Realizing a Renewable Energy Future through Power-to-Gas

California Fuel Cell Partnership

UCLA, Los Angeles, CA

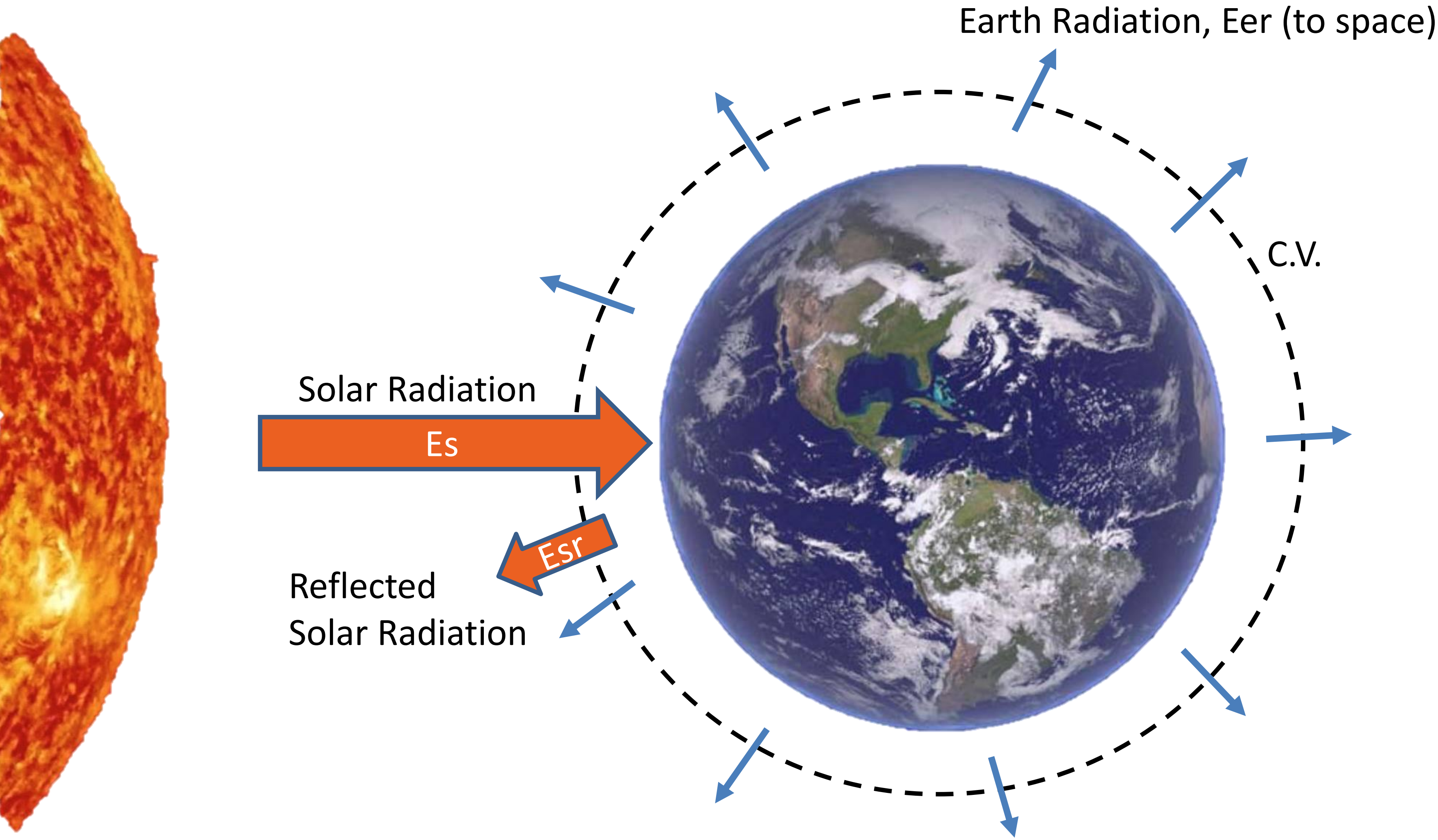
ADVANCED POWER & ENERGY PROGRAM
UNIVERSITY of CALIFORNIA · IRVINE

NATIONAL FUEL CELL RESEARCH CENTER
UNIVERSITY of CALIFORNIA · IRVINE

Jack Brouwer, Ph.D.
Associate Director

April 25, 2017

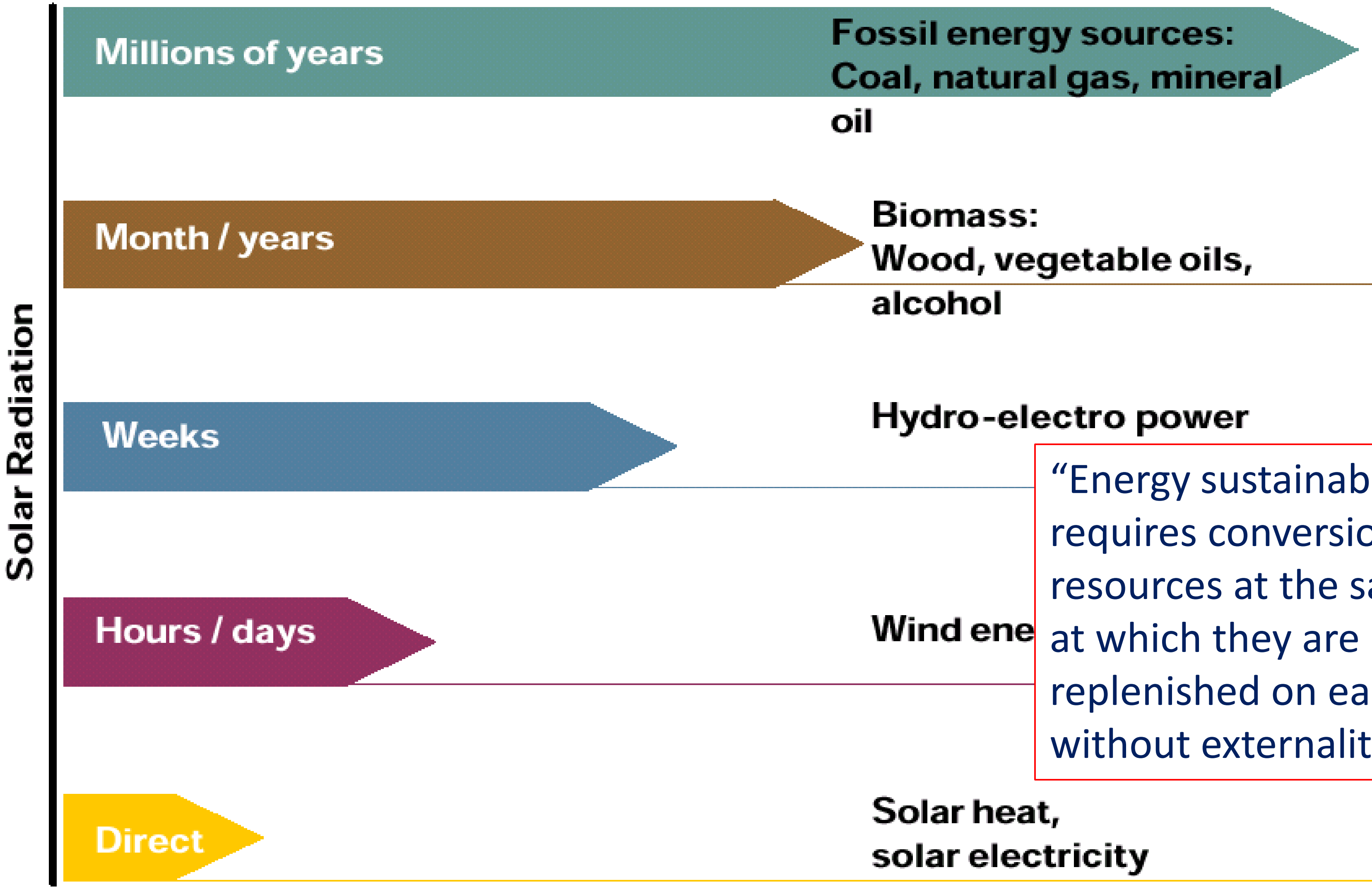
Earth Energy Balance



$$\Delta E_{earth} = Es - Esr - Eer$$

Earth Energy Resources

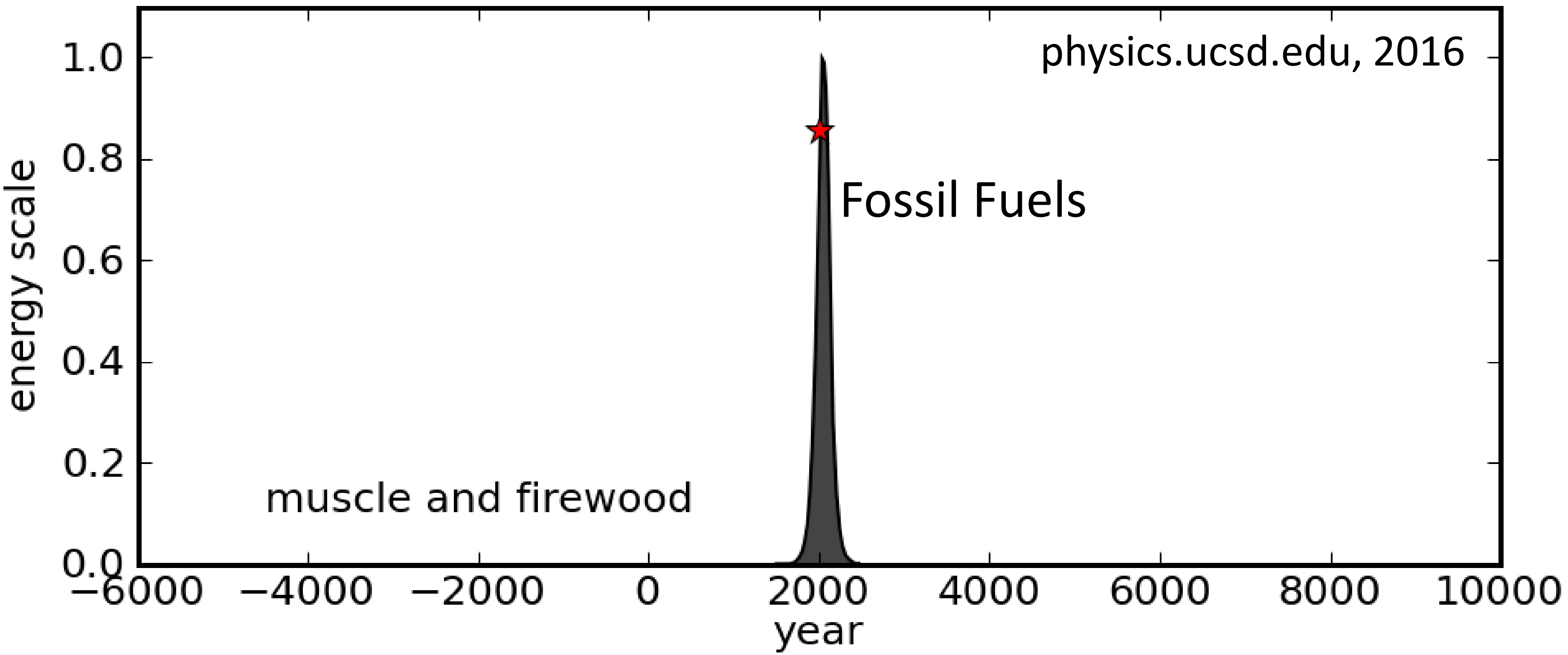
Primary Energy: All Comes from the Sun



"Energy sustainability requires conversion of resources at the same rate at which they are naturally replenished on earth without externalities"

Courtesy: BMW Group, 2000

Primary Energy: All Comes from the Sun



without externalities"

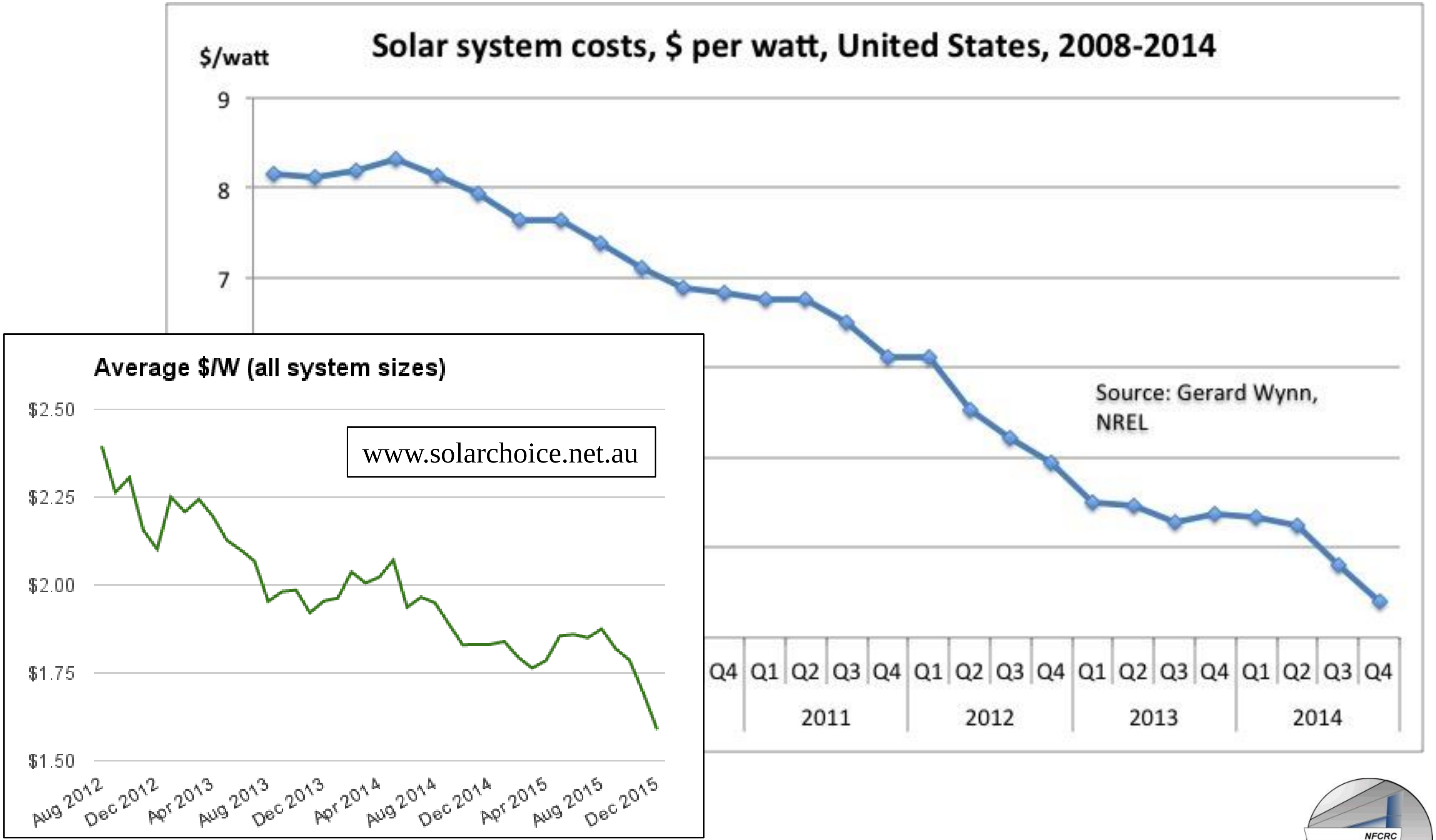
Direct

Solar heat, solar electricity

Courtesy: BMW Group, 2000

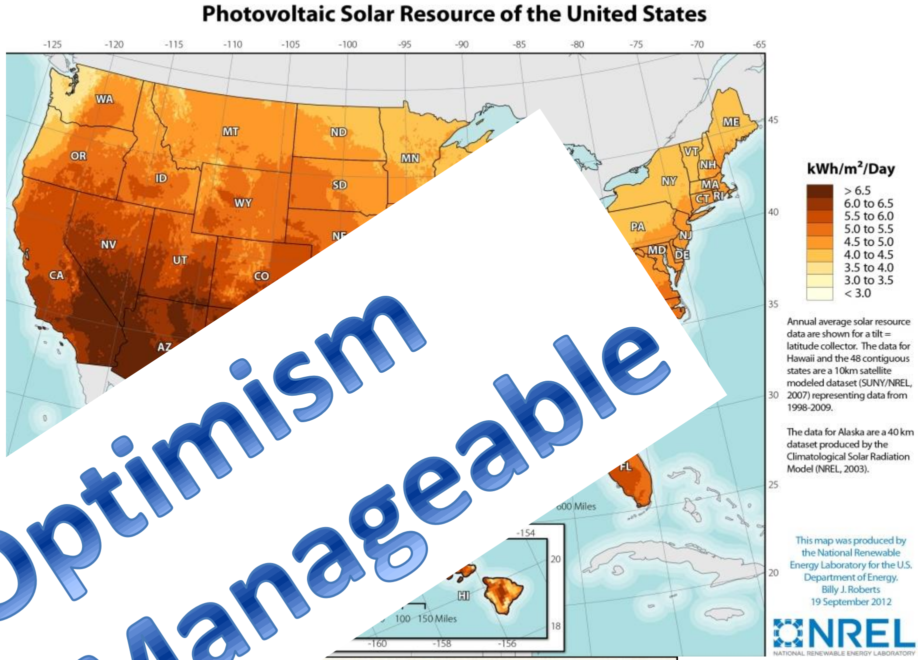
Cost of Solar Power

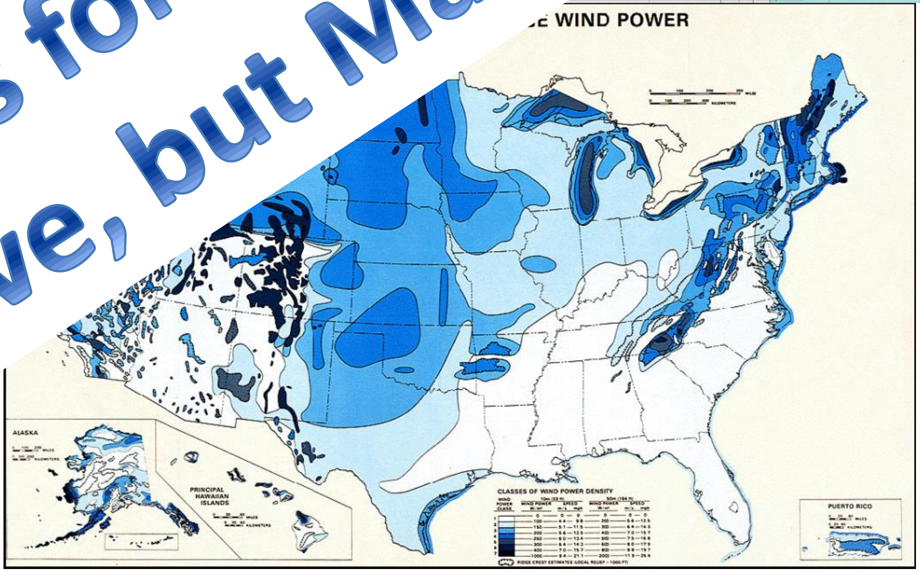
- Good News! Solar PV costs are dramatically falling



Cost of Solar/Wind Power

- Solar Cost Considerations
  - ~20 % capacity factor – effectively 5-times the cost/kWh
  - At \$1-\$2/W → \$5,000-\$10,000/kW for equivalent continuous generator
- Location Considerations
  - Need significant transmission and distribution infrastructur
  - Cost, aesthetics, legal





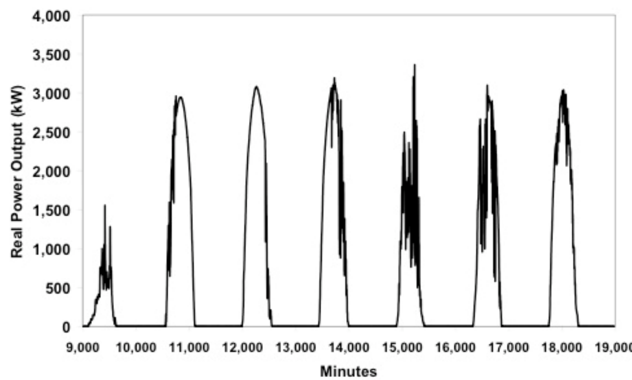
Causes for Optimism

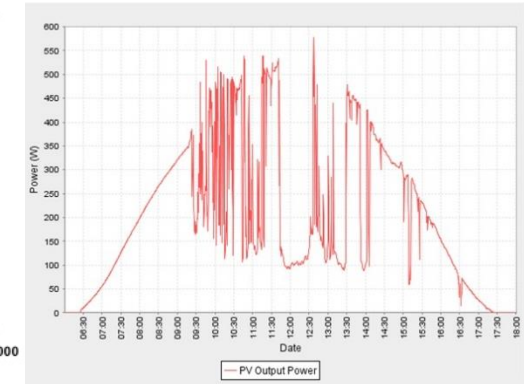
Expensive, but Manageable

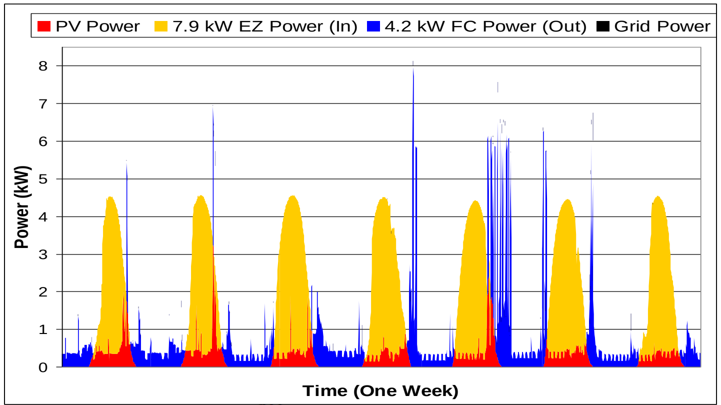
NREL, 2008

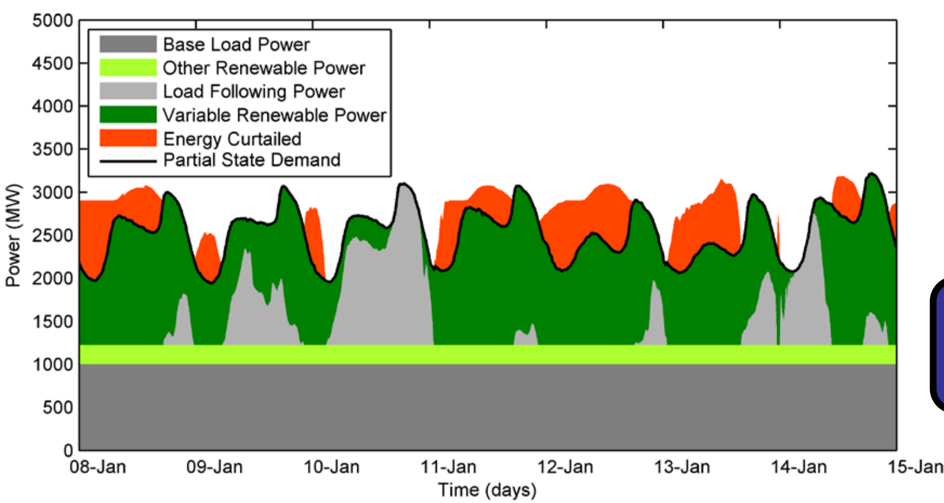
Dynamics of Solar, Wind and other Renewables

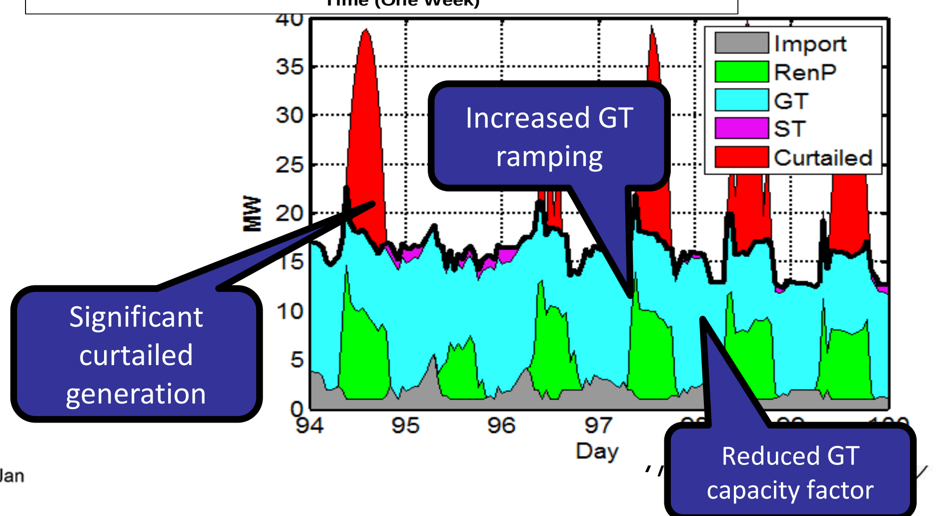
- Solar most regular, predictable and widely available
- Wind is more dynamic, somewhat complements solar
- Together these will eventually meet almost all demands
- Must be balanced with loads











Energy Storage Need

Gedankenexperiment – consider a completely solar world

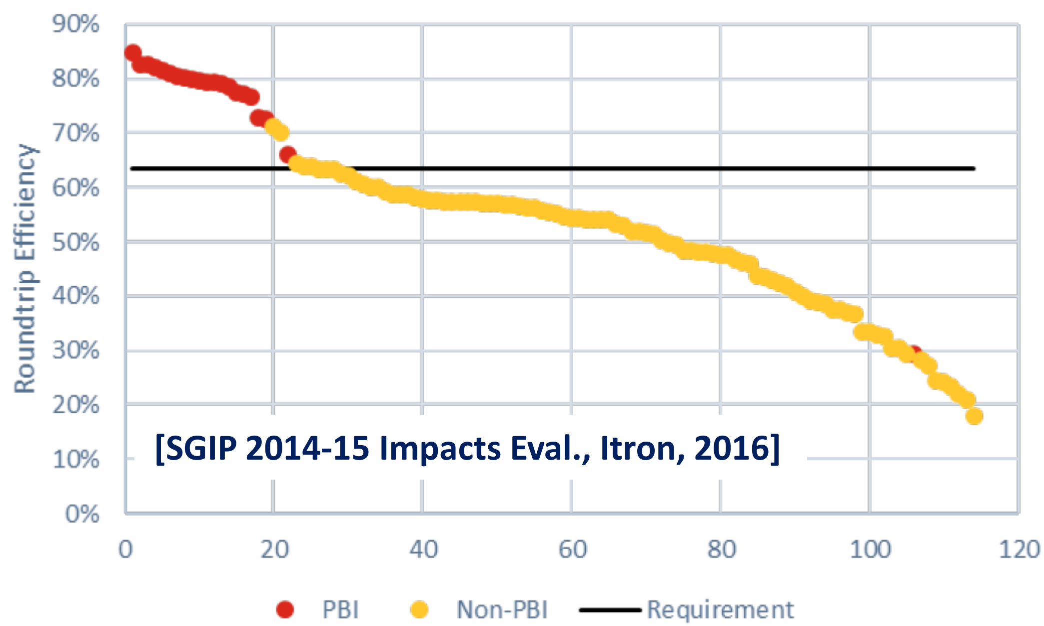
- Do as much conservation & efficiency as possible
  - How much storage is needed?

World Total (Mtoe)	kWh/toe	kWh	TWh
9,301	11,630	1.082E+14	108,171
Total Storage Needed		Daily shifting only:	**237**
		Seasonal shifting:	**28,846**

[Key World Statistics, IEA, 2015]

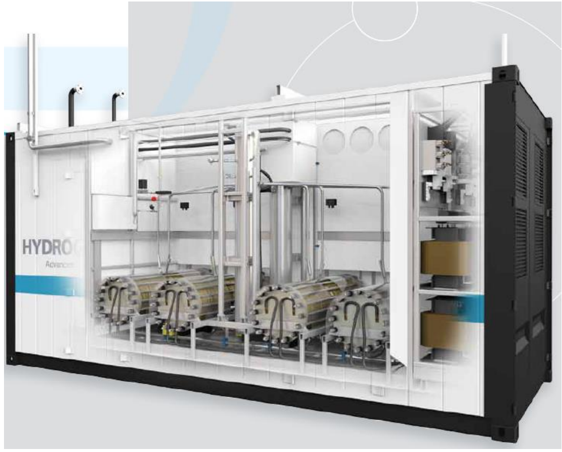
- Batteries needed, but, cannot do it all!
  - Massive cost (connected power & energy scaling)
  - Self discharge (measured performance in utility applications)

Figure 1-7: Roundtrip Efficiency for Observed Projects (all non-residential)

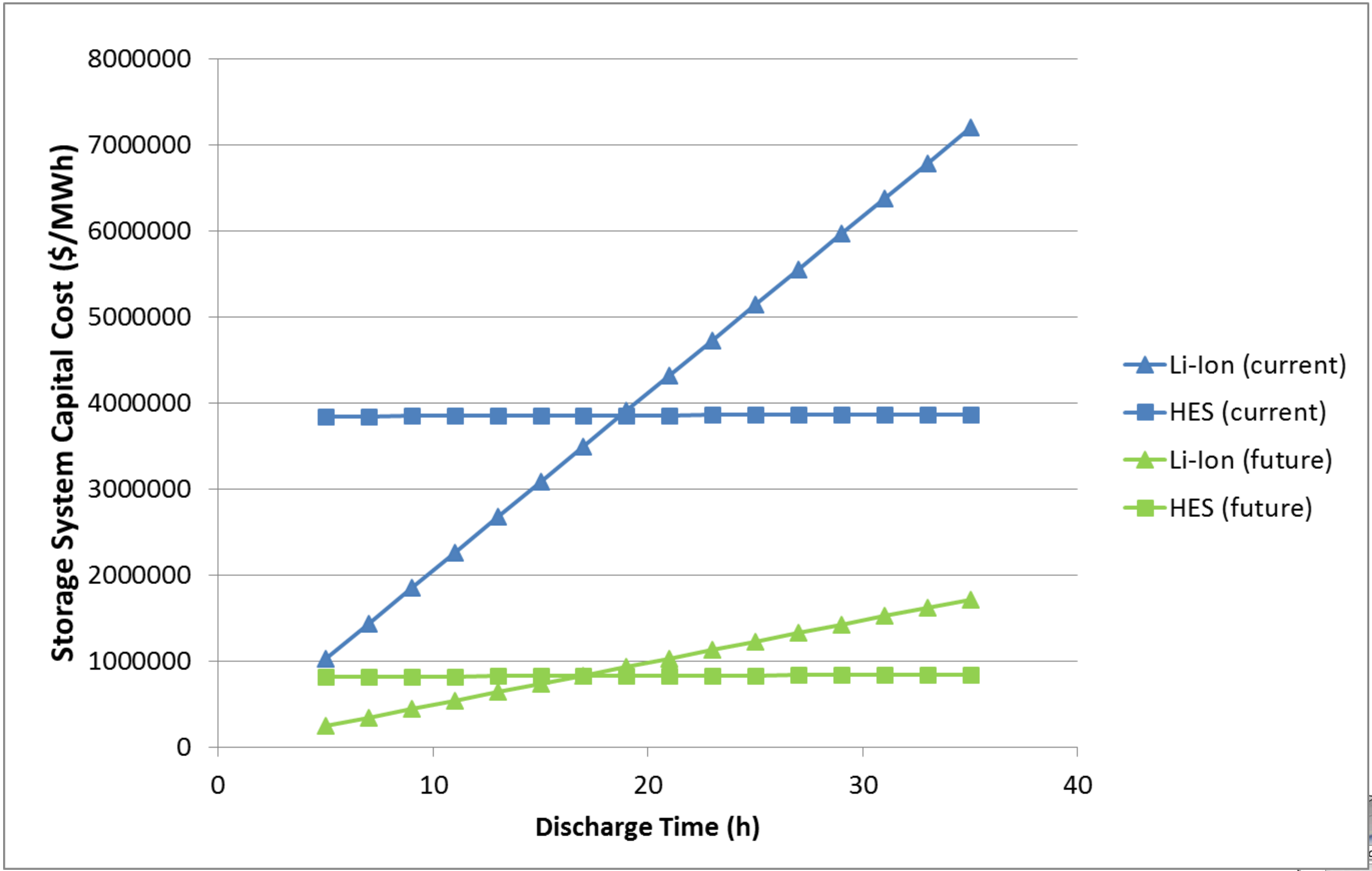


Electrolysis – A Flexible Load

- Electrolyzers (PEM, alkaline) produce hydrogen & oxygen from water
- Provide load when wind or solar would otherwise be curtailed
- Fast response allows for use with variable input (<2 sec)
- Fast response can provide other ancillary services (e.g., regulation, Volt/VAR support)
- Sizes range from 10's of KW to several MW (today)

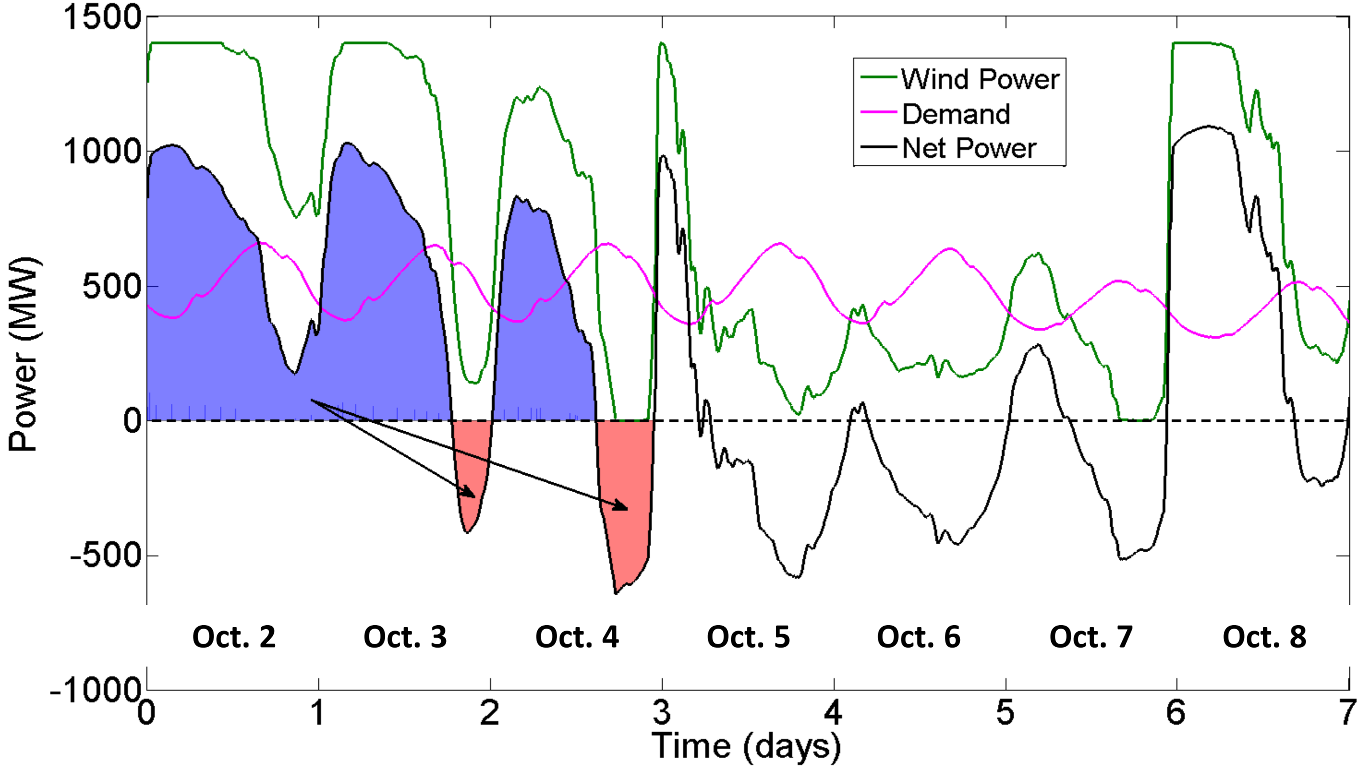


- HES Better for long-term energy storage



Hydrogen Energy Storage Dynamics

- Compressed Hydrogen Storage <u>complements</u> Wind & Power Demand Dynamics in Texas



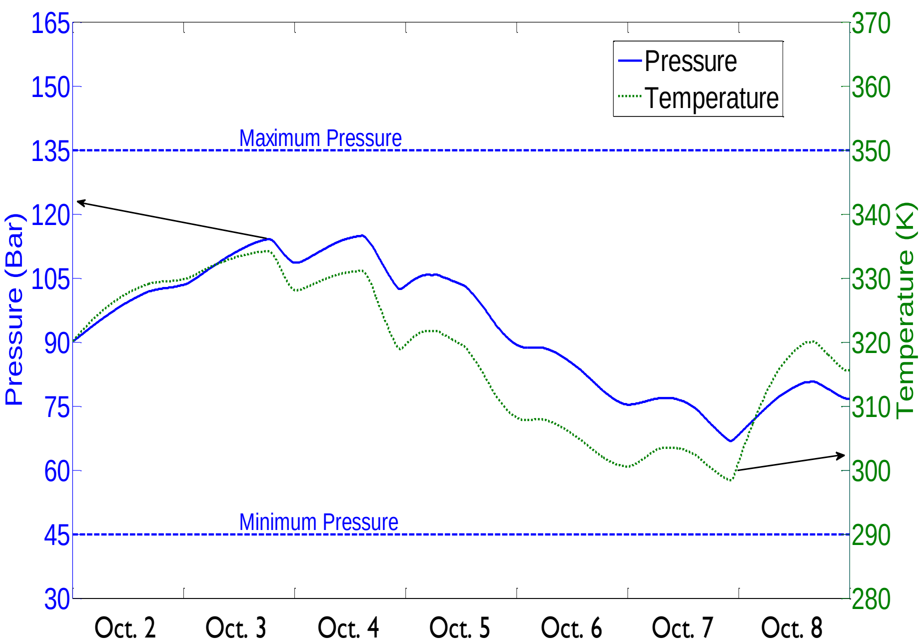
- Load shifting from high wind days to low wind days
- Hydrogen stored in adjacent salt cavern

Maton, J.P., Zhao, L., Brouwer, J., Int'l Journal of Hydrogen Energy, Vol. 38, pp. 7867-7880, 2013

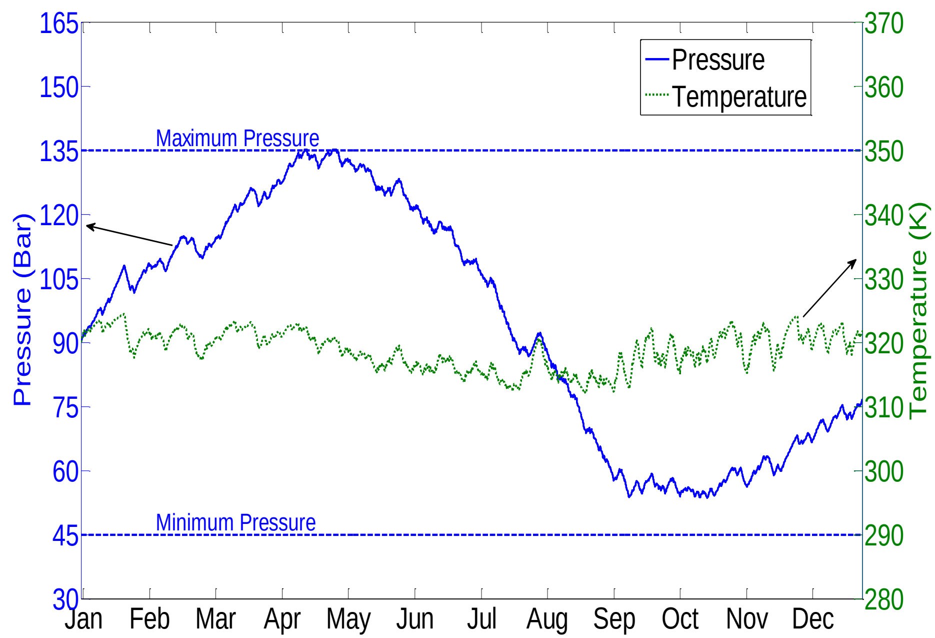
Hydrogen Energy Storage Dynamics

- Weekly storage and seasonal storage possible with hydrogen and fuel cells/electrolyzers – all zero emissions!

Weekly



Seasonal

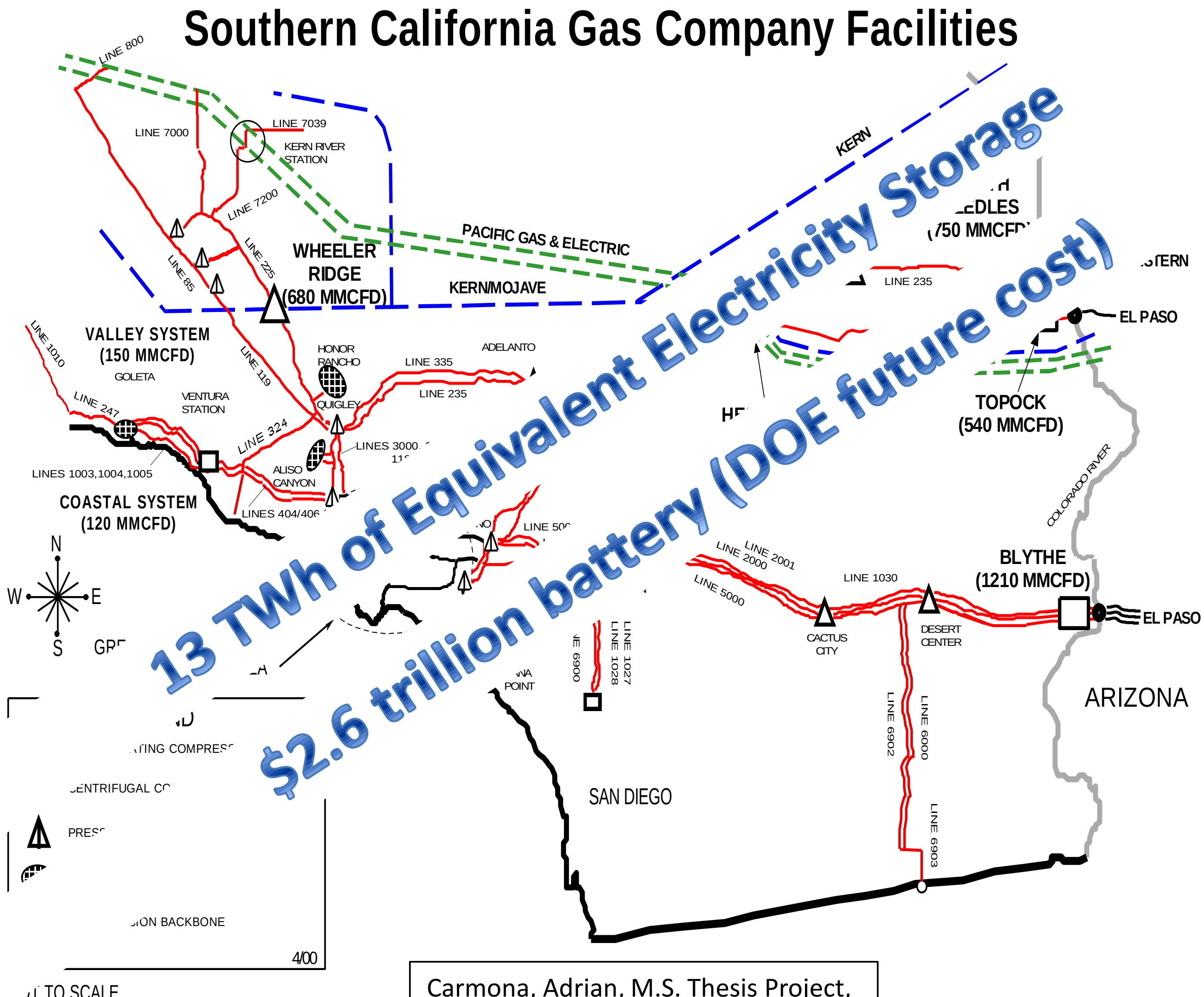


But what can we do if we don't have a salt cavern?

Maton, J.P., Zhao, L., Brouwer, J., Int'l Journal of Hydrogen Energy, Vol. 38, pp. 7867-7880, 2013

“Natural” Storage & Transmission/Distribution Resource

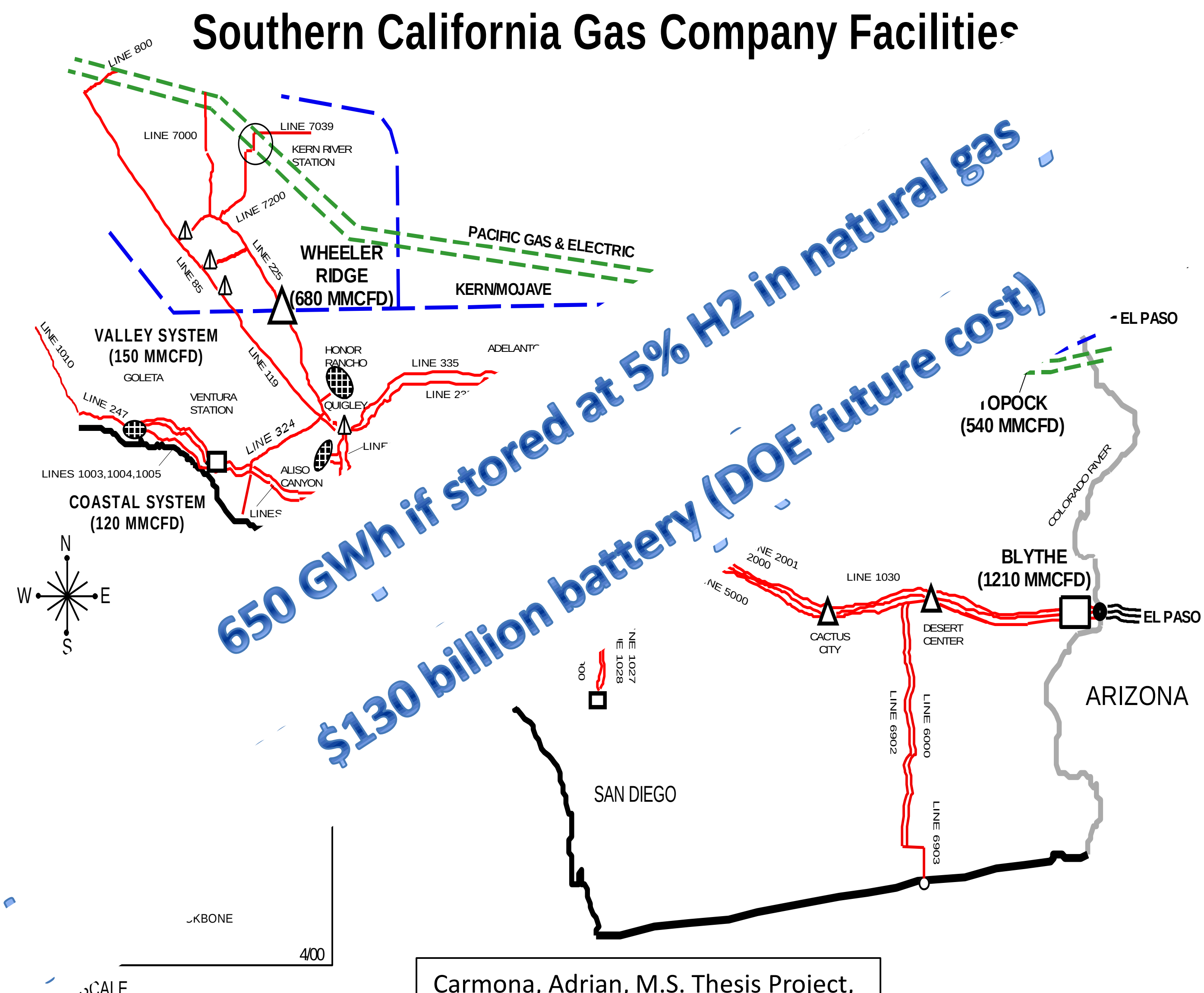
- Natural Gas Transmission, Distribution & Storage System



Carmona, Adrian, M.S. Thesis Project, UC Irvine, J. Brouwer advisor, 2014.

"Natural" Storage & Transmission/Distribution Resourc

- Natural Gas Transmission, Distribution & Storage System

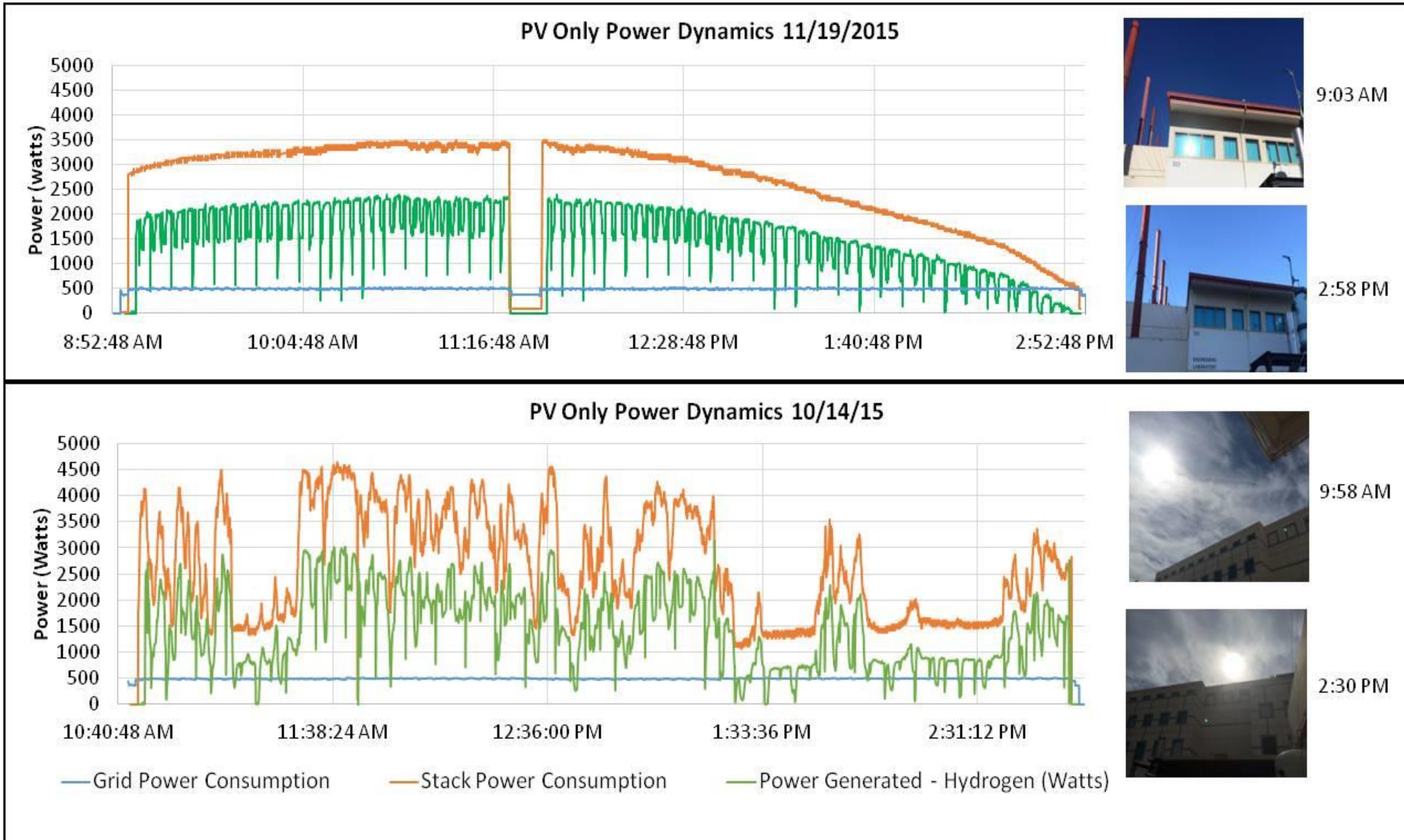


Carmona, Adrian, M.S. Thesis Project, UC Irvine, J. Brouwer advisor, 2014.

P2G Accomplishment: Lab-Scale Electrolyzer Dynamics

HOGEN-RE proton exchange membrane electrolyzer

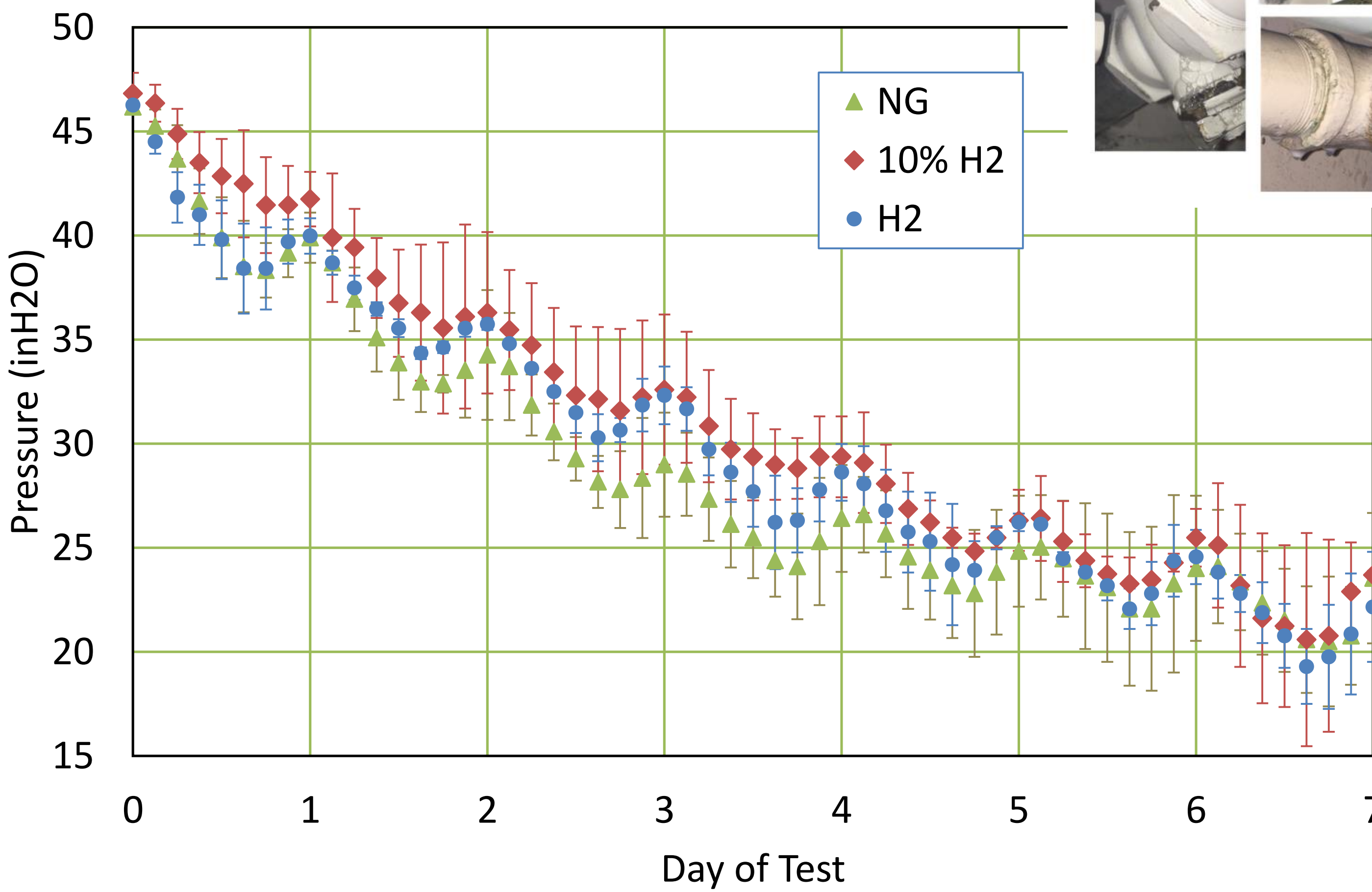
- Hydrogen production dynamics (with and without clouds)



P2G Accomplishment: Hydrogen Pipeline Injection

H2 injection into existing natural gas infrastructure (low pressure)

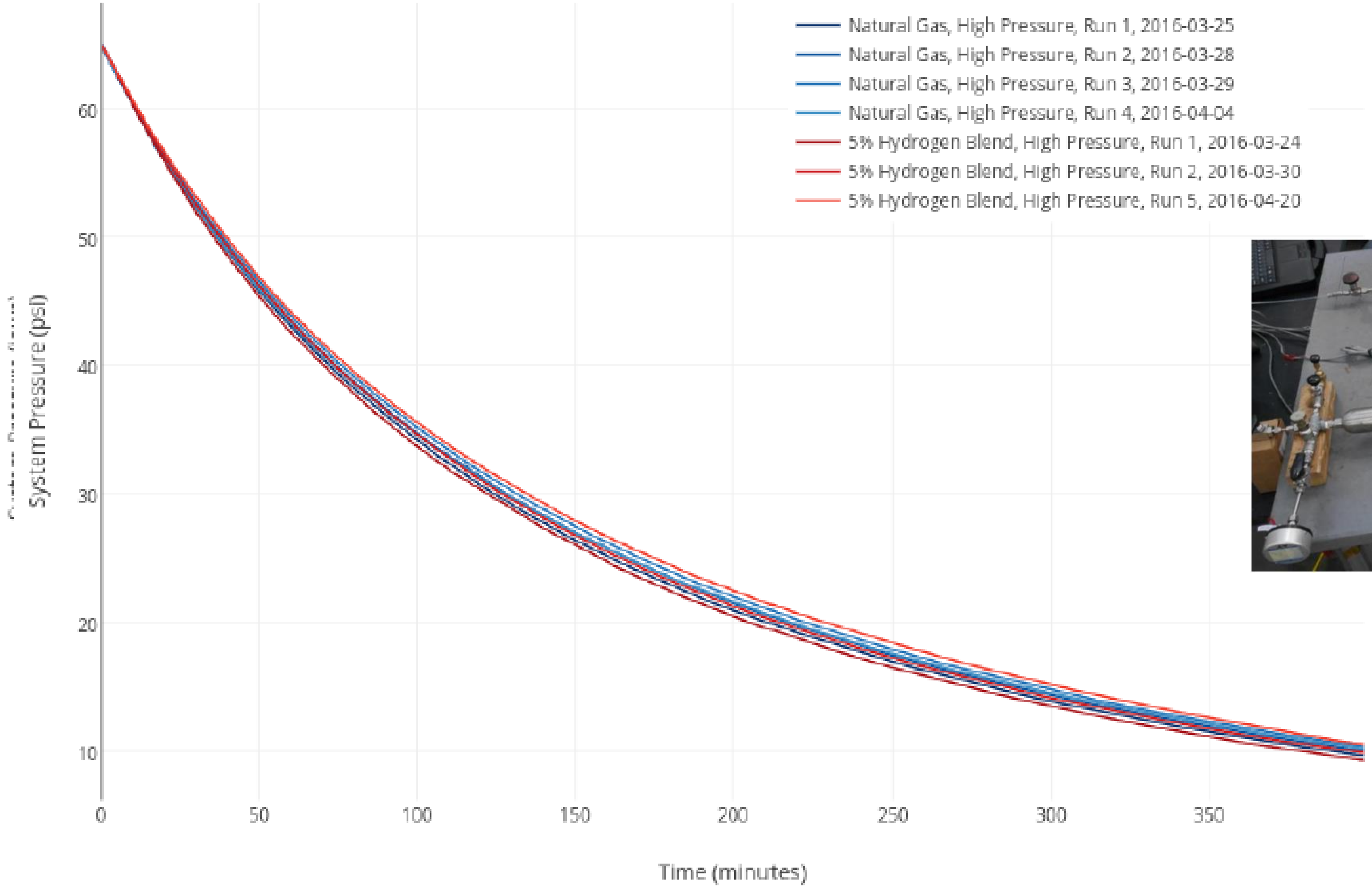
- NG, H2/NG mixtures, H2 leak at same rate

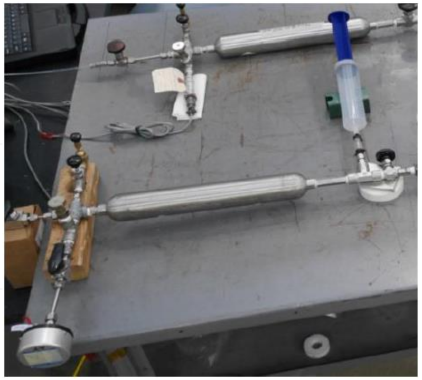


P2G Accomplishment: Hydrogen Leakage Assessment

H2 and H2/NG mixture leakage rates

- Test apparatus with fixed small orifice

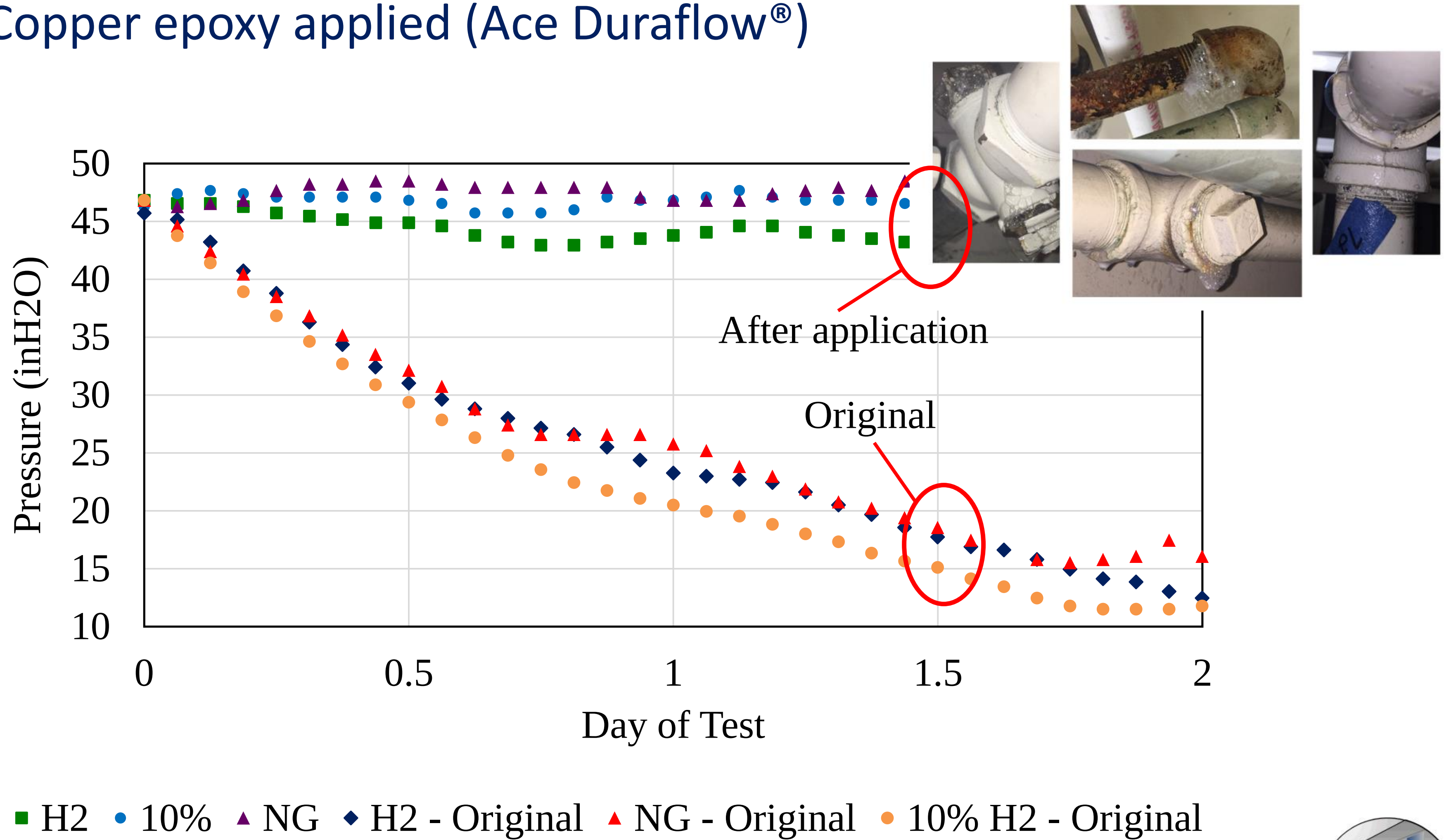




P2G Accomplishment: Leak Mitigation Evaluation

H2 injection into existing natural gas infrastructure (low pressure)

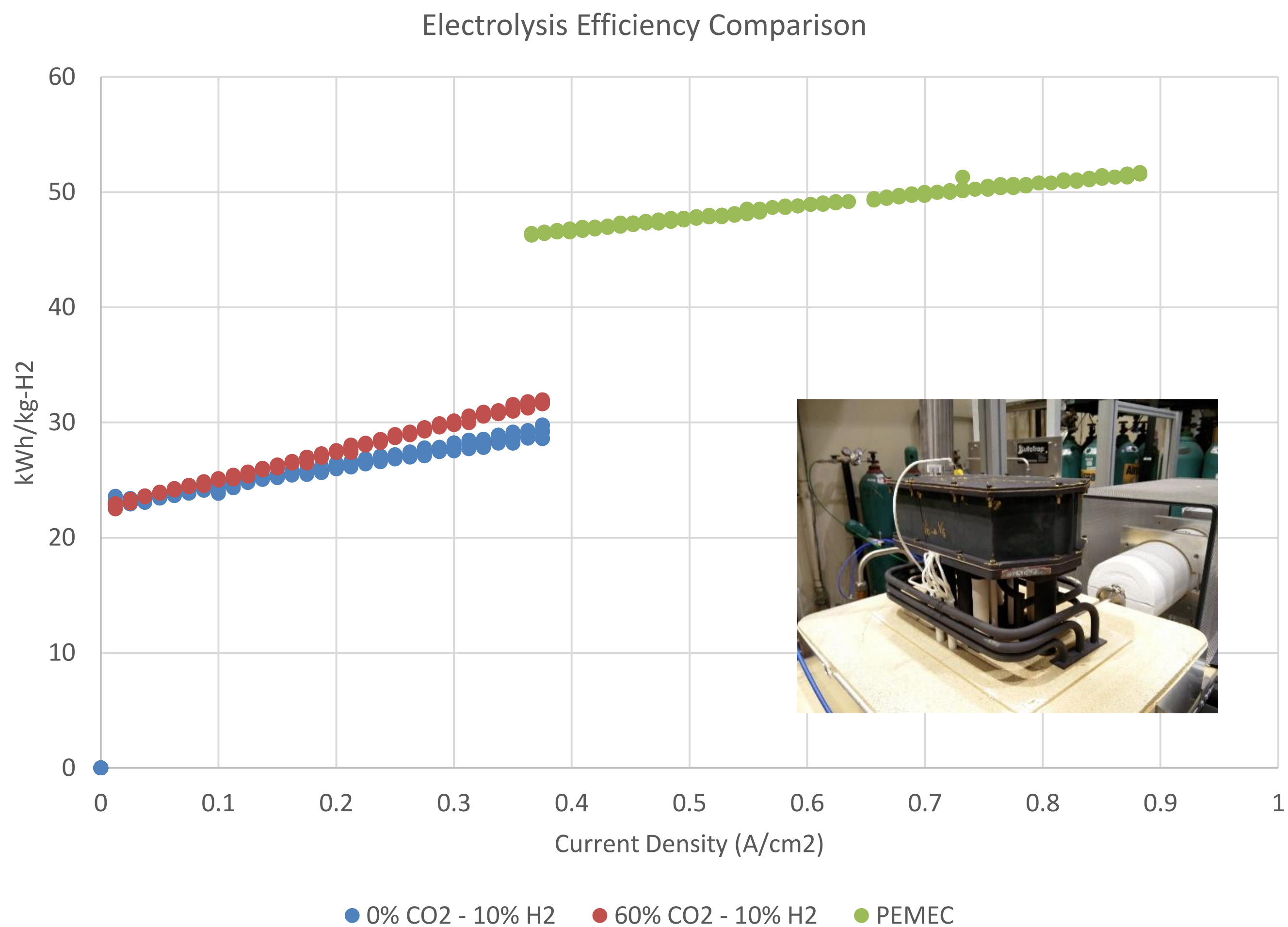
- Copper epoxy applied (Ace Duraflow®)



P2G Accomplishment: Electrolysis Alternatives

Solid Oxide Electrolysis and Co-Electrolysis

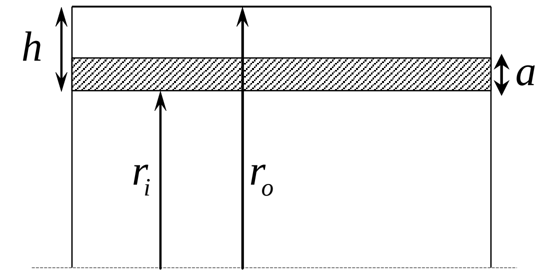
- Comparison to PEMFC (lower activation losses, higher ohmic losses)



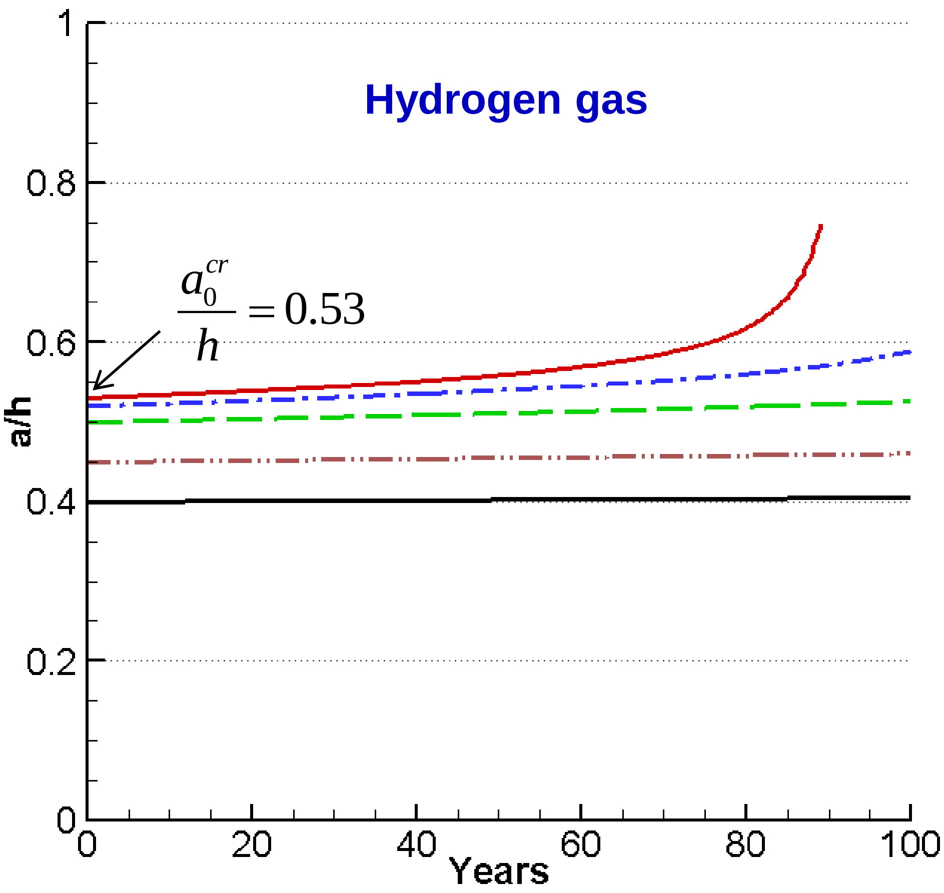
P2G Accomplishment: Pipeline Materials Impacts

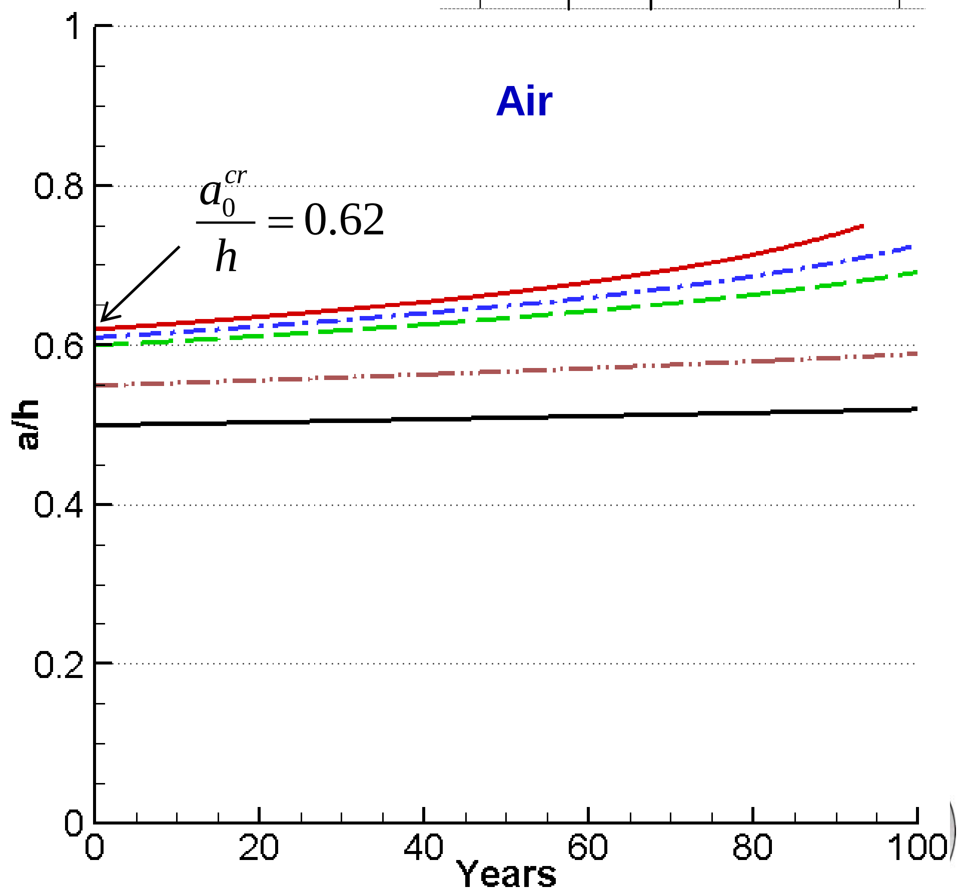
Simulation of H2 embrittlement and fatigue crack growth with UIUC

- Fatigue crack growth in 6” SoCalGas pipeline



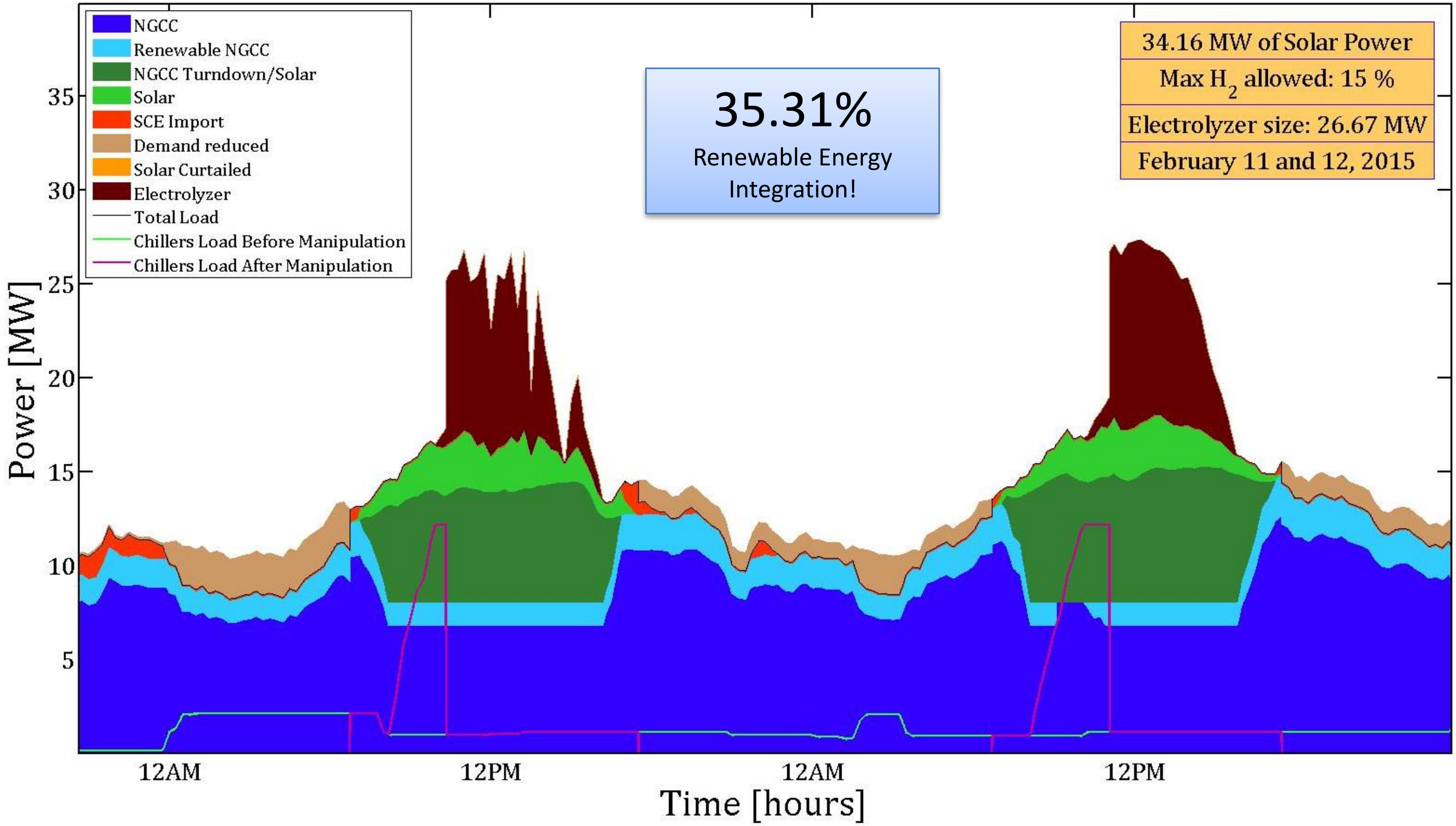
0.188” wall thickness: $(h = 0.188'' = 4.8\ \text{mm})$





P2G Accomplishment: UCI Microgrid Simulation

- P2G could significantly increase renewable percentage at UCI



P2G Accomplishment: Large Electrolyzer Deployment

P2G Accomplishment: Large Scale Electrolyzer

Injection and combustion of H2/NG mixture in NGCC (400 psi line)

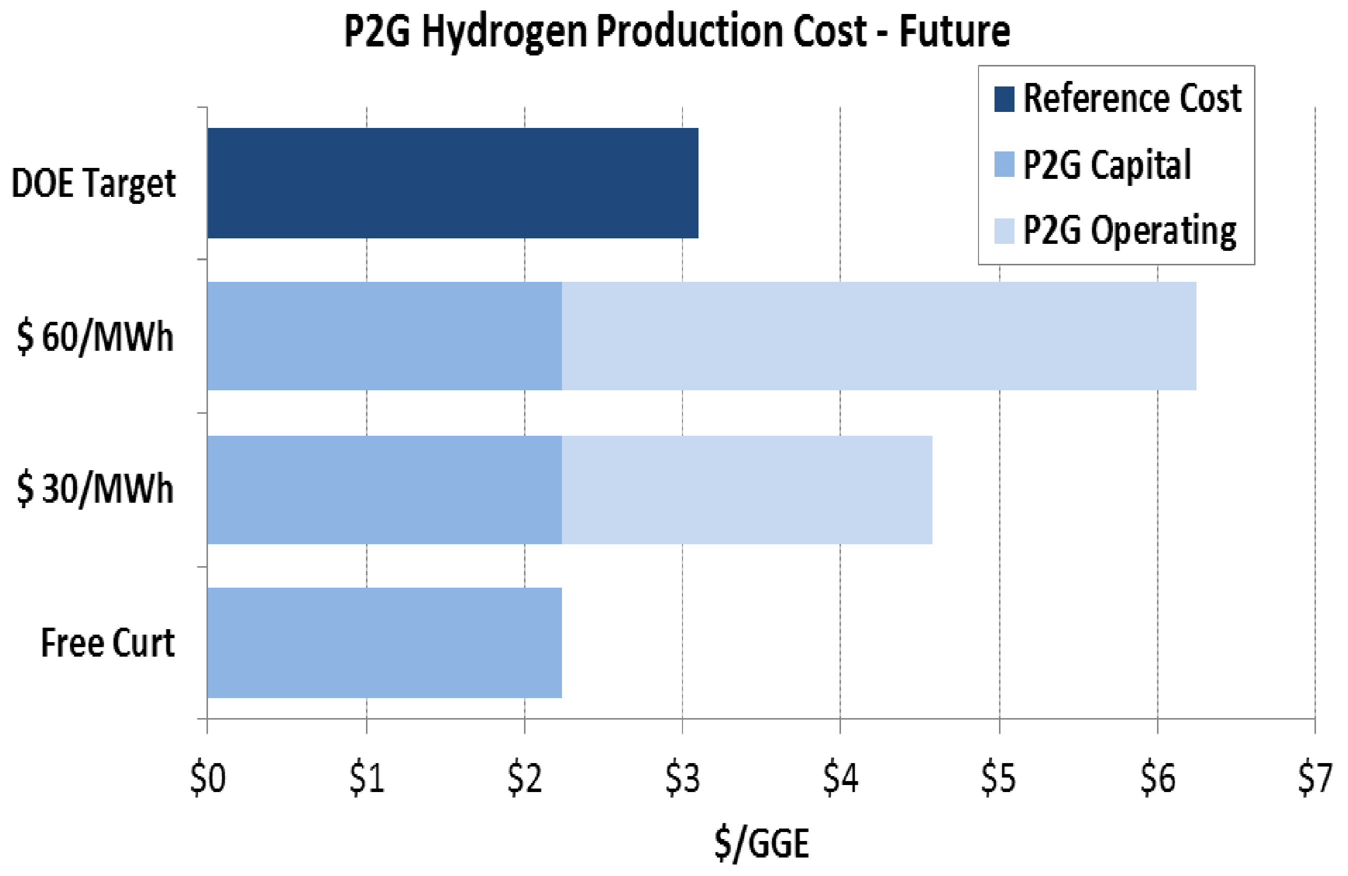
P2G Accomplishment: Large Scale Electrolyzer

Injection and combustion of H2/NG mixture in NGCC (400 psi line)

- ~0.24 volume % H2 in natural gas

Power-to-Gas Economics

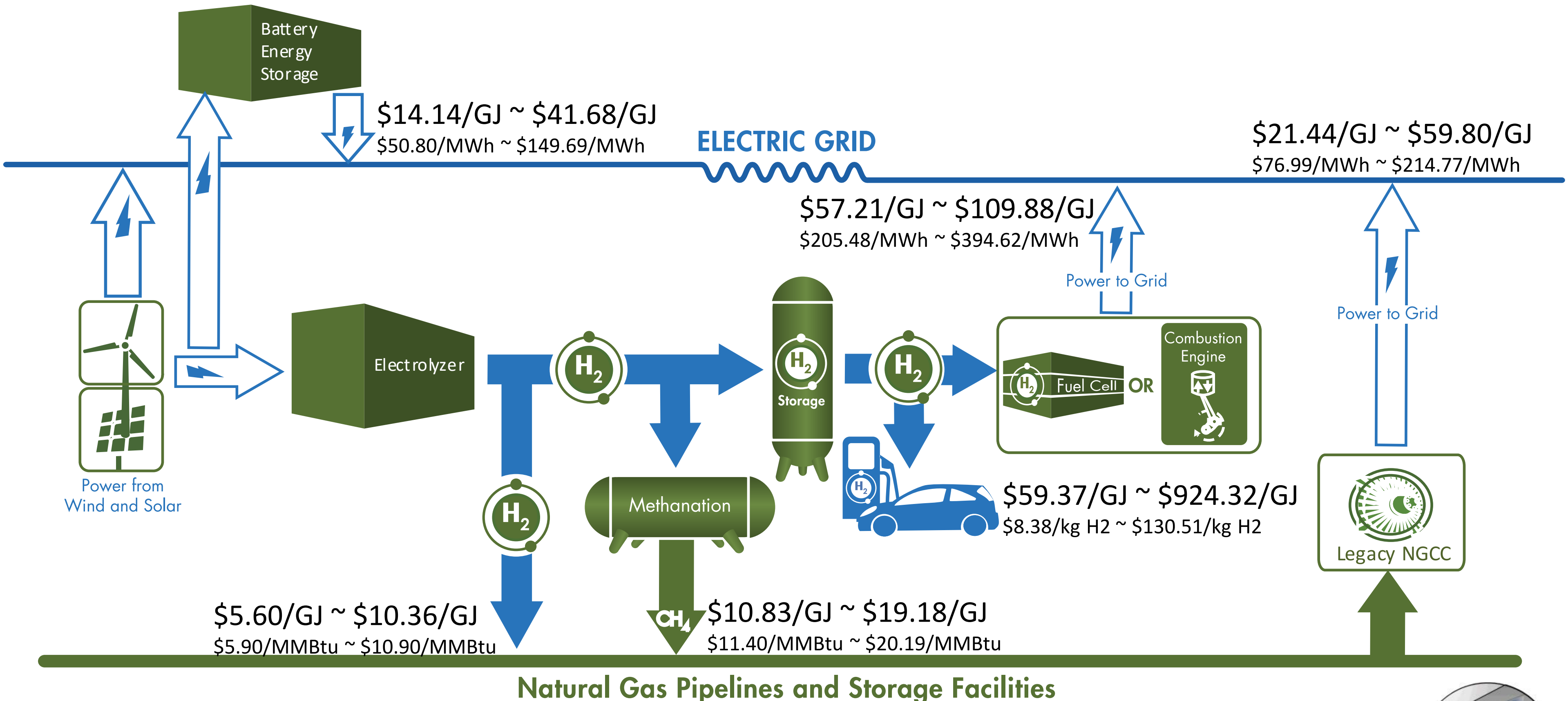
- Producing hydrogen from otherwise curtailed renewable power is economically attractive



Power-to-Gas Economics – Various Pathways

Levelized Cost of Returned Energy (LCORE)

- Future Costs & Efficiencies
- 50% capacity factor for all equipment



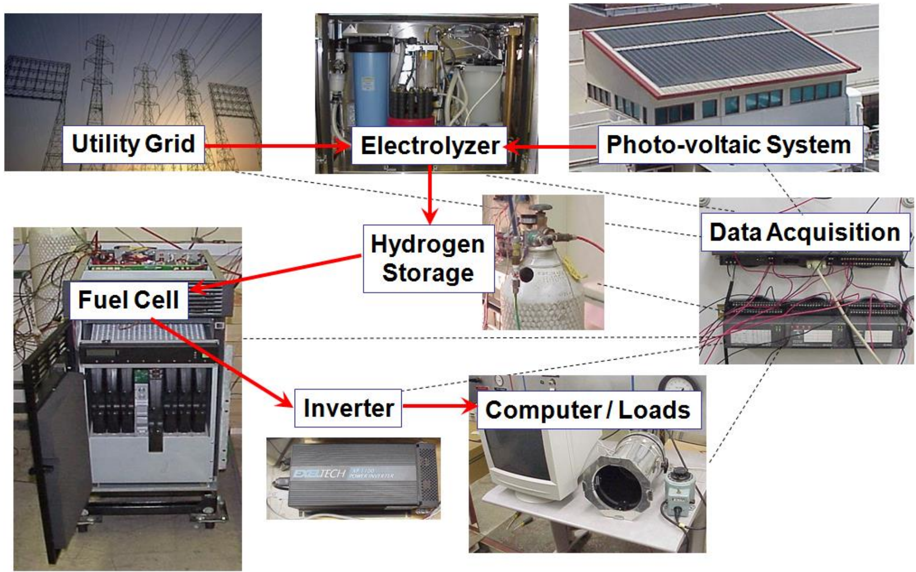
Thanks for your attention!

Backup Slides

SoCalGas P2G Support & Collaboration @ UC Irvine

Major Actions and Accomplishments in 2015-16

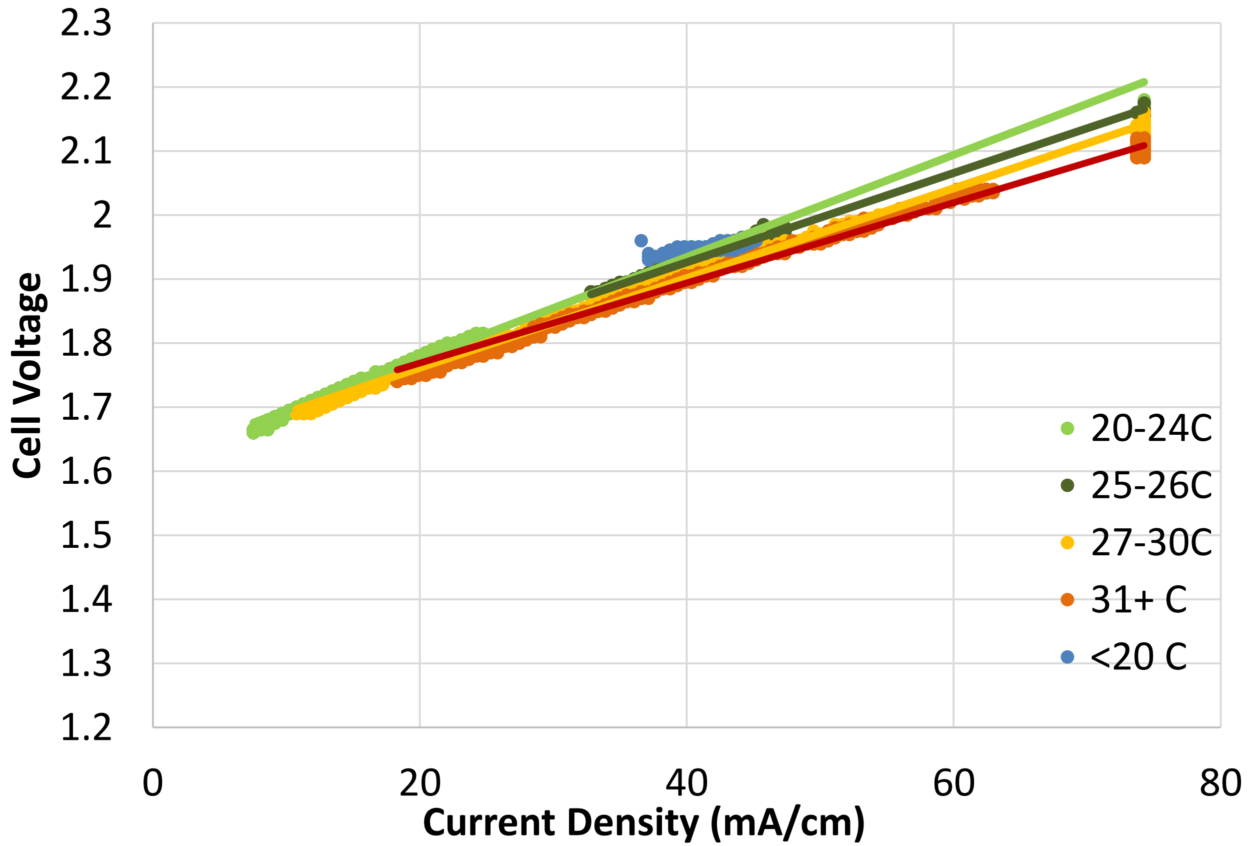
1. Lab-scale H_2 production dynamics by direct-DC & AC PV electrolysis
2. Hydrogen injection into existing natural gas distribution system infrastructure – leakage assessment
3. Evaluation of one customer-side leakage mitigation strategy
4. Evaluated alternative electrolysis technologies (PEME, SOE, REP)
5. Collaboration with SoCalGas to evaluate hydrogen and hydrogen blend leakage rates
6. Simulation of pipeline materials impacts (embrittlement, fatigue)
7. Simulation of P2G impacts in grid and microgrid
8. Full-scale hydrogen production & injection into 400 psi line
9. Combustion of P2G gas in NGCC
10. Economic analyses



P2G Accomplishment: Lab-Scale Electrolyzer Dynamics

HOGEN-RE proton exchange membrane electrolyzer

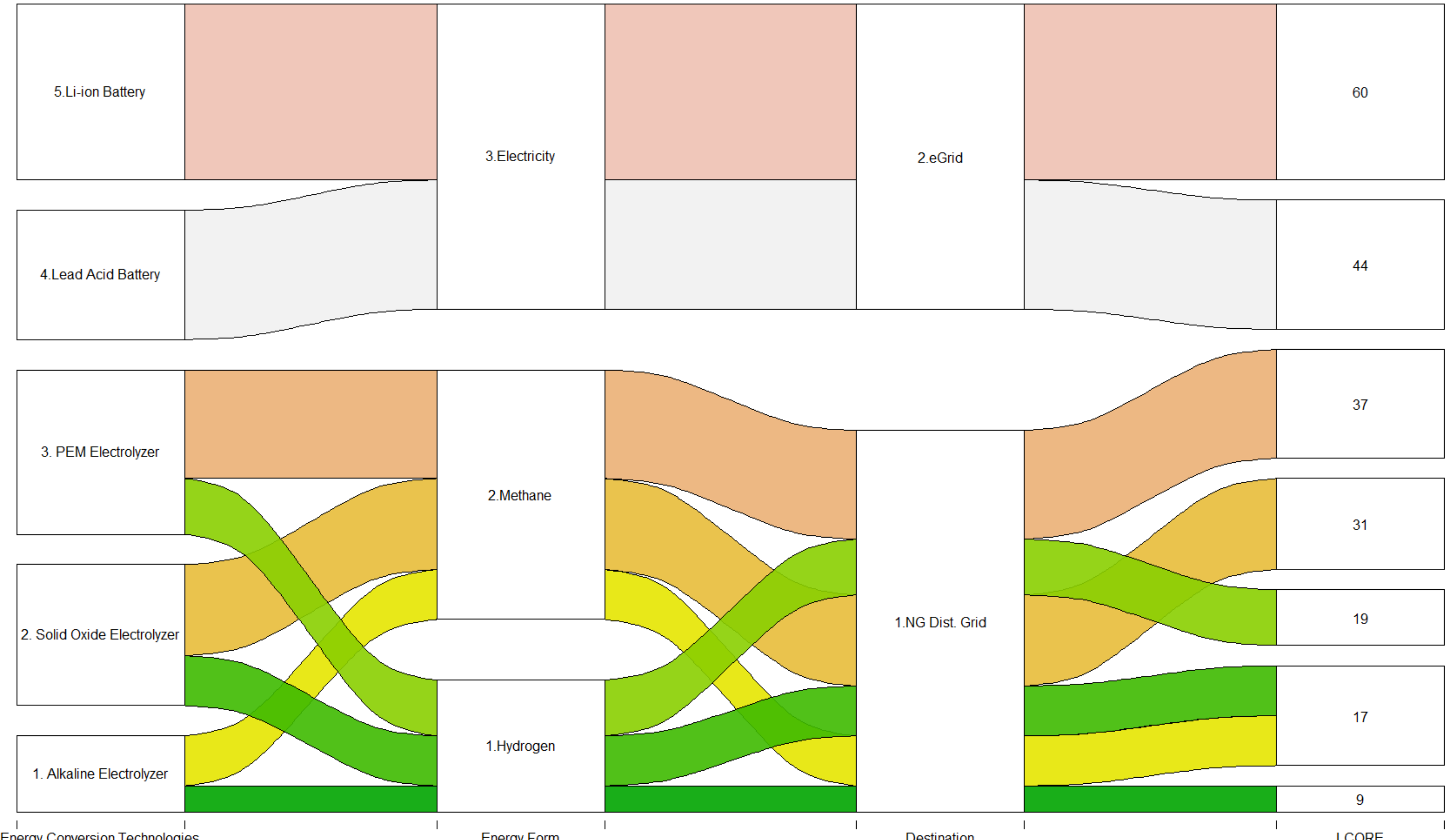
- Performs best when hot (summer vs. winter)



P2G Accomplishment: Detailed Economic Analyses

Levelized Cost of Returned Energy (LCORE)

- Future Costs & Efficiencies

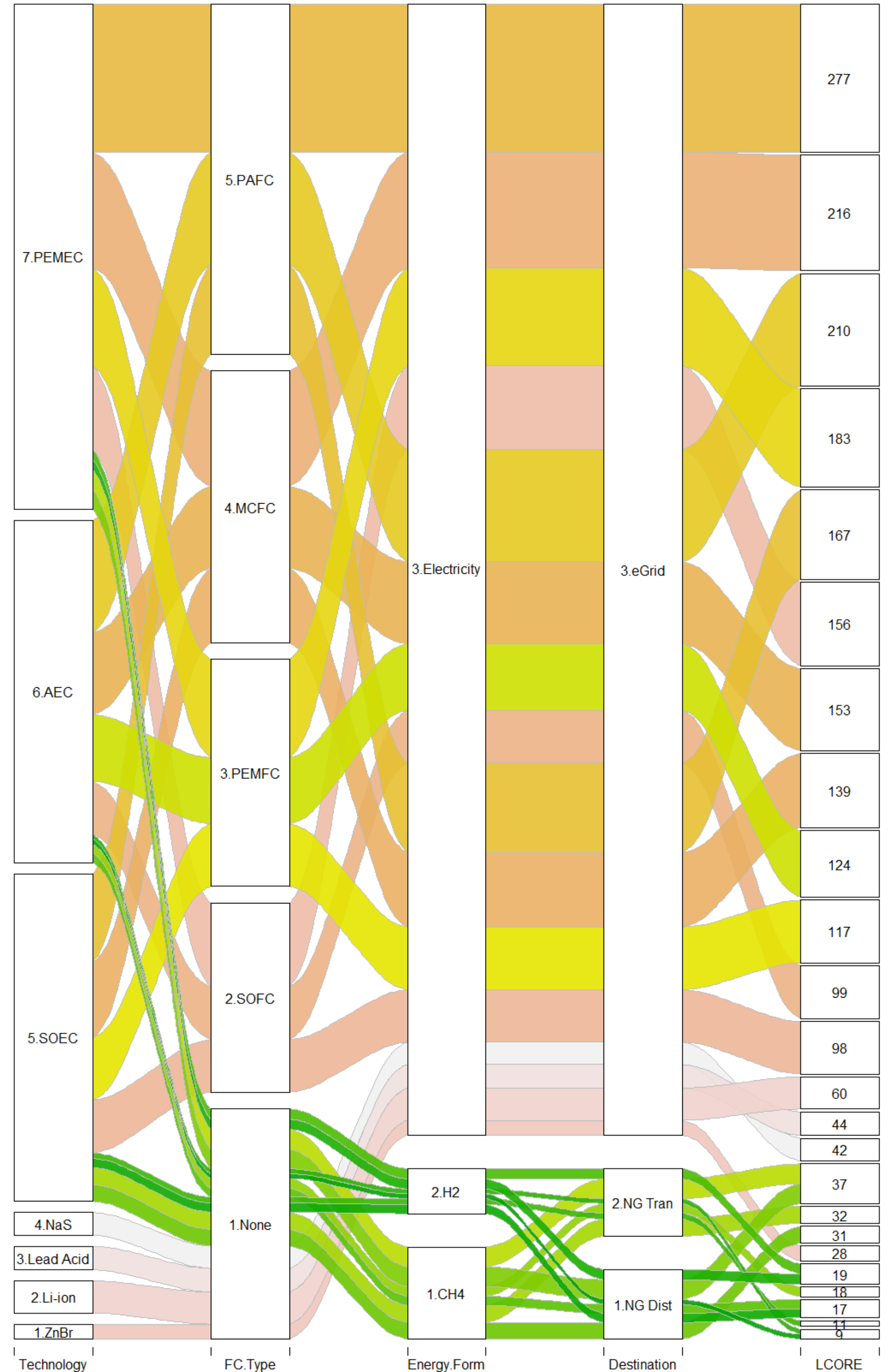


P2G Accomplishment: Detailed Economic Analyses

Levelized Cost of Returned Energy (LCORE)

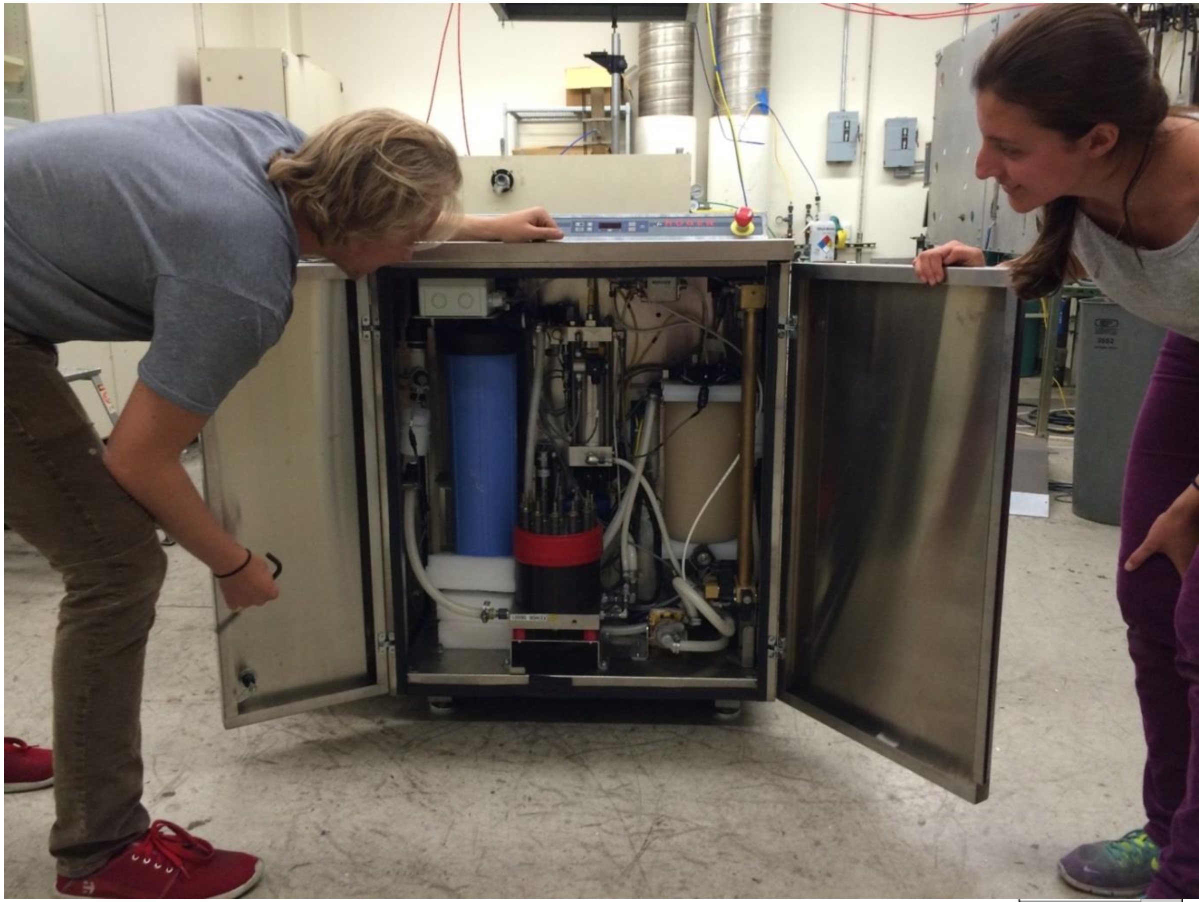
Pathways compared here:

- Electr. + Fuel Cell + Electricity to eGrid
- Electrolyzer + H2 to gas grid
- Electr. + Methanator + NG to gas grid
- Battery ES + Electricity to eGrid



P2G Accomplishment: Lab-Scale Electrolyzer Dynamics

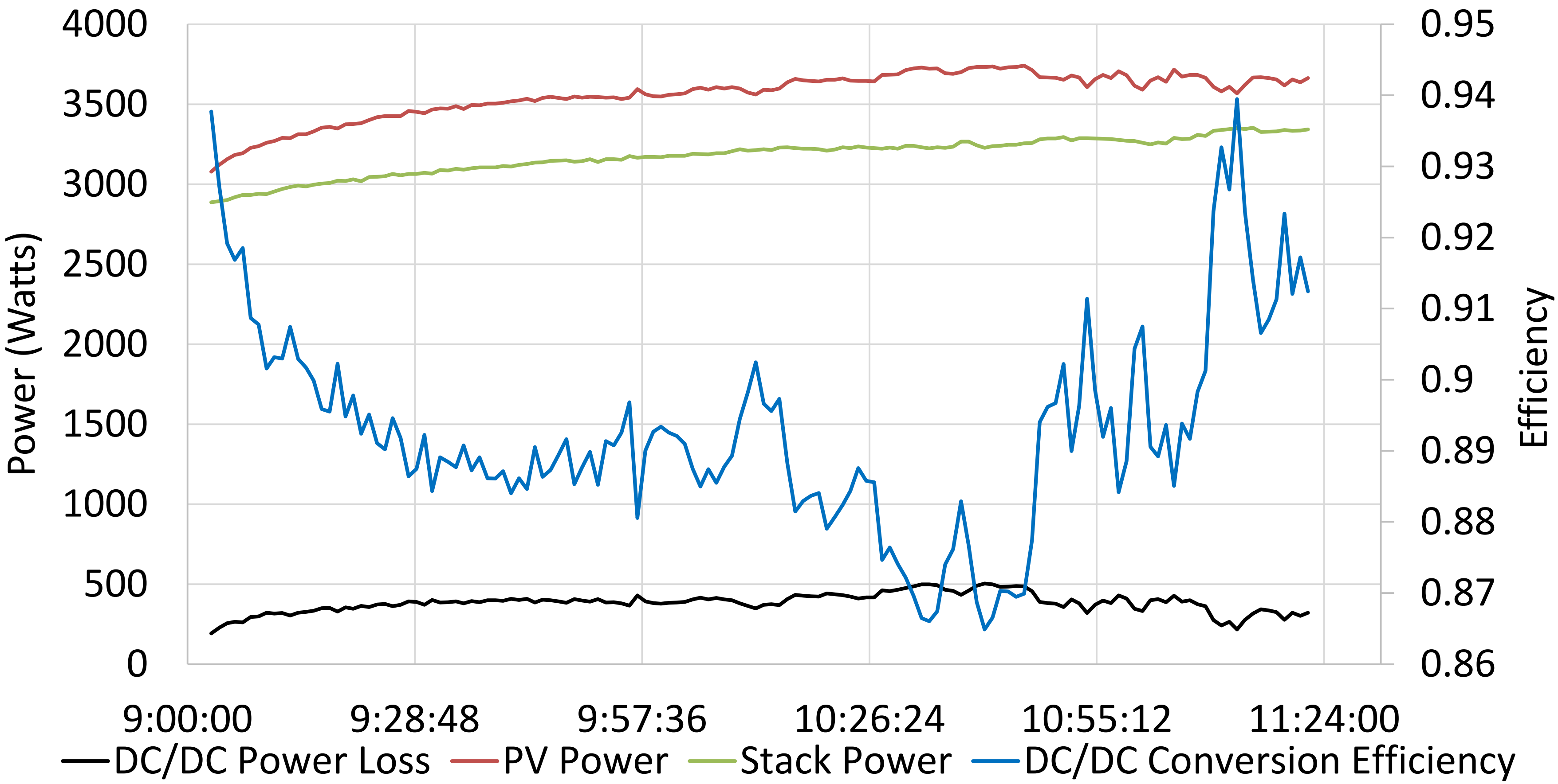
- HOGEN-RE proton exchange membrane electrolyzer
- Installed, connected, evaluated with PV direct-DC and 220V AC
- Sunny and cloudy days
- Overall performance
  - Efficiency in various operating modes
  - BoP losses
  - DC vs. AC
  - Dynamics
- Hydrogen uses
  (1) vented
  (2) stored
  (3) pipeline injected
  (4) end-use consumed



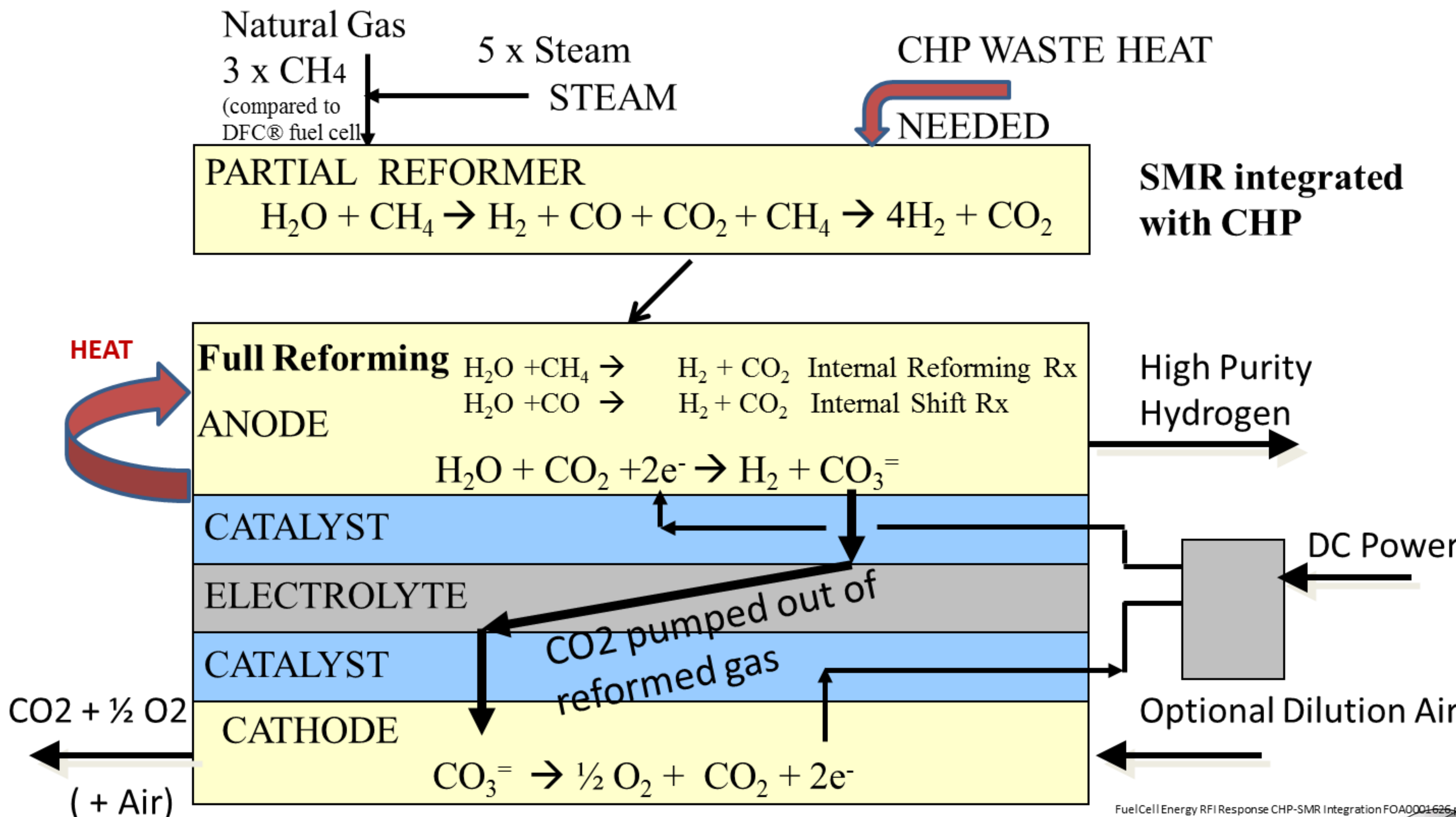
P2G Accomplishment: Lab-Scale Electrolyzer Dynamics

HOGEN-RE proton exchange membrane electrolyzer

- Balance of Plant loss dynamics (direct-PV mode)



Reformer Electrolyzer Purifier (REP) concept of FuelCell Energy



FuelCell Energy RFI Response CHP-SMR Integration FOA0001626.pptx

P2G Accomplishment: Electrolysis Alternatives

Reformer Electrolyzer Purifier (REP) concept of FuelCell Energy