CIF CLIMATE INVESTMENT FUNDS

Energy Storage Technologies: Ask the Experts

Moderator and Panelists

Chibulu Luo

Operations Officer, Climate Investment Funds

Vincent Sprenkle

Senior Advisor - Energy Storage, Electrochemical Materials and Systems Group, Pacific Northwest National Laboratory

Clifford Ho

Senior Scientist, Sandia National Laboratories

Neha Rustagi

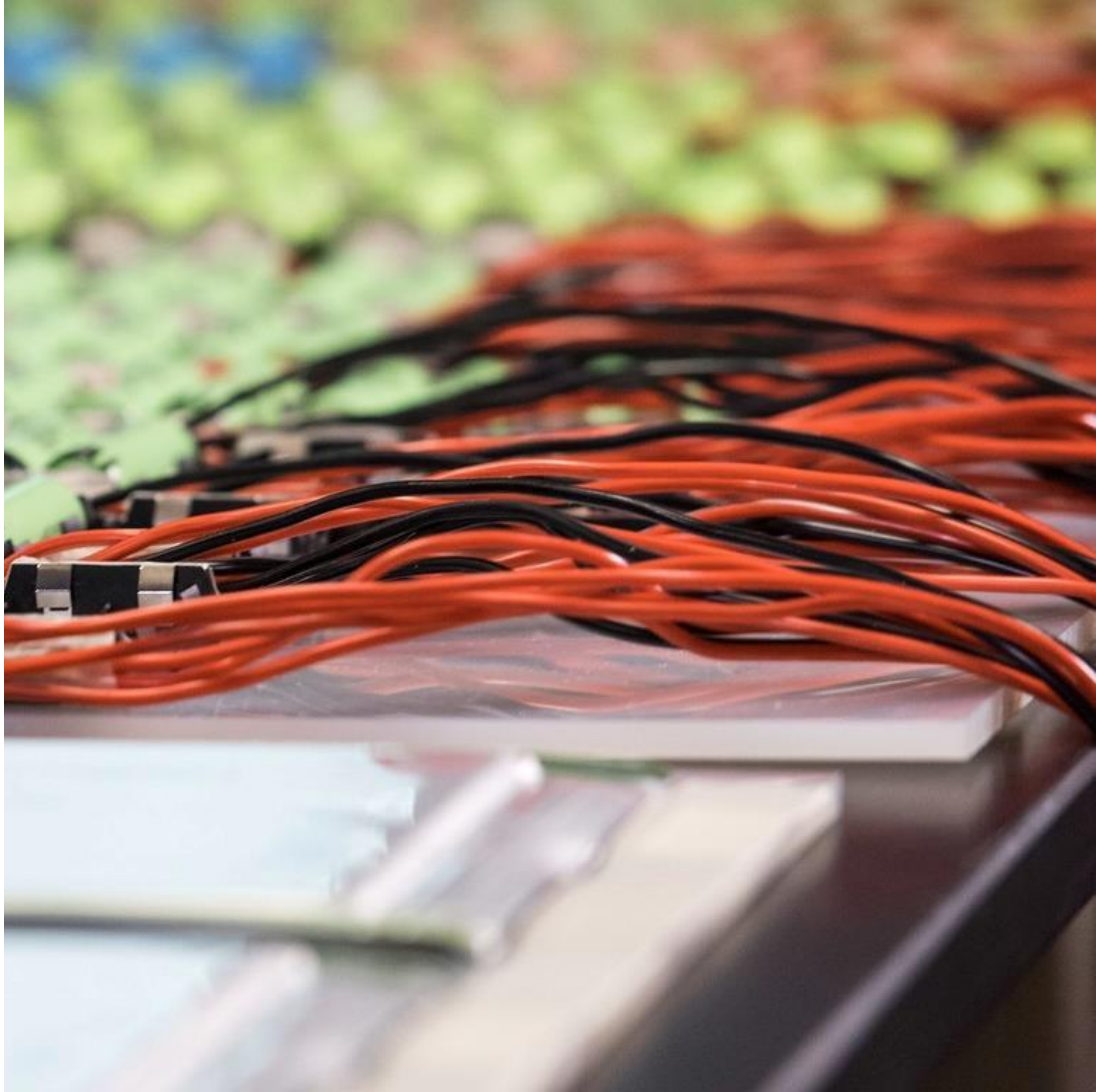
Technology Manager, Hydrogen & Fuel Cell Technologies Office,US Department of Energy

#KeepingthePowerOn

Vincent Sprenkle

Senior Advisor - Energy Storage,
Electrochemical Materials and Systems Group,
Pacific Northwest National Laboratory

Pacific Northwest
NATIONAL LABORATORY



Battery Storage Technologies

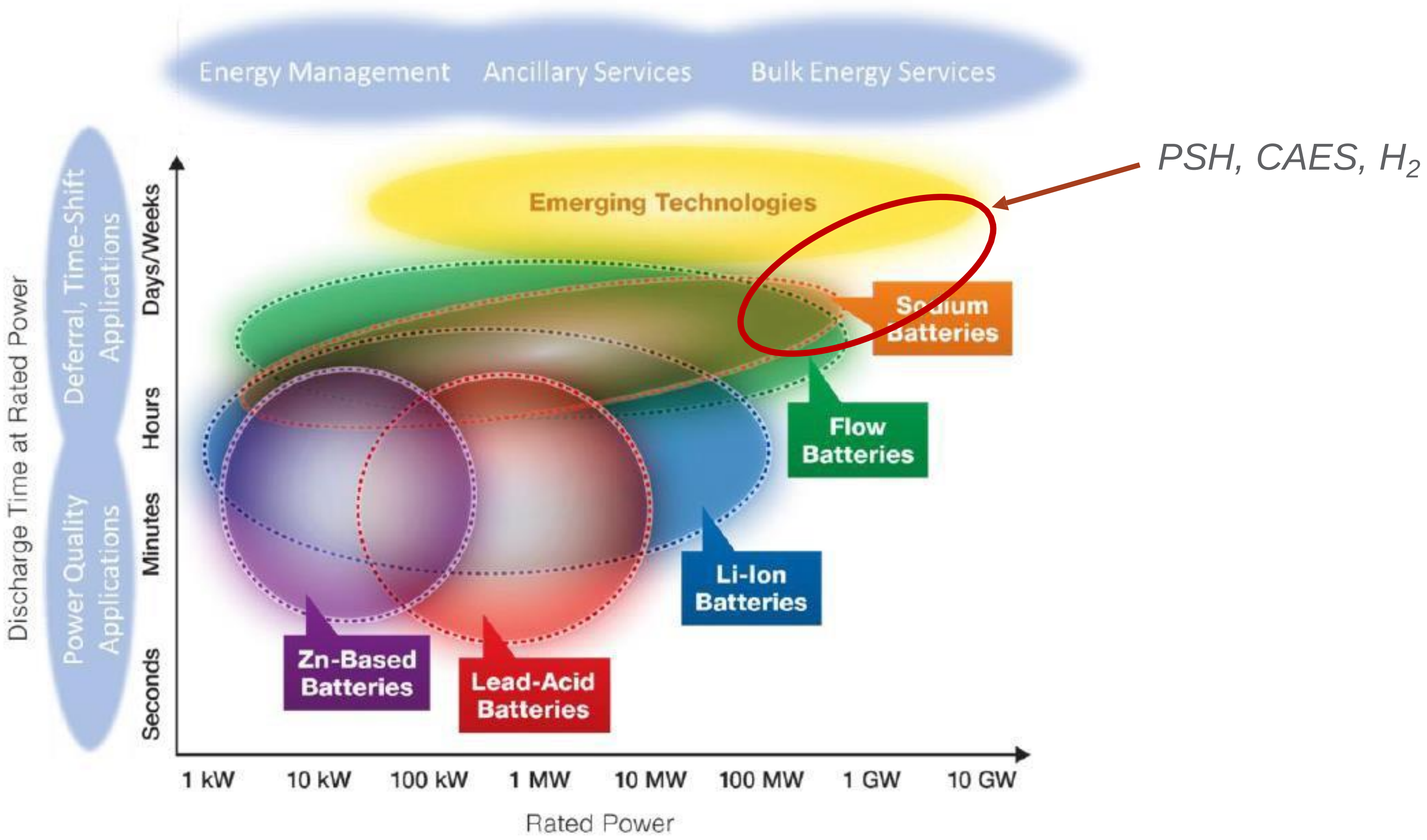
July 14th, 2021

Vincent Sprenkle
Sr. Advisor - Energy Storage

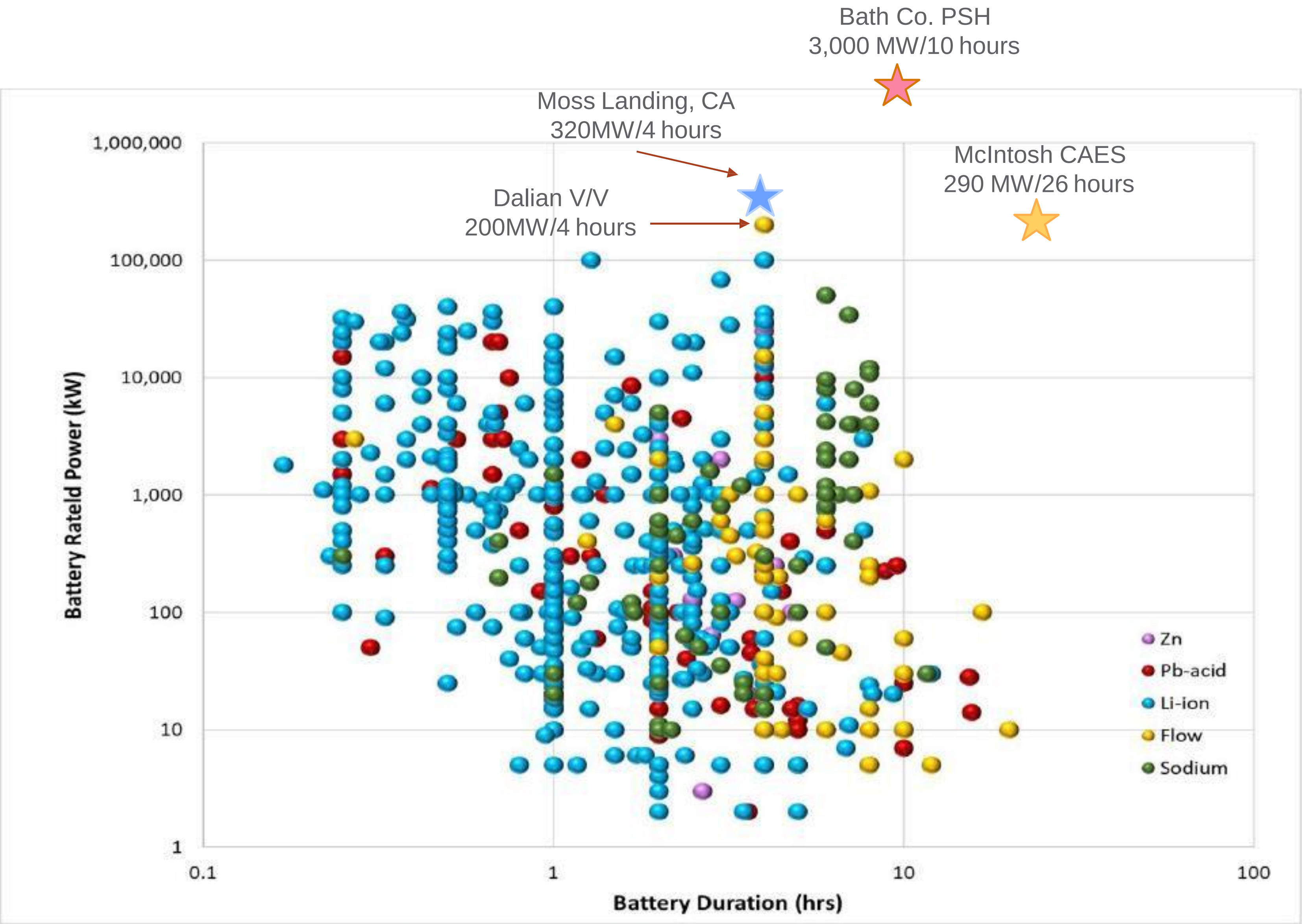
U.S. DEPARTMENT OF ENERGY BATTELLE

PNNL is operated by Battelle for the U.S. Department of Energy

Power-Duration ranges of battery storage solutions

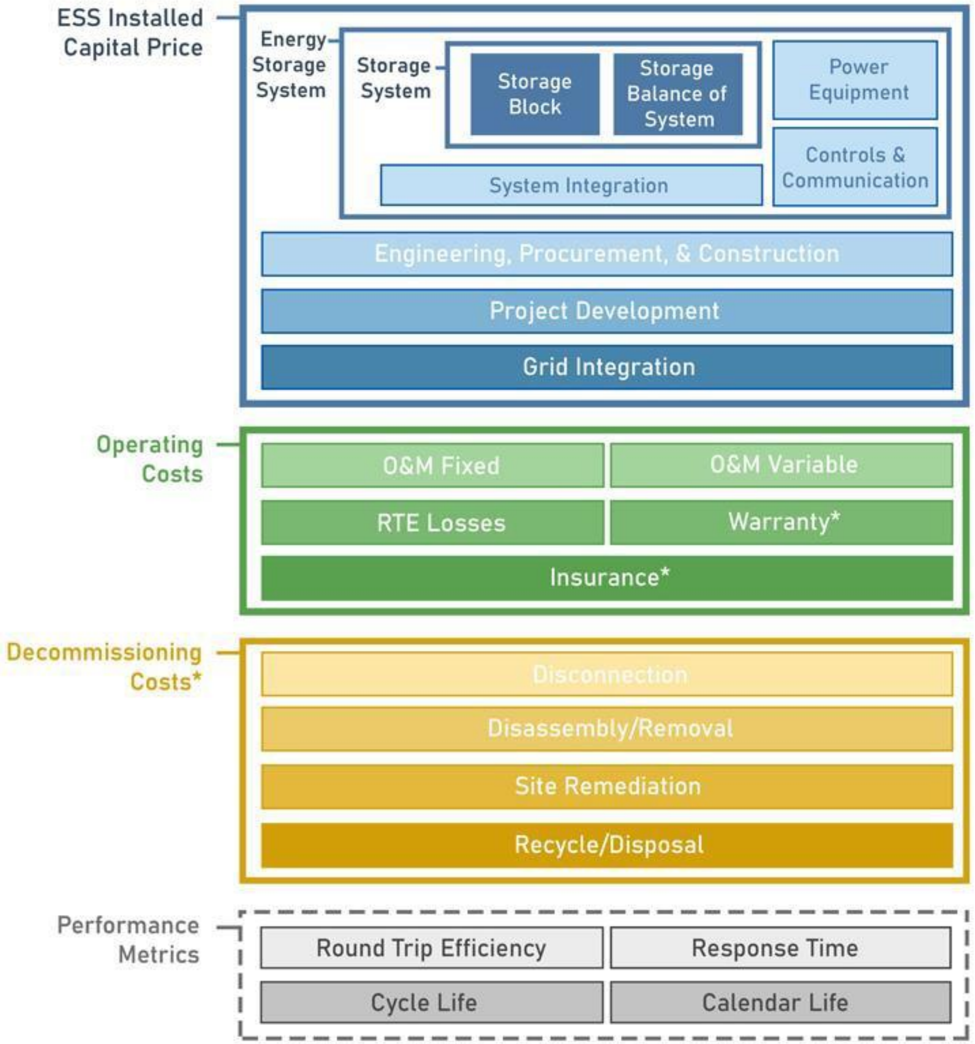


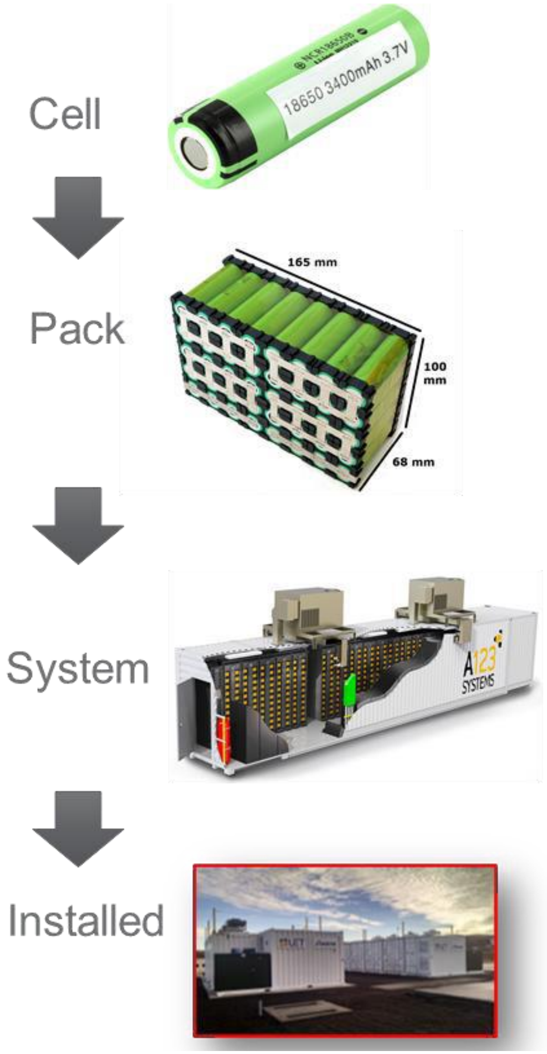
Power–duration parameters for deployed storage systems



Source: US DoE Energy Storage Database, March 2019, https://www.energystorageexchange.org/
Based on Shell International Exploration & Production (US) Inc.; analysis presented by Shell 11 March 2019, ARPA-e DAYS

Total installed cost of batteries more than just the technology





https://www.pnnl.gov/ESGC-cost-performance

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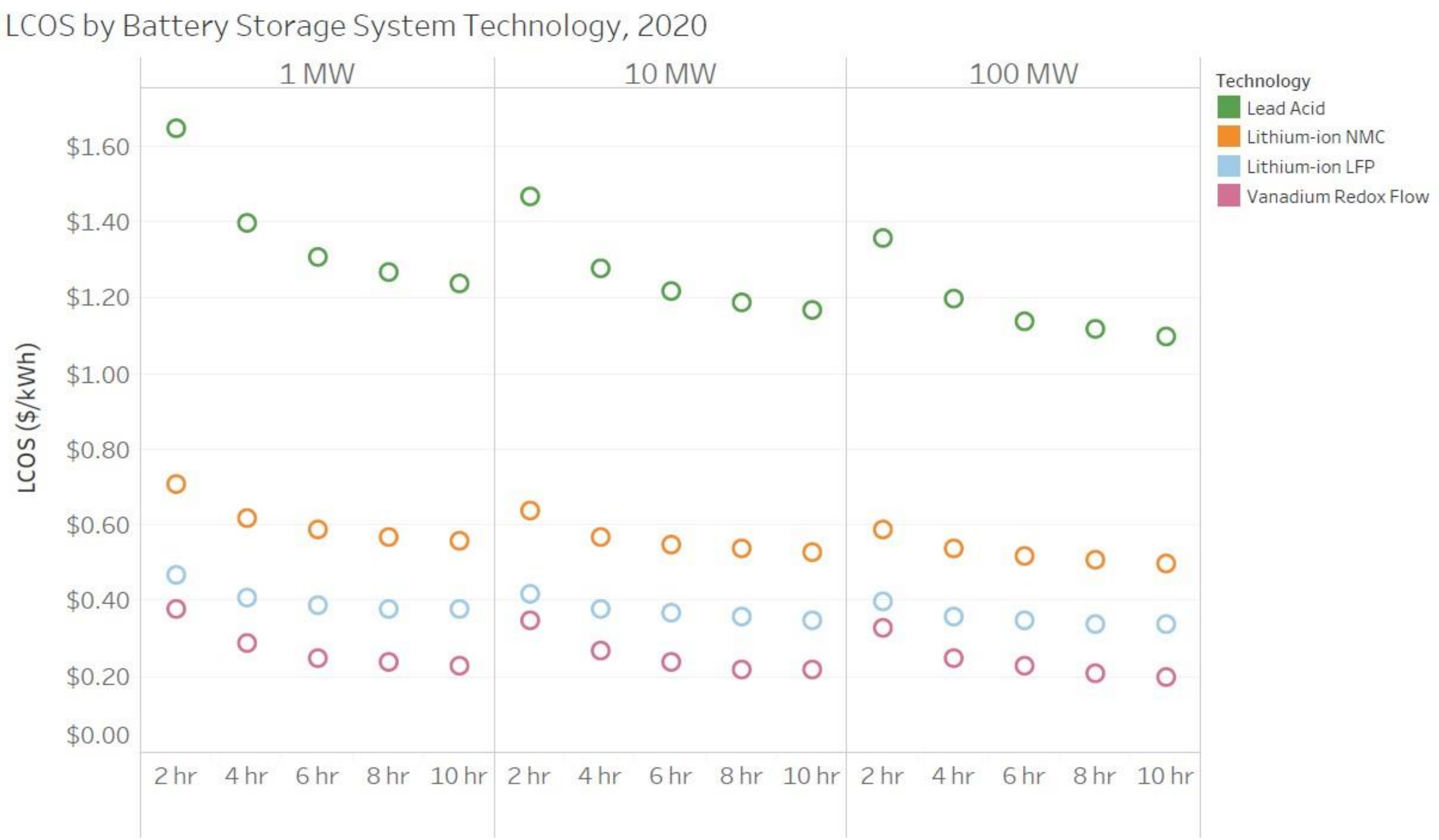
Levelized Cost of Storage (LCOS) battery comparison

- Levelized Cost of Electricity (LCOE): measures the ratio of the cost of owning and operating an asset over its usable life by the energy delivered.



Thank you

Vincent Sprenkle

Sr. Technical Advisor

Pacific Northwest National Laboratory

Vincent.sprenkle@pnnl.gov

(509) 375-2370

PNNL Storage Website

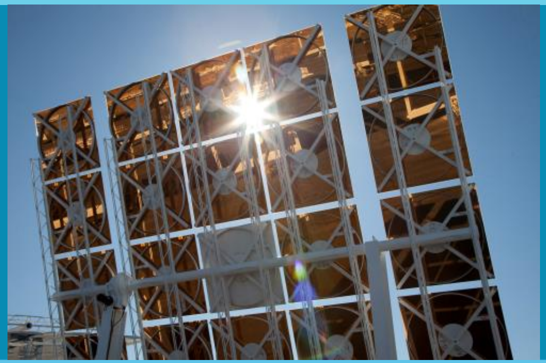
https://energystorage.pnnl.gov/

Storage Cost and Performance Assessment

https://www.pnnl.gov/ESGC-cost-performance

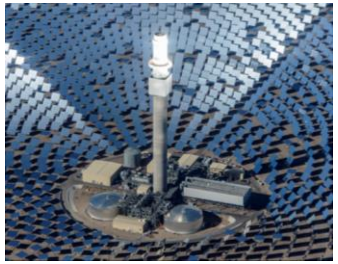
Clifford Ho

Senior Scientist, Sandia National Laboratories



Thermal Energy Storage Technologies



PRESENTED BY

Clifford K. Ho

Sandia National Laboratories, Albuquerque, NM

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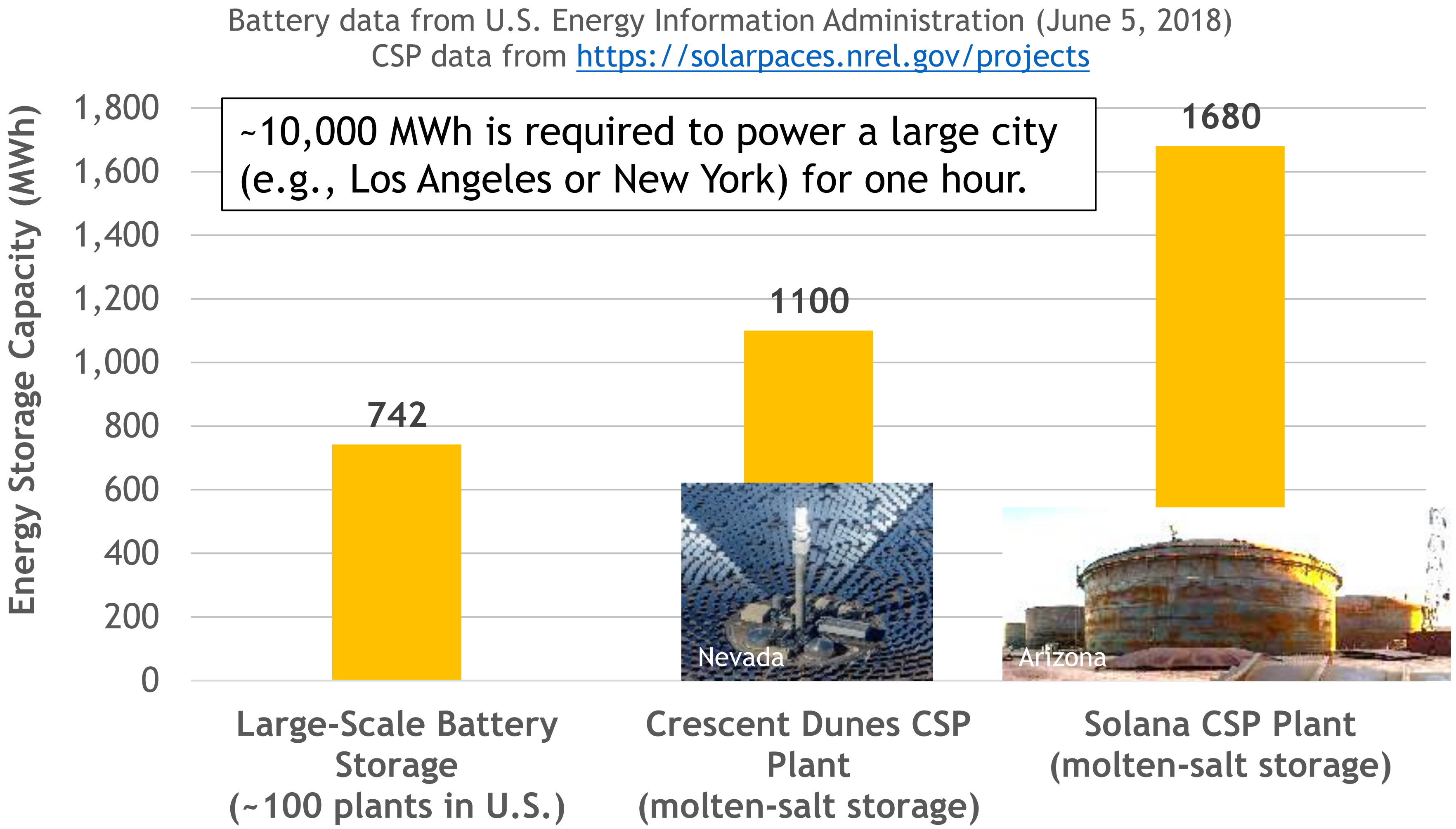
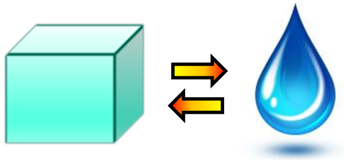
SAND2021-8138 PE

Growing Need for Large-Scale Energy Storage

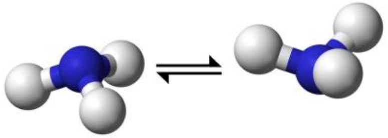


Thermal Energy Storage - Overview

- Sensible (single-phase) storage
  - Use temperature difference to store heat
  - Molten salts (nitrates <600 °C; carbonates, chlorides 700 – 900 °C)
  - Solids storage (graphite, concrete, ceramic particles), >1000 °C



- Phase-change materials
  - Use latent heat to store energy (e.g., molten salts, metallic alloys)



- Thermochemical storage
  - Converting thermal energy into chemical bonds (e.g., decomposition/synthesis, redox reactions)

Molten-salt storage tanks at Solana CSP plant in Arizona. Credit: Abengoa

Sensible Heat Storage

Molten Salt Storage

- Nearly 30 GWh_e of global thermal storage capacity using concentrating solar power

futurenergyweb.es

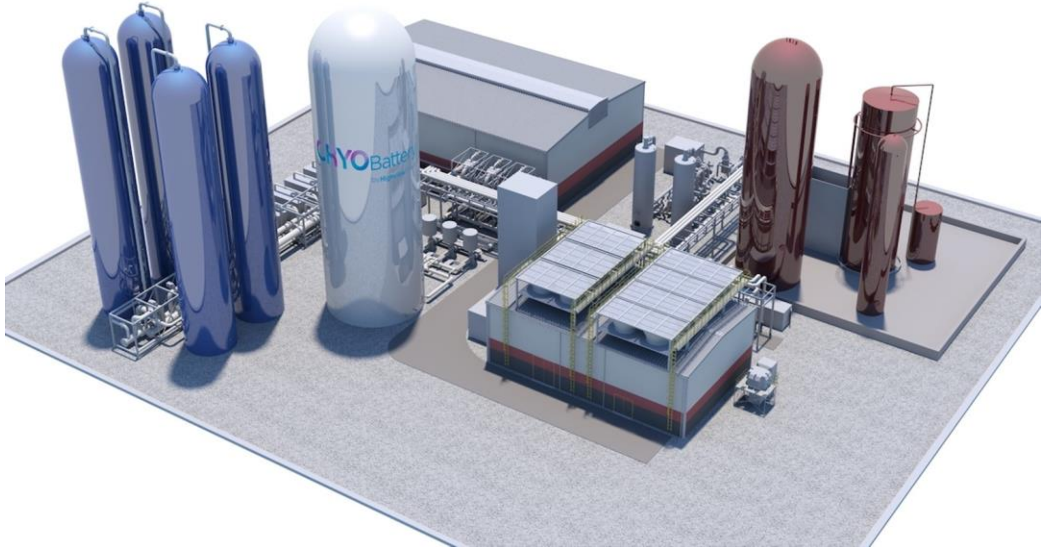
Solana Parabolic Trough Plant, AZ
(280 MW_e with 6 hrs storage (1.5 GWh_e)

Crescent Dunes Solar Tower, NV
110 MW_e with 10 hrs storage (1.1 GWh_e)

Latent Heat Storage

Liquefied Air Phase Change – Highview Power

- Electricity is used to compress air (Claude cycle) that is then stored as cryogenic liquid
- When needed, liquid is allowed to vaporize, expanding through turbines to generate electricity



Images: Highview Power

Highview Power Liquid Air Energy Storage
50 MW/400 MWh

Summary

Summary of Advantages and Challenges

Storage Technology	Advantages	Challenges
Pumped Hydro	▪ Mature technology ▪ Demonstrated large capacity (~GWh); >90% of U.S. grid energy storage ▪ Good reliability	▪ Unique geologic resources ▪ Water availability and evaporation
Compressed Air	▪ Demonstrated capability at large scales ▪ Moderate round-trip efficiency ▪ Good potential for long-duration storage	▪ Unique geologic resources ▪ Well integrity ▪ Repository integrity
Hydrogen	▪ Large-capacity, long-duration storage ▪ Can be used for both grid and transportation ▪ Environmentally friendly	▪ Low round-trip efficiency of hydrogen production and storage ▪ High cost ▪ Leakage and safety of hydrogen gas
Thermal (Sensible)	▪ Mature technology ▪ Demonstrated large capacity with concentrating solar power (~GWh) ▪ Low cost	▪ Heat loss ▪ Heat exchanger performance and reliability

Questions?

Cliff Ho, (505) 844-2384, ckho@sandia.gov

Backup Slides

Thermal Energy Storage Summary

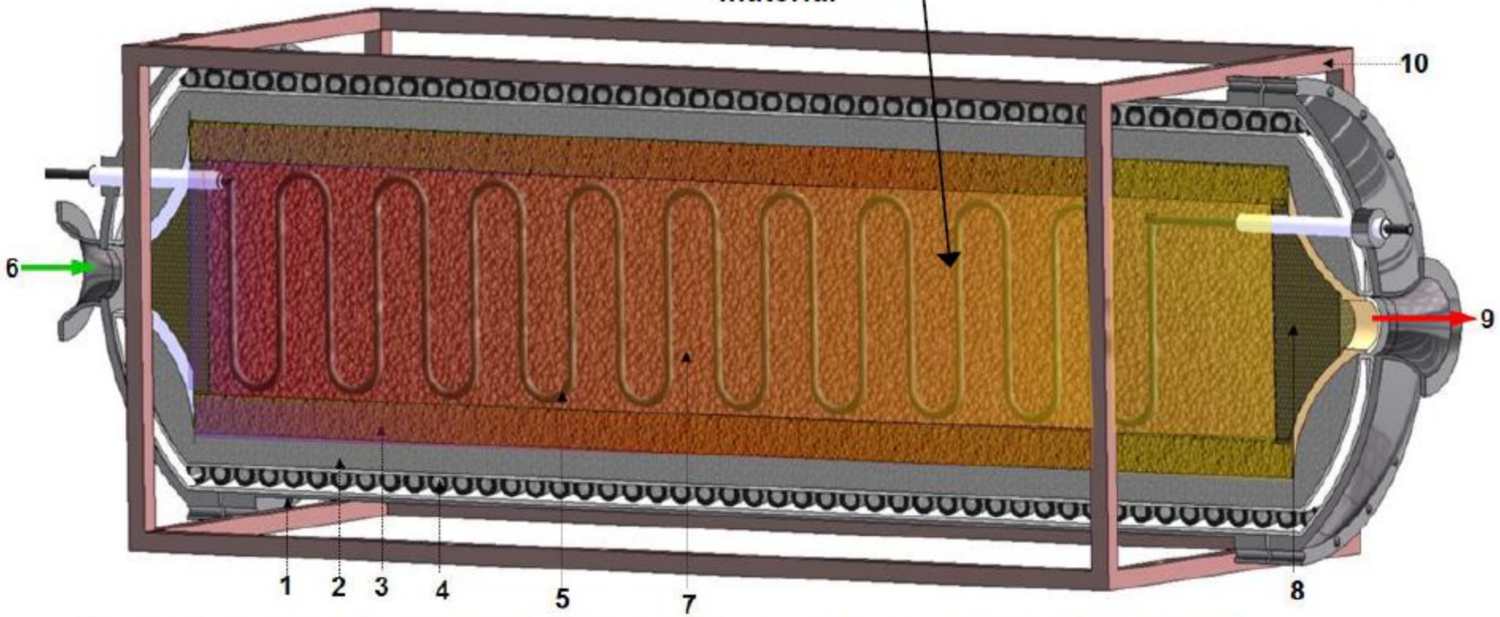
	Sensible Heat Storage	Latent Heat Storage	Thermochemical Storage
Storage mechanism	Energy stored as temperature difference in solid (e.g., concrete, rock, sand) or liquid media (molten salt)	Energy stored using phase change materials (e.g., salts, metals, organics)	Energy stored in chemical bonds
Energy Density	~200 – 500 kJ/kg (for ~200 – 400 °C temperature differential)	~100 – 200 kJ/kg for nitrate salts; ~200 – 500 kJ/kg for metals; ~1000 kJ/kg for fluoride salts	~300 – 6,000 kJ/kg
Advantages	• Demonstrated large energy capacity (~GWh) • Inexpensive media • Solid media does not freeze and can achieve >1000°C	• Good for isothermal applications • Can provide large energy density with combined sensible and latent heat storage	• Large energy densities • Small heat losses • Potential for long-term storage • Compact storage system
Challenges	• Heat loss at high temperatures • Lower energy density requires larger volumes • Molten salts freeze at ~200 °C.	• Potential for corrosion • For larger ΔT, may need cascaded systems (adds costs and complexity) • Low maturity	• Higher complexity • Low maturity • Higher capital costs
Maturity	**High**	**Low**	**Low**
Cost	• ~\$1/kg for molten salts and ceramic particles • ~\$0.1/kg for rock and sands • ~\$1/MJ – \$10/MJ (system capital cost)	• ~\$4/kg – \$300/kg • ~\$10/MJ – \$100/MJ (system capital cost)	• ~\$10/MJ – \$100/MJ (system capital cost)

Thermochemical Storage – Example

Scalable Thermochemical Option for Renewable Energy Storage (STORES)
Petrasch et al., Michigan State U., ARPA-E

- $MgO + 2MnO + \frac{1}{2}O_2 \leftrightarrow MgMn_2O_4$
- Charged by electrical heating,
- 1000-1500 °C,
- 2000 $MJ/m^3_{th\text{-}ch}$
- 40 ft-container module: 26 $MWh_{th\text{-}ch}$: 11-16 MWh_e

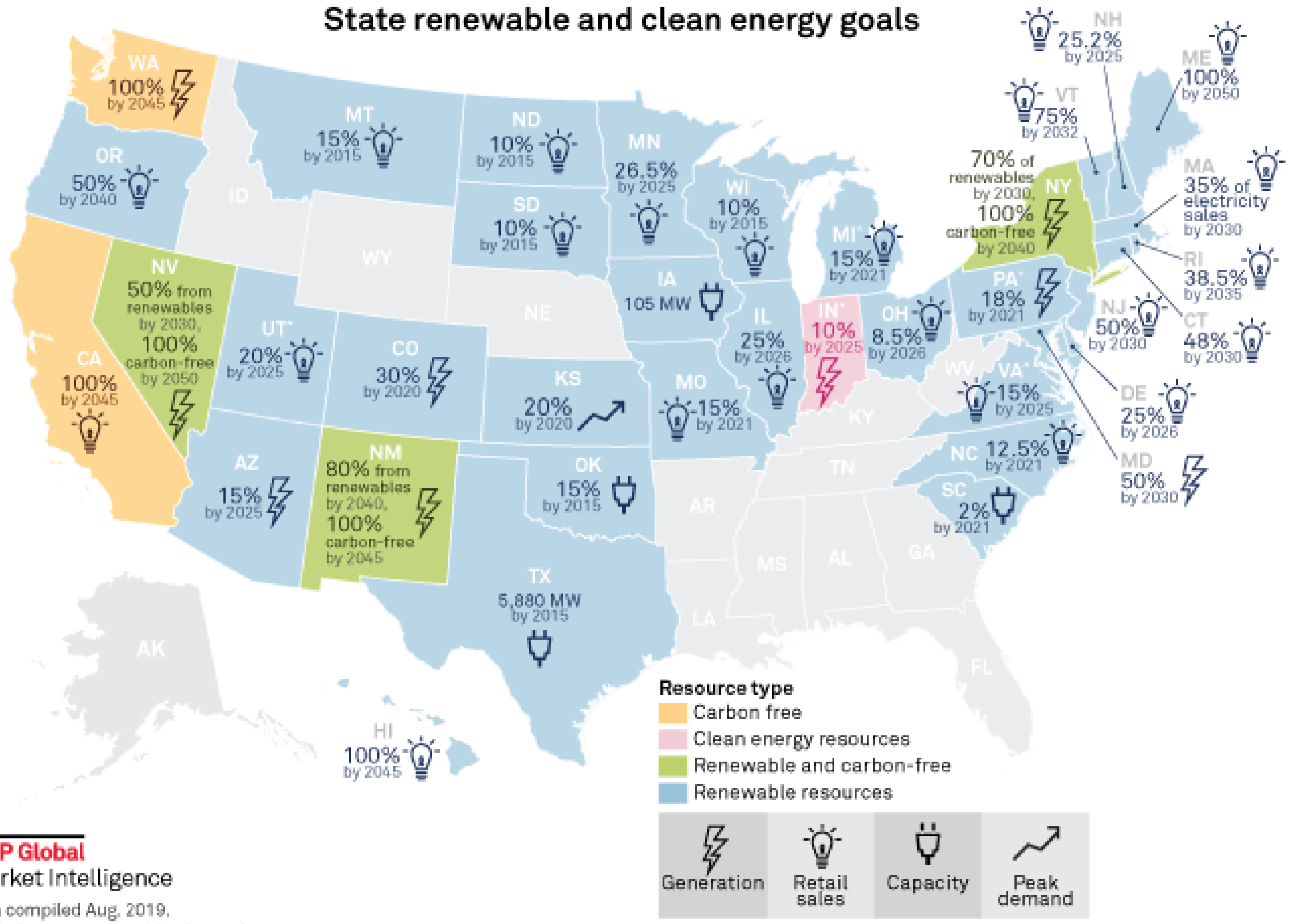
Porous redox material



1. Carbon steel enclosure, 2. Microporous insulation, 3. Refractory bricks, 4. Cooling air circulation tubes, 5. Molybdenum disilicide heating elements, 6. Compressed air inlet (from compressor), 7. Magnesium manganese oxide reactive material, 8. Ceramic grit support, 9. Heated air outlet (to turbine), 10. Supporting frame (standard shipping container dimensions)

Problem Statement

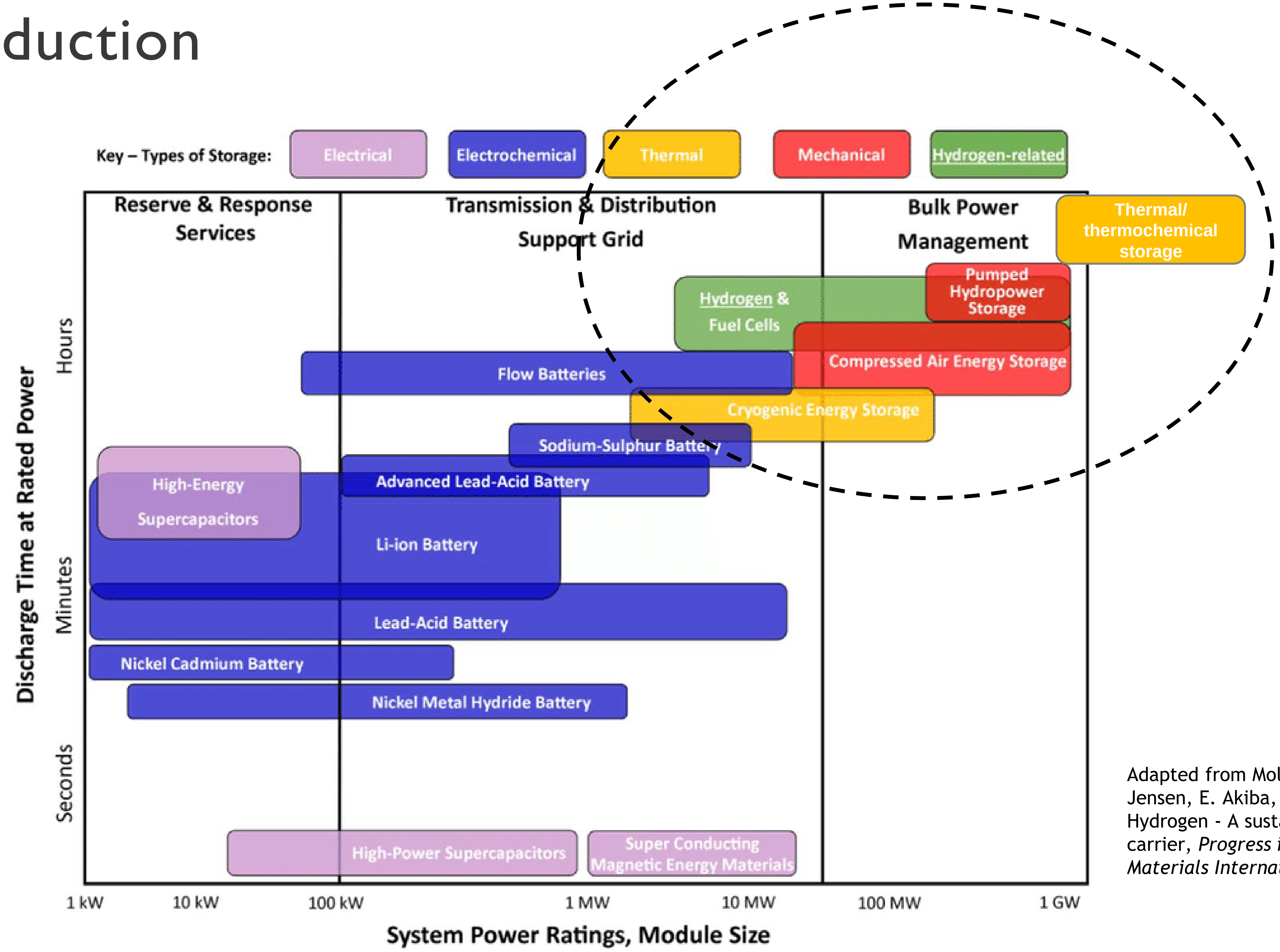
Large-capacity, long-duration energy storage solutions are needed to ensure grid stability with increasing intermittent renewables that Li-ion batteries cannot economically address



Data compiled Aug. 2019.
* Includes non-renewable alternative resources.
Indiana, Kansas, North Dakota, Oklahoma, South Carolina, South Dakota, Utah and Virginia have renewable portfolio goals instead of standards.
Virginia's RPS goal is based on the volume of electricity sold in 2007.
Map credit: Ciaralou Agpalo Palicpic
Sources: S&P Global Market Intelligence; Sierra Club; Union of Concerned Scientists; Database of State Incentives for Renewables & Efficiency; and state public utility commission websites

https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/us-states-face-uneven-paths-in-movement-for-100-clean-energy-53419260

Introduction



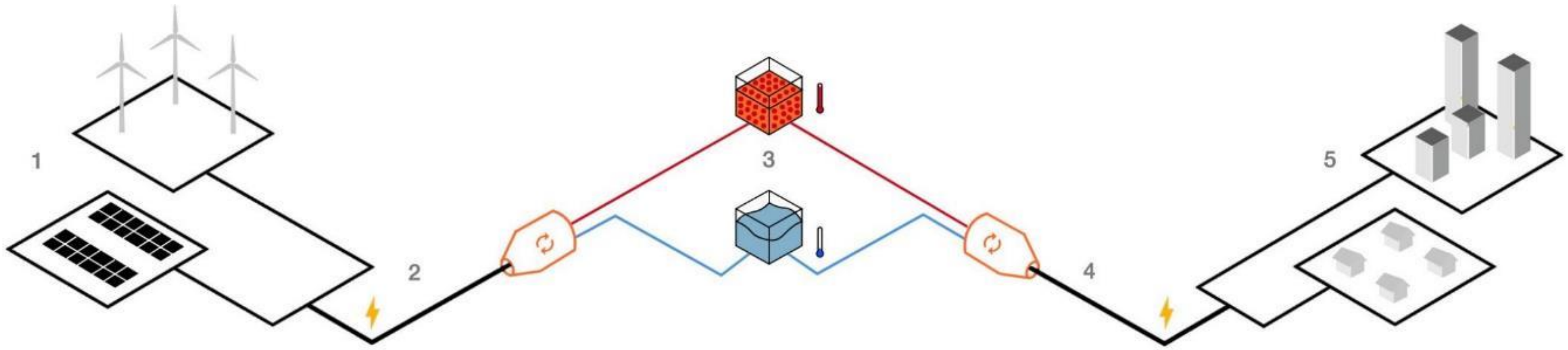
Adapted from Moller, K.T., T.R. Jensen, E. Akiba, and H.W. Li, 2017, Hydrogen - A sustainable energy carrier, *Progress in Natural Science-Materials International*, **27**(1), p. 34-40

Solid Particle Storage – Fixed Bed

Siemens Gamesa Electric Thermal Energy Storage pilot demonstration with thermal storage capacity of 130 MWh at temperatures of 750 °C (image from website).

Two-Tank Heat Pump Storage

"Malta"



1. Collects
Energy is gathered from wind, solar, or fossil generators on the grid as electrical energy and sent to Malta's energy storage system.

2. Converts
The electricity drives a heat pump, which converts electrical energy into thermal energy by creating a temperature difference.

3. Stores
The heat is then stored in molten salt, while the cold is stored in a chilled liquid.

4. Reconverts
The temperature difference is converted back to electrical energy with a heat engine.

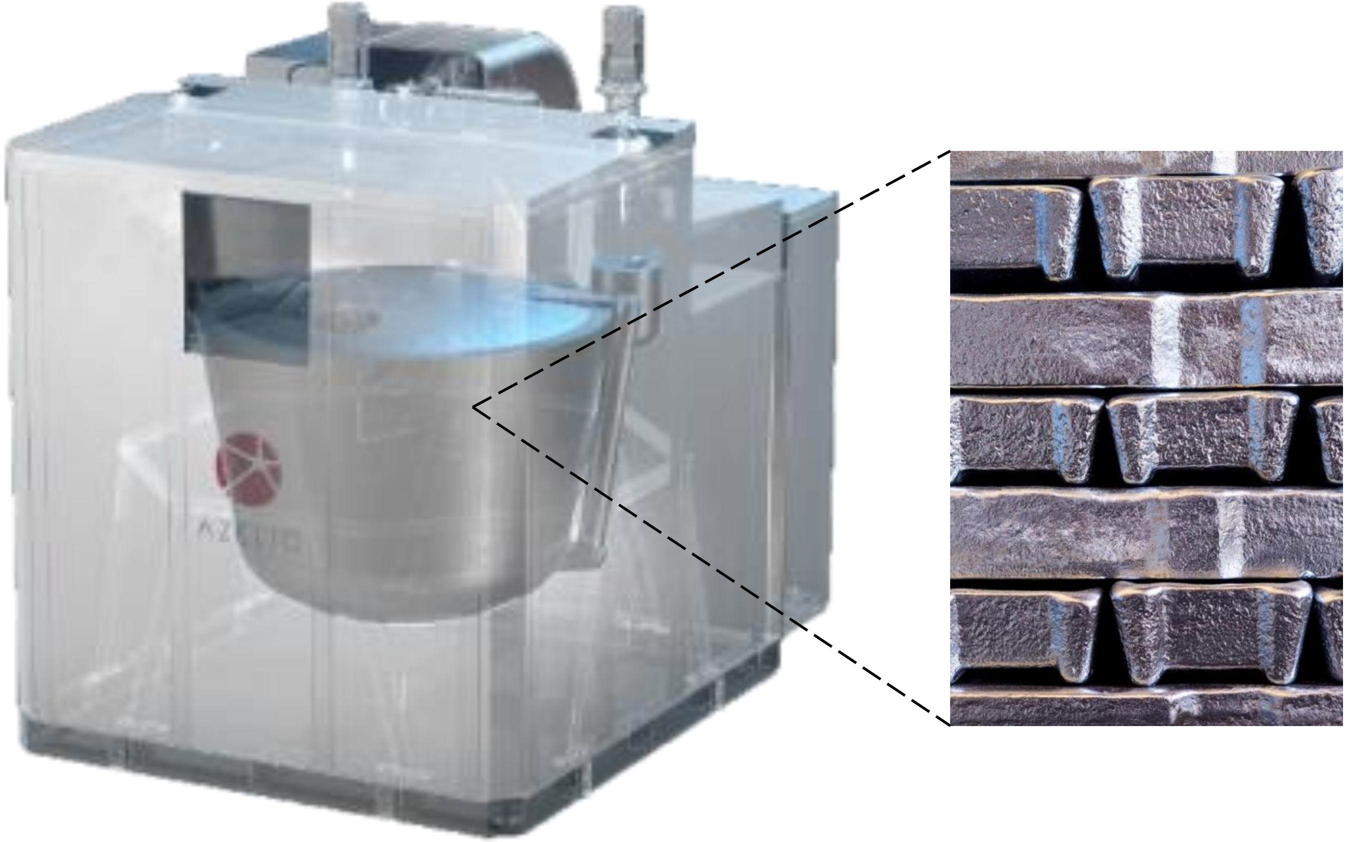
5. Distributes
Electricity is sent back to the grid when it is needed.

Google X

https://x.company/projects/malta/

Molten Aluminum Alloy Phase Change - Azelio

- Electricity melts recycled aluminum at 600 C
- Stored heat is used to generate electricity using Stirling engine



https://www.sandia.gov/ess-ssl/wp-content/uploads/2021/LDES/Torbj%C3%B6rn_Lindquist.pdf

Neha Rustagi

Technology Manager, US Department of Energy

U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

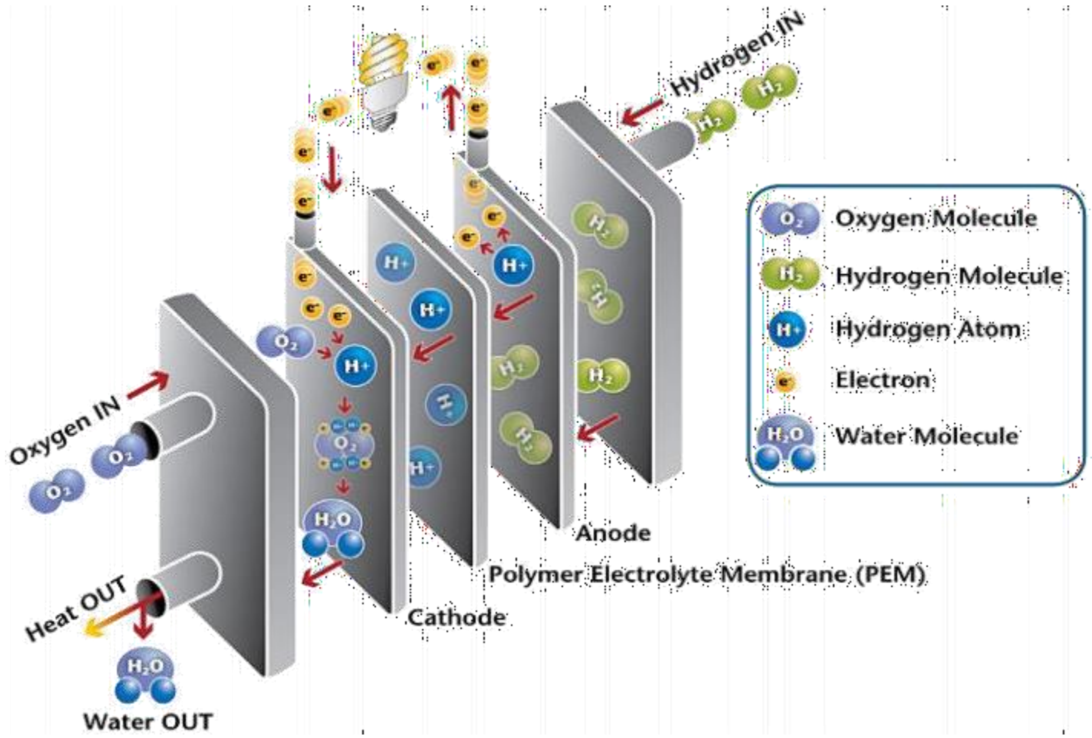
Overview of Hydrogen and Fuel Cell Technologies

Neha Rustagi, U.S. Department of Energy Hydrogen and Fuel Cell Technologies Office

July 14, 2021

Fuel Cells and Electrolyzers Intro

Fuel cells can operate on hydrogen or other fuels and do not involve combustion, so have high electrical efficiencies. Electrolyzers are like fuel cells 'in reverse' and split water to H_2 and O_2



Fuel Cells are:

✔ Convenient ✔ Quiet ✔ Clean

Refuels in minutes | No noise in operation | Low to zero emissions | No moving parts

✔ Versatile and easily scalable

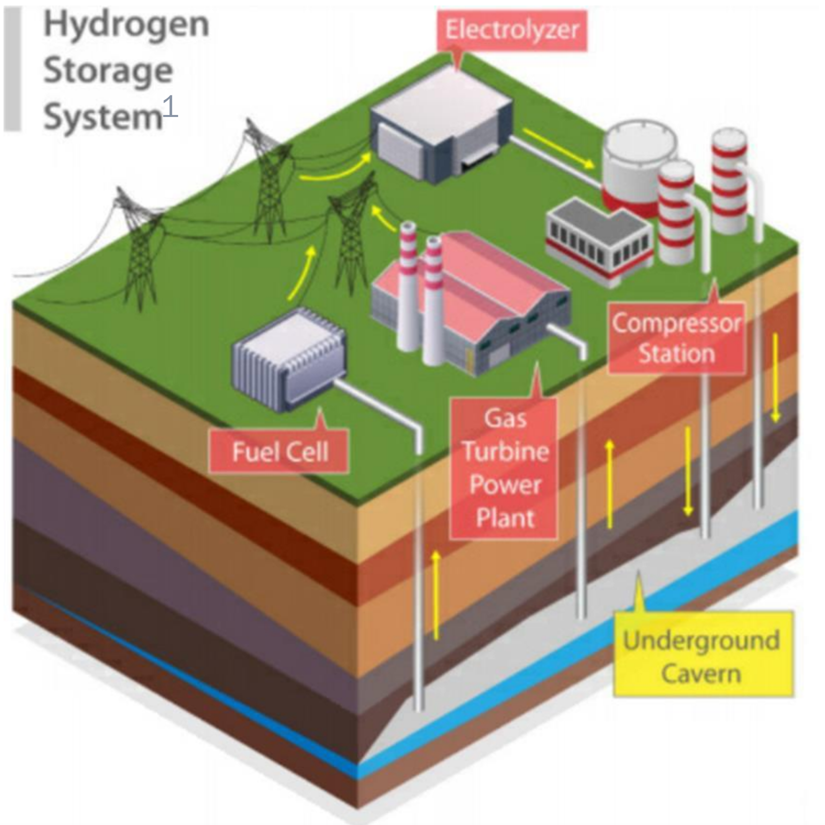
Transportation | Stationary

Fuel Cells can:

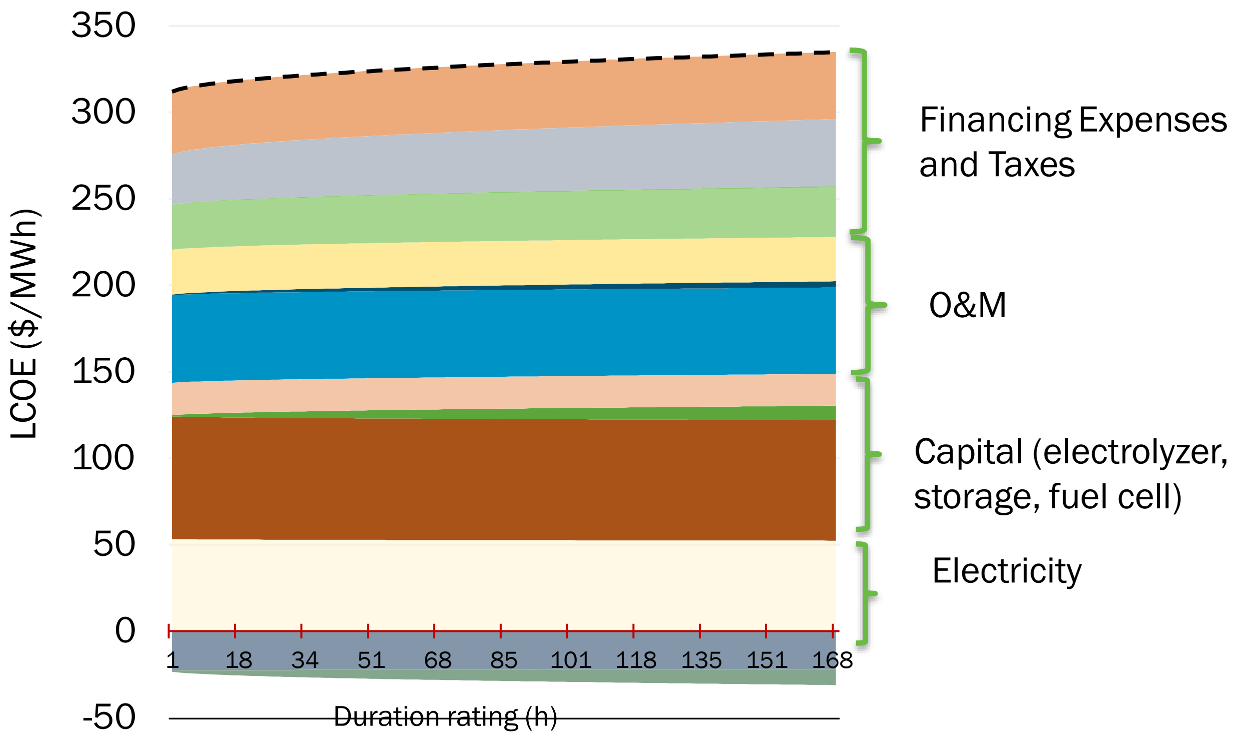
Have higher efficiencies compared to conventional technologies

Reduce life cycle emissions >90%

Example Hydrogen Energy Storage System



Hydrogen Energy Storage in Geologic Caverns[2]

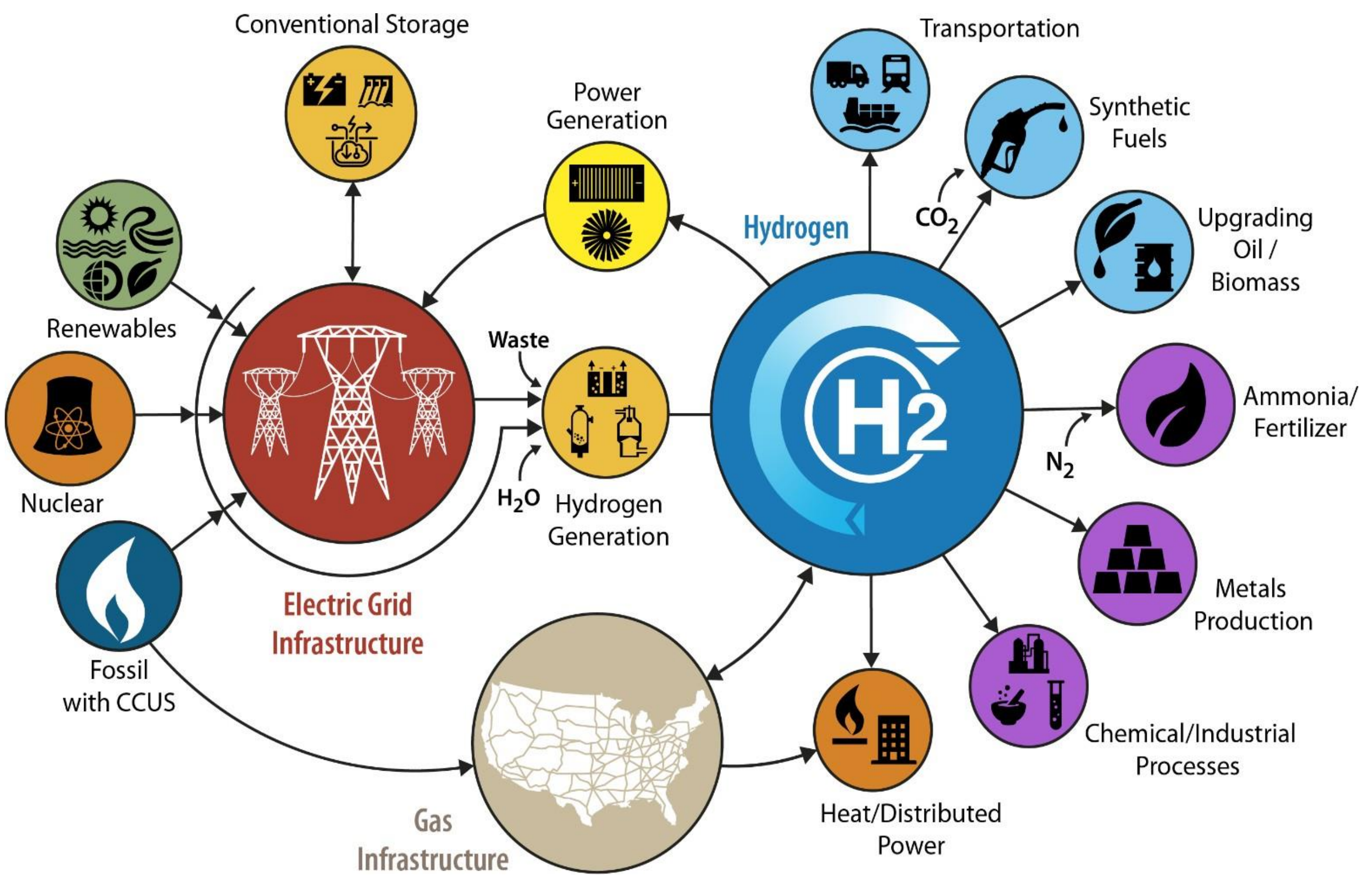


Hydrogen energy storage involves use of an electrolyzer, bulk storage (e.g. cavern or underground pipe), and fuel cell or turbine.

Hydrogen energy storage is competitive at long durations due to the low cost of each additional hour. Value proposition can be enhanced through co-location with other regional markets for hydrogen.

1. Source: "The Four Phases of Storage Deployment: A Framework for the Expanding Role of Storage in the U.S. Power System.". 2021. NREL. https://www.nrel.gov/docs/fy21osti/77480.pdf
2. Assuming 100 MW system with current technology costs. Source of cost analysis: NREL StoreFAST model. https://www.nrel.gov/storage/storefast.html

H2@Scale: Enabling affordable, reliable, clean, and secure energy



Administration Goals include:

- 100% carbon-pollution-free electric sector by 2035
- Net zero emissions economy by 2050

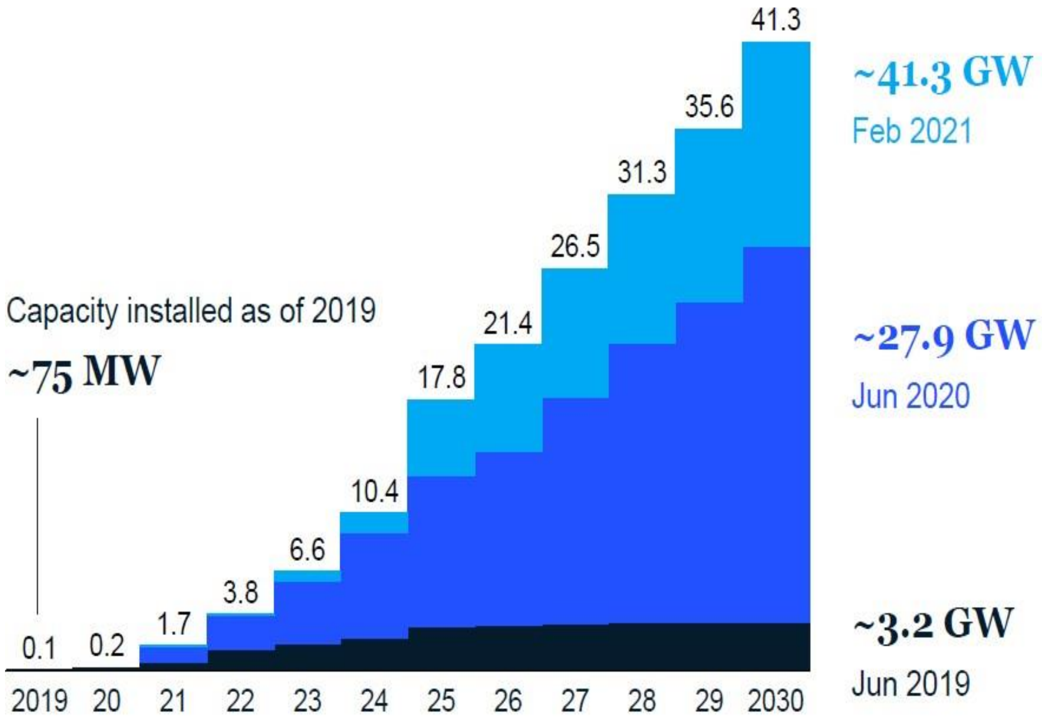
- Hydrogen can address specific applications across sectors that are hard to decarbonize
- Today: 10MMT H_2 in the U.S.
- Economic Potential: 2 to 5x more[1]

Source: U.S. DOE Hydrogen and Fuel Cell Technologies Office, https://www.energy.gov/eere/fuelcells/h2scale

Recent Increased Interest in Hydrogen: Global Drivers

- ✓ **Low-cost renewables** are now available
- ✓ **Countries see clean H_2 can help meet climate goals**
  - Hard to decarbonize sectors
  - Energy storage
  - Import/export opportunities

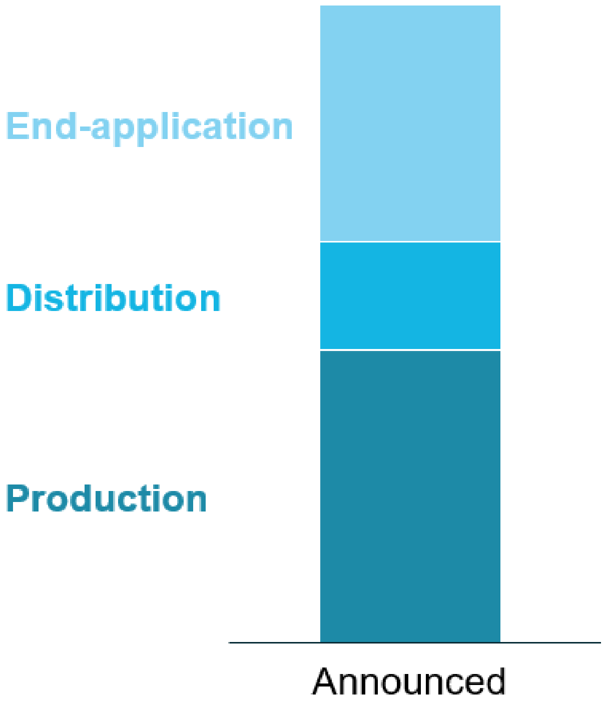
200-fold electrolyzer growth by 2030
Over 40 GW planned



1. For projects without known deployment timeline capacity additions were interpolated between known milestones

Source: McKinsey Hydrogen Project database

$80B Global Government Funding. 6X More with Private Sector through 2025



Source: McKinsey, H2 Council, Spring 2021

Studies show potential for 10 to 25% global GHG reduction using clean hydrogen. $2.5T Revenue. 30M Jobs.

Global Collaboration: Examples of International Collaborations

- International Energy Agency
- Clean Energy Ministerial
- Hydrogen Energy Ministerial
- Mission Innovation
  - Hydrogen
  - Shipping

Engagement with Europe's FCH-JU:
- PRESLHY – liquid hydrogen R&D
- PRHYDE – protocol for heavy duty refueling

H_2 PRHYDE
Protocol for heavy-duty Hydrogen refuelling

FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

PRESLHY

The International Partnership for Hydrogen and Fuel Cells in the Economy
Enabling the global adoption of hydrogen and fuel cells in the economy
www.iphe.net

Regulations, Codes, Standards, Safety and Education & Outreach Working Groups

RCS&S Compendium

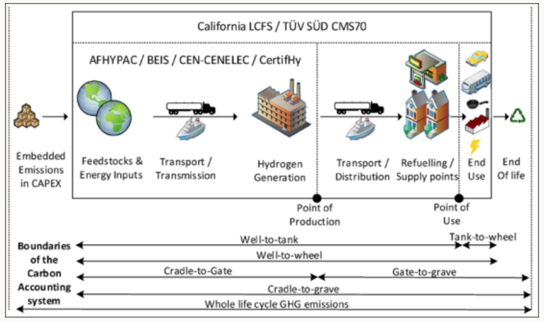
Hydrogen Infrastructure						Hydrogen for Mobility/Tr		
Hydrogen injection at transmission level	Hydrogen injection at distribution level	Methanation and injection of Methane (SNG) via methanation from hydrogen at transmission / distribution level	H2 refilling station (HRS)		Maritime Infra	Mobility infra (tunnel, bridge, underground parking...)	Heavy Duty vehicles	H
Legal framework: permissions and restrictions (and Ownership constraints (unbundling))	Legal framework: permissions and restrictions (and Ownership constraints (unbundling))	Legal framework: permissions and restrictions (and Ownership constraints (unbundling))	Land use plan (zone prohibition)		Off-shore refueling	Restrictions & Incentives	Type approval & Individual vehicle registration - Process	
Permission to connect/ inject	Permission to connect/ inject	Permission to connect/inject	(LH2) Permitting requirements/ process	(GH2) Permitting requirements/ process	On-shore refueling		Restrictions & Incentives	
			(LH2) Safety	(GH2) Safety				

- Reports, workshops, safety sharing
- Assessing gaps
- Education, student engagement, compiling country info

Task Force to facilitate international trade of H_2

H_2 Production Analysis (H2PA)

- Developing a common analytical framework to determine emissions footprint for H_2
- Harmonizing approach across countries and pathways



(Source: Abad et al., Energy policy 138 (2020) 111300)

Enabler: Center for Hydrogen Safety

Global Center for Hydrogen Safety established to share best practices, training resources and information

High Priority:
Lessons learned and best practices on safety

Encourage membership (industry, govt, universities, labs) to join CHS

CENTER FOR 水素安全センター
Hydrogen SAFETY
Connecting a Global Community

www.aiche.org/CHS

IPHE

Hydrogen Council

AIChE

Pacific Northwest NATIONAL LABORATORY

hySafe

Over 60 partners: government, industry, universities and more

Access to >110 countries, 60,000 members

CENTER FOR Hydrogen SAFETY
Connecting a Global Community

HYDROGEN Safety Panel

HYDROGEN Emergency Response Training Resources

Hydrogen Energy Earthshot

“Hydrogen Shot”

Launched June 7, 2021

President Biden and Energy Secretary Granholm at Climate Summit

"…I've asked the Secretary of Energy to speed the development of critical technologies to tackle the climate crisis. No single technology is the answer on its own because every sector requires innovation to meet this moment."

President Joseph R. Biden
April 23, 2021

Launch of Hydrogen Energy Earthshot
First of the Energy Earthshots
June 7, 2021
at DOE Hydrogen Program Annual Merit Review

Secretary Jennifer Granholm
June 7, 2021

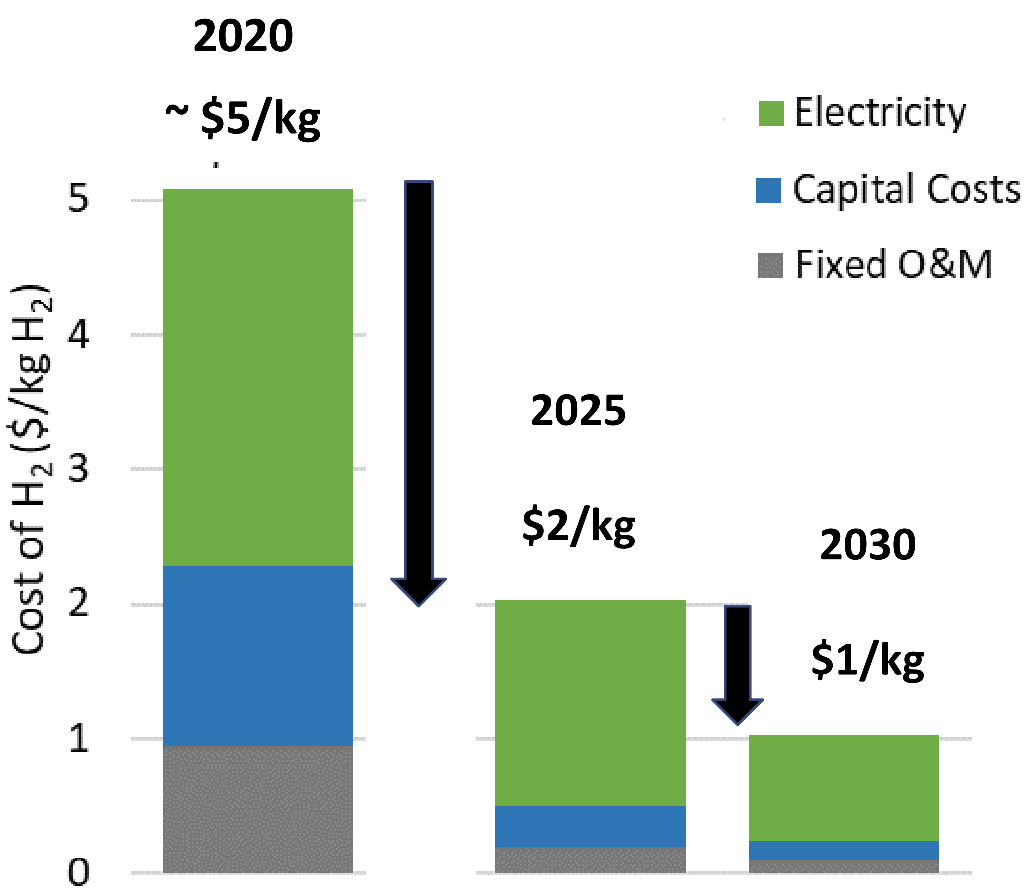
1 for 1 in 1

$1 — 1 kg H_2 — 1 decade

Hydrogen Shot: "1 1 1"
$1 for 1 kg in 1 decade for clean hydrogen

Energy Earthshots U.S. Department of Energy | Hydrogen

Example: Cost of Clean H_2 from Electrolysis



One of several pathways

- Reduce electricity cost from >$50/MWh to
  - $30/MWh (2025)
  - $20/MWh (2030)
- Reduce capital cost >80%
- Reduce operating & maintenance cost >90%

All pathways for clean hydrogen included: Thermal conversion (fossil/waste + CCS), advanced water splitting, biological approaches, etc.

2020 Baseline: PEM low volume capital cost ~$1,500/kW, electricity at $50/MWh. Need less than $300/kW by 2025, less than $150/kW by 2030 (at scale)

Hydrogen Shot Stakeholder Engagement and Next Steps

Stakeholder Engagement Planned

Industry, National Labs, Universities, Regional Coalitions, Labor Groups, Associations, Supply Chains, Federal and State Agencies, SBIRs/STTRs, Technology Commercialization Fund, Investors, International, Codes & Standards, Workforce Development and EJ Communities, and more

Timeline

- Announce Hydrogen Shot and RFI – June 7
- RFI Responses Due – July 7
- Office of Science Round Table- August
- Hydrogen Shot Summit
- Regional Analysis Preliminary Results – Fall
- Follow on Event – Oct 8: Hydrogen and Fuel Cell Day
- Stay tuned for more details

hydrogen.energy.gov

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Hydrogen

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Save the Date

The Hydrogen Shot Summit – Aug. 31 to Sept. 1

- Two-day summit **bringing together stakeholders from industry, research, academia and government to identify pathways to meet the Hydrogen Shot** in the next decade
- **Technical breakout sessions to cover multiple hydrogen production pathways** and other topics including:
  - Electrolysis
  - Thermal conversion with CCS
  - Advanced pathways
  - Deployment and financing
- More info available coming soon at **www.energy.gov/eere/fuelcells/hydrogen-shot**

Other Ways to Connect – Events, Resources and Career Opportunities

Save the Date

June 6 to 9, 2022:

DOE Hydrogen Program Annual Merit Review and Peer Evaluation Meeting (AMR)

Oct 8 - Hydrogen and Fuel Cells Day

- Held on hydrogen's very own atomic weight-day
- DOE EERE comms campaign all week

1 H 1.008 Hydrogen

Open ORISE Fellowships

- Fuel Cells (2 positions):
  - DOE-EERE-STP-HFTO-2021-1800
- Hydrogen Production:
  - DOE-EERE-STP-HFTO-2020-1804
- Hydrogen Infrastructure:
  - DOE-EERE-STP-HFTO-2020-1804

Apply at zintellect.com

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Visit H2tools.Org For Hydrogen Safety And Lessons Learned

https://h2tools.org/

CENTER FOR Hydrogen SAFETY
Connecting a Global Community

www.aiche.org/CHS

Sign up to receive hydrogen and fuel cell updates

www.energy.gov/eere/fuelcells/news

Learn more at: energy.gov/eere/fuelcells AND www.hydrogen.energy.gov

Thank You

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INCREASE YOUR H_2IQ
www.hydrogen.energy.gov

Save the Date

for next year's AMR

June 6 to 9, 2022

We hope in person!

Looking for more info?

#H2IQ

www.energy.gov/fuelcells

www.hydrogen.energy.gov

Moderator and Panelists

Chibulu Luo

Operations Officer, Climate Investment Funds

Vincent Sprenkle

Senior Advisor - Energy Storage, Electrochemical Materials and Systems Group, Pacific Northwest National Laboratory

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