Power Parks System Simulation

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This presentation does not contain any proprietary or confidential information.
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 \( \text{H}_2 \) systems
  - MYPP defined cost and efficiency targets for distributed \( \text{H}_2 \) 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 H₂ Program

Objectives

• Develop a flexible system model to simulate distributed power generation in energy systems that use H₂ 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 H₂ and power production

Relevance to the Multi-year Program Plan:

• Technical Analyses
  – Analyze H₂ and electricity as energy carriers and evaluate synergies
  – Analyze advanced power parks for production of both H₂ and electricity
  – Determine the economics of H₂ 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 H₂-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 H₂ 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 H₂ for storage
  - 5 kW PEMFC evaluated in FC testing center
- **Arizona Public Service (APS) refueling facility**
  - H₂ produced by PEM electrolyzer from grid and PV electricity
  - H₂ stored at low-p and used by PEMFC and ICE gen-sets
  - H₂ 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: \(~12 \ \text{kg/day} \) 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 H₂ for HNEI power park

- H₂ 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
  - H₂ 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
  - H₂ 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
  - H₂ 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 output 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 H₂ 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

\[ \eta_{\text{overall}} = f \eta_{\text{elect}} \]

\[ \eta = \frac{LHV}{\sum W} \]

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

<table>
<thead>
<tr>
<th></th>
<th>APS Data</th>
<th>2005 Target</th>
<th>2010 Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell &amp; BOP</td>
<td></td>
<td>35%</td>
<td>68</td>
</tr>
<tr>
<td>Comp, Store, Disp</td>
<td></td>
<td>96%</td>
<td>95</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>34%</td>
<td>64</td>
</tr>
</tbody>
</table>

* Estimated power conversion \( \eta \sim 76 \% \), so stack \( \eta \sim 54 \% \)
Thermodynamic efficiency for compression

- **Work required for compression**
  - Assume ideal intercooling of calorically perfect gas between stages
  
  \[
  \frac{\dot{W}_{\text{ideal}}}{m} = \frac{RT_1}{\eta} \frac{n\gamma}{\gamma - 1} \left[ \left( \frac{p_2}{p_1} \right)^{(\gamma - 1)/n\gamma} - 1 \right]
  \]

- **“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-\(\text{H}_2\) from electrolysis at APS scaled to MYPP target size facility

- **PEM electrolyzer**
  - Operates at 35% overall efficiency
  - Capital scaled by \(\$43k \times (\text{rate}^{0.6})\)
    - 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 \(\$11k \times (\text{rate}^{0.6})\)

<table>
<thead>
<tr>
<th>Compare to MYPP:</th>
<th>Targets</th>
<th>Projected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolyzer capital</td>
<td>0.80 $/kg</td>
<td>1.13 $/kg</td>
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<tr>
<td>Compression</td>
<td>0.77</td>
<td>0.43</td>
</tr>
<tr>
<td>Electricity</td>
<td>2.47</td>
<td>3.78</td>
</tr>
<tr>
<td>O&amp;M</td>
<td>0.71</td>
<td>0.16</td>
</tr>
<tr>
<td>Total</td>
<td>4.75 $/kg</td>
<td>5.50 $/kg</td>
</tr>
</tbody>
</table>

- Electrical cost is above target due to low \(\eta\)
- At target \(\eta = 68\%\)
  - Electricity = 1.96 \$/kg
  - Total cost = 3.70 \$/kg
Engineering/economic analysis of hybrid power system at CLV

- H₂ Generator (SMR) to feed FC and refueling
  - Reformer: ~150 kg/day at 68% thermal efficiency (H₂/CH₄ on LHV basis)
- Simultaneously vary reformer capital cost & size using a correlation fit to literature data: Capital = $15k * Rate⁰·⁷⁶
- Economic parameters from H2A
- H₂ cost includes compression & dispensing (0.8$/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 H₂ 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)

- H₂ storage in high-pressure tube bank

- Vehicle refueling station

- 10 PEMFCs (5 kW each) provide peak-demand power

- Examine the cost-of-H₂ 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 H₂ 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
  – H₂-ICE gen-set for APS data comparison

• Long-term studies of distributed H₂ production (30k$)
  – Expand existing analysis to examine thermodynamic availability

• Perform analysis of international H₂ stations (50k$)
  – Support IEA Task 18: Evaluation of integrated demonstration systems (Susan Schoenung, Longitude 122 West Inc.)
Publications and Presentations

Presentations:

Publications:
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.