Characterizing Electrolyzer Performance for Use in Wind Energy Applications

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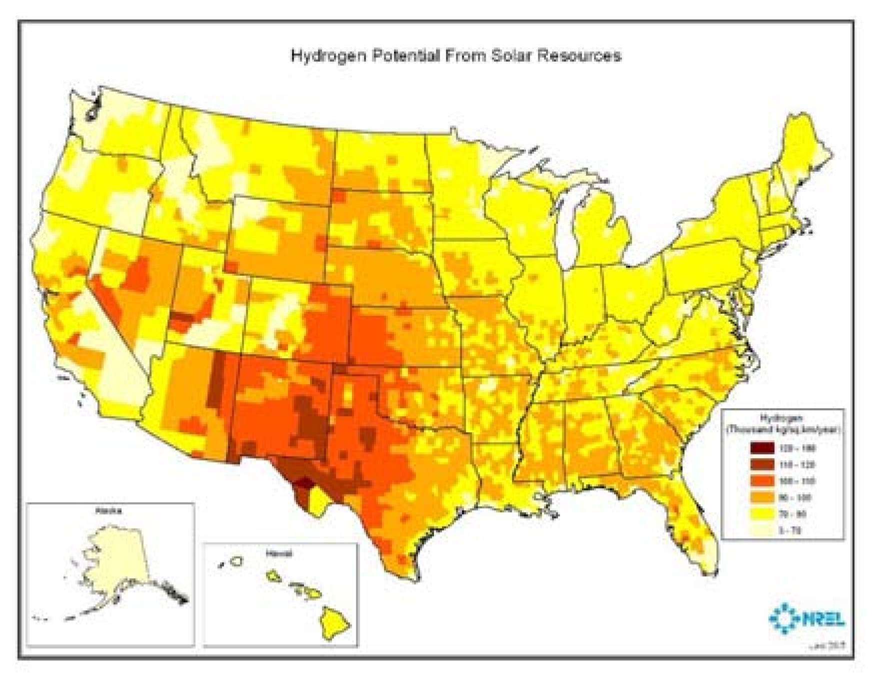
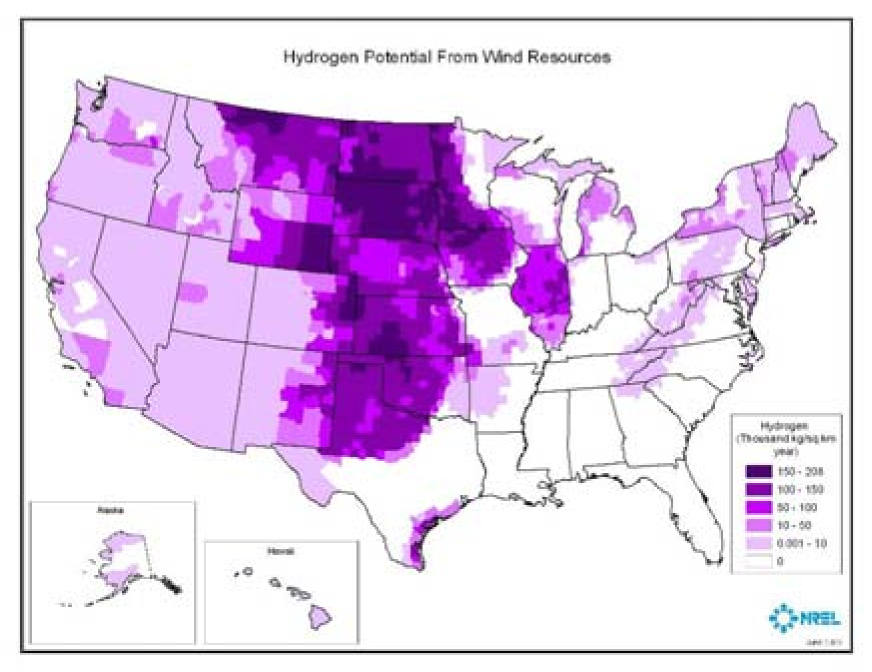
Presentation Outline

- Background
- Characterization, Testing and Modeling
- Economic Analysis
- Large-scale R&D

Wind and Solar Energy Potential



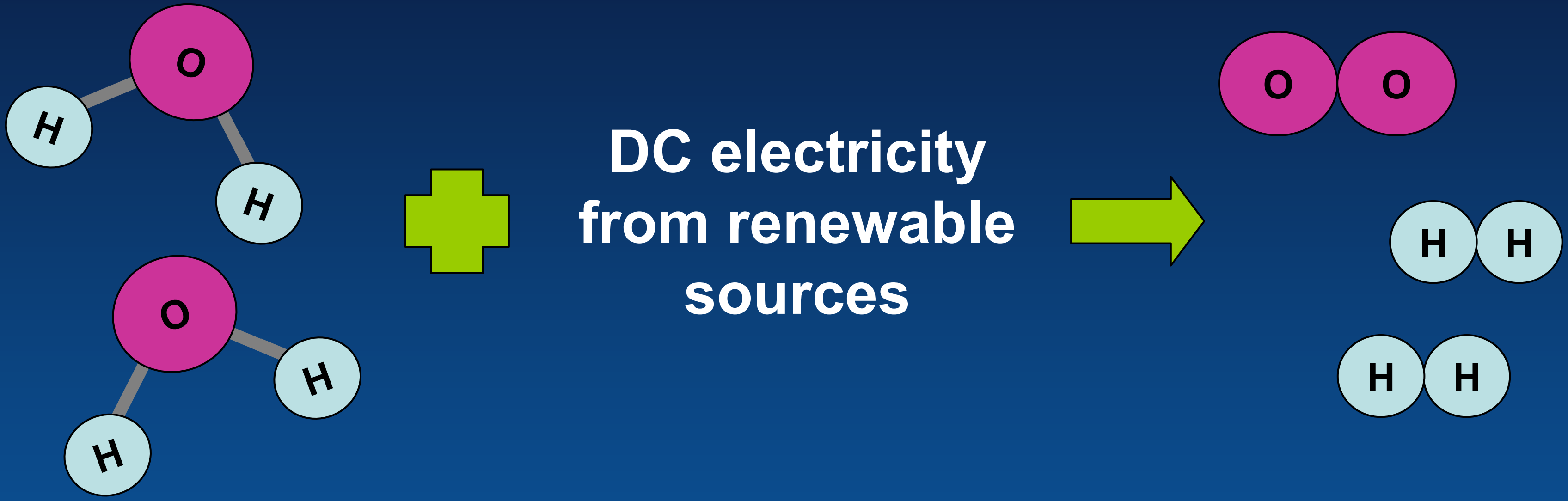


- The “Solar and Wind Technologies for Hydrogen Production” report was submitted to Congress as required by Section 812 of the 2005 Energy Policy Act
- The report shows that wind and solar energy sources for producing hydrogen are present in many parts of the country
- The report is available at www.hydrogen.energy.gov/congress_reports.html

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.

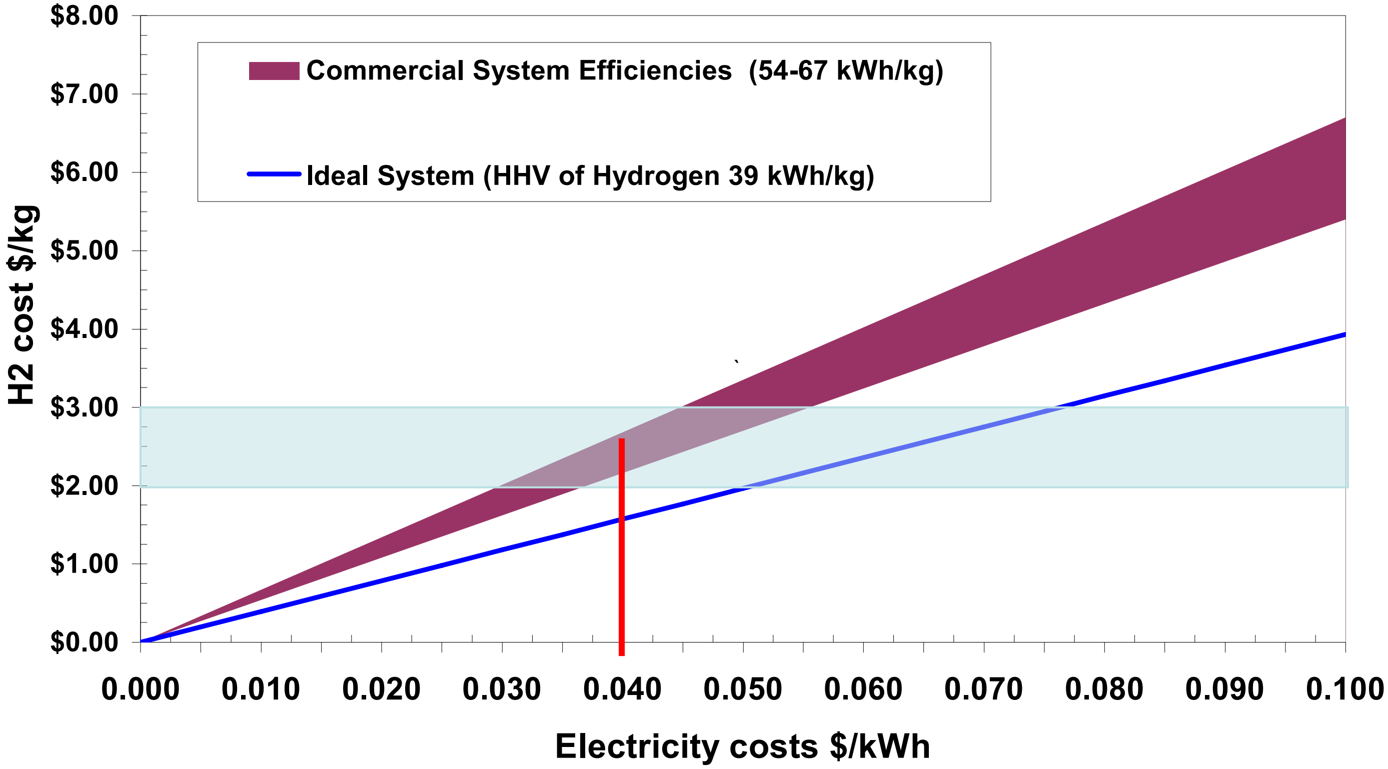


DC electricity
from renewable
sources

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

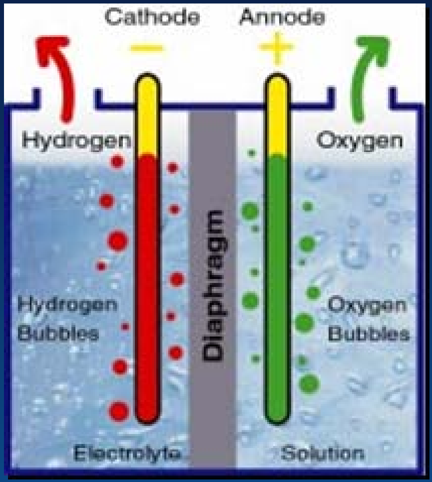
Electricity Costs are Key

Hydrogen costs via electrolysis with electricity costs only



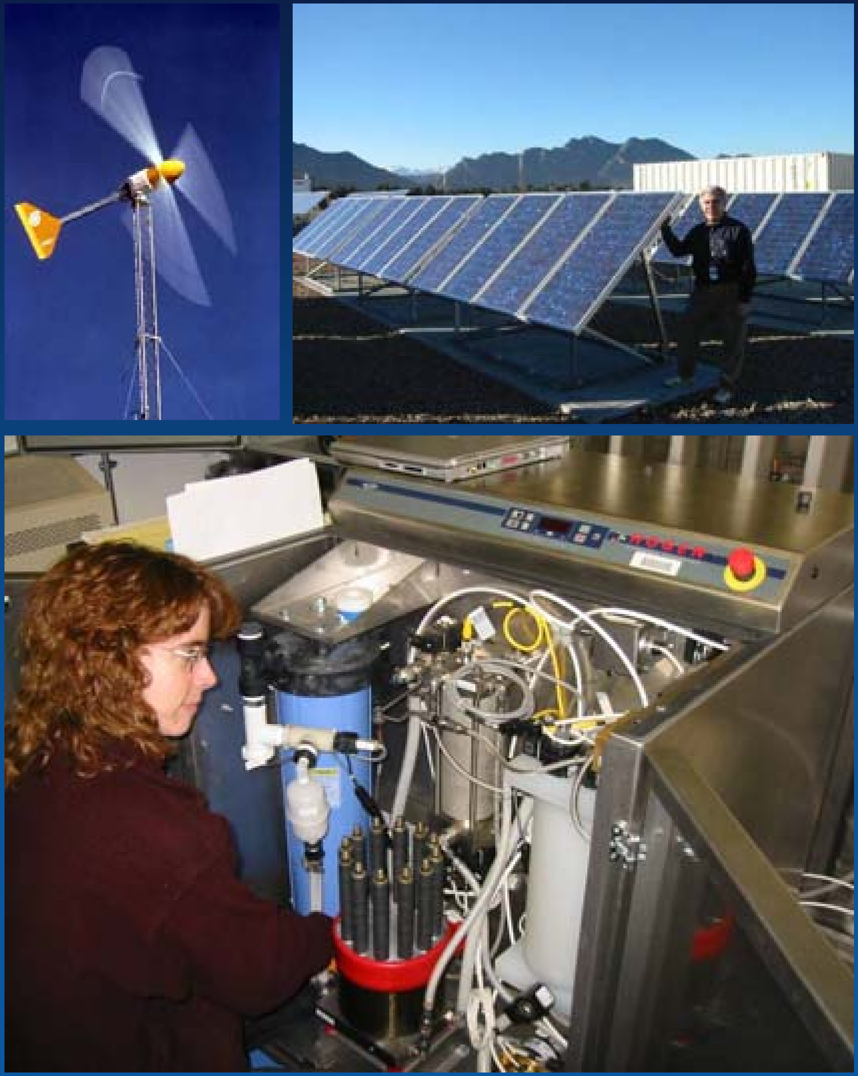
DOE: $2.00 - 3.00 kg $^{-1}$ delivered, untaxed, 2005$ by 2015

Technology Characteristics



- Alkaline
  - Cheaper catalyst (Ni v. Pt)
  - Low current density (↑ efficiency)
  - Largest system < 10^3 \$ kW^{-1}
- PEM
  - Pure water input requires H_20 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

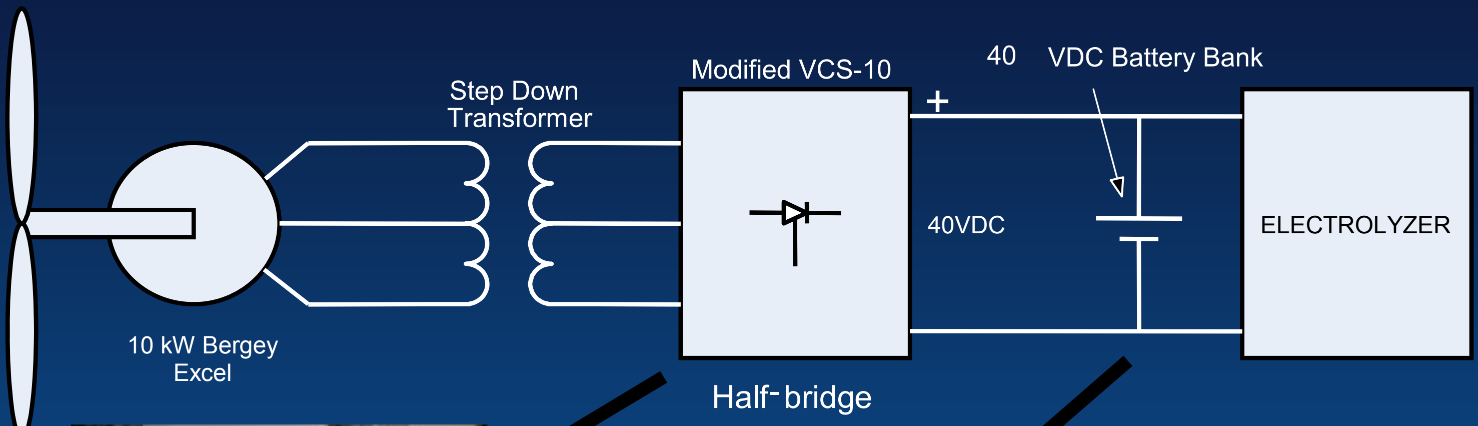
- Ideally ~1.2 V cell^{-1} → f (I,T,P)
- Practical cells ~ 2.0 – 2.5 V cell^{-1}
- N series-connected cells ↑ V

$$\text{System Efficiency} = \frac{\text{HHV}\left(\frac{\text{kWh}}{\text{kg}}\right)}{\frac{\left(\frac{\text{Stack Input Energy (kWh)}}{\text{Power Supply Efficiency}}\right) + \text{Ancillary Losses (kWh)}}{\text{Hydrogen Produced (kg)}}}$$

$$\text{Stack Efficiency} = \frac{\text{Ideal Stack Potential}}{\text{Actual Stack Potential}}$$

System Integration and Component Development

Completed Power Electronic Interface Modifications



Step Down Transformer

Modified VCS-10

40 VDC Battery Bank

+

40VDC

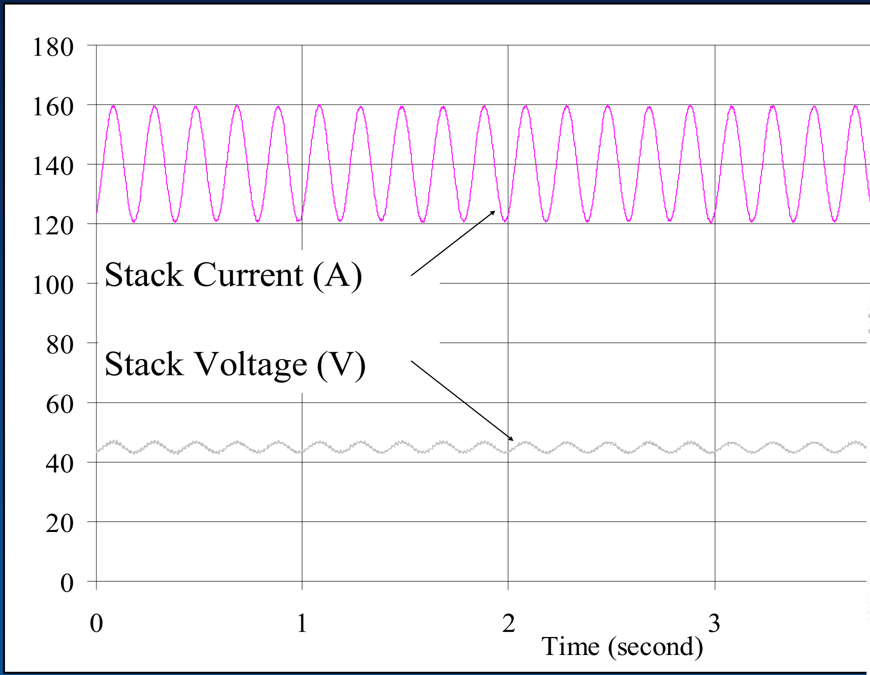
ELECTROLYZER

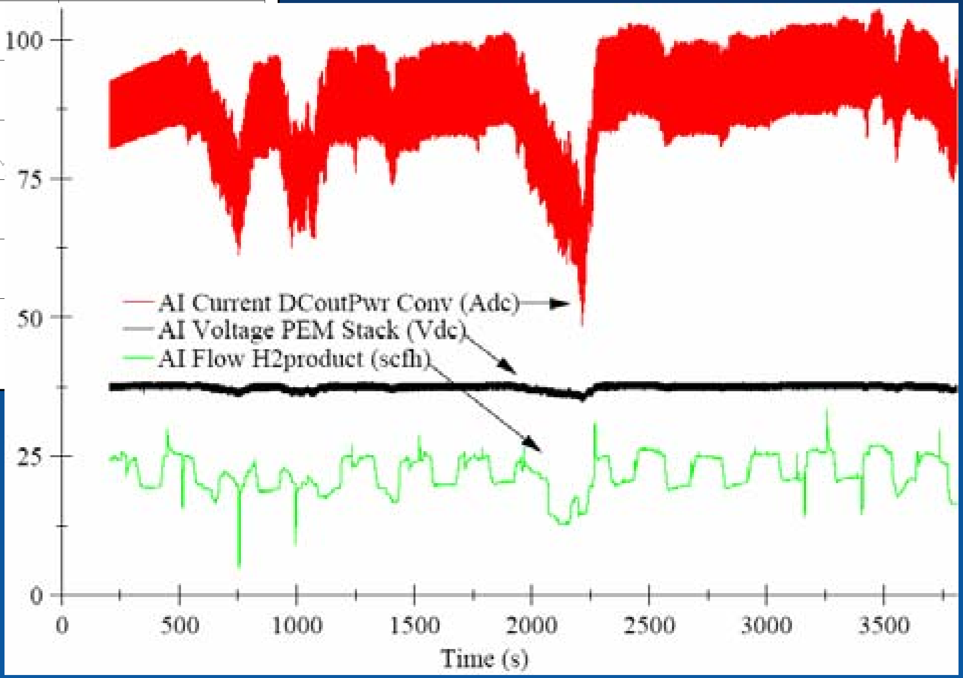
10 kW Bergey Excel

Half-bridge Controlled SCR Bridge

Variable Input Power

- Wind energy to stack and PV to DC/DC converter

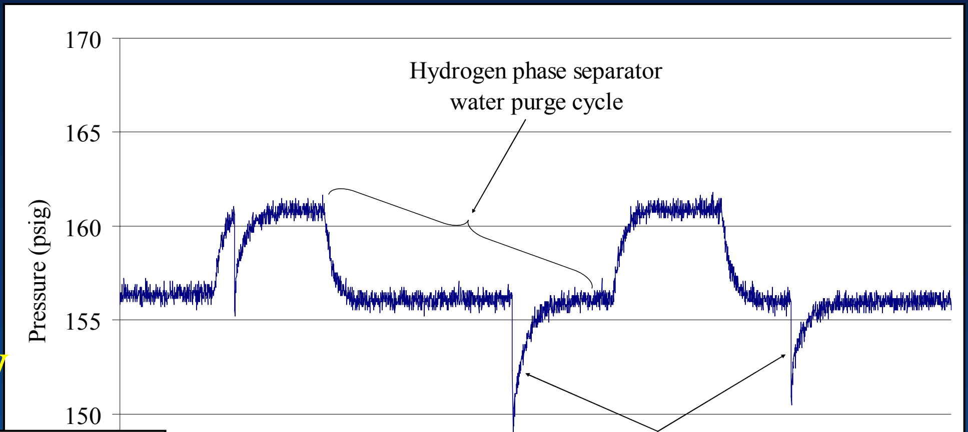


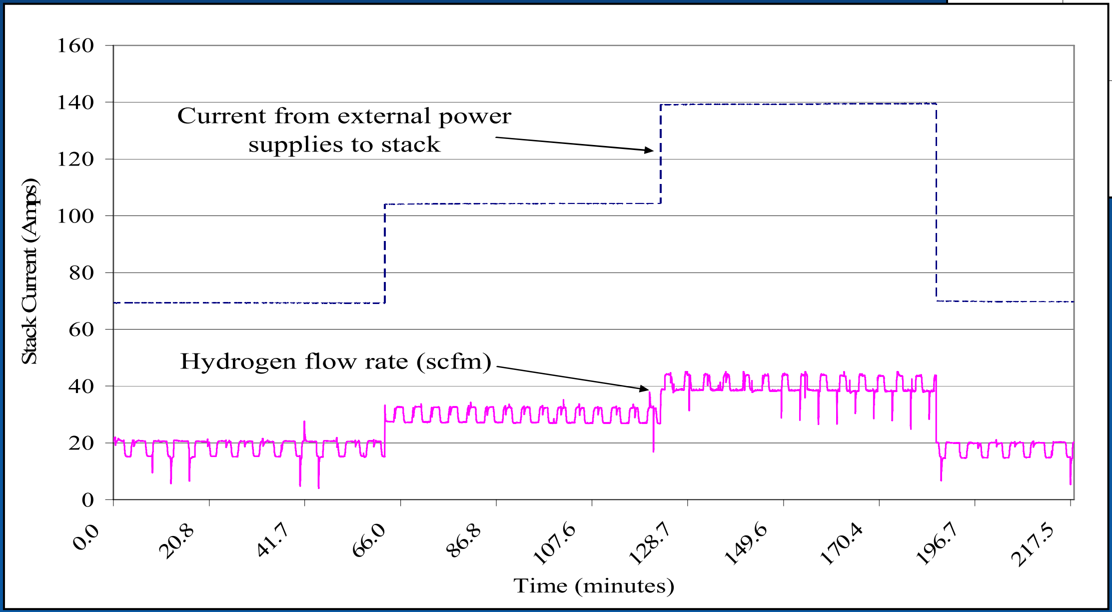


- Programmable power supplies to vary input power to stack

Monitor Performance

- Stack and system energy
- Hydrogen pressure, flow and quality
- Water temp., flow and quality

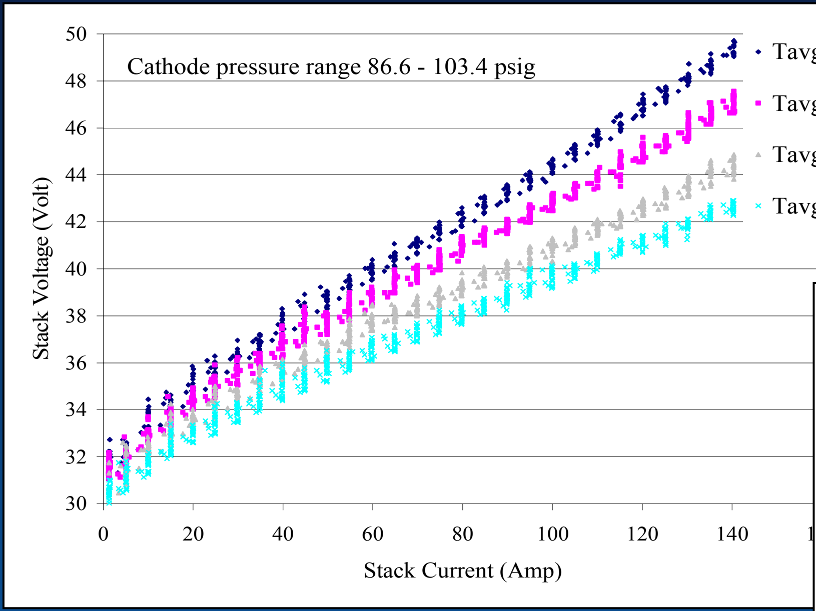


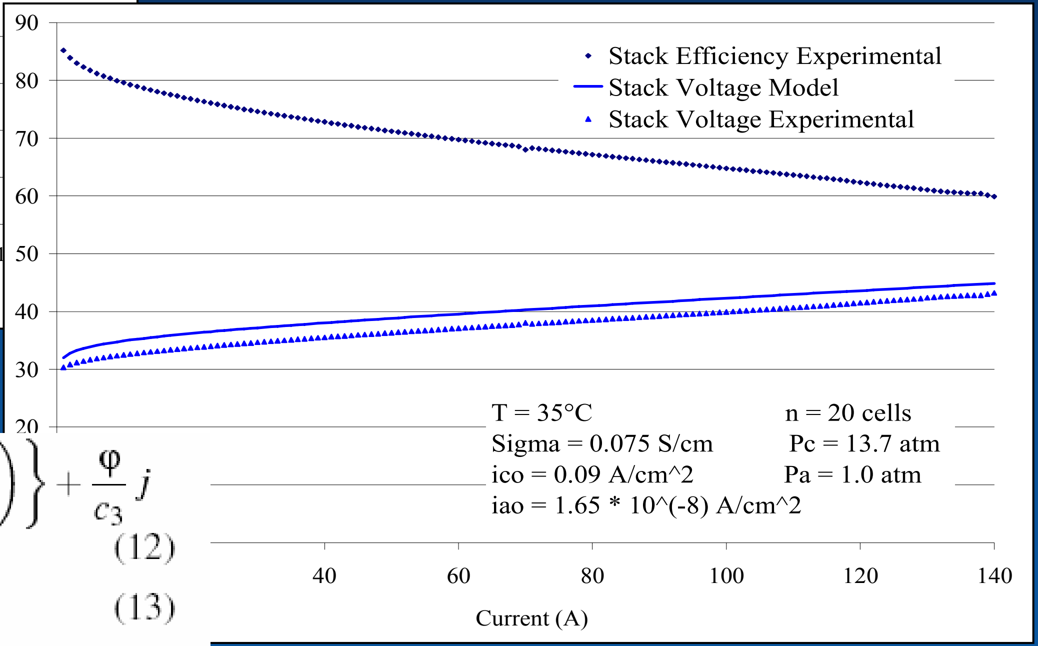


- Impacts on grid (pf, THD)

Modeling

- IV data and electrochemistry to extract stack characteristics





T = 35°C
Sigma = 0.075 S/cm
ico = 0.09 A/cm^2
iao = 1.65 * 10^(-8) A/cm^2

n = 20 cells
Pc = 13.7 atm
Pa = 1.0 atm

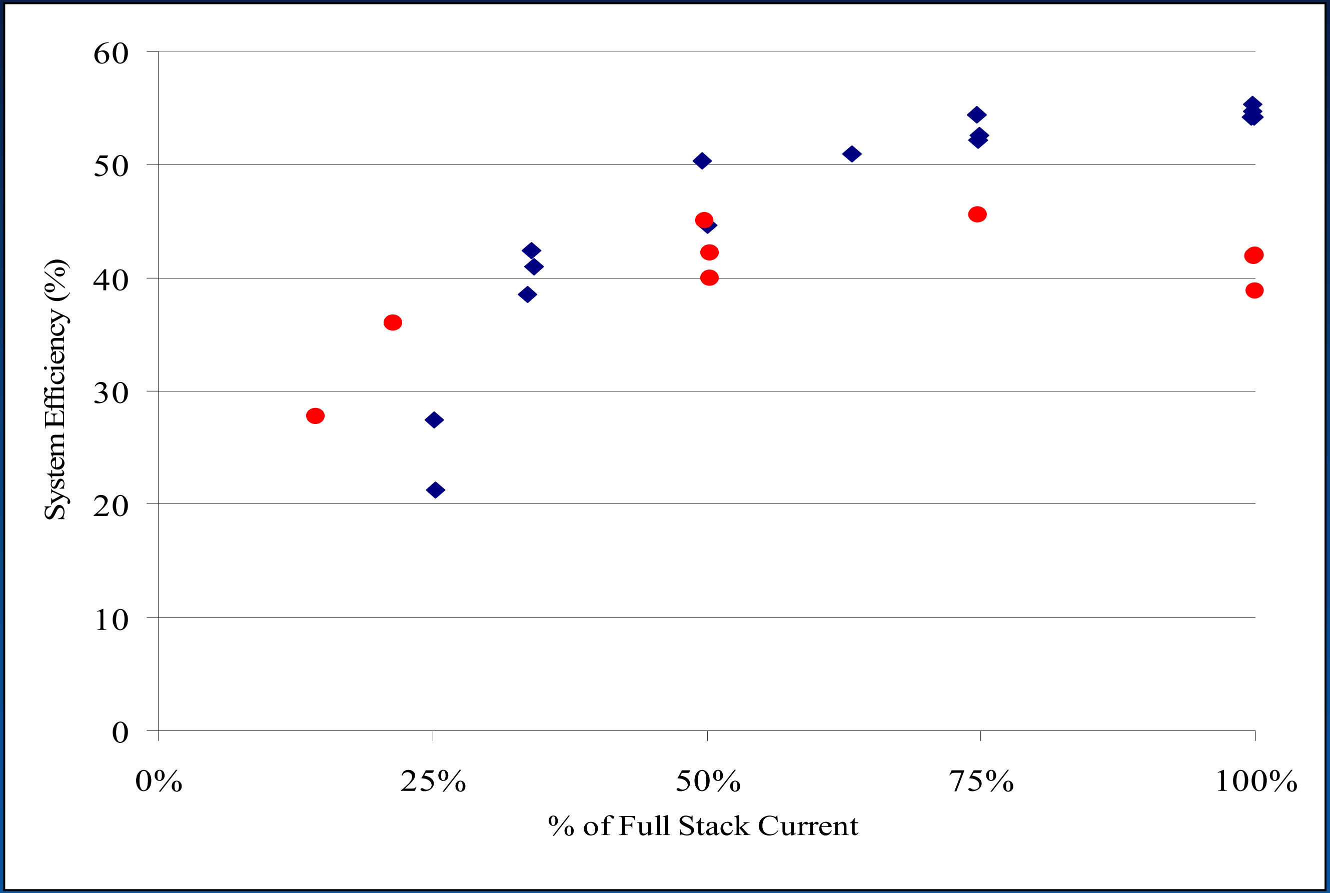
$$E = 1.20 + \frac{RT(I)}{\mathcal{F}} \left\{ \mathrm{Sinh}^{-1}\left(\frac{j}{2c_1}\right) + \mathrm{Sinh}^{-1}\left(\frac{j}{2c_2}\right) \right\} + \frac{\varphi}{c_3} j \quad (12)$$

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

$$c_2 = j_{C,o} = 0.09 \quad (14)$$

$$c_3 = \sigma = 0.075 \quad (15)$$

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

Case 1: Hydrogen Production at the Wind Site

Electricity

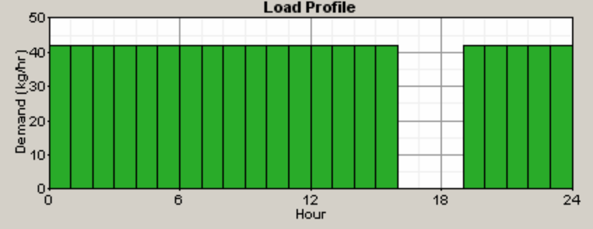
Hydrogen

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

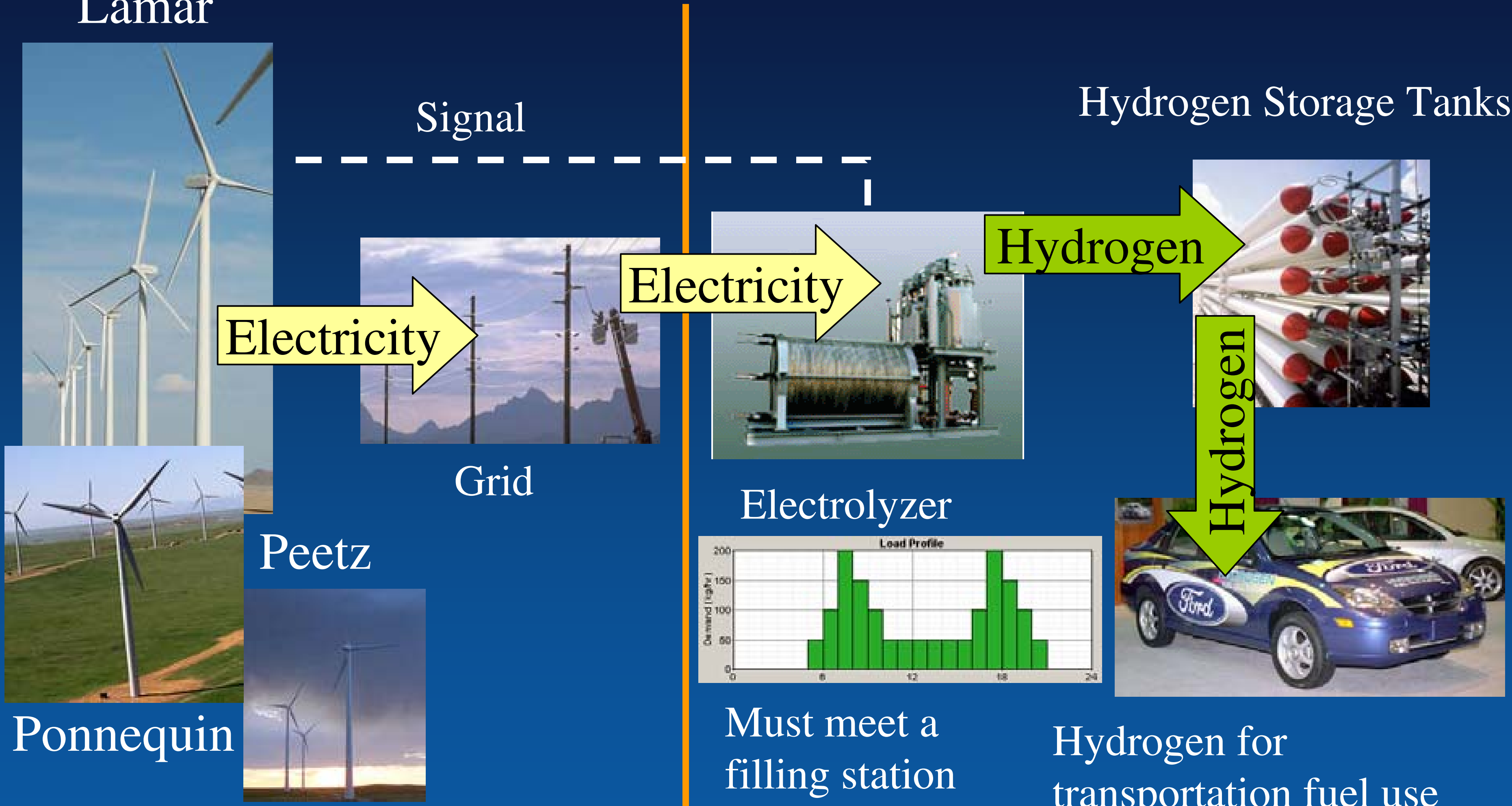
Hydrogen delivery costs are not included

Vestas V82 turbine
- 1.65 MW

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



Case 2: Distributed Hydrogen Production Using Xcel Aggregate Wind Power



Lamar

Signal

Electricity

Grid

Peetz

Ponnequin

Xcel Aggregate Wind

Wind Sites

Electricity

Electrolyzer

Hydrogen Storage Tanks

Hydrogen

Hydrogen

Must meet a filling station demand

Hydrogen for transportation fuel use

Hydrogen Fueling Station

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

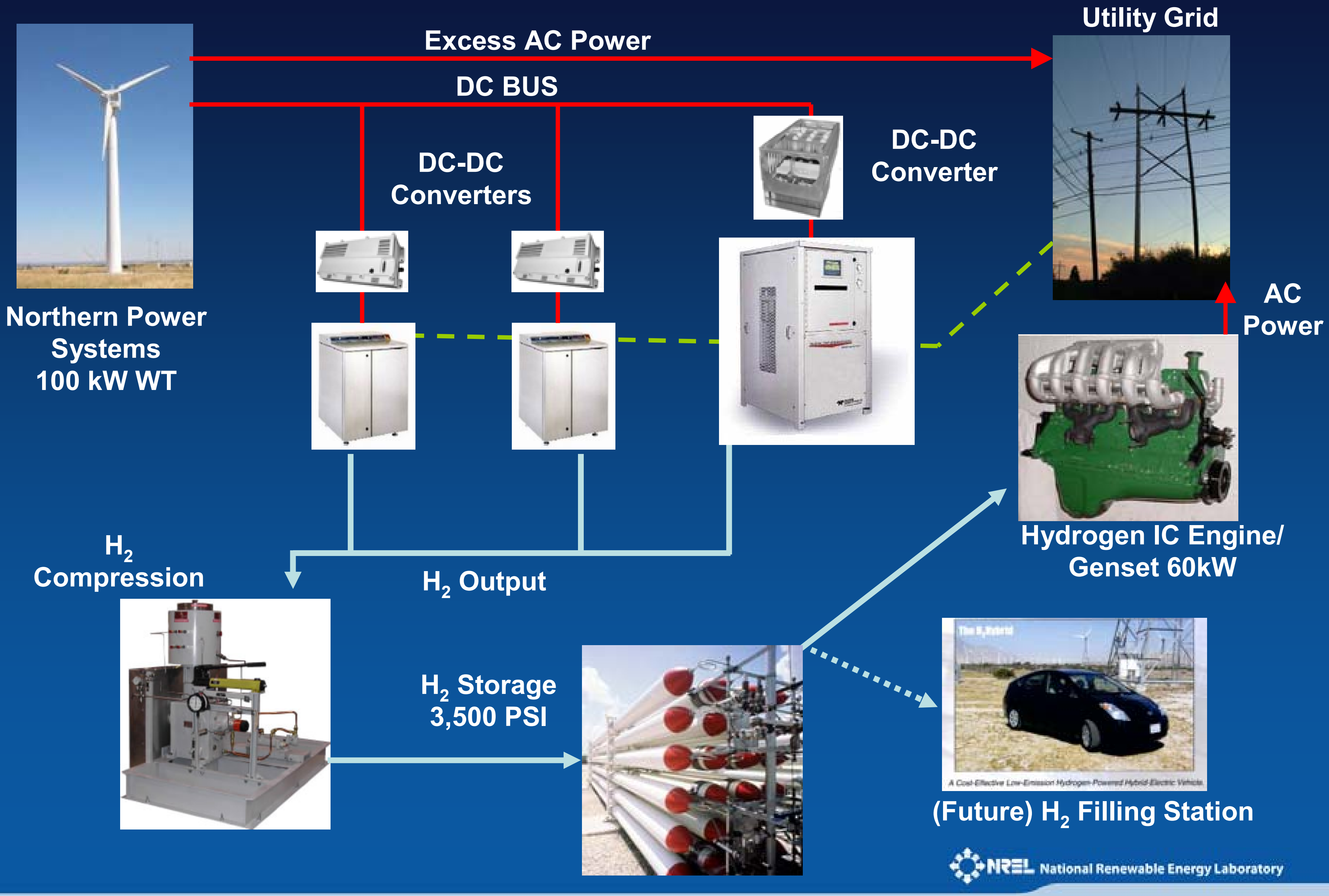
∴Xcel Decides Go!

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



Northern Power Systems
100 kW WT

Excess AC Power

DC BUS

DC-DC Converters

DC-DC Converter

Utility Grid

AC Power

H_2 Compression

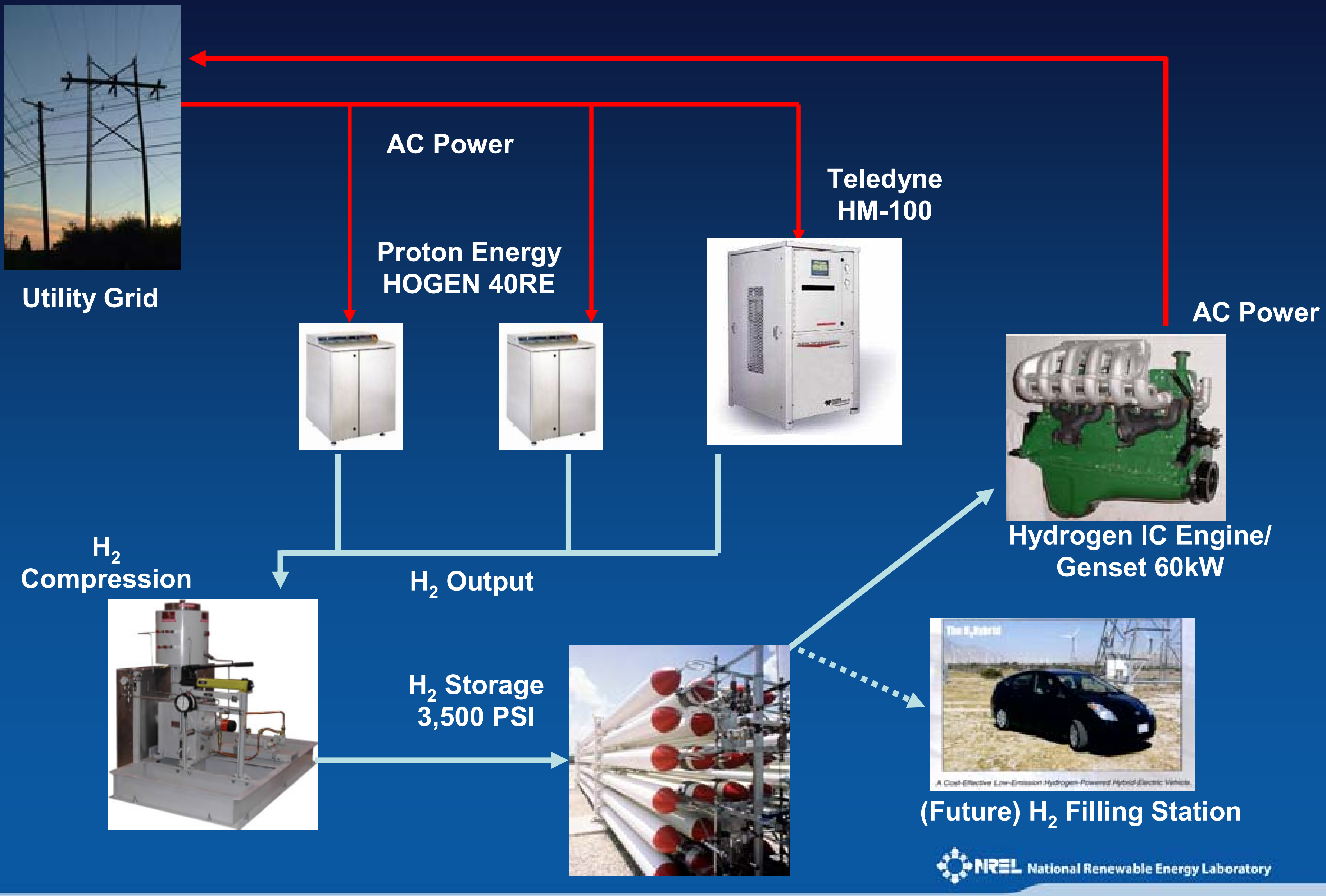
H_2 Output

H_2 Storage
3,500 PSI

Hydrogen IC Engine/
Genset 60kW

(Future) H_2 Filling Station

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

Acknowledgements and References

- Thanks to:
  - Johanna Levene, Ben Kroposki, Bill Kramer and Chris Pink
  - Peter Lilienthal and Tom Lambert for HOMER development and enhancements
  - 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

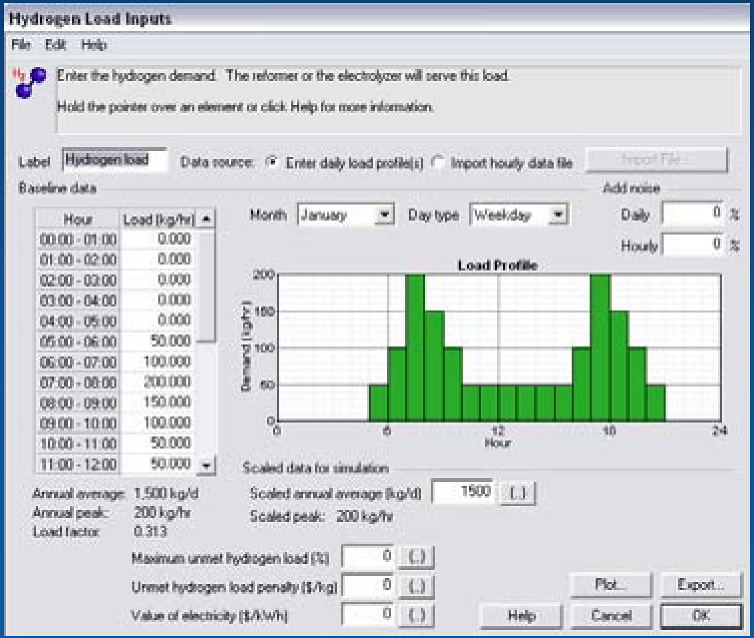
Detailed assumptions are available in Appendix A of Power-Gen paper

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



Enter the hydrogen demand. The reformer or the electrolyzer will serve this load.

Hold the pointer over an element or click Help for more information.

Label: Hydrogen load

Data source: ● Enter daily load profile(s) ○ Import hourly data file

Baseline data

Month: January

Day type: Weekday

Add noise

Daily: 0 %

Hourly: 0 %

Hour	Load (kg/hr)
00:00 - 01:00	0.000
01:00 - 02:00	0.000
02:00 - 03:00	0.000
03:00 - 04:00	0.000
04:00 - 05:00	0.000
05:00 - 06:00	50.000
06:00 - 07:00	100.000
07:00 - 08:00	200.000
08:00 - 09:00	150.000
09:00 - 10:00	100.000
10:00 - 11:00	50.000
11:00 - 12:00	50.000

Annual average: 1,500 kg/d

Annual peak: 200 kg/hr

Load factor: 0.313

Scaled data for simulation

Scaled annual average (kg/d): 1500

Scaled peak: 200 kg/hr

Maximum unmet hydrogen load (%): 0

Unmet hydrogen load penalty ($/kg): 0

Value of electricity ($/kWh): 0

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?