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Do we Really Need Hydrogen?

from: San Diego Union Tribune

Jack Brouwer

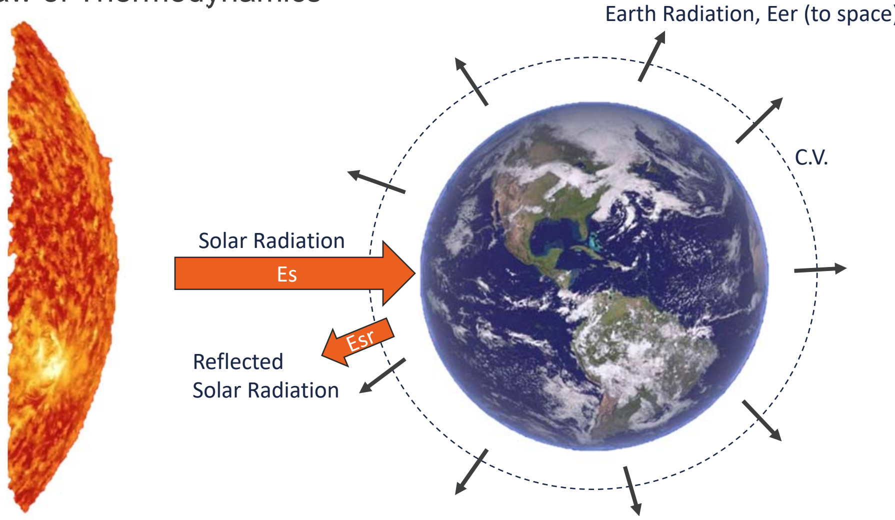
December 10, 2021

Fondazione Courmayeur Mont-Blanc
The future of energy: an analysis by international stakeholders

1

Earth Energy Balance

- First Law of Thermodynamics



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

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Primary Energy on Earth

All from the Sun!*

Sun Energy

- Dead plant/animal life, heat, pressure (millions – 100s of millions of years) – Fossil Fuels
  - coal, oil, natural gas
- Corn/Trees/Grass (months – years)
  - ethanol, biogas, biomass
- Hydro (weeks – months)
  - evaporation, clouds, rain, lakes
- Wind (days – weeks)
  - wind turbine
- Solar (instant)

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

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* except for nuclear

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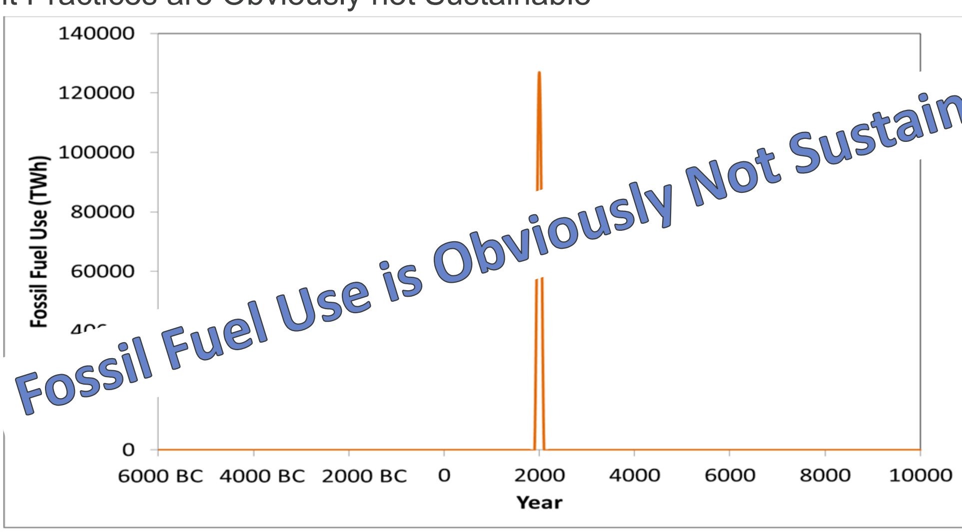
Energy on Earth

Current Practices are Obviously not Sustainable



Fossil Fuel Use is Obviously Not Sustainable

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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
  - Energy & Environmental Justice not well served by current paradigm
- Overall primary energy resource depletion – not sustainable

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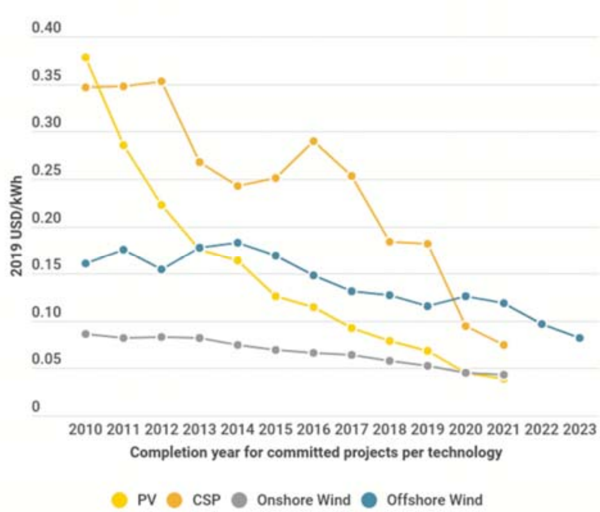
Renewable Energy Conversion (Solar & Wind)

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



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

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Popular Thinking & Arguments

Main Strategy:

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

Arguments against hydrogen & fuel cells:

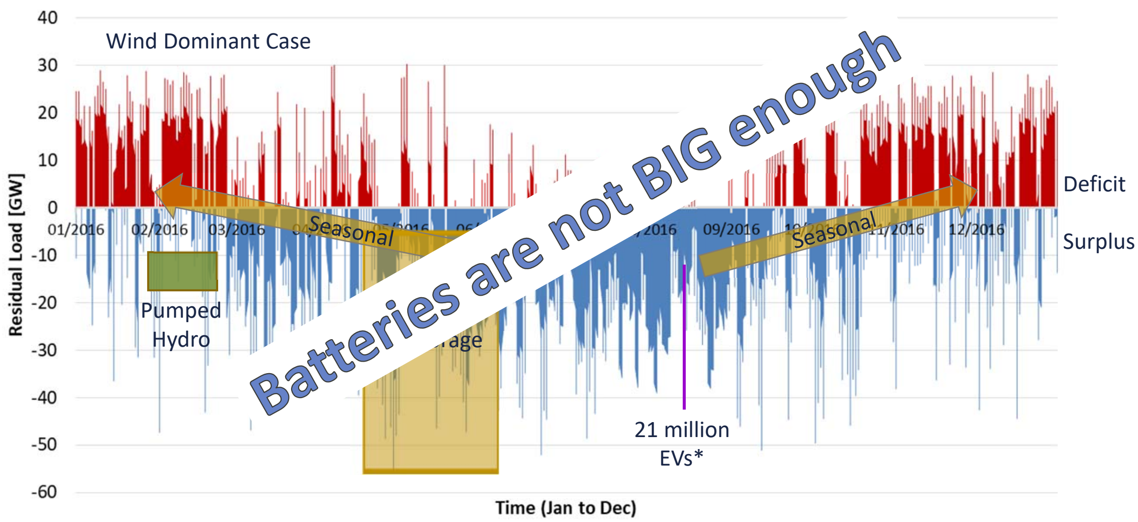
- Most hydrogen today is made from fossil fuels (natural gas)
- Making hydrogen from water & electricity is less efficient than charging a battery
- Making electricity from hydrogen in a fuel cell is less efficient than a batterv (i.e., round-trip efficiency is lower than a battery except for long duration 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

7

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

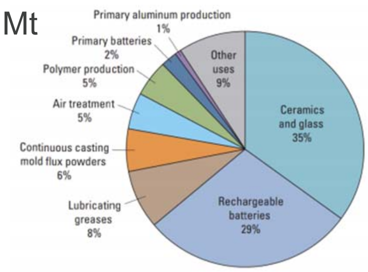
Simulate meeting of total world energy demand w/ Solar & Wind

	Solar contribution	Wind contribution	Consumption and storage ratio	Consumption (TWh)	Storage (TWh)
Africa	0.70	0.30	8.39	9 [illegible]	1,088
America	0.45	0.55	7.83	[illegible]	4,919
Asia	0.50	0.50	7.95	[illegible]	[illegible]0,178
Europe	0.30	0.70	7.50	[illegible]	[illegible],592
Oceania	0.50	0.50	[illegible]	[illegible]	205
TOTAL					19,981 TWh

[... 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



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Source: U.S. Geological Survey, 2018

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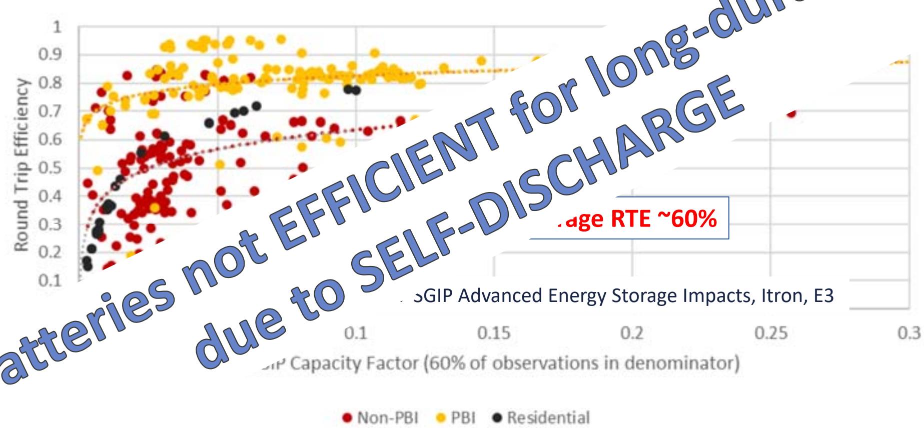
Lithium-Ion Battery Measured Performance

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

- Measured battery system performance in Utility Application...



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

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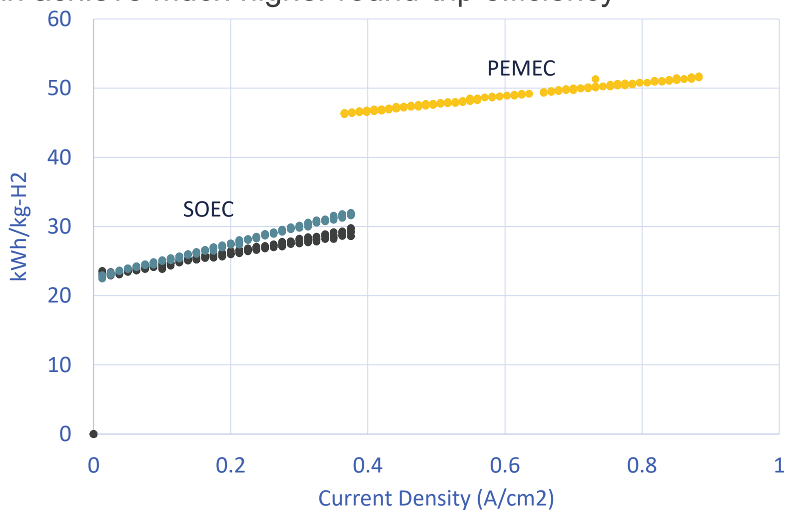
Solid Oxide Electrolyzers & Fuel Cells

- Can achieve much higher round-trip efficiency



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- **Future round trip efficiency of hydrogen energy storage will be higher**

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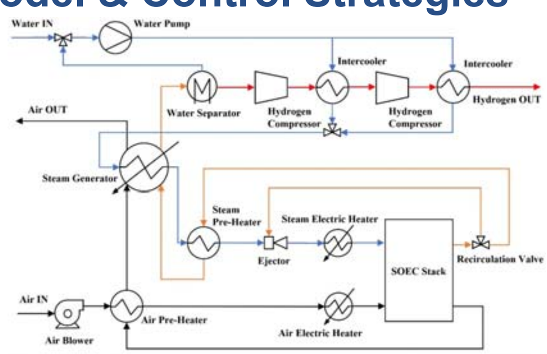
SOEC System Model & Control Strategies



Controlled Parameter	Manipulated Variable	Controller Type
Stack Average Temperature	Air Electric Heater Power	PI Feedback Loop Controller
Stack Temperature Gradient	Blower Power	PI Feedback Loop Controller
H_2 at Cathode Inlet	Valve Position	PI Feedback Loop Controller
Steam Utilization	Water Pump power	Feedforward Controller
Power Demand	Current	Feedforward Controller

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Saeedmanesh, A., Colombo, P., McLarty, D. and Brouwer, J., Journal of Electrochemical Energy Conversion and Storage, 2019.

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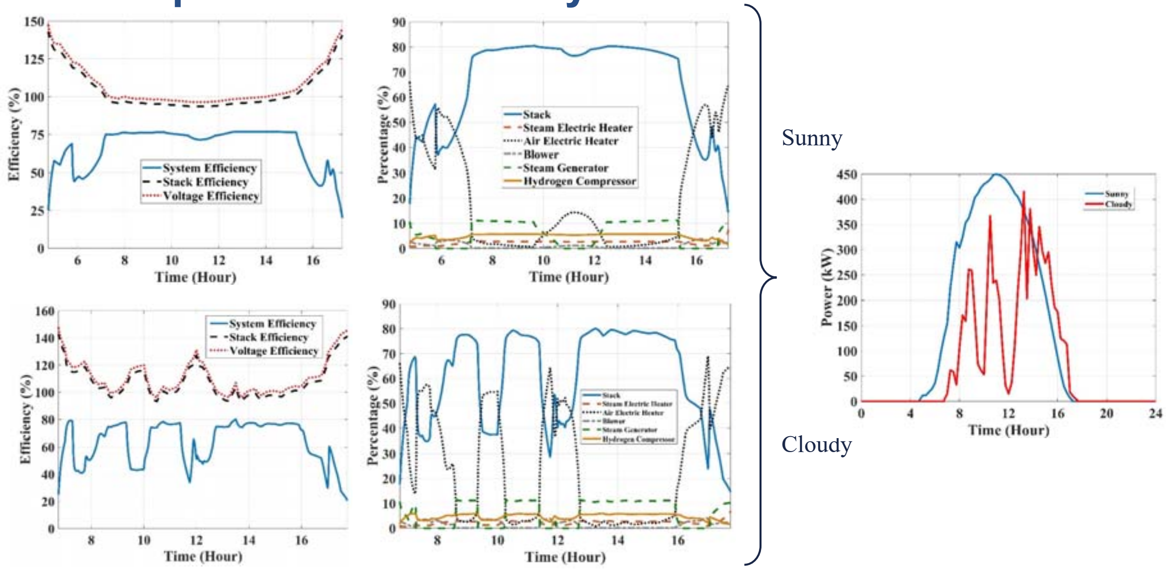
Dynamic Operation of SOEC System



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Saeedmanesh, A., Colombo, P., McLarty, D. and Brouwer, J., Journal of Electrochemical Energy Conversion and Storage, 2019.

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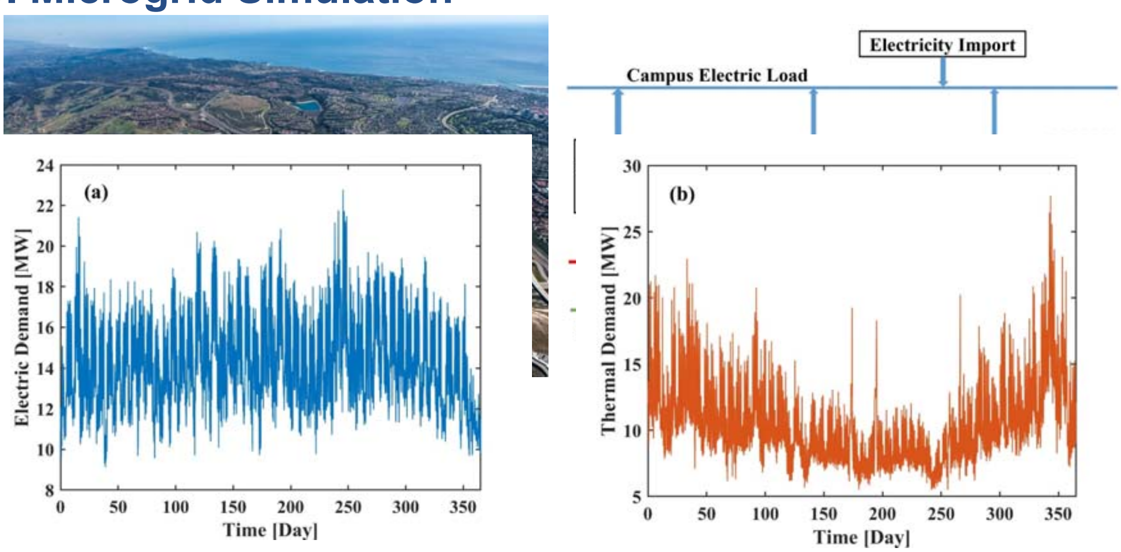
UCI Microgrid Simulation



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Colombo, P., Saeedmanesh, A., Santarelli, M. and Brouwer, J., Energy Conversion and Management, 2019.

NFCRC

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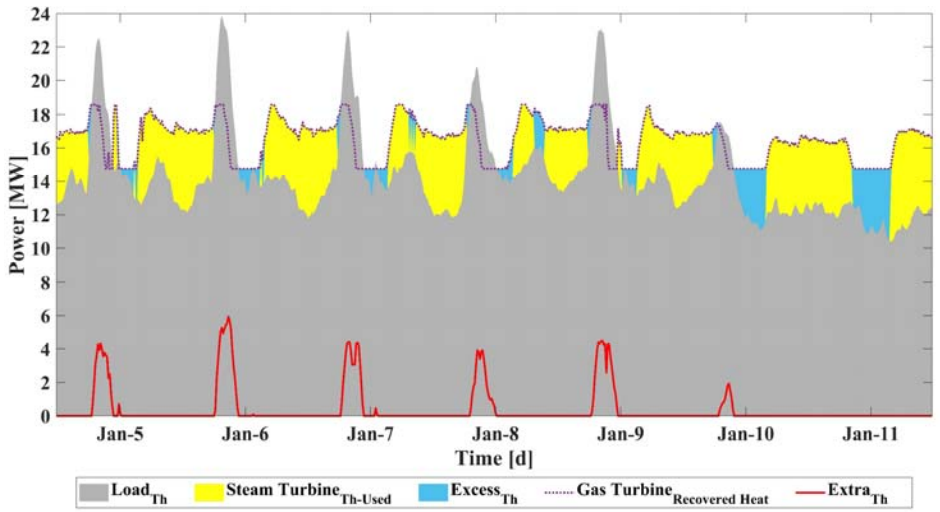
UCI Microgrid Results in High Renewable Use Cases



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Colombo, P., Saeedmanesh, A., Santarelli, M. and Brouwer, J., Energy Conversion and Management, 2019.

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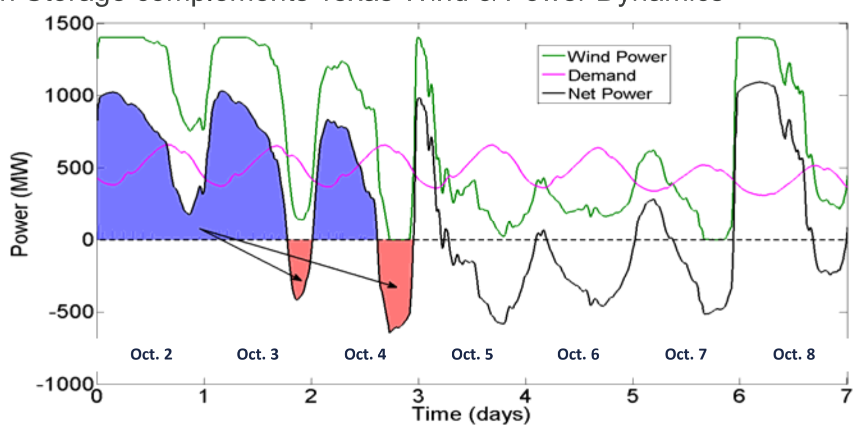
Hydrogen Energy Storage Dynamics

- 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

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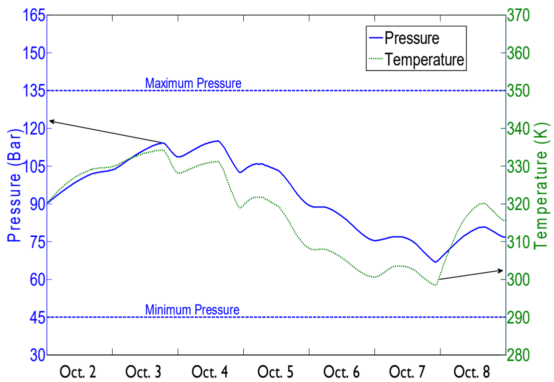
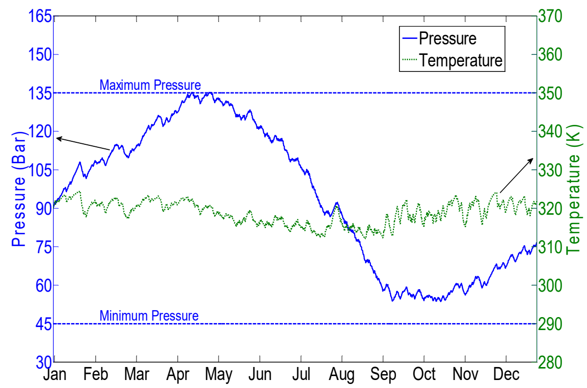
Hydrogen Energy Storage Dynamics

- 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?

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

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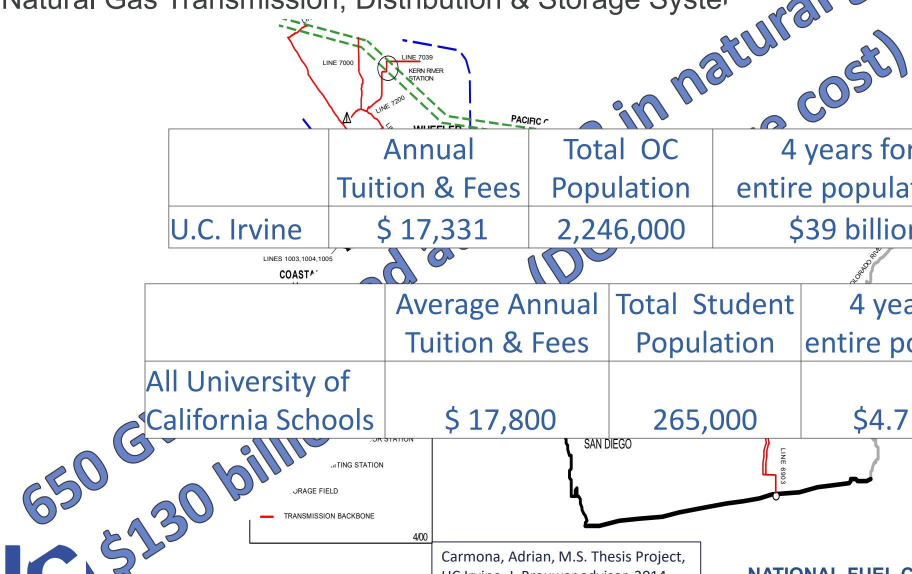
Resilient Storage & Transmission/Distrib… Resource

- Natural Gas Transmission, Distribution & Storage Syster…

> 99.999% available

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



	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

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

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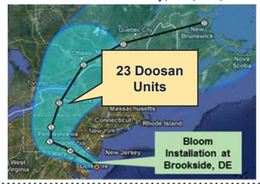
Demonstrated Resilience of Fuel Cells and Gas System

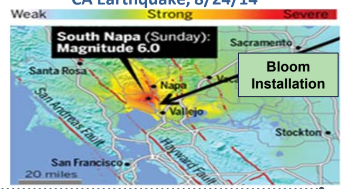
San Diego Blackout, 9/28/11

Winter Storm Alfred, 10/29/11

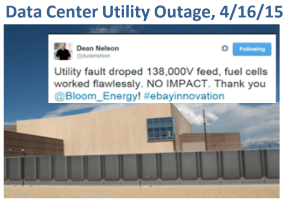
Hurricane Sandy, 10/29/12



CA Earthquake, 8/24/14



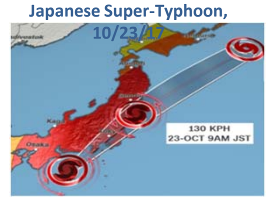
Data Center Utility Outage, 4/16/15



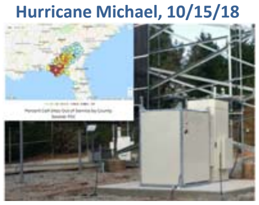
Hurricane Joaquin, 10/15/15

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

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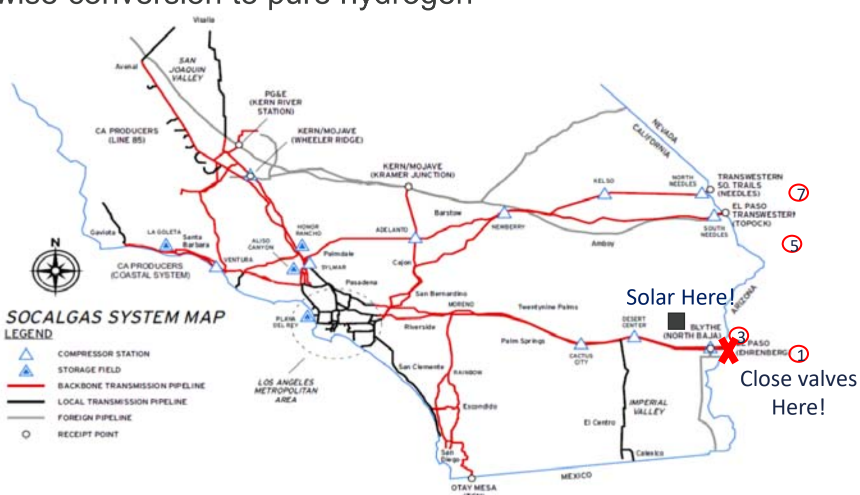
Gas System – MASSIVE Resource for Zero Emissions

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



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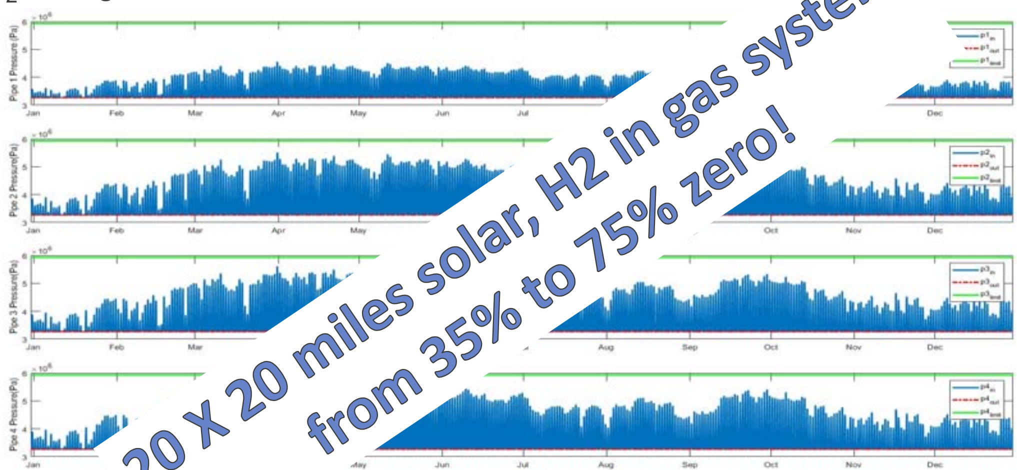
Gas System – MASSIVE Resource for Zero Emissions

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



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Heydarzadeh, Zahra, PhD Dissertation, UC Irvine, J. Brouwer advisor, 2020.

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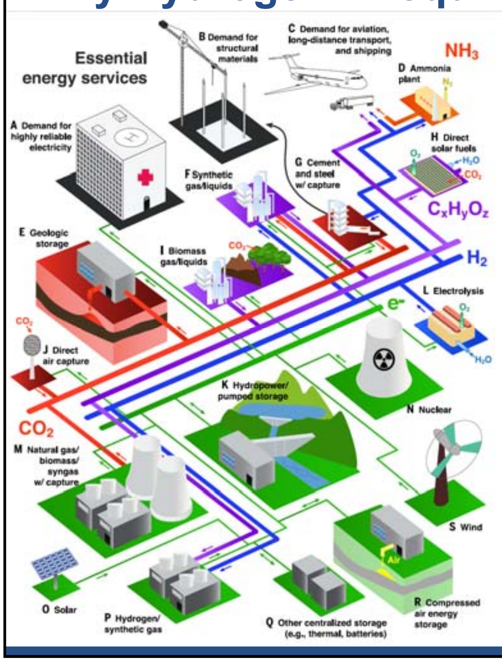
Why Hydrogen? Required for completely zero emissions



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

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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

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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)

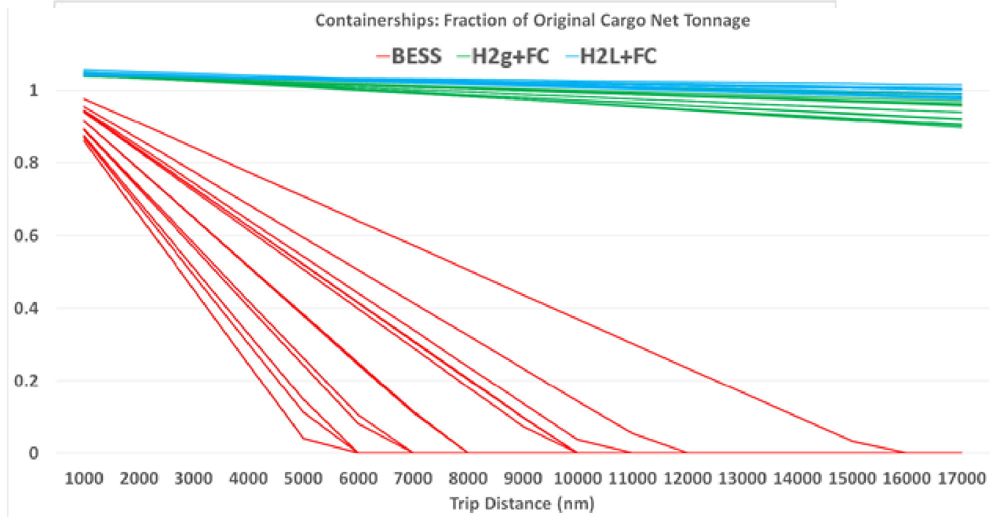
Pharmaceuticals

(Photo: Geosyntec Consultants)

24

Gedanken Exp.: Can LA/LB Port become Zero Emissions?

Batteries compared to Hydrogen & Fuel Cells for Container Ships



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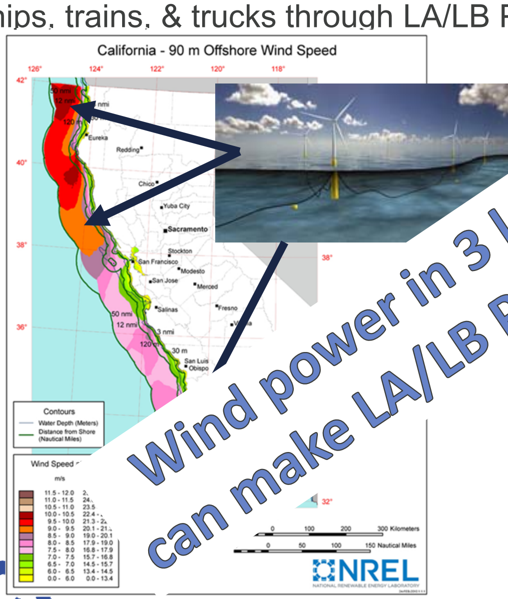
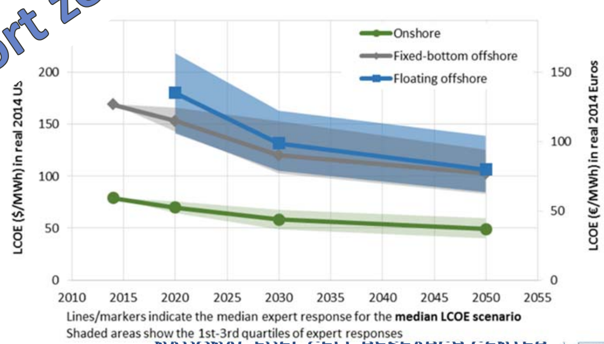
Gedanken Exp.: Can LA/LB Port become Zer… Emissions?

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



The C… …nous resource for … energy!

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



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

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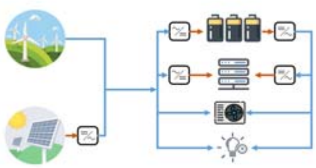
Gedanken Exp.: Can Data Centers become Zero Emissions?

Data Center Configurations/Locations Modeled

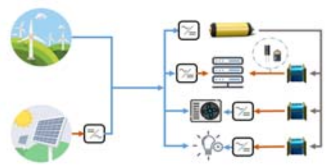
Battery - Central Storage



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

Wyoming
Iowa
Virginia
Texas

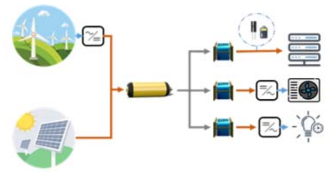
Excess power to gas



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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Gedanken Exp.: Can Data Centers bec e Zero Emissions?

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
V}h/#P Z #P Z k,	48	271				31	177	21,781
Ghzdu#wrq					520.6			
Olxhilhu#j2v					0.57			
RP#l{hg#P'2|u	0.43			.18	0.335	0.28	0.78	306.5
RP#ydu#2P Zk	-			154.7				
Frrdqj#frvw#2k					23.6			
Hqhuj|#frvw#2k					799.2			
Fdslwdo#P'			62.25	35.35	67.0	28.43	128.43	6224.1
Fhoo#fdsh{/#P'								3396.5
Srzhu#frqyhuvlrq#fds								2823.4
ERV#fdsh								2.12
Ghzd					13.8			
Ol					53.2			
	.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					
h			119.82				4,798.20	

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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 o
- 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

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Current Opinion in Electrochemistry

Review Article

Hydrogen is essential for sustainability

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

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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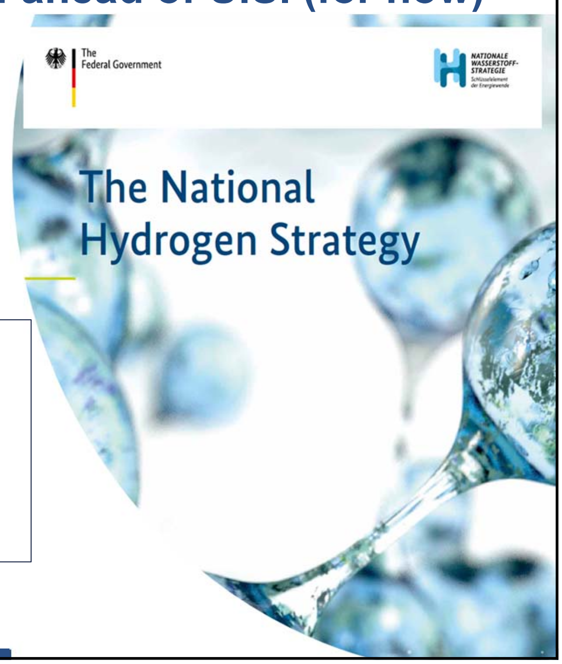
Europe, China, Japan, Australia, … ahead of U.S. (for now)

- Example: German National Hydrogen Strategy
- Announced: June, 2020

Description:

- German Government will invest 9 billion euros
- National strategy will invest in 38 specific measures in 10 hydrogen topics



Hydrogen Economy as part of European Union Recovery and Stability Plan, "Green Deal", and "Just Transition"

- 34 billion euros committed in "Recovery" plan
- Expected to double with "Green Deal" and "Just Transition" finalization

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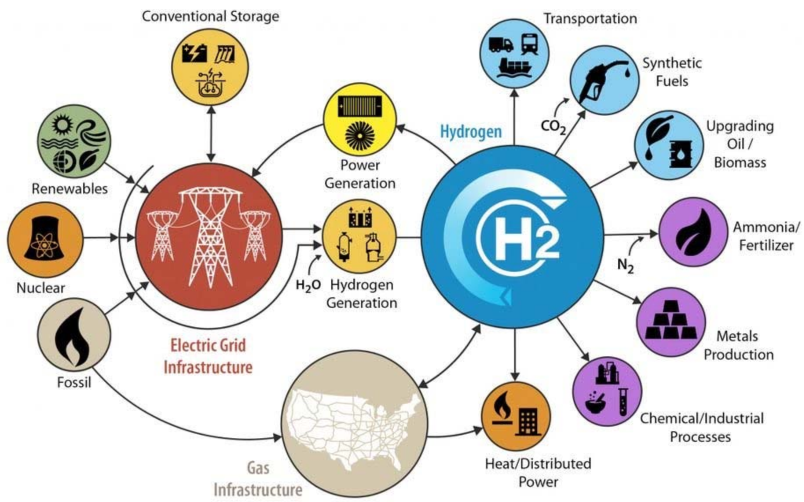
U.S. DOE's H2@Scale & Hydrogen Energy Earthshot



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From: U.S. DOE (https://www.energy.gov/eere/fuelcells/hydrogen-anc

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Infrastructure Bill Language on Hydrogen Hubs – Subtitle B:

"SEC. 813. REGIONAL CLEAN HYDROGEN HUBS.

"(a) DEFINITION OF REGIONAL CLEAN HYDROGEN HUB.—In this section, the term 'regional clean hydrogen hub' means a network of clean hydrogen producers, potential clean hydrogen consumers, and connective infrastructure located in close proximity.

"(b) ESTABLISHMENT OF PROGRAM.—The Secretary shall establish a program to support the development of at least 4 regional clean hydrogen hubs that—

"(1) demonstrably aid the achievement of the clean hydrogen production standard developed under section 822(a);

"(2) demonstrate the production, processing, delivery, storage, and end-use of clean hydrogen; and

"(3) can be developed into a national clean hydrogen network to facilitate a clean hydrogen economy.

"(c) SELECTION OF REGIONAL CLEAN HYDROGEN HUBS.—

"(1) SOLICITATION OF PROPOSALS.—Not later than 180 days after the date of enactment of the Infrastructure Investment and Jobs Act, the Secretary shall solicit proposals for regional clean hydrogen hubs.

"(2) SELECTION OF HUBS.—Not later than 1 year after the deadline for the submission of proposals under paragraph (1), the Secretary shall select at least 4 regional clean hydrogen hubs to be developed under subsection (b).

(4) FUNDING OF REGIONAL CLEAN HYDROGEN HUBS.—The Secretary may make grants to each regional clean hydrogen hub selected under paragraph (2) to accelerate commercialization of, and demonstrate the production, processing, delivery, storage, and end-use of, clean hydrogen.

(d) AUTHORIZATION OF APPROPRIATIONS.—There is authorized to be appropriated to the Secretary to carry out this section $8,000,000,000 for the period of fiscal years 2022 through 2026.

"At least 4 hubs" – rumor is that 3 are probably "already promised" (to WV, TX, CA).

It might be even 6-8 hubs. Funding is $8,000,000,000 (a.k.a. *billion*) over a 5-year period.

Geographic diversity is an important criteria: understanding of what is "regional" varies.

DOE is likely to choose National Laboratories to lead (NETL, INL, NREL, probably LBL).

Strong role for the industry; public/private partnerships.

Industry/consortia lead is not excluded. University lead is unlikely.

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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
  - Environmental Justice
- 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
  - Hydrogen & its derivative fuels
  - Will be lower cost (separate power/energy scaling)
  - High round-trip efficiency possible

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Do we Really Need Hydr n?

from: San Diego Union Tribune

Absolutely!

We can't get to ZERO without it!

Jack Brouwer

December 10, 2021

Fondazione Courmayeur Mont-Blanc

uture of energy: an analysis by international stakeholders

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