Performance and Cost Analysis for a 300 kW Tri-generation Molten Carbonate Fuel Cell System

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June 9, 2015

Project ID: SA054

Overview

Timeline

- Project start date: FY 2015
- Project end date: Sep. 2015

Barriers

- Future Market Behavior (A)
- Inconsistent Data, Assumptions and Guidelines (C)
- Unplanned Studies and Analysis (E)

Budget

- FY15 FCTO Funding: $100 K
- FY15 VTO Funding: $100 K

Partners/Interactions

- Fuel Cell Energy
- Argonne (ES, FMS)
- Strategic Analysis (SA)
- PDC Machines, RIX Industries

Objectives and Relevance

Objectives

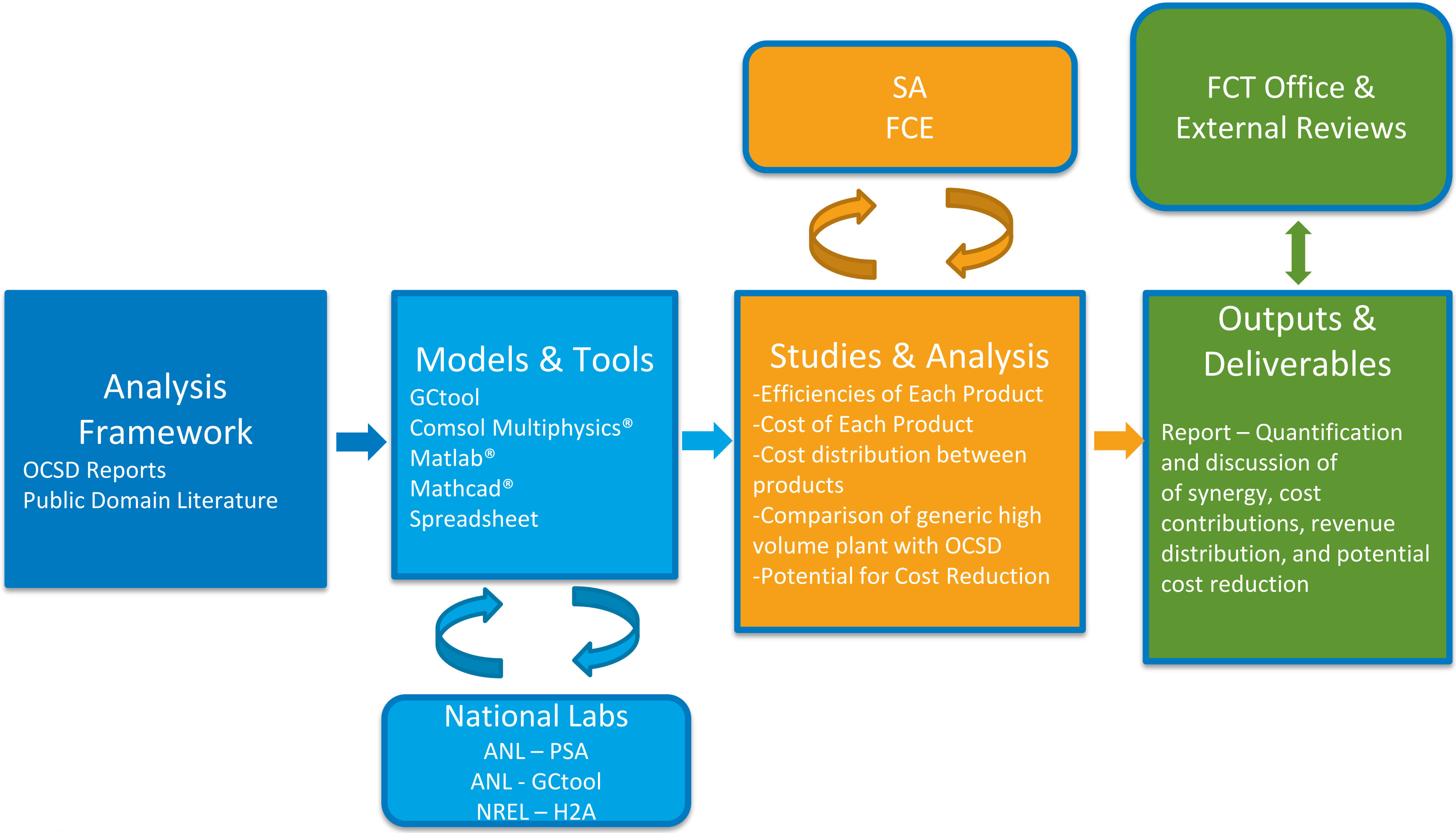
- Determine the performance and cost benefits of a molten carbonate fuel cell (MCFC) plant that can co-produce electric power, hydrogen, and heat.
- Develop meaningful definitions for cell, stack, electrical, hydrogen production efficiencies in tri-generation modes.
- Explore scenarios in which the MCFC trigeneration system has particular cost benefits including the scenario for charging electric vehicles.
- Examine strategies (waterfall chart) for improving the performance and reducing the cost relative to the one-off OCSD tri-gen system.

Relevance

- Tri-generation systems offer a blend of products (power, hydrogen, heat) to match local demand.
- The waste heat produced in high-temperature fuel cells can be utilized to reform hydrocarbon fuels.
- Flexibility in tri-generation offers an opportunity to produce hydrogen at night when the electricity demand (rates) is low and to produce electricity during day when the electricity demand (rates) are high.
- Revenue from electricity generation, electric vehicle charging and usable waste heat can subsidize (off-set) the cost of producing hydrogen.

Project Overview

Assessment of Efficiency, Cost, and Potential for Cost Reduction for a Tri-gen Plant



Approach

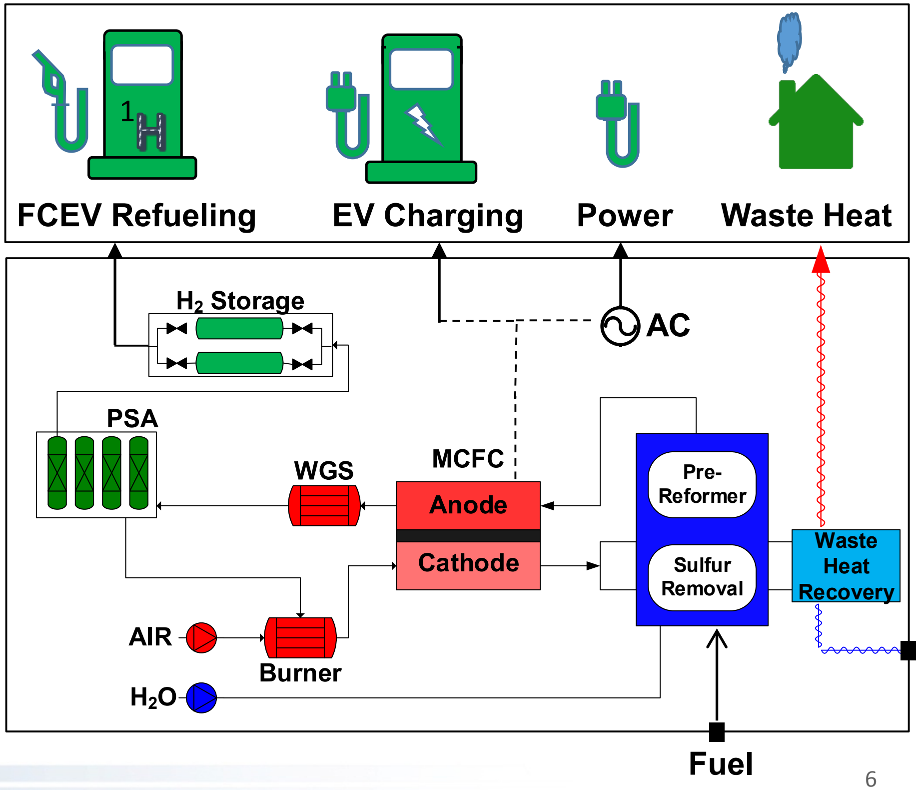
- Formulate a consistent system performance model of thermally-integrated natural gas (NG) fuel processor and MCFC stack in the electricity generation mode (CHP)
- Develop models for hydrogen purification by pressure swing adsorption (PSA) and hydrogen compression, storage and dispensing (CSD)
- Extend the CHP model to combined electricity, hydrogen and heat mode (CHHP) by coupling the CHP, PSA and CSD subsystems
- Develop performance metrics for the MCFC stack, electricity generation, hydrogen production, PSA, and hydrogen storage.
- Formulate cost models for MCFC stack, mechanical and electrical balance of plant (MBOP and EBOP), PSA, CSD, and vehicle charging system.
- Conduct cost studies and sensitivity analyses for the levelized cost of electricity generation and hydrogen production.
- Explore strategies to improve the performance of the system in CHP and CHHP modes
- Analyze scenarios to improve the economics of MCFC based tri-generation plants

MCFC Tri-Gen System Performance Model

GCtool model for system performance: 100% electric and combined electricity generation and hydrogen production modes

- MCFC stack with internal reforming
- Air supply system
- Fuel cleanup and reformate processing: sulfur removal, pre-reformer, WGS*
- H_2 purification by pressure swing adsorption (PSA)
- Compression storage and dispensing (CSD): 5-stage ionic compressor
- Waste heat recovery

Operating Mode	100% Electricity	Comments
Stack and Fuel Processing		
Fuel Utilization (%)	73	Maximum fuel utilization limited by 650°C stack temperature; determines Nernst potential
Oxygen Utilization (%)	60	Determines burner and stack temperatures, and Nernst potential
Steam to Carbon Ratio	2	Determines methane slip and carbon formation
Air Compressor Efficiency (%)	60	Typical data for air blowers
Inverter Efficiency (%)	97	Data from APCI, Fuel Cell Energy and OCSD
H_2 Purification (PSA) System		
Hydrogen Recovery (%)	75	Depends on PSA pressure (10 bar), reformate composition and H_2 purity, 64% at 5 bar
PSA Compressor Efficiency (%)	58	Data for RIX 2-stage, double acting, air-cooled, oil-free compressor
H_2 Compression Storage and Delivery (CSD)		
Storage Pressure (bar)	930	Overpressure needed for 700-bar refueling
H_2 Compressor Efficiency (%)	80	Data for Linde's 5-stage ionic H_2 compressor: 2.7 kWh/kg energy consumption over 5-1000 bar



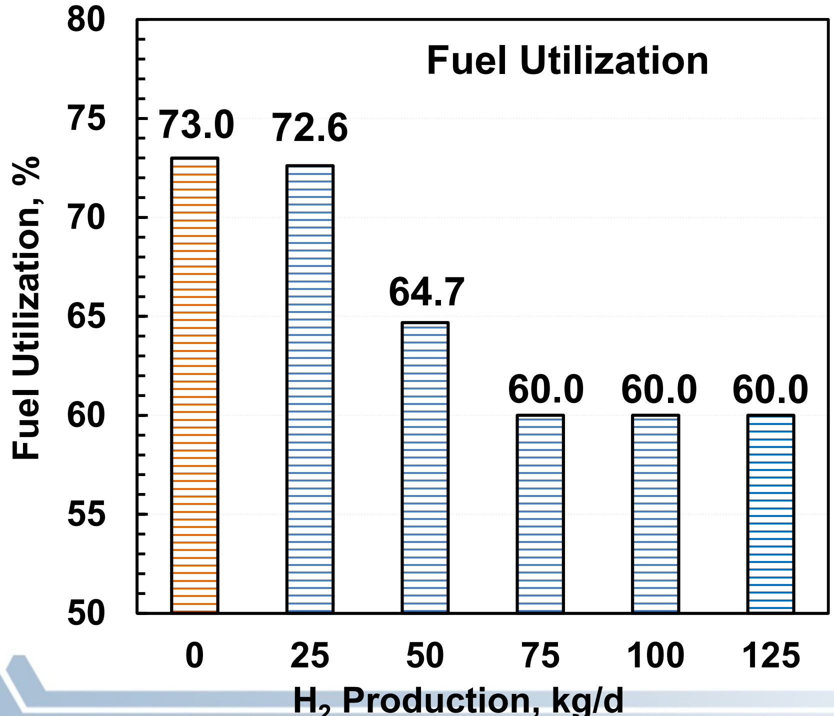
*WGS: water gas shift

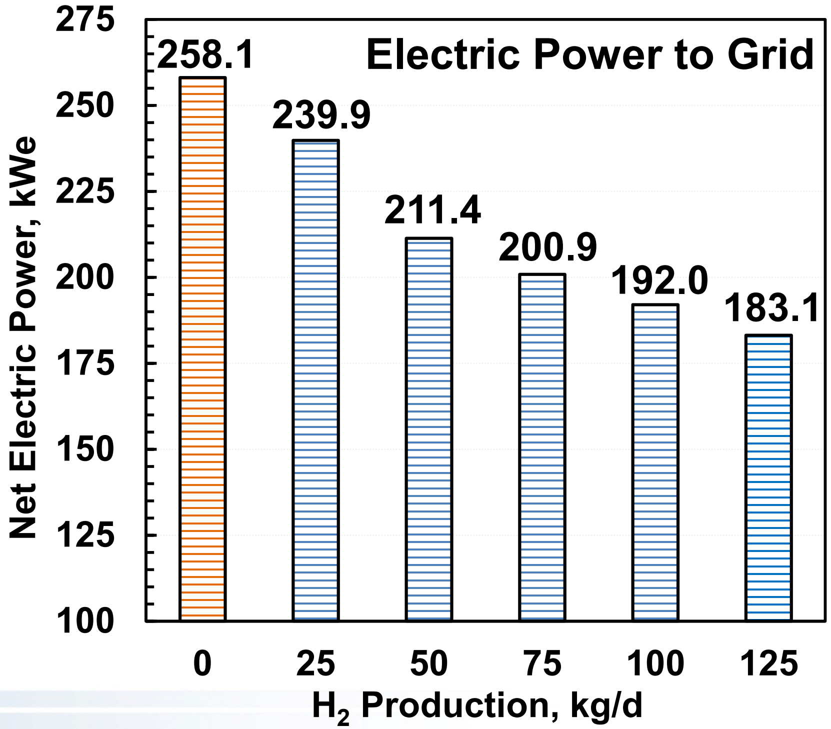
Higher fuel input, lower fuel utilization to co-produce H_2 without loss of electrical capacity

H_2 production >50 kg/d requires 5% increase in fuel input to stack and supplemental fuel to burner

- Fuel utilization (U_F) defined assuming 1 mole of C can produce 2 moles of H_2: $C + 2H_2O = CO_2 + 2H_2$

Parameter	Values	Constraint
Fuel Utilization (%)	73 - 60	Supply 0 - 125 kg/d H_2 to CSD
Air Flow Rate (g/s)	286 - 260	Operate stack at constant 60% oxygen utilization
Fraction Reformate to Burner (%)	100 - 15	Maintain 650°C stack temperature





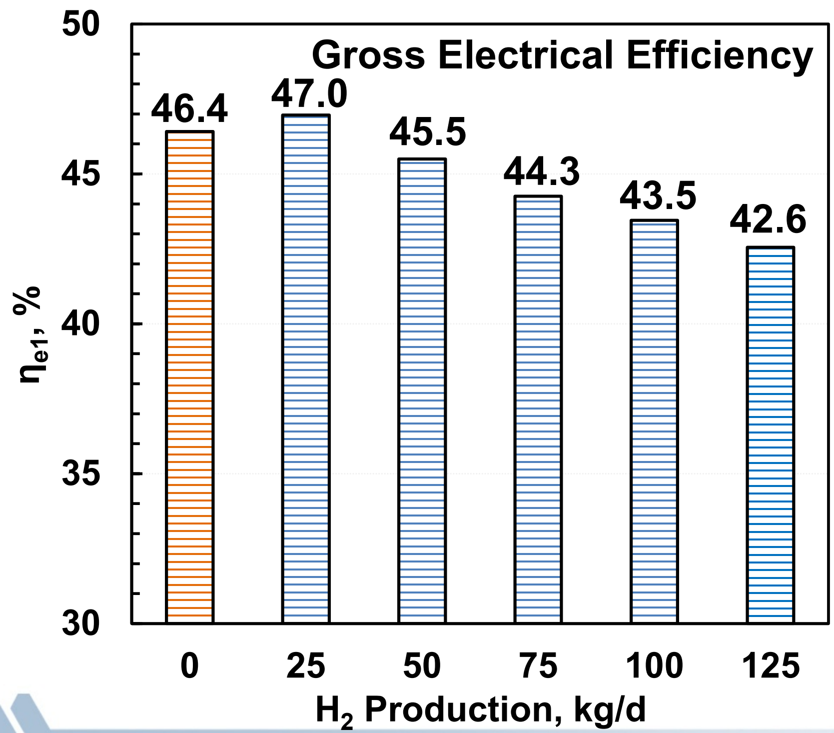
Electrical efficiencies decrease as more H_2 is co-produced

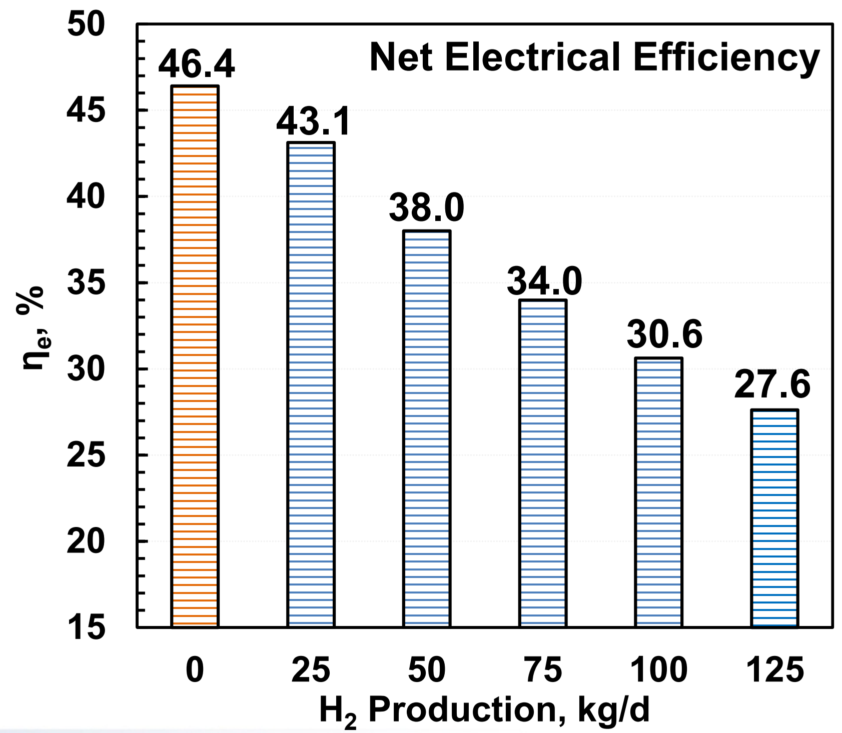
Gross Electrical Efficiency (η_{e1}): Ratio of gross AC power produced to the LHV of fuel consumed (Q_F - Q_{CSD}) in producing gross power

$$\eta_{e1} = \frac{\eta_{in} P_{MC} - P_d}{Q_F - Q_{CSD}} \qquad P_d = P_F + P_W + P_A + P_{AX} + P_{raf}$$

Net Electrical Efficiency (η_e): Ratio of AC power supplied to the grid to the LHV of fuel (Q_F) fed to the station

$$\eta_e = \frac{\eta_{in} P_{MC} - P_d - P_{PSA} - P_{CSD}}{Q_F}$$





η_{in}: inverter efficiency; P_d: parasitic power; Subscripts: F: fuel, W: water, A: air, AX: auxiliaries, raf: rafinate

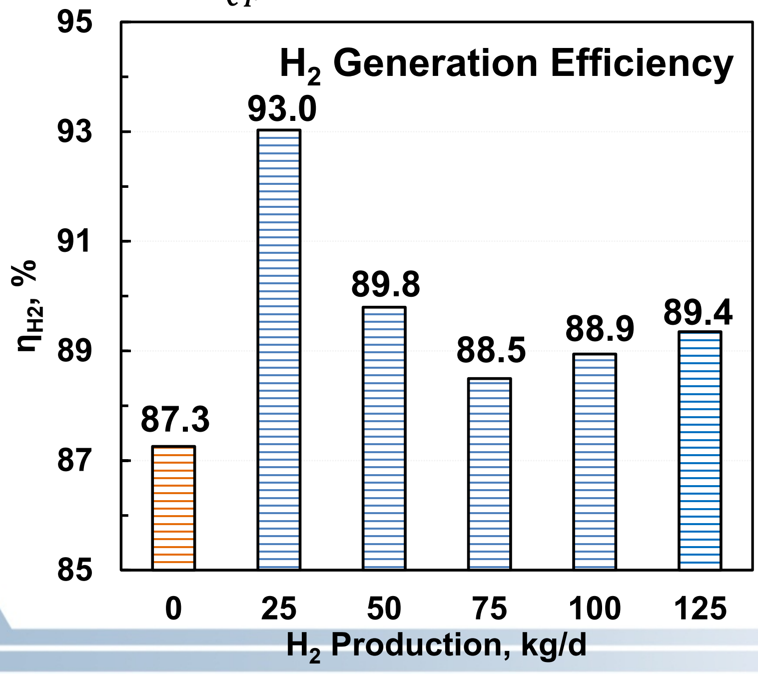
87% H_2 generation efficiencies possible with stack waste heat

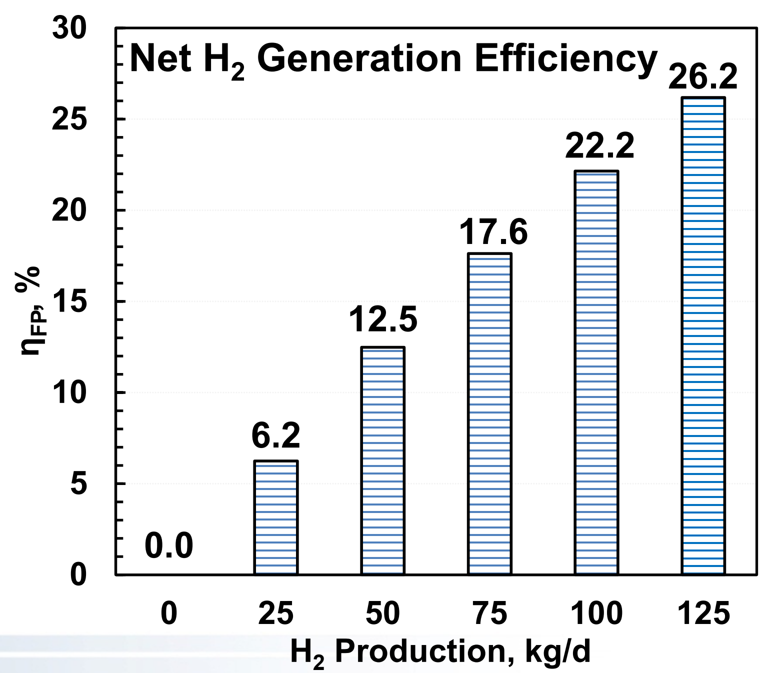
Hydrogen Generation Efficiency (η_{H_2}): Processes such as fuel oxidized in the burner, H_2 consumption in fuel cleanup (HDS: hydro-desulfurization) and waste heat contribute to the loss in H_2 generation efficiency

- All or some of the H_2 produced in the pre-reformer and MCFC stack (MC) is converted to DC power in the MCFC stack
- $\eta_{H_2} = \frac{(Q_{H_2,MC} + Q_{H_2,CSD})}{Q_F}$

Net Hydrogen Generation Efficiency (η_{FP}): Ratio of LHV of H_2 supplied to CSD to the LHV of fuel fed to the station

- $\eta_{FP} = \frac{Q_{H_2,CSD}}{Q_F}$





87% H_2 storage efficiency and 32% waste heat recovery efficiency is possible

H_2 Storage Efficiency (η_{CSD}): Accounts for the LHV of fuel expended in producing the power required by the H_2 compressor (P_{PSD}).

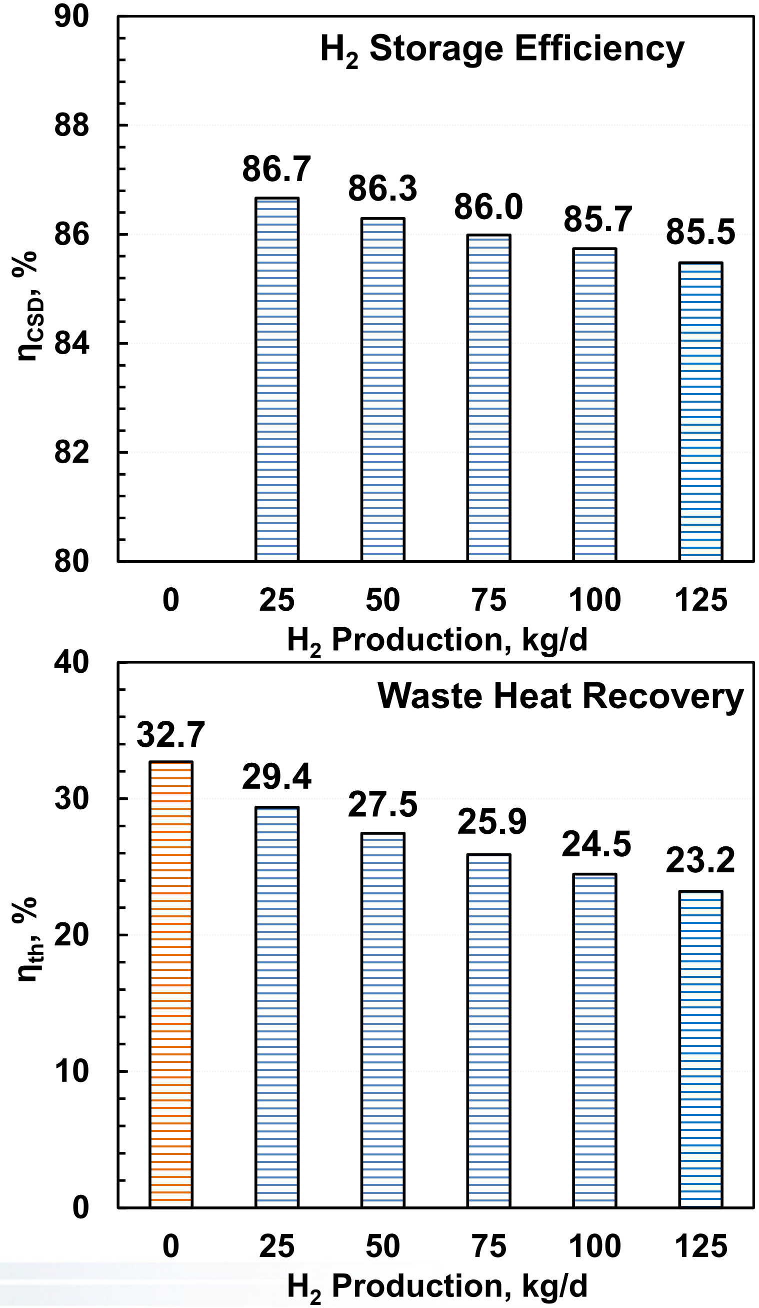
- $\eta_{CSD} = \frac{Q_{H_2,CSD}}{Q_{H_2,CSD} + \frac{P_{CSD}}{\eta_{e1}}}$

Heat Recovery Efficiency (η_{th}): Defined as the heat that can be recuperated (Q_{th}) at temperature above 100°C: $\eta_{th} = {}^{Q_{th}}/_{Q_F}$

- Lower grade heat also available in inter-stages of air, PSA and H_2 compressors.

Possible subjects for future study

- Include H_2 compressor operating curves,
- Alternate compressors, e.g., diaphragm compressor
- Electrochemical pumps for combined H_2 purification and compression
- Trade-off between PSA and H_2 compressor power by lowering the PSA pressure



MCFC Cost Model - Assumptions & Methodology

- Extensive literature and patent searches to identify process flow, material and equipment requirements. Direct inquiries with OEMs for BOP costs.

Cell Components
- Ball milling
- Slurry formulation
- Tape casting
- Sintering

Bipolar Plate
- Metal shaping, stamping
- Ni cladding
- Heat treatment
- Welding

Stack
- Assembly
- Conditioning

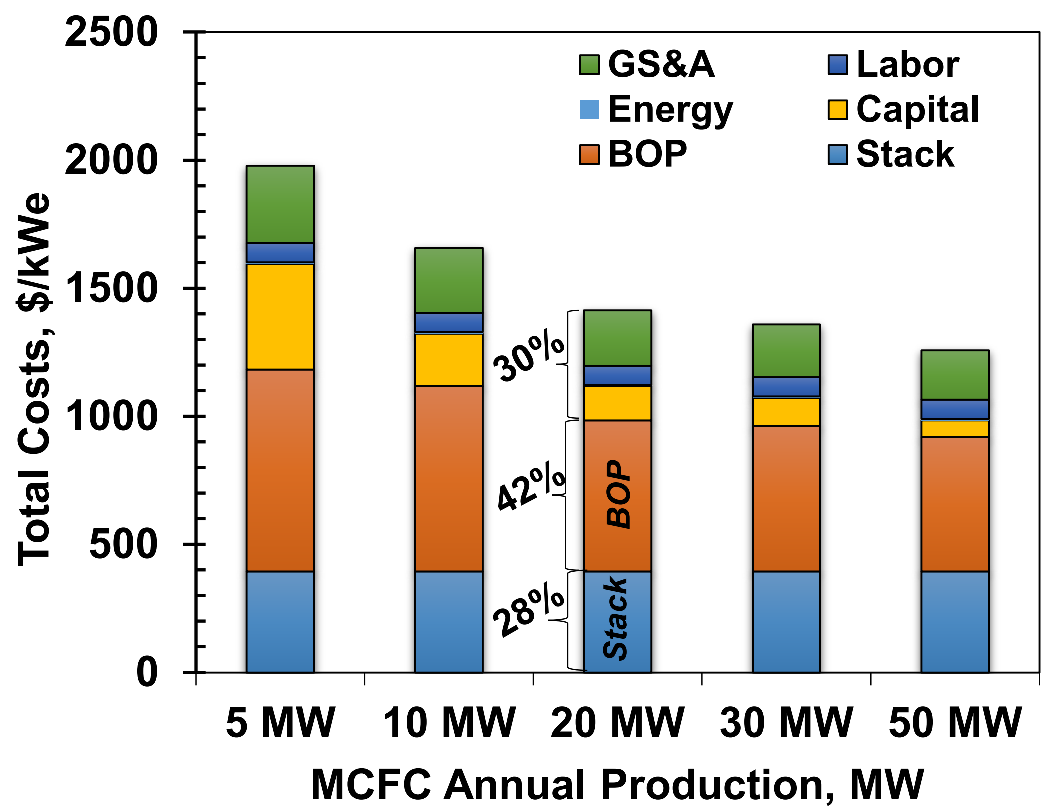
Category	Items	Assumptions
Cell & Bipolar Plate	Anode, Cathode Matrix, Bipolar plate	Material purchased from suppliers* Multiple lines operating in parallel
Stack	Assembly	Includes cost of labor and parts
BOP	MBOP/EBOP	OEM quotes/literature
Capital	Equipment Maintenance/Parts Building Recovery factor	10-yr lifetime 5% direct capital $150/ft^2$ 0.24
Energy	Electricity	$0.07/kWh
Labor		$45/h

*Ni ($32/kg), NiO ($32/kg), Al_2O_3 ($12/kg), Li_2CO_3 ($5.8/kg), K_2CO_3 ($1.3/kg)

MCFC Cost reduction due to economy of scale levels off beyond a MCFC unit production rate of 50 MW per year

- BOP accounts for the largest portion (40-42) of the total system cost, major contributors to BOP cost (excluding the PSA) are the raffinate compressor, shift reactor, desulfurizer and the DCAC inverter
- MCFC system cost reduced by 30% as annual production increases from 20 to 50 MW (e.g., 50 units/year of 1000 kW capacity)

MBOP	**Compressor/Pump**
	Air blower
	Raffinate compressor
	Water pump (fuel processing)
	Water pump (fuel processing)
	Heat Exchanger
	Air preheater
	Fuel preheater
	Steam superheater
	Heat recovery-1
	Heat recovery-2
	Heat recovery-3
	Condenser
	Boiler
	Reactor
	Burner
	Pre-reformer
	WGS
	HDS/ZnO (desulfurizer)
EBOP	DCAC inverter



Summary of main capital costs – Modeled system compared to OCSD

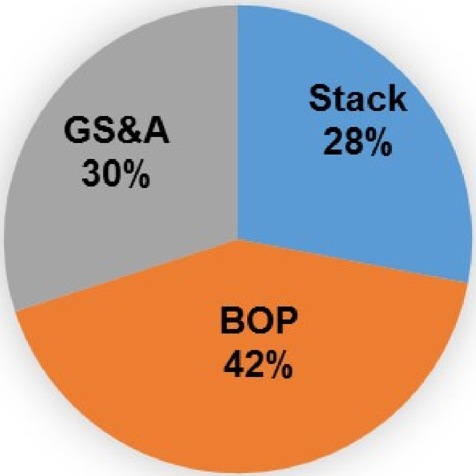
OCSD Comparison

	Capital Cost	Modeled System ($K)	OCSD ($K)
Fuel Cell System	MCFC Stack	143	(TBD)
	MCFC BOP	214	(TBD)
	MCFC GS&A	153	(TBD)
Compression, Storage, Dispensing + PSA	H_2 Compressors	191	725
	Reformate Compressor	22	150
	PSA	96	(TBD)
	Storage and Dispensing	306	TBD

Modeled System

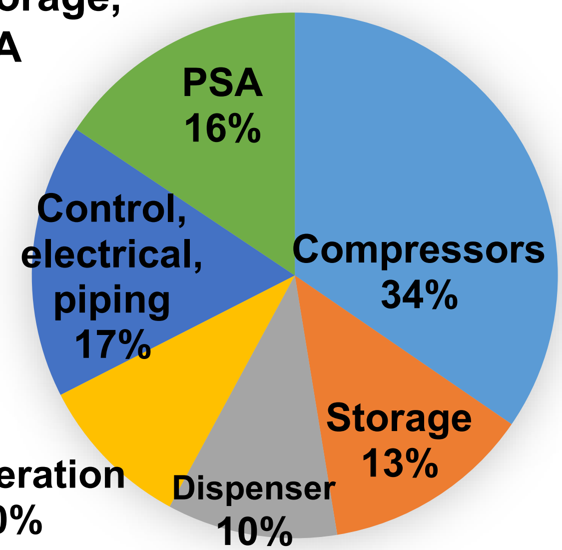
MCFC Fuel Cell System

Installed cost: $510,000



Compression, Storage, Dispensing + PSA

Installed cost: $615,000

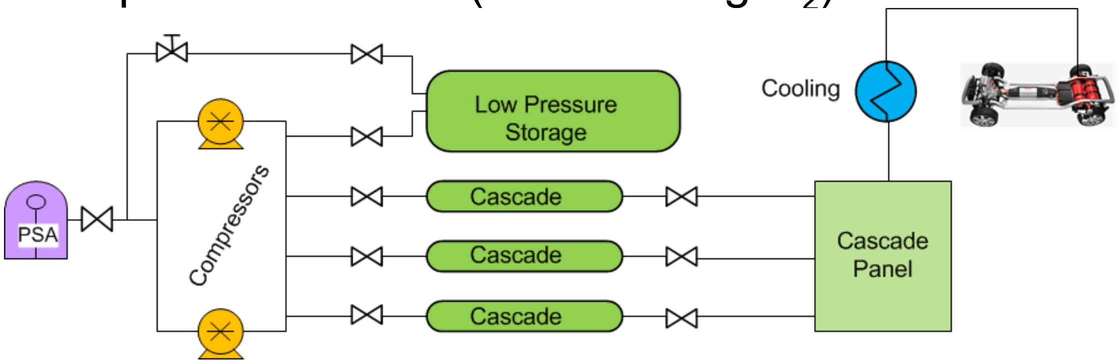


Compression, Storage, and Dispensing – Assumptions & Methodology

- Two compressors, each operates at 50% of designed flow rate
- Low pressure on-site storage type IV tanks and high/low pressure cascade type IV tanks for refueling
  – Netting analysis, calibrated with ABAQUS model, to determine the tank geometry and the amount of carbon fiber composite needed

	H_2 Stored (kg)	Pressure (bar)	CF Composite Weight (kg)	Liner Weight (kg)	Tank Cost ($)
On-site Storage Tank	20 kg	482	293.3	65.3	$6,548
Cascade Low Pressure Tank	12 kg	482	179.4	46.9	$4,286
Cascade High Pressure Tank	10 kg	875	204.4	35.3	$4,325

- Hydrogen supply and dispensing
  – 125 kg/day, cascade dispensing with cooling for 700-bar onboard storage
  – Refrigeration unit required for fast fill (0.24 kWh/kg-H_2)



CSD capital cost can be reduced to $500,000

- H2A model for compressor cost
  - PDC Machines compressors at OCSD were oversized and expensive (150 kW, $725K compared to a needed 2 x 31 kW units costing $191K)
  - H2A model includes spare compressor (eliminated in this analysis)
- Storage tank costs provided by SA based on annual 5k production volume
- Refrigeration, dispenser, electrical, control & safety costs derived from H2A
- Total installed capital cost $498,000or $1,658/ kW

H_2 compression, storage and dispensing capital costs for a system similar to OCSD

	# of Units	Unit Size/ Description	Lifetime, yr	Uninstalled Cost, $	Installation Factor	Installed Cost, $
Compressors	2	31 kW	10	159,300	1.2	191,100
On-site Storage Tanks	6	20 kg (482 b)	20	39,300	1.3	51,100
Cascade Pressure Tanks	3	12 kg (482 b)	20	12,800	1.3	16,700
Cascade Pressure Tanks	2	10 kg (875 b)	20	8,700	1.3	11,200
Dispenser	1	-	10	53,700	1.2	64,400
Refrigeration Equipment	1	3.3 tons	15	49,200	1.2	59,000
Electrical Upgrade	-	480 V	20	28,400	2.2	62,500
Control and Safety			20	20,300	1.2	24,400
Piping	-		20	17,000	1	17,000
Total CapEx				**389,000**		**498,000**

The charging station adds ~5 cents to the cost of power

- Fuel cell generated power can be sold to recharge electric vehicles

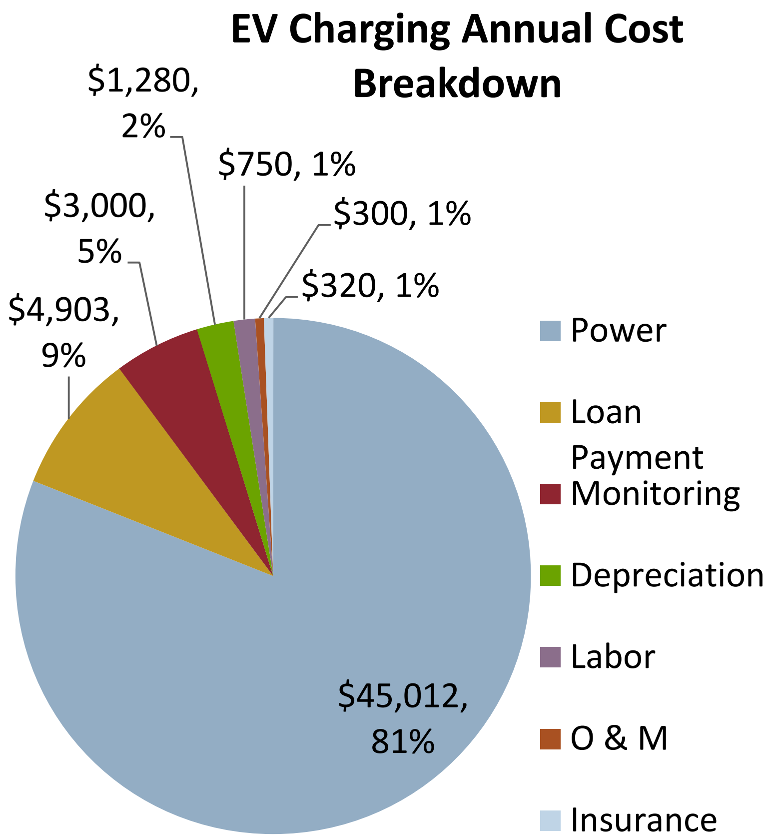
Assumptions

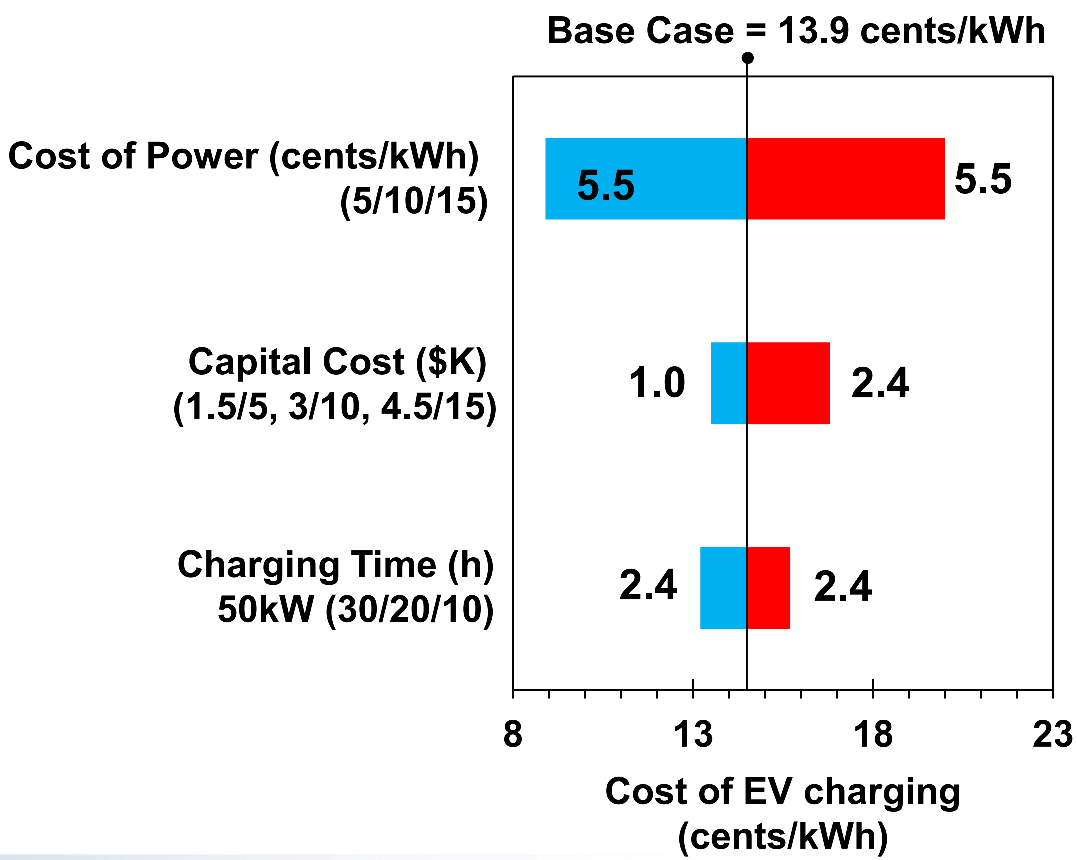
- Number of charging stations:
  - 4 (6 kW) costing $3,000 each
  - 2 (50 kW) costing $10,000 each
- Availability:
  - 330 days, 1240 kWh/day
- Charger Efficiency = 90%
- Total Investment = $36,800
- Loan Period = 10 years at 6%

Capital Investment	**$36,800**	
Loan Payment, $/year	$4,903	
Monitoring, $/year	$3,000	
Labor, $/year	$750	
Depreciation, $/year	$1,280	
Operation & Maintenance, $/year	$300	
Desired Rate of Return, %	10%	
Cost of FC Plant Electricity, $/kWh	$0.10	$0.15
Cost of FC Plant Electricity, $/year	$55,565	$78,071
Cost of Power to Vehicle, $/kWh	**$0.145**	**$0.200**

Cost of EV charging dominated by power generation cost

- The cost of generated power dominates the cost of power to the Evs
- Labor hours and monitoring adds little to the cost of EV charging



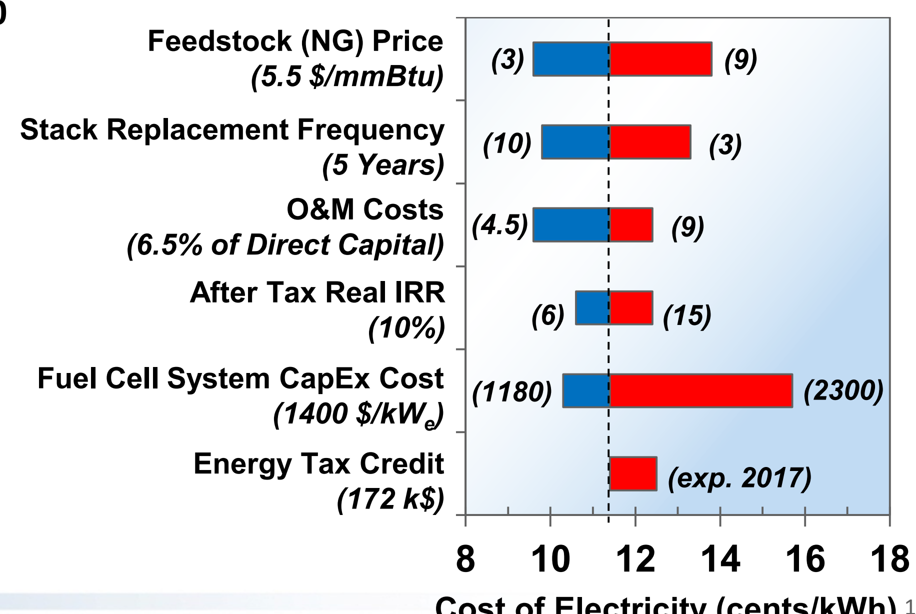


CHP mode: 11-19 cents/kWh LCE cost

- Assumptions
  - Federal tax credit for 300 kW_e facility (H.R. 1424, 2008, expiring in 2017)
  - 100% equity financing at 8% interest rate, IRR 10%.
  - NG price in start-up year: $5.5 /mmBtu (2014 average industrial price, EIA)
  - Fuel cell stack replaced every 5 years; O&M at 6.5% of direct capital cost
  - Indirect capital cost (site preparation, project contingency, permits, etc) $180,000

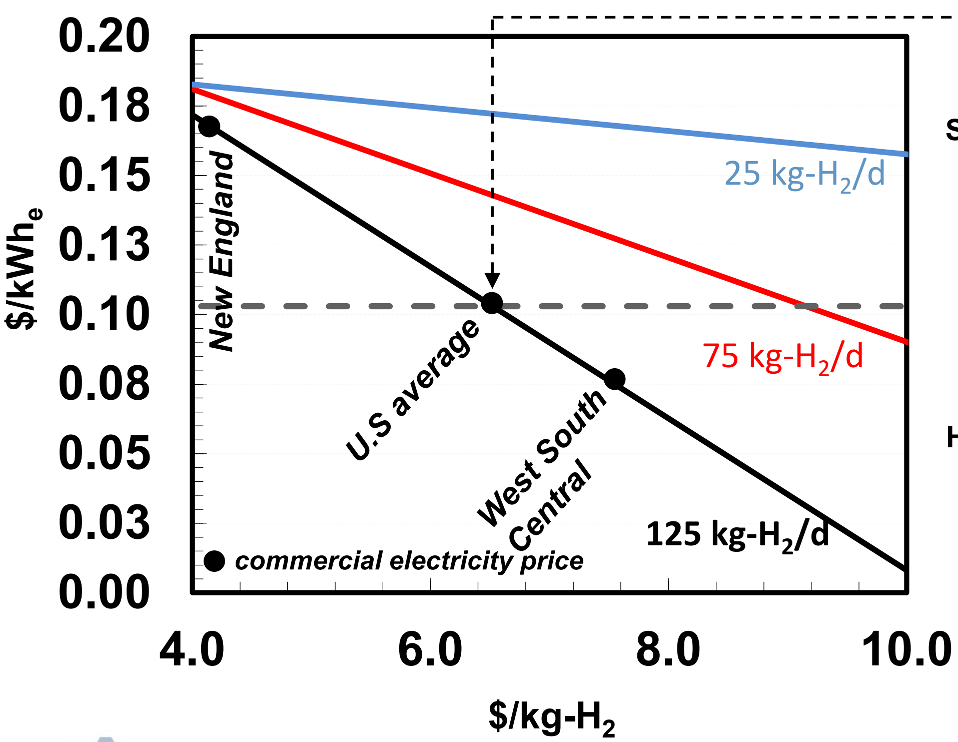
Molten carbonate fuel cell	$509,800	Auxiliary heater and water distribution	$55,000
H2 purification (excl. control)	$99,700	EV charging	$36,800
H2 compression, storage and dispensing	$497,500	System integration and control	$30,000
Total uninstalled capital cost	**$1,228,800**		

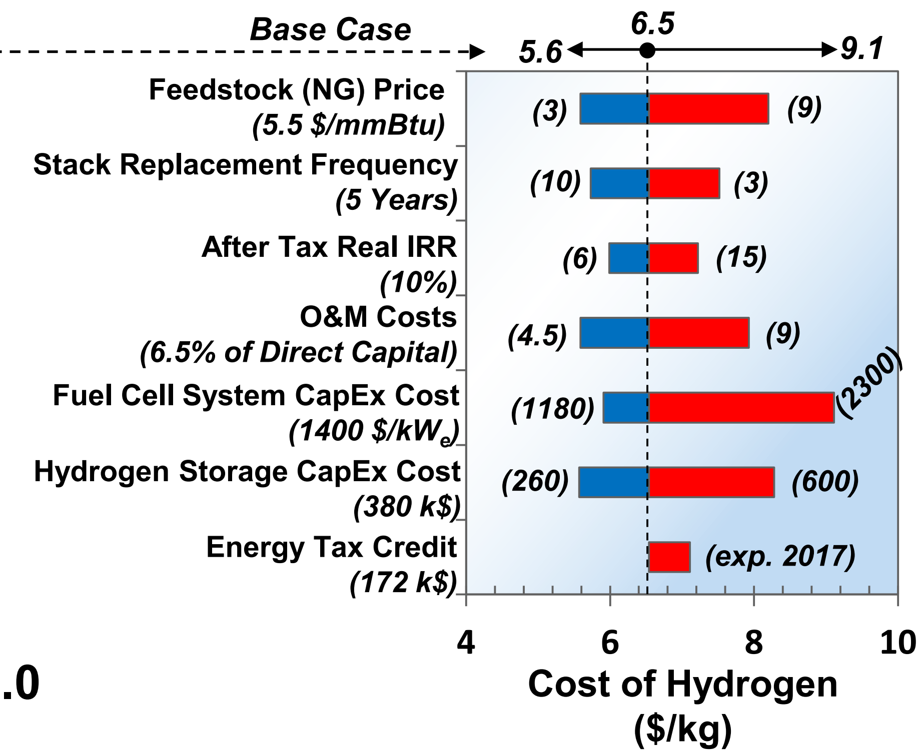
- CHP operation: constant net 250 kW_e, no hydrogen co-production
  - Levelized cost of electricity (LCE) is 11 cents/kWh without installation of H_2 purification and CSD components
  - LCE increases to 19 cents/kWh for CHHP system producing electricity only



H_2 can be priced at 6.5-9.2 \$/kg depending on the price of electricity

- Increasing H_2 production reduces the price of electricity more rapidly for given levelized cost of energy (electricity, hydrogen and heat)
- For fixed charge of 10.3[a] cents/kWh_e, hydrogen can be priced at \$6.5/kg for 125 kg-H_2/d co-production, increasing to \$9.2/kg for 75 kg-H_2/d co-production
- The minimum price of hydrogen varies significantly with location from \$4.3/kg in New England to \$7.5/kg in West South Central because of variability in grid price

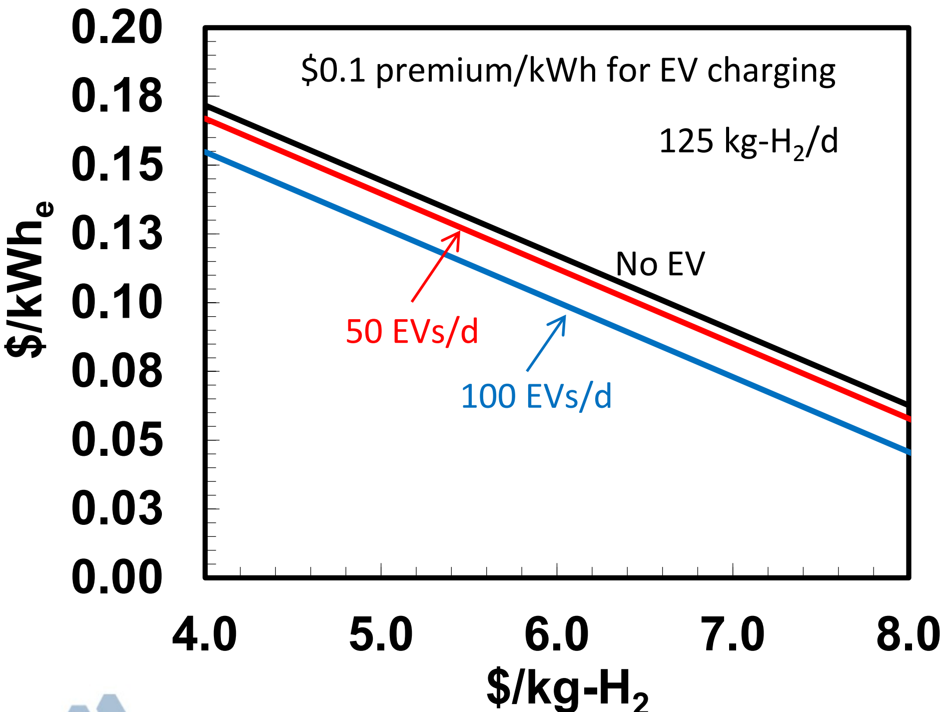


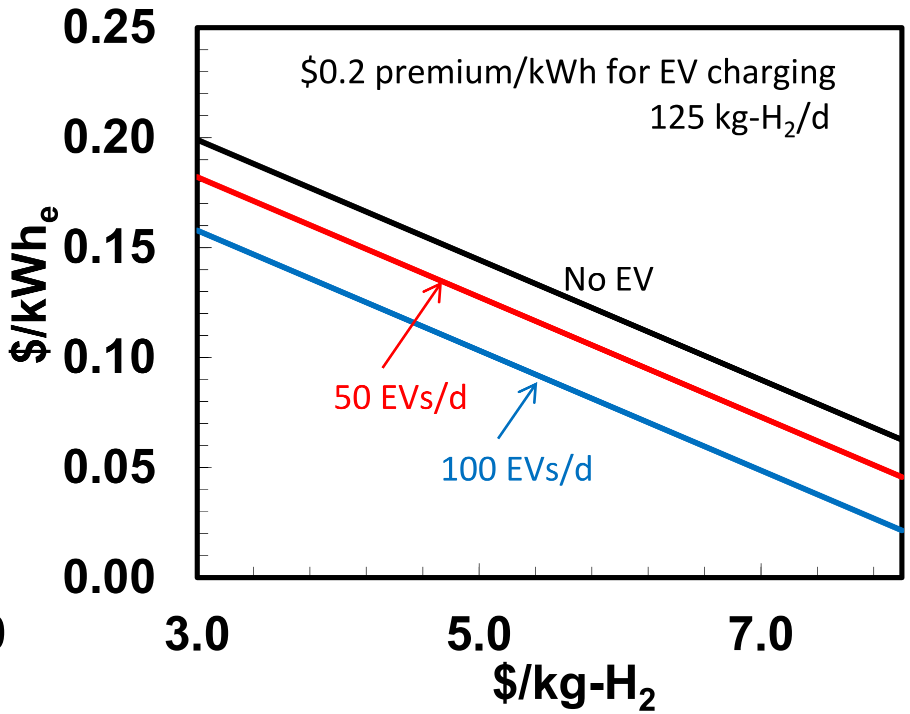


[a] U.S. average commercial electricity price 2014, EIA

The price of vehicle charging and hydrogen can be adjusted to market demands

- Charging station capacity
  - Assume 10 hours of operation per day, 12 kWh/vehicle
  - For 125 kg-H_2/d co-production, facility can charge up to 150 vehicles/day
- For given levelized cost of energy, pricing of electricity and/or hydrogen can be reduced if a portion of the electricity produced is used for EV charging
  - At full charging capacity utilization, price of hydrogen is reduced by ~$0.8/kg for each $0.1/kWh premium for EV charging





Summary

- System performance

	Pure Electric	Combined Electric and H_2 Mode	Comments for Performance in Combined Electric and H_2 Mode
Net H_2 Production (kg/d)	**0**	**125**	79 kW_t supplemental fuel to burner
Net Electrical Power (kW_e)	258.1	183.1	5% increase in fuel input to stack
Fuel Utilization (%)	73.0	60.0	Terminal limits of fuel utilization (U_F)
Oxygen Utilization (%)	60	60	Fixed O_2 utilization, variable U_F
Cell Voltage (mV)	768.9	816.4	Higher Nernst potential at lower U_F
Stack DC Gross (kW_e)	300.0	274.9	
Stack Actual Efficiency (%)	51.1	51.1	Stack efficiency does not increase because of higher burner load
Gross Electrical Efficiency (%)	46.4	42.6	Lower gross electrical efficiency in spite of higher cell voltage
H_2 Production Efficiency (%)	87.3	89.4	
PSA Efficiency (%)		43.0	Efficiencies inclusive of electric power consumed in PSA and H_2 compressors
H_2 Storage Efficiency (%)		83.9	
Net Electrical Efficiency (%)	46.4	27.6	
Fuel Processor Efficiency (%)	0.0	26.2	
Thermal Efficiency (%)	32.7	23.2	Waste heat used to raise hot water. Lower if steam is raised.

- Cost
  - ~\$1.2 M direct capital cost, MCFC \$1400/kW, LCE \$0.11/kWh_e
  - At \$0.10/kWh_e, hydrogen needs to be priced at > \$6.5/kg
  - Hydrogen price can be reduced by ~\$0.8/kg for each \$0.1/kWh premium for EV charging

Remaining Work (FY 2015)

1. Explore strategies to improve the performance of the system in CHP and CHHP modes
2. Electrochemical separation and compression of H_2
   - Trade-off between PSA compressor, H_2 recovery, and H_2 compression
3. Analyze scenarios to improve the economics of MCFC based tri-generation plants (waterfall chart)
   - Consider larger 1000 and 1500 kW_e MCFC systems
   - Additional revenues from grid stabilization
4. Additional calibration and validation of performance and cost models against OCSD data and published Fuel Cell Energy and APCI studies
5. Publish and document performance and cost models and results

Collaborations and Interactions

- Fuel Cell Energy
  - System layout, electrochemical hydrogen separation and compression
  - Fuel utilization limits
  - Performance in CHP and CHHP modes
  - Cost projections
  - Scenario assumptions
- PDC Machines, RIX Industries
  - Costs of compressors at OCSD plant
- Argonne National Laboratory

Ted Bohn (ES), Frank Perrotta (FMS-BS)
  - Costs of battery vehicle charging stations
  - Availability and charging efficiencies
- Strategic Analysis (SA)

  Brian James
  - Costs of hydrogen storage tanks, pressure swing adsorption (PSA)

Acronyms

AC	Alternating Current
CHP	Combined Heat and Power
CHHP	Combined Heat, Hydrogen and Power
CSD	Compression, Storage and Dispensing
DC	Direct Current
EBOP	Electrical Balance of Plant
EV	Electric Vehicle
HDS	Hydro-Desulfurization
kWh	Kilowatt-hour
LCE	Levelized Cost of Electricity
LHV	Lower Heating Value
MBOP	Mechanical Balance of Plant
MCFC	Molten Carbonate Fuel Cell
MMBtu	Million British Thermal Units
NG	Natural Gas
OCSD	Orange County Sanitation District
O&M	Operation and Maintenance
PSA	Pressure Swing Adsorption
SA	Strategic Analysis
WGS	Water-Gas Shift