Power Parks System Simulation

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TV-P-4
Hydrogen Program Annual Review
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Overview

- Timeline
  - Started FY03
  - Finish: end of FY06
  - Percent complete: 65%
- Budget
  - FY 2005: 250 K$
  - FY 2006: 250 K$

- Barriers addressed
  - Overall performance for stationary H_2 systems
  - MYPP defined cost and efficiency targets for distributed H_2 production
  - Natural gas:
    - 3 $/kg (2005) and 1.50 $/kg (2010) with 4 $/GJ gas and 0.07 $/kWh
    - Reforming efficiency:
      - 69 % (2005), 80 % (2010)
  - Electrolysis:
    - 4.75 $/kg (2005) and 2.85 $/kg (2010) from electricity at 0.04 $/kWh
    - Efficiency: (electrolyzer + BOP)
      - 68 % (2005), 76 % (2010)

Overview (con't)

- Partners
  - Arizona Public Service (APS)
    - Ray Hobbs
    - Scott McCamman, Dimitri Hochard (ETEC)
  - City of Las Vegas Transit
    - Mark Wait (Air Products)
  - DTE Energy
    - Rob Regan, Bruce Whitney
    - Rob Fletcher (Lawrence Technological University)
  - Energy Resources Group, UC Berkeley
    - Carl Mas, Tim Lipman
  - Hawaii Natural Energy Institute (HNEI)
    - Mitch Ewan, Richard Rocheleau, Severine Busquet

Objectives and Relevance to H_2 Program

<u>Objectives</u>

- Develop a flexible system model to simulate distributed power generation in energy systems that use H_2 as an energy carrier
  - Power parks combine power generation co-located with a business, an industrial energy user, or a domestic village
- Analyze the performance of demonstration systems to examine the thermal efficiency and cost of both H_2 and power production

<u>Relevance to the Multi-year Program Plan:</u>

- Technical Analyses
  - Analyze H_2 and electricity as energy carriers and evaluate synergies
  - Analyze advanced power parks for production of both H_2 and electricity
  - Determine the economics of H_2 and electricity co-production compared to stand-alone hydrogen facilities

Approach

Combine engineering and economic analysis

- Assemble engineering model as system of components
- Component models based on fundamental physics and chemistry
  - Coupled to Chemkin software for thermodynamic properties and equilibrium solutions
- Economic analysis modules linked to components
- Validate simulations to data from DOE demonstration projects
  - Conduct site visits to establish working relationships with engineers

Software Design

- Create a library of Simulink modules for H_2-specific components
- Library components can be quickly re-configured for new systems
- Generic components can be customized using specific data
- Initiating GUI development using Sandia internal funds

Library of Simulink modules

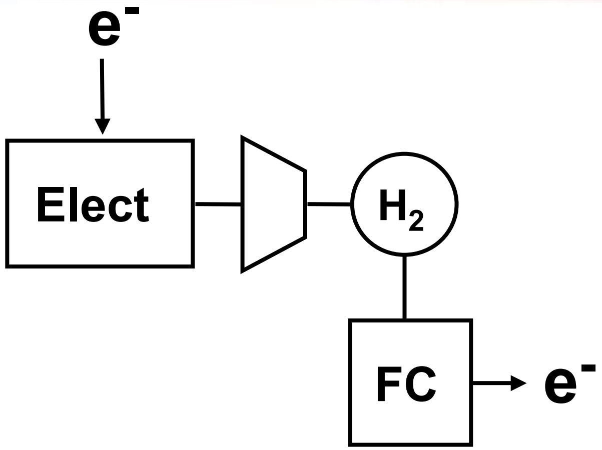
- Reformers
  - Steam methane - T determined by internal energy balance & chemical equilibrium
  - Autothermal (partial oxidation) - optimize air/carbon ratio to balance energy
- Electrolyzer
  - Energy & mass balances – including water phase change and H_2 purification
  - Simulates performance vs stack operating conditions and physical characteristics
- PEM Fuel cell
  - Steady-state model uses first principles & experimental data for polarization curve
  - Energy & mass balances for anode/cathode flows, including water phase change
- Economic analysis modules are consistent with H2A
  - Levelized cost approach that follows H2A spreadsheet analysis
  - Defaults to H2A parameters for interest, taxes, depreciation, capacity factor, etc
- Examples of other components:
  - Compressor – multi-stage with intercooling, isentropic efficiency
  - High-pressure storage vessel – real-gas equation-of-state
  - Photovoltaic solar collector

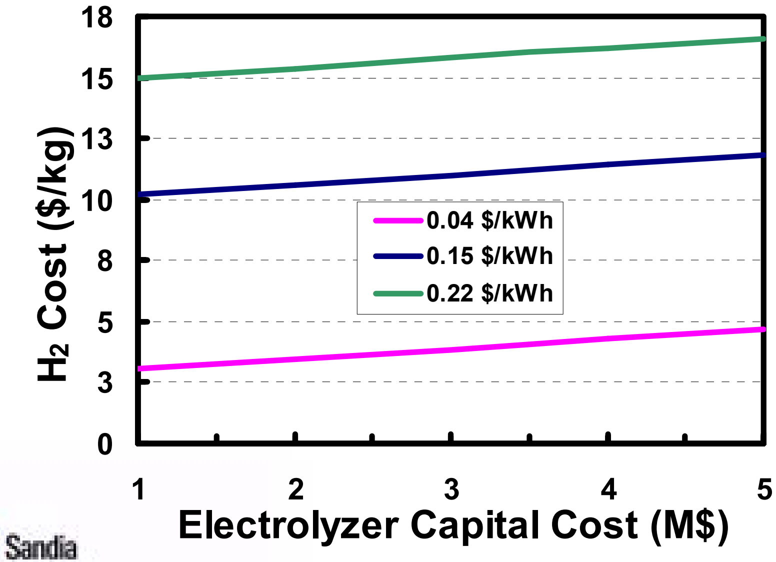
Simulations of DOE demonstration systems

- Hawaii Natural Energy Institute
  - Stuart electrolyzer provides compressed H_2 for storage
  - 5 kW PEMFC evaluated in FC testing center
- Arizona Public Service (APS) refueling facility
  - H_2 produced by PEM electrolyzer from grid and PV electricity
  - H_2 stored at low-p and used by PEMFC and ICE gen-sets
  - H_2 compressed for vehicle refueling
- City of Las Vegas (CLV) refueling facility
  - Steam-methane reformer (SMR) supports vehicle refueling
- DTE Energy Hydrogen Technology Park
  - PV arrays, Stuart electrolyzer feed PEMFCs (10 at 5 kW each) and vehicle refueling station

Engineering/economic analysis of HNEI power park

- Alkaline electrolyzer generates H_2 that is compressed and stored on-site
  - Output: ~12 kg/day at 53 % efficiency (LHV)
  - Compressor modeled as 70% efficient
- PEM FC generates DC current
  - Fuel cell peak output: 5 kW at 44 % efficiency (LHV) – *APS Data for similar unit*

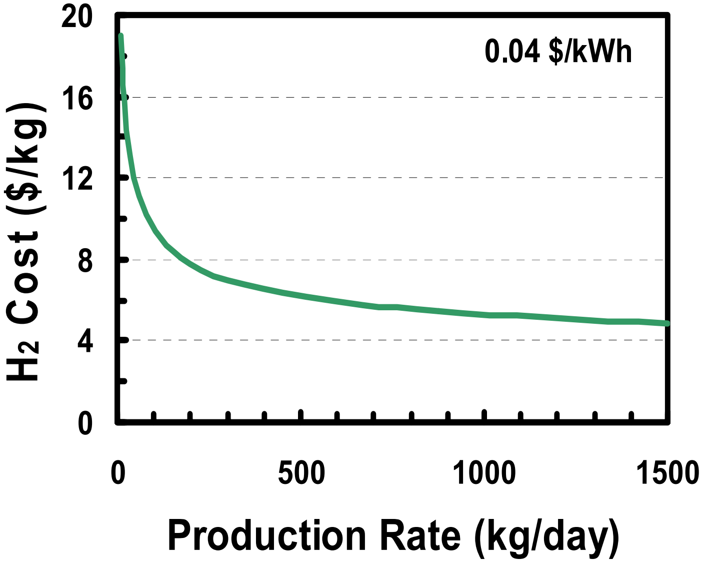


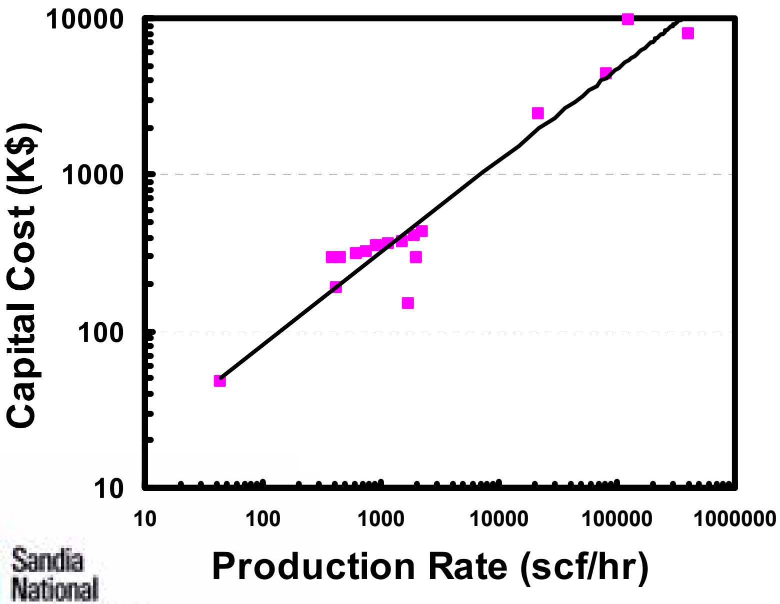


- Capital cost for 1500 kg/day system, including compressor
- Economic analysis uses H2A parameters
- Parameter Studies:
  - Electrolyzer capital cost
  - Electricity price
    - DOE Goal: 0.04 $/kWh
    - Honolulu: 0.15 $/kWh
    - Big Island: 0.22 $/kWh
- Includes O&M = 2% Capital

Projected cost of H_2 for HNEI power park

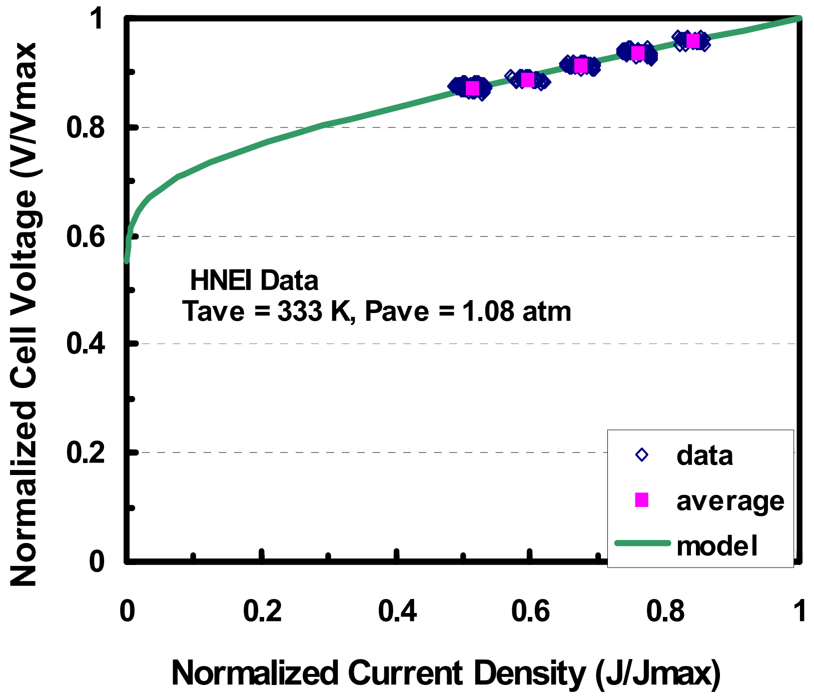
- H_2 production rate has non-linear effect on cost
- Use literature correlation to *simultaneously* vary electrolyzer capital cost and production rate
- Electricity price set to 0.04 $/kWh





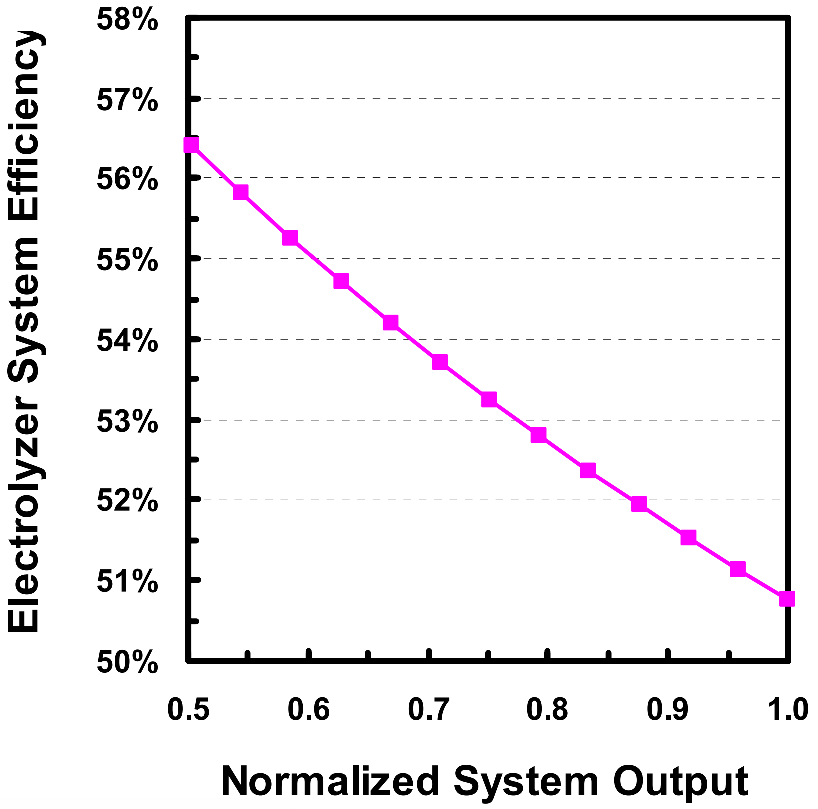
- To meet DOE electrolysis targets
  - 2005: 4.75 $/kg achievable for 1500 kg/day electrolyzer
  - 2010: 2.85 $/kg will need innovation

Calibration of electrolyzer polarization curve



- Model requires V-I curve as input to electrolyzer
  - Determines component efficiency versus load
- Adjust polarization curve to fit data provided by HNEI
  - Operated Stuart electrolyzer in steady-state at 5 loads
  - Normalized data for use in generalized model

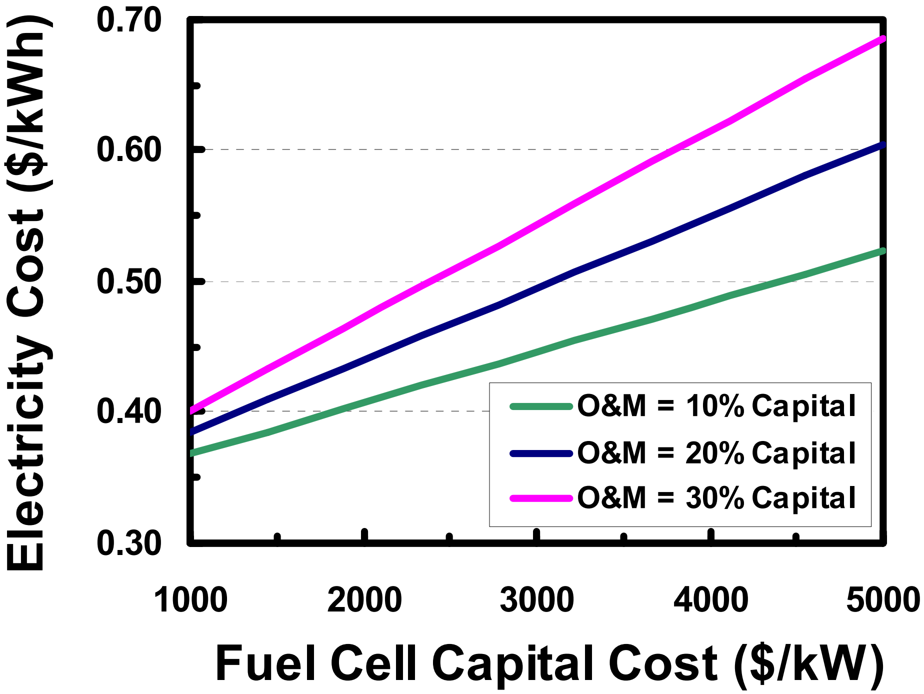
Model of electrolyzer at HNEI power park



- Model of alkaline electrolyzer efficiency
  - Based on hydrogen production and grid electricity input
  - System includes electrolyzer stack, balance of plant, AC-DC converter, and compressor
  - H_2 produced at 140 atm
  - Turn-down 2:1
  - Normalized results for use in generalized model

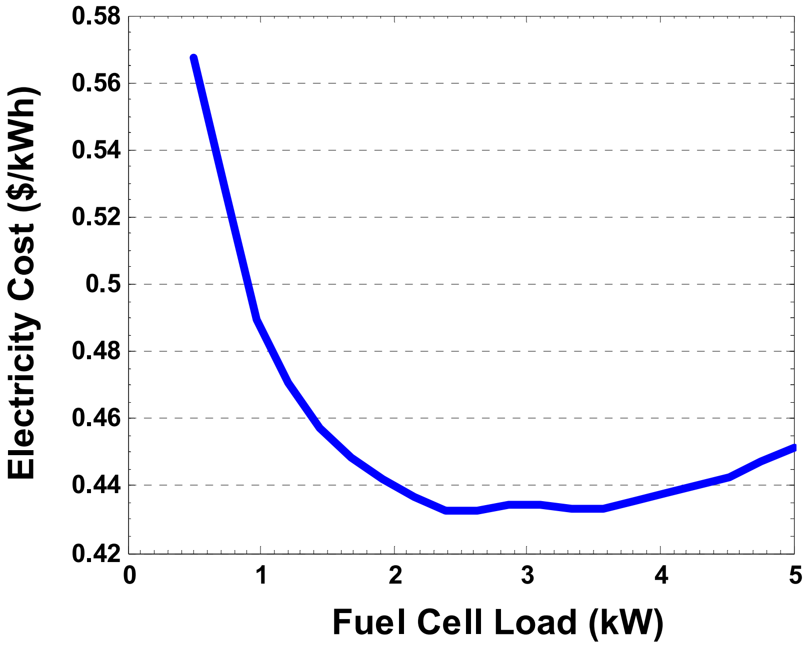
Projected cost of electricity for HNEI power park

- Capital cost for 5 kW-DC fuel cell system
  - Parameter Study:
    - Fuel cell capital cost
    - Vary O&M from 10-30%
  - Economic analysis uses H2A Parameters
  - H_2 at 4.86 $/kg from electrolyzer at nominal conditions:
    - 1500 kg/day production rate
    - 0.04 $/kWhr electricity

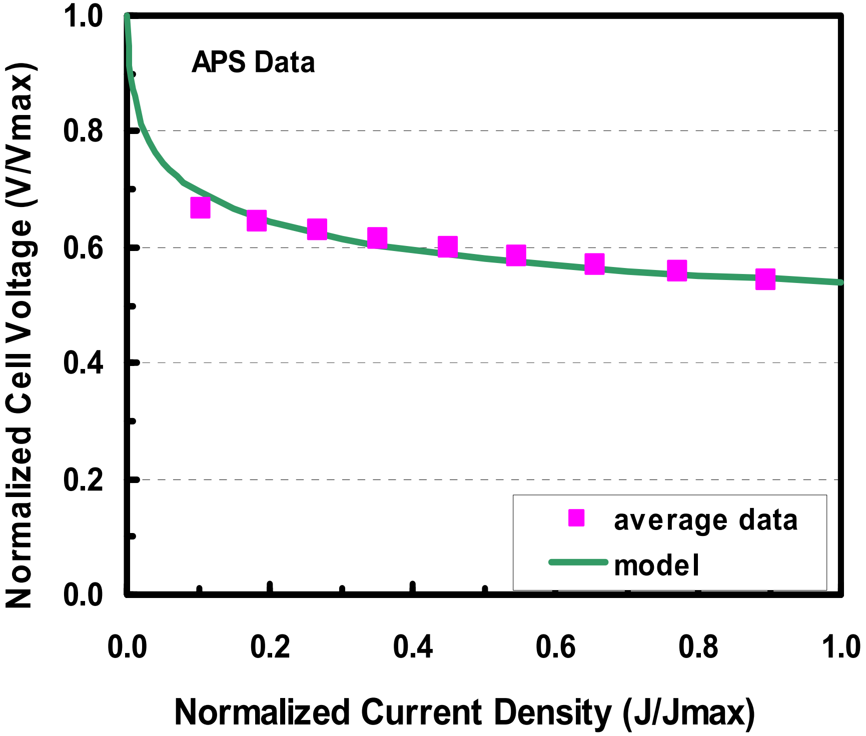


Cost-of-electricity vs Fuel Cell Load

- Based on APS data
- COE as a function of fuel cell load for a 5 kW fuel cell
- COE depends on fuel consumption
  - H_2 is expensive (4.86 $/kg)
  - Least expensive operation occurs at half-load because of increased efficiency
    - Minimum: 0.43 $/kWh @ 2.6 kW
    - At full load: 0.45 $/kWh

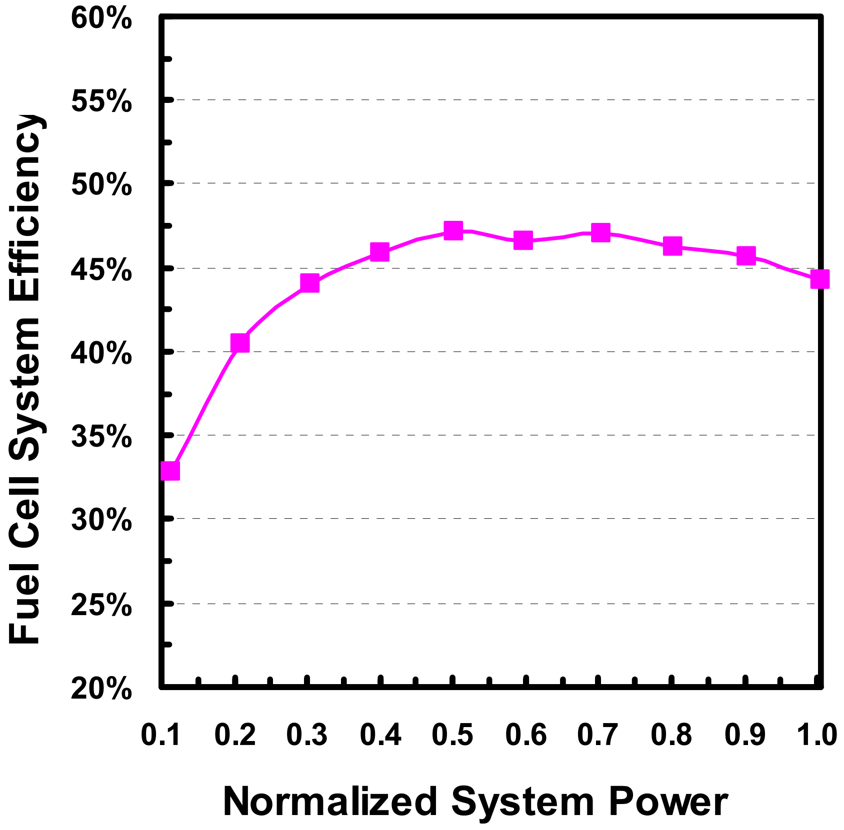


Calibration of FC polarization curve to APS data



- Model requires V-I curve as input to fuel cell
  - Determines component efficiency versus load
- Adjust polarization curve to fit data provided by APS
  - Operated Plug Power FC in steady-state at 9 loads
  - Normalized data for use in generalized model

Model of fuel cell system at APS power park



- Model of hydrogen fuel cell system efficiency (LHV)
  - Based on net DC power out and hydrogen flow
  - Power regulated to 48V
  - Data for turn-down to 10:1
  - Normalized results for use in generalized model
  - System includes fuel cell stack, balance of plant, and DC-DC converter

Electrolyzer system efficiencies at APS

- APS data provides average electrical work per unit H_2 produced
  - Broken out by component in the system
- MYPP groups cell stack and balance-of-plant in electrolyzer efficiency
- Compressor grouped with storage and dispensing
  - Second group factor is relative to overall system
- Apply running totals to work and efficiency

$$\eta_{\text{overall}} = f\,\eta_{\text{elect}}$$

$$\eta = \frac{LHV}{\sum W}$$

Component	Electrical use (kWh/kg)	Running Total (kWh/kg)	Running Efficiency (LHV)
Electrolyzer *	81.0	81.0	41.2%
Chiller	10.3	91.2	36.5%
Control Room	0.4	91.6	36.4%
Dryer	0.6	92.3	36.1%
N2 System	2.1	94.3	35.3%
Instrument Air	1.8	96.2	34.7%
Compressor	2.4	98.5	33.8%

	APS Data	2005 Target	2010 Target
Cell & BOP	35%	68	76
Comp, Store, Disp	96%	95	99
Total	34%	64	75

* Estimated power conversion η ~ 76 %, so stack η ~ 54 %

Thermodynamic efficiency for compression

- Work required for compression
  - Assume ideal intercooling of calorically perfect gas between stages

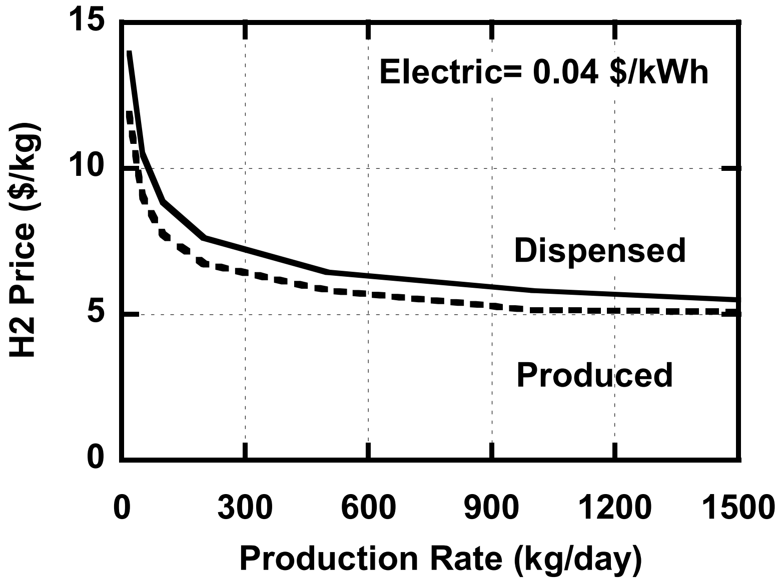
$$\frac{\dot{W}_{\text{ideal}}}{\dot{m}} = \frac{RT_1}{\eta} \frac{n\gamma}{\gamma - 1} \left[\left(\frac{p_2}{p_1} \right)^{(\gamma-1)/n\gamma} - 1 \right]$$

- "Task" efficiency for compression work: $\eta = \frac{W_{\text{ideal}}}{W_{\text{actual}}}$
- Compressor efficiency for APS data
  - 2-stage compressor to 6000 psi
  - Average task efficiency = 70%
  - This efficiency is NOT comparable to MYPP target
    - MYPP defines an efficiency factor that is system dependent

Projected cost-of-H_2 from electrolysis at APS scaled to MYPP target size facility

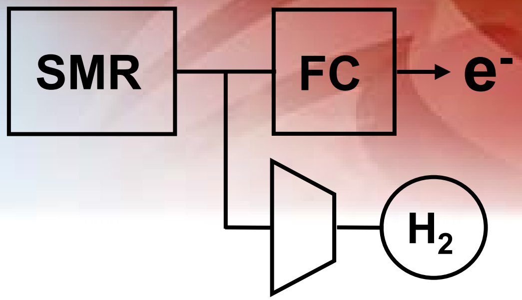
- PEM electrolyzer
  - Operates at 35% overall efficiency
  - Capital scaled by $43k x (rate^0.6)
    - Includes storage, BOP costs
  - O&M is 2% of capital
    - Not including any stack replacement
- Compressor
  - 2-stage operating at 70% efficiency
  - Capital scaled by $11k x (rate^0.6)

Compare to MYPP:	Targets	Projected
Electrolyzer capital	0.80 $/kg	1.13 $/kg
Compression	0.77	0.43
Electricity	2.47	3.78
O&M	0.71	0.16
Total	4.75 $/kg	5.50 $/kg

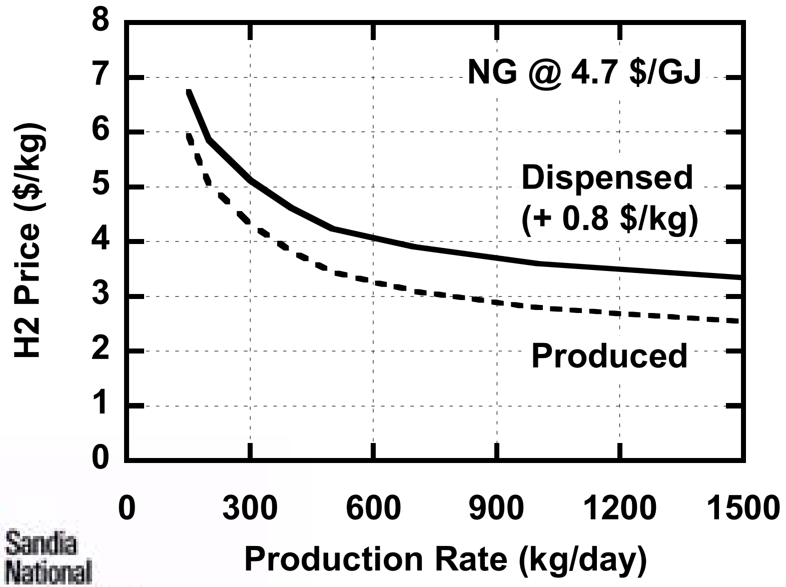


- Electrical cost is above target due to low η
- At target η = 68 %
  - Electricity = 1.96 $/kg
  - Total cost = 3.70 $/kg

Engineering/economic analysis of hybrid power system at CLV



- H_2 Generator (SMR) to feed FC and refueling
  - Reformer: ~150 kg/day at 68% thermal efficiency (H_2/CH_4 on LHV basis)
- *Simultaneously* vary reformer capital cost & size using a correlation fit to literature data: Capital = \$15k * Rate$^{0.76}$
- Economic parameters from H2A
- H_2 cost includes compression & dispensing (0.8\$/kg from MYPP)



- To meet MYPP cost targets for distributed reforming (1500 kg/day)
  - 2005: 3 \$/kg is achievable
  - 2010: 1.50 \$/kg requires drastic reductions in capital cost

Dynamic modeling of DTE Energy H_2 Tech park

- Park contains 25 kW photovoltaic capacity
  - Daily and seasonal variation in solar electricity
- Electrolyzer at full capacity (~3 kg/hr) draws ~ 200 kW
  - Capacity operation requires grid power at peak solar incidence
  - Off-peak operation uses inexpensive electricity (5-6 ¢/kWh)
- H_2 storage in high-pressure tube bank
- Vehicle refueling station
- 10 PEMFCs (5 kW each) provide peak-demand power
- Examine the cost-of-H_2 generated at off-peak hours and cost-of-electricity supplied peak-demand

Response to FY 2004 review

- Reviewers' major comments focused on communication of results and utility of the simulations
  - *"Would encourage expansion of communication effort."*
  - *"Would like to see expanded effort to add database/systems analysis."*
  - *"Unclear on potential impact of simulation."*
- Sandia response:
  - Committed additional internal funds (40k$) to develop GUI so others can perform system simulations.
  - Developed closer working relationships with power park personnel
  - Conducted site visits to HNEI, APS, DTE to exchange data and simulation results

Future Work

- Compare model to data from DOE power parks (140k$)
  - Arizona Public Service
    - APS has ~1 year of data on H_2 production, few months on PEMFC
    - Apply model to continued data on electrolyzer and PEMFC
    - Apply new model to engine gen-set data
  - DTE Energy
    - Newly commissioned park has only a couple months data
    - Apply preliminary model to next year's data and refine analysis
    - Collaborate with Lawrence Tech by hosting summer student
  - HNEI
    - Complete initial data comparison to electrolyzer performance
    - Compare PEMFC model to new operation data
    - Collaborate with HNEI study of renewable resources on Hawaii
  - Follow-up activities at Las Vegas and SunLine Transit

Future Work (con't)

- Develop user-friendly GUI for sample power parks
  - "Advisor-like" interface
  - Sandia internal funding (40k$)
- Continue to build the component library (30k$)
  - Wind turbine generator – in collaboration with Prof. Fletcher at Lawrence Technological University and DTE Energy
  - H_2-ICE gen-set for APS data comparison
- Long-term studies of distributed H_2 production (30k$)
  - Expand existing analysis to examine thermodynamic *availability*
- Perform analysis of international H_2 stations (50k$)
  - Support IEA Task 18: Evaluation of integrated demonstration systems (Susan Schoenung, Longitude 122 West Inc.)

Supplemental Slides

Publications and Presentations

Presentations:

- "Sandia Hydrogen Modeling Capabilities", DOE Systems Analysis Workshop, July (2004).

Publications:

- Lutz, A E, Bradshaw, R W, Bromberg, L and Rabinovich, A, "Thermodynamic Analysis of Hydrogen Production by Partial Oxidation Reforming," *Int J of Hyd Engy*, 29 (2004) 809-816.
- Lutz, A E, Bradshaw, R W, Keller, J O, and Witmer, D E, "Thermodynamic Analysis of Hydrogen Production by Steam Reforming," *Int J of Hyd Engy*, 28 (2003) 159-167.
- Lutz, A E, Larson, R S, and Keller, J O, "Thermodynamic Comparison of Fuel Cells to the Carnot Cycle," *Int J of Hyd Engy*, 27 (2002) 1103-1111.

Safety

- The most significant hydrogen hazard associated with this project is:
  - **This project consists entirely of computer simulations of hydrogen systems. The safety issues reside with our collaborative partners who are building and demonstrating the equipment to generate and store hydrogen.**
- Our approach to deal with this hazard is:
  - **We cooperate with our collaborative partners when we visit their facilities to ensure that we follow the established safety operating procedures.**