Power Parks System Simulation

Andy Lutz, Adam Simpson*, Emma Stewart**
Combustion Research Facility
Sandia National Laboratories
Livermore, CA

*Stanford University
**University of Strathclyde, Scotland

TVP-7
Hydrogen Program Annual Review
May 17, 2007

Overview

- **Timeline**
  - Started: FY03
  - Finish: FY07
  - Complete: 85%
- **Budget**
  - FY 2006: 150 K$

- **Barriers addressed**
  - Performance for stationary H_2 systems
  - MYPP cost and efficiency targets for distributed H_2 production
  - Reforming natural gas:
    - Cost: 2.50 $/kg (2010), 2 $/kg (2015)
    - Efficiency: 72% (2010), 75% (2015)
  - Distributed electrolysis:
    - Cost: 3.70 $/kg (2012), <3 $/kg (2017)
    - Cost: 3.70 $/kg (2012), <3 $/kg (2017)
  - Biomass Gasification/Pyrolysis
    - Cost: 1.60 $/kg (2012), 1.10 $/kg (2017)
    - Efficiency: 43 % (2012), 60 % (2017)

Overview (con't)

- Partners
  - Hawaii Natural Energy Institute (HNEI)
    - Richard Rocheleau, Scott Turn, Mitch Ewan
  - Arizona Public Service (APS)
    - Ray Hobbs
  - DTE Energy
    - Rob Bacyinski
    - Rob Fletcher, Elliott Schmitt (Lawrence Tech.)
  - Stanford's Global Climate & Energy Project
    - Adam Simpson, Chris Edwards
  - University of Strathclyde
    - Emma Stewart, Andrew Cruden

HAWAII NATURAL ENERGY INSTITUTE

DTE Energy

APS

GCEP

University of Strathclyde

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 H2 and electricity production co-located with a load
- Analyze the efficiency and cost of H_2 and electricity at demonstration systems
- Support IEA Annex 18 modeling task
  - Evaluate, guide and assist in the development of hydrogen demonstration systems
  - Analyze the "Idrogeno Dal Sole" (Hydrogen from the Sun) demonstration

Relevance to the Multi-year Program Plan:

- Technical Analyses
  - Analyze H_2 and electricity as energy carriers and evaluate system synergies

Approach

Combine engineering and economic analysis

- Assemble engineering model as system of components
- Component models based on fundamental physics and chemistry
- Economic analysis modules linked to components
- Validate simulations with data from DOE demonstration projects
  - Conducted site visits to establish working relationships with engineers
  - Supported graduate students to help with 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

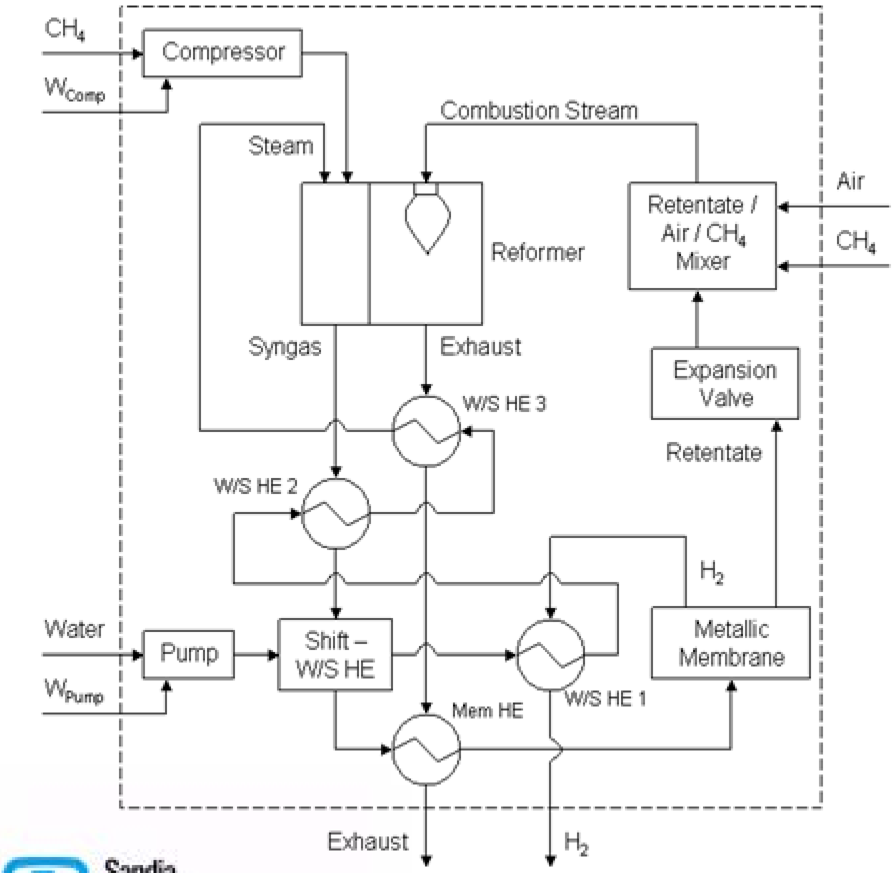
- Engineering component models:
  - *Separation*: model work by minimum work, efficiency, & effectiveness
  - *Reformers*: steam methane and autothermal (partial oxidation)
  - *Electrolyzer*: balances mass & energy, including phase change
  - *PEM Fuel cell*: uses experimental data for polarization 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
  - *Wind turbine*: model power map & wind shear using hourly wind data
  - *Chiller*: model pump work and refrigerant cycle with coefficient-of-performance
- Economic analysis modules consistent with H2A
  - *Levelized-cost approach*: interest, taxes, depreciation, capacity factor

Simulations of DOE demonstration systems

- Exergy (2^{nd} law) analysis of steam-methane reforming
  - Revisited analysis of City of Las Vegas refueling station
- Hawaii Natural Energy Institute
  - Gasification of biomass to produce H_2
  - Electrolyzer to produce compressed H_2 for transportation on Big Island using geothermal electricity
- IEA Task 18 Integrated H_2 systems analysis
  - Simulation of Italian H_2 House
- DTE Energy Hydrogen Technology Park
  - Electrolyzer feeds stationary PEMFC's and vehicle refueling
- Arizona Public Service (APS) refueling facility
  - PEM electrolyzer feeds PEMFC, ICE gen-sets & vehicle refueling

Exergy analysis of Steam Methane Reforming

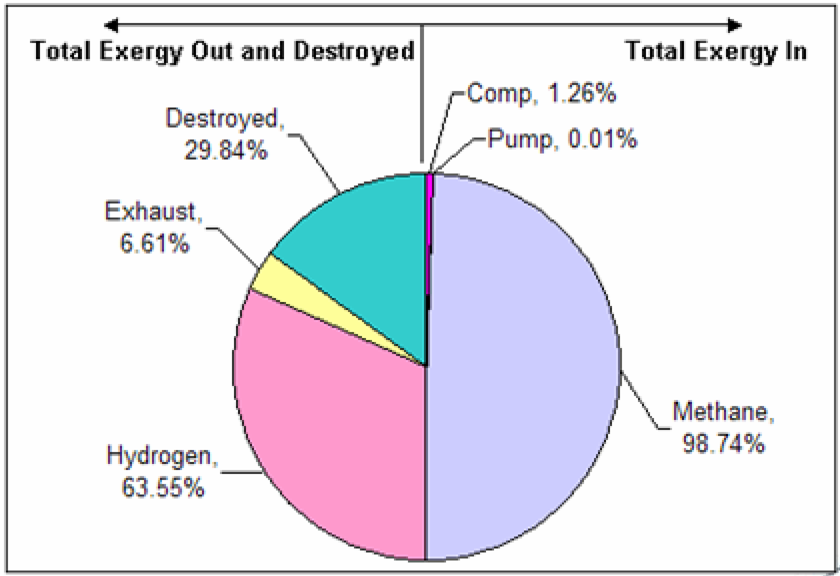
Model includes heat integration



Exergetic efficiency definition:

$$\eta_{ex} = \frac{X_{H_2}}{X_{CH_4} + W_{comp} + W_{pump}} = 63.3\%$$

$$X = U + P_o V - T_o S - \sum_k N_k \mu_{ko} - \sum_k \left[\sum_i \mu_{ko} \left({}^{\nu_{ki}}\!/_{\nu_i} \right) \right] N_k$$



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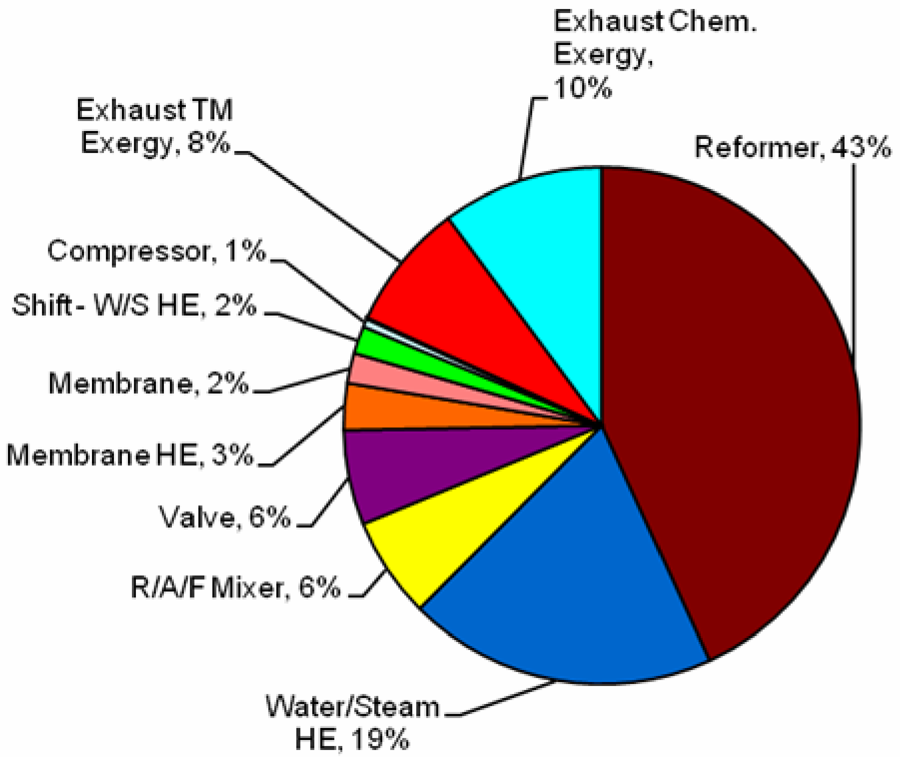
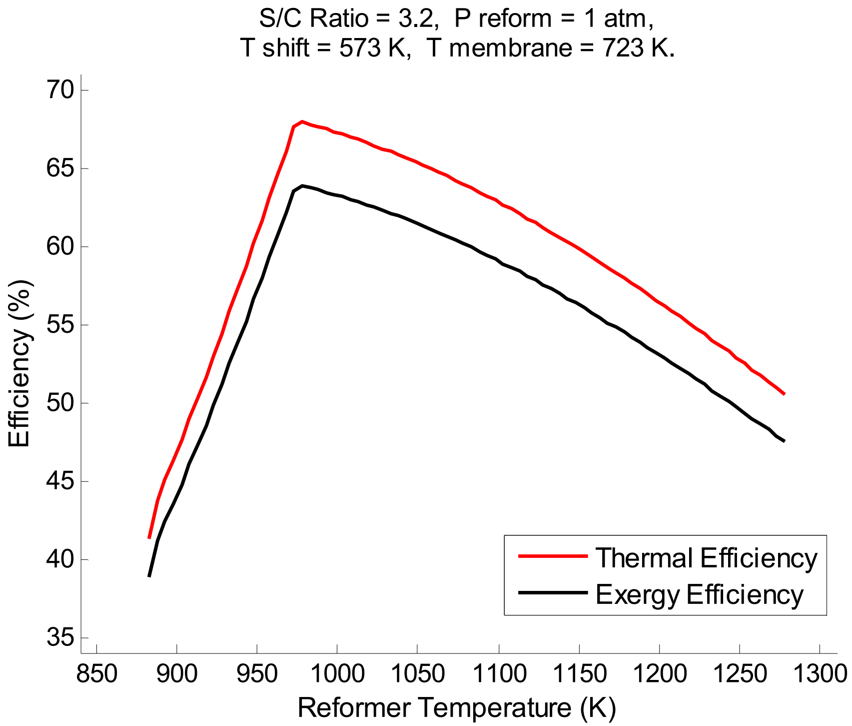
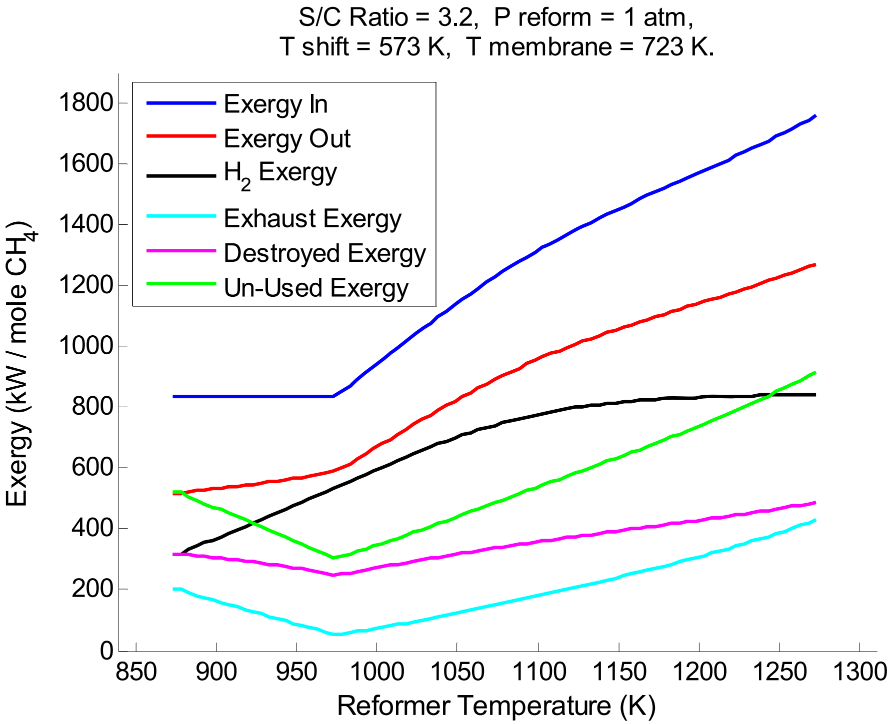
Exergy analysis locates and compares the inefficiencies in the SMR system



- Break down of unused exergy
  - “Unused” = exhaust + destroyed
- Majority of exergy destruction occurs in reformer
  - Inherent irreversibilities: combustion, heat transfer, mixing
- Second largest destroyer of exergy is the water-to-steam heat exchanger
- Exergy left in the exhaust is significant, but not dominant
- 1st-law analysis alone would suggest exhaust is the main cause of inefficiency

Equilibrium model shows that SMR system efficiency is a strong function of temperature

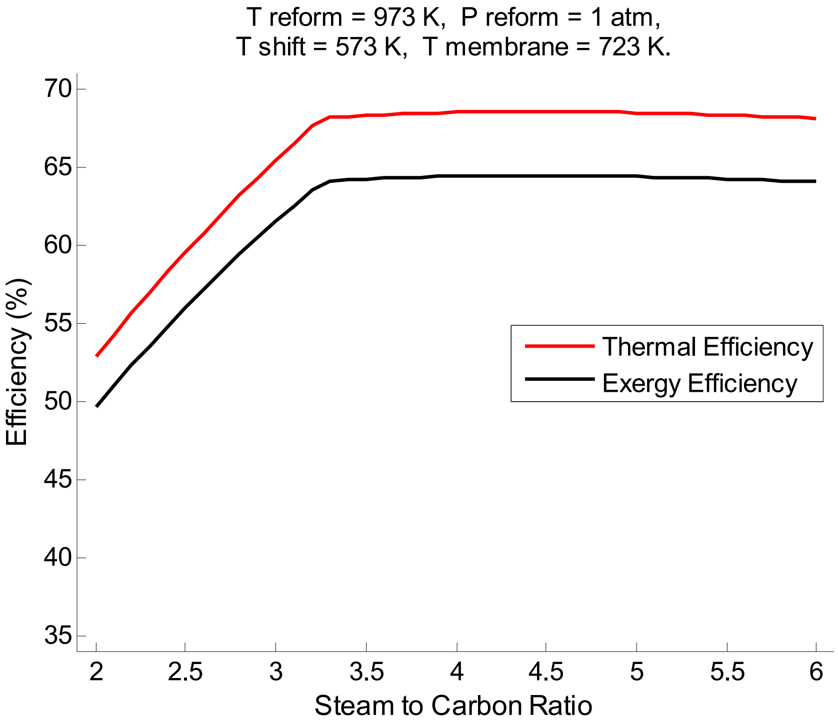


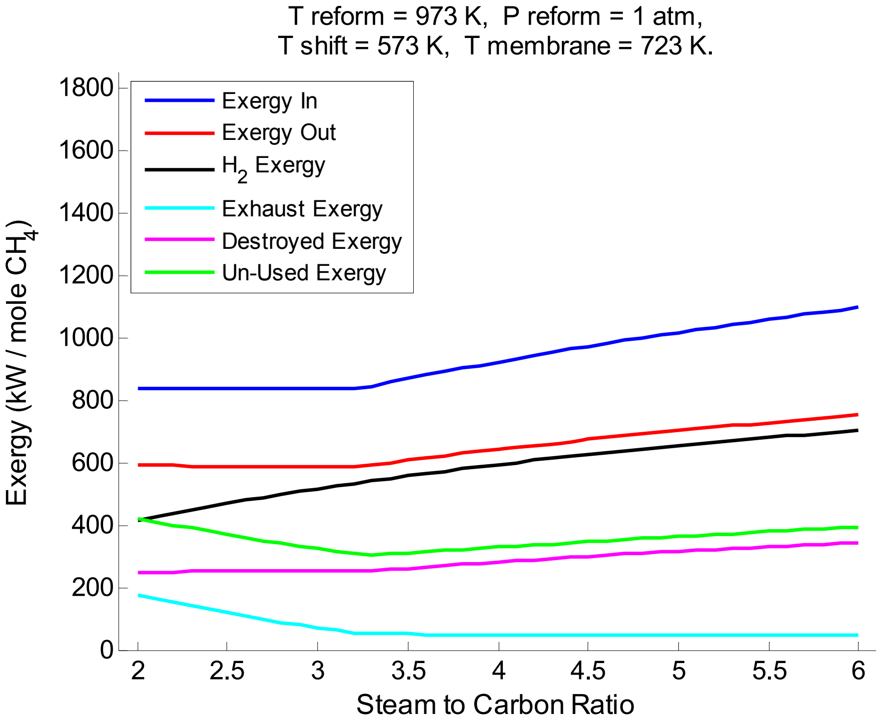


For T < 975 K : Increasing T shifts equilibrium toward more H_2

For T > 975 K : Additional methane needed to supply heat

Model shows benefit of excess steam


T reform = 973 K, P reform = 1 atm,
T shift = 573 K, T membrane = 723 K.


T reform = 973 K, P reform = 1 atm,
T shift = 573 K, T membrane = 723 K.

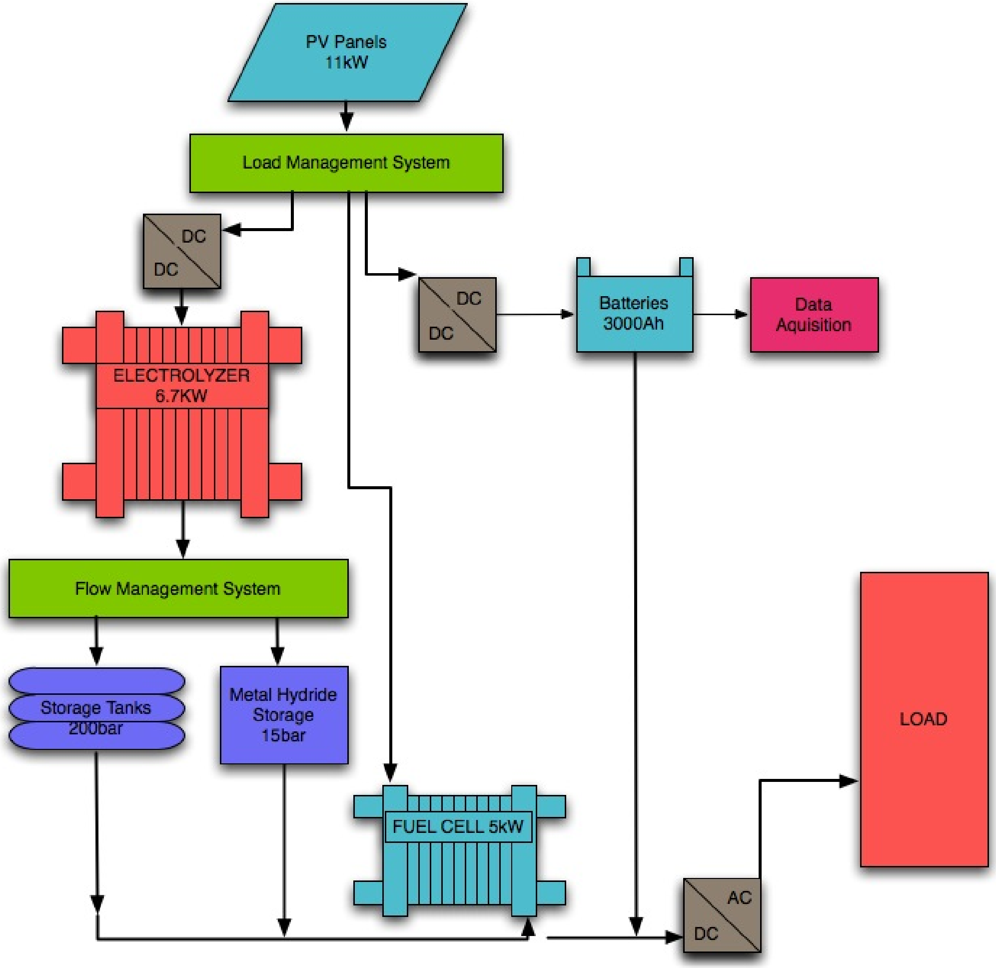
For 2 < (S/C) < 3.3 : Excess steam shifts equilibrium toward H_2

For (S/C) > 3.3 : Additional steam requires burning more methane

Analysis of "Idrogeno Dal Sole" demonstration

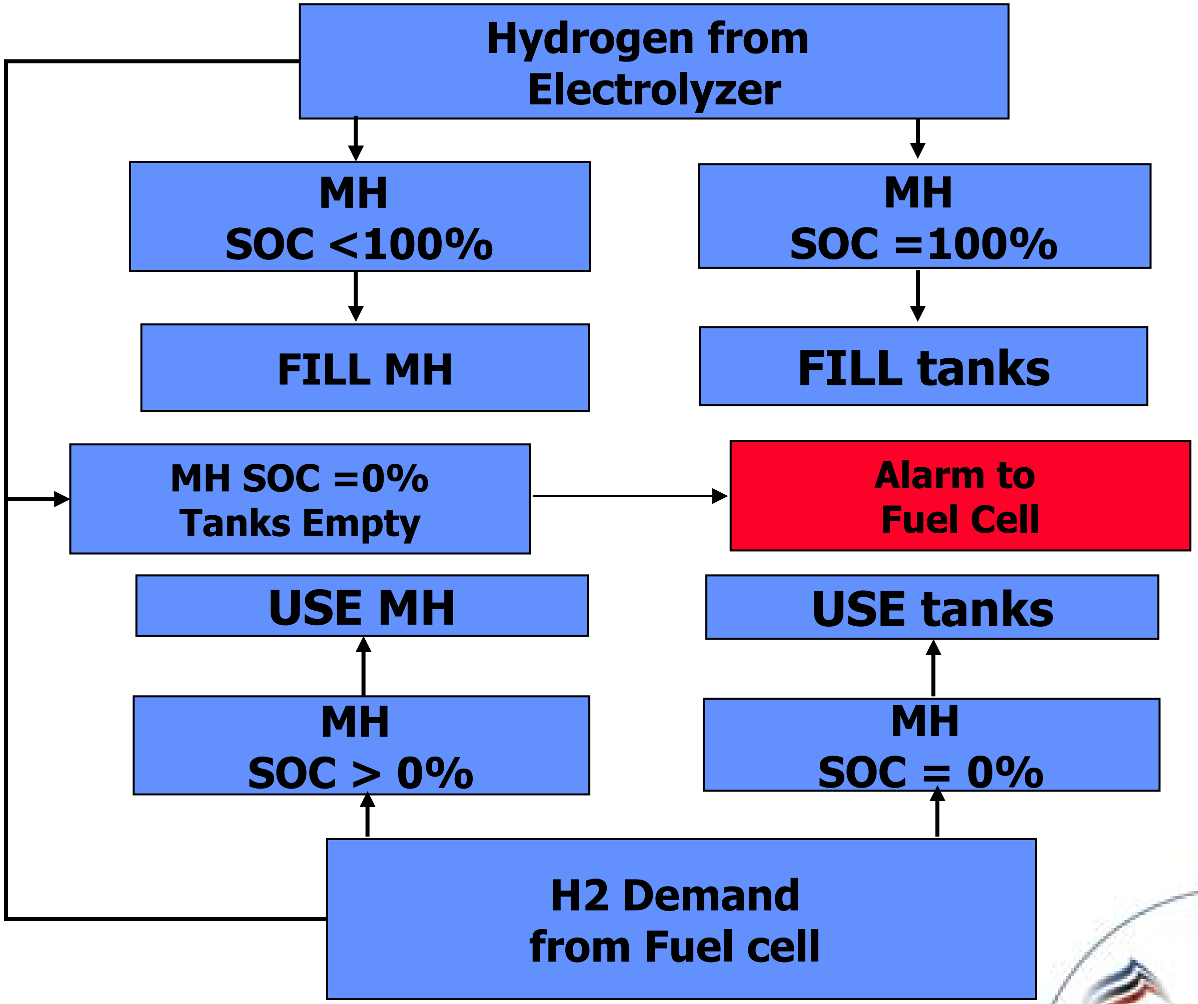
H2 solar house design

- Brescia, Italy
- 6.7kW High pressure alkaline electrolyser
  - Produces 1NM^3/hr H_2 at 200 bar
- 5 kW PEM fuel cell
- 3000 Ah battery
- 30 Nm^3 Hydrogen stored in metal hydride
- 120 Nm^3 Hydrogen in storage cylinders
- 11 kW peak power available from photo-voltaic panels



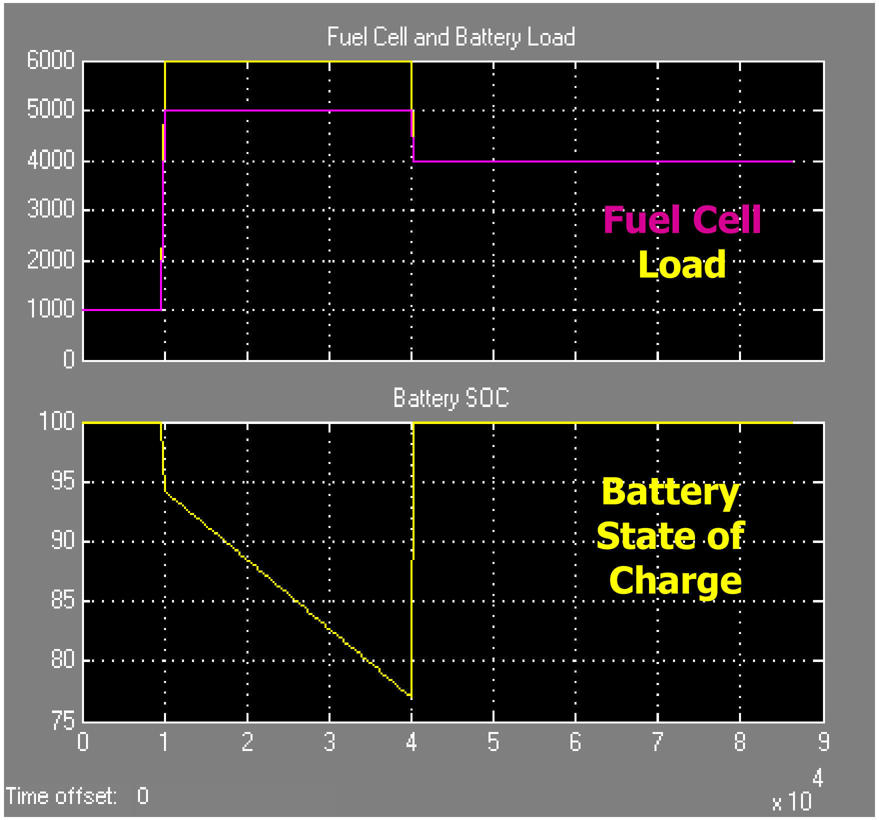
Italian H2 house control system fills metal hydride and high-pressure storage

- Control System
  - Load management
  - Hydrogen storage
  - Event monitoring and control
- Hydrogen Flow Control System
  - A goal is to demonstrate metal hydride (MH) storage
- Analysis of system dynamics



Italian H2 house electrical load control

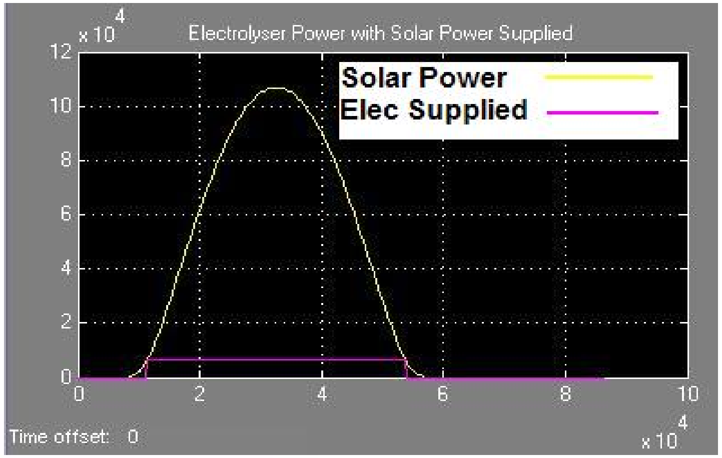
- Load Control System
  - Modeled using “if-else” strategy
  - Future development to include system dynamics with detailed controller – closed loop PI
  - Electrical load distribution monitoring
  - Component status monitoring and alarm management
  - Real time analysis of data from components
  - Remote control operation and visualization



Preliminary economic analysis estimates cost of H2 and electricity from the Italian house

- **Estimated H2 cost**
  - **Electrolyzer capital cost by scaling with production rate to 0.6 power**
  - **Use project cost data when available**
  - **O & M 2% of capital cost**
  - **Electricity cost estimated using off-peak power at 0.025 $/kWh**
- **Estimated electricity cost from fuel cell**
  - **0.76 $/kWh based on off-peak power**
  - **Future study will include solar PV costs**

CONTRIBUTION	COH ($/kg-$H_2$)
Capital	7.702
Feedstock	2.458
O&M	1.118
TOTAL	11.28



- **Electrolyzer efficiency ~54%**
  - **Future study will include standby operation when solar power is insufficient**

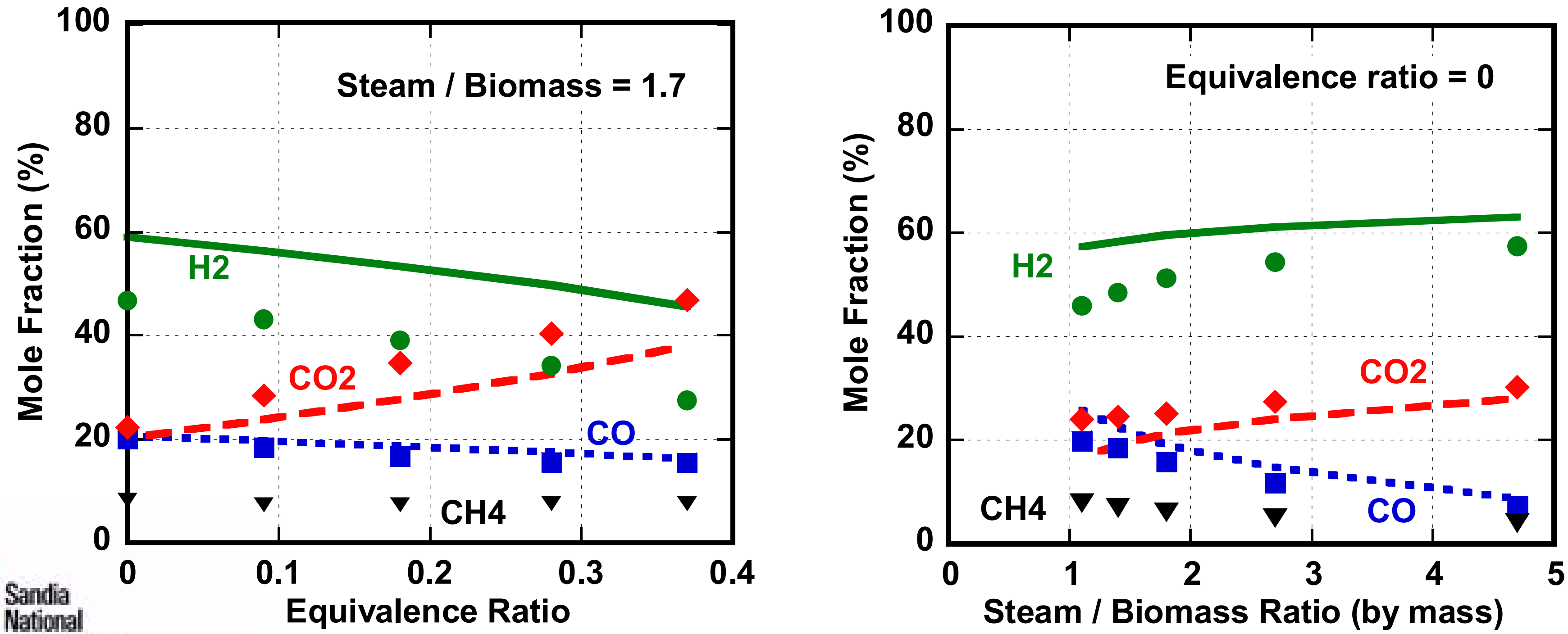
HNEI is investigating production of H_2 on Big Island by electrolysis using curtailed power

- **Geothermal power from Puna Plant on east side of island**
  - **Plant willing to sell curtailed power (not purchased by utility) at 2 ¢/kWh**
- **Utility charge for transmission across island**
  - **Add estimated 2 to 5 ¢/kWh based on line costs**
- **Build H2 power park on west side near demand**
  - **Electrolyzer (400 $\$/kW_e$, 60% efficient), storage, compression**
  - **Generate electricity by either:**
    - Engine genset at 35% efficiency, 50 $\$/kW_e$
    - SOFC at 50% efficiency, 800 $\$/kW_e$

Transmission	H2 cost	Genset elect.	SOFC elect.
2 ¢/kWh	3.28 $/kg	29 ¢/kWh	24 ¢/kWh
5 ¢/kWh	4.94 $/kg	42 ¢/kWh	34 ¢/kWh

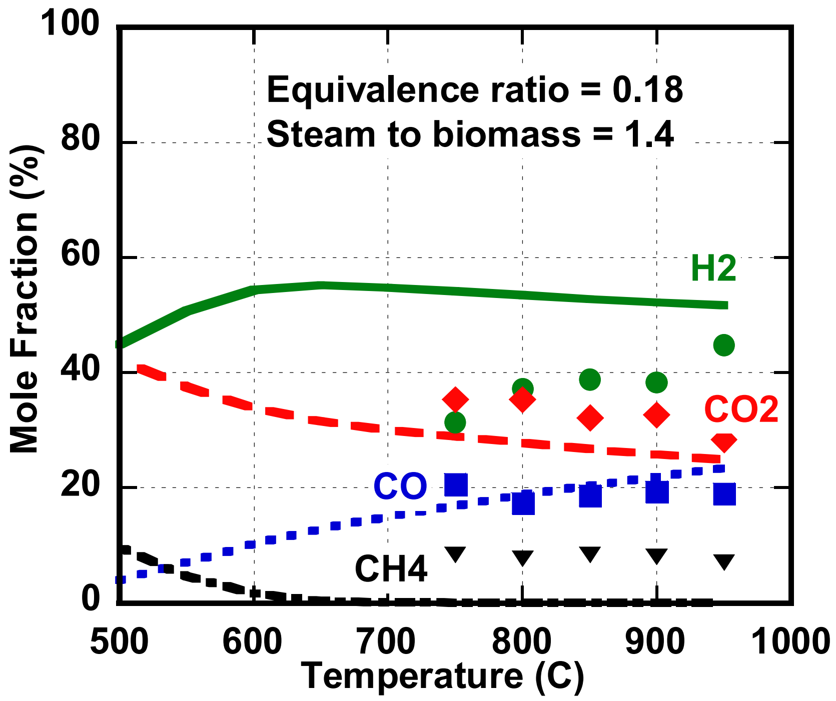
HNEI is investigating H2 production by biomass gasification

- Compare model to experiments by Turn *et al* (Hawaii)
- Chemical equilibrium captures dependence of H_2 concentration on equivalence and steam/biomass ratios



Temperature effect on biomass gasification

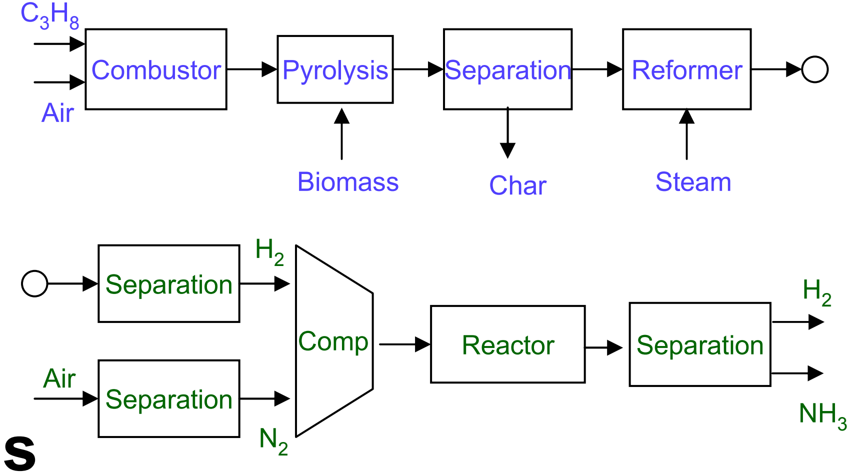
- Chemical equilibrium does not capture temperature dependence
  - Predicts increasing H_2 only at lower T (500-650 C)
  - Predicts decreasing H_2 with T above 700 C
- Equilibrium suggests methane should only exist at lower T (< 600 C)
- Kinetics affect gas composition and char
  - Experiments observed char and tar, but not quantified



Analysis of fertilizer co-production from peanut shell pyrolysis char with integrated ammonia synthesis

- **Process being developed by Eprida / NREL / U. Georgia**
- **Process efficiencies**

Production	H_2 Yield	Efficiency
H_2 alone	6 %	22 %
Ammonia	4 %	29 %

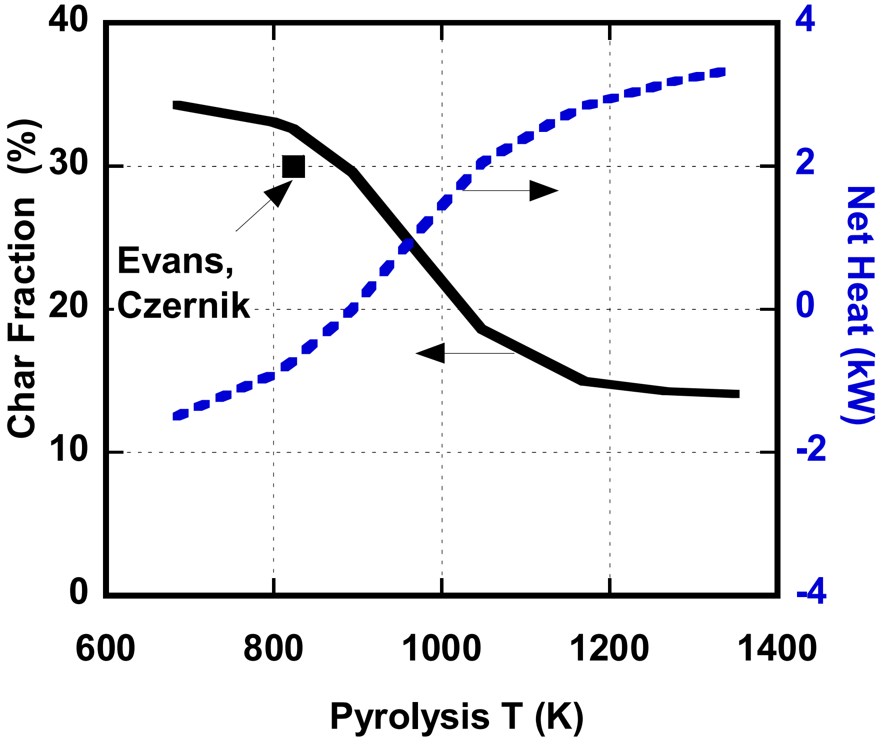


- **Economic analysis assumptions**
  - **Biomass feed = 40 $/ton**
  - **Co-product fertilizer price**
    - **1500 $/ton on ammonia basis**
    - **Scaled from 400 $/ton (urea)**
  - **Finance parameters from H2A**
  - **Capital costs are largest uncertainty**

Contribution	H_2 Cost
Capital, O&M	4.85 $/kg
Biomass feed	0.94
Electricity	0.63
Co-product	-3.27
Net	3.15 $/kg

Biomass pyrolysis simulated by equilibrium

- Low-temperature pyrolysis produces char
  - Slow-release fertilizer to be sold as co-product
- Compare model to NREL exp'ts
  - Nominal conditions
    - Pyrolysis T = 823 K
    - Steam/carbon = 3.9
  - Chemical equilibrium estimates char fraction and H_2 yield
    - H_2 yield = 6.1% (of biomass)
    - Data: 5.6% < H_2 yield < 6.7%
  - Exothermic for T < 900 K
- Trade-off between H_2 and char production versus temperature is consistent with experiments



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Future Work

- Support IEA Task 18 Analysis effort
  - Support Emma Stewart (Strathclyde) in US/UK exchange program
  - Continue analysis of Italian H_2 Solar House
  - Compare operation data to simulations
- Analysis of biomass gasification
  - Analyze data from gasification demonstration at HNEI
  - Provide economic analysis of H_2 from gasification
- Follow-up analysis of DOE power parks
  - DTE Energy:
    - Evaluate new electrolyzer expected in summer ’07
    - Revisit economics of H_2 production over system life
    - Apply exergy analysis to electrolysis model for comparison to SMR

Summary

- Exergy analysis of SMR identifies losses of useful energy
  - Major losses (48%) are heat transfer and reaction in reformer
  - Exhaust is only 18% of unused available energy
  - Maximum practical efficiency is 68%
- Analysis of electrolysis at HNEI
  - H2 from curtailed geothermal power costs 3 to 5 $/kg
    - Short of MYPP target, but competitive with gasoline at low end
  - Electricity from fuel cells can be competitive
    - For isolated cases like Big Island where peak electricity is 0.32 $/kWh
- Biomass pyrolysis: co-product helps, but H2 still > 3 $/kg
  - H2 yield (6%) and process efficiency (29%) are relatively low