Electrification is Important!
Then We Must Add Hydrogen!

Ohio Fuel Cell & Hydrogen Coalition Summit (October 27, 2025)

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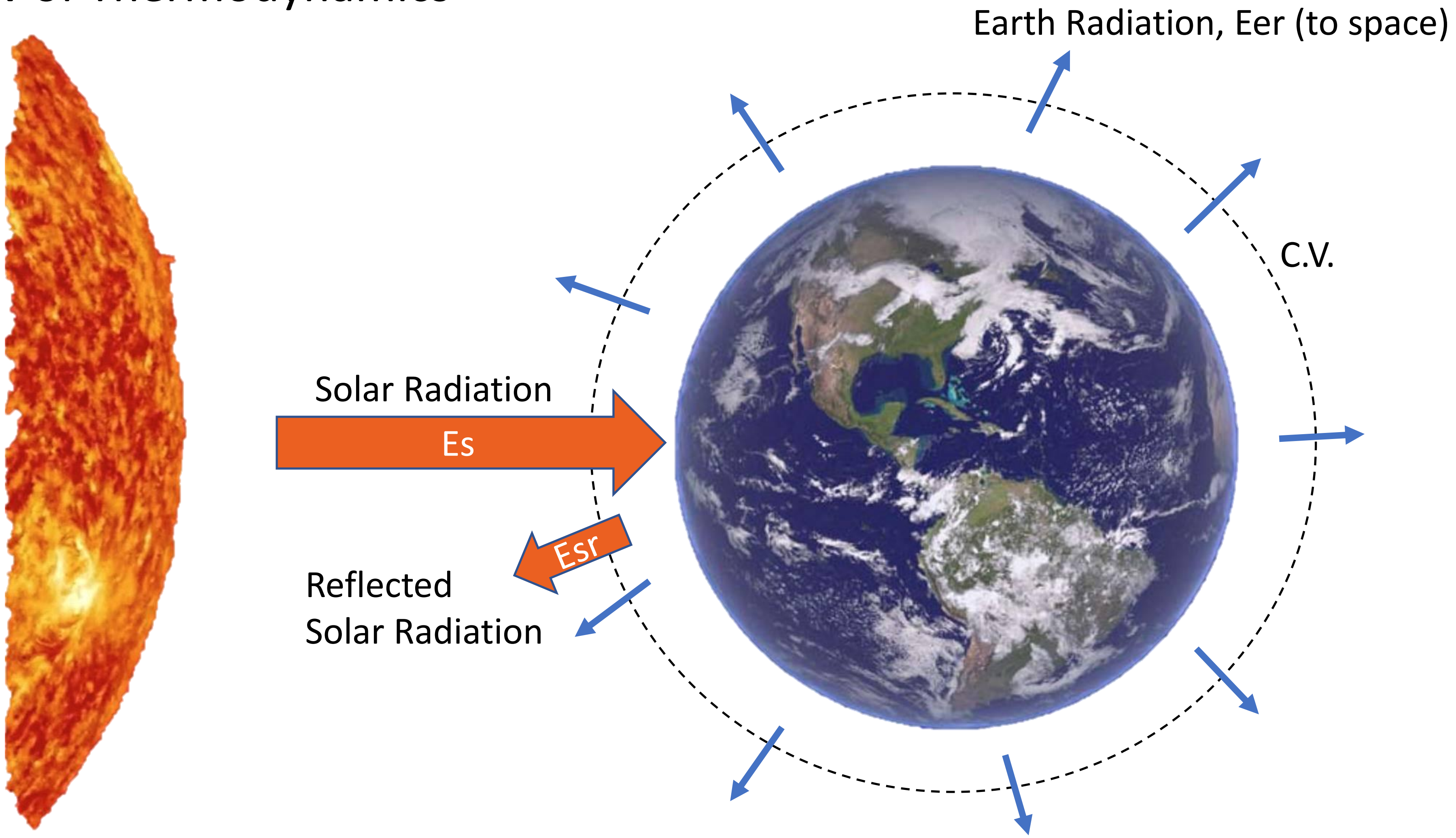
Prof. Jack Brouwer, Director
Clean Energy Institute, UC Irvine

Earth Energy Balance

- First Law of Thermodynamics



$$\Delta E_{earth} = Es – Esr - Eer$$

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"

* except for nuclear

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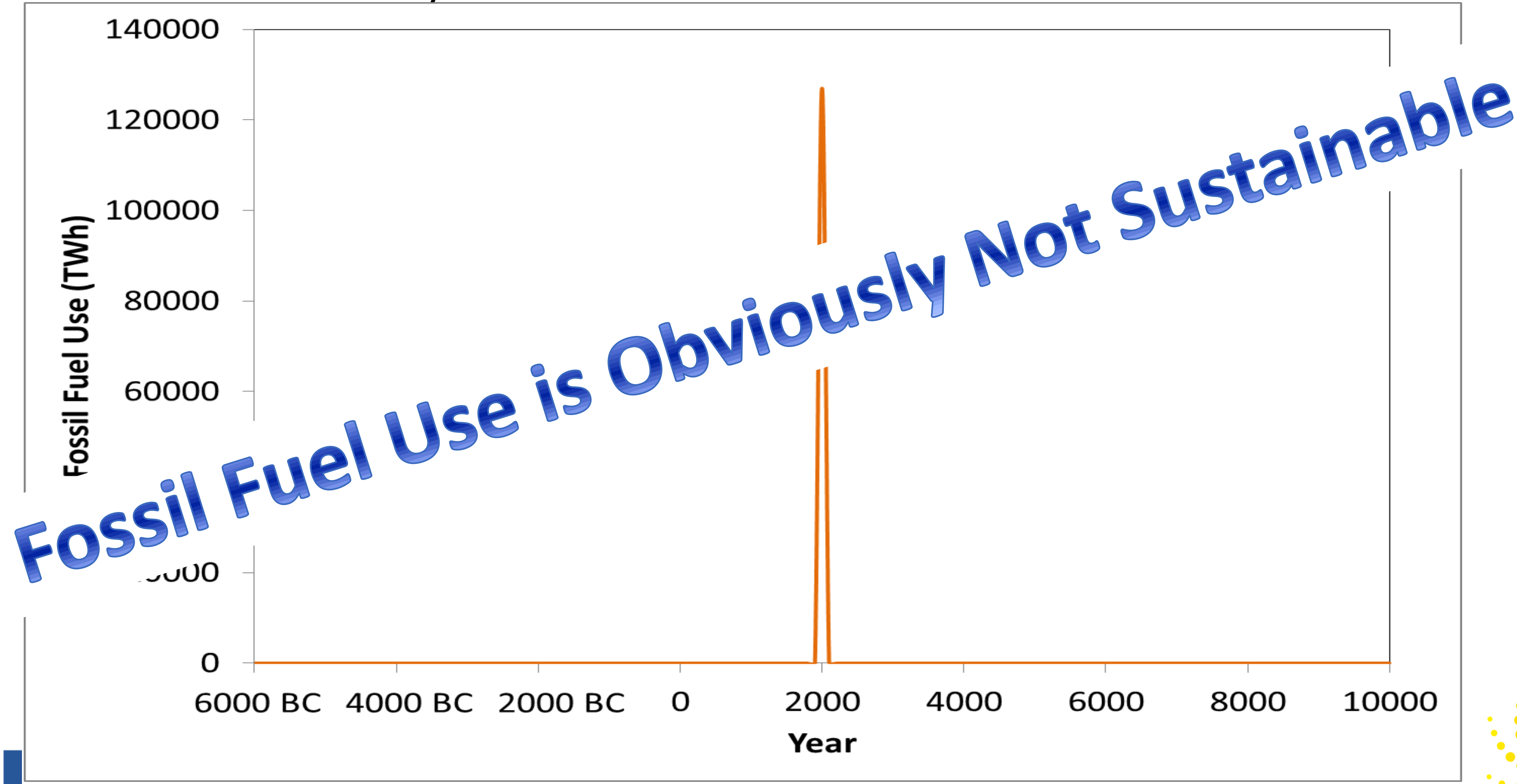
Energy on Earth

Current Practices are Obviously not Sustainable



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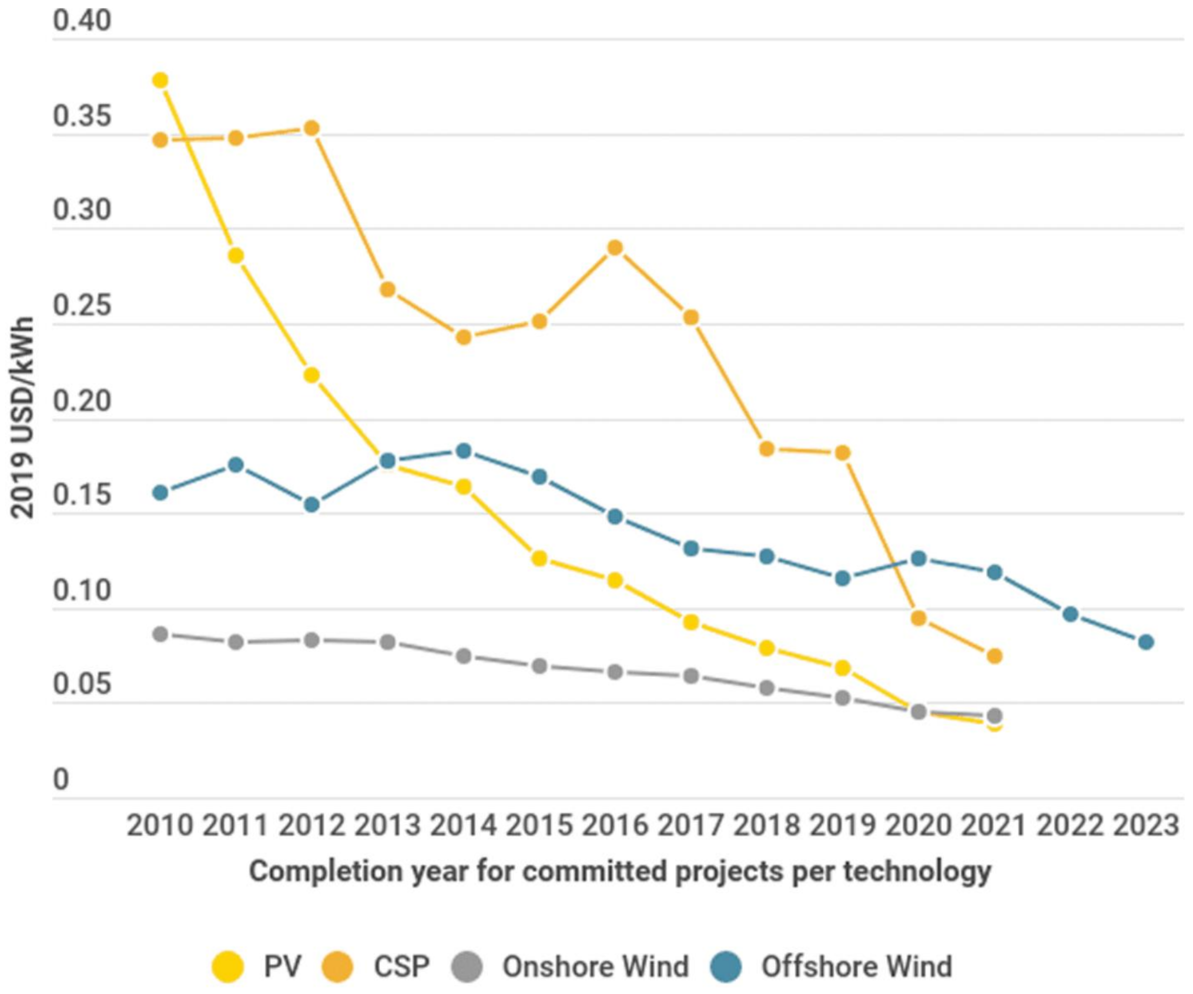
Adopt More Solar & Wind and Use It Directly – Electrify!

Must increasingly adopt energy conversion that is sustainable & naturally replenished quickly

<u>Good News!</u>

- Widely & more equitably available around world
- Now typically cheapest form of primary energy
- We must increase pace of installation & match production to demand
- Should electrify as many end-uses as possible



From: IRENA, www.irena.org/newsroom/pressreleases/2023/Jun , 2023

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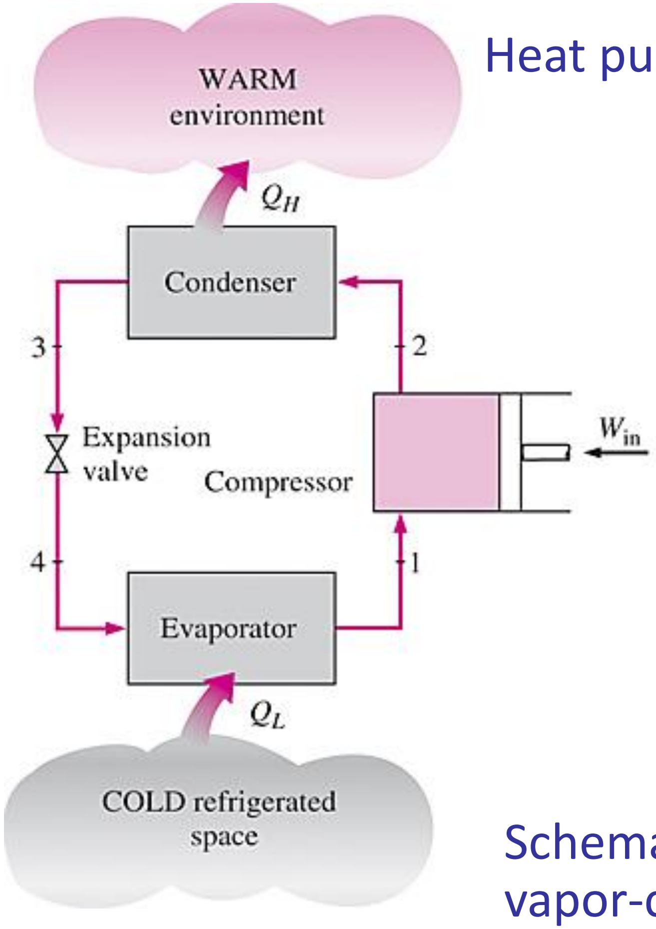
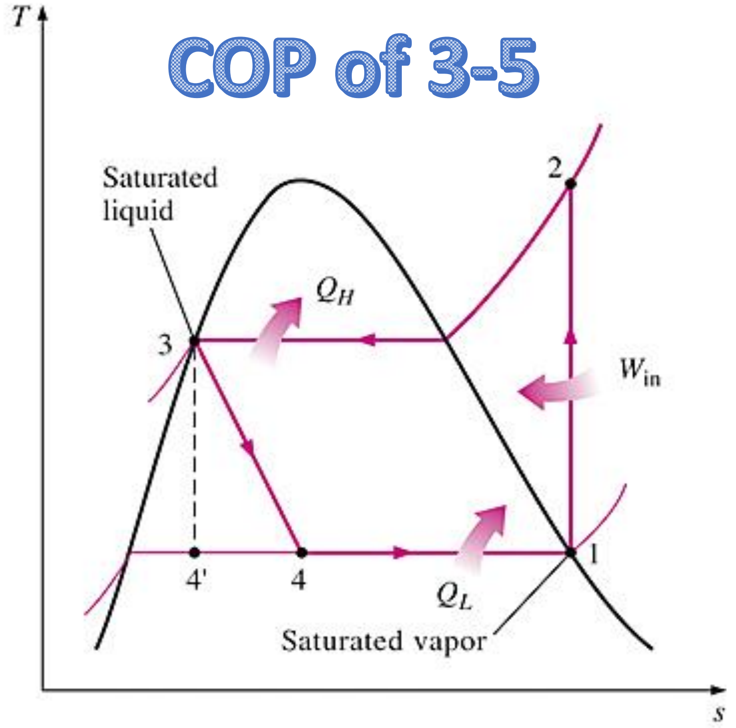
Electrification Loading Order

- Decarbonize and depollute electricity generation
- Use clean electricity to serve existing end-uses (e.g., buildings) by matching supply/demand
- Convert additional end-uses to electricity (matching supply/demand)
  - Heat pumps
  - Battery electric vehicles
- Use efficient storage
  - Batteries (short duration only)
  - Pumped hydro (long duration)

Heat pump / Refrigeration / Air Conditioning

COP of 3-5





Schematic and *T-s* diagram for the ideal vapor-compression refrigeration cycle

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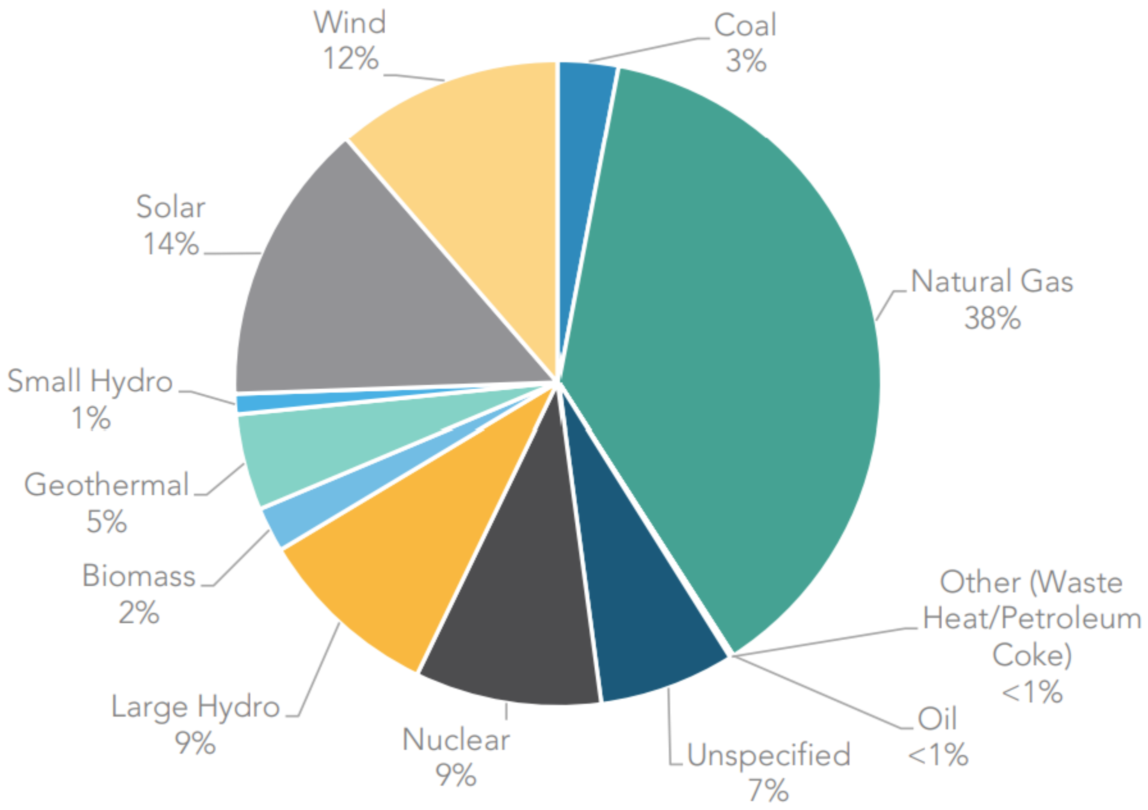
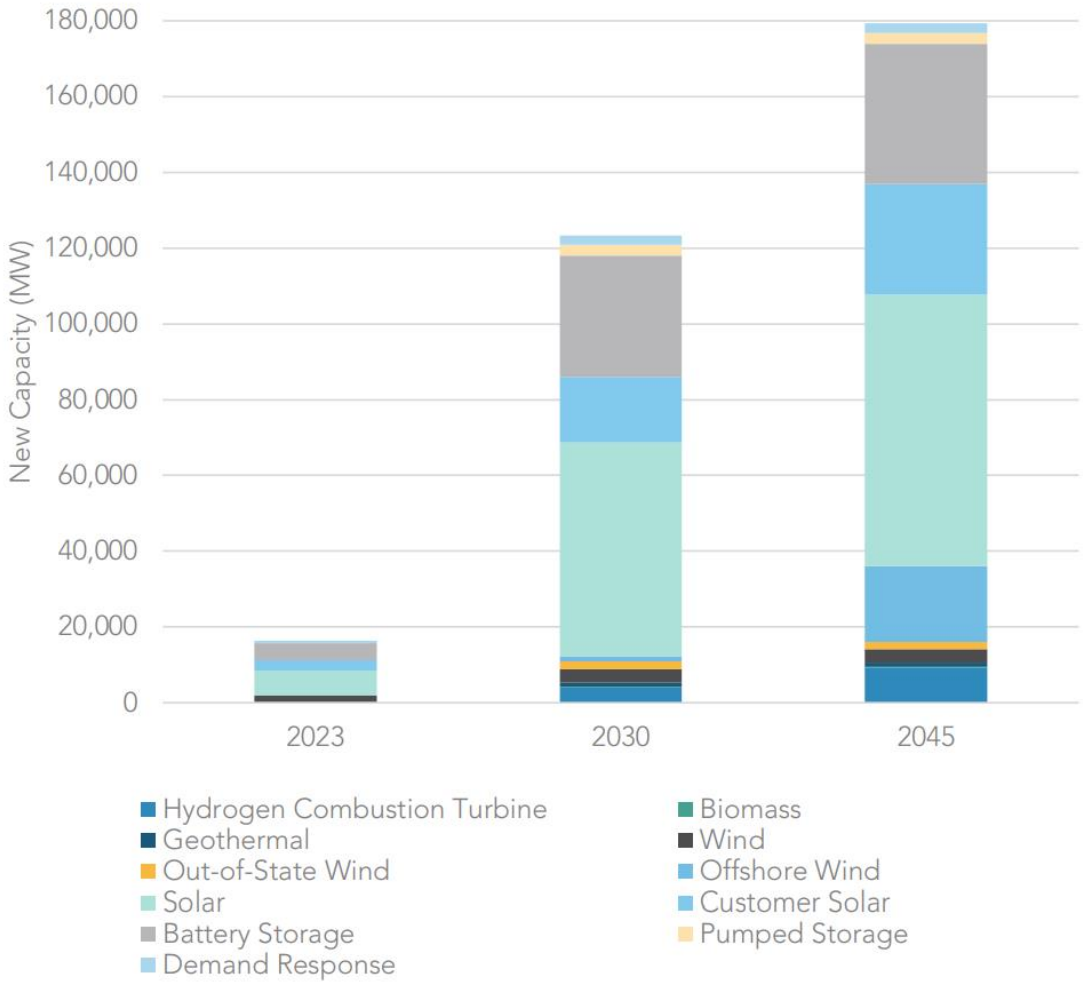
California: some of the best Energy/Environment policies in the World

- CA is leading the U.S. in solar & batteries



Note: Imports contributing to total system generation are comprised of 58% zero-carbon energy and 42% non-renewable and unspecified energy. Percentages do not add to exactly 100 due to rounding.



From: CARB 2022 Scoping Plan
https://ww2.arb.ca.gov/sites/default/files/2022-12/2022-sp.pdf

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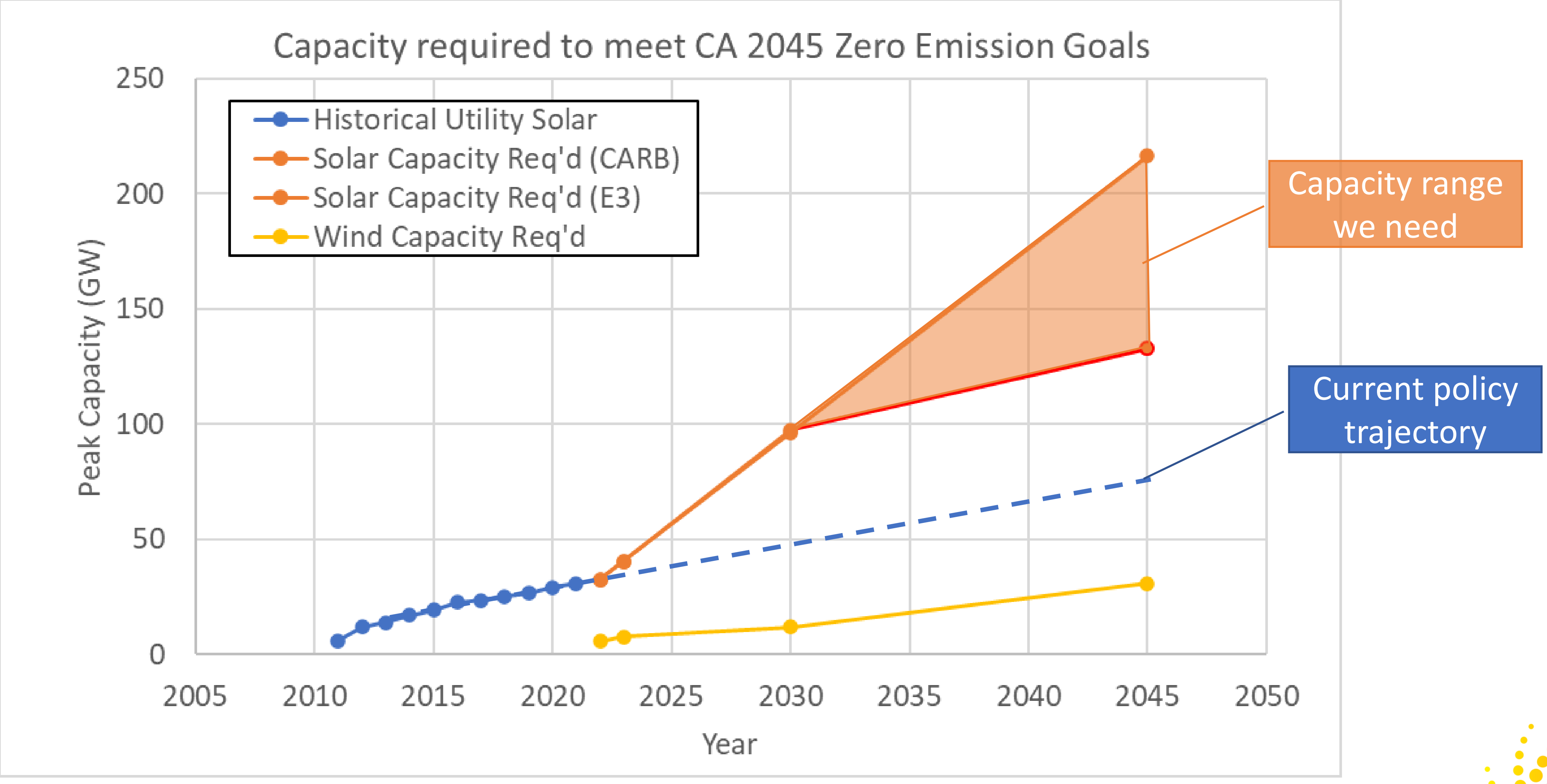
Not installing renewable generation fast enough

- We must dramatically increase the pace of adoption



From: CARB 2022 Scoping Plan, ww2.arb.ca.gov/sites/default/files/2022-12/2022-sp.pdf
Energy + Environment + Economics (E3), 2023

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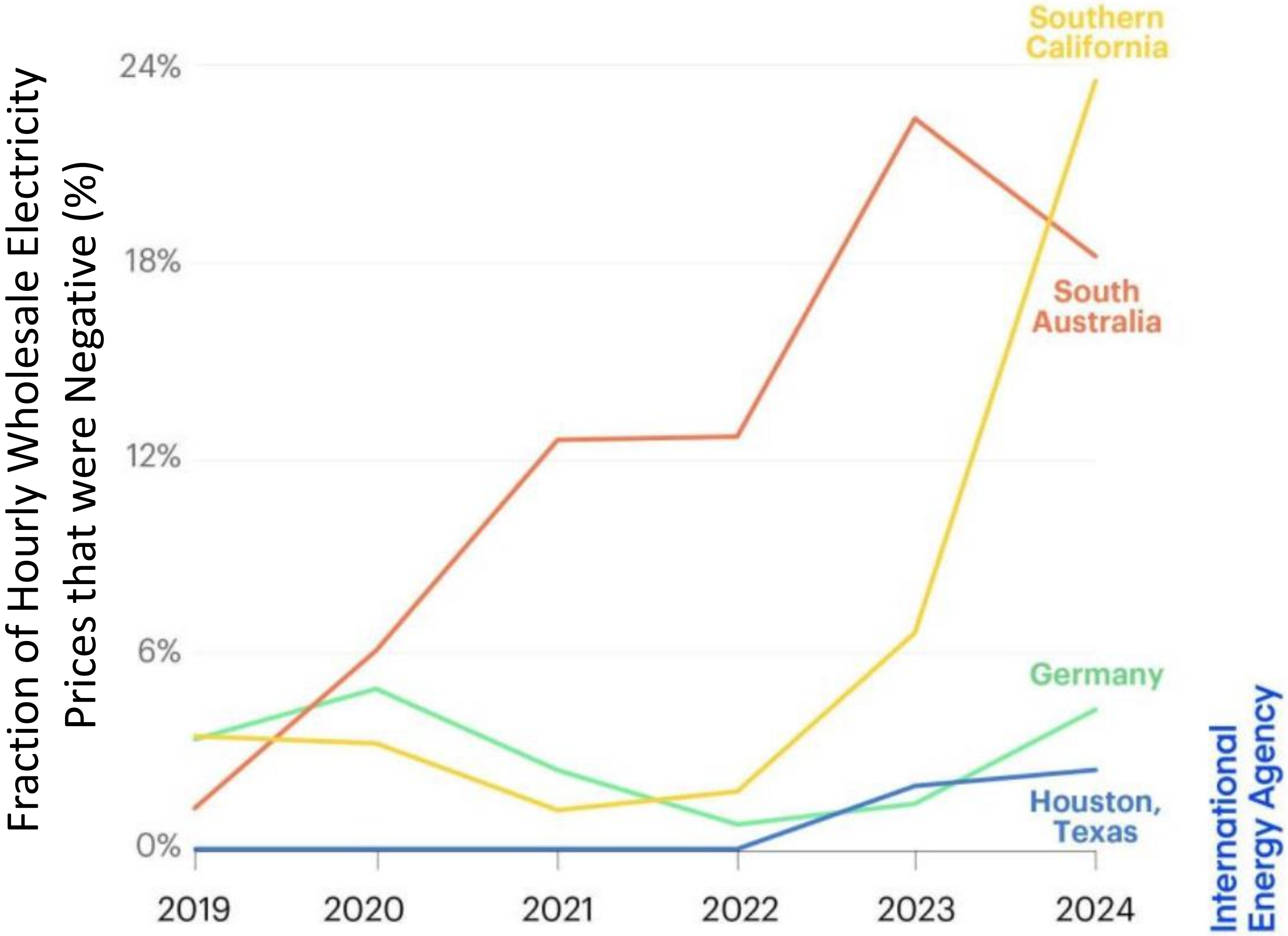
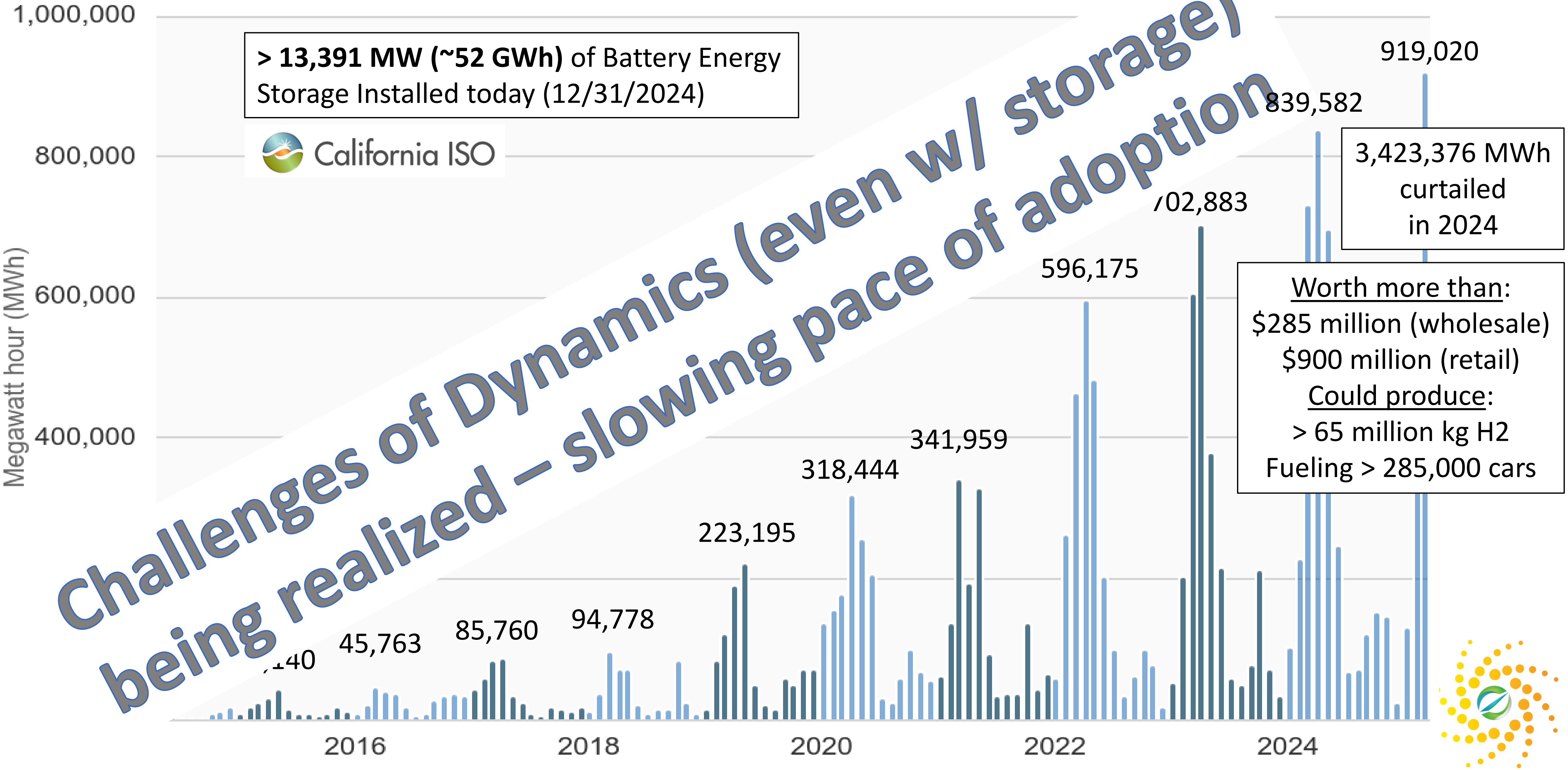
High Renewable Use is Challenging (Negative Prices)

- Trends of negative prices in U.S. (CA & TX), Germany and South Australia (2019 – 2024)



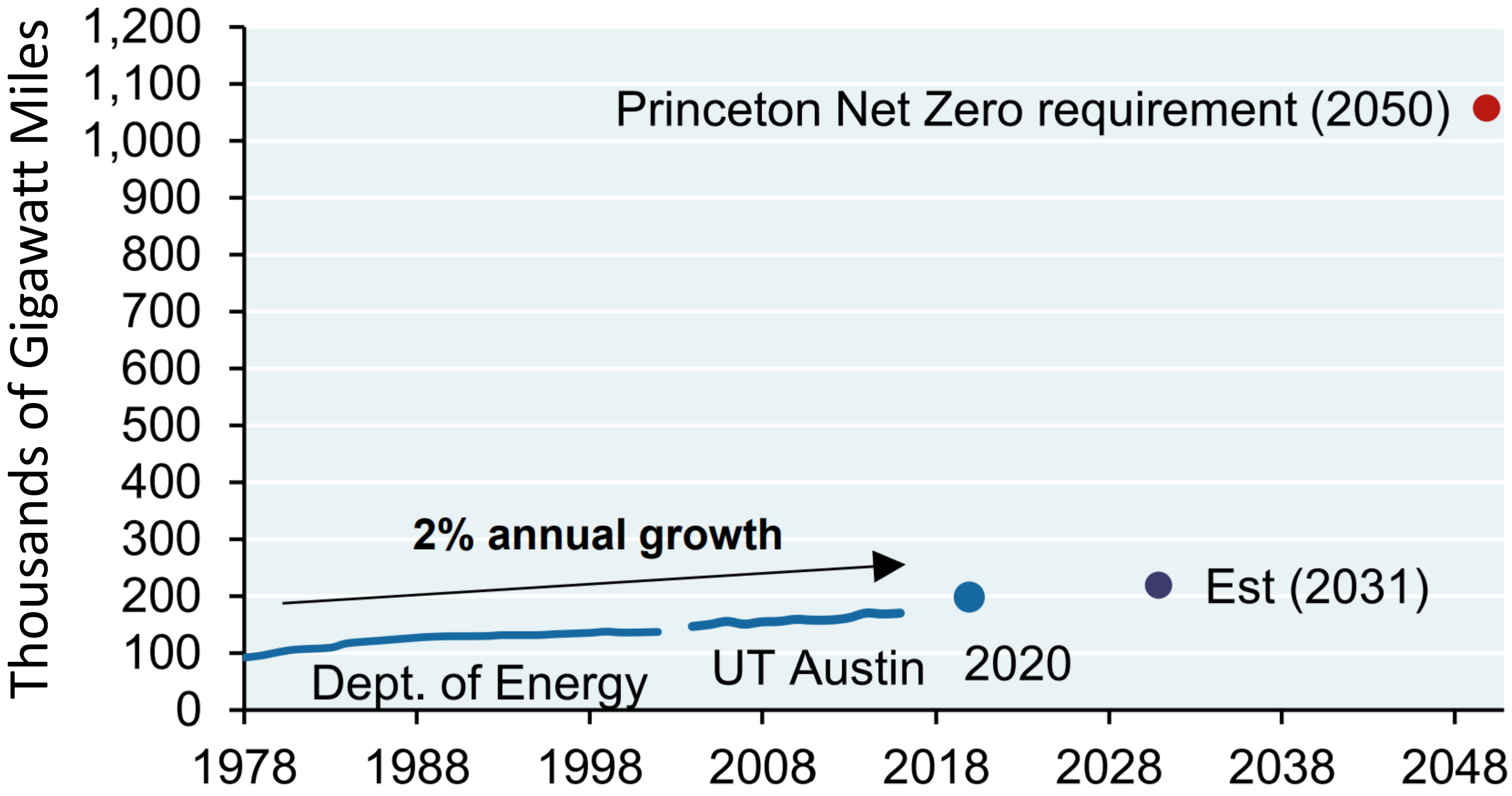
Source: International Energy Agency, https://www.linkedin.com/posts/international-energy-agency_negative-electricity-prices-are-becoming-activity-7232328008030638080-cPku/

High Renewable Use is Challenging (Solar & Wind Curtai… ent in CA)



Transmission Constraints – Generation & Storage Interconnection Queue

- U.S. transmission grid has been growing at just 2% per year since 1978



We need "new" and "additional" energy vectors

From: JP Morgan, 2022 Annual Energy Report, https://privatebank.jpmorgan.com/content/dam/.../2022-energy-paper/elephants-in-the-room.pdf (original sources include DOE, UT Austin, Princeton Net Zero study)

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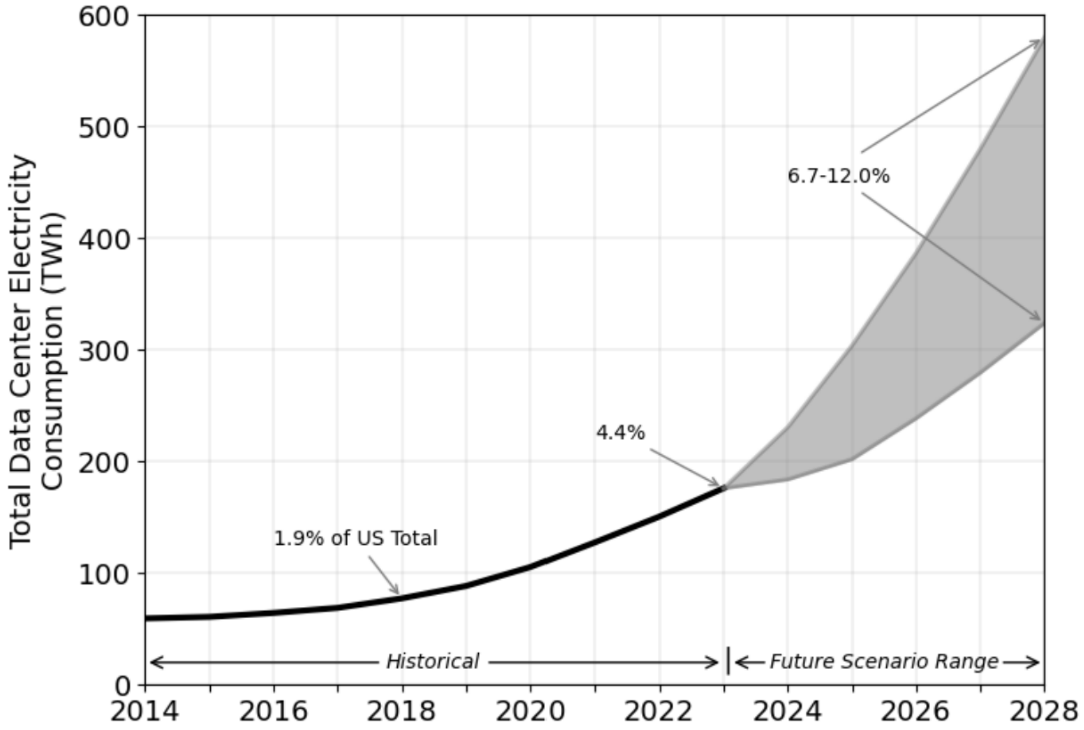
EV Charging & AI Data Center (Demand) Interconnection Queue

- Very significant growth experienced & projected

Data Center Electricity Demand



Shehabi, A., et al. 2024. 2024 United States Data Center Energy Usage Report. Lawrence Berkeley National Laboratory. LBNL-2001637

EV Electricity Demand

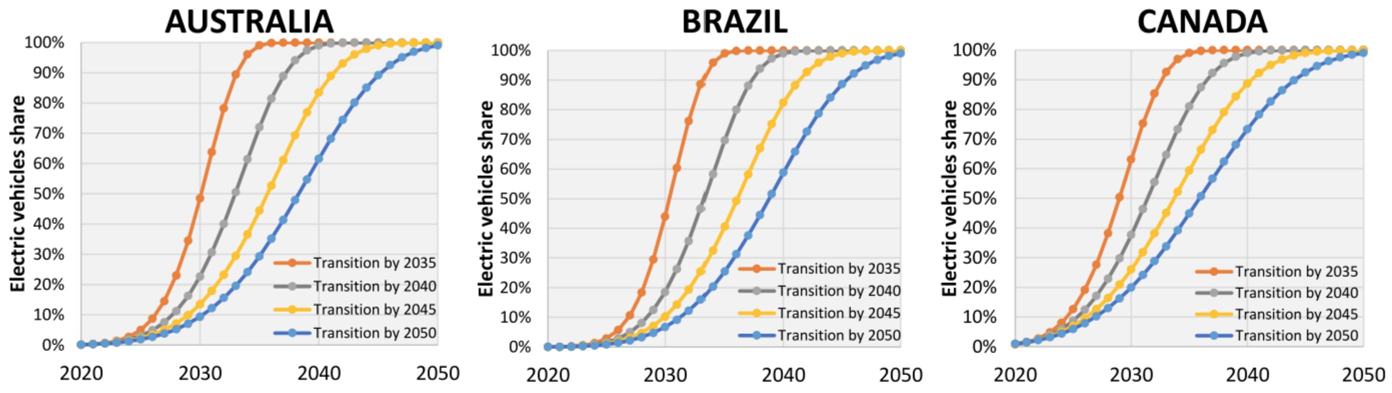


Fig. 7. Evolution of the EV fleets in four scenarios of transition.

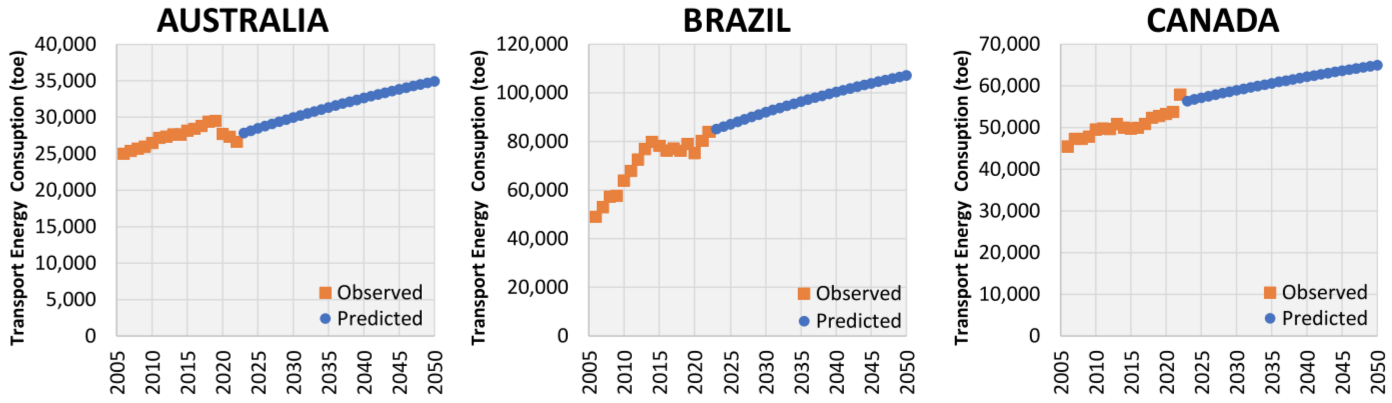


Fig. 8. Forecast of energy consumption in road transport.

Ruoso, A.C. et al., "Electric vehicles' impact on energy balance: Three-country comparison." Renewable and Sustainable Energy Reviews 203, 2024.

We must install more renewables & batteries AND **whole new vectors**

- Battery energy storage system, Menifee, CA (2,000 MW, 680,000 homes for 4 hours)

Electrolysis – Helps Renewable Dynamics & Difficult to Electrify Uses

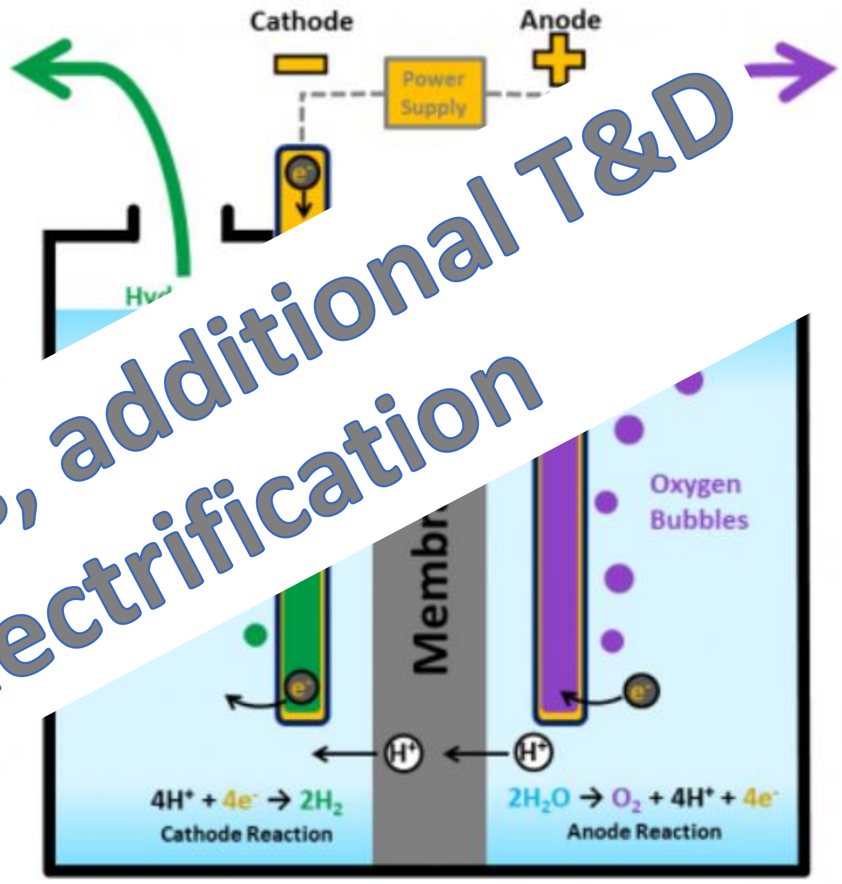
<u>Electrolysis</u>

- $2\ H_2O$ + Energy → $2\ H_2 + 1\ O_2$
- 1 liter of Water yields ~ 1 $Nm^3\ H_2$
- Typical System Power Demand:
  4 – 7 kWh/Nm^3 or
  45 – 78 kWh/kg (60 – 75% efficiency)

<u>Types</u>:

- Alkaline (commercial, lowest
- Proton Exchange Memb
  dynamic operation
- Solid Oxide
  (88% efficie integration)

Additional end uses, additional T&D vector for electrification



From: U.S. DOE

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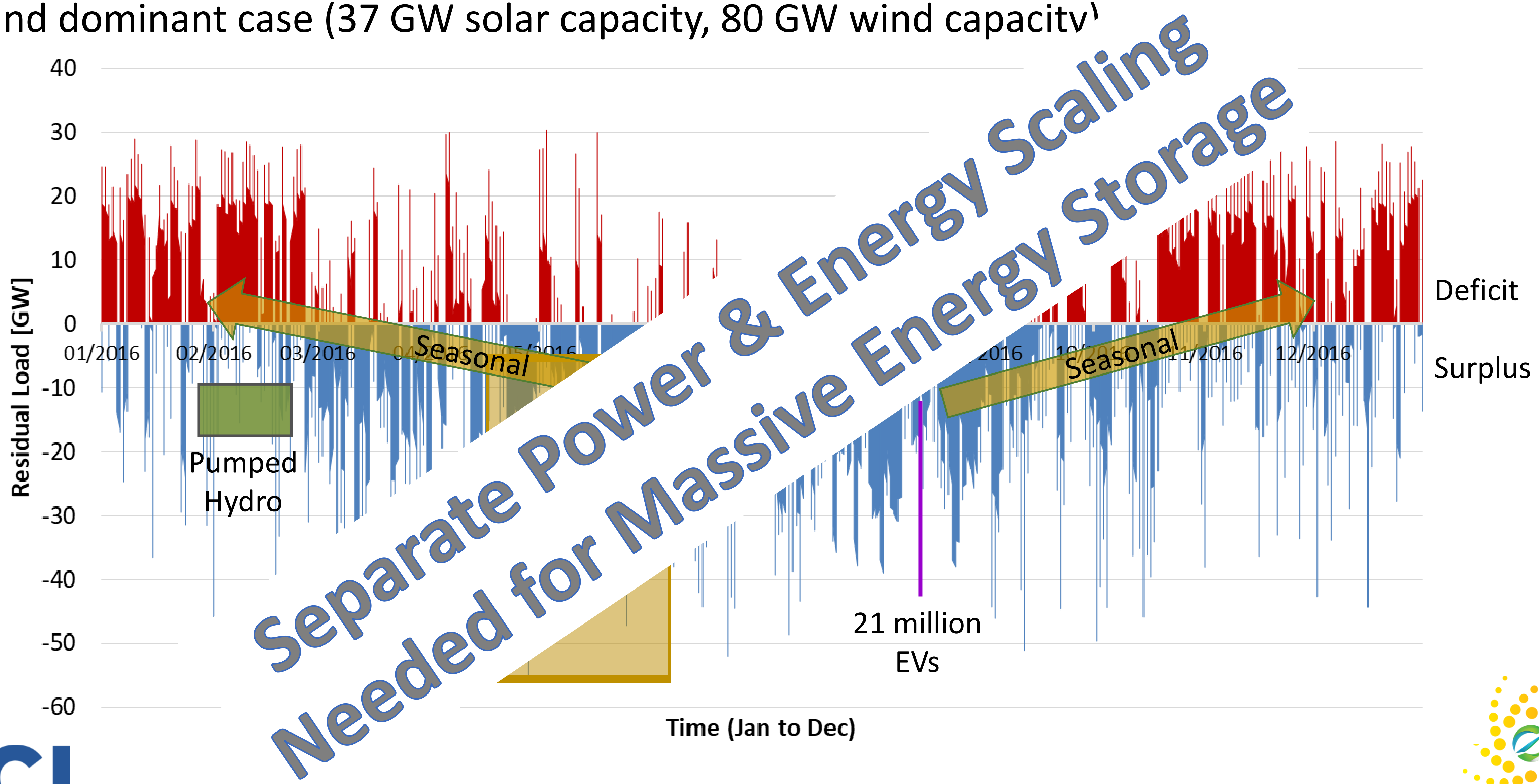
H2 Feature: Separate Power & Energy Scaling (lower cost, long duration)

- Wind dominant case (37 GW solar capacity, 80 GW wind capacity)



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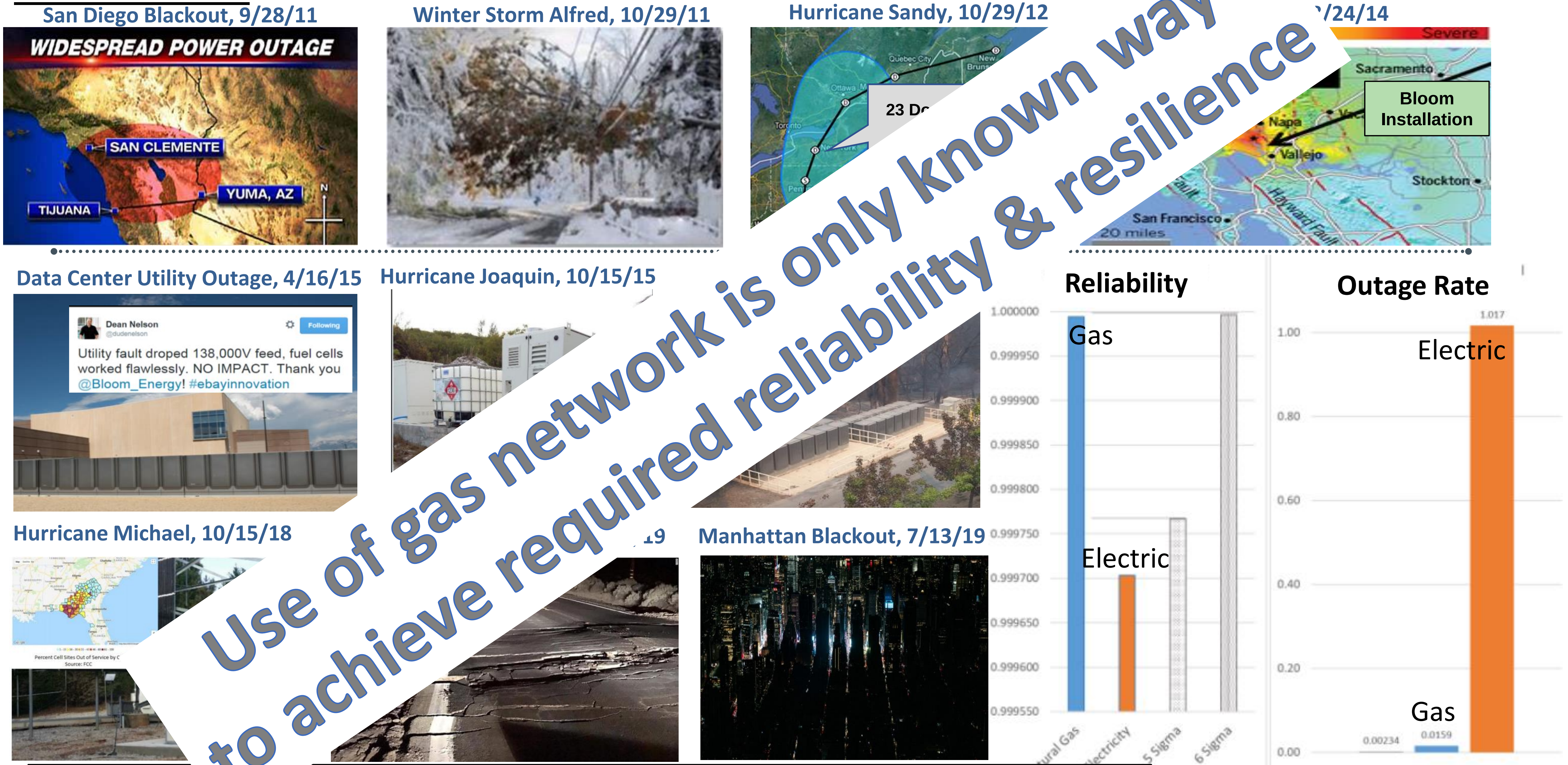
H2 Feature: Demonstrated Resilience of Fuel Cells ar… …ystem



Liss, W., & Rowley, …). *Assessment of natural gas and electric distribution service reliability*. Gas Technology Institute.

H2 Feature: Lightweight Zero Emission Fuels Required

- Provide zero emissions fuel to difficult end-uses

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

H2 Feature: Industry Requirements for Heat, Feedstock, Reducing Gas

- Many examples of applications that cannot be electrified

Steel Manufacturing & Processing

Cement Production

(Photo: ABB Cement)

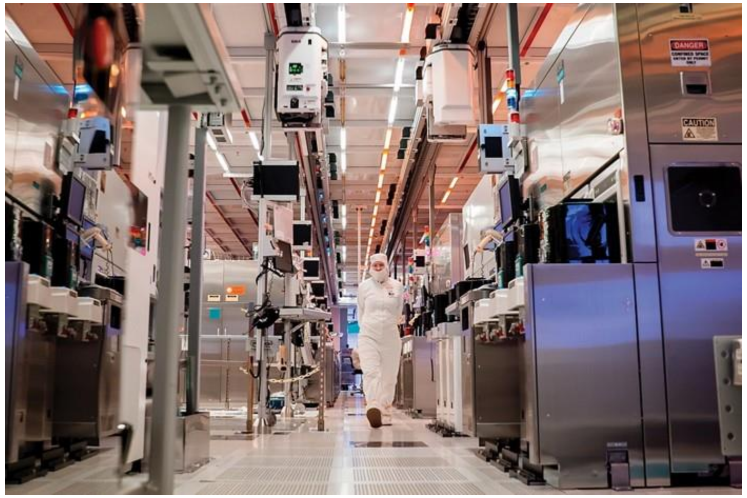
Plastics

(Photo: DowDuPont Inc.*)*

Ammonia & Fertilizer Production

(Photo: Galveston County Economic Development)

Computer Chip Fabrication



(Photo: American Chemical Society)

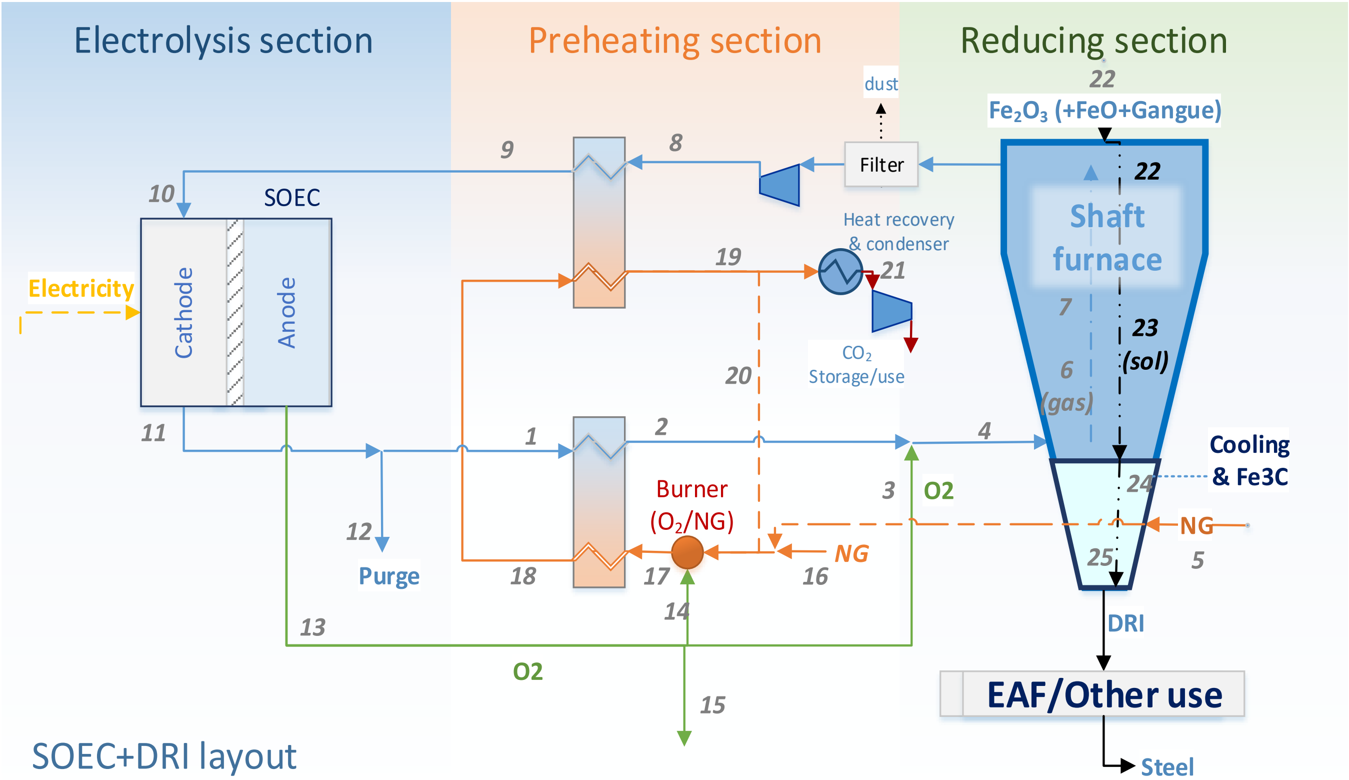
Pharmaceuticals

(Photo: Geosyntec Consultants)

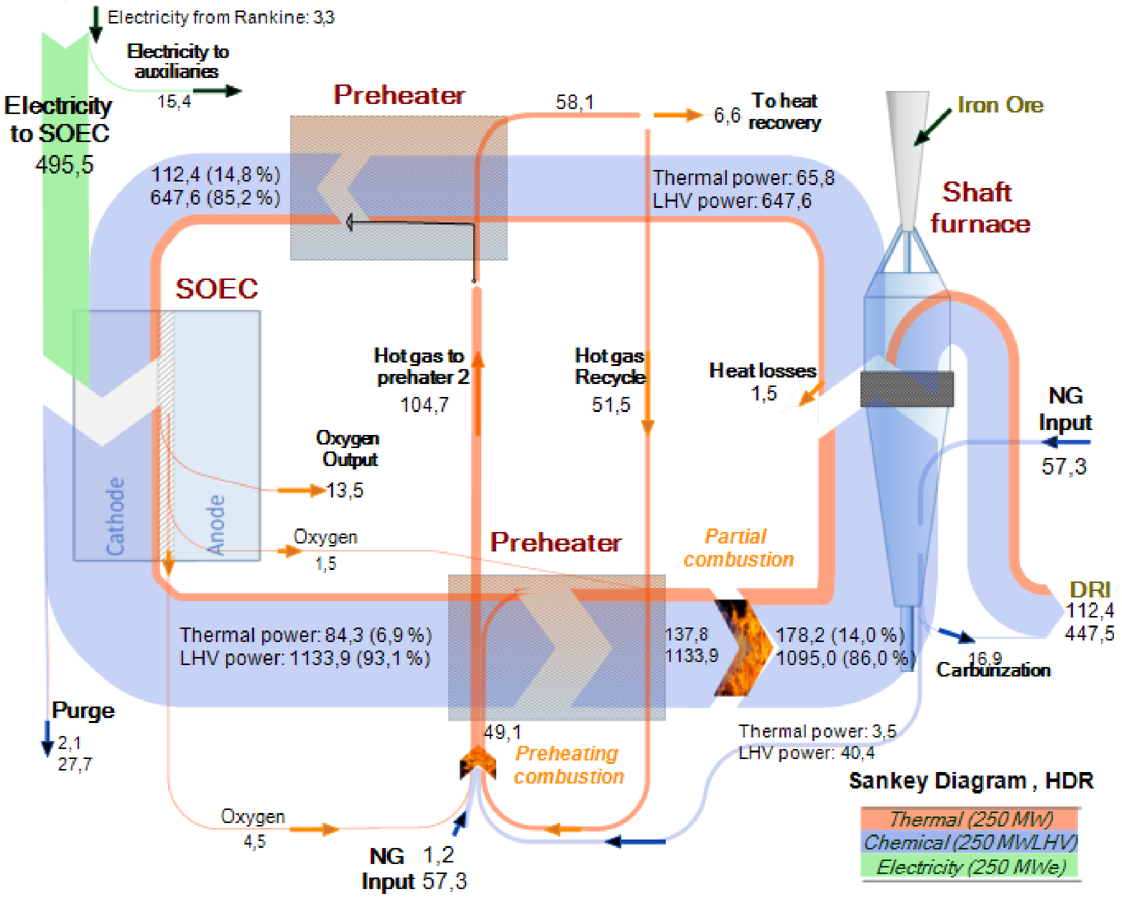
H2 Example: Integrated SOEC + Direct Reduced Iron (DRI) for Green

Team

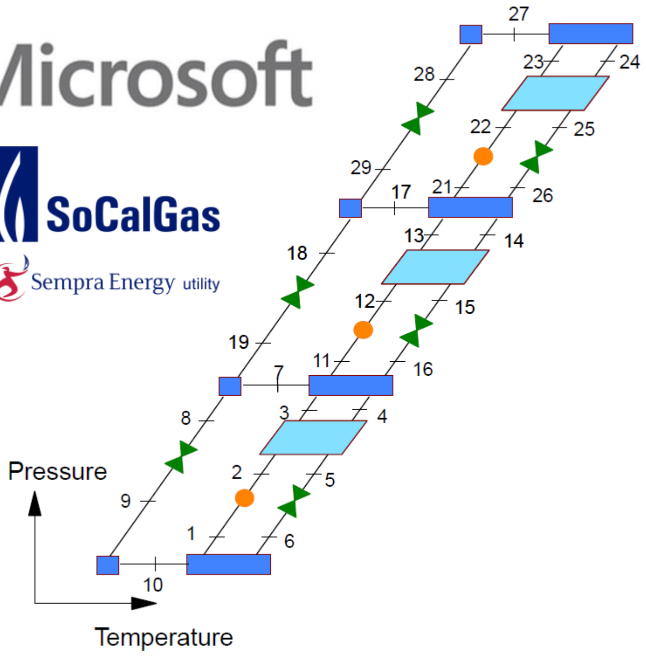
Advisors

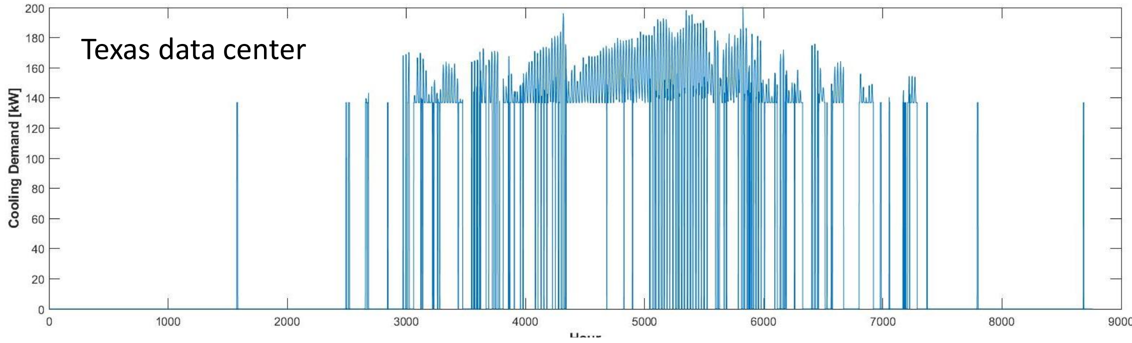


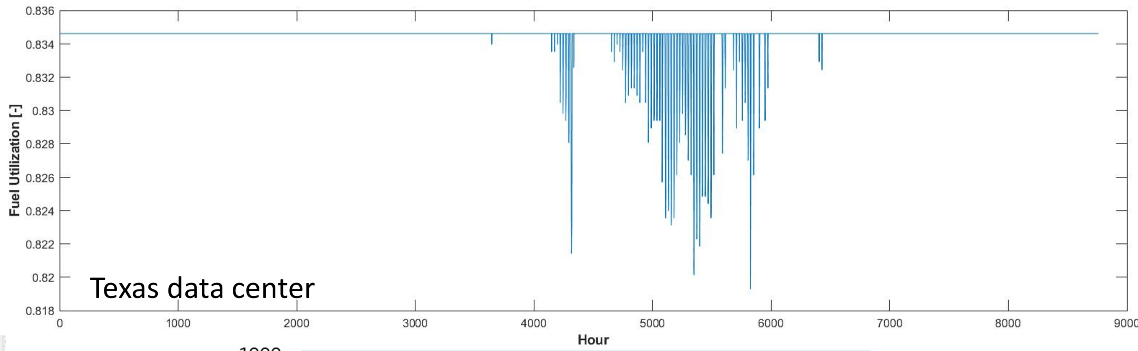
SOEC+DRI layout

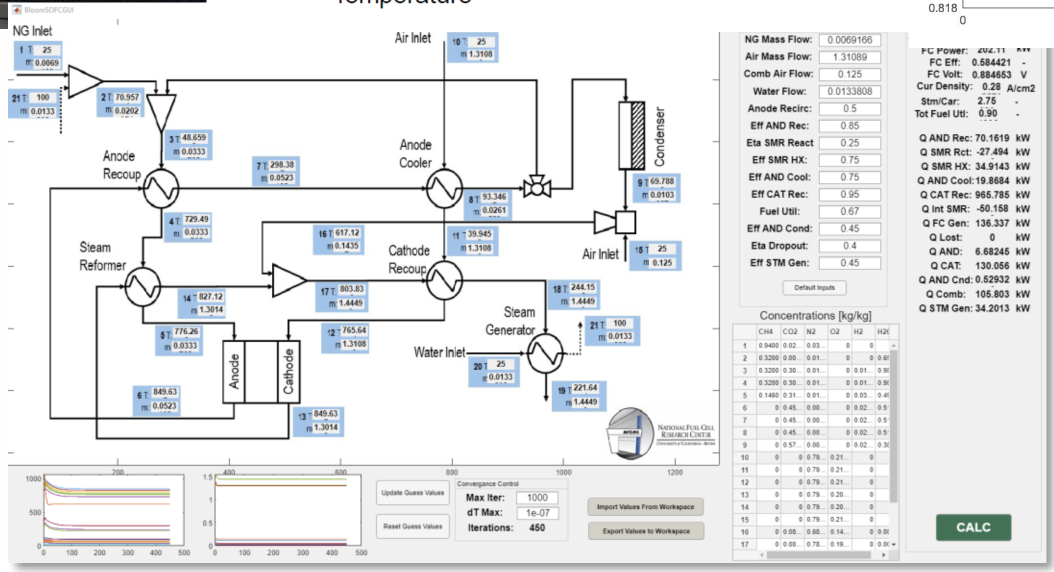


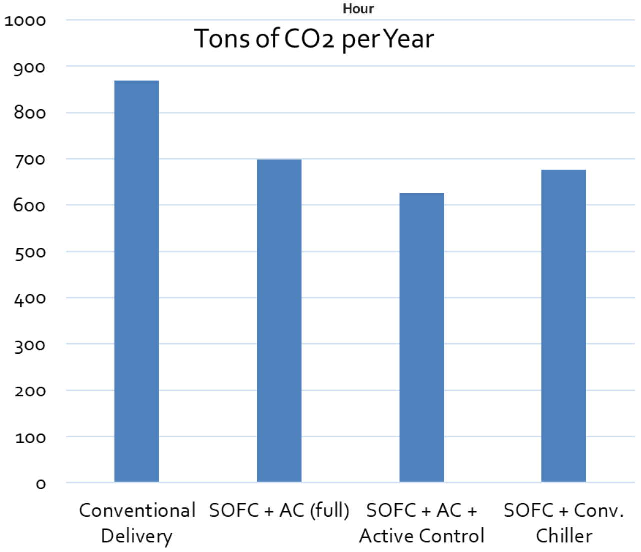
H2 Example: Integrated SOFC + Absorption Chilling for Data Centers







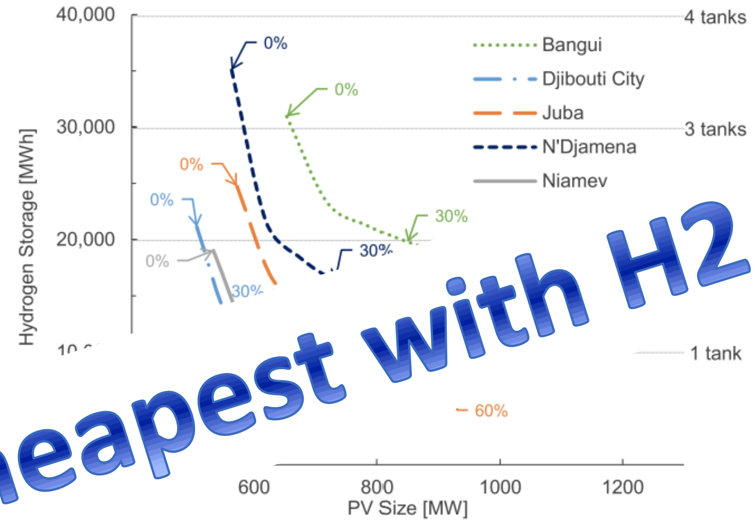


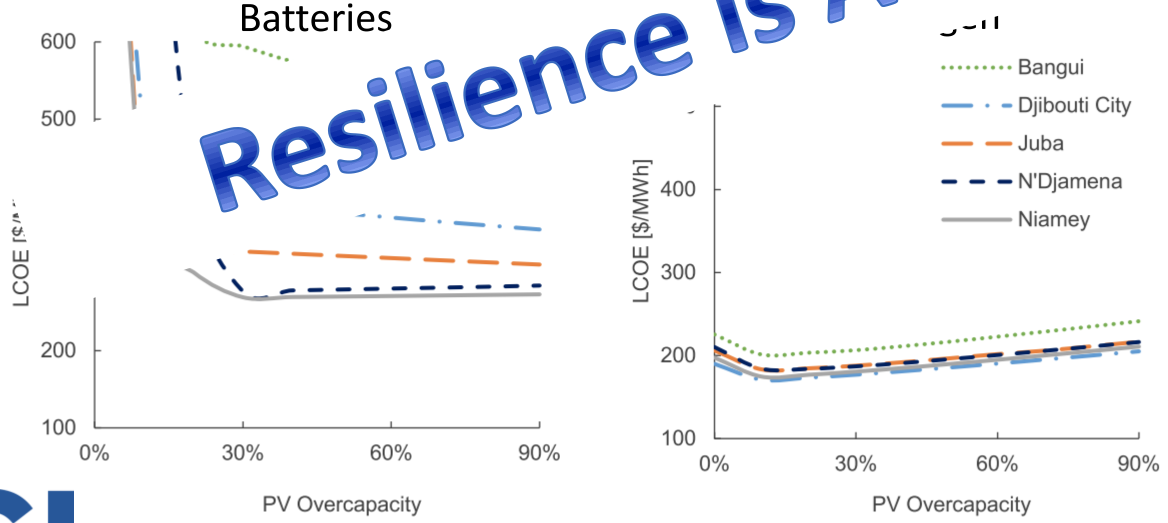


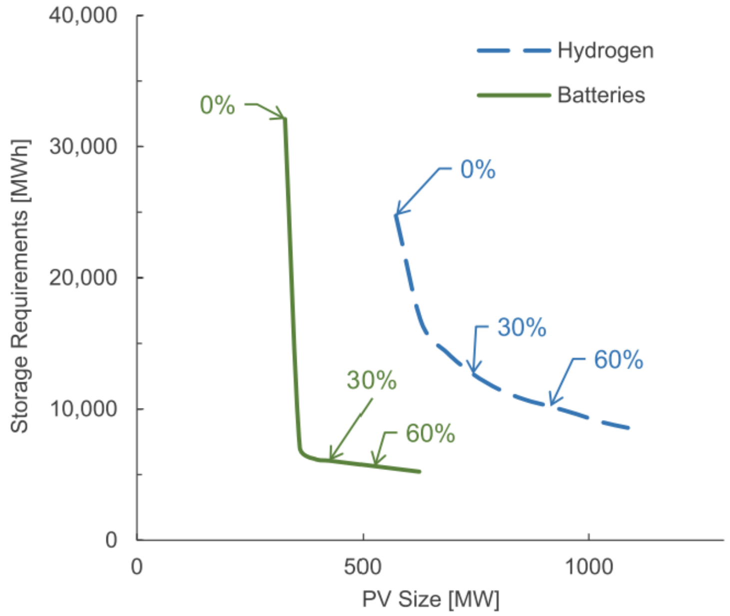
Lavernia, A. C., Asghari, M., Mastropasqua, L., & Brouwer, J. (2021). *ECS Transactions*, *103*(1), 807.

H2 Example: 100% Renewable Data Centers & Economic Development

- Sub-Saharan Africa Data Center Locations







Resilience is Always Cheapest with H2

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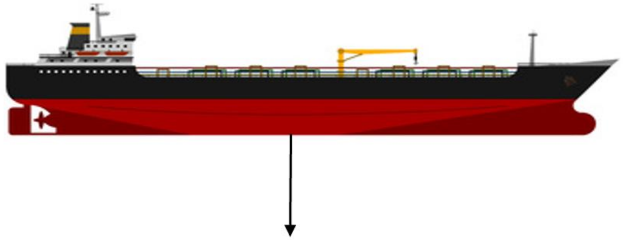
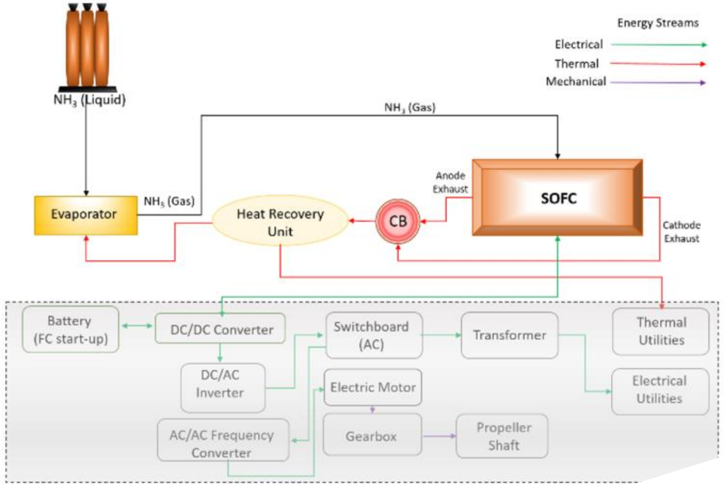
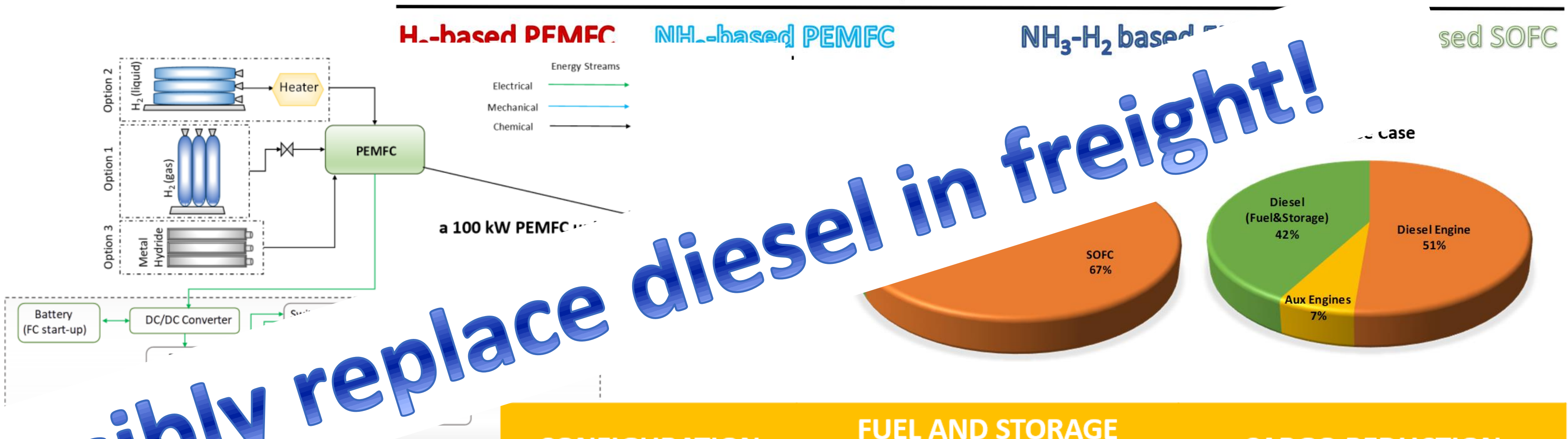
Huff, A., Melchor, M. A., & Brouwer, J. (2025). *Energy Conversion and Management*, *340*, 119990.

H2 Feature: Physical Modeling of Ships

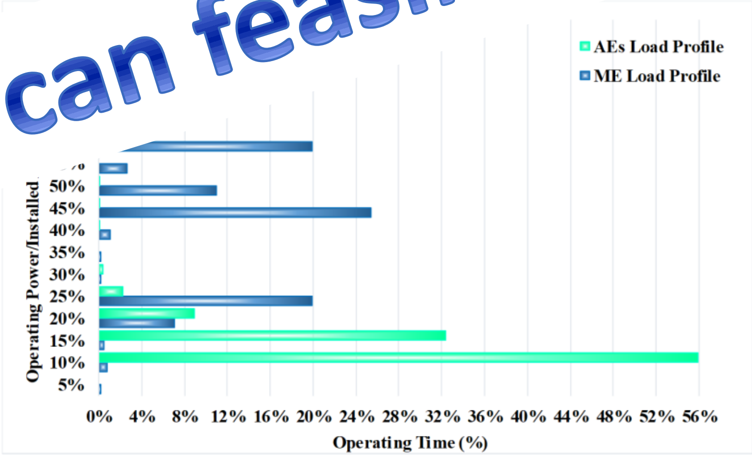
- Collaboration w/ U. Naples-Parthenope







H2 can feasibly replace diesel in freight!



CONFIGURATION	FUEL AND STORAGE WEIGHT (TONS)				CARGO REDUCTION			
H_2-based PEMFC	LH2	GH2 (350 bar)	GH2 (700 bar)	MH	LH2	GH2 (350 bar)	GH2 (700 bar)	MH
	353.5	896.7	810.3	4369.3	0.1%	1.3%	1.1%	9%
NH3-based PEMFC with Pd-Membrane	852.3				1.6%			
NH3-based PEMFC with PSA as purification system	872.8				1.3%			
NH3-H2 based ENGINE with H2 STORED on-board	NH3-LH2	NH3-GH2 (350 bar)	NH3-GH2 (700 bar)		NH3-LH2	NH3-GH2 (350 bar)	NH3-GH2 (700 bar)	
	590.1	721.1	712.2		0.8%	1.08%	1.06%	
NH3-H2 based ENGINE with H2 PRODUCED on-board	Pd-Membrane	PSA			Pd-Membrane	PSA		
	706.5	711.3			1.4%	1.09%		
NH_3-based SOFC	244				2.88%*			

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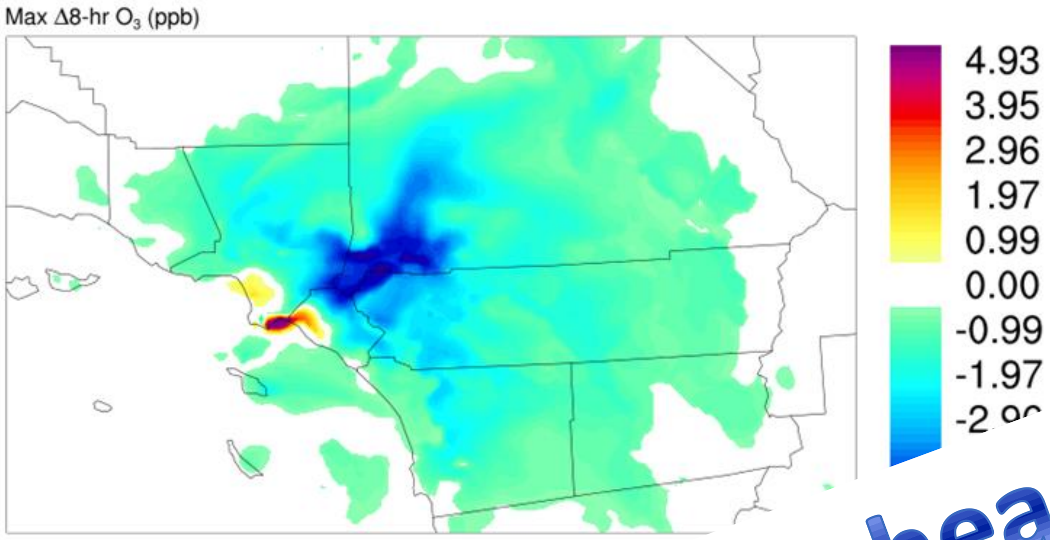
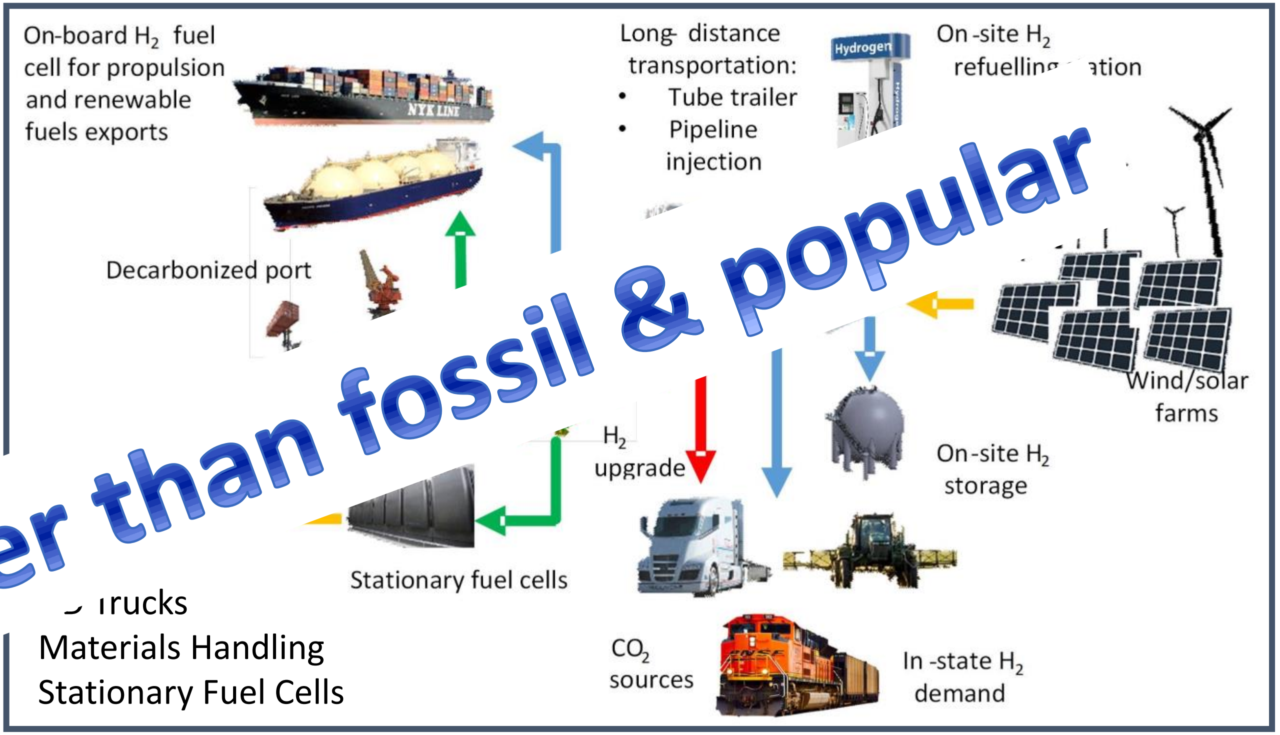
Di Micco, S., Mastropasqua, L., Cigolotti, V., Minutillo, M., & Brouwer, J. (2022).. *Energy Conversion and Management*, *267*, 115893.

H2 Feature: Port Transformation w/ Renewable H2 – LA/LB Port

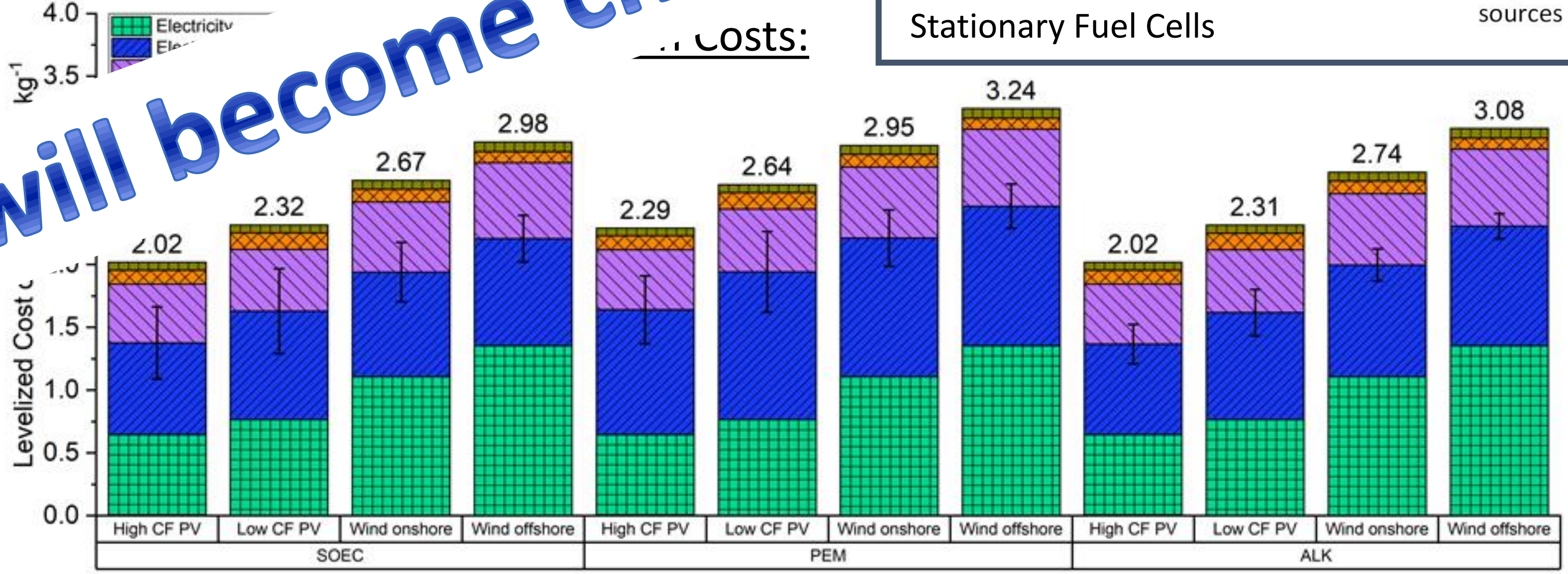
AQ Improvements:





H2 will become cheaper than fossil & popular

Costs:



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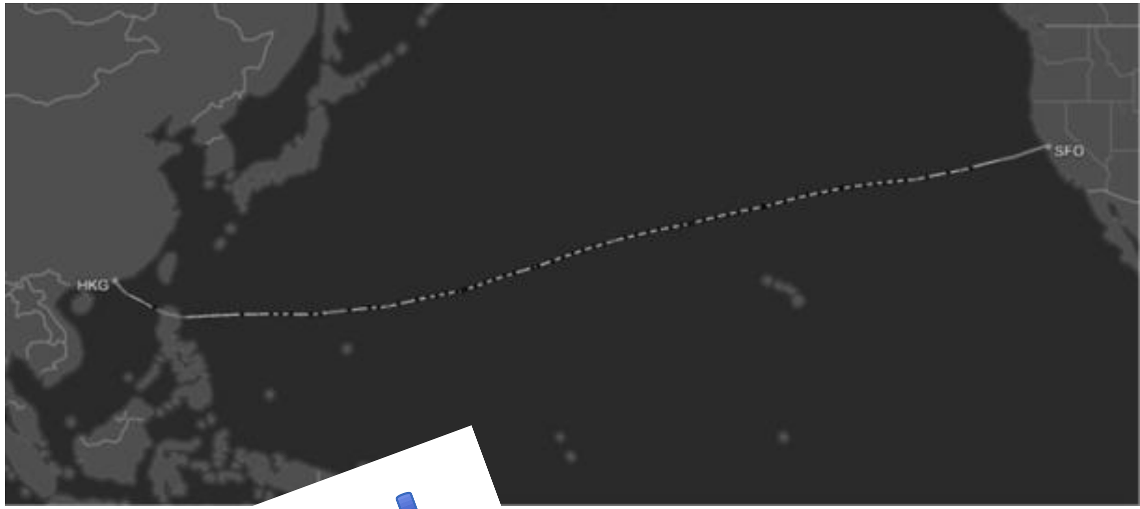
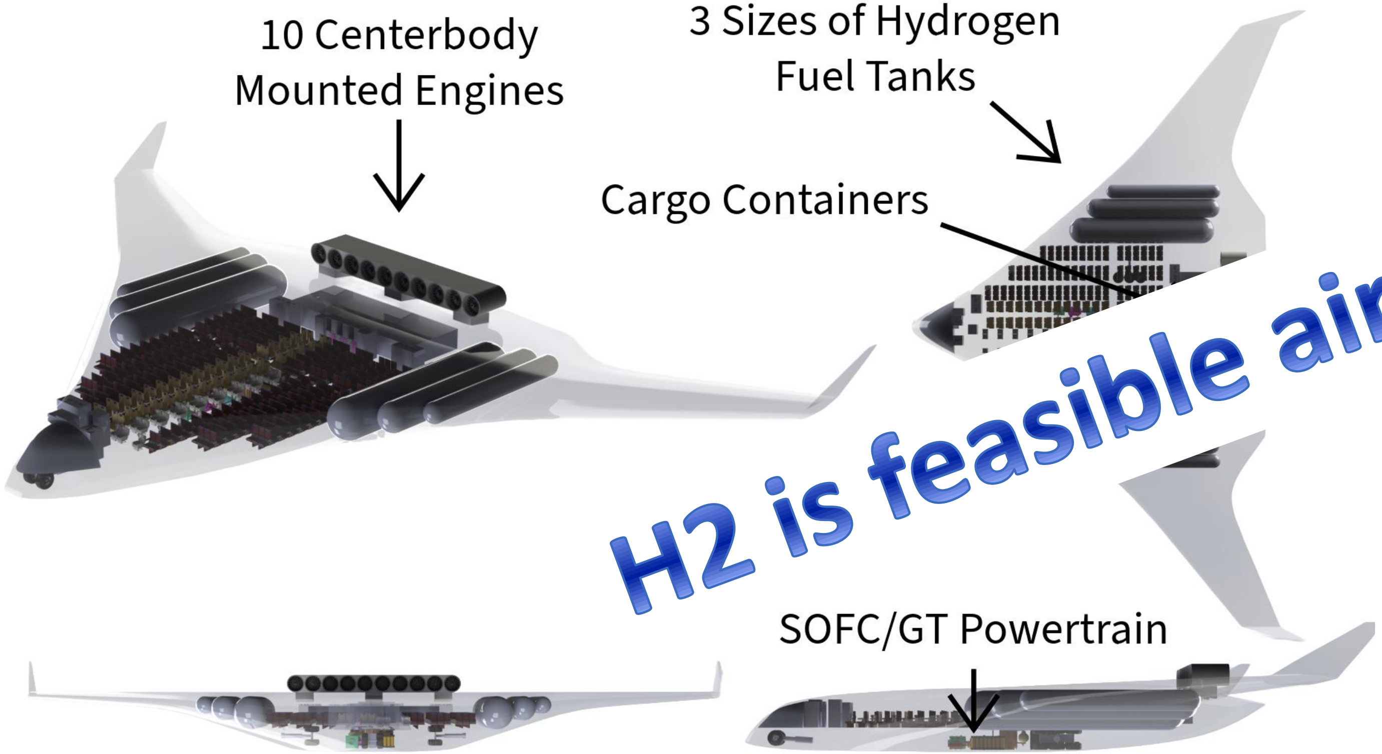
Aircraft Transformation: H2 Class 365 (SFO ↔ Shanghai)

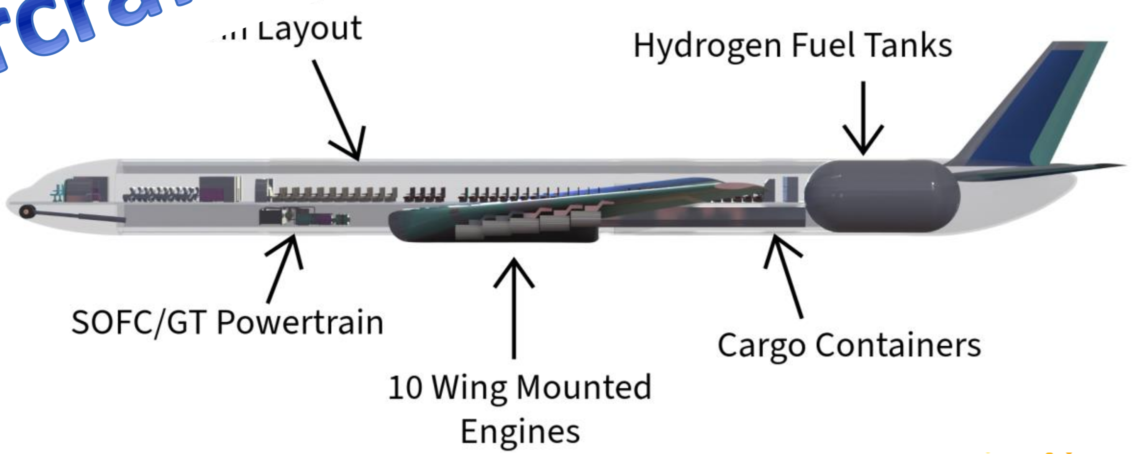


Hydrogen BWB-365



H2 is feasible aircraft fuel

T&W-365



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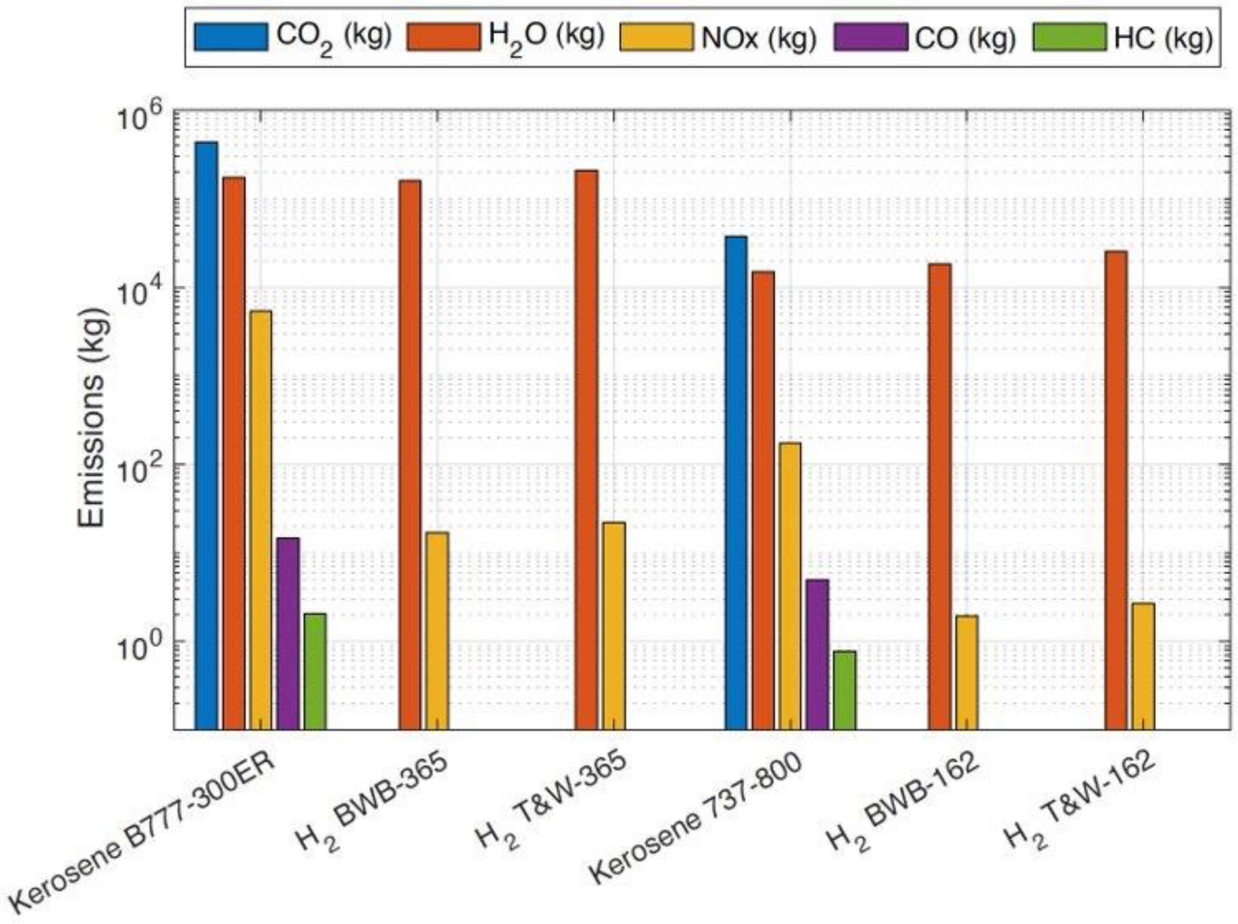
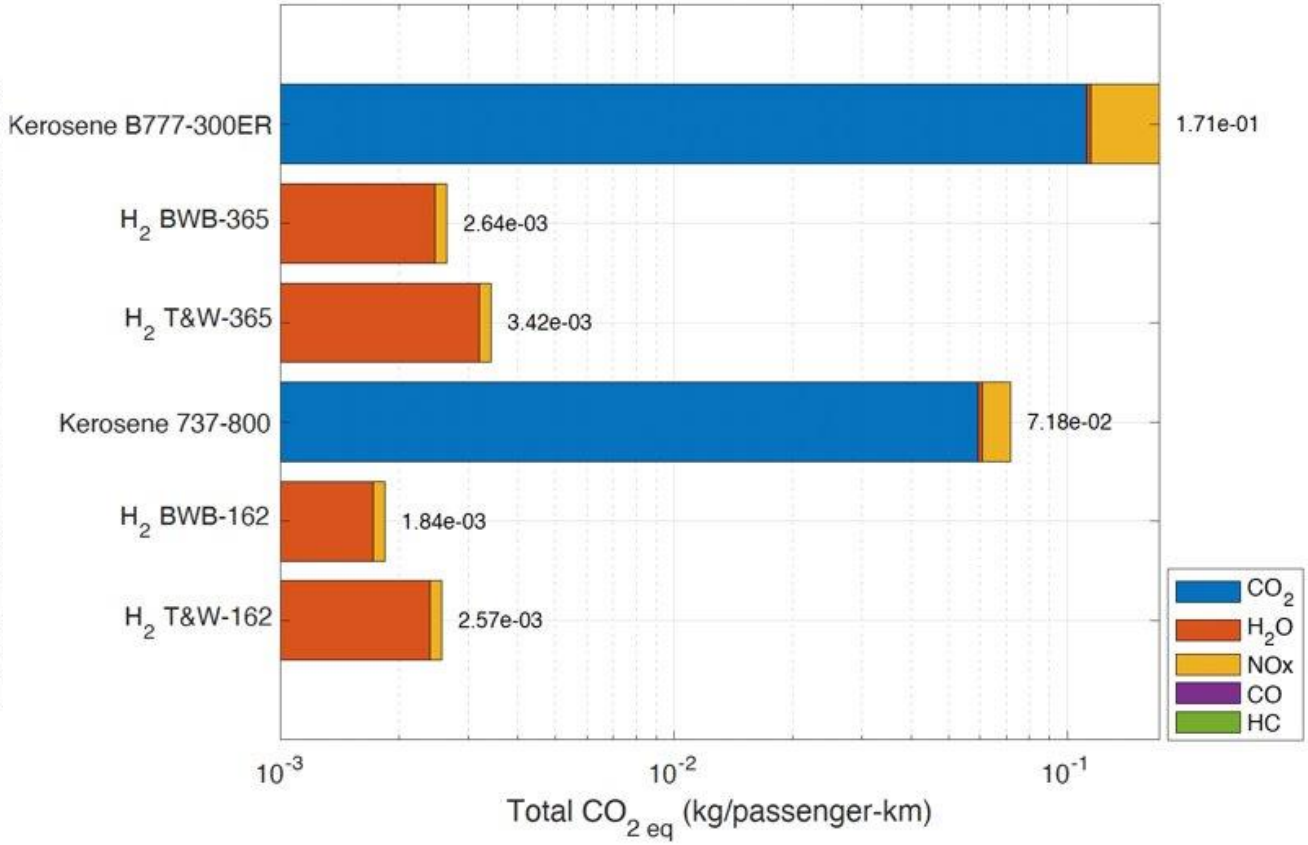
Alsamri, K., De la Cruz, J., Emmanouilidi, M., Huynh, J., & Brouwer, J. (2024). *Journal of Propulsion and Power*, *40*(5), 661-676.

H_2 BWB & T&W vs. Conventional Aircraft Emissions

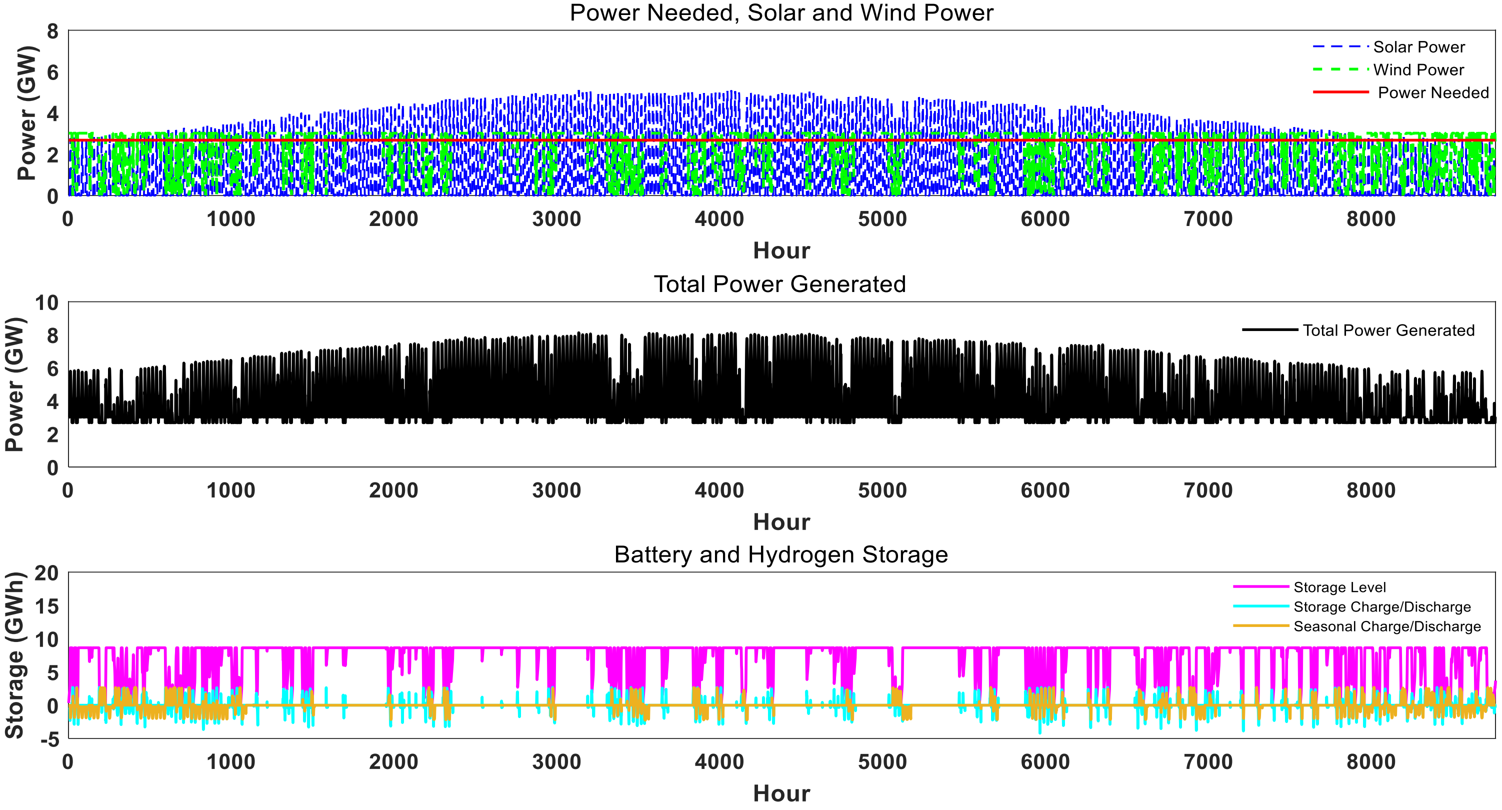


Lifecycle CO_{2eq} Emissions



Alsamri, K., De la Cruz, J., Emmanouilidi, M., Huynh, J., & Brouwer, J. (2024). *Journal of Propulsion and Power*, *40*(5), 661-676.

LAX Airport Transformation: H2 Production Dynamics in 2050



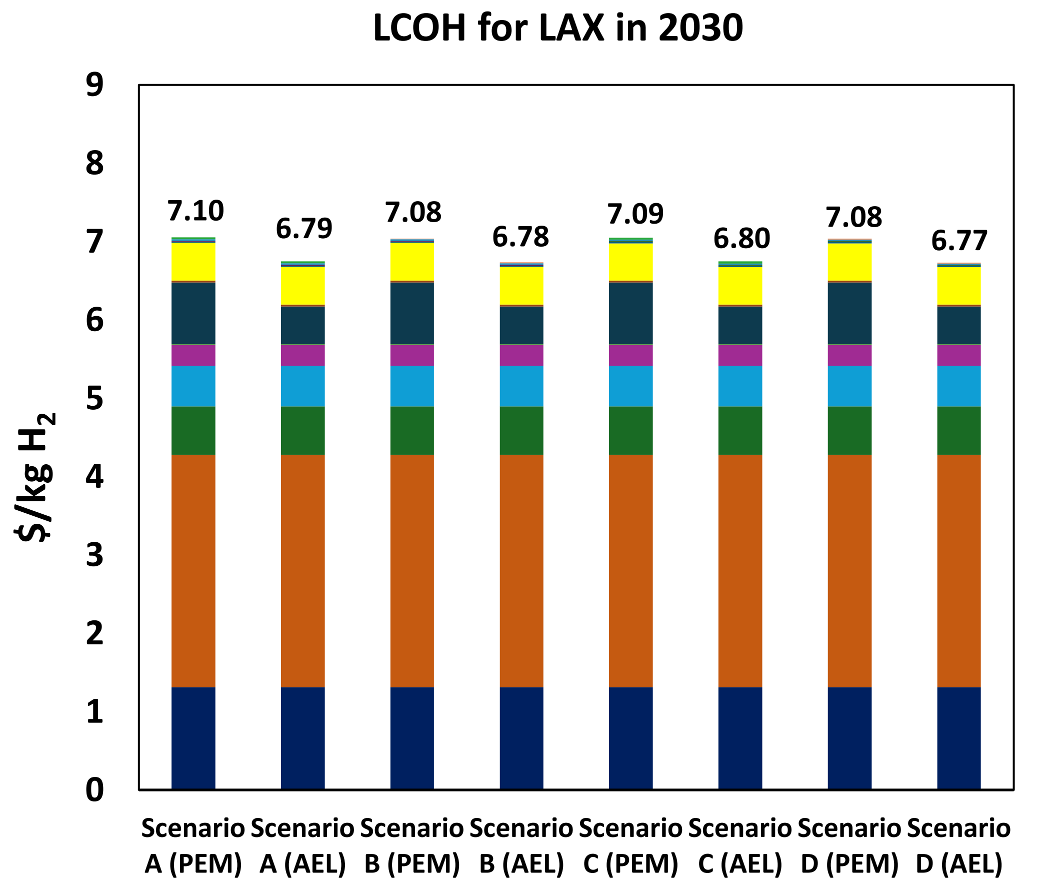
Rezaei, S., Alsamri, K., Simeoni, E., Huynh, J., & Brouwer, J. (2025). *Energy Conversion and Management*, *340*, 119946.

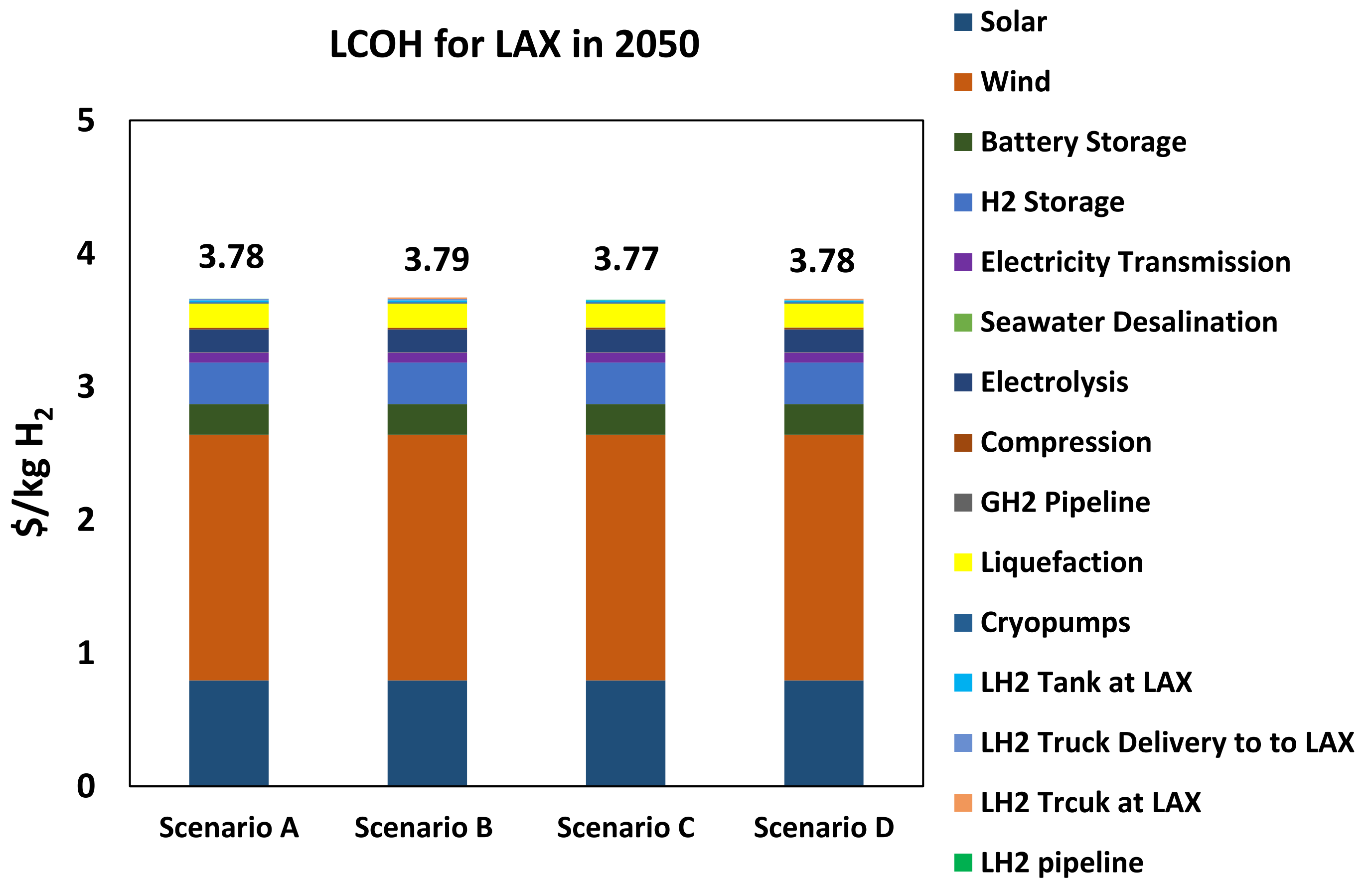
Segment	2030 (MW)	2050 (MW)
RO Desalination	0.42	1.96
Electrolysis	516.4	2,153.90
Compression	9.9	34.75
Liquefaction	108.504	296.568
Cryopumps	1.95	9.8
Total	637.174	2,496.978

Renewable Power Mix	2030	2050
Maximum Solar Power Generated (GW)	1.27	5.12
Maximum Wind Power Generated (GW)	0.75	3
Battery Storage Capacity (GWh)	1.9	7.6
Seasonal Storage Capacity (GWh)	32	128

LAX Airport Transformation: Levelized Cost of Hydrogen (LCOH)

- **Electricity is the largest cost component for LH_2**
- **Competitive renewable hydrogen requires significantly low electricity prices**





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Rezaei, S., Alsamri, K., Simeoni, E., Huynh, J., & Brouwer, J. (2025). *Energy Conversion and Management*, *340*, 119946.

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 potential
- Sufficient raw materials on earth
- Water naturally recycled in short time on e
- Feedstock for industry heat
- Feedstock for industry chemicals (e.g., am
- Pre-cursor for high energy density renew
- Re-use of existing infrastructure (lower c

Saeemanesh, A., Mac Kinnon, M
Hydrogen is Essential for Sustai
Opinion in Electrochemistry, 2019.


Available online at www.sciencedirect.com

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Current Opinion in Electrochemistry

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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].

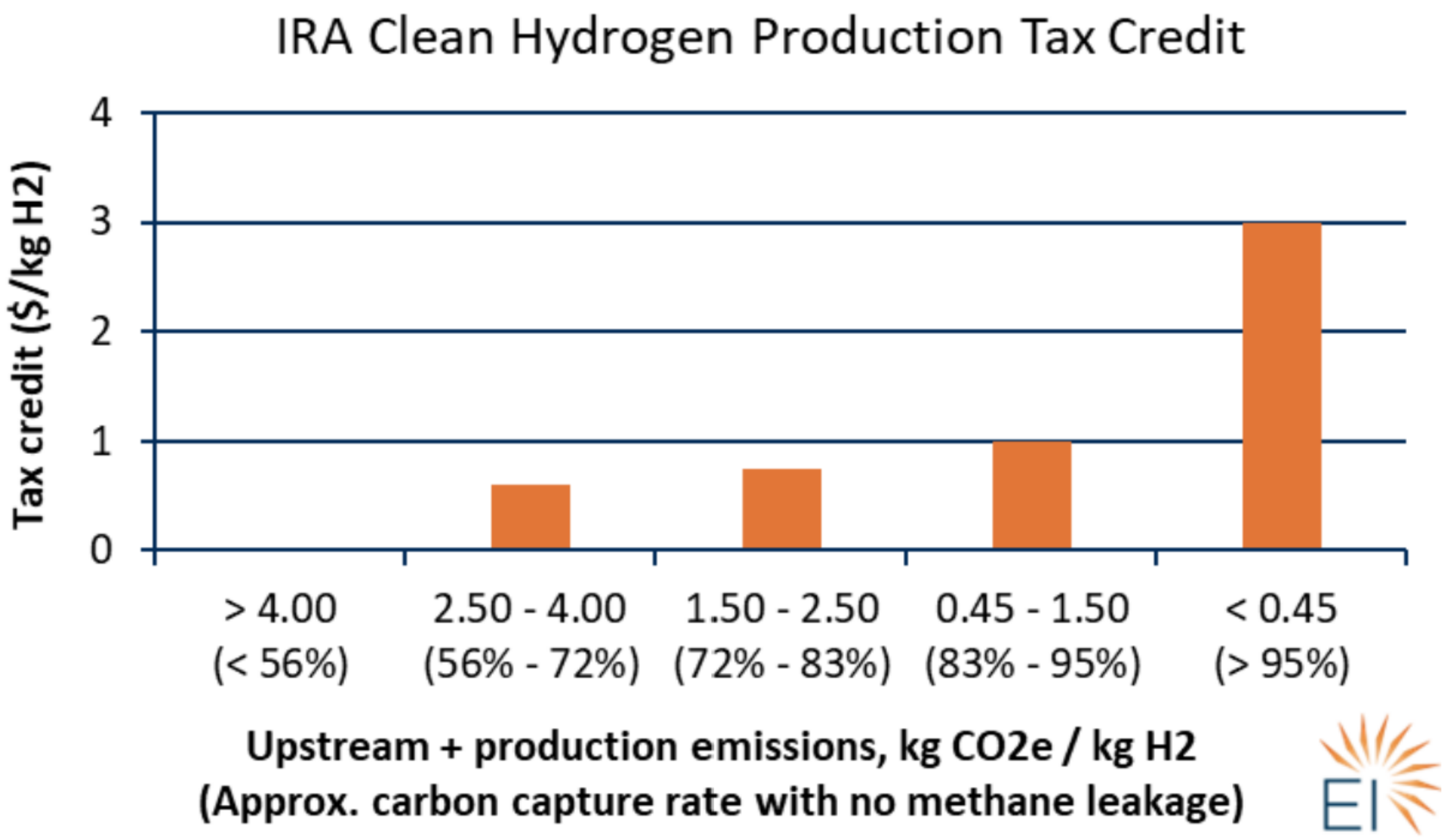
Since the Industrial Revolution, the vast majority of energy converted in society has been obtained from fossil fuels – coal, natural gas, and petroleum – which require tremendously long times for earth and the power of the sun to produce. This trend is widely expected to continue in coming decades [15–18]. 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

Production Tax Credit (PTC)

Inflation Reduction Act – 45V part of IRS tax code

- Although restricted by "3 pillars" – great opportunity in next few years



from Utility Dive (9/30/22); original figure from Energy Innovation Policy and Technology

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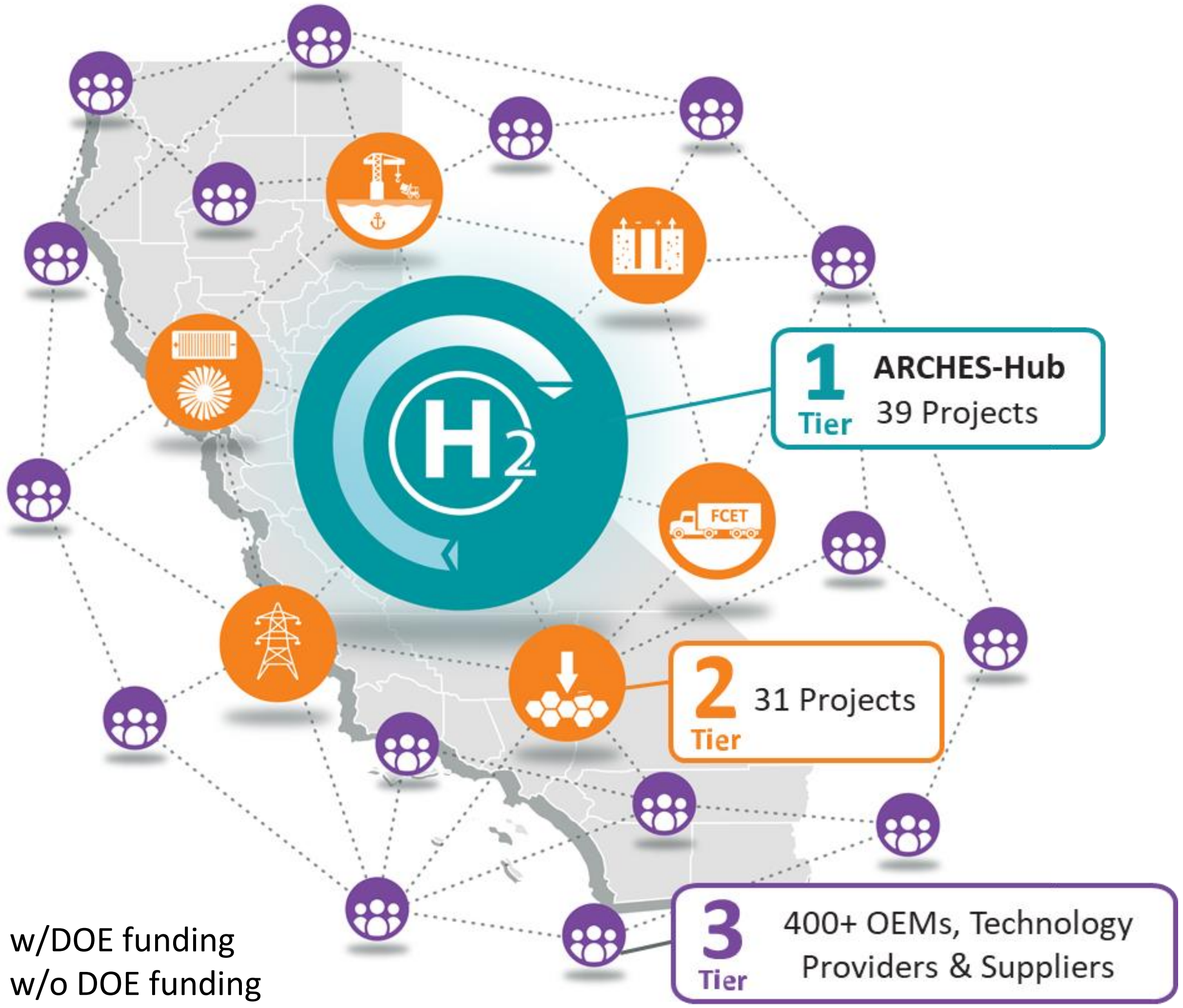
Novel Market Development in California

First Public Hydrogen (municipal utility)

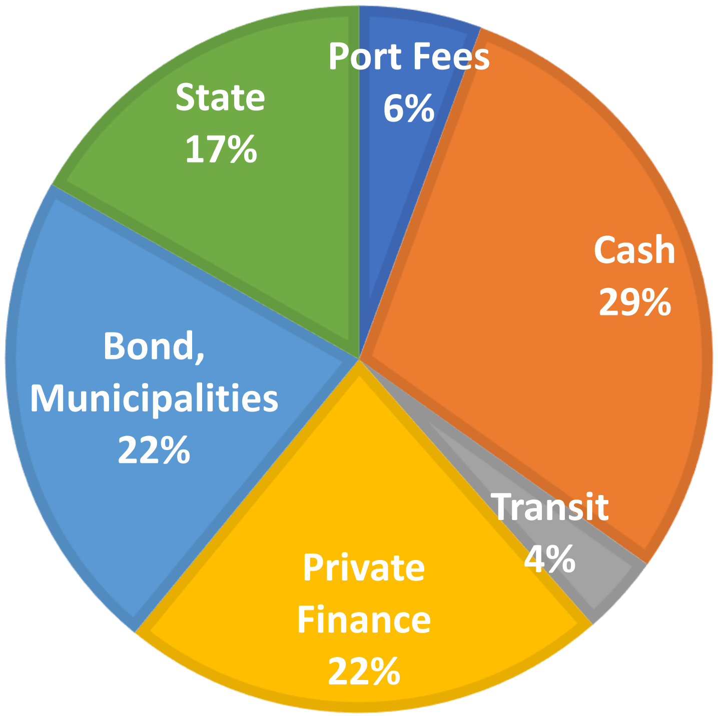
- U.S. first market establishing innovation
- Established through a Joint Exercise of Powers Agreement between the City of Lancaster and the City of Industry, California (Cities of Fresno, Stockton, …, also joining)
- Committed to clean hydrogen projects
- Innovative partnerships and a public ownership model
- Leverage municipal authority to issue bonds, issue permits, …, and establish and operate public processes for a utility market

Alliance for Renewable Clean Hydrogen Energy Systems (ARCHES) Projects: A Resilient H2 Ecosystem for California

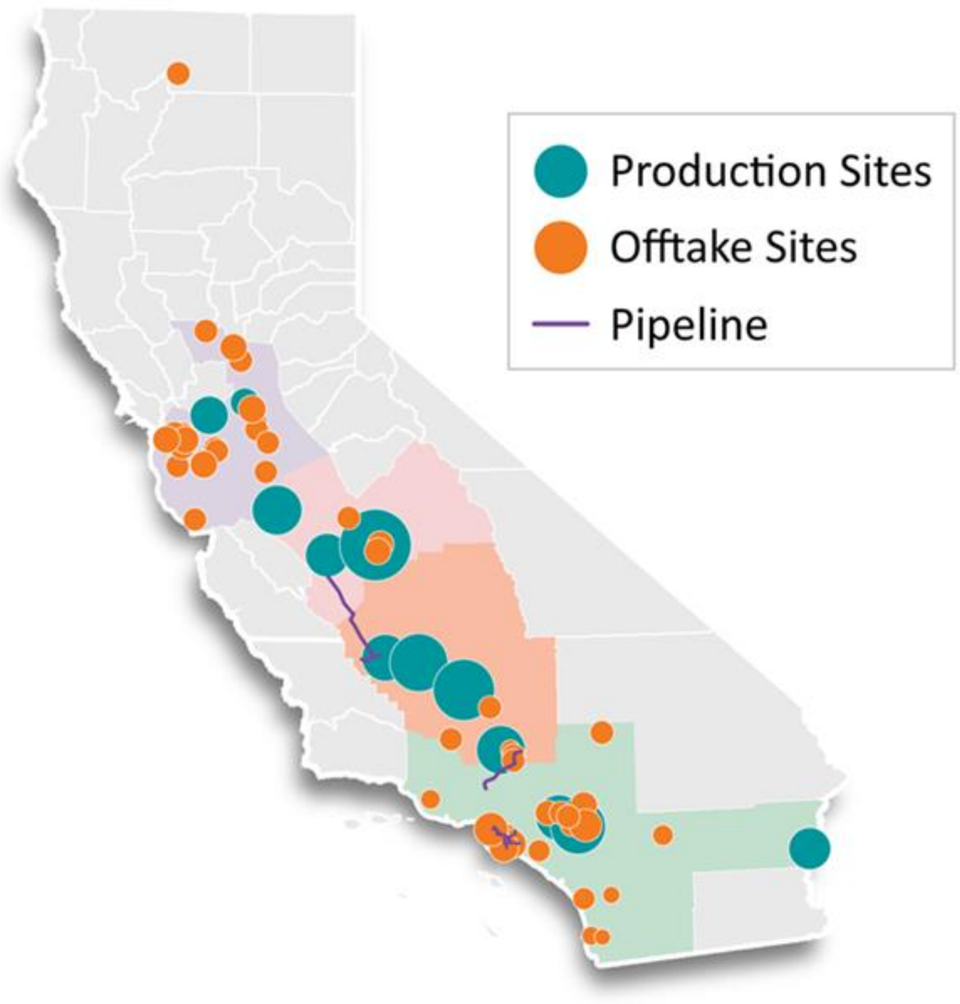


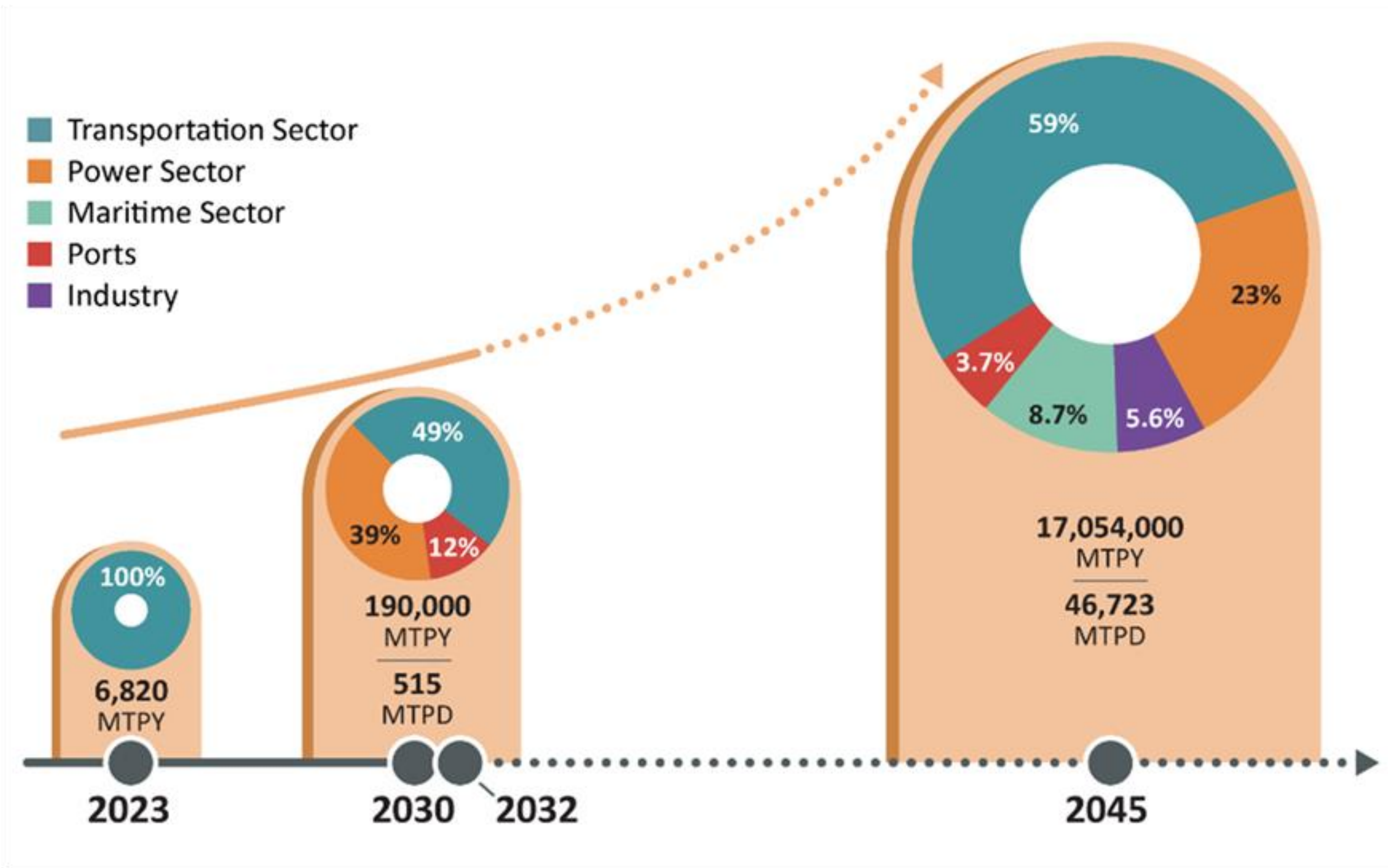
Tier 1 = w/DOE funding
Tier 2 = w/o DOE funding

~~$1.2B DOE~~ funds plus **$11.7B in matching funds**

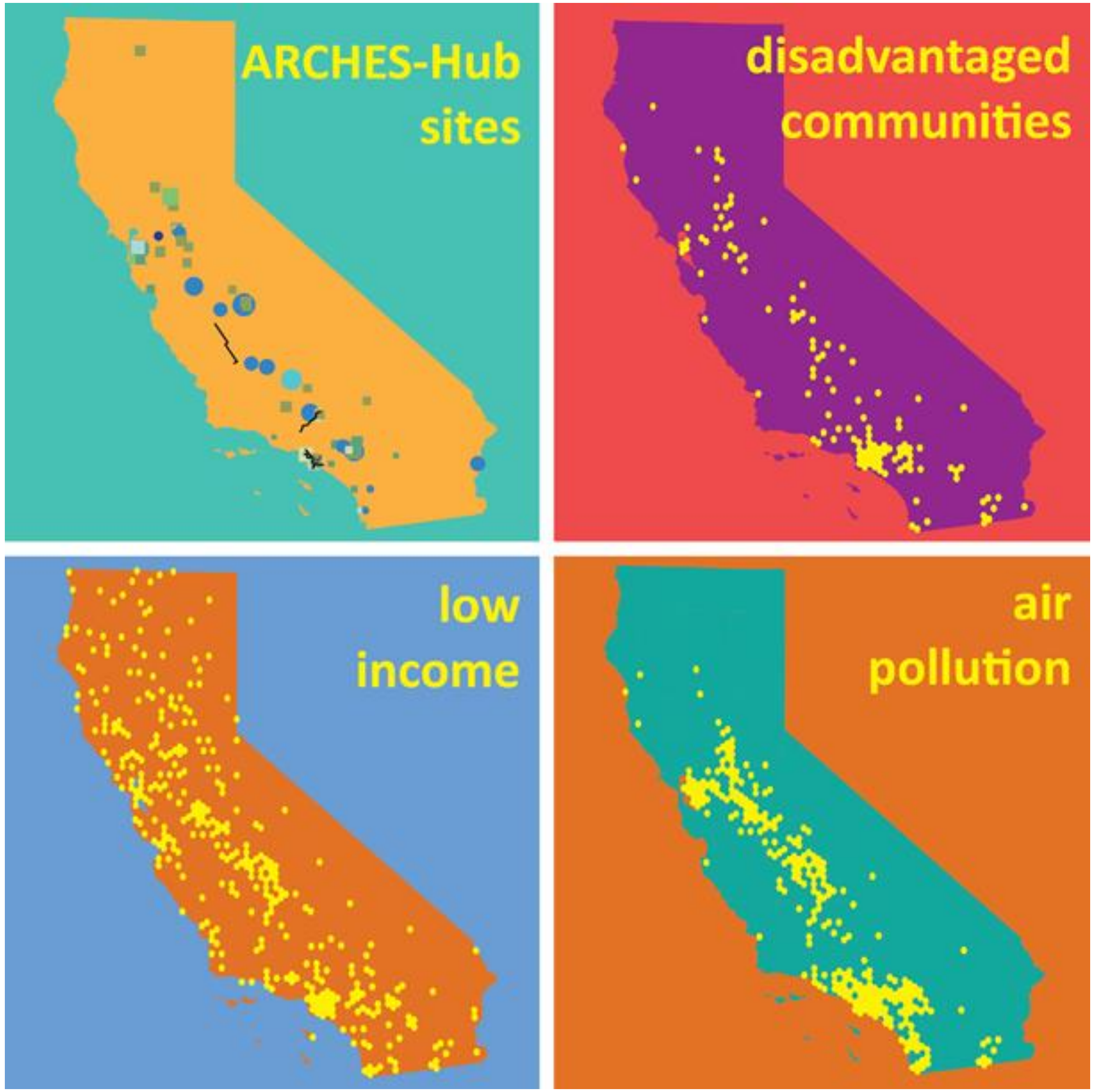


ARCHES Systems Approach Initiates Large Future Hydrogen Growth in California





ARCHES Benefits California Communities



*EJ40 database and CalEnviroScreen

COMMUNITY

- ▲ **$2.95 billion** — Economic value of increased health* and associated health costs savings per year
- ▲ **222,400** — Number of jobs created
- ▼ **2,097** — Fewer hospitalizations for respiratory & cardiac illness per year
- ▼ **13,292** — Fewer work loss days per year
- ▼ **6,900** — NO_x — Nitrogen oxide net emissions avoided MTPY
- ▼ **239** — SO_2 — Sulfer dioxide net emissions avoided MTPY
- ▼ **326** — PM 2.5, 10 — Particulate matter net emissions avoided MTPY
- ▼ **48** — Fewer premature deaths per year
- ▲ **$380 million** — Invested in community benefits & workforce development

** Reduced premature death, asthma, cancer risk, missed work days*

“Carrot” & “Stick” Remain in California for Transit

- AC Transit example – considering “range capability, route block pairing, operating cost, **[infrastructure,]** and performance data”

Figure 2: ZEB Technology Cost

ZEB Technology	Fleet Qty	Bus Cost	Infrastructure Cost	Technology Total
Battery Electric Bus	178	$255,000,000	$152,000,000	$407,000,000
Fuel Cell Bus	458	$740,000,000	$120,400,000	$860,400,000
	636	$995,000,000	$272,400,000	$1,267,400,000

Figure 10: Bus and Infrastructure Estimated Capital Cost (in 2022 dollars)

ZEB Technology	Bus Procurement/ Avg per Unit	Infrastructure
Battery Electric Bus	$1.4M	$24.9M for 50 BEB Deployment
Fuel Cell Electric Bus	$1.6M	$7.2M for 50 FCEB Deployment

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AC Transit ZEB Transition Plan, https://www.actransit.org/

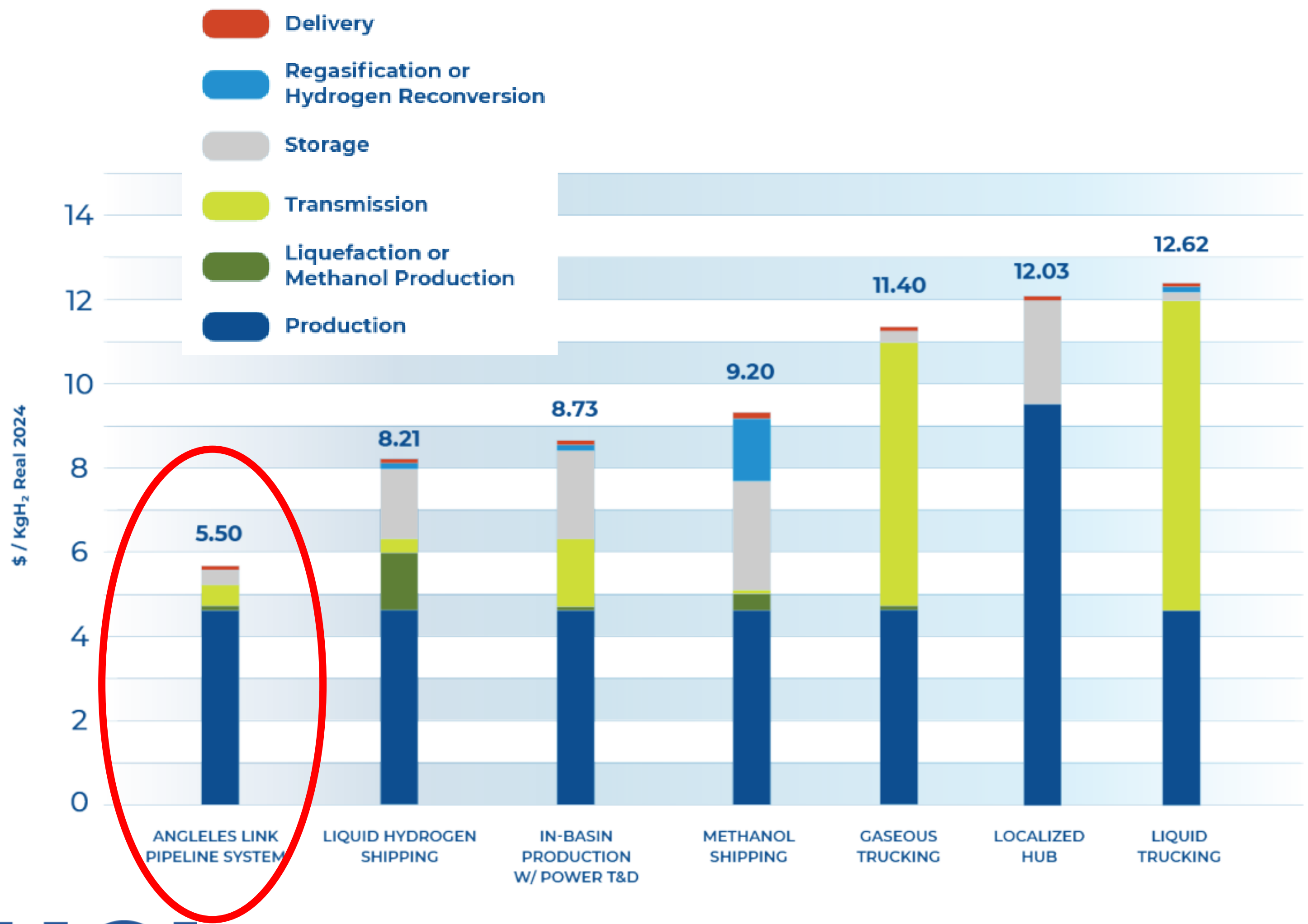
Hydrogen for Power Generation – LADWP ARCHES Project

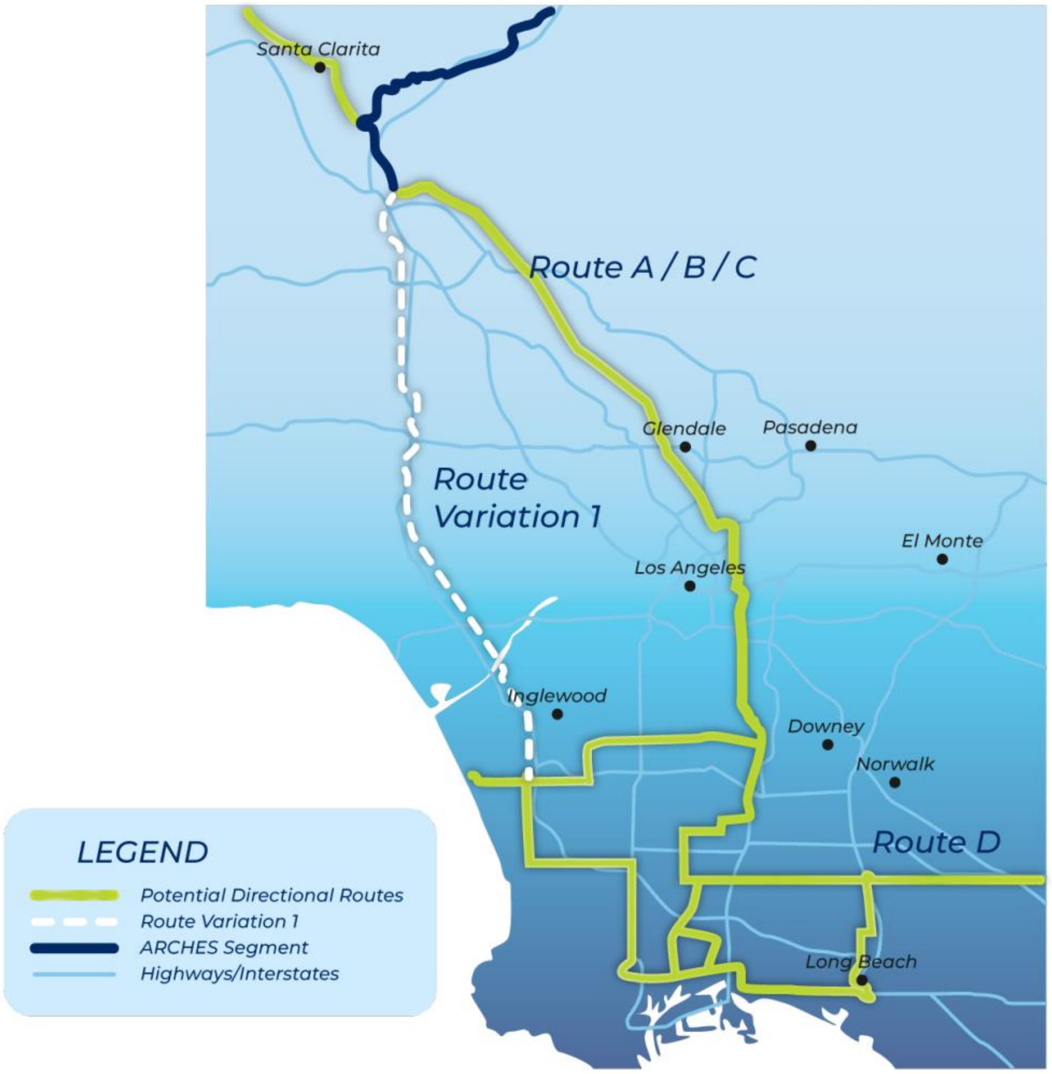
- ACES (Advanced Clean Energy Systems) Project
- LADWP, Mitsubishi Power, Magnum, Chevron
- Western Energy Hub ("WEH") site, located adjacent to the Intermountain Power Project ("IPP") in Millard County, Utah
- Similar in-basin plant conversion for Sustainable City pLAn for Los Angeles, Southern California, and the Western region

Reed, J. et al., UC Irvine, 2019, Integrating Clean Energy White Paper https://www.apep.uci.edu/PDF_White_Papers/Integrating_Clean_Energy_013020.pdf

“Angeles Link” of SoCalGas

- Common Carrier H_2 Pipelines





From: https://www.socalgas.com/sites/default/files/alproject/Angeles-Link-Phase-1-Consolidated-Report.pdf

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Electrification is Important!
Then We Must Add Hydrogen!

Ohio Fuel Cell & Hydrogen Coalition Summit (October 27, 2025)

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Prof. Jack Brouwer, Director
Clean Energy Institute, UC Irvine