Characterizing Electrolyzer Performance for Use in Wind Energy Applications

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Presentation Outline

- Background

- Characterization, Testing and Modeling

- Economic Analysis

- Large-scale R&D

Wind and Solar Energy Potential

Hydrogen Potential From Solar Resources

Hydrogen Potential From Wind Resources
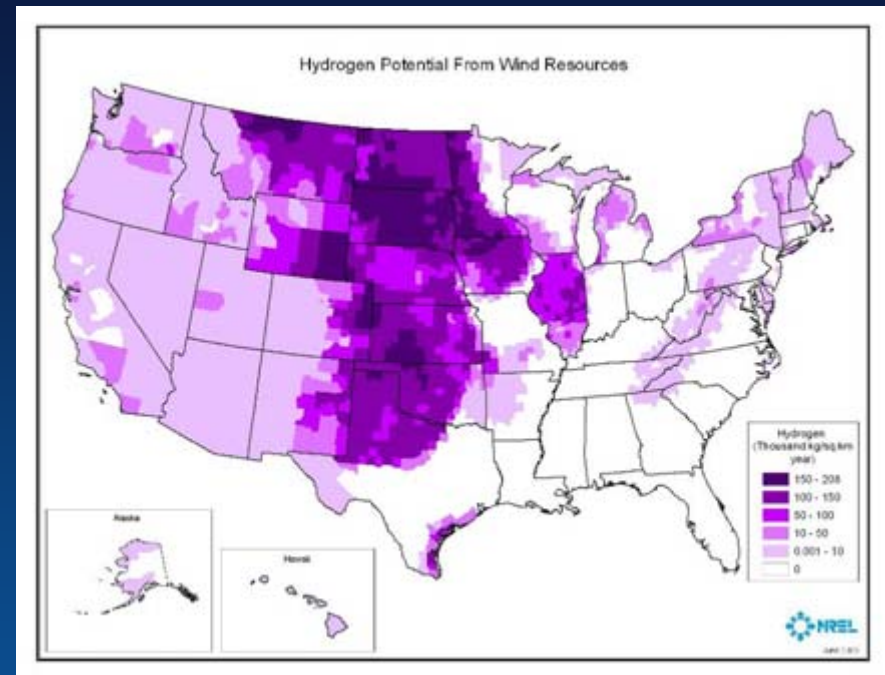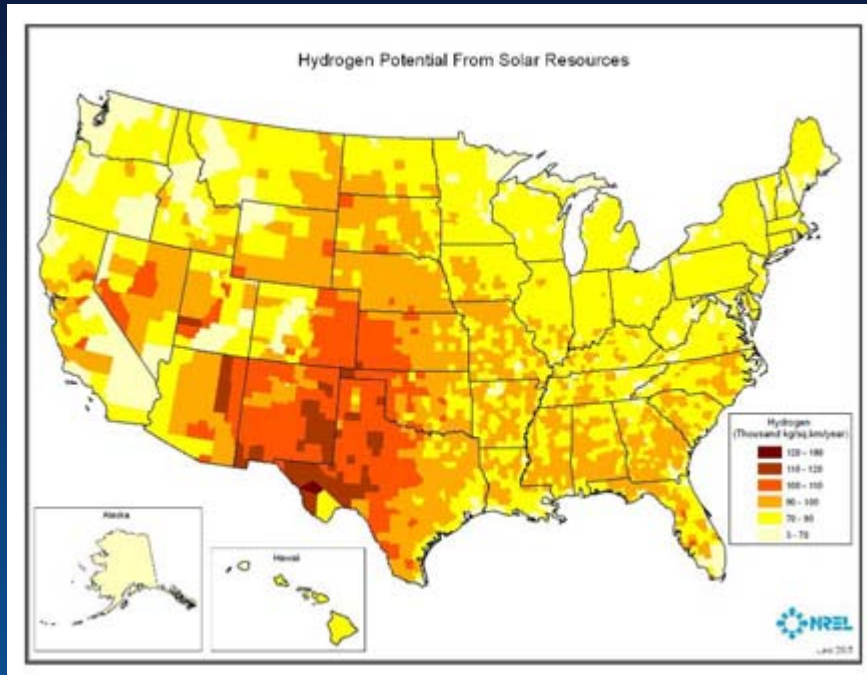
- The "Solar and Wind Technologies for Hydrogen Production" report was submitted to Congress as required by Section 812 of the 2005 Energy Policy Act

- The report shows that wind and solar energy sources for producing hydrogen are present in many parts of the country

- The report is available at www.hydrogen.energy.gov/congress_reports.html

Definition:
A Gallon of Gasoline vs. a Kilogram of Hydrogen

- Gasoline
  - ✓ 108,000 – 123,500 BTU/gal
- Hydrogen
  - ✓ 116,000 BTU/kg
- 1 kilogram of hydrogen ≈ 1 gallon of gasoline
- One caveat, if fuel cells are twice as efficient as gasoline internal combustion engines then only half the amount of hydrogen would be needed
  - – Twice the mileage with hydrogen

How to produce hydrogen RE? Electrolysis.

DC electricity from renewable sources
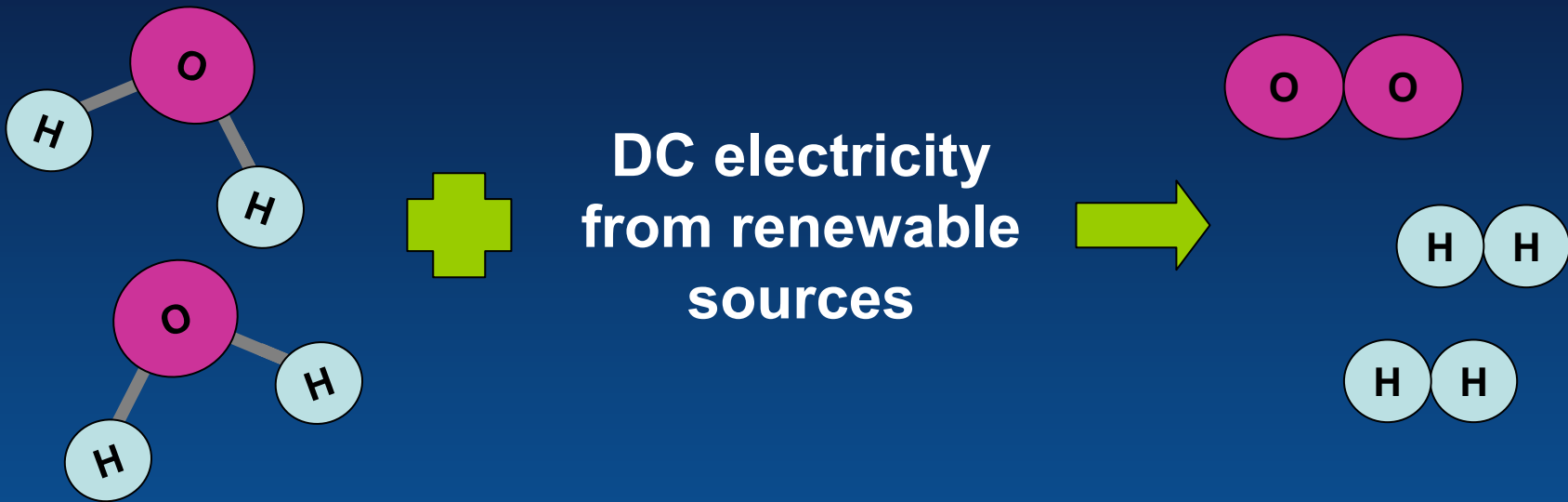
Focus of this research is on renewable H_2 production because it is the only way (today) to produce the gas without emissions.

Electricity Costs are Key

Hydrogen costs via electrolysis with electricity costs only
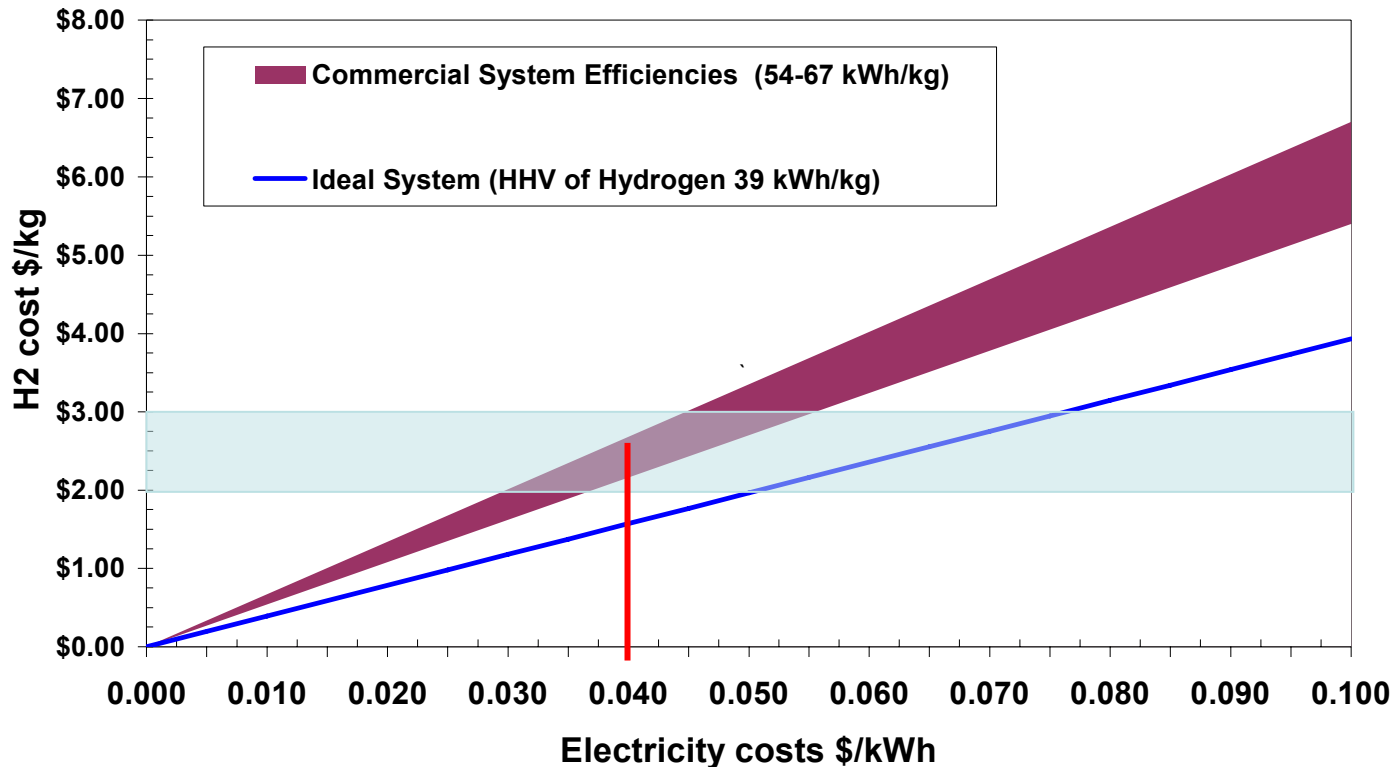
DOE: $2.00 - 3.00 kg $^{-1}$ delivered, untaxed, 2005$ by 2015

Technology Characteristics

- Alkaline
    - Cheaper catalyst (Ni v. Pt)
    - Low current density ($\uparrow$ efficiency)
    - Largest system < 10^3 $ kW^{-1}

- PEM
    - Pure water input requires H_2O vapor removal
    - Higher differential output pressure
    - Solid (not corrosive) electrolyte
    - $10^3 - 10^4$ $ kW^{-1}

- Solid Oxide
    - R&D
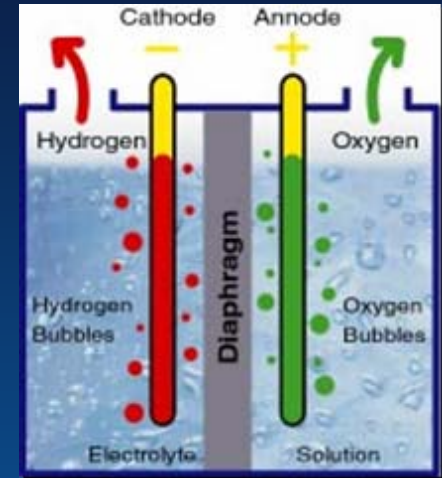
Characterization Testing and Protocol Development

- Completed initial characterization of 6 kW PEM electrolyzer for power electronics design

- Completed testing with simulated PV and wind using power supplies

- Completed testing with 5 kW PV array

- Continued testing with 10 kW wind turbine

Electrolyzer Requirements

- Ideally ~1.2 V cell^{-1} $\rightarrow$ f (I,T,P)

- Practical cells ~ 2.0 – 2.5 V cell^{-1}

- N series-connected cells $\uparrow$ V

$$SystemEfficiency = \frac{HHV\left(\frac{kWh}{kg}\right)}{\frac{\left(\frac{StackInputEnergy(kWh)}{PowerSupplyEfficiency}\right) + AncillaryLosses(kWh)}{HydrogenProduced(kg)}}$$

$$StackEfficiency = \frac{IdealStackPotential}{ActualStackPotential}$$

System Integration and Component Development
Completed Power Electronic Interface Modifications

10 kW Bergey Excel

Step Down Transformer

Modified VCS-10

Half-bridge Controlled SCR Bridge

40 VDC Battery Bank

40VDC

+

ELECTROLYZER
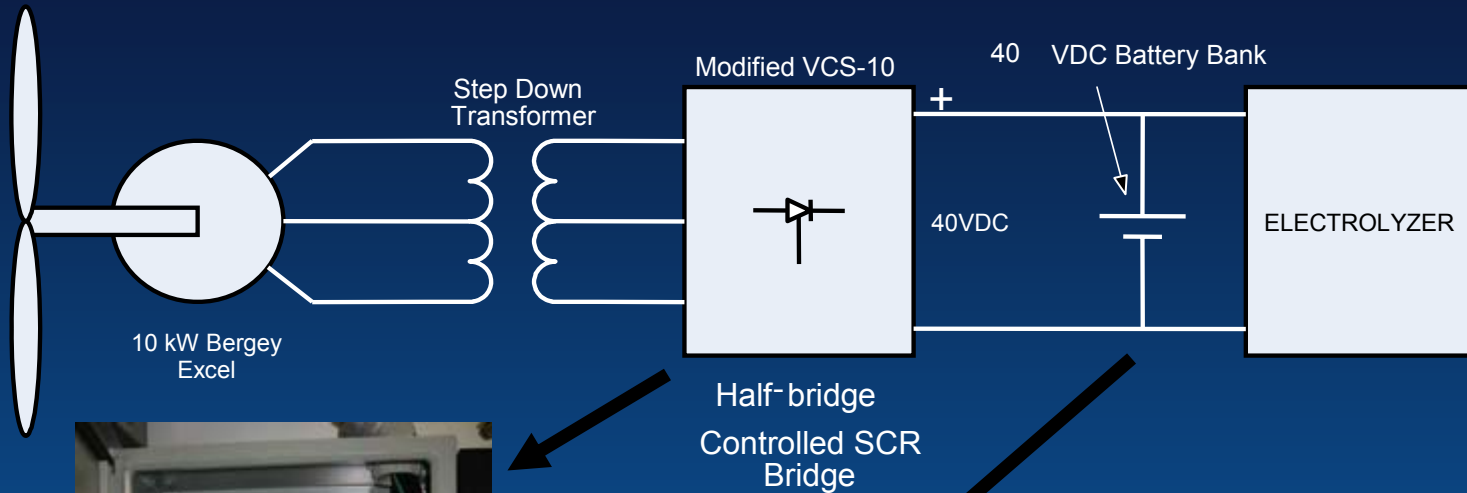
Variable Input Power

- Wind energy to stack and PV to DC/DC converter
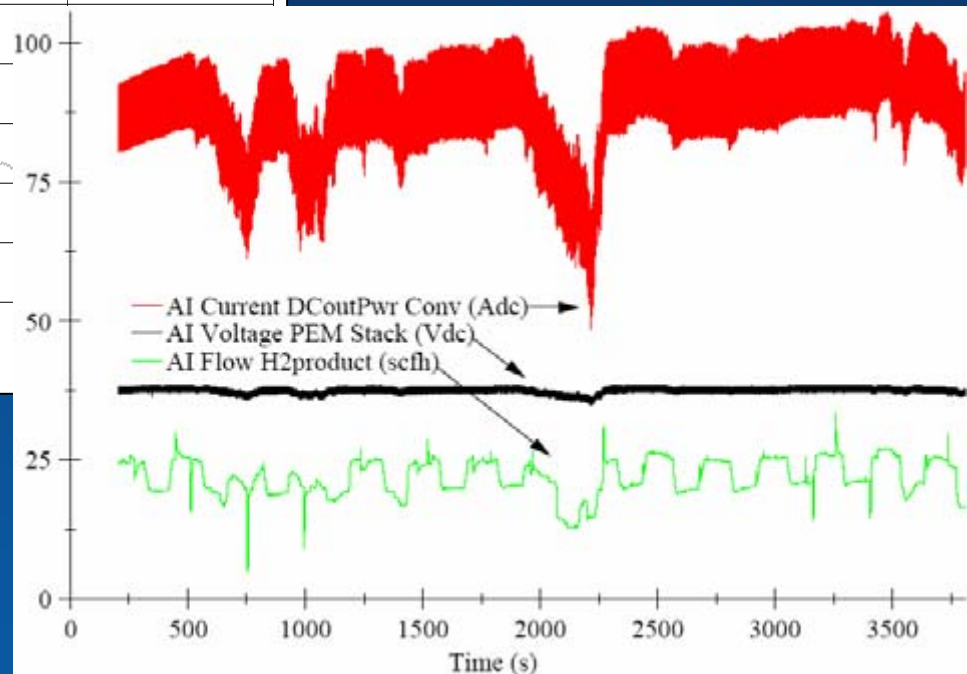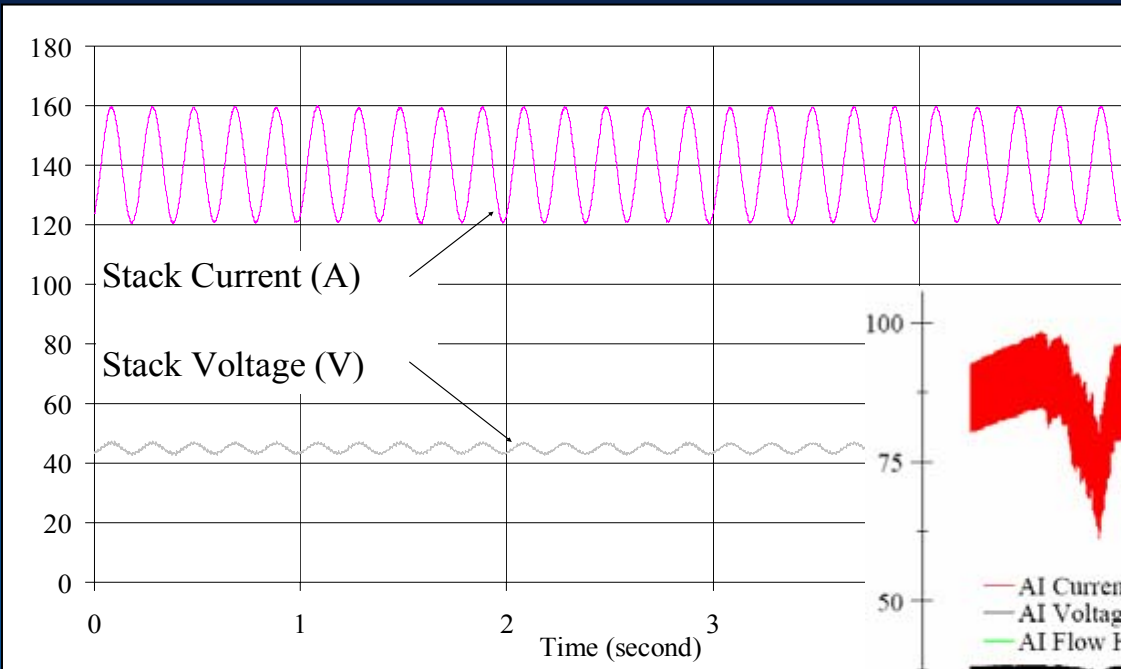
- Programmable power supplies to vary input power to stack

Monitor Performance

- Stack and system energy

- Hydrogen pressure, flow and quality

- Water temp., flow and quality
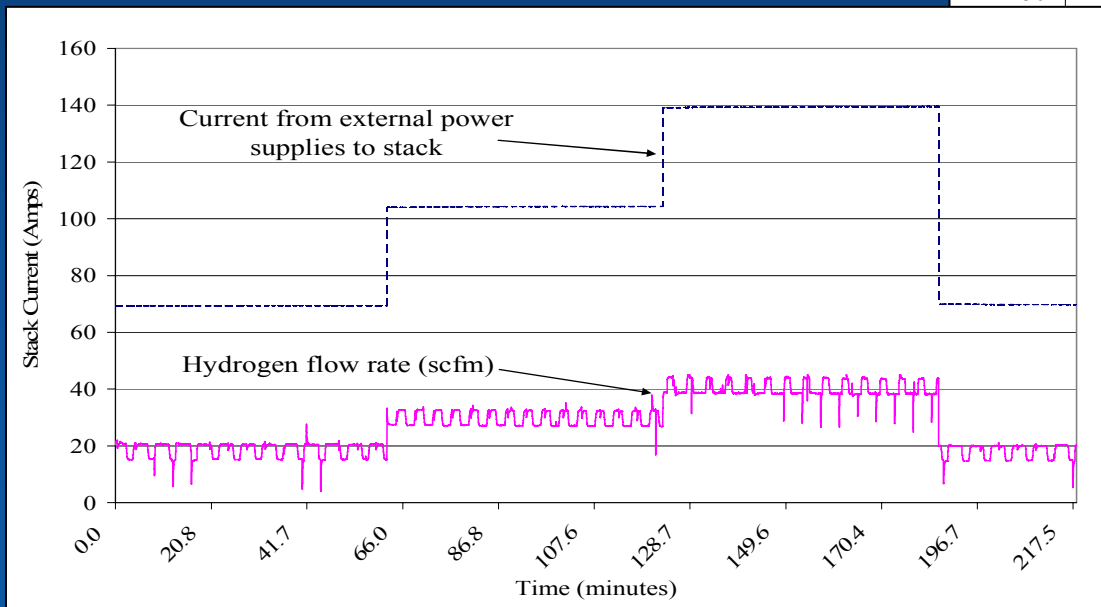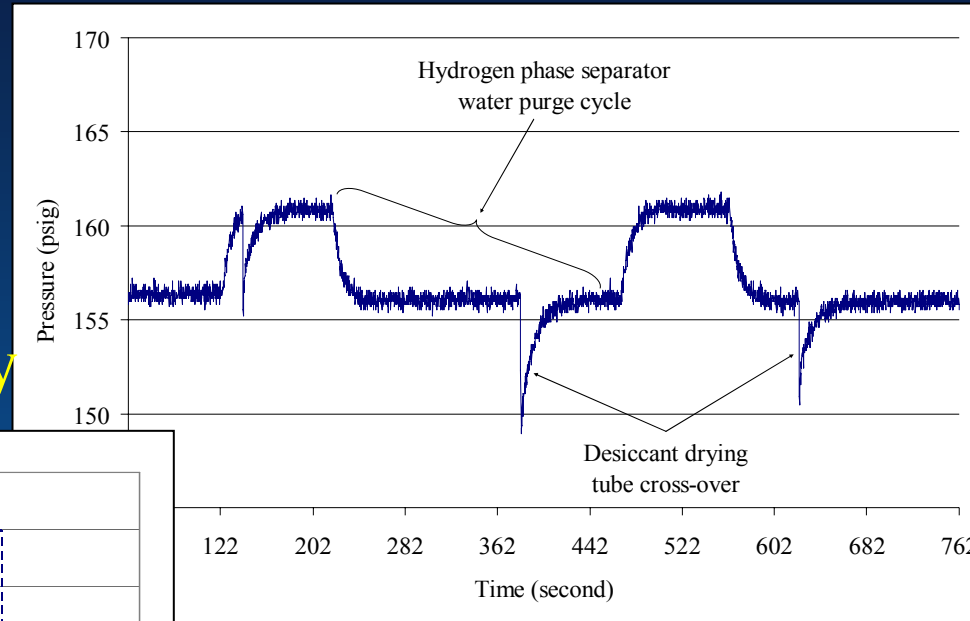
- Impacts on grid (pf, THD)

Modeling

Cathode pressure range 86.6 - 103.4 psig

- Tavg = 9.0 °C
- Tavg = 14.8 °C
- Tavg = 24.1 °C
- Tavg = 32.4 °C

- IV data and electrochemistry to extract stack characteristics

- Stack Efficiency Experimental
- Stack Voltage Model
- Stack Voltage Experimental

T = 35°C   n = 20 cells
Sigma = 0.075 S/cm   Pc = 13.7 atm
ico = 0.09 A/cm^2   Pa = 1.0 atm
iao = 1.65 * 10^(-8) A/cm^2
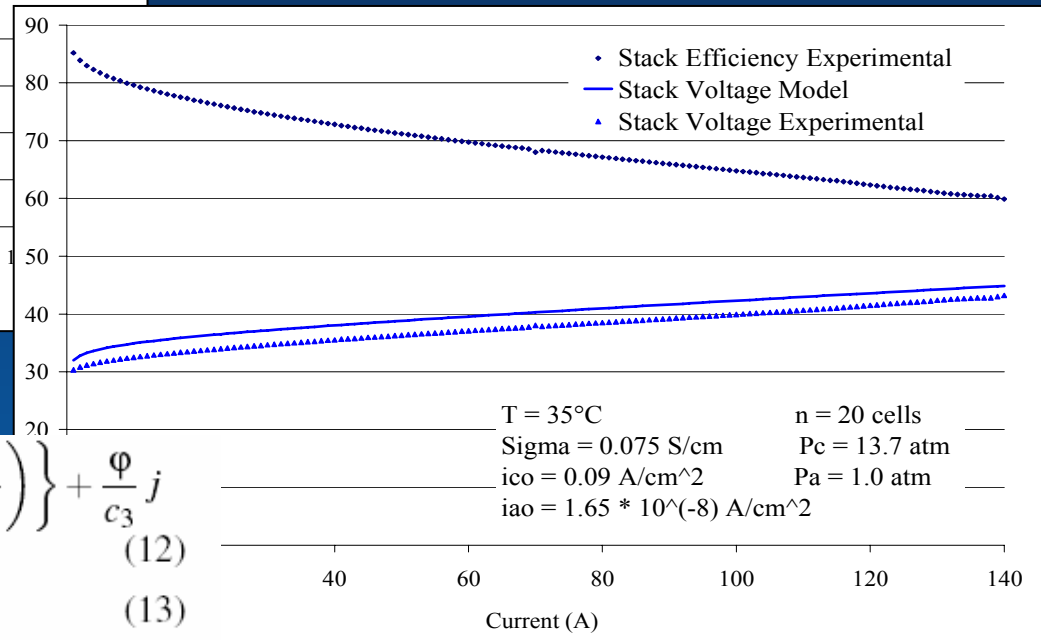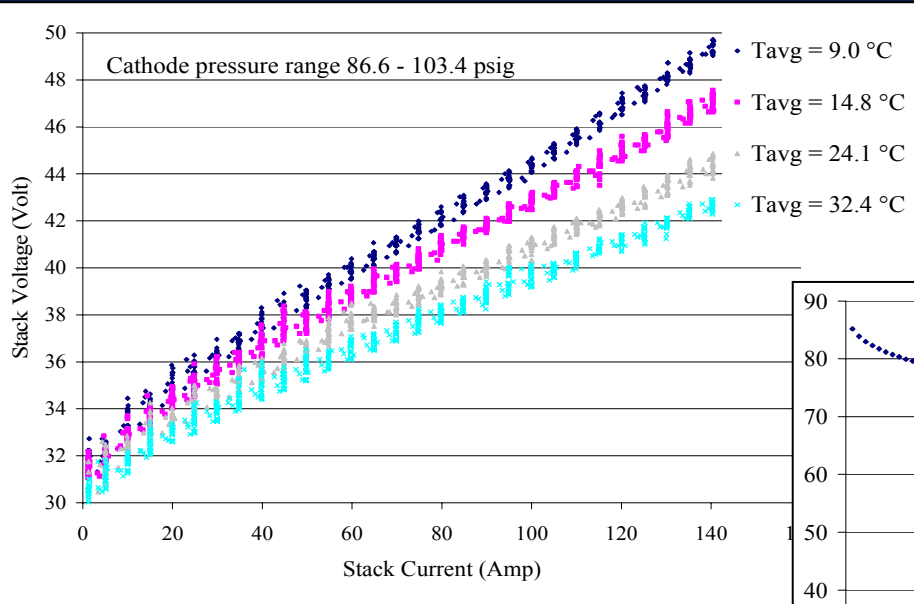
$$E = 1.20 + \frac{RT(I)}{\mathcal{F}} \left\{ \text{Sinh}^{-1}\left(\frac{j}{2c_1}\right) + \text{Sinh}^{-1}\left(\frac{j}{2c_2}\right) \right\} + \frac{\varphi}{c_3} j \tag{12}$$

$$c_1 = j_{A,o} = 1.65 \times 10^{-8} \tag{13}$$

$$c_2 = j_{C,o} = 0.09 \tag{14}$$

$$c_3 = \sigma = 0.075 \tag{15}$$

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Analysis of Performance
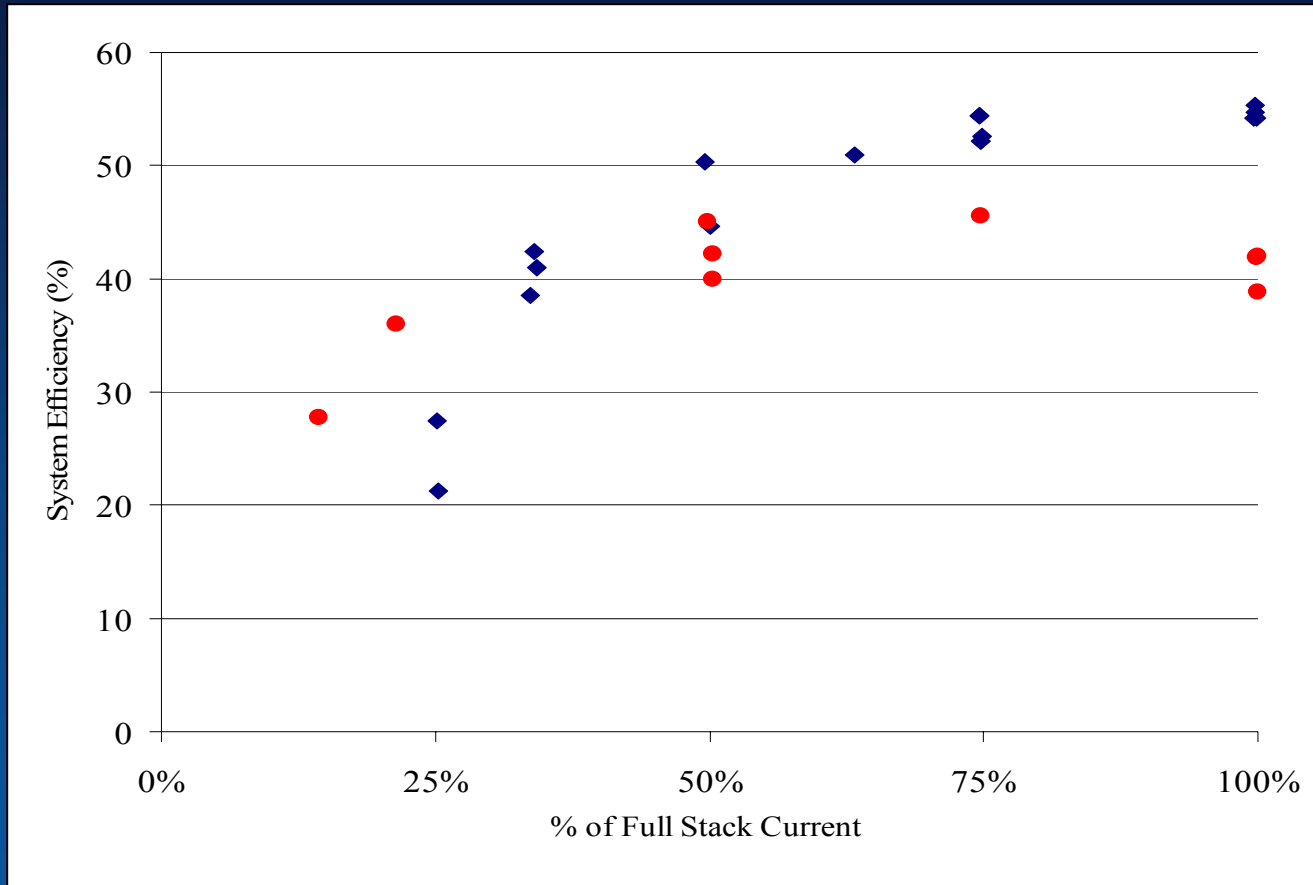
- System efficiency of PEM system at various levels of current and temperature

Economic Analysis Purpose

Hydrogen Production

– How much does it cost to produce hydrogen for use as a transportation fuel?

– System uses wind electricity to produce hydrogen for transportation purposes

– Results in $/kg of hydrogen

– Whether wind at site can compete with distributed H_2 production

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Case 1: Hydrogen Production at the Wind Site

Electricity → Electrolyzer → Hydrogen → Hydrogen delivery

Electrolyzer
- Produces hydrogen whenever the turbine produces electricity, except during peak electricity demand hours

Hydrogen delivery costs are not included

Vestas V82 turbine
- 1.65 MW

Evaluated two wind sites
- Minnesota WROC Site
- Gobblers' Knob

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Case 2: Distributed Hydrogen Production Using Xcel Aggregate Wind Power

Lamar

Signal

Hydrogen Storage Tanks

Electricity

Electricity

Hydrogen

Grid

Electrolyzer

Hydrogen

Peetz

Ponnequin

Xcel Aggregate Wind
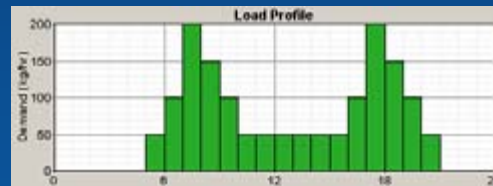
Must meet a filling station demand

Hydrogen for transportation fuel use

Wind Sites

Hydrogen Fueling Station

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Model Results

- Good wind resource is a key to producing low price hydrogen
    - 12-16% price reduction in hydrogen production
- Production at the wind site makes fiscal sense if cost reductions offset delivery cost
- Cost reductions and efficiency improvements must be obtained by electrolyzer manufacturers to obtain low price hydrogen
- If aggregate wind electricity is available at the filling station for $0.038/kWh, the potential exists for hydrogen production, compression and storage from wind below the DOE cost target of $2-3/kg delivered

$\therefore$ **Xcel Decides Go!**

Project Objectives

This project examines the issues with using renewable energy to produce hydrogen by electrolyzing water

- Characterize electrolyzer performance under variable input power conditions

- Design and develop shared power electronics packages and controllers to reduce cost and optimize system performance and identify opportunities for system cost reduction through breakthroughs in component integration

- Test, evaluate and optimize the renewable electrolysis system performance for both

  - Dedicated hydrogen production
  - Electricity/hydrogen cogeneration

Wind2H2E Wind Testing Configurations

Excess AC Power

DC BUS

DC-DC Converters

DC-DC Converter

Utility Grid

Northern Power Systems 100 kW WT

AC Power

H_2 Compression

H_2 Output

Hydrogen IC Engine/ Genset 60kW

H_2 Storage 3,500 PSI

(Future) H_2 Filling Station

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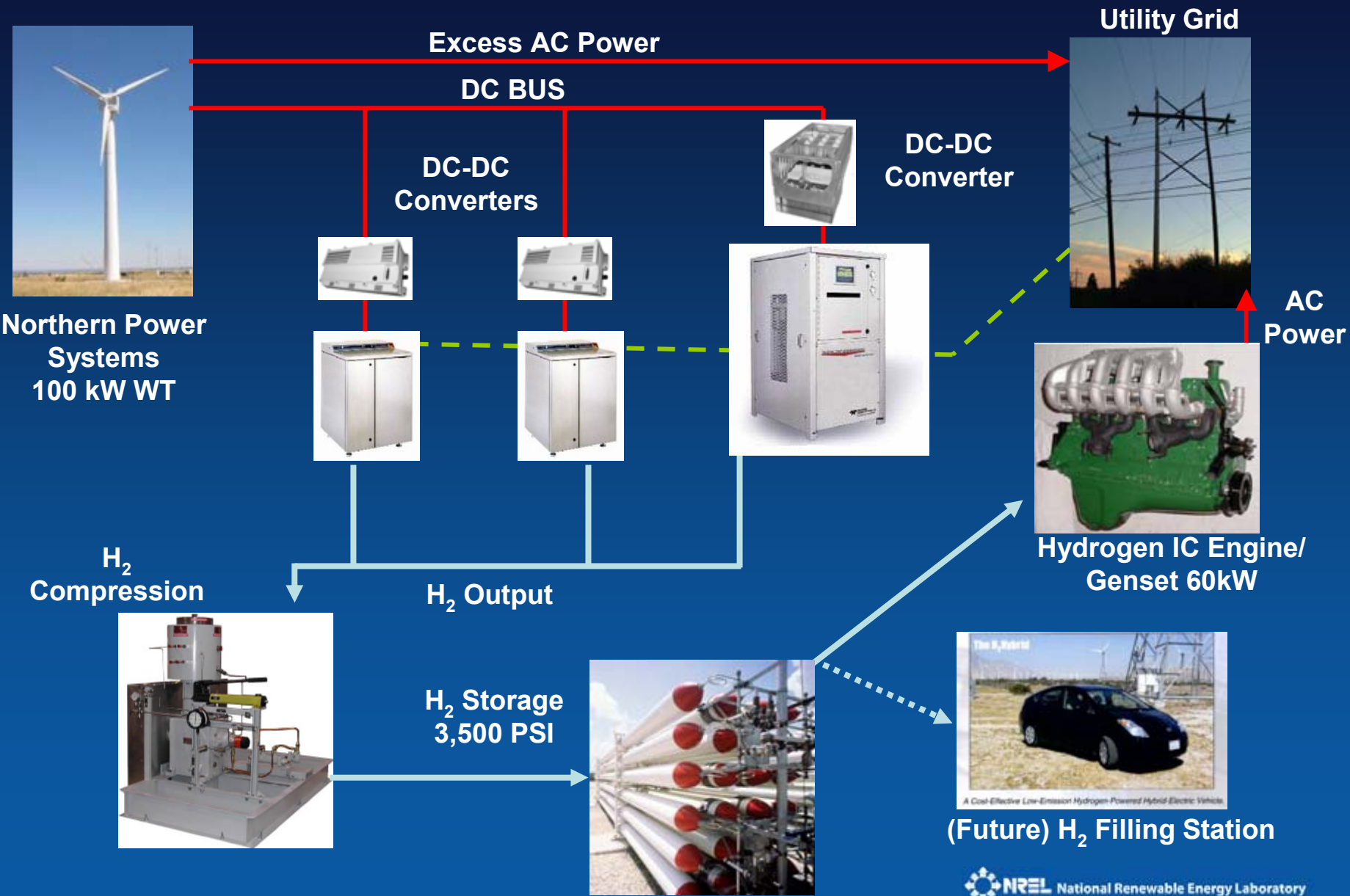
Wind2H2E Grid Testing Configurations

Utility Grid

AC Power

Proton Energy
HOGEN 40RE

Teledyne
HM-100

AC Power

Hydrogen IC Engine/
Genset 60kW

H$_2$
Compression

H$_2$ Output

H$_2$ Storage
3,500 PSI

(Future) H$_2$ Filling Station

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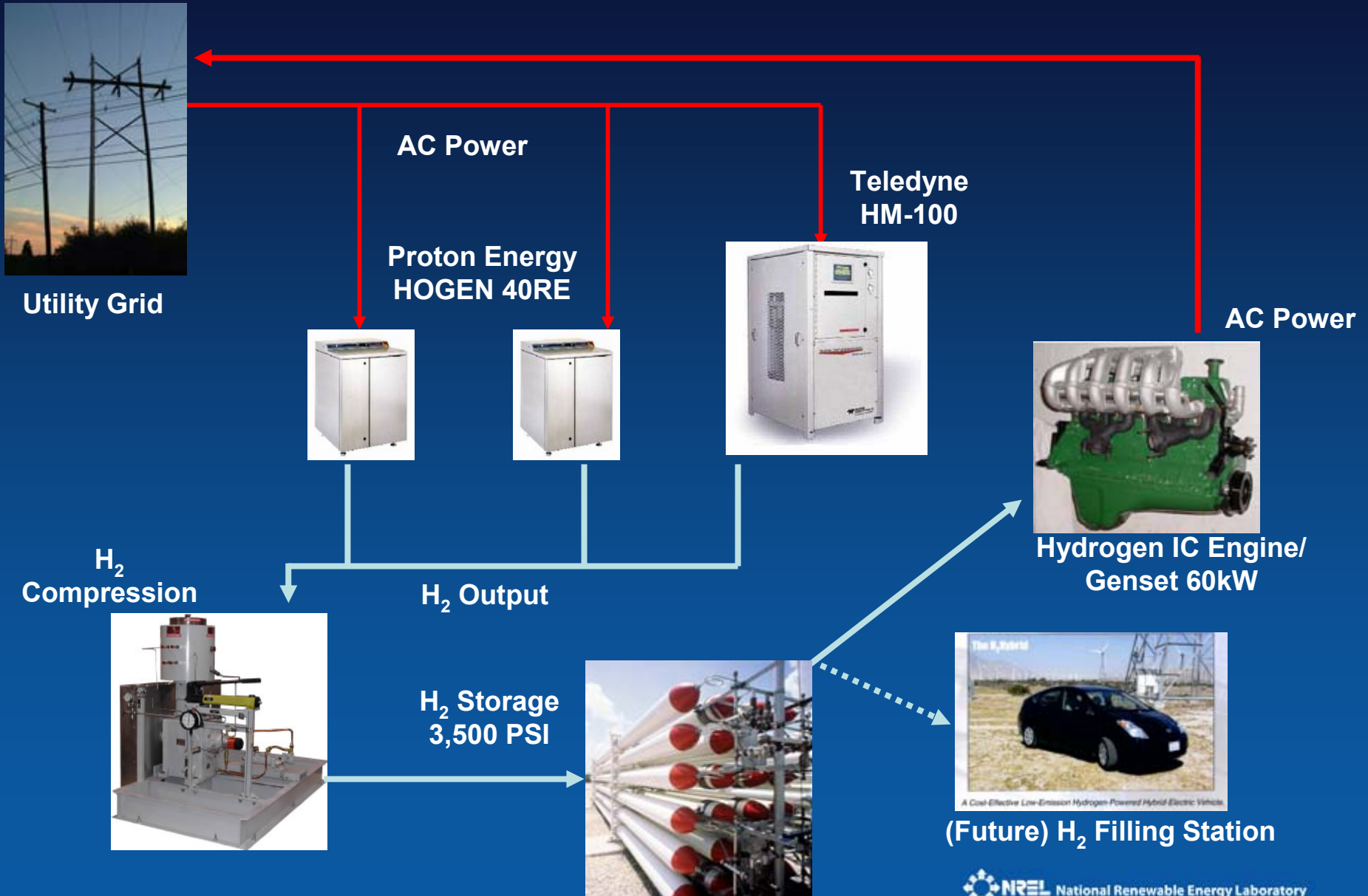
Acknowledgements and References

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  - Johanna Levene, Ben Kroposki, Bill Kramer and Chris Pink
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  - H2A team for hydrogen equipment assumptions
  - Team of Xcel, NREL, EPRI and John Cornish
  - Specifically Frank Novachek and Vicki McCarl of Xcel Energy for their invaluable assistance and support during this project.
- References:
  - www.nrel.gov/homer
  - WindPower paper and presentation, *An Economic Analysis of Hydrogen Production from Wind*
  - www.hydrogen.energy.gov/h2a_analysis.html

Backup Slides

Key Common Assumptions

Parameter	Assumption
Electrolyzer	• Costs are assumed to be $740/kW, $400/kW, and $300/kW in near, mid and long term • Electrolyzer and compression efficiencies are 70, 78 and 83% (based on 39 kWh/kg HHV) in short, mid and long term • Uses AC power
Compressor	• $600,000, $300,000 and $100,000 for a 1500 kg compressor in near, mid and long term • Includes compressor energy requirements of 2.09 kWh/kg
Annual Real Interest Rate	• Discount rate used to convert between one-time costs and annualized costs • Study uses 10%
Hydrogen Dispensing	• No hydrogen dispensing costs included

Detailed assumptions are available in Appendix A of Power-Gen paper

Key Common Assumptions (cont…)

| Parameter	Assumption
Peak Electricity	• Peak electricity usage is from 4-7 p.m. on weekdays, so no hydrogen can be produced during those three hours • There are no peak hours during the weekend, so electrolyzer can run 24 hours a day
System Pressure	• Hydrogen is compressed after production to 6500 psi • Storage is provided at 6500 psi
Wind Turbine Capital and Operating Costs	• Turbine costs are not specifically used in analyses, rather the cost of wind generated electricity is used • Assumes this cost includes capital, replacement and operating costs of the wind turbines • Xcel Energy purchases wind generated electricity at a rate of $0.038/kWh

Detailed assumptions are available in Appendix A of Power-Gen paper

Wind2H2E Project Features

Feature	Importance
Direct DC feed to electrolyzer	Grid connected <u>and</u> isolated wind farm simulations, system efficiency gains & future control system integration capital cost reductions
Concurrent AC feed to electrolyzer	Permits clear comparison to direct DC feed performance
Multiple commercial electrolyzers	Grid connected <u>and</u> isolated wind farm simulations and reduced operability risk, and system efficiency gains
Medium pressure range compression and storage	Reduced operability risk, reduced cost to compress hydrogen & improved reliability
Hydrogen ICE generator set	H_2 or H_2/NG mixed fuel option
Initial siting at NREL controlled facility	World class R&D practices and opportunity to learn H_2 handling practices from experienced practitioners
System transportability for redeployment	Utility value after R&D testing

Analysis Tool

- The HOMER® Model was developed at NREL to allow users to optimize electric systems and make it easier to evaluate the many possible system configurations
  - Hydrogen added in 2004, enhanced in 2005
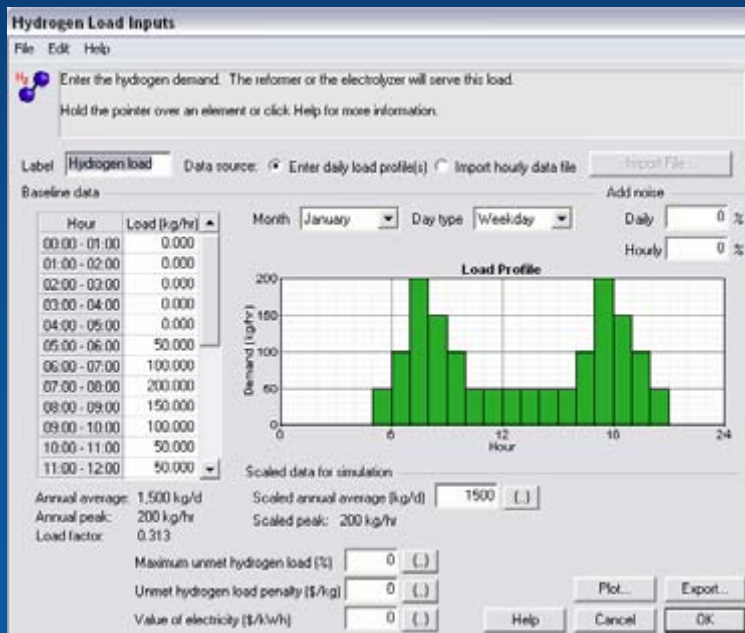
The Problem:

Case 2: You are trying to meet a hydrogen load (shown to the left)

- How much electricity can aggregate grid provide?

- Should you add more electrolyzers, or more storage to meet demand?

- How much does the hydrogen cost?