Power Parks System Simulation

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TV-2

Hydrogen Program Annual Review

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Overview

- **Timeline**
  - Started FY03
  - Finish: end of FY06
  - Percent complete: 85%
- **Budget**
  - 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) with 4 $/GJ natural gas
    - 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)
  - DTE Energy
    - Rob Regan, Bruce Whitney
    - Rob Fletcher, Elliott Schmitt (Lawrence Tech.)
  - Energy Resources Group, UC Berkeley
    - Carl Mas, Tim Lipman
  - Hawaii Natural Energy Institute (HNEI)
    - Mitch Ewan, Richard Rocheleau, Severine Busquet
  - Stanford's Global Climate & Energy Project
    - Adam Simpson, A. J. Simon, Chris Edwards

APS®

DTE Energy®

HAWAII NATURAL ENERGY INSTITUTE

Objectives and Relevance to H_2 Program

Objectives

- 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

Relevance to the Multi-year Program Plan:

- 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

Approach

Combine engineering and economic analysis

- Assemble engineering model as system of components
- Component models based on fundamental physics and chemistry
  - ex: Chemkin for thermodynamic properties and chemical equilibrium
- Economic analysis modules linked to components
- Validate simulations with data from DOE demonstration projects
  - Conducted site visits to establish working relationships with engineers
  - Hosted LTU summer student to coordinate data collection & modeling

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
- GUI developed for a sample system (Sandia internal funds)

Library of Simulink modules

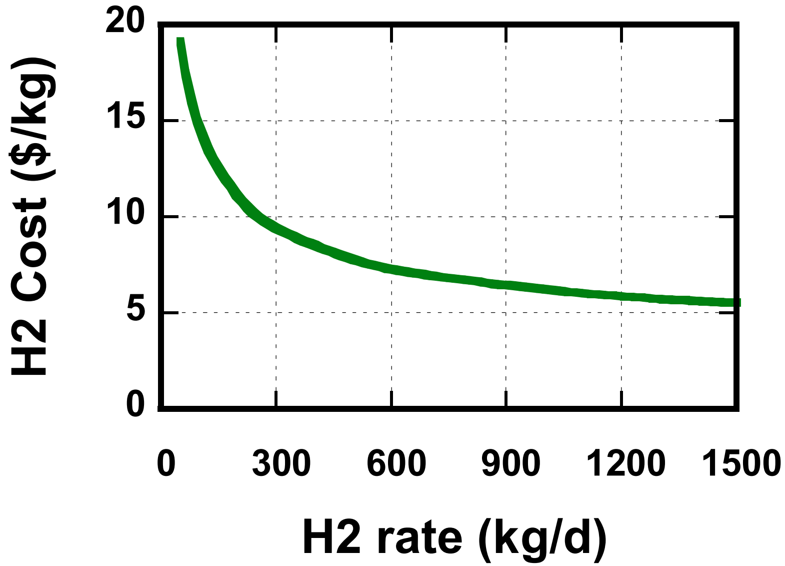
- Newly developed components:
  - Wind turbine and resource
    - Wind resource model takes hourly wind data as input
    - Turbine model power map and wind shear
  - Chiller
    - Model pump work and refrigerant cycle with coefficient-of-performance
- Existing components:
  - Reformers - steam methane and autothermal (partial oxidation)
  - Electrolyzer – balances mass & energy, including phase change and purification
  - PEM Fuel cell - uses experimental data for polarization curve
  - Compressor – multi-stage with intercooling, isentropic efficiency
  - High-pressure storage vessel – real-gas equation-of-state
  - Photovoltaic solar collector – solar incidence with location & time of day
- Economic analysis modules are consistent with H2A
  - Levelized cost approach uses H2A parameters for interest, taxes, depreciation, capacity factor

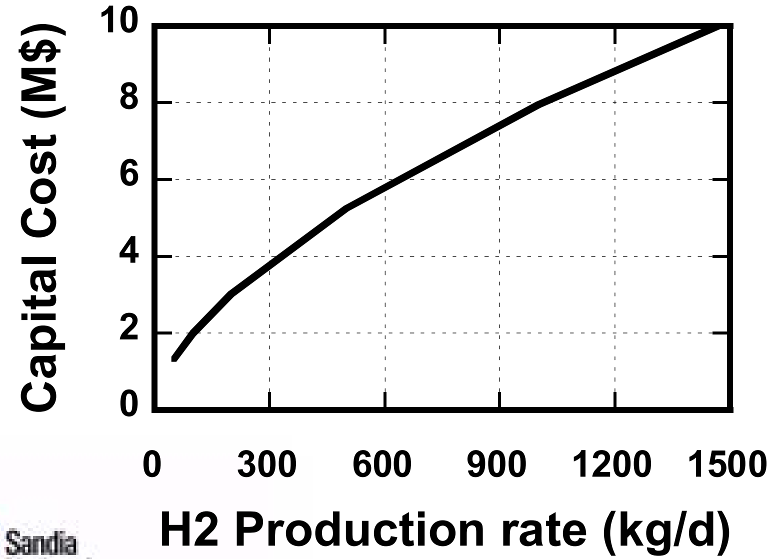
Simulations of DOE demonstration systems

- DTE Energy Hydrogen Technology Park
  - PV arrays & grid feed electrolyzer
  - H_2 for PEMFCs (10 at 5 kW each) and vehicle refueling station
- Hawaii Natural Energy Institute
  - Wind turbine proposed for Big Island
  - Electrolyzer to produce compressed H_2 for transportation
  - 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

Projected cost of H_2 from electrolysis at DTE

- H_2 production rate has non-linear effect on cost
- Scale electrolyzer capital cost with production rate to 0.6 power
- Electricity price set to 0.025 $/kWh for off-peak power

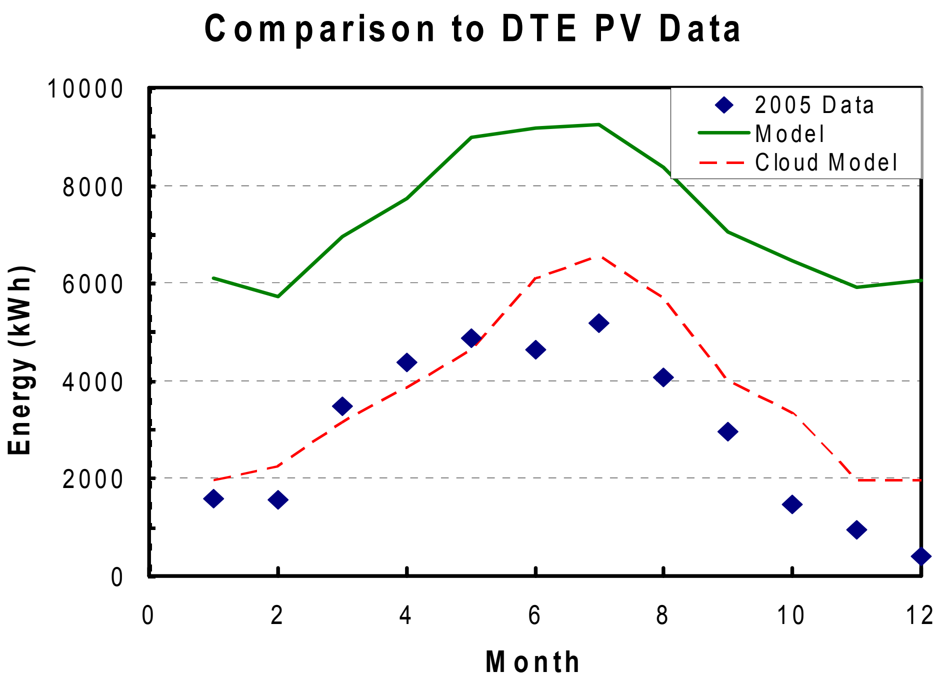




- To meet DOE electrolysis targets
  - 2005: 4.75 $/kg maybe feasible, depending on scaling to 1500 kg/d
  - 2010: 2.85 $/kg will need innovation and capital reduction

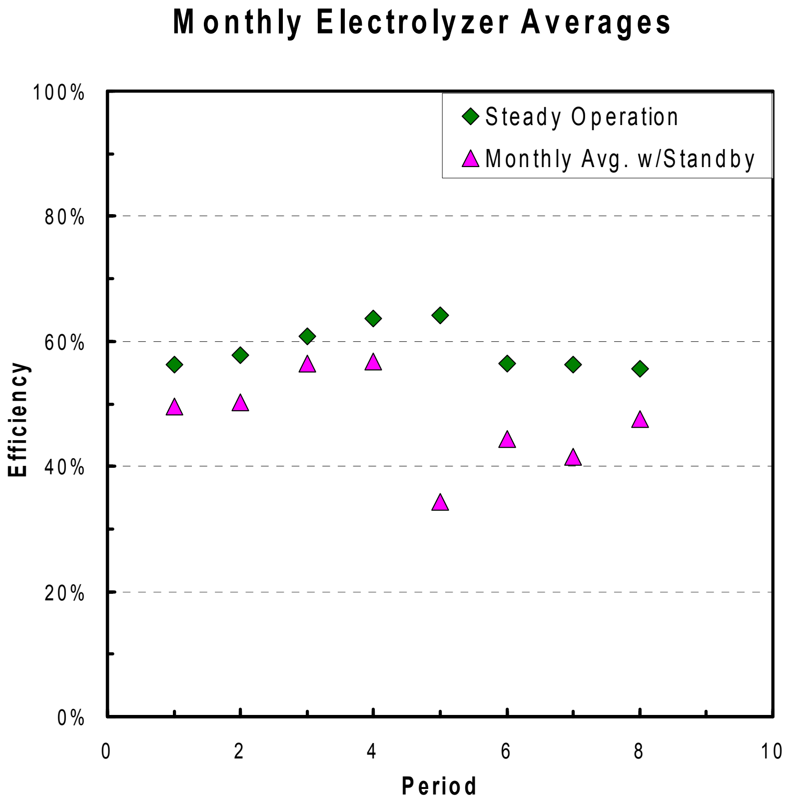
Simulation of photovoltaic panels at DTE Energy

- **Solar insulation model**
  - Clear-sky algebraic model uses geographic location
  - Adjusted model solar-to-electric efficiency = 9%
  - Correct monthly energy collection for number of cloudy days
- **Data from DTE park**
  - 26.7 kW capacity in 2 arrays: fixed and tracking
  - Peak capacity factor ~ 0.3



Electrolyzer operation at DTE Energy H_2 park

- **Hydrogenics/Stuart unit**
  - Rated capacity: 225 kW
  - Operation range: 150 – 180 kW
- **Efficiency data**
  - Data from DTE Energy website
  - Stack and BOP, not compression
  - Steady operation data collected for runs > 10 hrs
  - Monthly average data includes standby power use
  - Difference emphasizes the influence of duty-cycle
  - Average over 8 months
    - Steady operation = 59 %
    - Operation with standby = 48%

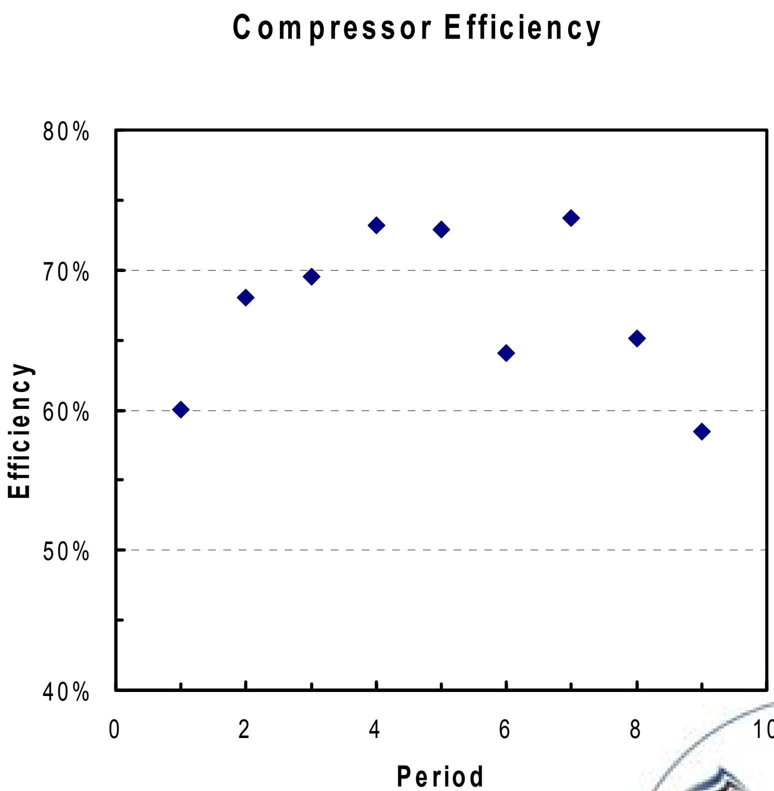


Compressor meets DOE target for the relative work in an electrolyzer system

- **Isentropic efficiency definition:** $\eta = \frac{W_{\Delta S = 0}}{W_{comp}}$
- **MYPP specifies 2 groups**
- **Compressor group is <u>not</u> an efficiency**
  - **Merely a relative factor between electrolyzer and total system efficiencies**

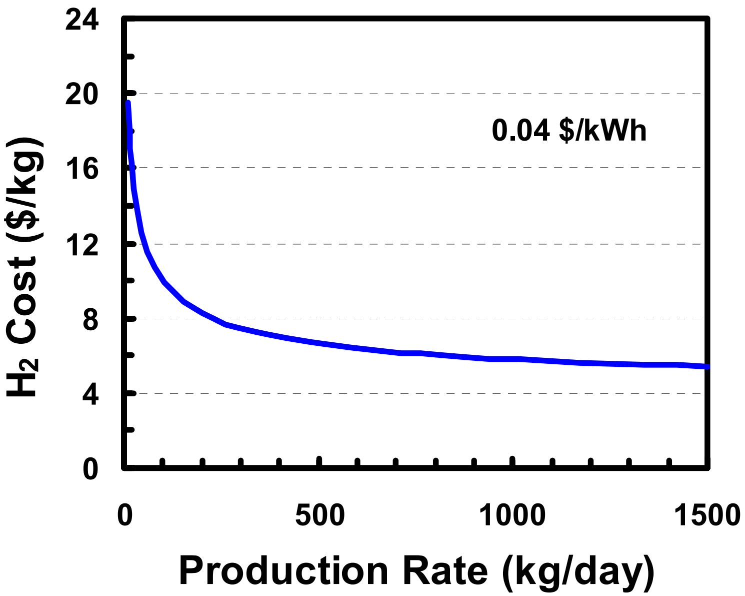
$$\eta_{total} = f \, \eta_{elect}$$

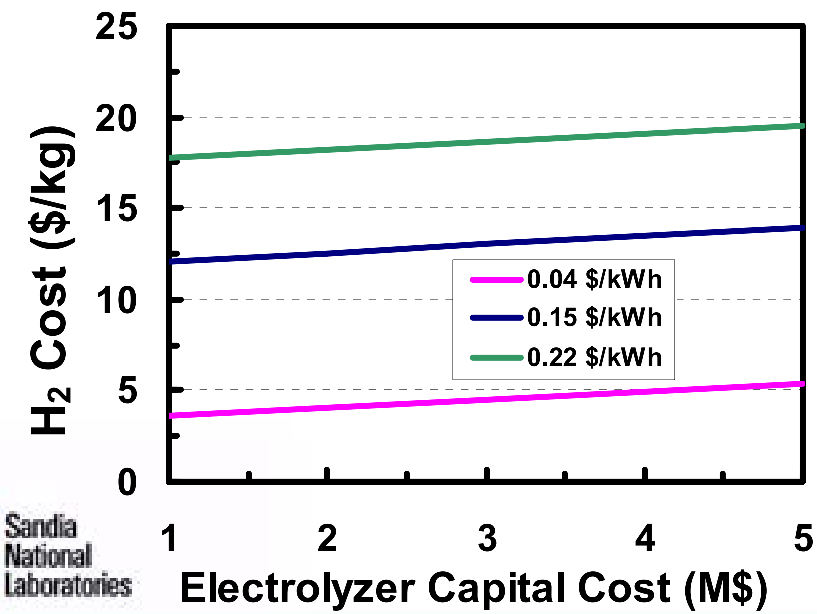
	DTE Data	2005 Target	2010 Target
Cell & BOP	60%	68	76
Comp, Store, Disp	95%	95	99
Total	57%	64	75



Updated economic analysis of HNEI electrolysis

- **Alkaline electrolyzer data used to set model**
  - 12 kg/d at 43% efficiency (LHV)
  - Compressor: 21 MJ/kg-H_2 at 2000 psi
- Scale capital cost to 1500 kg/day
  - Includes compression and 2% O&M
  - Electricity variation:
    - DOE target assumed 0.04 $/kWh
    - Honolulu: 0.15 $/kWh
    - Big Island: 0.22 – 0.32 $/kWh





- To meet DOE targets for water electrolysis (0.04 $/kWh)
  - 2005: 4.75 $/kg achievable for 1500 kg/day electrolyzer
  - 2010: 2.85 $/kg will need innovation

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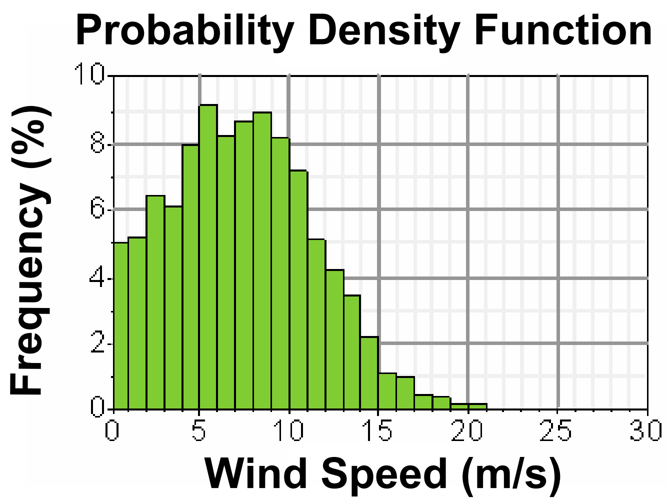
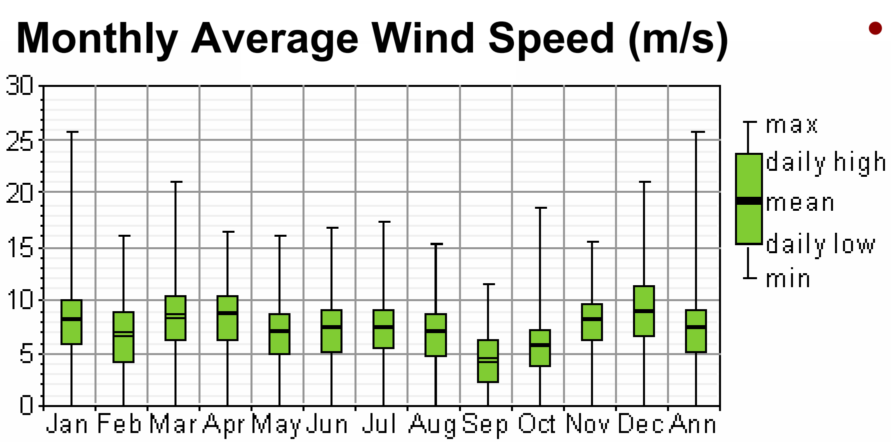
Wind resource for proposed HNEI power park

- Wind resource at Kahua Ranch, Big Island, HI
  - Hourly average wind speed data at 27 m in 1993
  - Wind power class: 5
- 500 kW wind turbine
  - Hub height: 30 m
  - Swept area: 866 m^2
  - Predicted capacity factor: 0.24
  - Expanded correlation to long-term data, capacity factor: 0.37



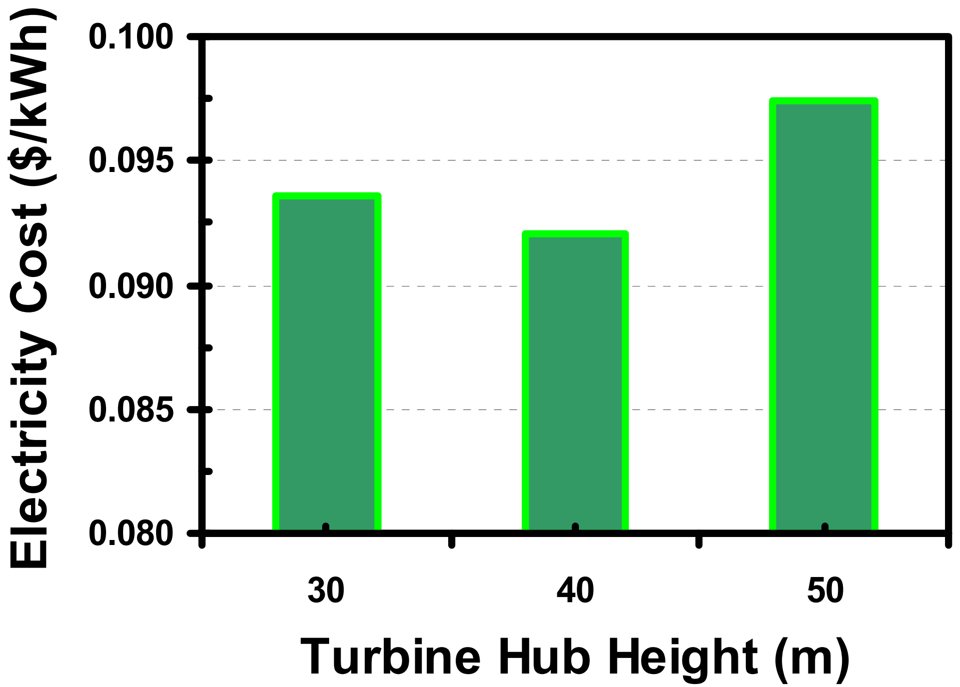


- Modeling approach
  - Input hourly average wind speed and air density
  - Wind shear characterized using power-law relation
  - Wind turbine power map predicts hourly average power output

Wind data source: http://www.hawaii.gov/dbedt/ert/winddata/winddata.html

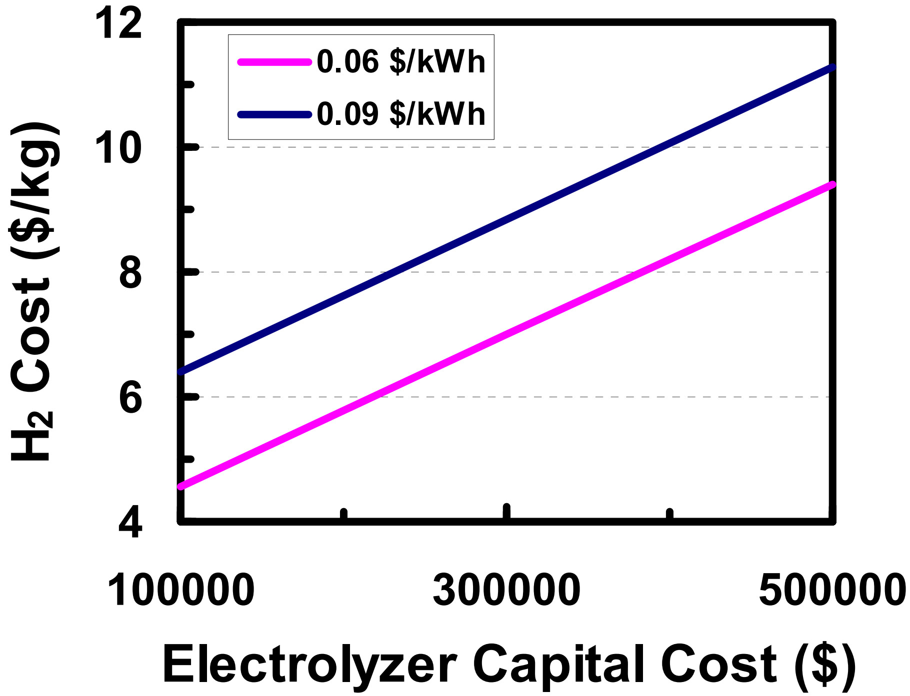
Projected cost of electricity from HNEI wind turbine

- Parameter Study:
  - Vary wind turbine hub height
- Wind turbine rated at 500 kW
- Wind speed data from Kahua Ranch in 1993
- Economic analysis uses H2A Parameters
- Capital cost includes turbine, tower, and installation
- ~ 2 / 3 of electricity cost is from capital cost of turbine



Projected cost of H_2 from proposed HNEI wind turbine

- Turbine rated at 500 kW
- Model assumptions:
  - Electrolyzer output:
    - 50 kg/day
    - 60% efficiency (LHV)
    - Includes compression
  - Parameter study
    - Electrolyzer capital cost
    - Electricity from wind turbine
  - Includes O&M = 2% Capital
- Cost contributions at:
  - 0.06 $/kWh
  - 7 $/kg-$H_2$



CONTRIBUTION	COH ($/kg-$H_2$)
Electricity Use	3.35
Capital	3.19
O&M	0.46

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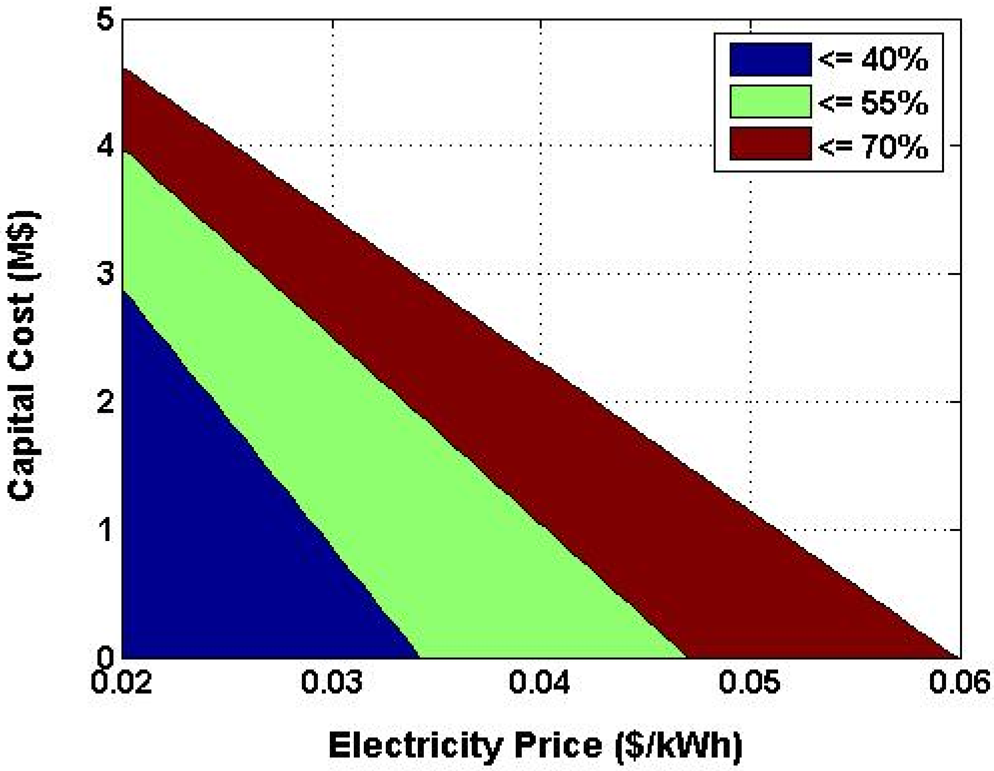
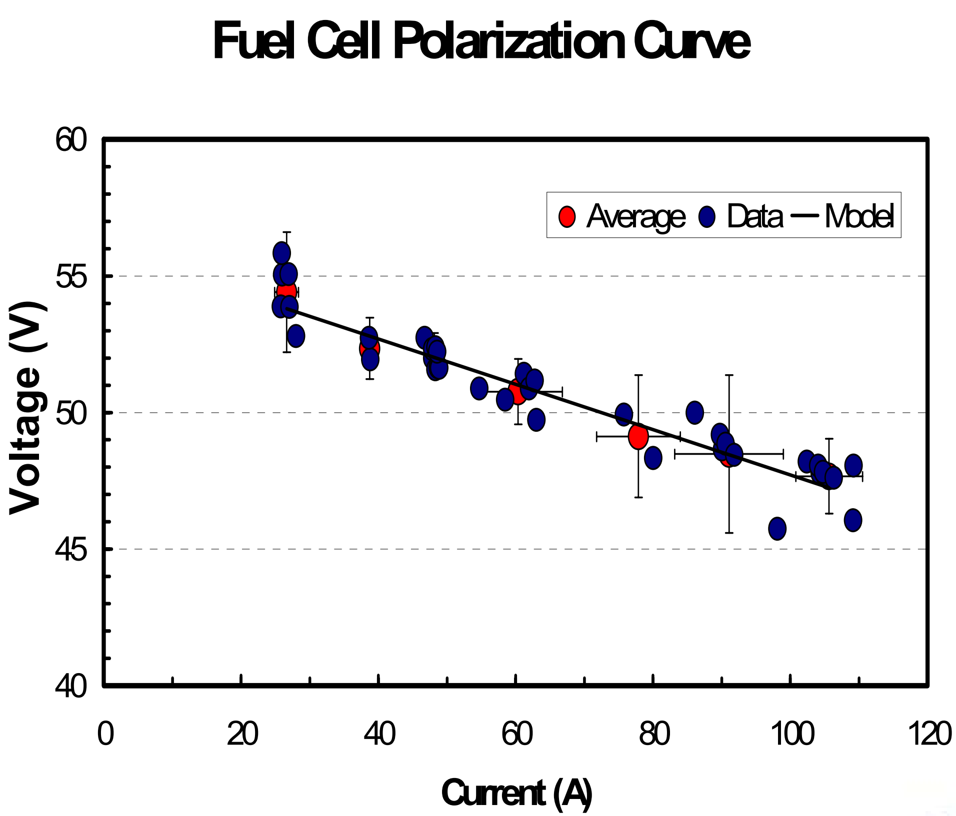
Economic parameter study: electrolyzer capital cost to meet program targets

- Levelized cost using default H2A values
  - With O&M = 2% of capital
- Variables:
  - cost-of-electricity
  - efficiency
- MYPP target: 2.85 $/kg
- Shaded regions are range of capital to meet goal at given efficiency

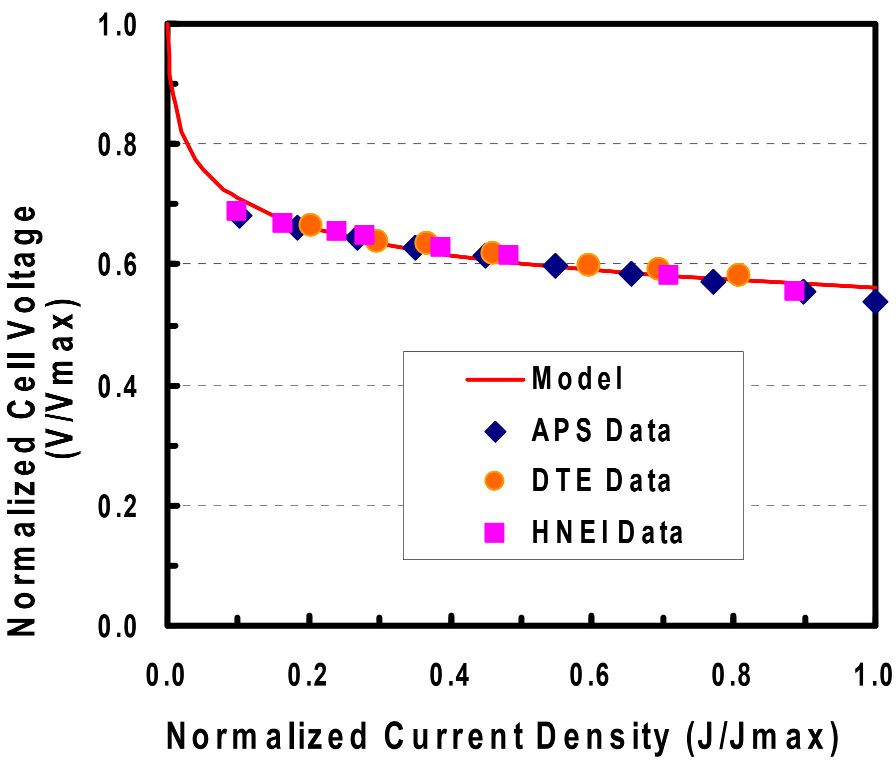


FC stack performance at DTE hydrogen park

- Polarization data
  - Stack V-I data averaged over periods of steady-operation
  - Data from 10 stacks grouped by load
  - Averaged data used to fit linear model
    - Error bars show 2 std. dev.
- V-I data can be used in 2 levels of FC model
  - Detailed model
  - Simple efficiency vs. power curve-fit



FC polarization data from 3 sites agree, providing model calibration



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

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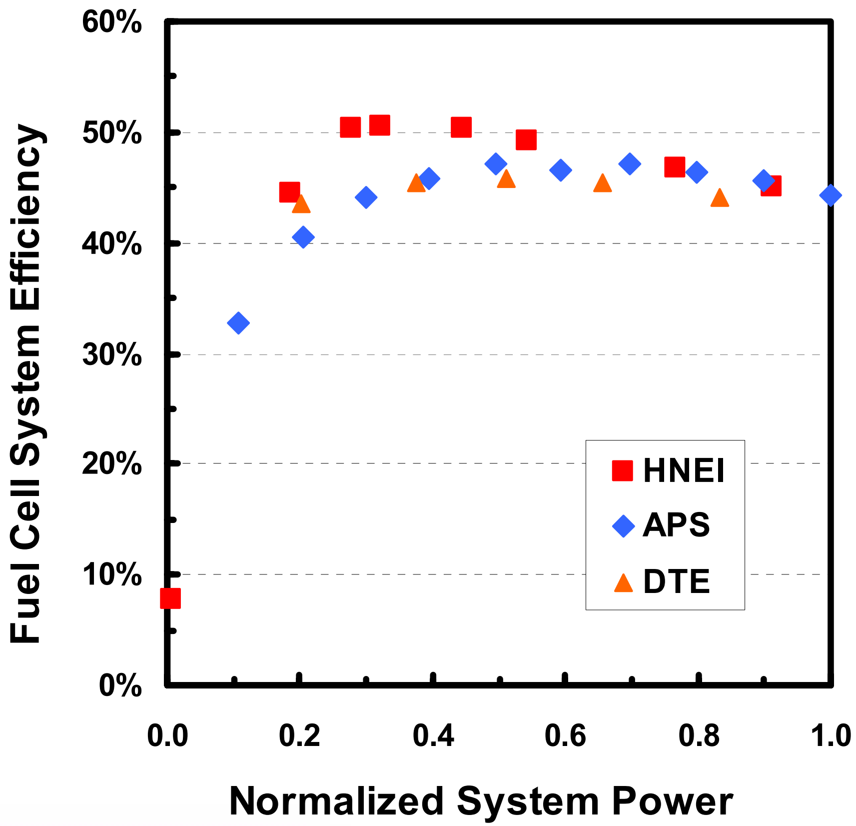
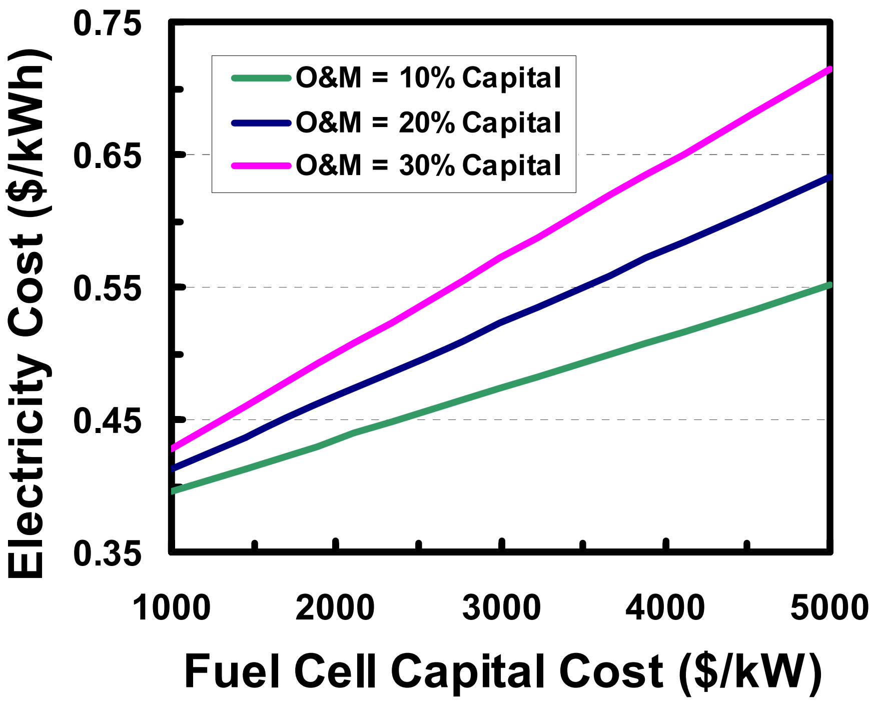
Fuel cell system operating data at 3 sites



- Hydrogen fuel cell system efficiency (LHV)
  - Based on net DC power out and hydrogen flow
  - Power regulated to 48V
  - System includes fuel cell stack, balance of plant, and DC-DC converter
- Agreement in practical range:
  - 48 % system at half load
  - 45 % at full load
- Model analysis performed in this load range

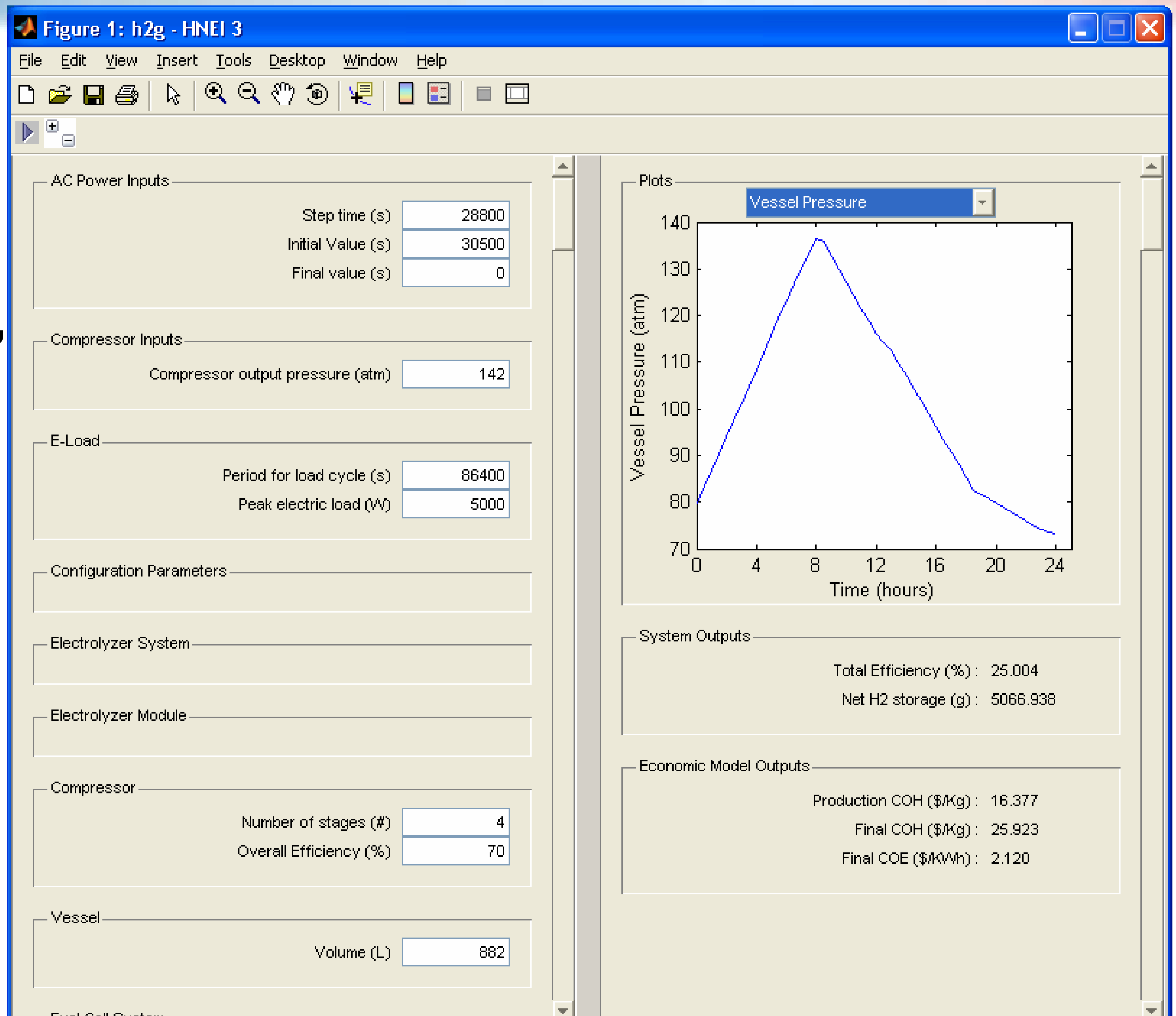
Projected cost of electricity from HNEI FC

- Capital cost for 5 kW-DC fuel cell system
  - 45% efficiency (LHV)
  - Parameter Study:
    - Fuel cell capital cost
    - Vary O&M from 10-30% for stack replacement
  - H_2 at 5.37 $/kg from electrolyzer at nominal conditions:
    - 1500 kg/day production rate
    - 0.04 $/kWhr electricity



We developed a GUI for non-Simulink users

1st GUI: Electrolyzer, H_2 storage (gaseous), Compressor, Fuel cell



<u>Left side:</u> user inputs

<u>Right side:</u> model outputs and a choice of graphs

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Future Work

- Compare model to data from DOE power parks
  - APS: apply model to new data on HBR electrolyzer
  - DTE Energy: evaluate new electrolyzer expected in summer
  - HNEI: Compare model predictions with wind turbine data
- Analysis of biomass pyrolysis
  - Analyze data from peanut shell pyrolysis demonstration
    - Collaborate with EPRIDA, U. of Georgia, NREL
- Collaborate with Stanford's Global Climate & Energy Project
  - Implement 2nd-law exergy analysis to measure efficiency in terms of availably energy for a process

$$A = (E - U_0) + p_0(V - V_0) - T_0(S - S_0)$$

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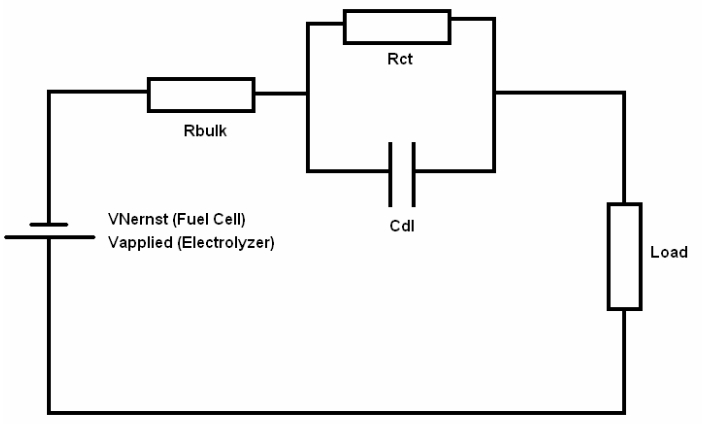
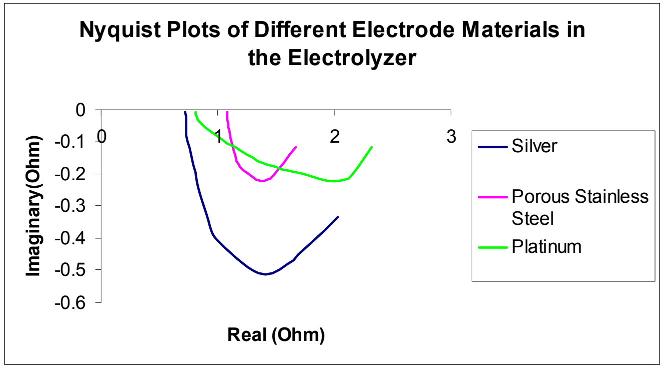
Future Work (con't)

- Collaborate with grad-student visitor in UK/US exchange program
- Emma Stewart (U of Strathclyde)
- Research Interests
  - Modeling of fuel cells for electrical power systems and distributed generation
  - Power electronics modeling for electrical grid network integration
  - Testing methods for analyzing electrical performance in relation to the electrochemical reactions
    - Electro-Impedance Spectroscopy
    - Load and Transient Analysis



Randles Cell



Impedance Analysis

Summary

- **Analysis of electrolysis at 3 power parks: APS, DTE, HNEI**
  - **System efficiency range: 35 to 57 % including BOP & compression**
    - **Best efficiency is about 10 % points short of 2005 target**
      - Standby power and chiller loads are significant
    - **Duty cycle is an issue—as in driving cycle for vehicle mileage**
  - **H2 cost depends on:**
    - **Electricity price – which depends on region and time-of-day**
    - **Capital cost – which depends on scale**
    - **H2 price range:**
      - 20 $/kg at scale of power parks
      - ~5 $/kg at 1500 kg/d with optimistic scaling factor
  - **Electricity from fuel cells returned at peak load is not competitive**
    - **except for isolated cases like Big Island at 0.32 $/kWh**

Supplemental Slides

Response to FY 2005 review

- **Reviewers' major comments:**
  1. *Be more proactive with technology validation power park projects to ensure good quality data*
  2. *Consider approaches to enable broader dissemination of analytical models*
  3. *What is plan for interfacing with HFCIT Systems Analysis & Systems Integration activities?*
- **Response:**
  1. ***Working directly with engineers at APS, HNEI and DTE***
     - ***supporting LTU student to work in data analysis at DTE***
  2. ***Committed Sandia internal funds (20k$) to develop GUI so others can perform system simulations***
  3. ***Sandia is developing the high-level architecture (HLA) for the macro-system model (MSM)***
     - ***Can link H2Lib modules in future system analysis activities***

Publications and Presentations

Presentations:

- "Power Park Simulations", Tech Val working meeting, July (2005).
- "Power Park Simulations", IEA Task 18 meeting, March (2006).

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.