Power Parks System Simulation

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Objectives and Relevance

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

Deliverables

- A flexible, computational tool to provide simulations of a variety of energy systems that produce H_2
- Independent analysis of system performance
  - Thermodynamic efficiency
  - Cost of H_2 and electricity

Technical Barriers and Targets

Relevance to the Multi-year Program Plan:

- Technical Analyses
  - Analyze H_2 and electricity (e^-) as energy carriers and evaluate potential synergies
  - Analyze advanced power parks for production of both H_2 and e^-
  - Determine the economics of H_2 and e^- co-production compared to stand-alone hydrogen facilities
- Cost targets for distributed production from natural gas
  - 700 kg/day of H_2 produced from 4$/GJ gas & 0.07$/kWh power
  - Stations built at volume of 100/yr without sequestration
  - 2005: 3.00 $/kg (untaxed)
  - 2010: 1.50 $/kg (untaxed)

Approach

Software Design

Use Simulink software as platform for transient simulations

- Simulink provides:
  - Graphical workspace for block diagram construction
  - ODE solvers for integration of system in time
  - Quick-look output from simulation
  - Control strategies and iterative loop solutions

Create a library of Simulink modules to represent components

- Component models based on fundamental physics and chemistry to the extent practical
  - Coupled Chemkin software routines as Simulink functions
  - Thermodynamic properties of gas mixtures used in energy balances
  - Equilibrium composition used for catalytic reforming and combustion burners
- Library components can be quickly re-configured for new system concepts
- Generic components from library can be customized using data on the performance of specific unit

Project Timeline & Budget

		FY2004				FY2005			
Item	Task	Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3	Qtr 4
1.	SunLine - simulation	*	♦						
	- comparison to data			*	♦				
2.	Las Vegas – simulation	*	♦						
	- comparison to data			*	*	*	♦		
3.	HNEI system - simulation	*	*	*	♦				
	- comparison to data					*	*	*	♦

* Continuous development
♦ Milestone for completion

Budget:

- FY03 = 250 K$
- FY04 = 250 K$

Progress: Library of Simulink modules

- Reformers
  - Steam methane - T determined by internal energy balance
  - Autothermal (partial oxidation) - optimize air/carbon to balance energy
- Electrolyzer
  - Steady-state model uses first principals and experimental data
    - Energy balance – including phase change of water in the electrolyzer
    - Mass balance – including separation of water vapor from the hydrogen product stream
    - Simulates performance versus stack operating conditions and physical characteristics
- Fuel cell
  - PEMFC - efficiency versus power scaled to data
  - SOFC – sub-model for kinetics of operation (Kee et al., Colorado School of Mines)
- Economic analysis modules
  - Capital cost spread over life using capital-recovery-factor
  - O&M costs per year by component
- Other components:
  - Compressor – multi-stage with intercooling, isentropic efficiency
  - High-pressure storage vessel – real-gas equation-of-state
  - Photovoltaic Solar Collector

Cooperative Efforts

Collaborations:

- U C Berkeley – Energy and Resources Group (ERG) - Tim Lipman
  - Carl Mas – masters thesis: "H_2 as an Energy Carrier: System Modeling in Distributed H_2 Generation"
- City of Las Vegas Refueling Station –
  - Air Products - Mark Wait, Greg Keenan, Dave Guro
  - Plug Power - Bob Sinuc, Rob Dross
- SunLine Transit Agency – Bill Clapper, Polo Deltoro
- Hawaii Natural Energy Institute (HNEI) – Mitch Ewan, Richard Rocheleau
- Colorado School of Mines – Bob Kee, Kevin Walters

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.

Simulation of DOE demonstration systems

City of Las Vegas (CLV) refueling facility

- Co-produces H_2 and electricity
- H_2 Generator with Steam-methane reformer (SMR)
  - sized for 50 kW fuel cell with extra for vehicle refueling

Watervliet Arsenal fuel cell demonstration

- 5kW fuel cell units with autothermal reformers
- Data collected over a full year's operation

Hawaii Natural Energy Institute

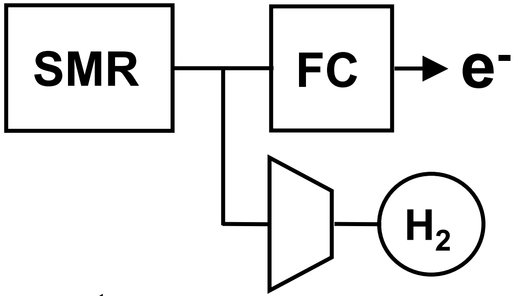
- PV arrays will power Stuart electrolyzer
- H_2-ICE generator and fuel cell will power building

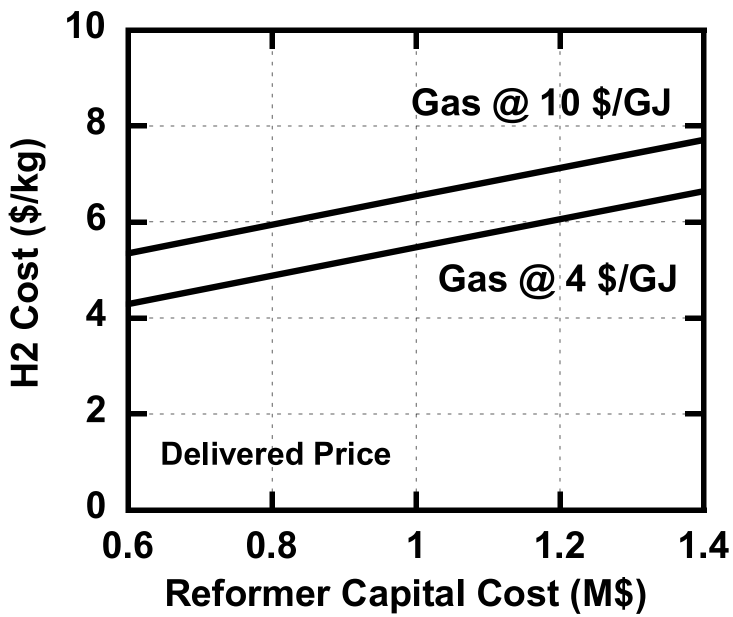
SunLine Transit

- H_2 production from:
  - Electrolyzer powered by PV arrays
  - HyRadix autothermal reformer
  - H_2 stored for vehicle refueling

Engineering/economic analysis of hybrid power system at CLV

- H_2 Generator (SMR) feeds fuel cell and compressed storage
  - Reformer: ~150 kg/day at 68% thermal efficiency (H_2/CH_4 on LHV basis)
  - Compressor: used 82% efficiency from MYPP target
- Hybrid system efficiency = 47%
  - Electricity + Compressed H_2
  - Gas-to-electric efficiency = 29%

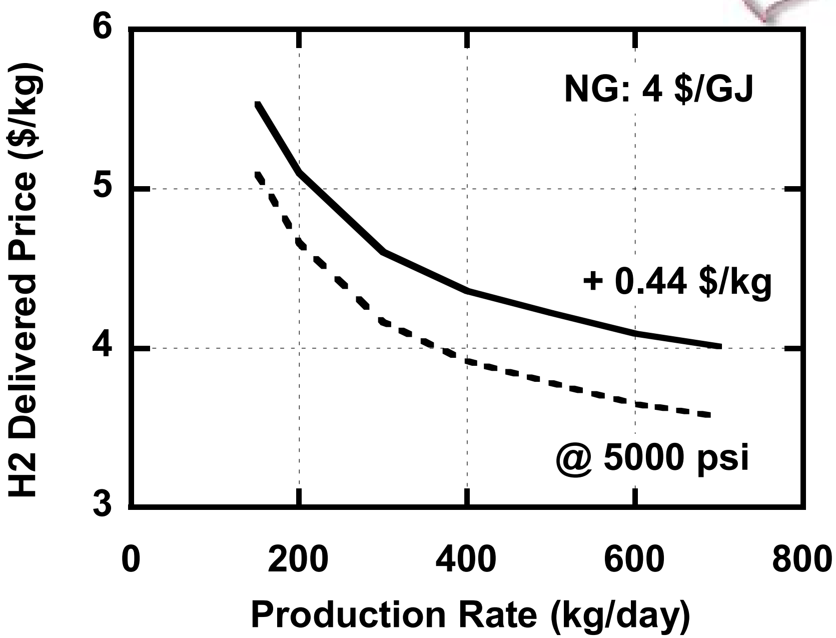


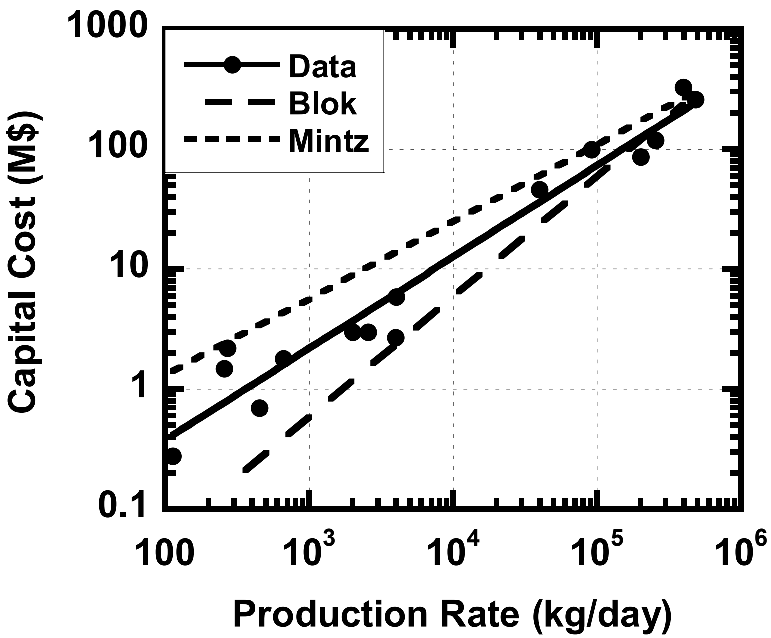


- Economic parameters
  - 10 year life at 10% interest
- Parameter studies:
  - Reformer capital cost
  - Natural gas price
- H_2 cost includes
  - Compressor: capital + power at 8¢/kWh
  - Refueling station: 0.92$/kg (MYPP target)

Cost of H_2 projected for a refueling station

- H_2 production rate has non-linear effect on cost
- Use literature correlation to *simultaneously* vary reformer capital cost & production rate
- Add 0.44$/kg for refueling station
  - From DOE 2010 target costing

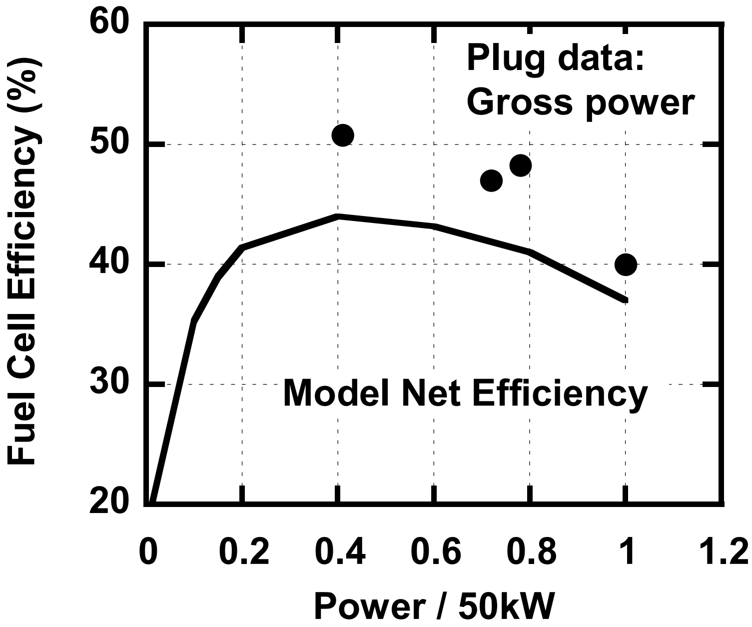


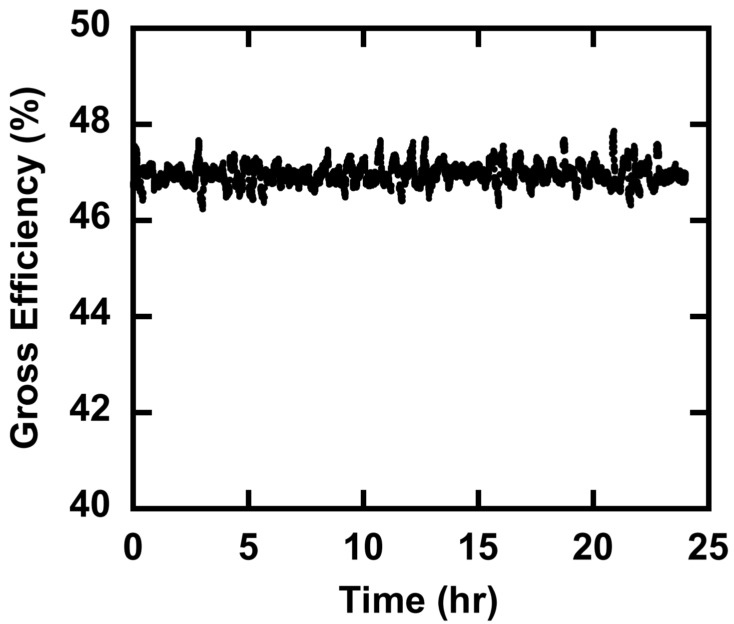


- To meet DOE targets for distributed reforming (4$/GJ gas)
  - 2005: 3$/kg will need 700 kg/day reformer installed for 2.5M$ instead of 3.4M$
  - 2010: 1.50$/kg requires changing the capital cost vs production rate relation

Model for fuel cell at CLV demonstration

- Model uses CLV operation data
  - Adjusted efficiency to measurement: 47% for 36kW gross DC power out
  - Assume a 10% reduction to account for parasitics & power conditioning
  - Net efficiency for model = 42%

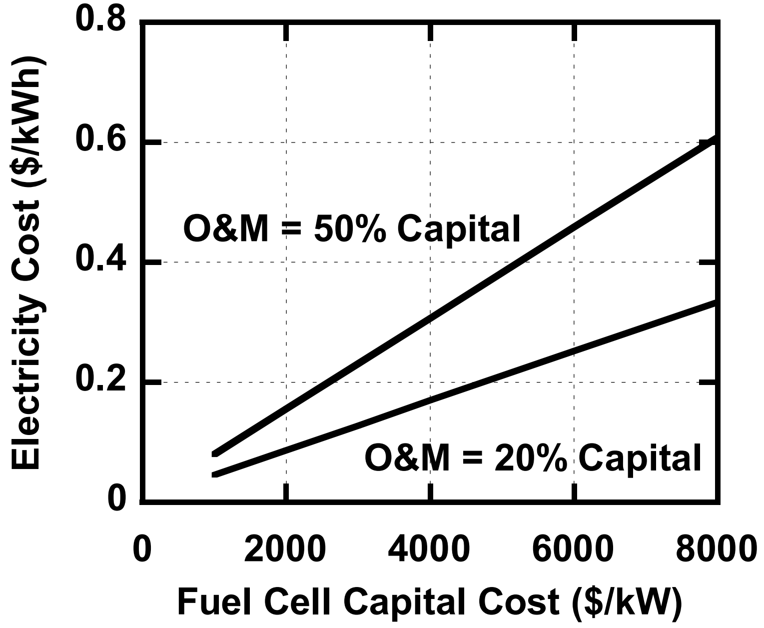




- Operation data from Plug Power (with permission)
  - Steady-state operation at 36 kW

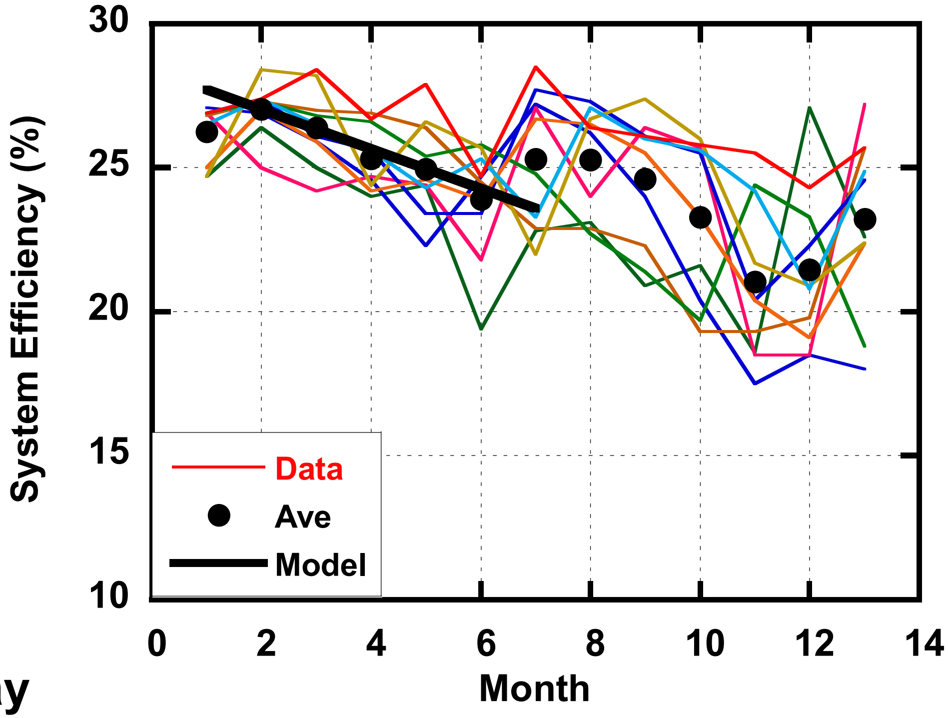
Cost of electricity for hybrid system

- Economic assumptions
  - Maintenance includes yearly stack replacement
    - Vary O&M over range 20-50% of original capital cost
  - H_2 at 4.81$/kg from reformer at nominal conditions:
    - 150 kg/day production rate
    - 6 $/GJ natural gas



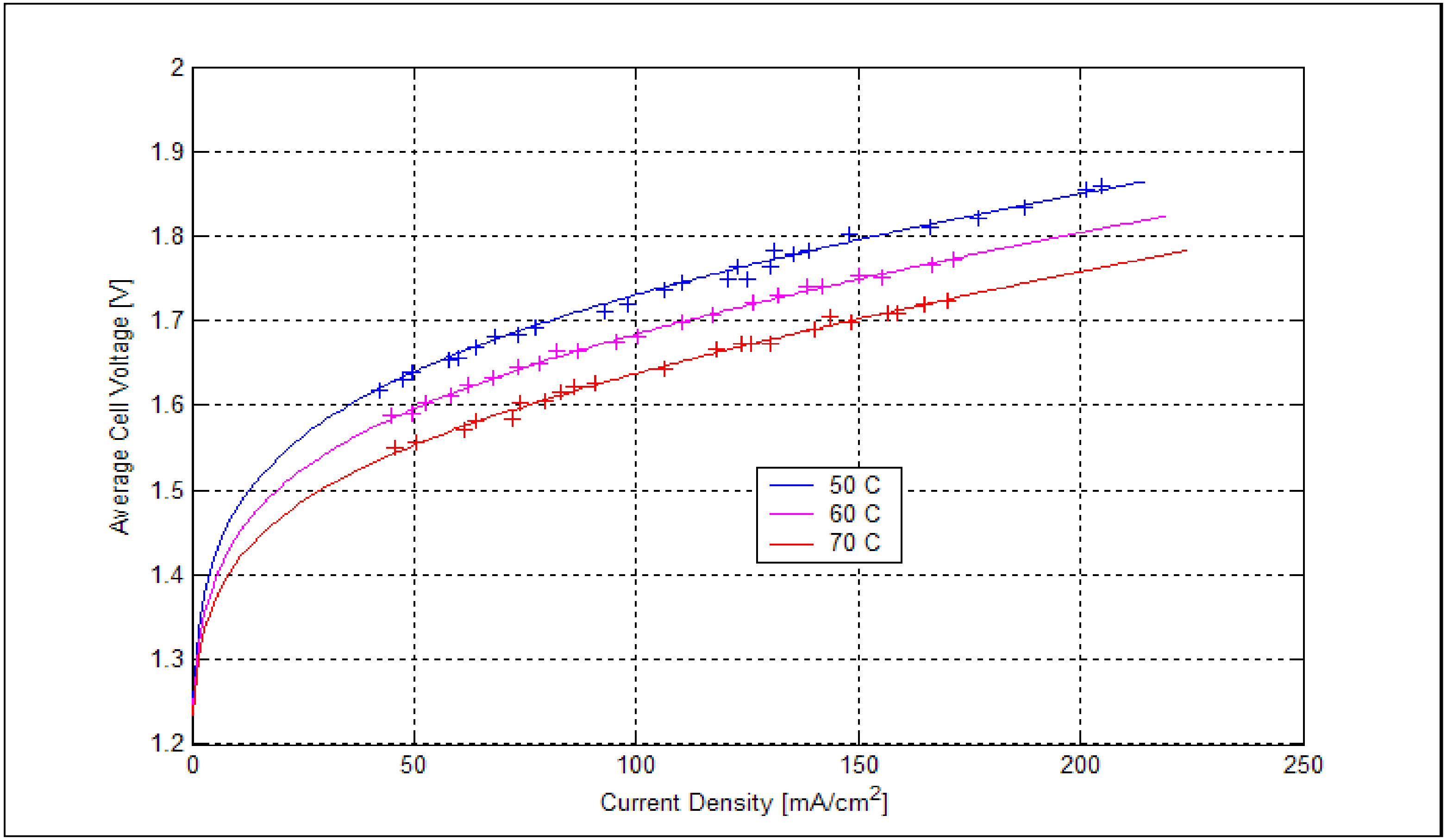
Analysis of integrated reformer/fuel cell

- Comparison to data from Watervliet Arsenal (DoD demonstration)
- Plug Power 5kW units operated at 2.5 kW
- Net thermal efficiency
  - Natural gas to electricity
  - Varies with age of stack
  - New: 27%
  - 6 months: 24%
- Autothermal reformer
  - Assume 1073 K
  - Gas-to-H_2 efficiency = 63%
  - FC exhaust heats reformer
- Simulation of FC efficiency
  - Adjusted for dilute mix & decay
  - 30% efficient at 83% utilization

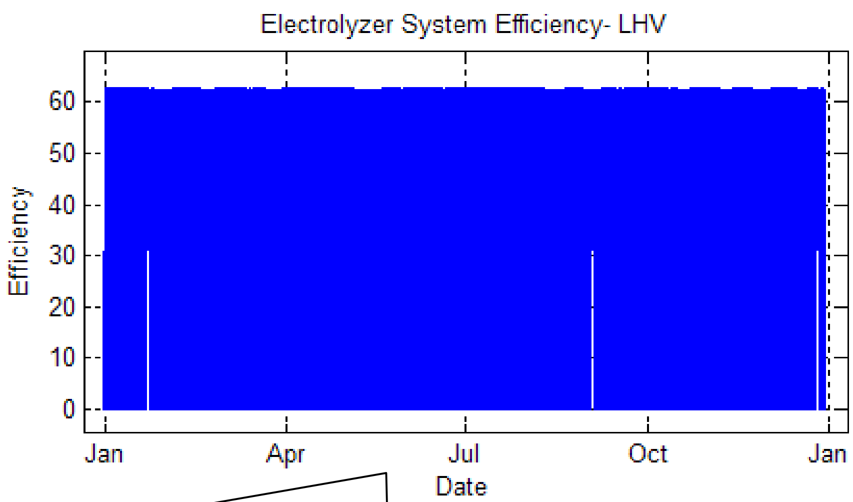


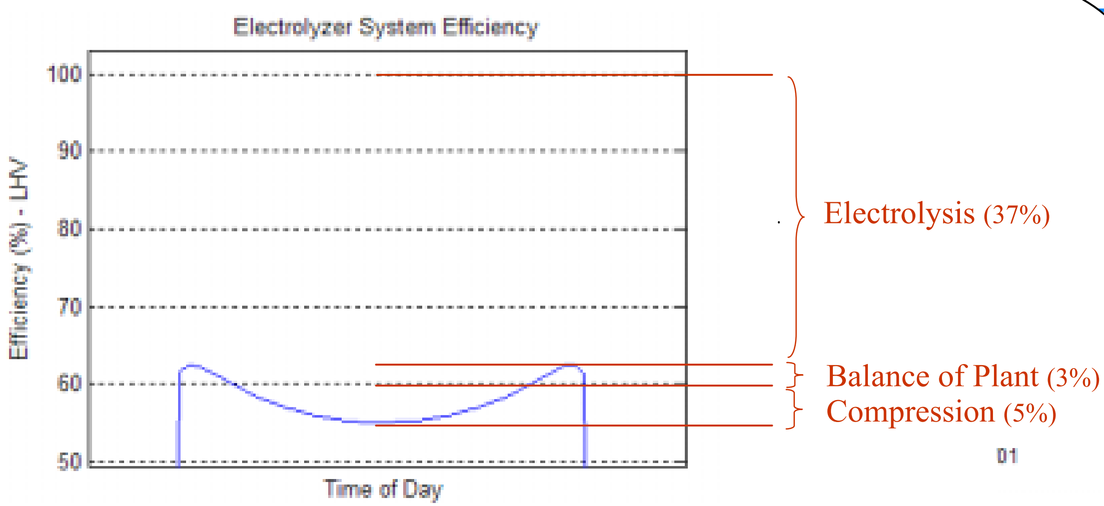
Alkaline Electrolyzer Parametric Model

- **Temperature Dependent V-I Curve fit to Experimental Data from the PHOEBUS plant in Julich, Germany.**



HNEI Solar-Hydrogen System Simulation

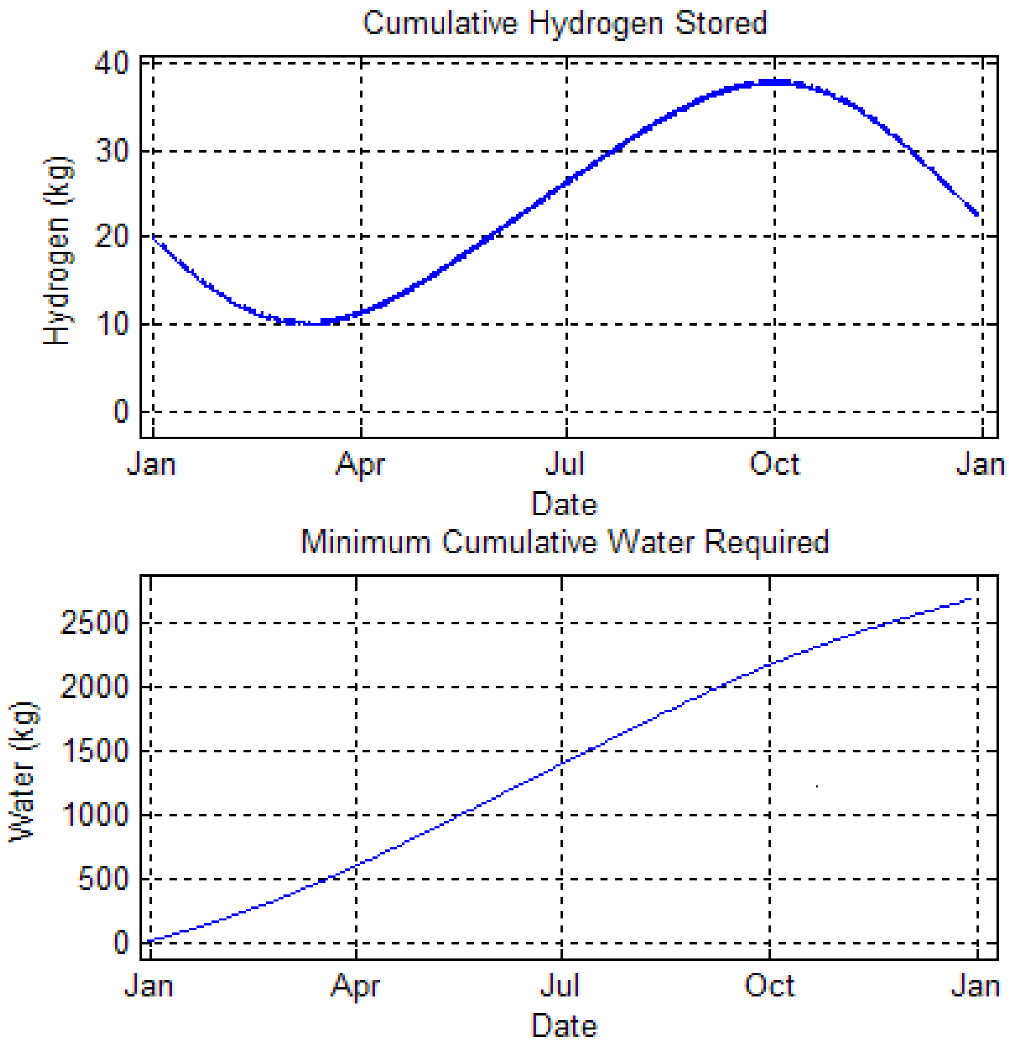




Preliminary Simulation

- $100\ m^2$ PV array
- 7.5 kW Electrolyzer
  - 60 ^oC, 1.5 atm
  - Max. Cell Voltage = 1.9 V
- 5.4 kW PEM Fuel Cell
- 2 Stage Intercooled Compressor
  - 170 atm
- Time Dependent Electric Load
  - Assumed daily cycle

HNEI Solar-Hydrogen System Simulation

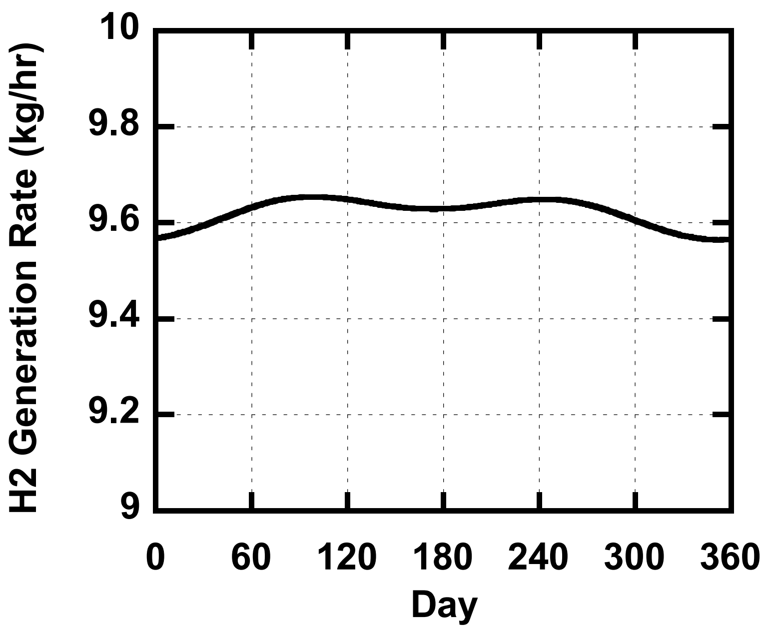


Preliminary Simulation

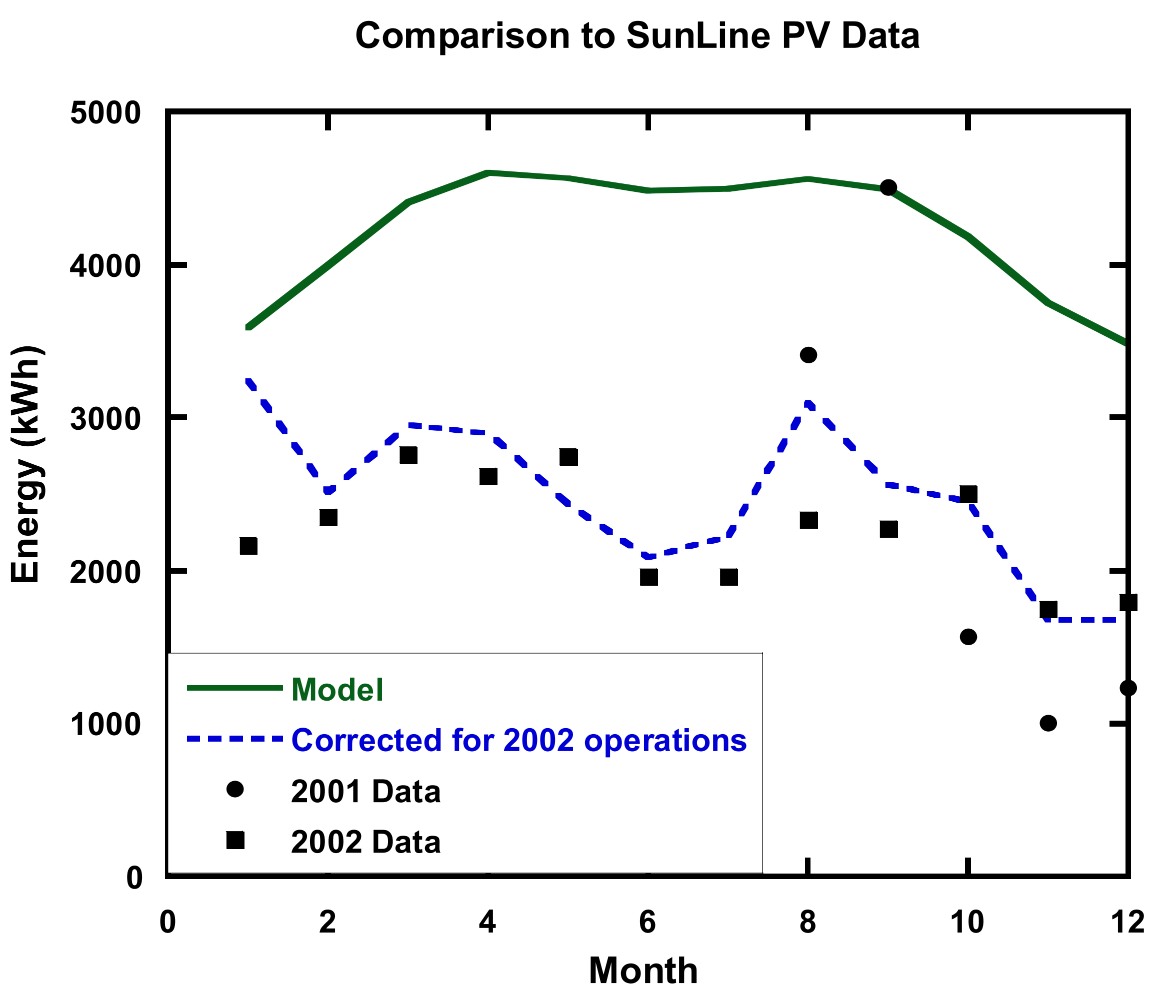
- Annual H_2 storage from solar energy
  - FC daily load cycle is constant during year
  - H_2 storage varies with seasonal solar insolation
  - Model could be used to optimize PV array size
- Annual water consumption
  - Cumulative during year's seasonal variation

SunLine system analysis

- New HyRadix autothermal H_2 generator currently in test-out phase
  - 100 Nm^3/hr capacity
  - Preliminary simulation shows seasonal H_2 generation when combined with existing PV system
- SunLine expects new buses to run on H_2-CNG blend & pure H_2 in next year



Simulation of SunLine PV collector



- **Model simulation**
  - Run yearly variation
  - Integrate daily collection
  - Sum monthly to compare to SunLine data
- **Solar radiation model**
  - Analytic function of longitude, latitude, altitude
- **PV panel model**
  - Area = 360 m^2, slope 23°
  - Adjust solar-electric conversion efficiency 7 %
- **Correct monthly sums to SunLine's operations**
  - Operating days / month
  - Sunny days / month

Response to FY 2003 review

- **FY2003 Ranking**
  - **Project ranked 3rd in Technology Validation category with score 3.55 / 4.0**
- **FY2002 reviewer's suggestion:**

"We encourage further collaborations and modeling of actual power park sites such as Las Vegas, SunLine, etc."

- **Collaborations with power park sites:**

1. **Continuing collaboration with SunLine transit, City of Las Vegas, Air Products, Plug Power**
2. **Established collaboration with HNEI to simulate the power park being constructed at Kapolei Hale city hall**

Proposed Future Work

Task 1

- Continue to build and refine the component library
  - Add fundamental physics to fuel cell model: polarization curve, water management, parasitic losses
  - Wind turbine generator (for SunLine facility)
  - H_2-ICE generator (for HNEI facility)
  - H_2 storage as liquid or metal hydride

Task 2

Collaborate with researchers at existing power parks

- SunLine, City of Las Vegas, HNEI, and other DOE sites

Task 3

Perform long-term studies of distributed H_2 production

- Expand existing analysis to examine thermodynamic *availability*