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NATIONAL FUEL CELL RESEARCH CENTER

NFCRC

100% Renewable and Zero Emissions Energy with Hydrogen

Jack Brouwer

March 18, 2021

UCI Solutions that Scale

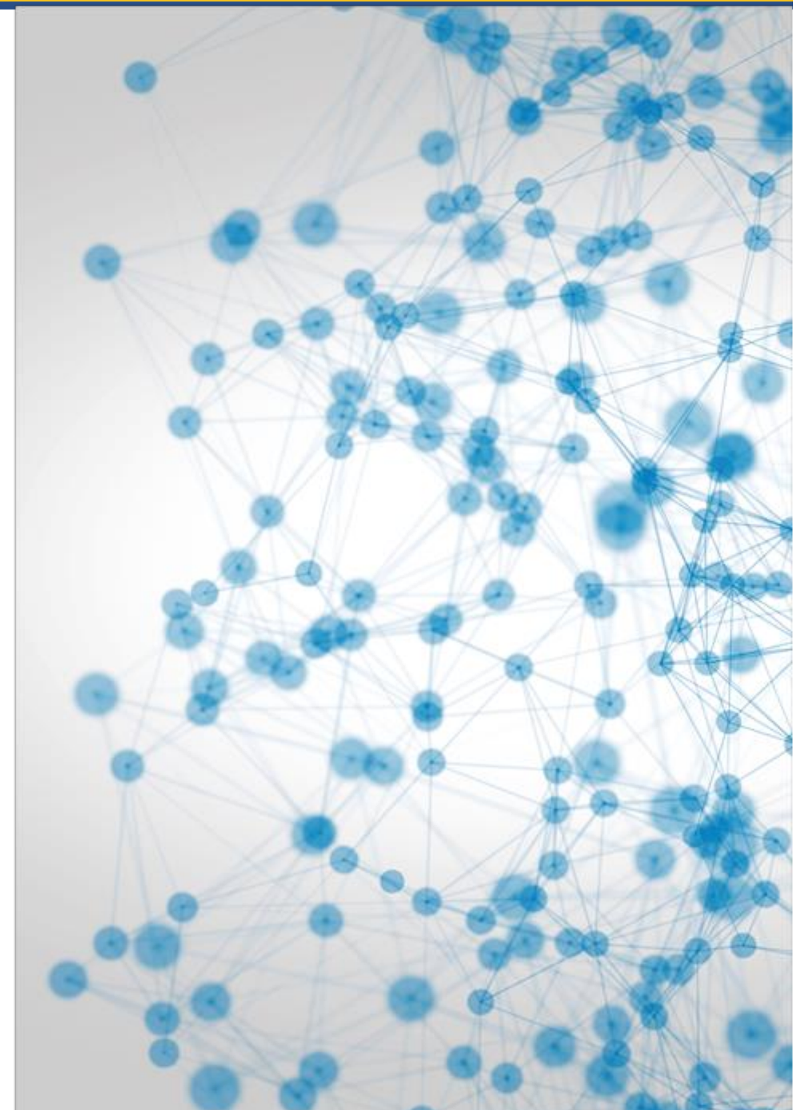
A new campus-wide initiative: UCI Solutions that Scale

Solutions to global environmental problems exist, but they are not always obvious or easy to implement.

Problems and solutions are complex, multidimensional and differently affect stakeholders who have distinct concerns, interests, and priorities—and who often lack trust in each other.

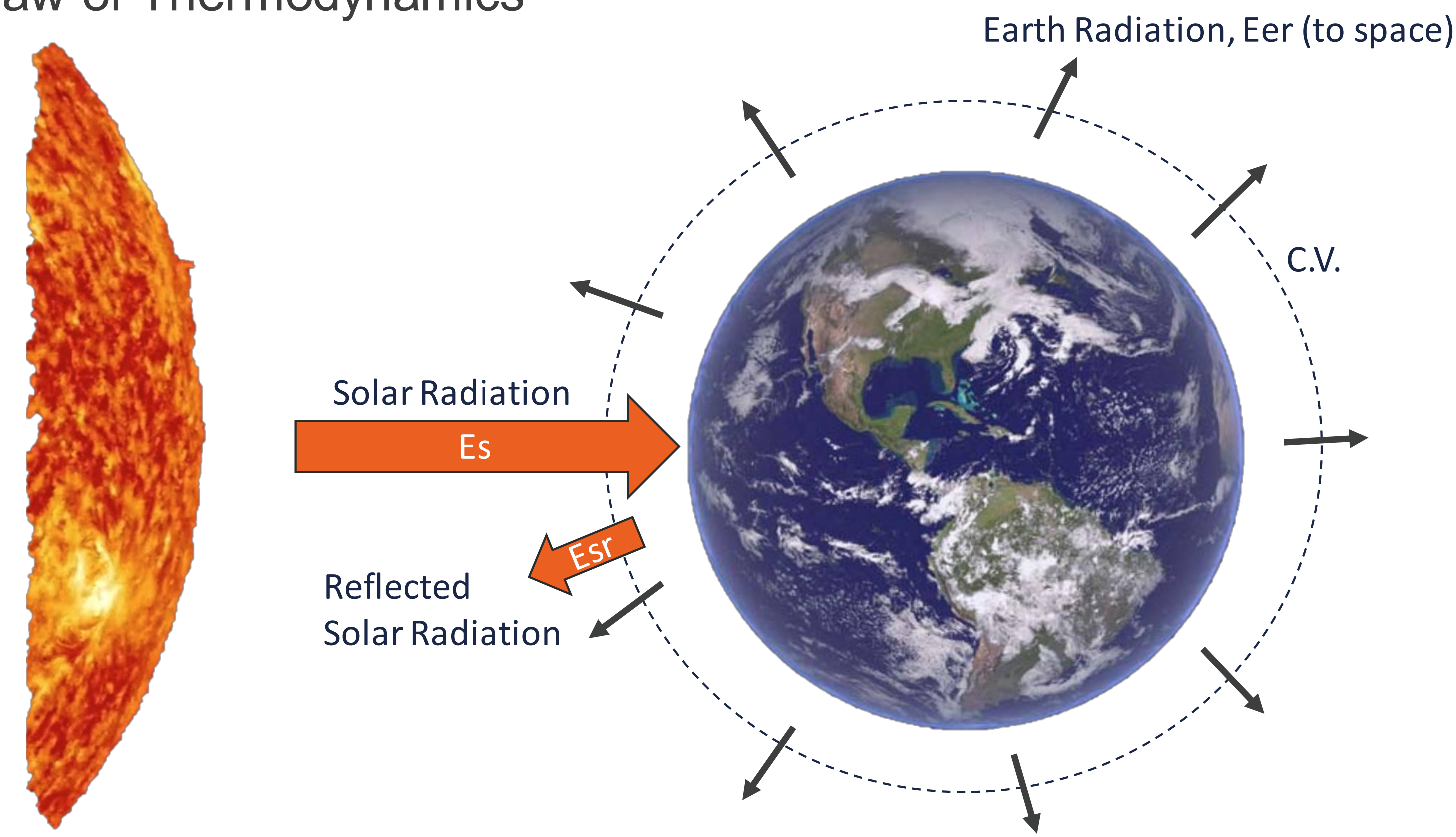
StS is building bridges among researchers, stakeholders and decisionmakers. *Our goal is globally actionable science and broader trust in it.*

Visit our website to learn more and join us:
https://sites.ps.uci.edu/solutions/



Earth Energy Balance

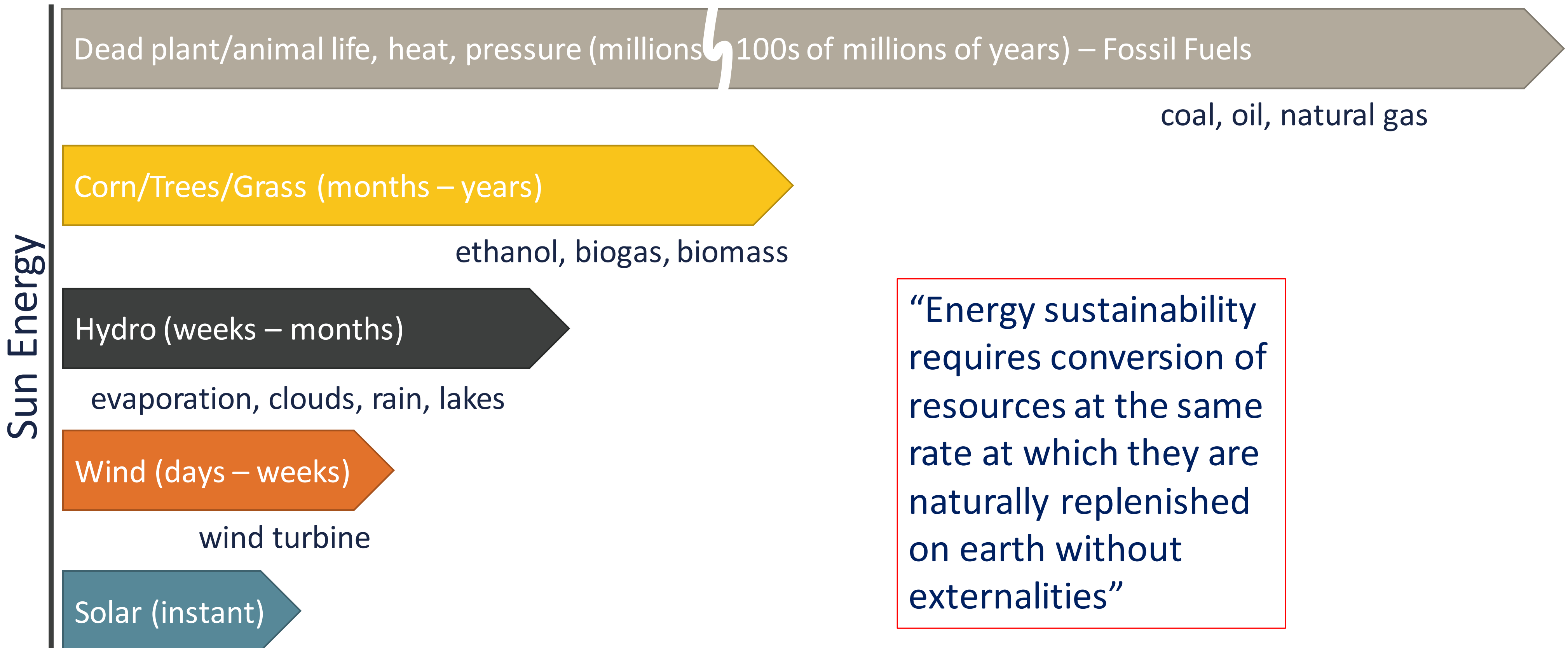
- First Law of Thermodynamics



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

Primary Energy on Earth

All from the Sun!*

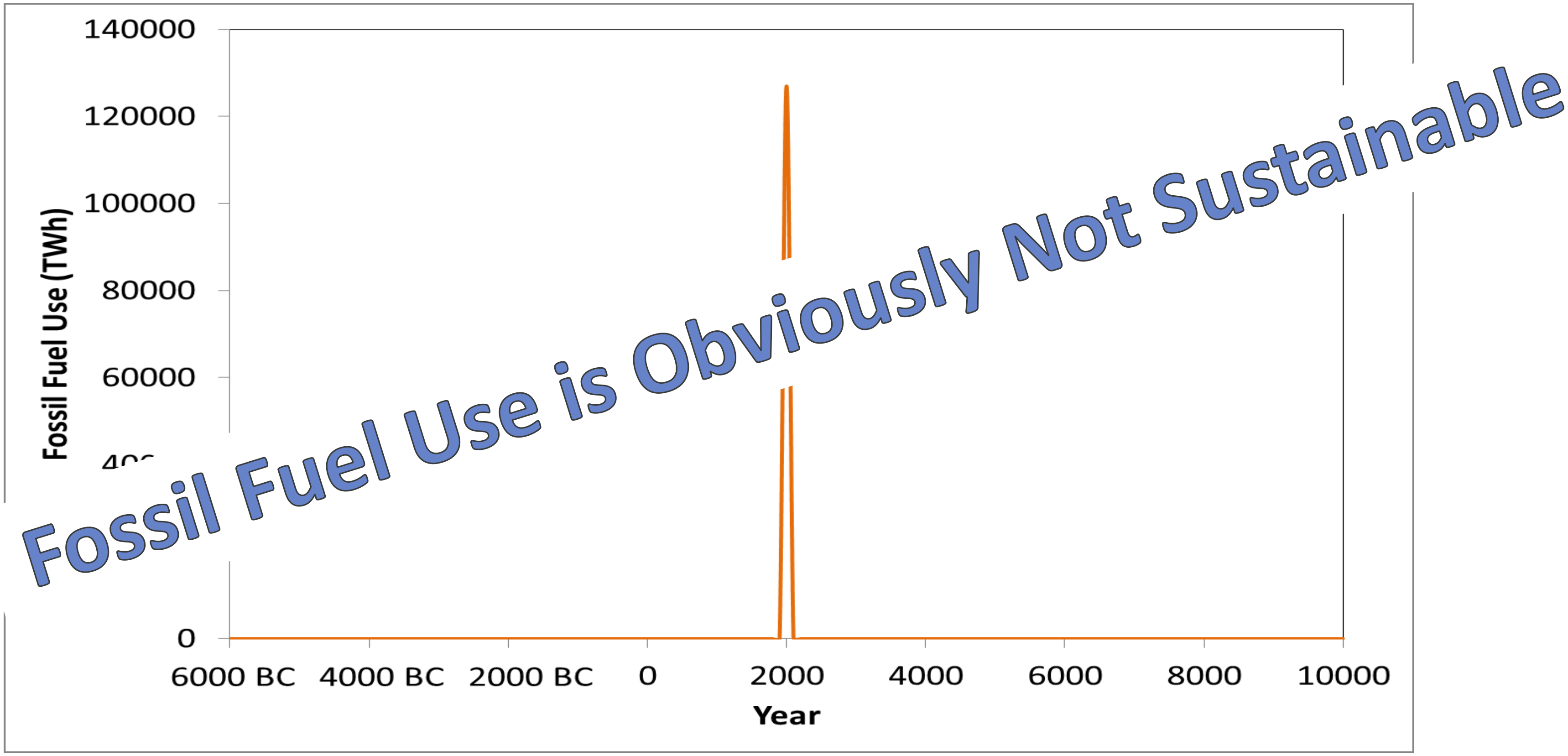


"Energy sustainability requires conversion of resources at the same rate at which they are naturally replenished on earth without externalities"

* except for nuclear

Energy on Earth

Current Practices are Obviously not Sustainable



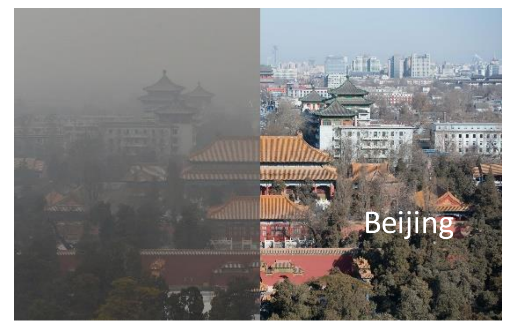
Not Just Renewable – Zero Externalities

Energy Conversion has improved quality of life, but, unfortunately also is the most significant cause of environmental and geopolitical problems (externalities)

- Criteria Pollutant Emissions
  - Acid Rain
  - Particulate Matter
  - Volatile Organic Compounds
  - Nitrogen and Sulfur Oxides
  - Carbon Monoxide
  - …

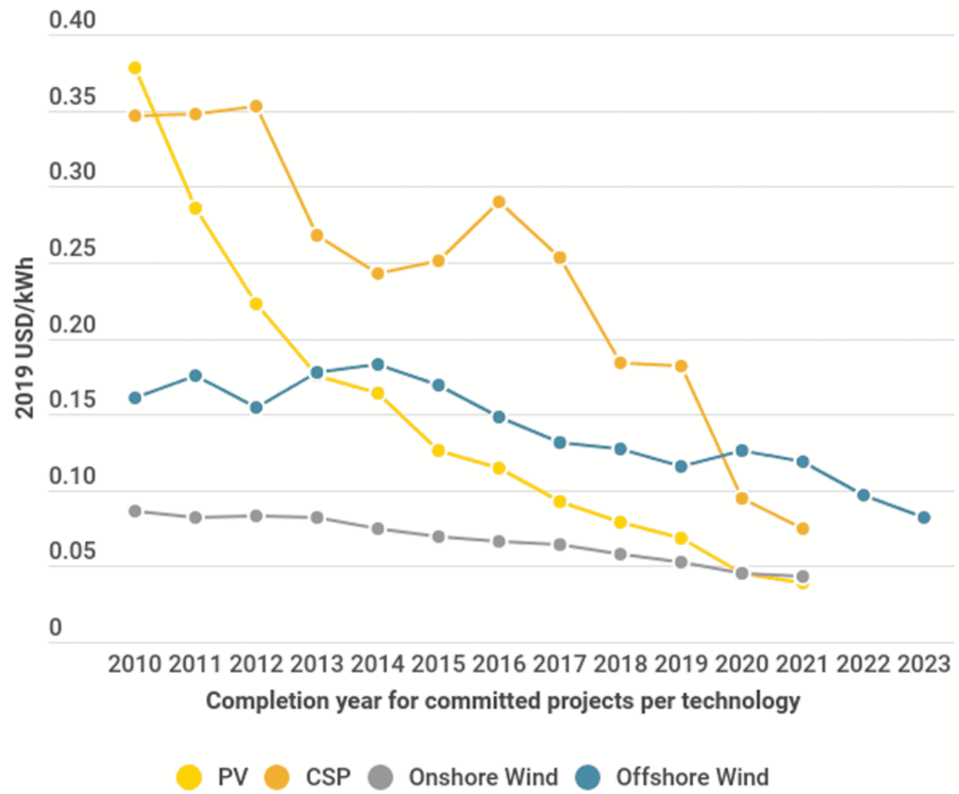
Serious Health and Air Quality Consequences

- Greenhouse Gas Emissions
  - Carbon dioxide, methane, nitrous oxide, …
- Resource recovery damage (e.g., mines)
- Regional resource depletion – geopolitical dependencies
- Overall primary energy resource depletion – not sustainable



Renewable Energy Conversion (Solar & Wind)

Good News! Solar & wind power, (and battery) costs have dramatically fallen



From: IRENA, www.irena.org/newsroom/pressreleases/2020/Jun, 2020

Popular Thinking & Arguments

<u>Main Strategy</u>:

- 100% renewable (solar, wind, geothermal, …) power generation
- Electrify ~~all~~ end-uses
- Use batteries to handle **some** intermittency on grid & for **some** end-uses

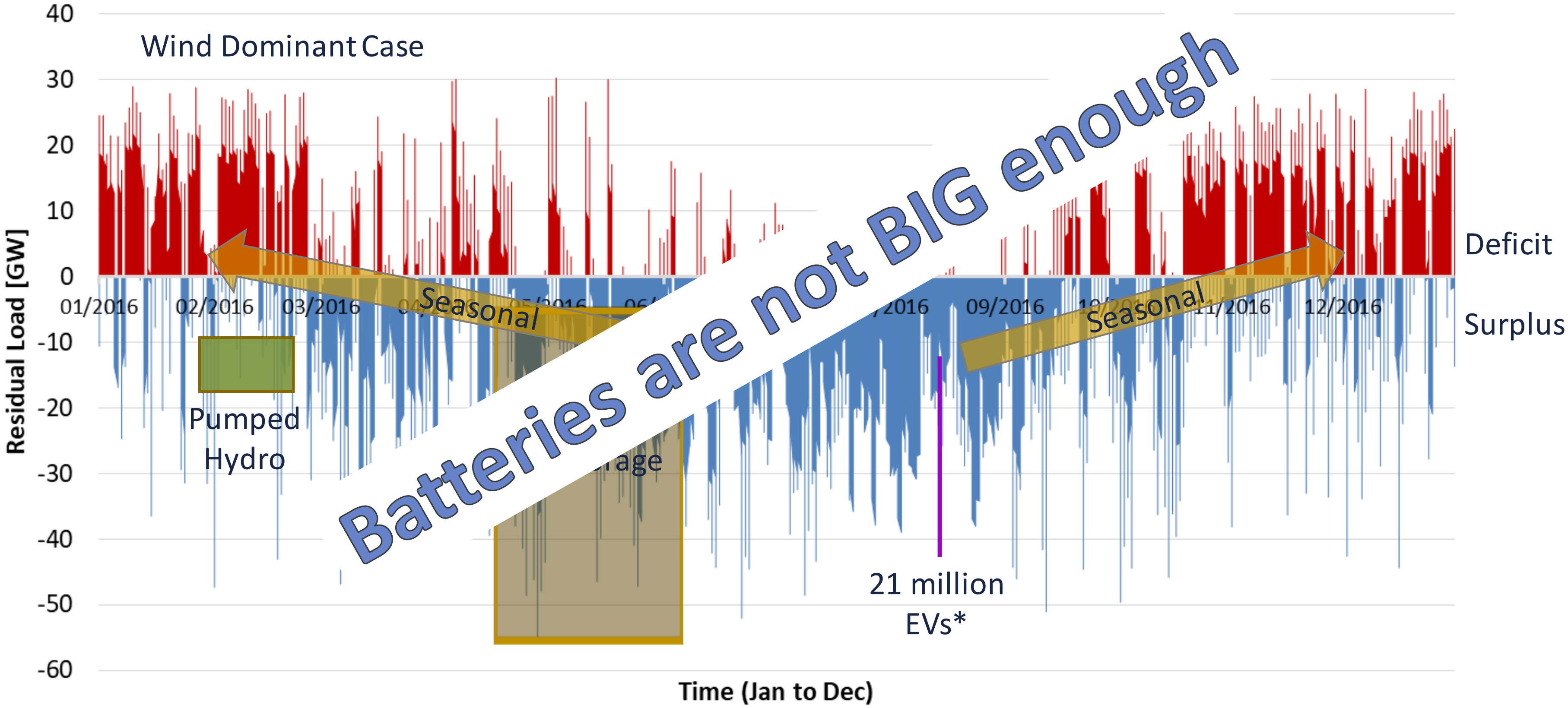
<u>Arguments against hydrogen & fuel cells:</u>

- Most hydrogen today is made from fossil fuels (natural gas)
- Making hydrogen from water & electricity is less efficient than charging a battery
- Making electricity from hydrogen in a fuel cell is less efficient than a batterv (i.e., round-trip efficiency is lower than a battery **except for long duration storage!)**
- Hydrogen is difficult to store and move around in society **compared to fossil fuels!**

I agree with most of this!

Subtly untruthful - Not the whole story

Amount of Storage Required for 100% Renewable – CA



* Nissan Leaf Equiv. – 62 kWh

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Saeedmanesh, A. Mac Kinnon, M. Brouwer, J., Current Opinion in Electrochemistry, Vol. 12, pp. 166-181, 2018

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Energy Storage Need - World

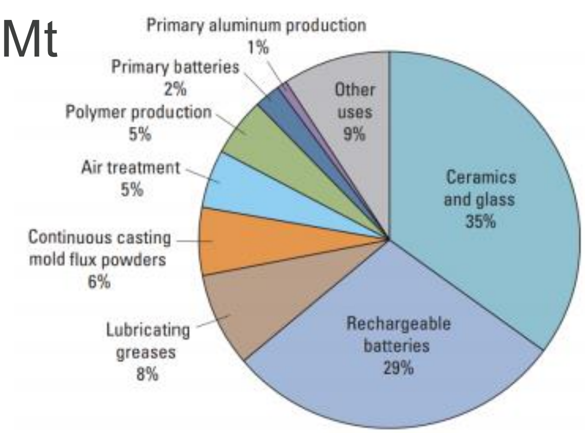
Simulate meeting of total world energy demand w/ Solar & Wind

	Solar contribution	Wind contribution	Consumption and storage ratio	Consumption (TWh)	Storage (TWh)
Africa	0.70	0.30	8.39	9.1[illegible]	1,088
America	0.45	0.55	7.83	[illegible]	4,919
Asia	0.50	0.50	7.95	[illegible]	10,178
Europe	0.30	0.70	7.50	[illegible]	3,592
Oceania	0.50	0.50	[illegible]	[illegible]	205
TOTAL				[illegible]	**19,981 TWh**

[...S. Thesis, 2018]

There is not enough lithium or cobalt in the world

- To build one Li-ion batter[...] Co: 25,815 Mt
- World Li resources: [...]
- World Co resou[...]al), 120 Mt (ocean floor)
- > 60% of Co com[...] Democratic Republic of Congo



Source: U.S. Geological Survey, 2018

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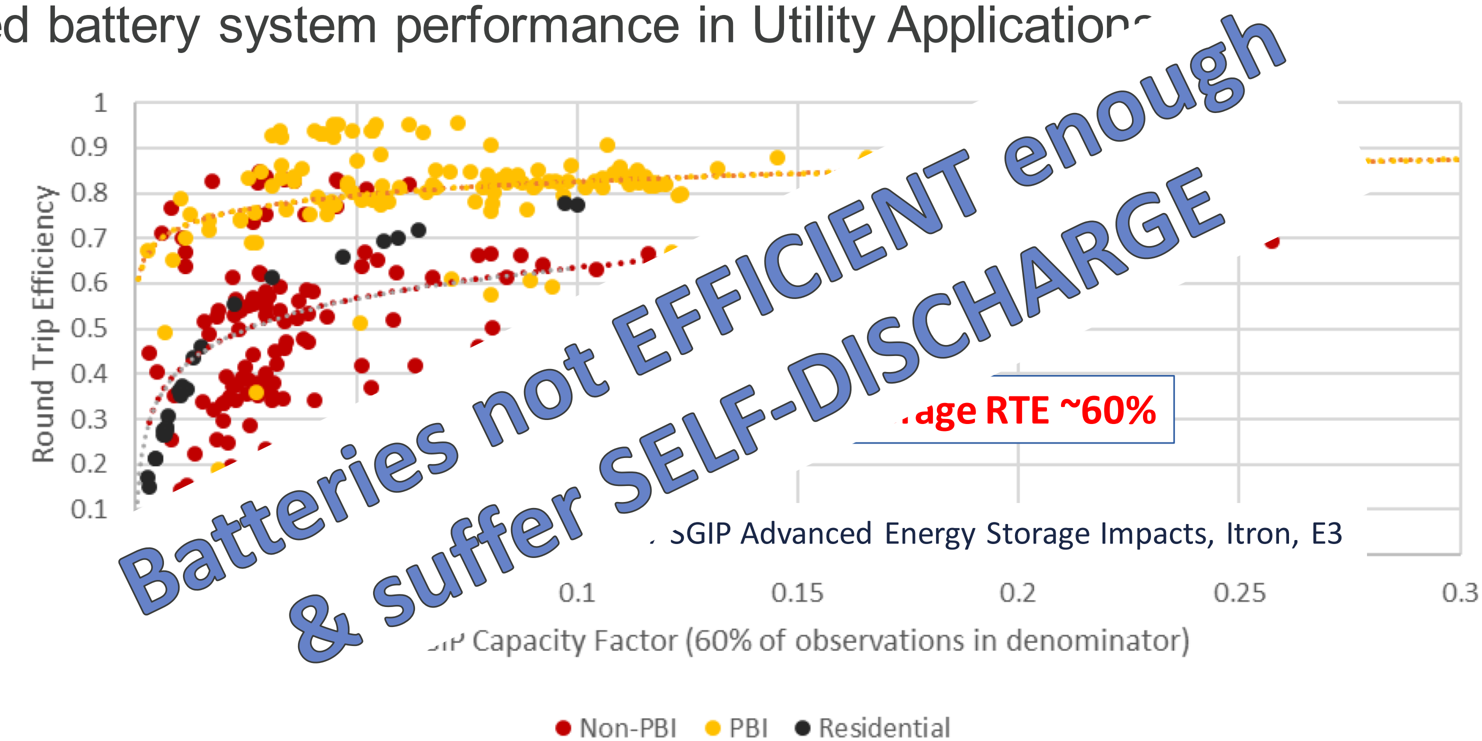
Lithium-Ion Battery Measured Performance

Round-Trip Efficiency (>90% in Laboratory Testing)

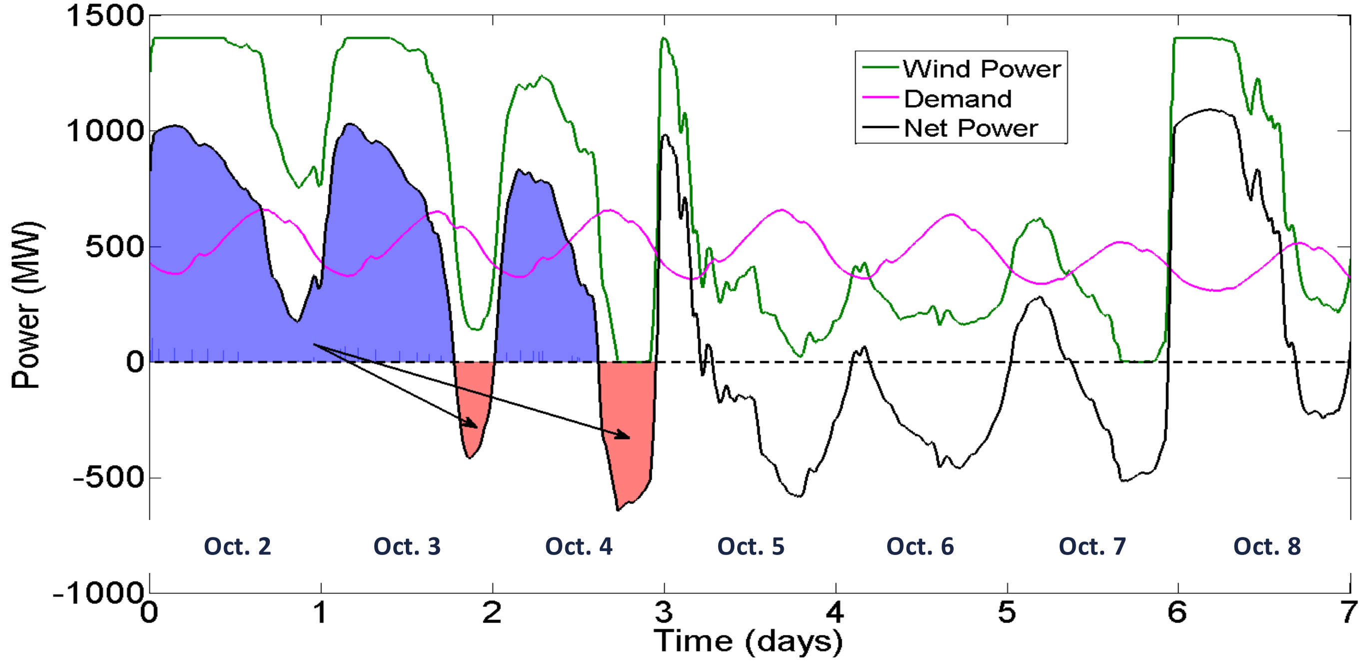
- Measured battery system performance in Utility Applications



- Self-Discharge (the main culprit), plus cooling, transforming, inverting/converting, ...

Hydrogen Energy Storage Dynamics

- Hydrogen Storage complements Texas Wind & Power Dynamics

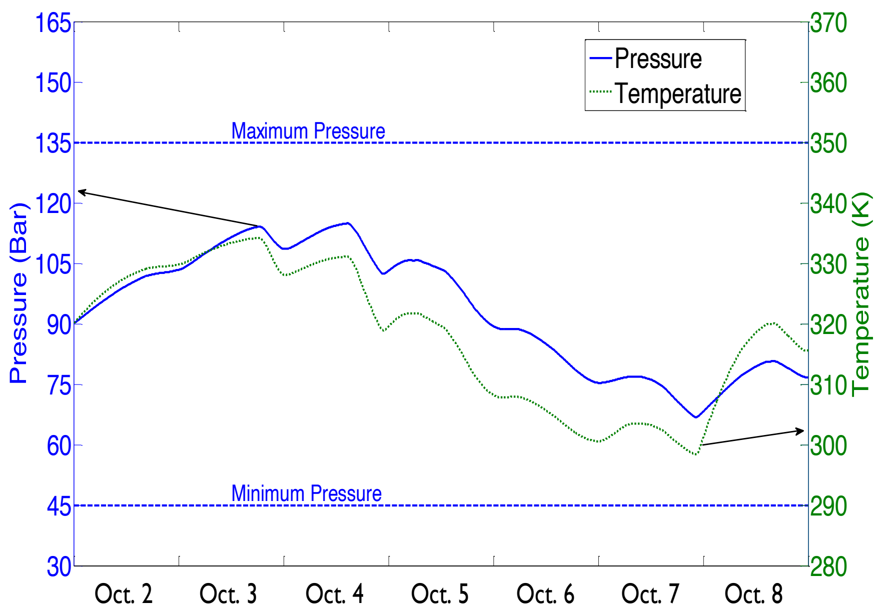


- Load shifting from high wind days to low wind days
- Hydrogen stored in adjacent salt cavern

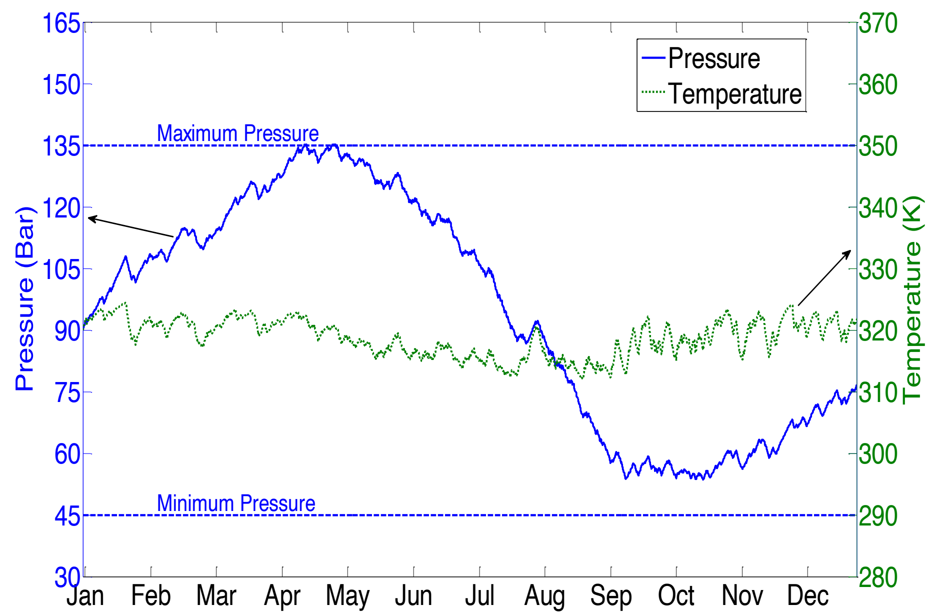
Maton, J.P., Zhao, L., Brouwer, J., Int'l Journal of Hydrogen Energy, Vol. 38, pp. 7867-7880, 2013

Hydrogen Energy Storage Dynamics

- Weekly and seasonal storage w/ H_2, fuel cells, electrolyzers
  - 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

Resilient Storage & Transmission/Distrib... Resource

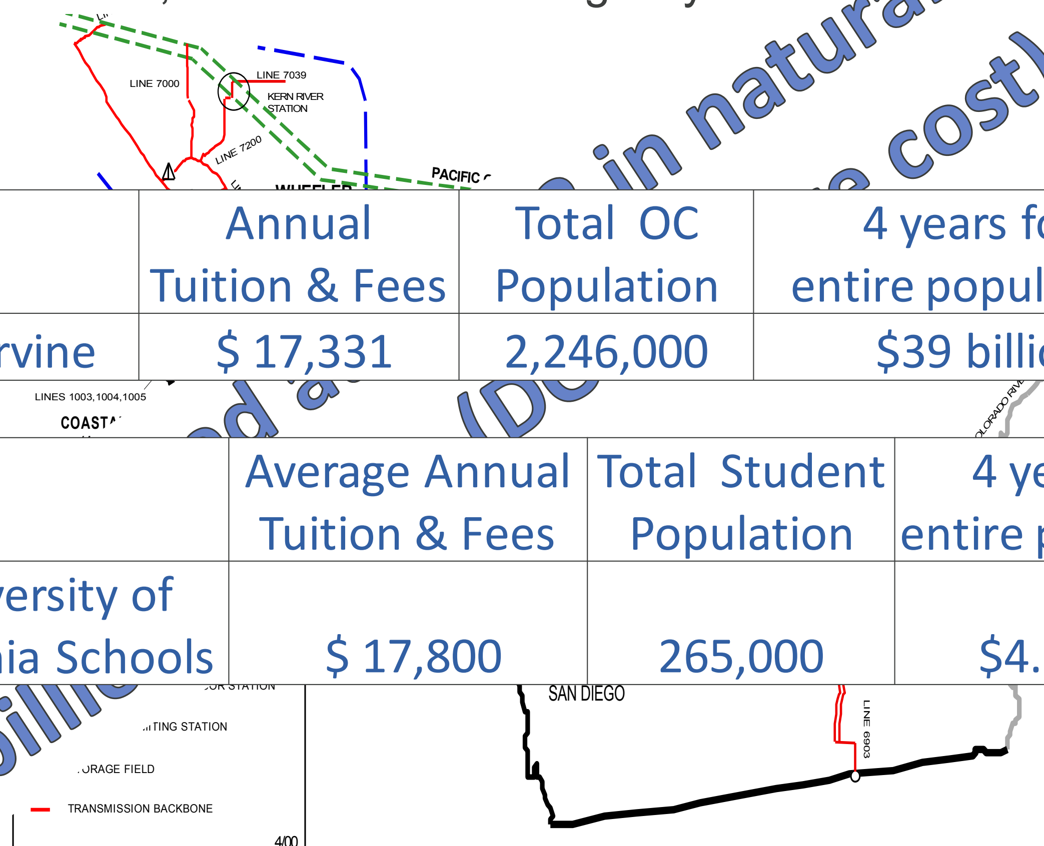
- Natural Gas Transmission, Distribution & Storage System

> 99.999% available

Gas Technology Institute, Assessment of Natural Gas … Service Reliability, 2018.

650 G… in natural gas

$130 billi… (D… cost)



	Annual Tuition & Fees	Total OC Population	4 years for entire population
U.C. Irvine	$ 17,331	2,246,000	$39 billion

	Average Annual Tuition & Fees	Total Student Population	4 years for entire population
All University of California Schools	$ 17,800	265,000	$4.7 billion

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

UC… …ions …at Scale

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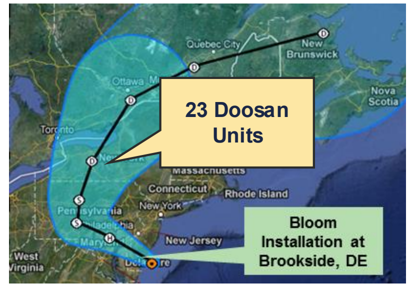
Demonstrated Resilience of Fuel Cells and Gas System

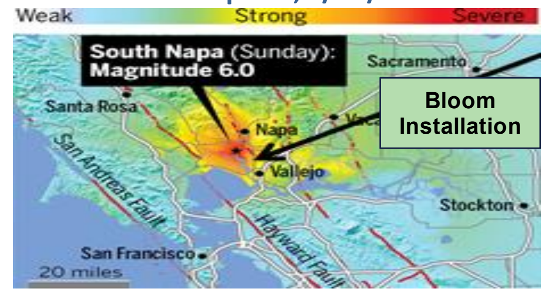
San Diego Blackout, 9/28/11

Winter Storm Alfred, 10/29/11

Hurricane Sandy, 10/29/12



CA Earthquake, 8/24/14

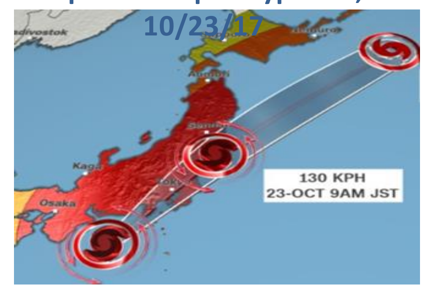


Data Center Utility Outage, 4/16/15

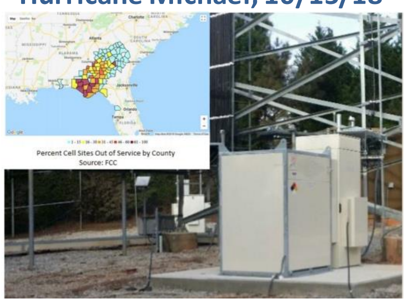
Hurricane Joaquin, 10/15/15

Napa Fire, 10/9/17

Japanese Super-Typhoon, 10/23/17

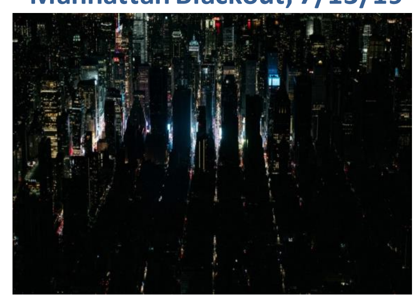


Hurricane Michael, 10/15/18

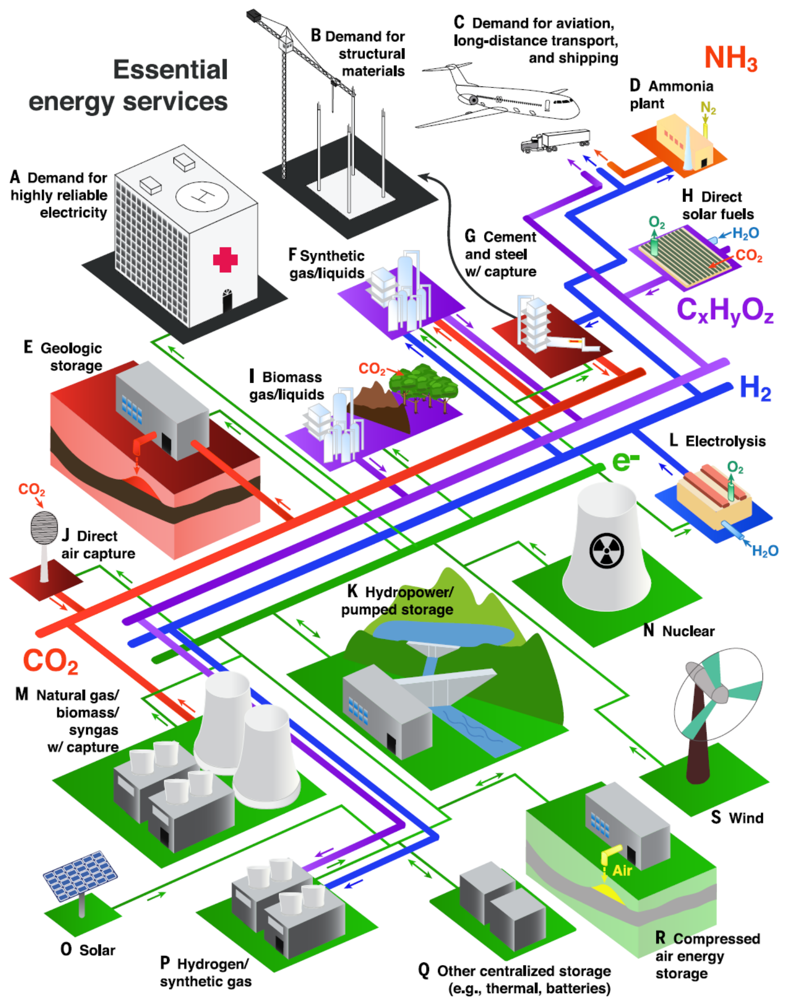


Ridgecrest Earthquakes, 7/4-5/19

Manhattan Blackout, 7/13/19



Why Hydrogen? Required for completely zero emissions



REVIEW SUMMARY

ENERGY

Net-zero emissions energy systems

Steven J. Davis*, Nathan S. Lewis*, Matthew Shaner, Sonia Aggarwal, Doug Arent, Inês L. Azevedo, Sally M. Benson, Thomas Bradley, Jack Brouwer, Yet-Ming Chiang, Christopher T. M. Clack, Armond Cohen, Stephen Doig, Jae Edmonds, Paul Fennell, Christopher B. Field, Bryan Hannegan, Bri-Mathias Hodge, Martin I. Hoffert, Eric Ingersoll, Paulina Jaramillo, Klaus S. Lackner, Katharine J. Mach, Michael Mastrandrea, Joan Ogden, Per F. Peterson, Daniel L. Sanchez, Daniel Sperling, Joseph Stagner, Jessika E. Trancik, Chi-Jen Yang, Ken Caldeira*

Davis *et al.*, *Science* **360**, 1419 (2018) 29 June 2018

Why Hydrogen? Zero Emission Fuels Required

- Provide zero emissions fuel to difficult end-uses

Anything that requires (1) rapid fueling, (2) long range, (3) large payload

Why Hydrogen? Industry Requirements for Heat, Feedstock,

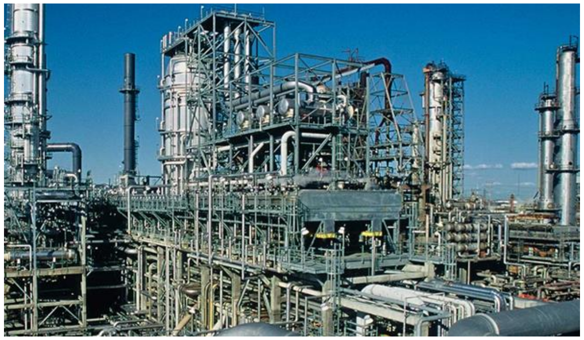
- Many examples of applications that cannot be electrified

Steel Manufacturing & Processing

Cement Production

(Photo: ABB Cement)

Plastics

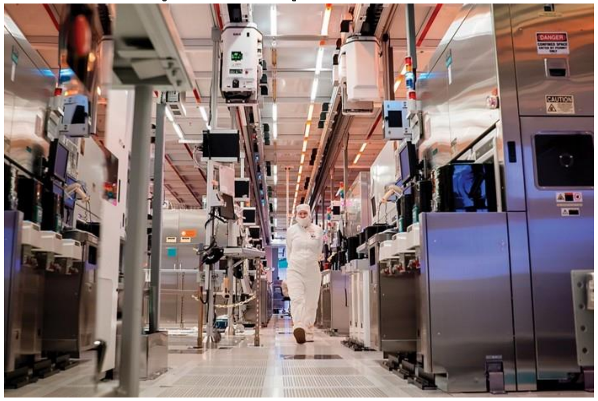


(Photo: DowDuPont Inc.*)*

Ammonia & Fertilizer Production

(Photo: Galveston County Economic Development)

Computer Chip Fabrication



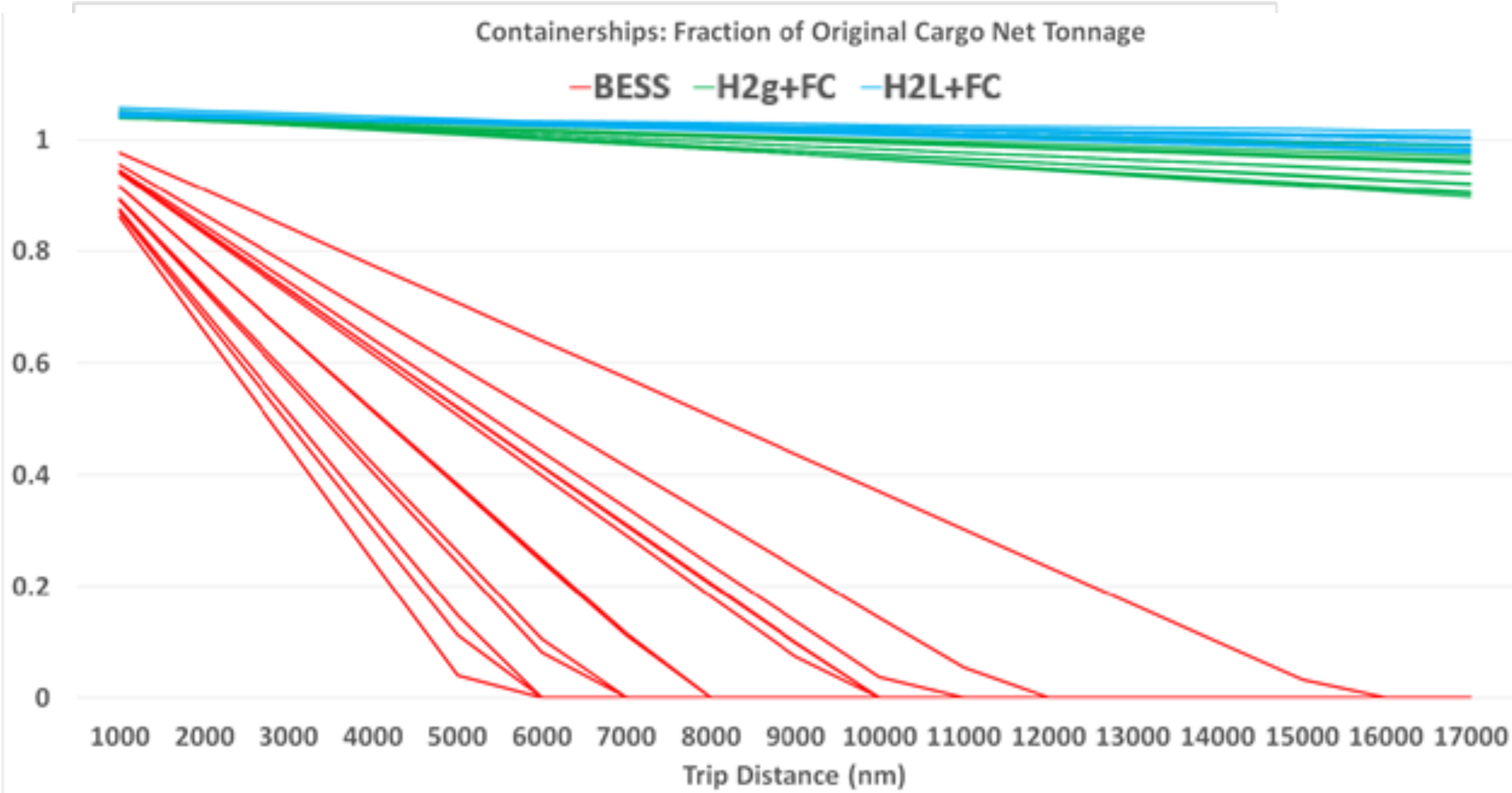
(Photo: American Chemical Society)

Pharmaceuticals

(Photo: Geosyntec Consultants)

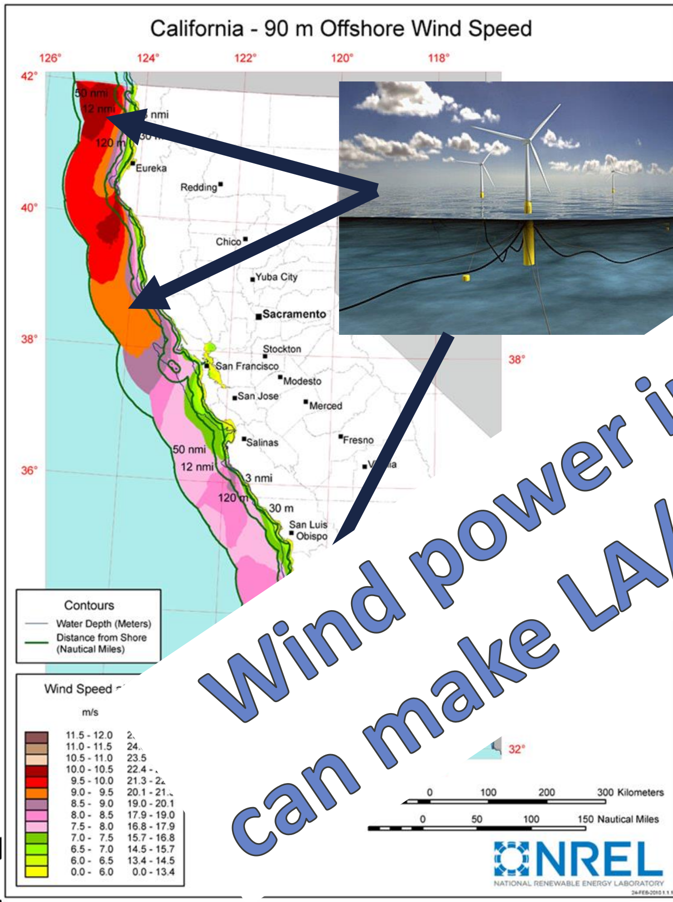
Can LA/LB Port become Zero Emissions?

Batteries compared to Hydrogen & Fuel Cells for Container Ships



Can LA/LB Port become Zero Emissions?

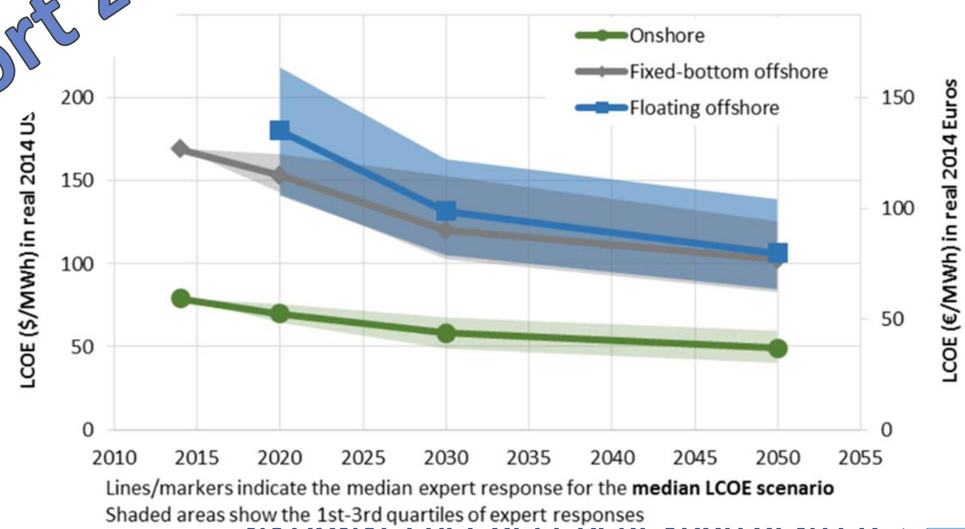
All ships, trains, & trucks through LA/LB Port: 8.89M tons '



Wind power in 3 large wind farms can make LA/LB Port zero emissions!

The C ... nous resource for ... energy!

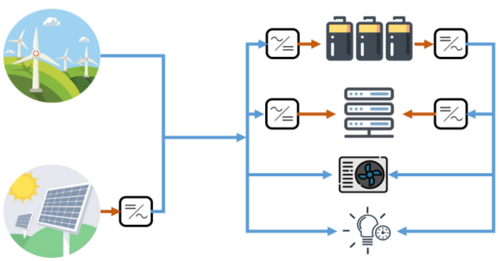
... perts anticipate significant cost ... ns in offshore wind technology:



Can Data Centers become Zero Emissions?

Data Center Configurations/Locations Modeled

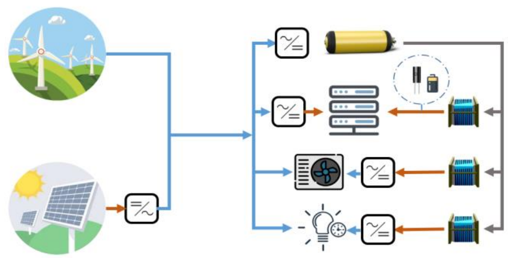
Battery - Central Storage



Data Center powered directly from renewable generators when available. Excess of electricity stored in batteries.

Wyoming
Iowa
Virginia
Texas

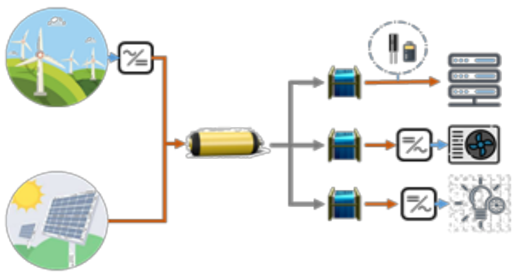
Excess power to gas



Data Center powered directly from renewable generators when available. Excess of electricity converted to hydrogen and used when required.

Wyoming
Iowa
Virginia
Texas

Power to gas



All renewable electricity generation converted to hydrogen. Data Center powered from hydrogen.

Wyoming
Iowa
Virginia
Texas

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Can Data Centers become Zero Emissions?

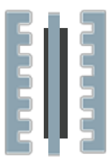
Modeling Assumptions

Power Generation Systems

- Standard modules
- Single axis tracking system
- System Losses 14.08%

- V90-2.0 MW™
- Rated wind speed: 13.0 m/s
- Cut in, cut out speed: 4.0 m/s – 25.0 m/s
- Diameter: 90 M

Energy Conversion Systems



- $\eta_{electrolyzer}$: 75%
- $\eta_{fuel\ cell}$: 55%
- Degradation: 1.3 % per year

- η_{charge}: 90.3 %
- $\eta_{discharge}$: 90.3 %
- Minimum state of storage: 20%
- Degradation: 1.7 % per year.

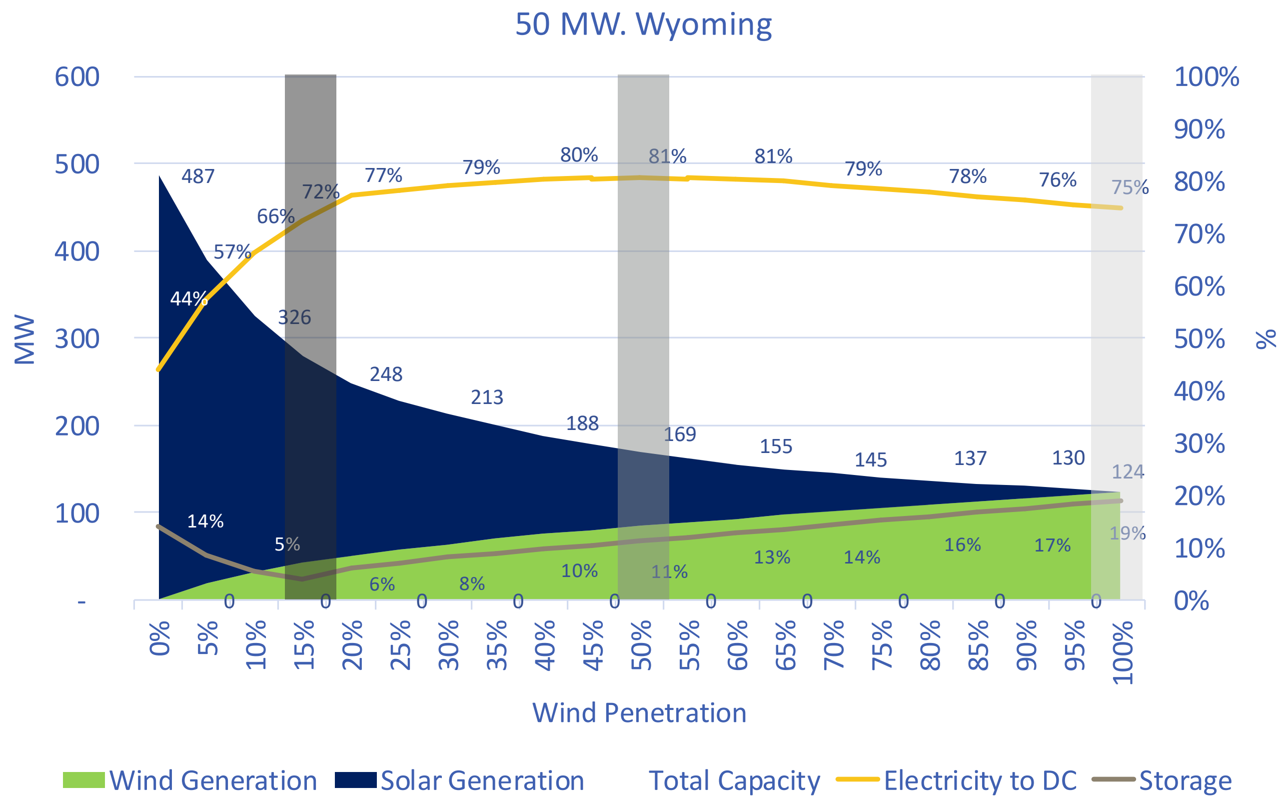
Energy Storage Systems

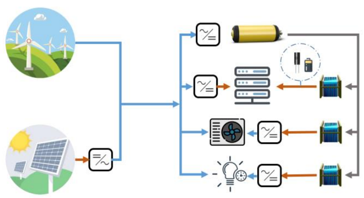
- Liquid hydrogen. 20.3 K, 1 atm
- Boil off losses: 0.1% per day
- Liquefaction energy requirements: 4.94 kWh/kg

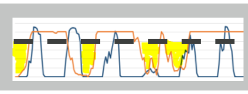
- Self-discharge: 3-9 % per month

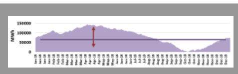
Can Data Centers become Zero Emissions?

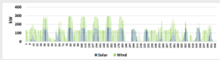
Data Center Designs (Wyoming location)











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Can Data Centers become Zero Emiss…s?

Excess P2G & Battery Cases – Wyoming (optim… …/wind)

Every H2 case for 100% renewable w/ all storage is significantly cheaper!

	Hydrogen Ca…					Battery Case		
	Wind Onshore	Solar PV	Elec…		…+ …ction	Wind onshore	Solar PV	Battery
Size, MW (MWh)	48	271				31	177	21,781
Dewar, ton					520.6			
Liquefier, kg/s					0.57			
OM fixed, M$/yr	0.43			0.18	0.335	0.28	0.78	306.5
OM var, $/MWh	-			154.7				
Cooling cost, $/h					23.6			
Energy cost, $/h					799.2			
Capital, M$			62.25	35.35	67.0	28.43	128.43	6224.1
Cell capex, M$								3396.5
Power conversion cap…								2823.4
BOS capex…								2.12
Dewar…					13.8			
Liq…					53.2			
	6.86E-2	6.86E-2	6.86E-2	6.86E-2	7.06E-2	6.86E-2	6.86E-2	7.06E-2
	29.57	67.05	131.5	371.2	23.2	29.57	67.05	4,744.5
			5.16					
…le	119.82					4,798.20		

Hydrogen is Essential for Sustainability

Hydrogen: 11 features required for 100% zero carbon & pollutant emissions

- Massive energy storage potential
- Rapid vehicle fueling
- Long vehicle range
- Heavy vehicle/ship/train payload
- Seasonal (long duration) storage potent
- Sufficient raw materials on earth
- Water naturally recycled in short time c
- Feedstock for industry heat
- Feedstock for industry chemicals (e.g.
- Pre-cursor for high energy density ren
- Re-use of existing infrastructure (lowe

Available online at www.sciencedirect.com

ScienceDirect

ELSEVIER

Current Opinion in Electrochemistry

Review Article

Hydrogen is essential for sustainability

Alireza Saeedmanesh, Michael A. Mac Kinnon and Jack Brouwer*

CrossMark

Sustainable energy conversion requires zero emissions of greenhouse gases and criteria pollutants using primary energy sources that the earth naturally replenishes quickly, like renewable resources. Solar and wind power conversion technologies have become cost effective recently, but challenges remain to manage electrical grid dynamics and to meet end-use requirements for energy dense fuels and chemicals. Renewable hydrogen provides the best opportunity for a zero emissions fuel and is the best feedstock for production of zero emission liquid fuels and some chemical and heat end-uses. Renewable hydrogen can be made at very high efficiency using electrolysis systems that are dynamically operated to complement renewable wind and solar power dynamics. Hydrogen can be stored within the existing natural gas system to provide low cost massive storage capacity that (1) could be sufficient to enable a 100% zero emissions grid; (2) has sufficient energy density for end-uses including heavy duty transport; (3) is a building block for zero emissions fertilizer and chemicals; and (4) enables sustainable primary energy in all sectors of the economy.

Address
National Fuel Cell Research Center, University of California, Irvine, 92697-3550, United States

electricity generation, and industrial applications, will increase substantially over this century [7–14].

Since the Industrial Revolution, the vast majority of energy converted in society has been obtained from fossil fuels – coal, natural gas, and petroleum – which require tremendously long times for earth and the power of the sun to produce. This trend is widely expected to continue in coming decades [15–18]. Although the available global quantity of these fuels is extremely large, they are nevertheless finite and so will inevitably 'run out' at some near future time as we consume them much faster than the earth produces them [19]. A primary reason for their continued use is economics – energy from fossil fuels has been more cost effective than most other sustainable forms of energy, including renewable resources.

In addition, the continued use of fossil fuels is associated with increased criteria pollutant and greenhouse gas emissions [20]. Emissions from fossil fuel combustion degrade air quality, pose human health risks, and drive global climate change. In 2017, global energy-related CO_2 emissions reached an historic high of 32.5 Gt as a result of

Saeemanesh, A., Mac Kinno
Hydrogen is Essential for Sustainability, Curr
Opinion in Electrochemistry, 2019.

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100% Renewable and Zero Emissions Energy with Hydrogen

Jack Brouwer

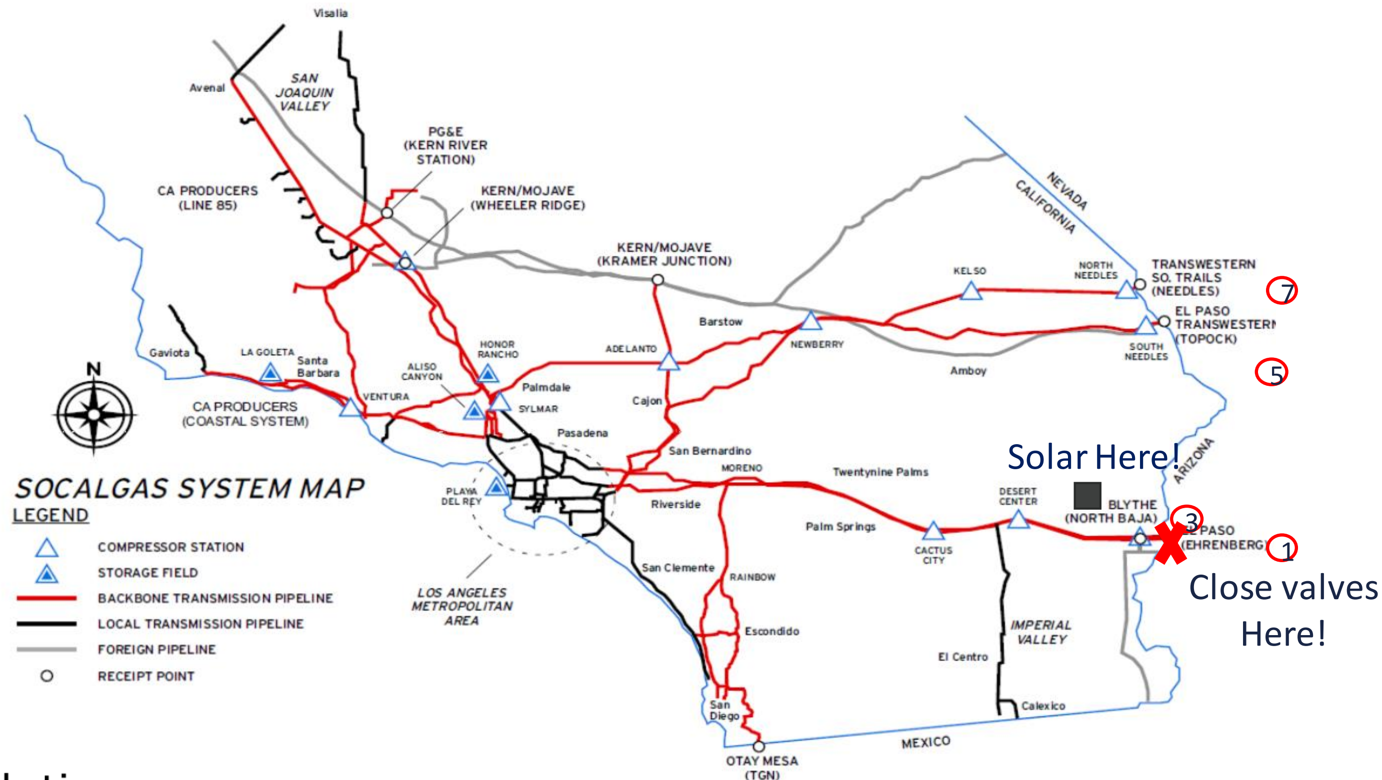
March 18, 2021

UCI Solutions that Scale

Backup Slides

Gas System – MASSIVE Resource for Zero Emissions

- First mix up to X% – ADD grid renewables & transportation electrification
- Then piecewise conversion to pure hydrogen



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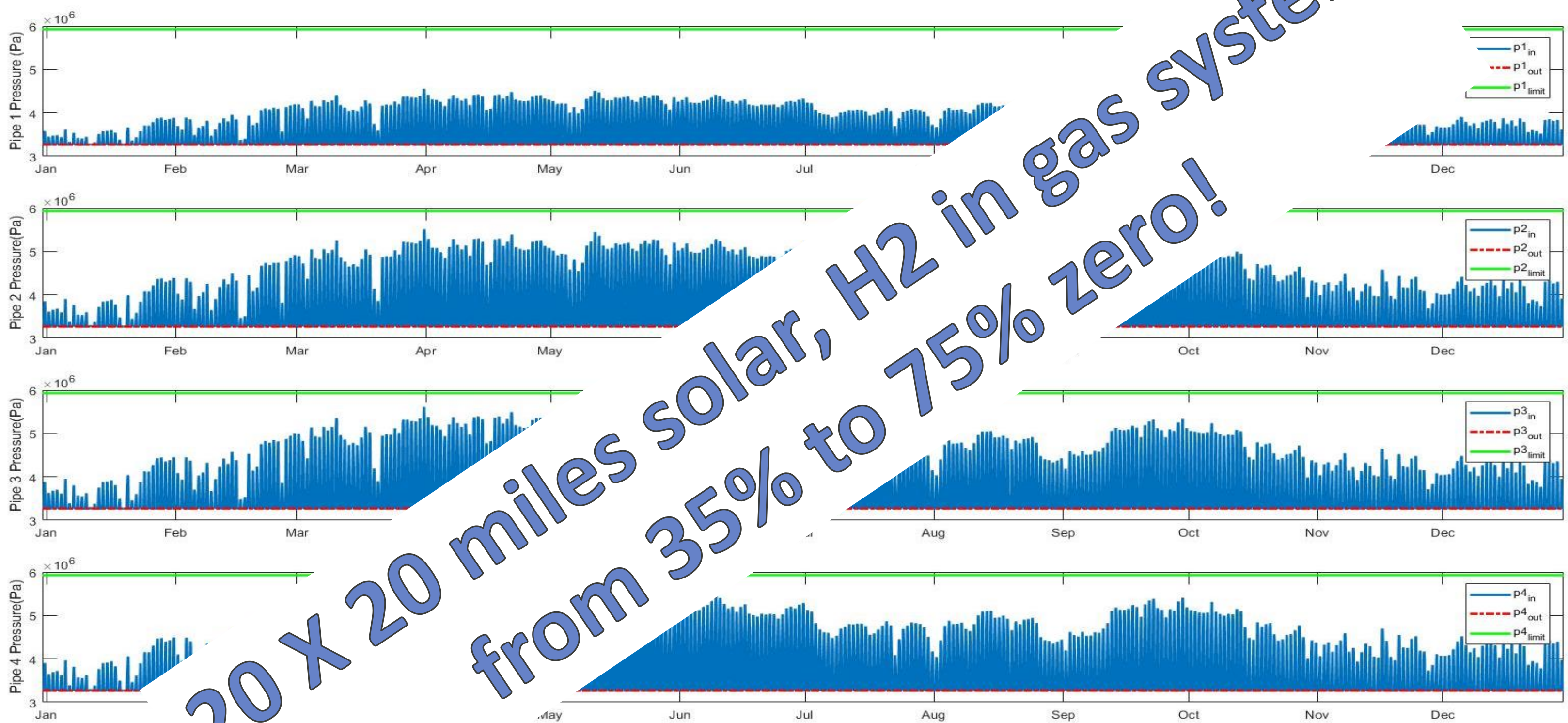
Gas System – MASSIVE Resource for Zero Emissions

- 40% of all electric demand – 20 sq. miles of solar, only gas syst ... use for H_2 storage AND all T&D

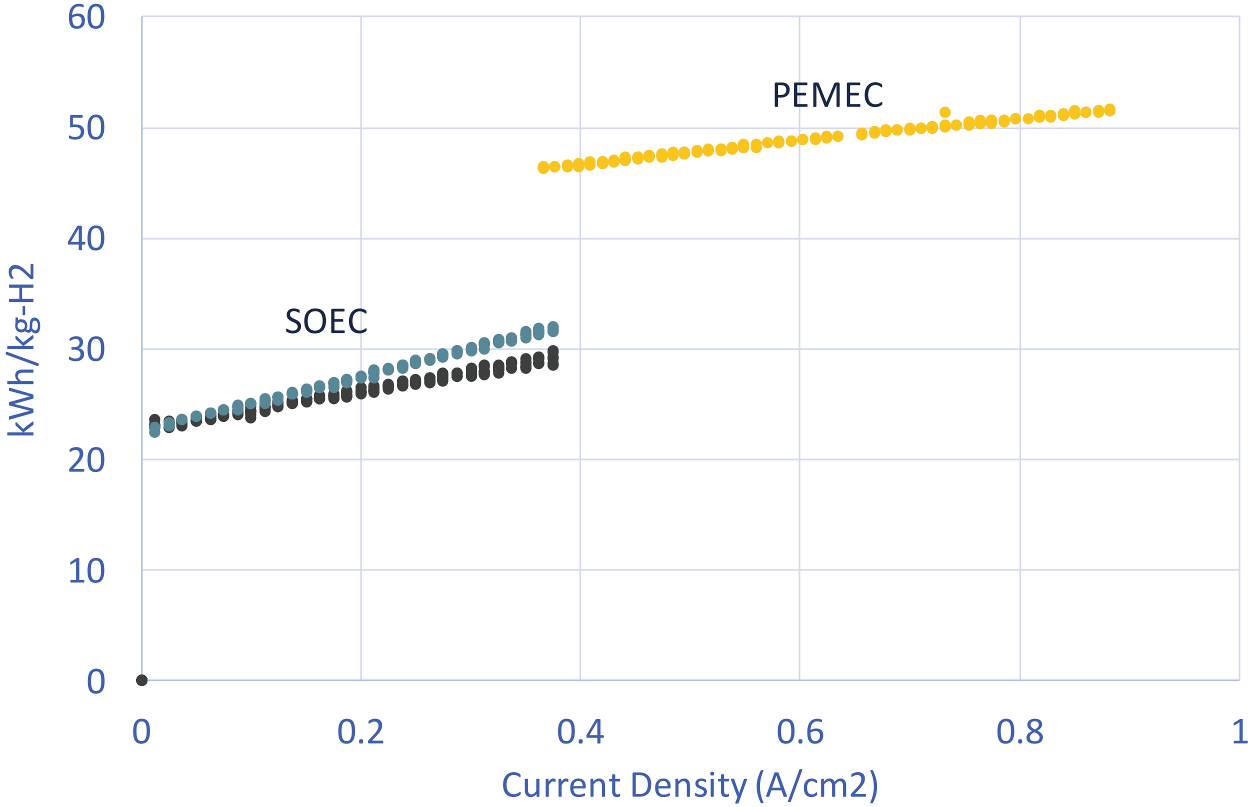


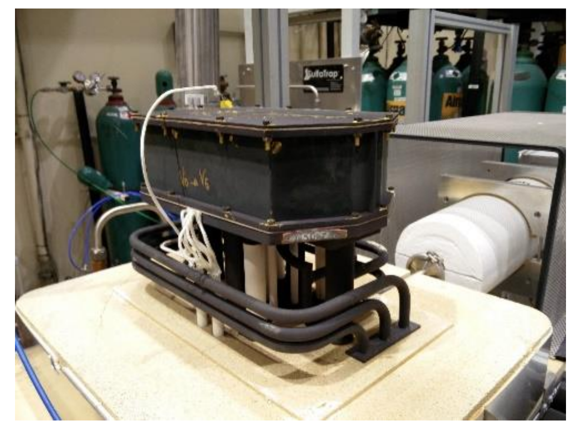
Summary

- We must and will inevitably increasingly depend upon solar power and its more direct derivatives (e.g., wind)
  - Air quality
  - Greenhouse gas emissions & climate
  - Energy, environment, & geopolitical sustainability
- The DYNAMICS of such a future are challenging – require complementary dispatch, massive storage, and seasonal storage
  - Batteries, hydro, power-to-gas (P2G), hydrogen energy storage (HES)
- P2G & HES will become the indispensable zero emissions fuel and energy storage medium to enable this future
  - Long duration energy storage
  - Massive energy storage amount
  - Will be lower cost (separate power/energy scaling)
  - High round-trip efficiency possible

Solid Oxide Electrolyzers & Fuel Cells

- Can achieve much higher round-trip efficiency

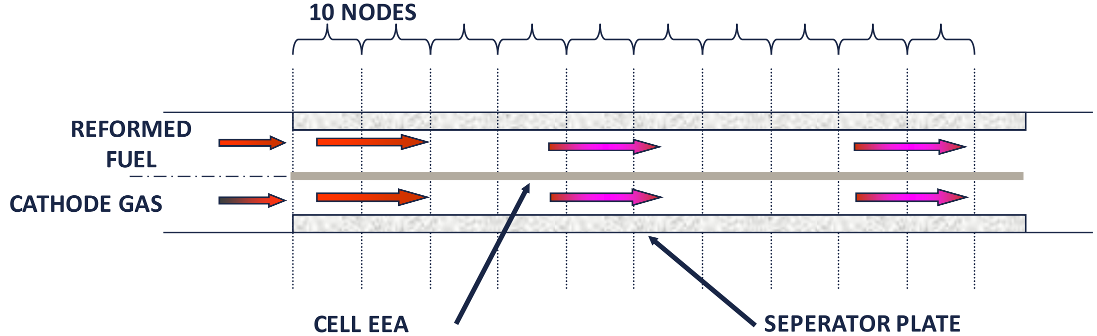




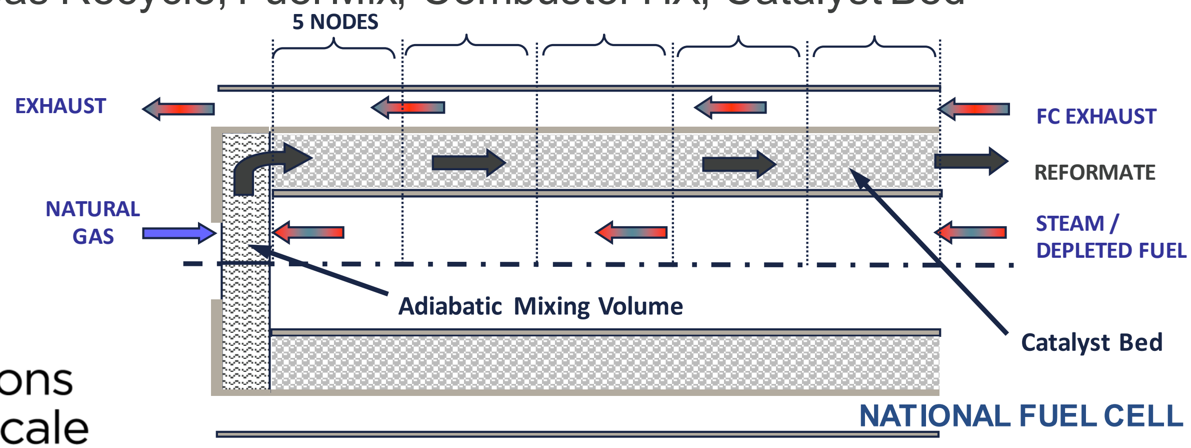
- **SOFC & SOEC systems not known for highly dynamic operation**

Key Simplification: Limited Geometric Resolution

- Planar SOFC with 10 Discrete Computational Nodes
  - Anode Gas, Cathode Gas, Cell EEA, Separator Plates



- Reformer Module with 5 Discrete Computational Nodes
  - Anode Off-Gas Recycle, Fuel Mix, Combustor HX, Catalyst Bed



Sample Dynamic Conservation Equations

Species Conservation

$$V\frac{dC_i}{dt} = N_{i_{inlet}} - N_{i_{outlet}} + R_i$$

Momentum Conservation

$$V\frac{d(\rho\bar{v})}{dt} = P_{inlet}\,A_{inlet} - P_{outlet}\,A_{outlet} - F_s$$

Nernst Equation

$$E = E^{\circ} + \frac{R_u T}{nF}\ln\left[\frac{[y_{H2}][y_{O2}]^{1/2}[y_{CO2,c}]P^{1/2}}{[y_{H2O}][y_{CO2,a}]}\right], P_c = P_a = P$$

Electrochemical Losses

$$L_R = R_{cell}\,i$$

$$L_A = \frac{R_u T}{n\alpha F}\ln(i/i_o)$$

$$L_C = -\frac{R_u T}{nF}\ln(1 - i/i_L)$$

Cell Voltage

$$Vcell = E - L_R - L_C - L_A$$

Sample Mass Conservation Equations

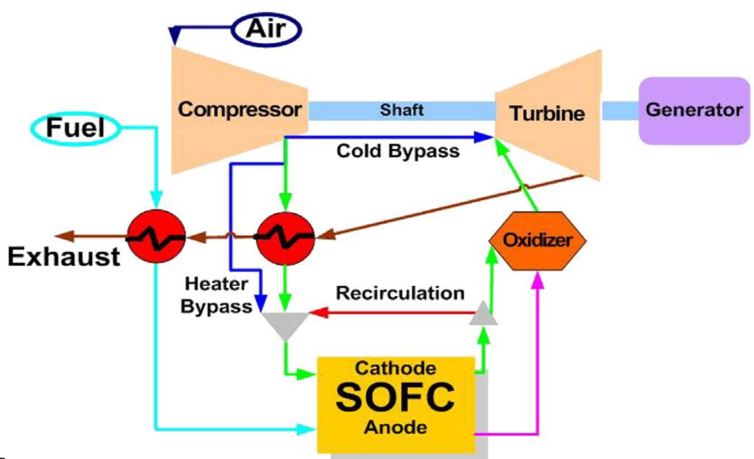
$$\begin{cases} C_{out} = \dfrac{P_{out}}{RT_{out}} \\ N_{out} = N_{in} + N_R - \dfrac{d(C_{out}V)}{dt} \\ (X_{H2})_{out} = \dfrac{N_{in}(X_{H2})_{in} + R_{H2} - \dfrac{d(C_{H2}V)}{dt}}{N_{out}} \\ (X_{CO2})_{out} = \dfrac{N_{in}(X_{CO2})_{in} + R_{CO2} - \dfrac{d(C_{CO2}V)}{dt}}{N_{out}} \\ (X_{H2O})_{out} = \dfrac{N_{in}(X_{H2O})_{in} + R_{H2O} - \dfrac{d(C_{H2O}V)}{dt}}{N_{out}} \\ (X_{N2})_{out} = \dfrac{N_{in}(X_{N2})_{in} - \dfrac{d(C_{N2}V)}{dt}}{N_{out}} \end{cases}$$

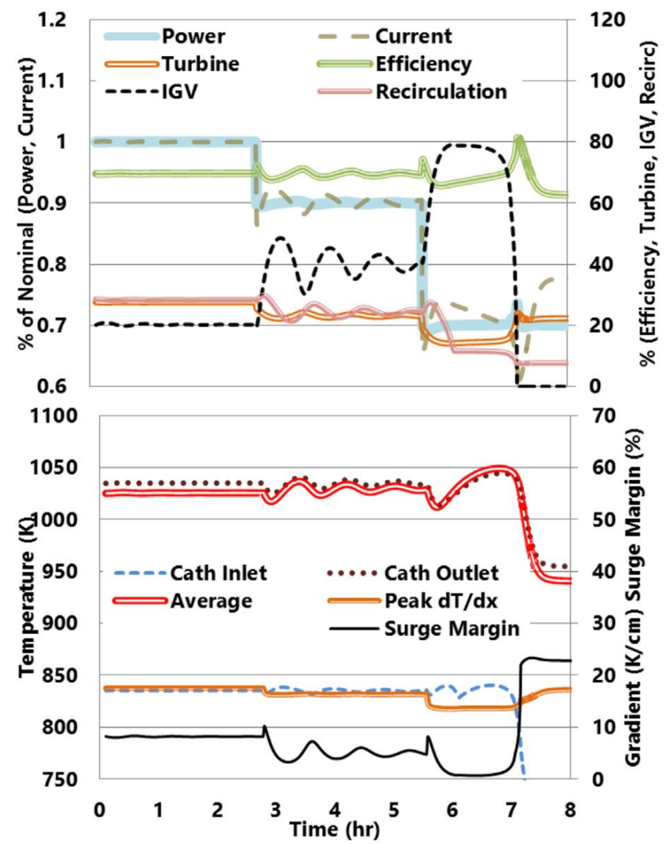
Roberts, R., Mason, J., Jabbari, F., Brouwer, J., Samuelsen, S., Liese, E. and Gemmen, R., ASME Paper Number 2003-GT-38774, 2003.

Fuel Cell System Dynamic Simulation

Minimal spatial resolution to enable full system dynamic simulation

- Electrochemistry spatially resolved
- Heat transfer dynamics
- Energy conservation dynamics
- Pressure dynamics (momentum conservation)

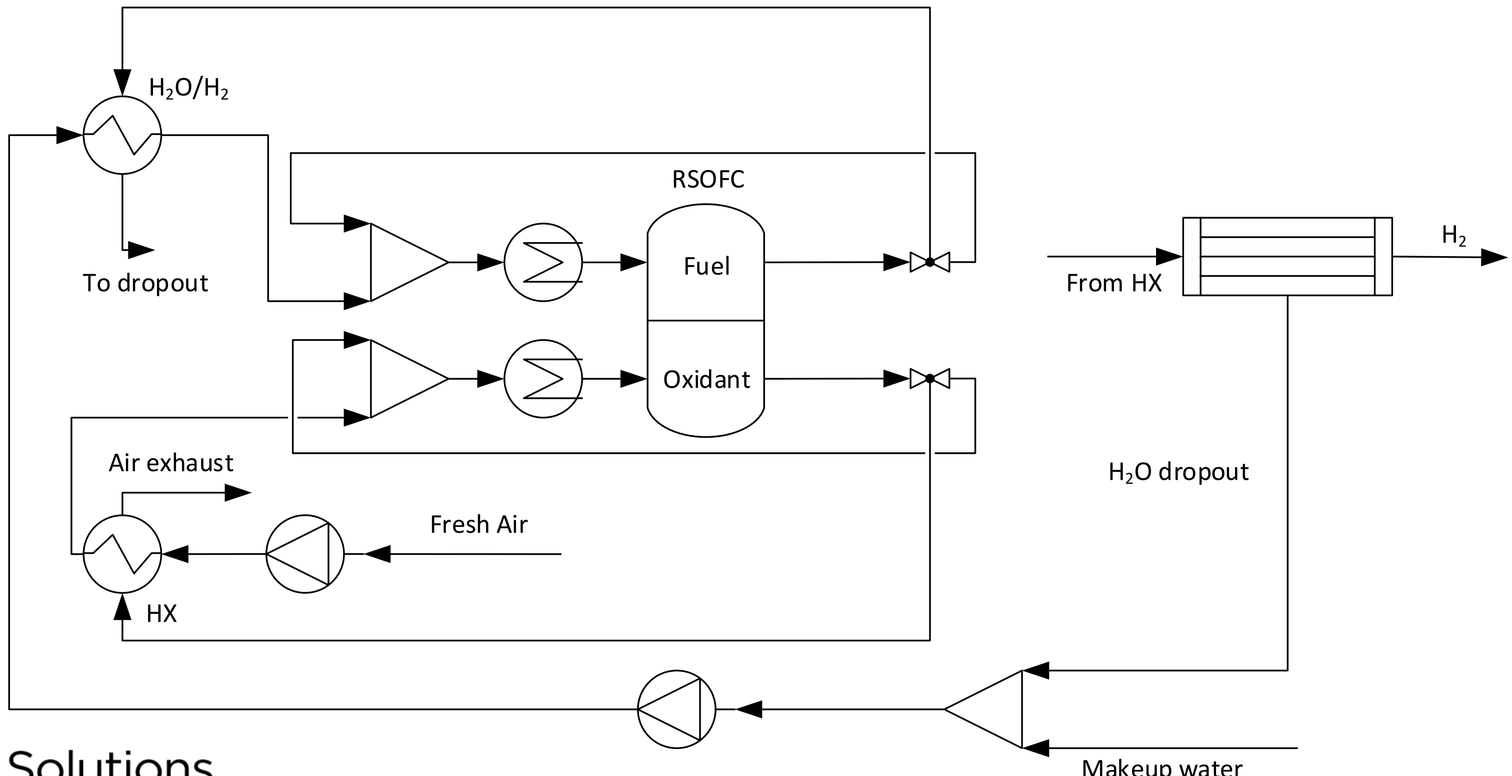




McLarty, D.F., Samuelsen, S., and Brouwer, J. Journal of Power Sources, vol. 254, pp. 126-136, 2014

Integrated Reversible Solid Oxide (rSO) System

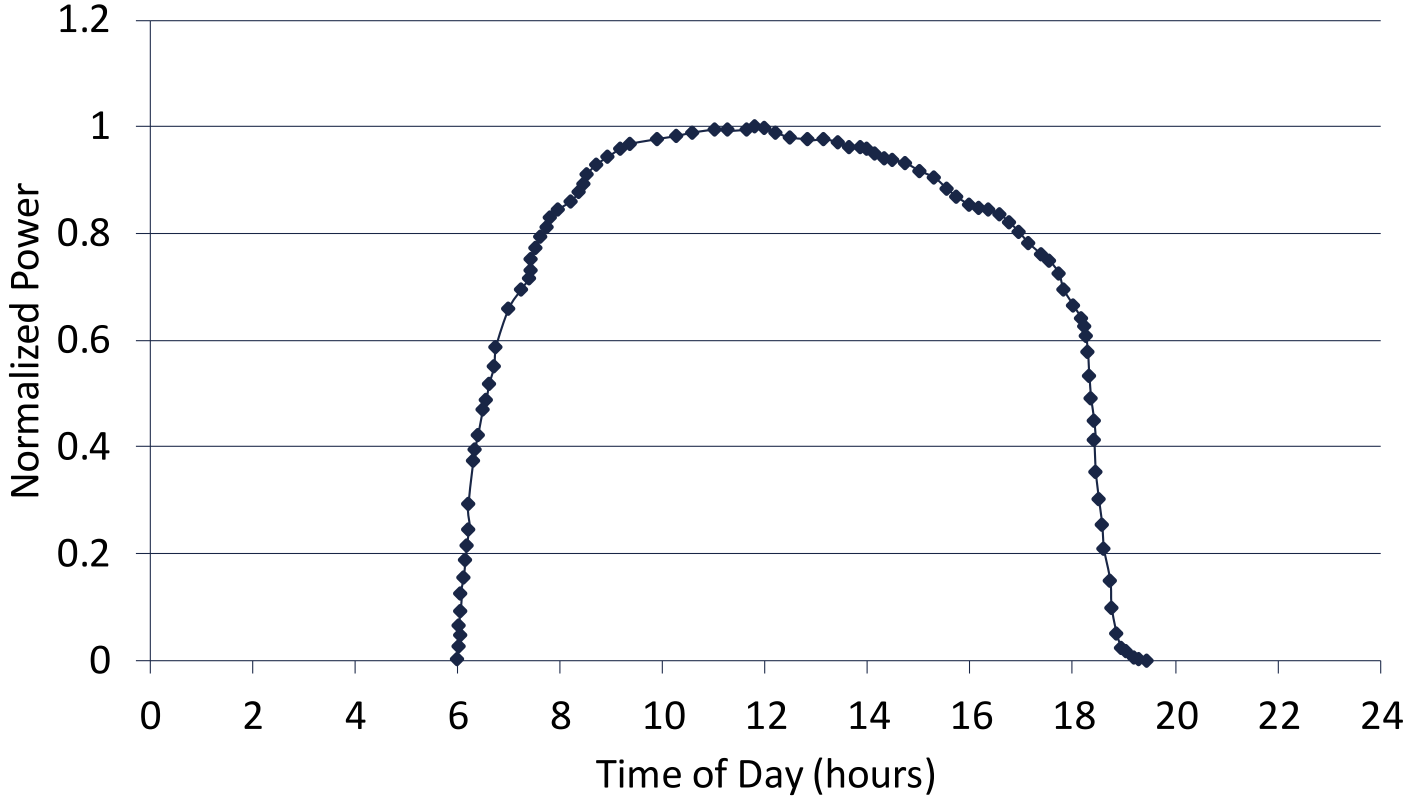
- Variety of system configurations could enable reversible operation
- Electric heater supported concept shown



McVay, D., Zhao, L., Brouwer, J., Transactions of the Electrochemical Society, Vol. 78, pp. 2975-2985, 2017

Integrated Reversible Solid Oxide (rSO) System

- Fifteen minute solar data on a clear summer day



UCI Solutions that Scale

McVay, D., Zhao, L., Brouwer, J., Transactions of the Electrochemical Society, Vol. 78, pp. 2975-2985, 2017

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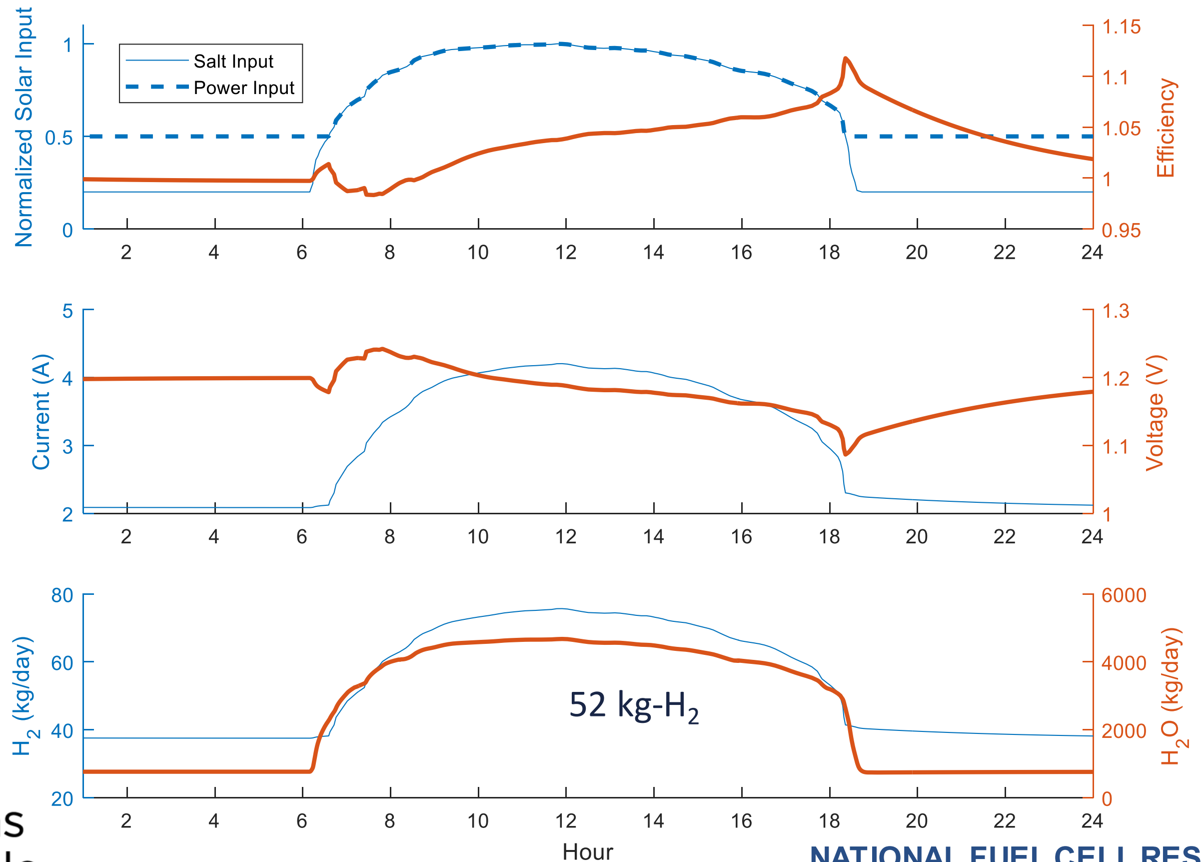
Integrated Reversible Solid Oxide (rSO) System

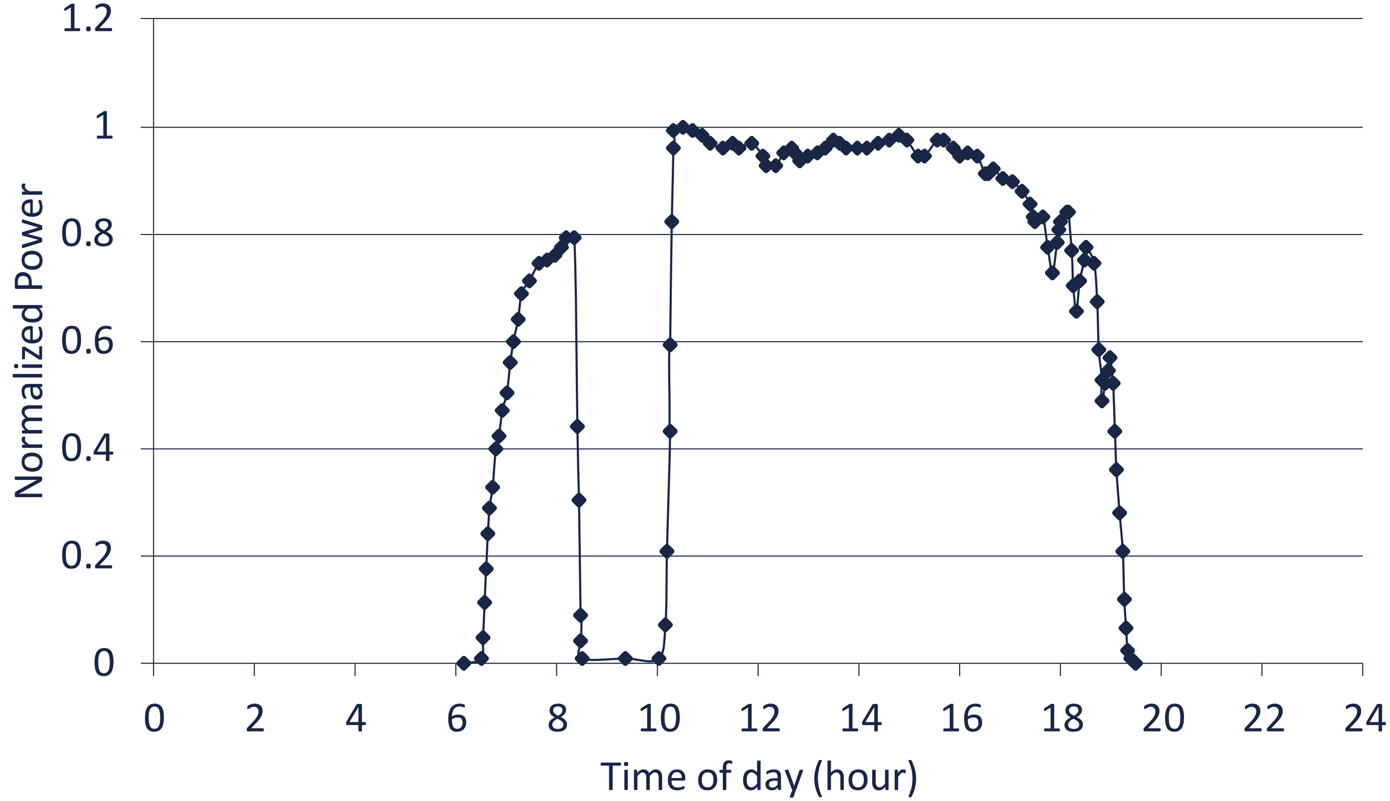
- Combined effects of power and salt flow increase with a diurnal (solar thermal) heat input



McVay, D., Zhao, L., Brouwer, J., Transactions of the Electrochemical Society, Vol. 78, pp. 2975-2985, 2017

Integrated Reversible Solid Oxide (rSO) System

- Fifteen minute solar data on a cloudy summer day



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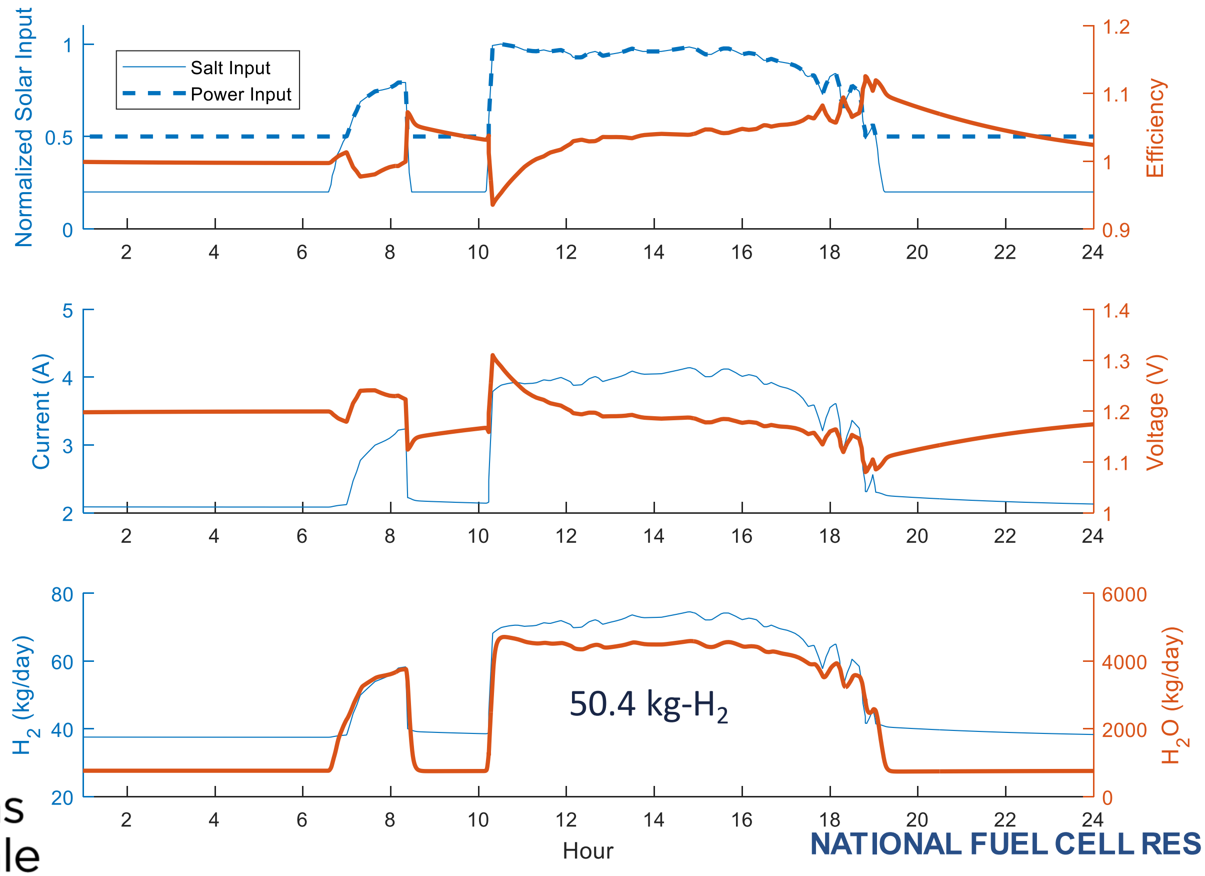
Integrated Reversible Solid Oxide (rSO) System

- The system is capable of operating within safe bounds even under cloudy conditions



McVay, D., Zhao, L., Brouwer, J., Transactions of the Electrochemical Society, Vol. 78, pp. 2975-2985, 2017

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