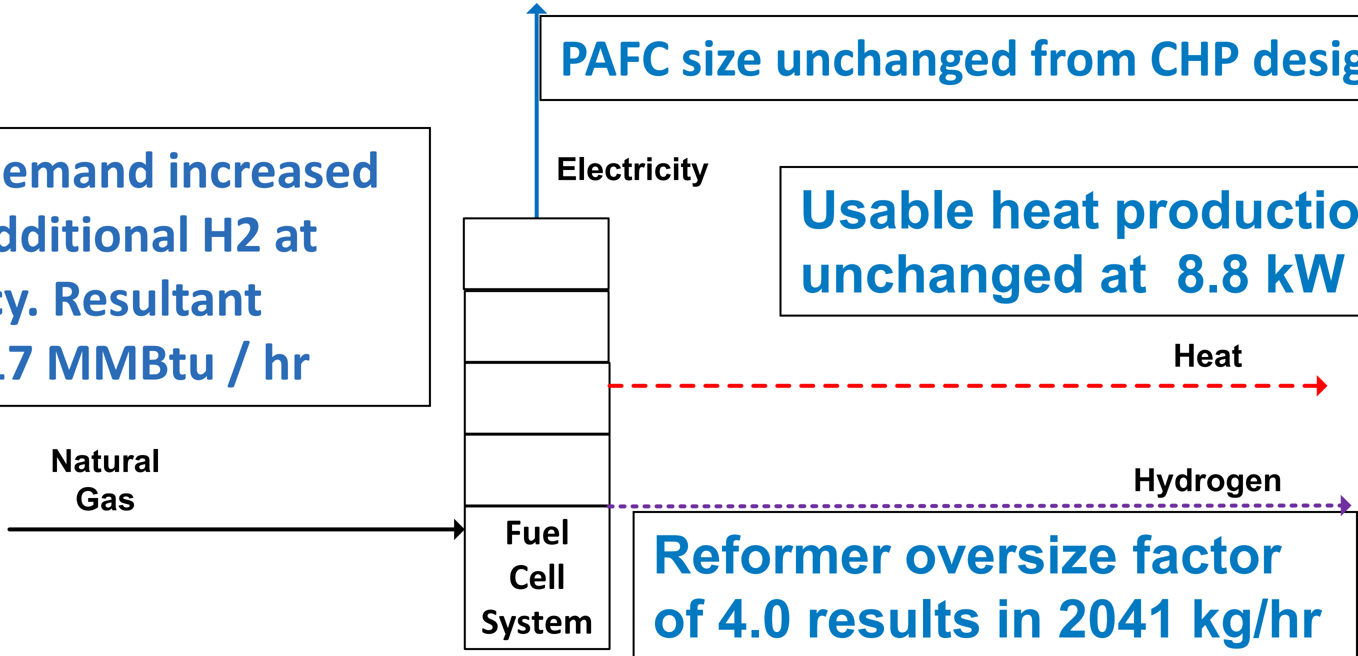
Produces 8.8 MW usable heat reducing char utilization by 1150 kg / hr, ash production by 220 kg / hr, and combustion system purchase cost by \$0.9MM

PAFC System Cost = $\$6837e^{-0.046*(2017-1992)}$ / kW = \$2165/kW = \$24.9MM
Installed cost = \$28.6MM
Resultant fixed capital investment (FCI) = \$227MM

PAFC System Integrated to Provide CHHP

Accomplishment

A PAFC system with the reformer sized to produce H_2 sufficient for both the oil-processing and the FC results in a levelized cost of $2.22/gal



PAFC size unchanged from CHP design

Natural gas demand increased to produce additional H2 at 75% efficiency. Resultant demand is 417 MMBtu / hr

Usable heat production unchanged at 8.8 kW

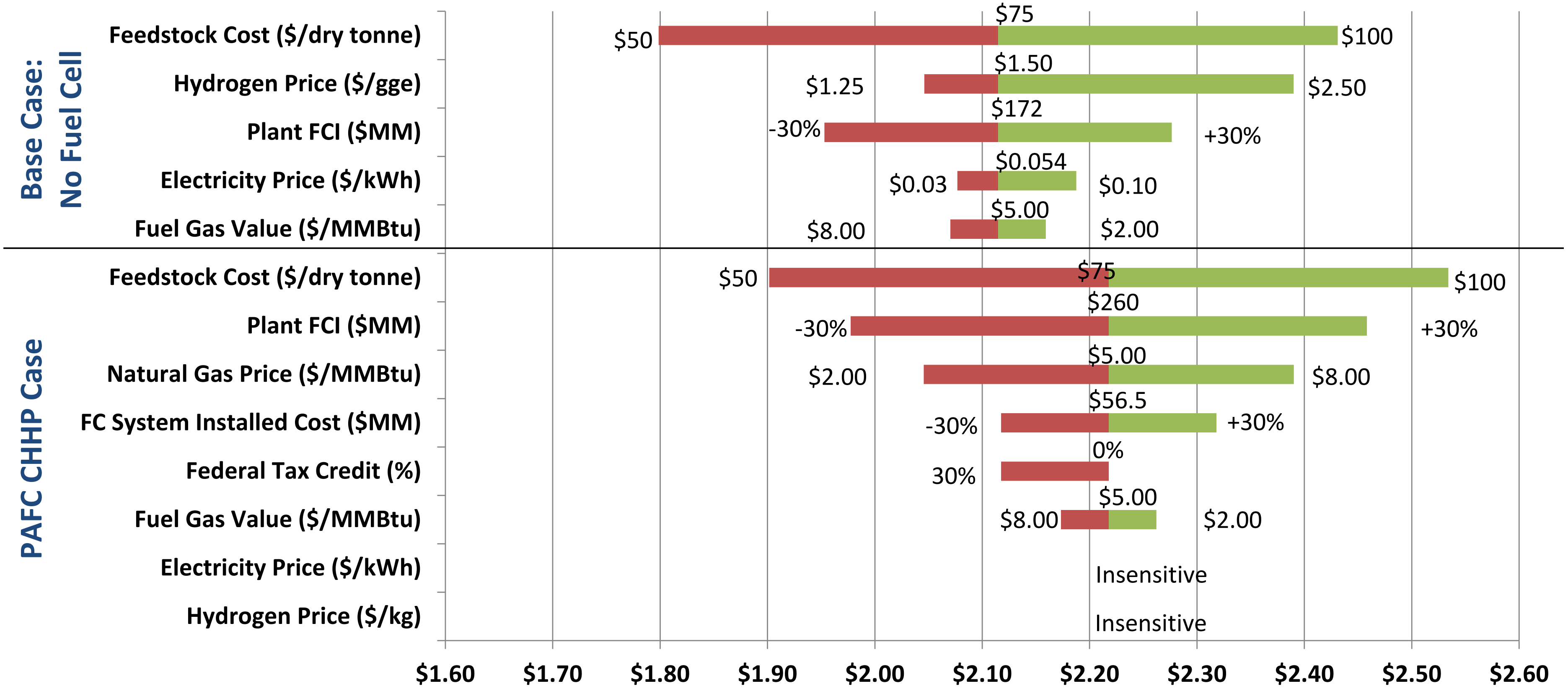
Reformer oversize factor of 4.0 results in 2041 kg/hr H_2 production (100% of total hydrogen demand)

Reformer cost: $24MM purchased ($525/kW AC)
Resultant fixed capital investment (FCI) = $260MM

Sensitivities on PAFC CHHP System

Accomplishment

The PAFC CHHP case eliminates sensitivity to volatility in both electricity and hydrogen price but requires a higher electricity to natural gas cost ratio than MCFC



- **Single-point sensitivity analyses for the base case (without a fuel cell) and the PAFC CHHP cases are shown above**

Comparative Cost Results for Five Options

Accomplishment

FC systems designed for CHHP result in lower levelized costs than those designed for CHP but all have higher levelized costs than the base case due to increased capital costs

	Base Case	**MCFC CHP**	**MCFC CHHP**	**PAFC CHP**	**PAFC CHHP**
Fixed Capital Investment ($)	$172MM	$199MM	$202MM	$223MM	$255MM
Electricity Expenditure ($ / yr)	$4.9MM	$0	$0	$0	$0
Hydrogen Expenditure ($ / yr)	$23.7MM	$23.7MM	$21.9MM	$23.7MM	$0
Natural Gas Expenditure ($ / yr)	$0	$3.4MM	$3.4MM	$4.1MM	$16.5MM
Biofuel Levelized Cost ($ / gal)	$2.11	$2.19	$2.17	$2.29	$2.22

Next Steps and Future Work

- **Quantify other benefits of FC systems**
  - Potential greenhouse gas emission reductions
  - Potential electricity and H_2 market volatility
  - System reliability and resilience
- **Investigate CHP opportunities for near-term biomass processes**
  - Processes include both first and second generation biofuels facilities
  - Focus on those that produce biogas thus providing feed to the fuel cell system
- **Identify additional options where fuel cells can be used in conjunction with other renewable energy technologies**

Project Summary

Fuel Cell CHHP Integration with Biofuel Production Summary	
Approach	Analyze potential of fuel cells for CHHP application in emerging biorefineries by focusing on the cost competitiveness of MCFC and PAFC CHP and CHHP systems in fast pyrolysis biorefineries.
Relevance	• Evaluate potential options for fuel cells in industrial CHHP applications to identify new markets for fuel cells • Leverage Fuel Cell Technologies Office funds by working with other Energy Efficiency and Renewable Energy (EERE) Offices
Technical Accomplishments	• Completed an initial analysis of fuel cells in a fast pyrolysis biorefinery • Analyzed process with MCFC and PAFC systems • Analyzed both CHP and CHHP options with both systems
Collaborations	• DOE Bioenergy Technologies Office & NREL analysts • NREL Fuel Cell Power Modeling Team
Future Work	• Quantify other benefits of FC systems in biorefineries • Investigate CHP opportunities for near-term biomass processes • Identify additional options where fuel cells can be used in conjunction with other renewable energy technologies

Questions & Discussion

THANKS!

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BACK-UP SLIDES

Fast Pyrolysis Biorefinery Design Basis (1)

Particle size	Reduced to 10 mm from incoming average of 10- 25 mm
Drying	Dried to 7% moisture content using steam at 200°C
Grinding	Particle size reduction to 3 mm after chopping
Pyrolysis	Performed at 480°C
	1 atmosphere
	2.75 kg of fluidizing gas/ kg of biomass
	Heat provided by char combustion
Solids Removal	~90% particle removal
Bio-Oil Recovery	Collection of rapidly condensing vapors at ~50°C
	95% collection of aerosols
Storage of bio-oil & char	4 weeks storage capacity
Combustion	120% excess air
	1,100°C process heat
	200°C steam generation

Fast Pyrolysis Biorefinery Design Basis (2)

- Facility produces 58,270,000 gallons naphtha-diesel weight liquids/ year
- Pyrolysis oil produced is upgraded by hydrotreating and hydrocracking
- Facility uses 2,000 MT/day corn stover feedstock
- Electricity required for chopping, grinding, other operations is 90,740,741 kW-hr/year
- On line time is 7900 hrs/ year (CF = 90.2%)

Fast Pyrolysis Biorefinery Design Basis (3)

- **Model developed by Wright, Satrio, Brown, Daugaard and Hsu had TWO versions based on origin of H2 for hydrotreating and hydrocracking**
  - On-site H2 production from reforming a portion of the bio-oil
  - Merchant H2 is brought into the plant from outside source
- **Merchant scenario is considered in this analysis**
- **Fuel cells sized to offset ALL of electricity demand for pyrolysis facility (chopping & grinding of corn stover, facility lighting & controls, etc.)**
- **This provides partial offsets to process heat and H_2**