Generation of High-Pressure Hydrogen for Fuel-Cell Electric Vehicles Using Photovoltaic-Powered Water Electrolysis

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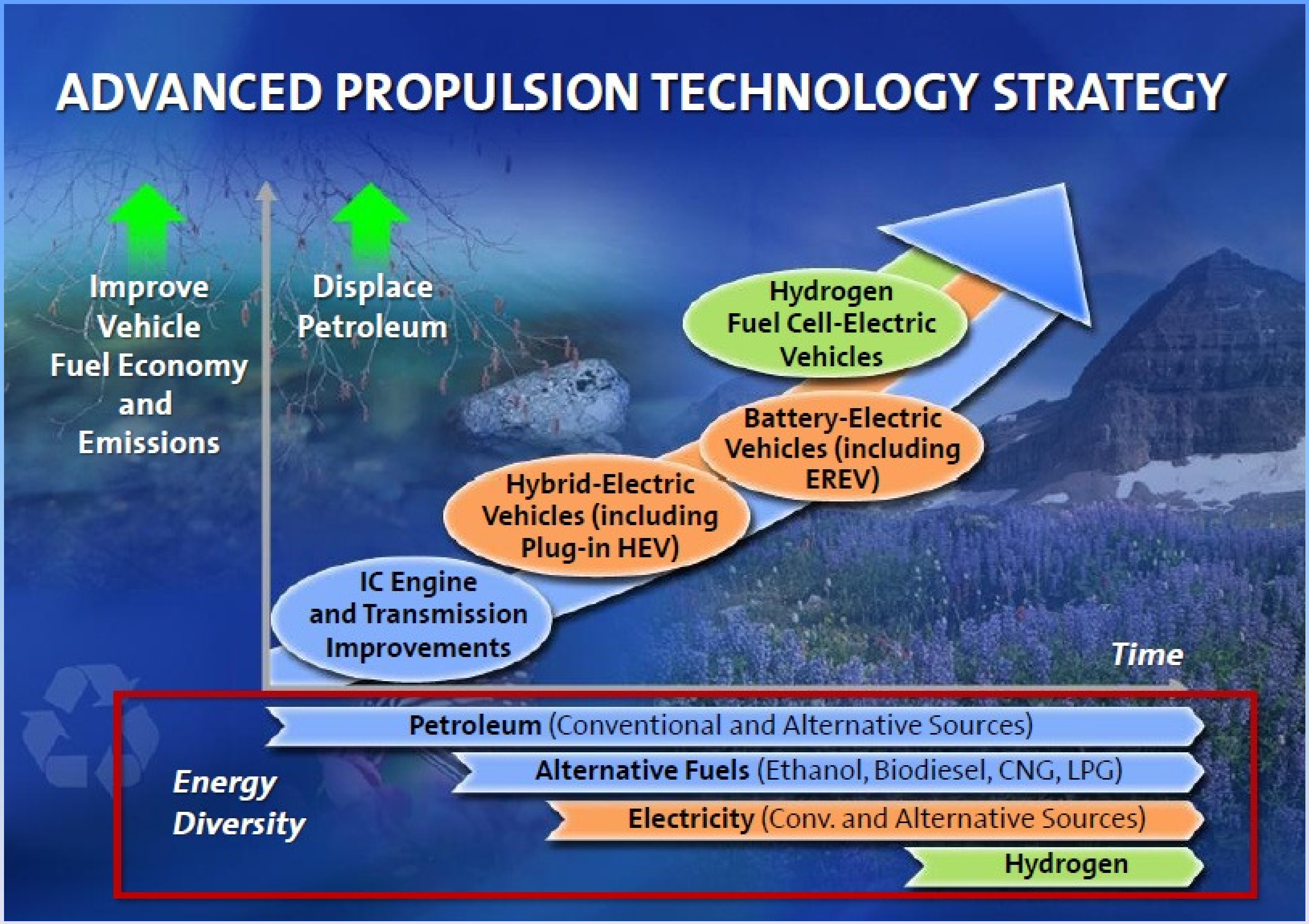
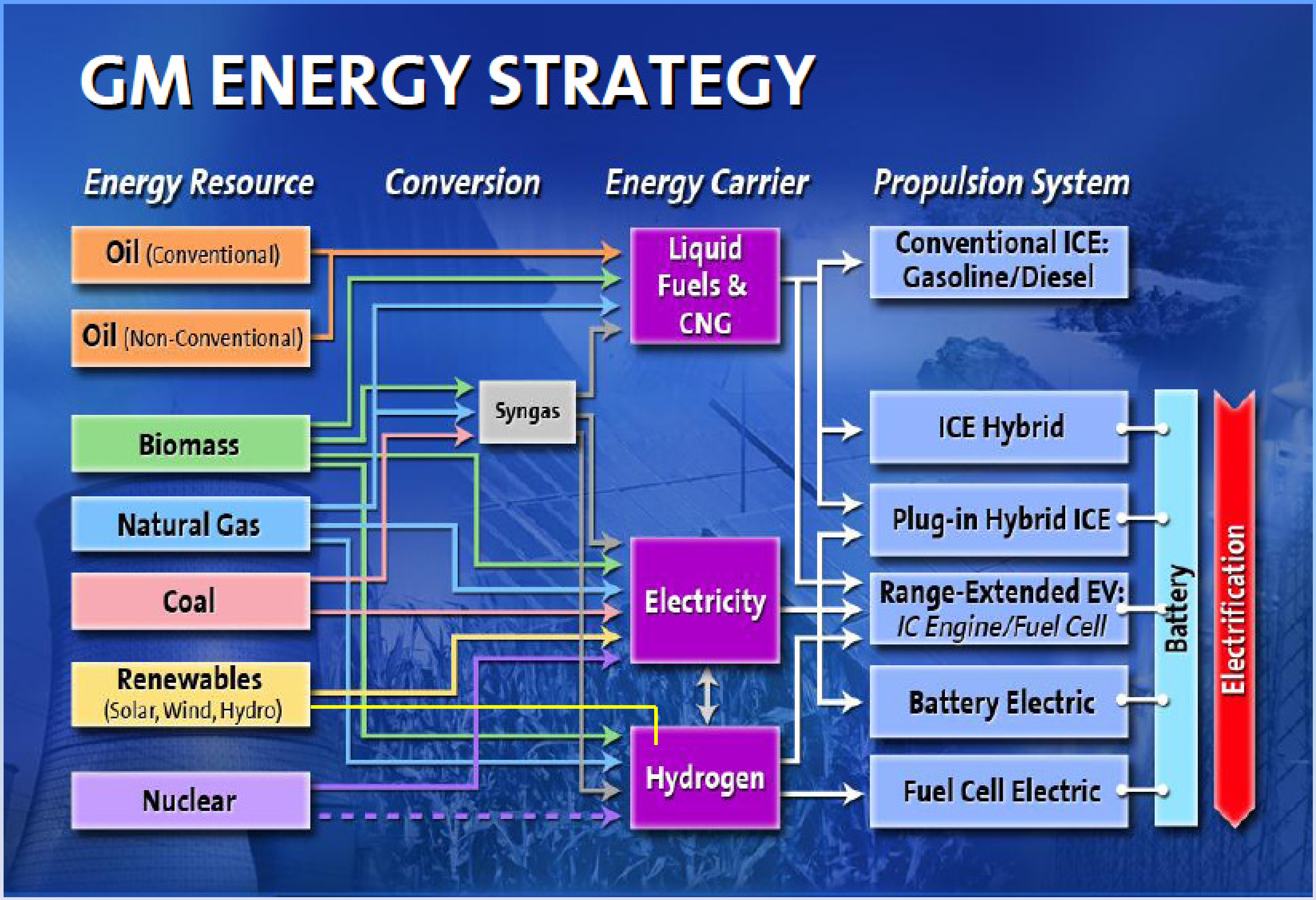
Statement of the Problem

- Future transportation systems need to:
  - Become sustainable
  - Reduce/eliminate pollutant emissions including greenhouse gases
  - Reduce dependence on petroleum
- GM is implementing vehicle powertrain electrification to help achieve these goals
- Solar energy can contribute to this effort
  - Water electrolysis to make hydrogen for fuel cell electric vehicles, FCEV, (topic addressed in this talk)
  - Charge batteries for battery-powered vehicles


ADVANCED PROPULSION TECHNOLOGY STRATEGY
Improve Vehicle Fuel Economy and Emissions
Displace Petroleum
IC Engine and Transmission Improvements
Hybrid-Electric Vehicles (including Plug-in HEV)
Battery-Electric Vehicles (including EREV)
Hydrogen Fuel Cell-Electric Vehicles
Time
Energy Diversity
Petroleum (Conventional and Alternative Sources)
Alternative Fuels (Ethanol, Biodiesel, CNG, LPG)
Electricity (Conv. and Alternative Sources)
Hydrogen

GM R&D


GM ENERGY STRATEGY
Energy Resource
Conversion
Energy Carrier
Propulsion System
Oil (Conventional)
Oil (Non-Conventional)
Biomass
Natural Gas
Coal
Renewables (Solar, Wind, Hydro)
Nuclear
Syngas
Liquid Fuels & CNG
Electricity
Hydrogen
Conventional ICE: Gasoline/Diesel
ICE Hybrid
Plug-in Hybrid ICE
Range-Extended EV: IC Engine/Fuel Cell
Battery Electric
Fuel Cell Electric
Battery
Electrification

Presentation Outline

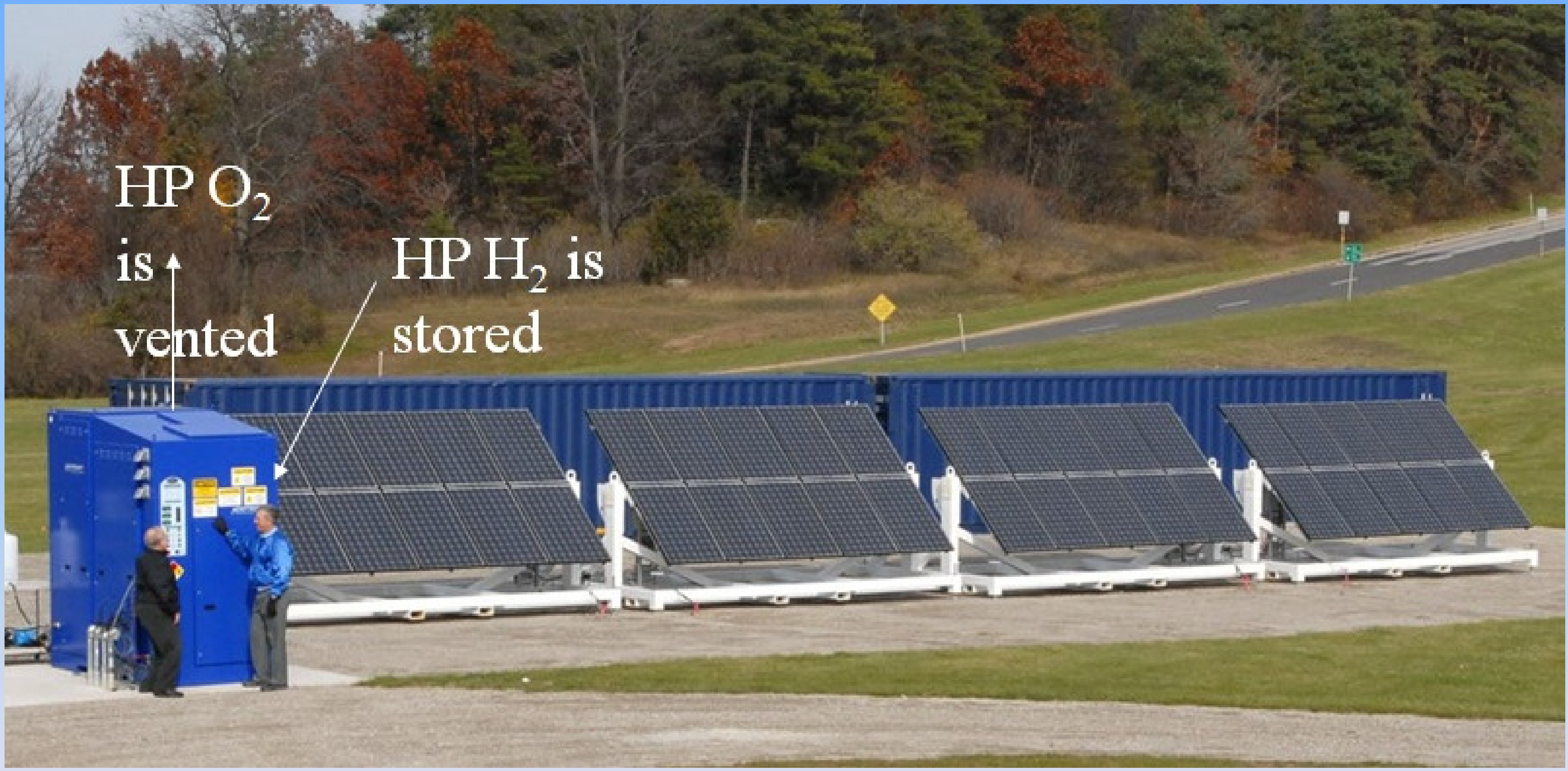
- GM Solar Hydrogen Fueling System
  - Design, initial characterization summary (phase 1)
  - Extended system operation (phase 2)
- Efficiency optimization procedure
- Results of field testing
  - System and sub-system efficiencies
  - System coupling factor (PV-electrolyzer)
    - Derivation of PV maximum efficiency (model)

GM Solar Hydrogen Fueling System

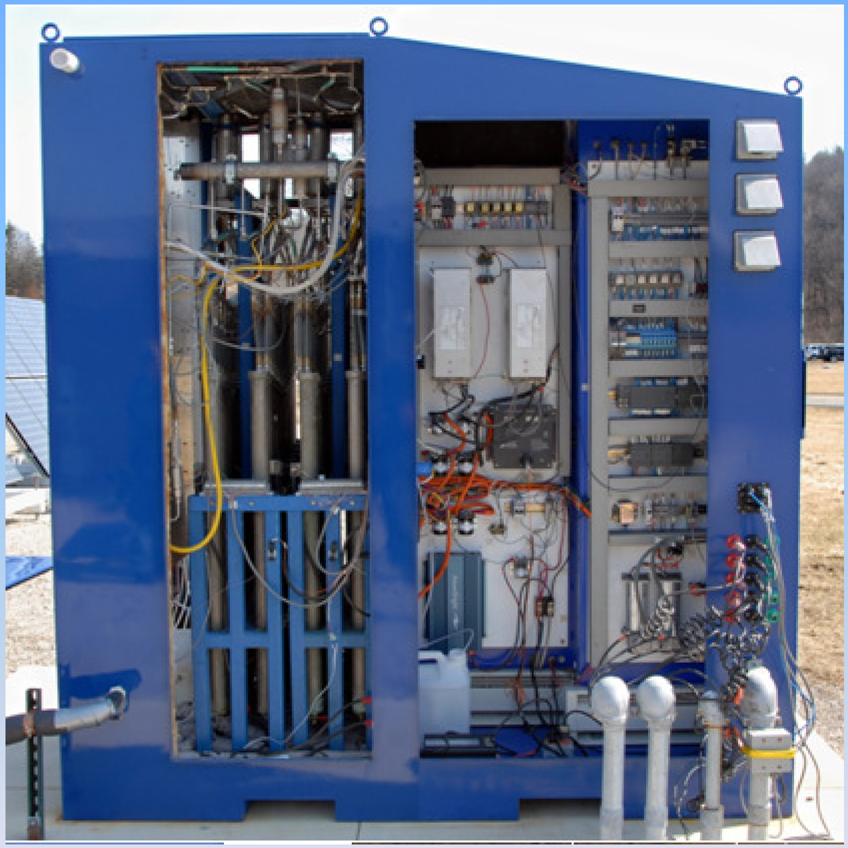
- PV system
  - High efficiency Sanyo modules (~16% efficient)
- Electrolyzer/storage/dispensing system (ESD)
  - High-pressure Avalence electrolyzer (6500 psi)
- Couple PV and ESD systems for optimized solar to hydrogen efficiency
- Proof of concept for home hydrogen fueling

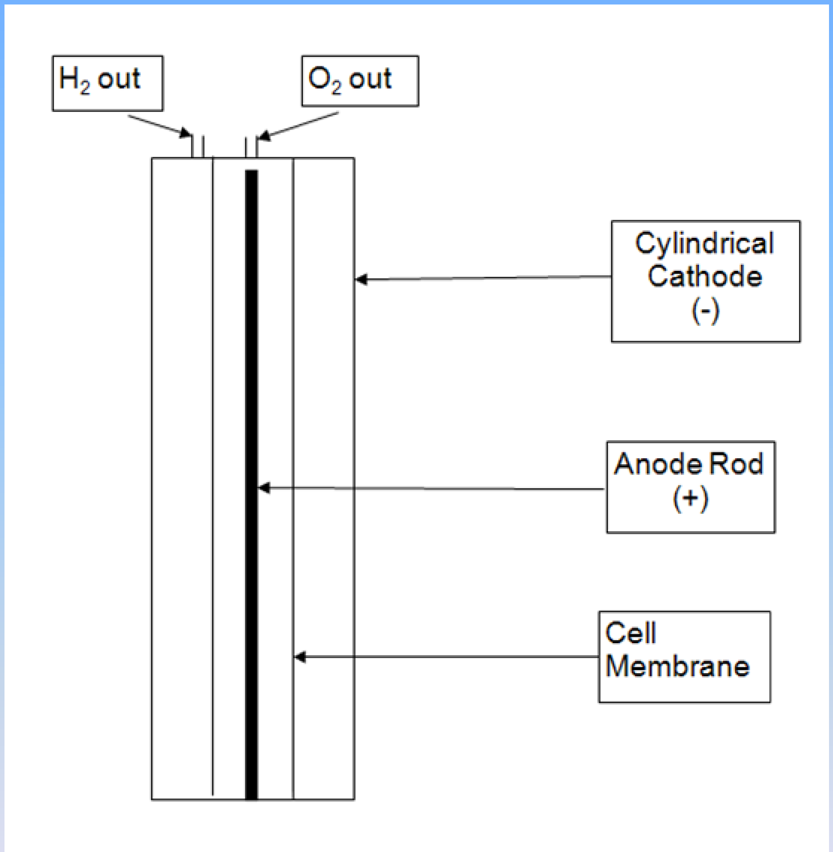
GM Solar Hydrogen Fueling System and Project Driveway FCEV

GM Solar Hydrogen Fueling System

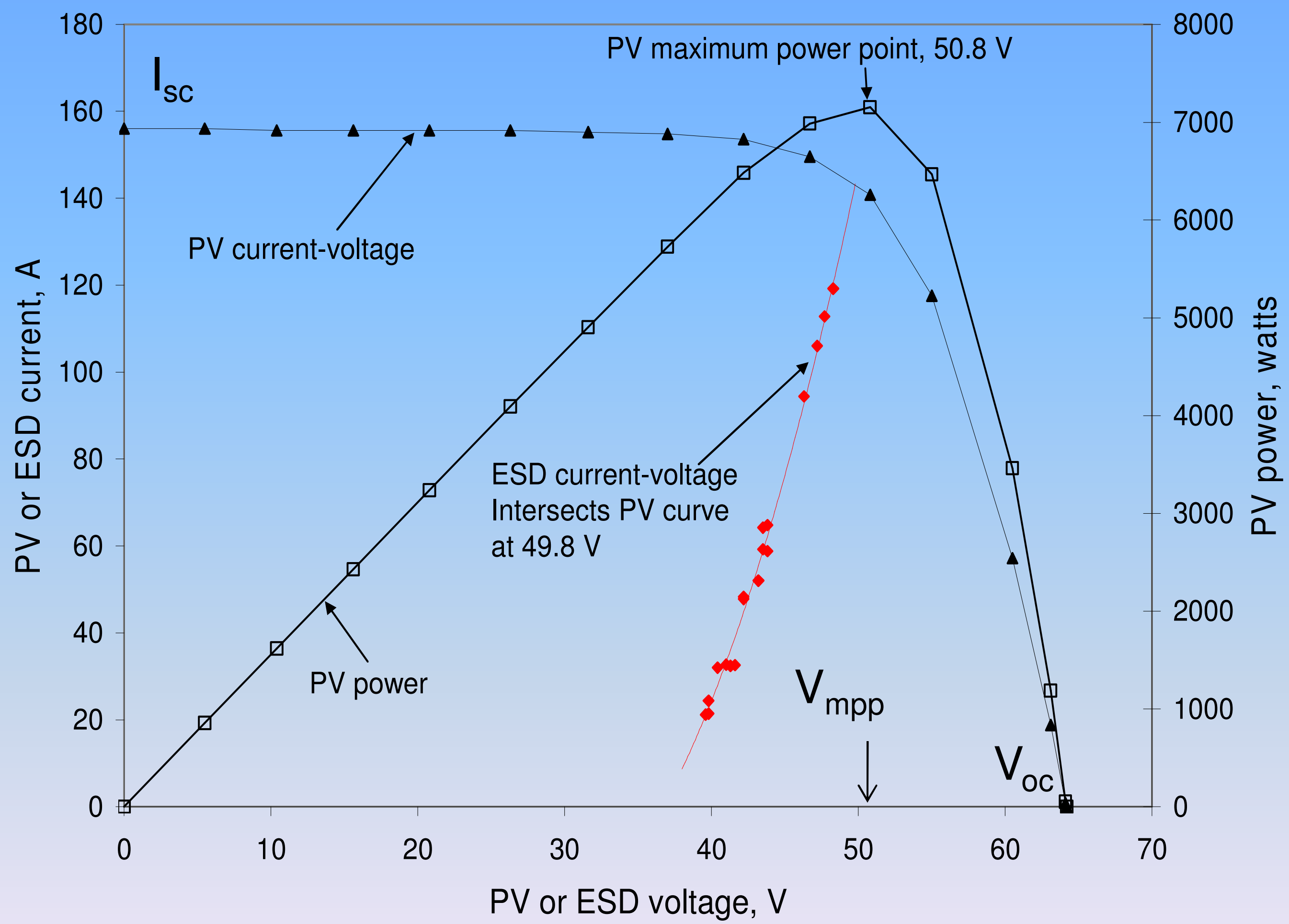


Avalence High-Pressure Electrolyzer





PV-ESD Optimized Coupling Example (phase 1)



Design and Initial Characterization (phase 1 study)

- November 2006 to February, 2007
  - 14 days of data
  - Solar to H_2 efficiency (LHV) = 8.5% at 6500 psi
  - details in IJHE, 33, 2747-2764, 2008 and FCSE, 2007

- Study termination due to gas pressure-system failure
  - H_2 permeation through cell membrane into O_2 resulting in elastomeric hose heating and failure
  - System refurbished for phase 2 study

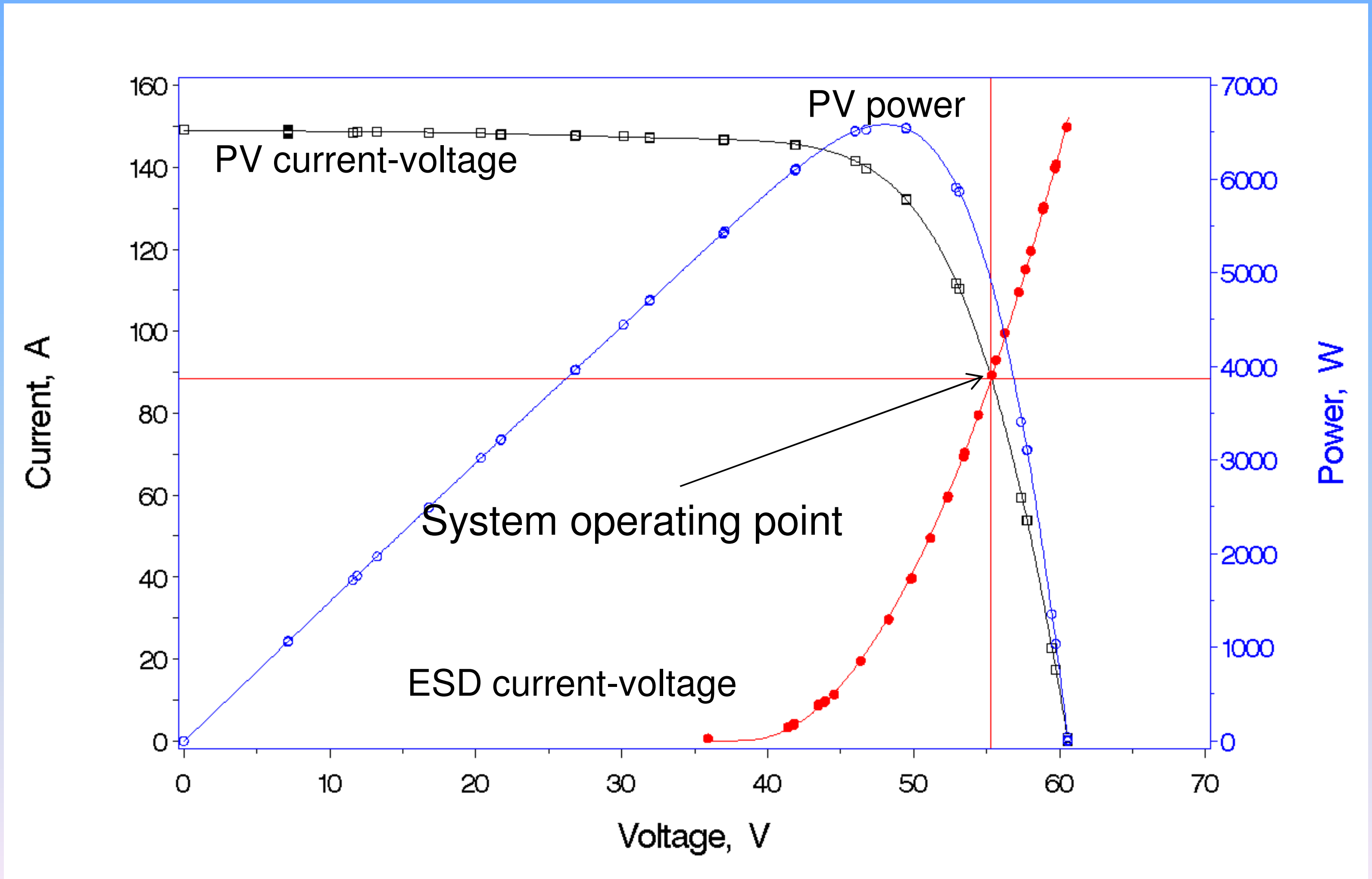
Changes to the ESD for Phase 2 Study

- Electrolysis cell membrane parameters varied by the manufacturer to reduce H_2 permeation
  - Composition
  - Thickness
  - Output pressure
- Due to time constraints we settled for a lower pressure output and slightly lower electrolysis cell efficiency
  - 2000 psi (vs. original design value of 6500 psi)
  - Thicker membrane (slight increase in resistance)

Important Parameters in the Study

- PV efficiency – solar to electric efficiency
- ESD efficiency – electric to hydrogen efficiency
- System efficiency = PV efficiency x ESD efficiency x Coupling Factor
- PV-ESD coupling factor – indicates how efficiently PV energy is utilized by the load

Illustration of the Coupling of the PV and ESD Systems, Phase 2



Coupling Factor Calculation from PV and ESD Current-Voltage Curves

- V_{oper} = 55.3 V
- I_{oper} = 88A
- P_{oper} = 4910 W

- V_{mpp} = 48.0 V
- I_{mpp} = 137.1 A
- $P_{max} = V_{mpp} \times I_{mpp}$ = 6580 W

- Coupling factor = P_{oper}/P_{max} = 0.75

PV-ESD Coupling Factor Characteristics

- Coupling factor = P_{oper}/P_{max}
- Coupling factor = 1 at MPP
- Coupling factor = 0 at V_{oc} and I_{sc}
- $0 \leq$ Coupling Factor ≤ 1

The Coupling Factor is a New Concept

- Coupling factor = PV power hooked to load divided by the maximum PV power
  - Coupling factor = P_{oper}/P_{max}
- We measured the actual PV power hooked to the ESD load, P_{oper}
- So we need a way to calculate the maximum PV power, P_{max}, in order to determine the coupling factor between the PV and ESD systems

Predicting the Maximum PV Power, P_{max}

- Sandia National Laboratories PV modeling
  - V_{mpp} = f(solar irradiance, module temperature)
  - I_{mpp} = f(solar irradiance, module temperature)
  - $PV_{max} = V_{mpp} \times I_{mpp}$
- Derive explicit regression model from Sandia spreadsheet together to predict for V_{mpp}, I_{mpp}, and P_{max} for each solar irradiance and module temperature experienced in the study

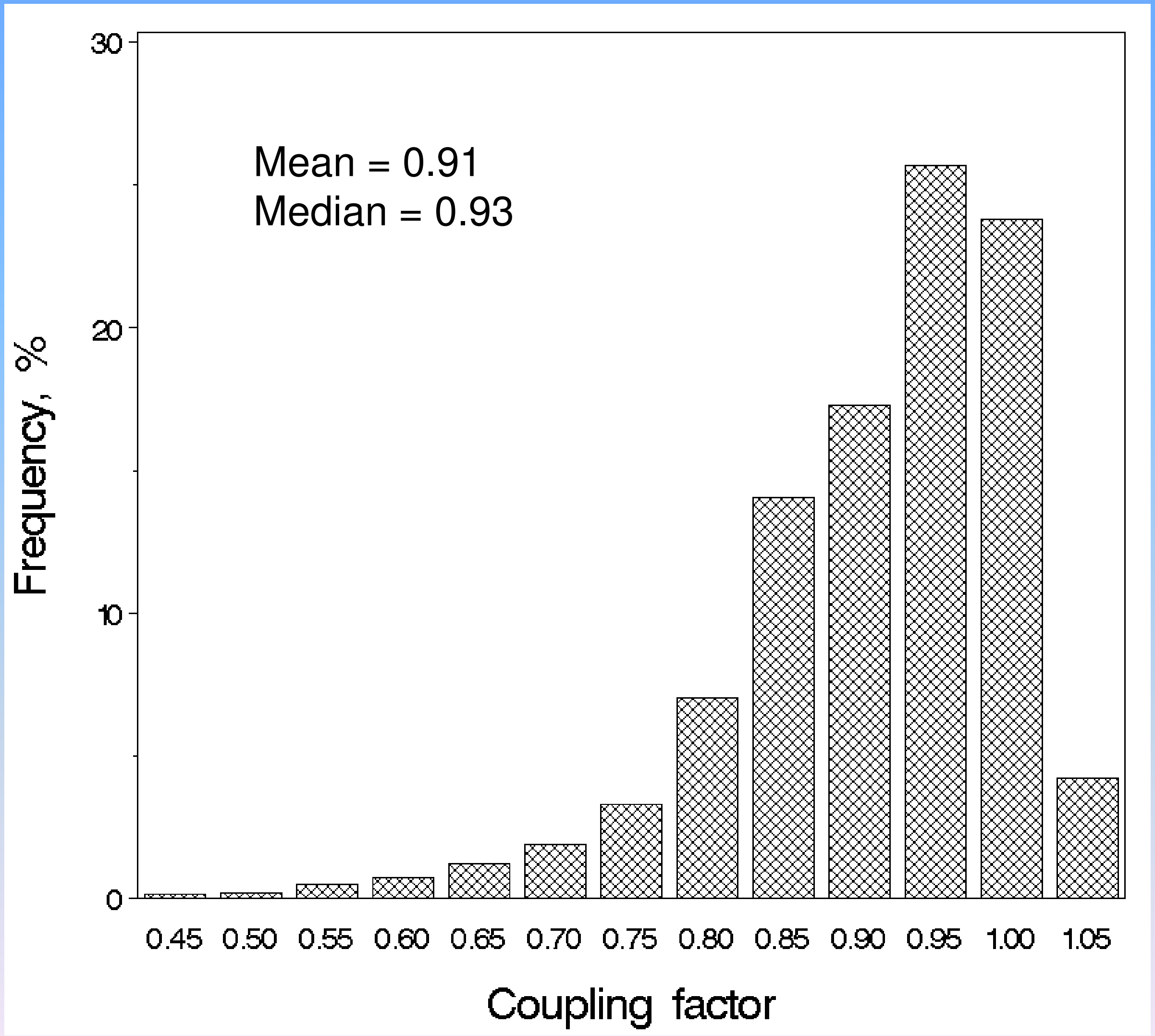
Regression Equations for Predicting the Maximum PV Power, P_{max}

- $V_{mpp} = 9.85 – (0.168 \times T_{module}) + (14.5 \times \ln(\text{irradiance})) – (1.06 \times \ln^2(\text{irradiance}))$

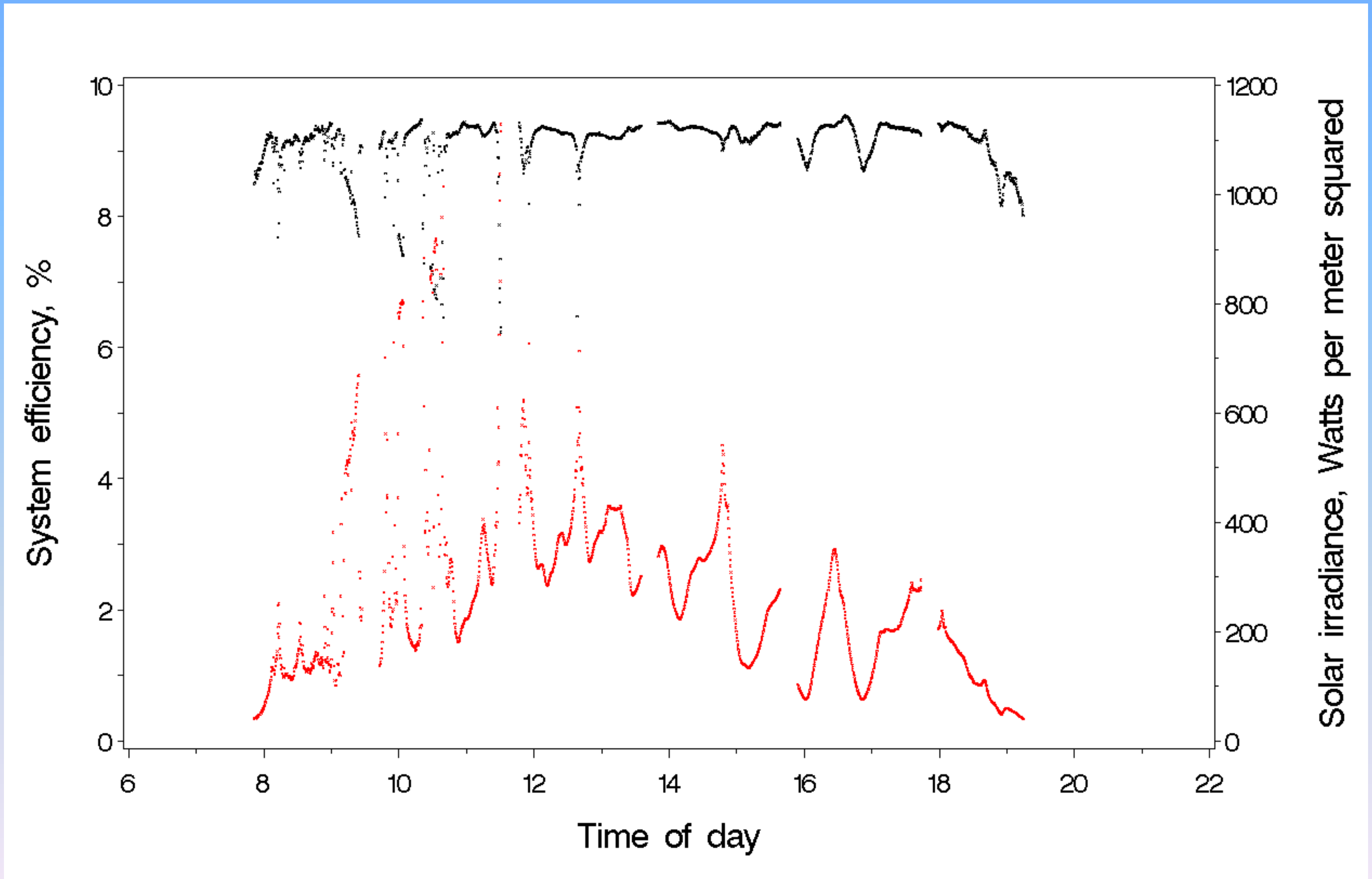
- $I_{mpp} = -0.0051 – (2.17 \times 10^{-4} \times T_{module}) + (3.48 \times 10^{-3} \times \text{irradiance})$

- $P_{max} = V_{mpp} \times I_{mpp}$

Variation in the Coupling Factor



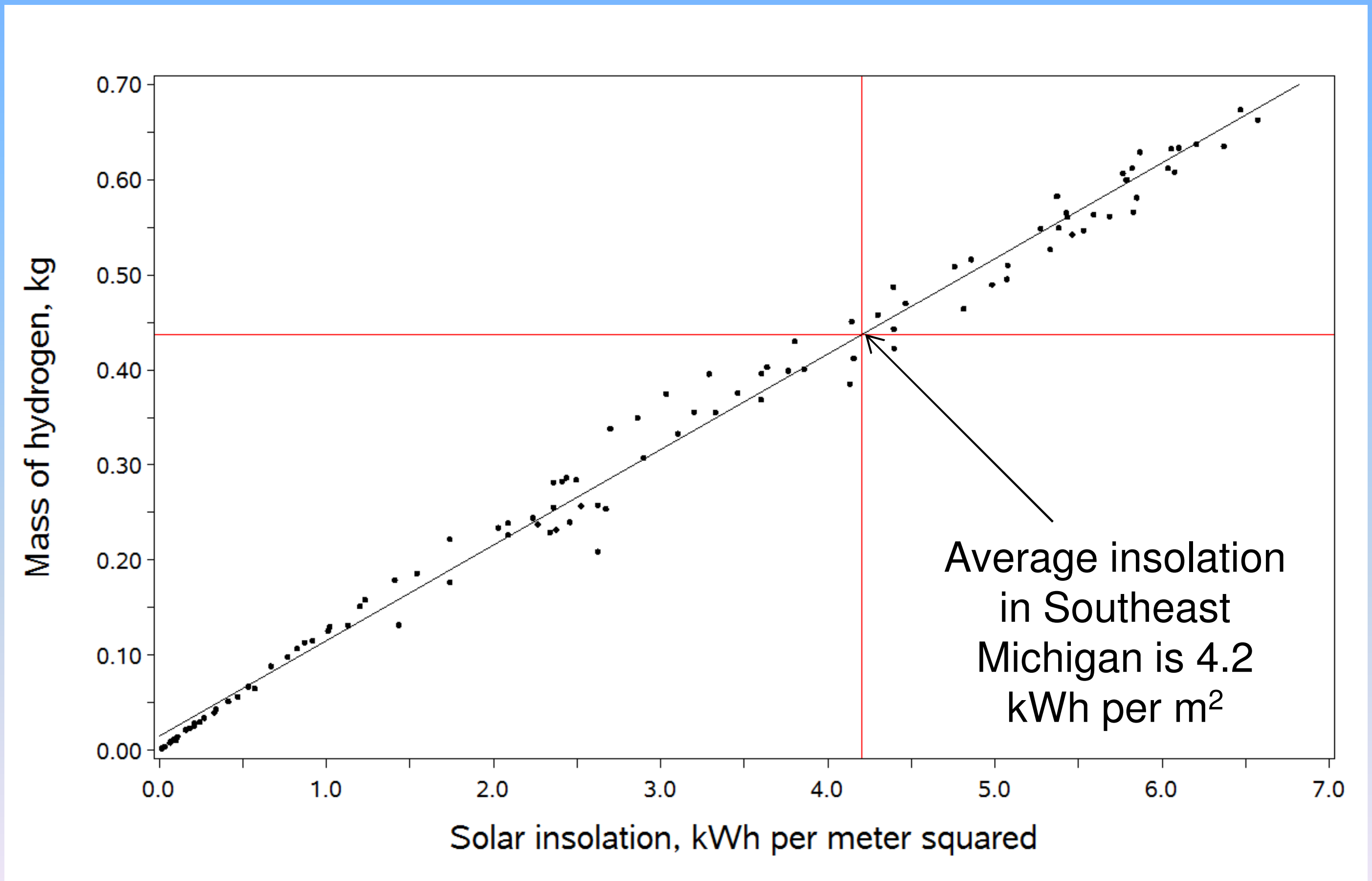
Example of System Response to Sudden Changes in the Solar Irradiance



Overall Results for the 109 Day Test Period

Parameter	Average
PV efficiency, %	13.7
Calculated maximum PV efficiency, %	15.0
Electrolyzer efficiency, %	59.7
System coupling factor	0.91
Solar to H_2 efficiency, % (based on H_2 LHV)	8.2

Hydrogen Mass Generated Each Day versus Solar Insolation



Summary of Results, Phase 2

- System was operated without any major failures
  - 109 days
  - necessary to reduce the H_2 output pressure from 6500 psi to approximately 2000 psi
  - electrolyzer responded well to intermittent solar power
- Solar energy to hydrogen efficiency averaged 8.2%
  - solar to electric efficiency of 13.7%
  - electric to hydrogen (electrolysis) efficiency of 59.7%
  - coupling factor averaged 0.91
- Coupling factor is a new concept for characterizing how well the PV system was matched to the load
  - fraction of maximum PV power utilized
- ~0.7 kg of hydrogen generated on a sunny day