U.S. DEPARTMENT OF ENERGY


Eric L. Miller


Devinn Lambert


John Vetrano


Katie Randolph


Mark Ackiewicz


Alison Hahn


Vivien Lecoustre


Hannah Murdoch


Dinesh Mehta


Crystal Farmer

From Hydrogen Shot to Hydrogen Hubs

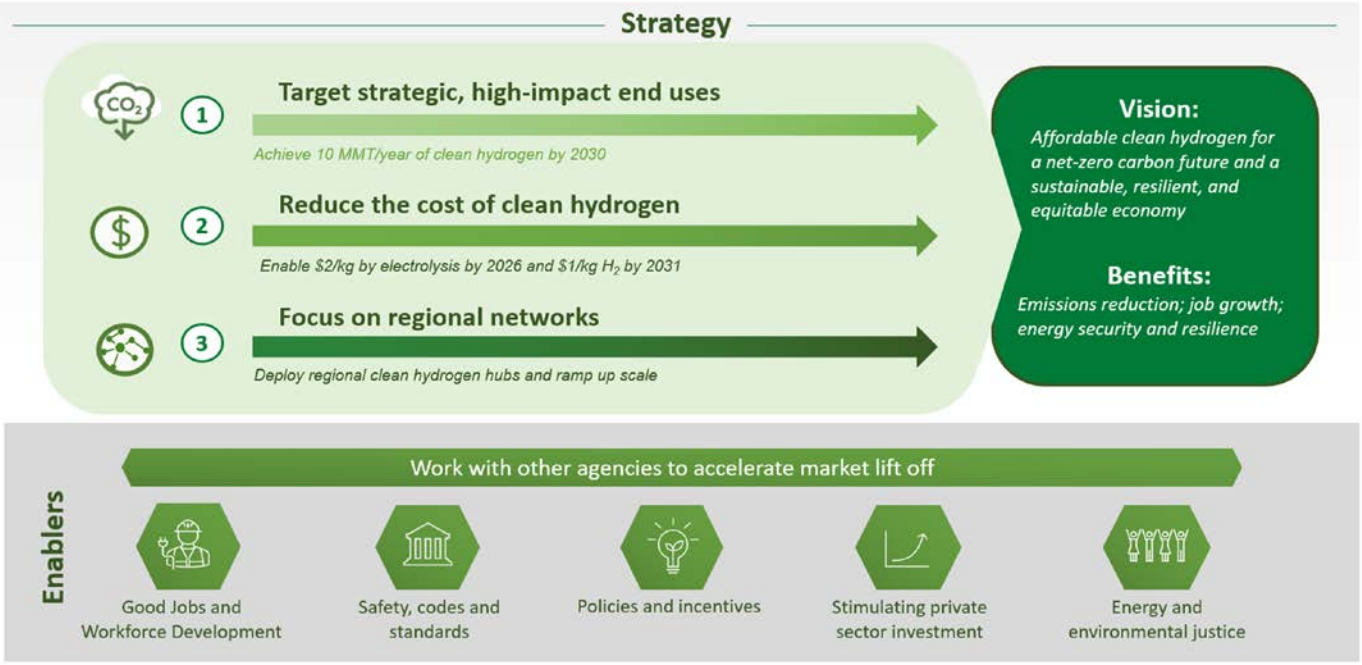
Moderated by Eric L. Miller, HFTO Chief Scientist

Hydrogen Program Annual Merit Review and Peer Evaluation Meeting, June 5, 2023, Arlington VA


Exciting
Times for
Hydrogen!

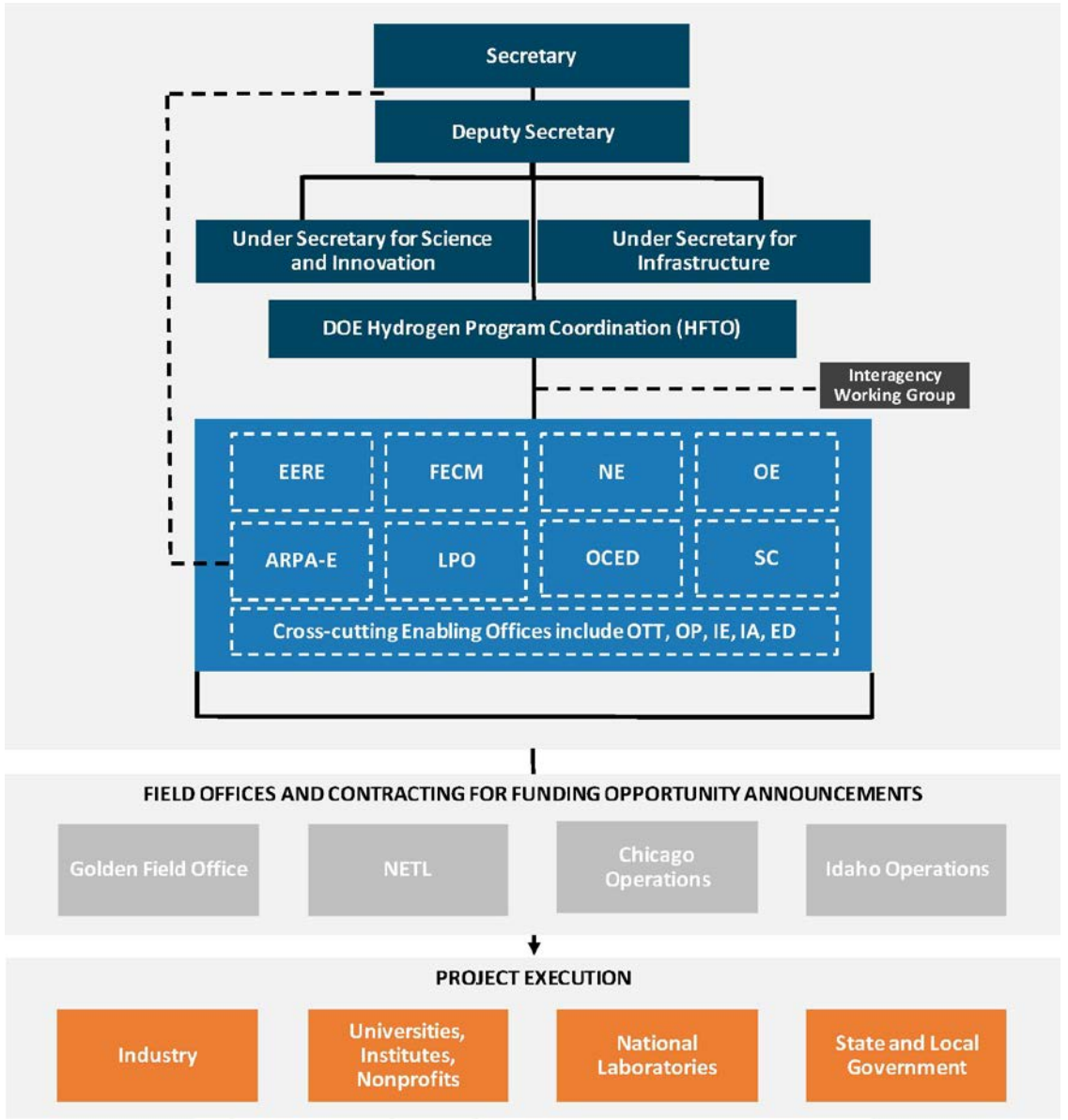
U.S. DOE Hydrogen Program – *All-Hands-on-Deck!*

Hydrogen is one part of a broad portfolio of activities Includes multiple offices and the entire RDD&D value chain from production through end use



www.hydrogen.energy.gov

Coordinated across Offices by DOE Hydrogen and Fuel Cell Technologies Office (HFTO)



Distinguished Panelists

Devinn Lambert
Deputy Director

Crosscuts & Energy Earthshots
Office of the Under Secretary of Science & Innovation

John Vetrano
Program Manager

Office of Basic Energy Sciences
SC

Katie Randolph
Operations Supervisor

Hydrogen & Fuel Cell Technologies Office
EERE

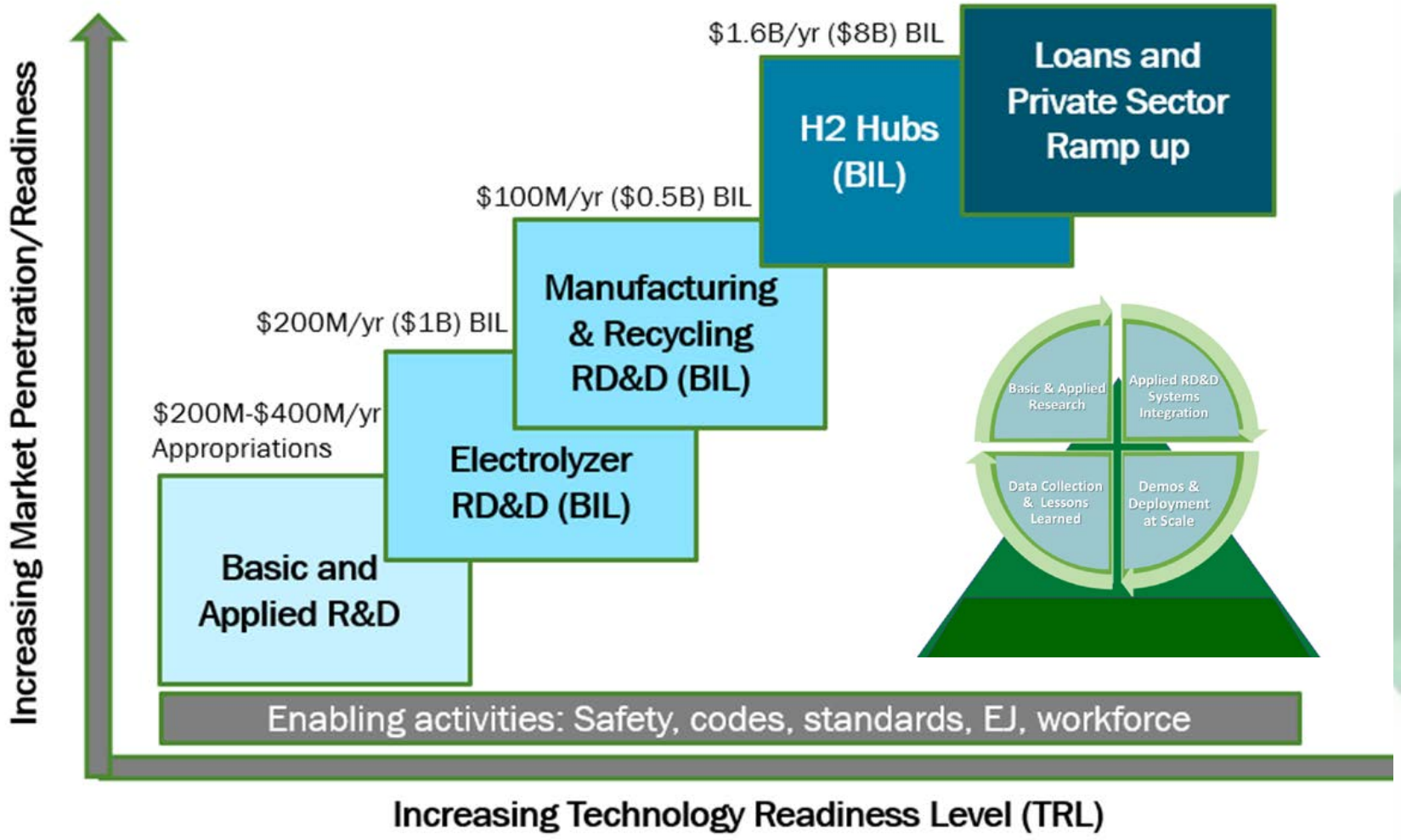
Mark Ackiewicz
Director

Office of Carbon Management Technologies
FECM

Alison Hahn
Director

Office of Nuclear Reactor Deployment
NE

Comprehensive Strategic Approach Spanning RDD&D



Foundational and crosscutting efforts support the entire lifecycle of activities at DOE, from basic research through large-scale deployment

Hydrogen Energy Earthshot

“Hydrogen Shot”

“1 1 1”
$1 for 1 kg clean hydrogen in 1 decade

Launched June 7, 2021
Summit Aug 31-Sept 1, 2021

Energy Earthshots: Call to Action

The Energy Earthshots are designed to drive integrated program development across the U.S. Department of Energy's science and applied energy offices and ARPA-E and take an all-hands-on-deck approach to leading science and technology innovations to address tough technological challenges and cost hurdles, and rapidly advance solutions to help achieve our climate and economic competitiveness goals.

- Make a major impact to reduce emissions
- Address the hardest technology barriers
- Set highly ambitious decadal targets
- Are compelling, bold, and inspirational
- Significantly engage stakeholders

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Hydrogen

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Storage™

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Carbon Negative

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Enhanced Geothermal™

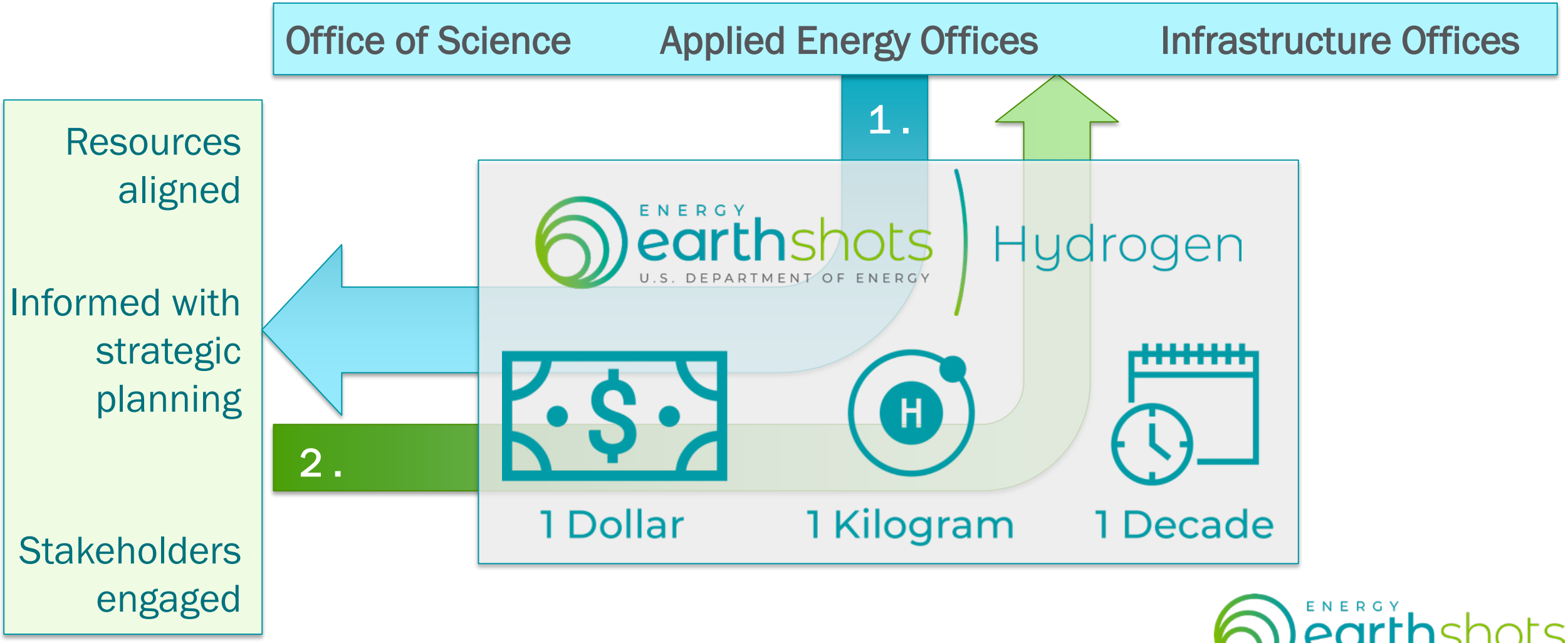
ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Floating Offshore Wind™

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Industrial Heat Shot™

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Clean Fuels & Products Shot

Strategic Alignment: Feedback loop

1. An Energy Earthshot focuses “All-hands” attention on a singular target
2. Scientific and strategic learnings, guides “All-hands”



Strategic Alignment: What "All-Hands" looks like from the street

Energy Earthshots | Hydrogen

1 Dollar | 1 Kilogram | 1 Decade

Snapshot of work
June 21-March 23

	Office of Science	Applied Energy Offices	Infrastructure Offices
Resources aligned	Energy Earthshot Research Centers	BIL: Clean Hydrogen Electrolysis, Manufacturing, and Recycling	BIL: Regional Clean Hydrogen Hubs
Informed with strategic planning	BES Roundtable Foundational Science for Carbon-Neutral Hydrogen Technologies	DOE Clean Hydrogen Strategy and Roadmap	Pathways to Commercial Liftoff: Clean Hydrogen
Stakeholders engaged	PI Meetings	Hydrogen from Next-generation Electrolyzers of Water Workshop	H2 Matchmaker

Decisive & Creative: Hydrogen Shot Fellowship

Energy Earthshots U.S. Department of Energy

U.S. DEPARTMENT OF ENERGY | Office of Science

SC Mission:

Delivery of scientific discoveries and major scientific tools to transform our understanding of nature and advance the energy, economic, and national security of the United States.

More than **29,000** Researchers supported at more than **300** Institutions and **17** DOE Labs

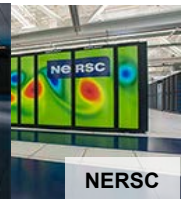
Steward **10** of the 17 DOE National labs

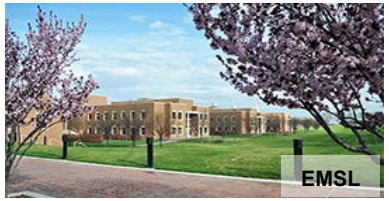
More than **37,000** Users of **28** SC Scientific Facilities

$8.1B
(FY 23 enacted)

SC User Facilities Have Important Roles in Hydrogen Research

- **Advanced Scientific Computing Research** leadership class computers cross many disciplines to accelerate transformative progress
- **Biological and Environmental Research** user facilities bring bioanalytical instrumentation, genomic sequencing, and systems biology tools for innovative approaches for biological hydrogen generation
- **Basic Energy Sciences** light, neutron, and nanoscience facilities provide advanced synthesis and characterization to enable next-generation energy technologies





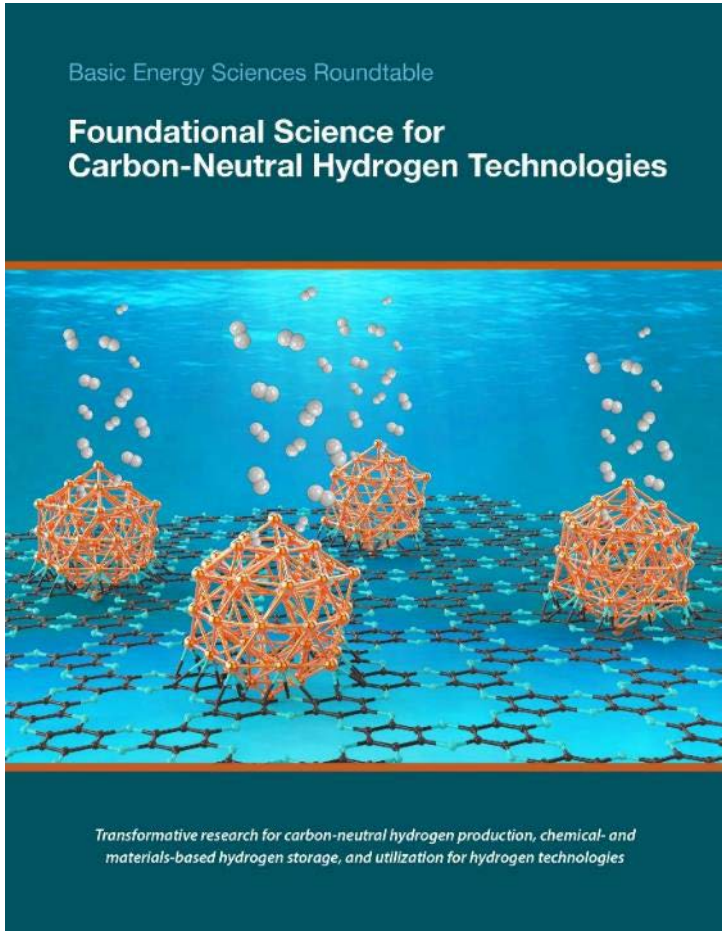
Strong collaboration between SC-BES User facilities and hydrogen-related consortia have resulted in joint publications in high-impact, peer reviewed journals.

U.S. DEPARTMENT OF ENERGY | Office of Science

Priority Research Opportunities to Advance Foundational Science *for Carbon-Neutral Hydrogen Technologies*

Priority Research Opportunities:

- Discover and Control Materials and Chemical **Processes to Revolutionize Electrolysis** Systems
- Manipulate Hydrogen Interactions to Harness the Full Potential of **Hydrogen as an Energy Carrier**
- **Elucidate** the Structure, Evolution, and Chemistry of **Complex Interfaces** for Energy and Atom Efficiency
- Understand and **Limit Degradation Processes** to Enhance the Durability of Hydrogen Systems

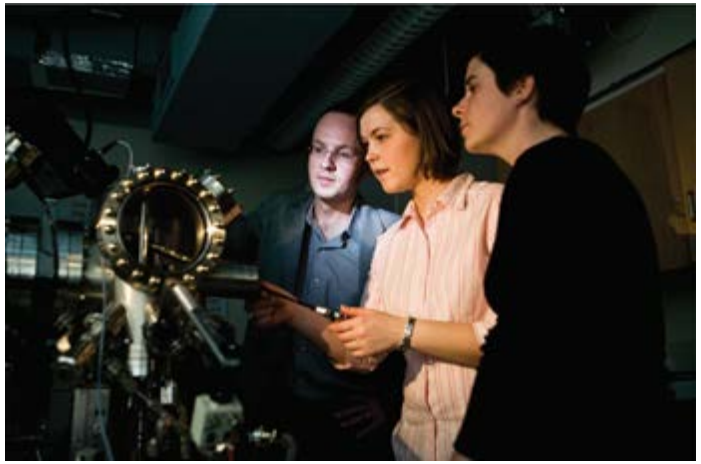


https://science.osti.gov/-/media/bes/pdf/brochures/2021/Hydrogen_Roundtable_Report.pdf

U.S. DEPARTMENT OF ENERGY | Office of Science

FY 2024 Request: SC Energy Earthshots Initiative

- **Funding for the SC Energy Earthshots Initiative started in FY 2023 with $100M**
- **Joint initiative between BES, ASCR, and BER to address key research challenges at the interface between basic research and applied R&D to realize DOE Energy Earthshots stretch goals.**
- **Two complementary programs:**
  - Energy Earthshot Research Centers (EERCs): Multi-disciplinary, multi-institutional teams led by DOE laboratories focused on key research challenges at the interface of basic and applied R&D.
  - Scientific Foundations for Energy Earthshots: Small group awards led by academic or private sector institutions focused on use-inspired foundational science addressing knowledge gaps limiting achievement of Earthshot goals.

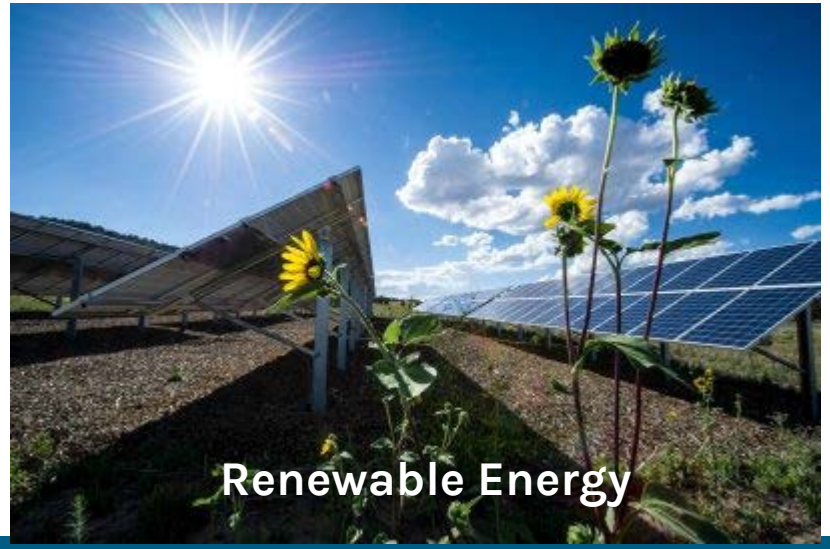


https://www.energy.gov/policy/energy-earthshots-initiative

U.S. DEPARTMENT OF ENERGY | Office of Science

About the Office of Energy Efficiency and Renewable Energy

EERE's MISSION *is to accelerate the research, development, demonstration, and deployment of technologies and solutions to equitably transition America to net-zero greenhouse gas emissions economy-wide by no later than 2050, and ensure the clean energy economy benefits all Americans, creating good paying jobs for the American people—especially workers and communities impacted by the energy transition and those historically underserved by the energy system and overburdened by pollution.*



EERE Clean Hydrogen Mission & Portfolio

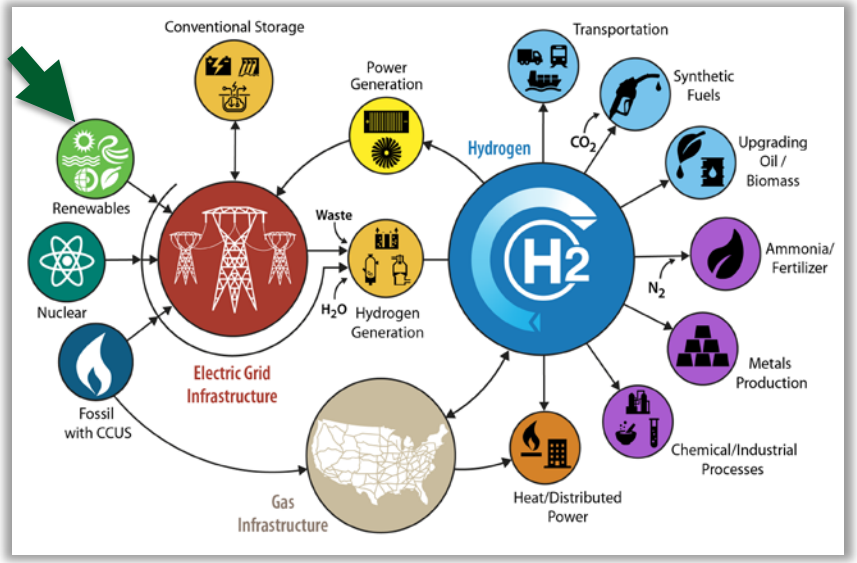
Feedstocks:

- Renewable Energy and Water

Technologies

- Electrolysis: Low- and High-Temperature
- Advanced Water Splitting: Photo-electrochemical, Solar/High-T Thermochemical
- Biological Approaches

Production, Storage, Delivery, Conversion, and End-Use RD&D; Emphasis on Renewable Integration



Example Activities

- Hydrogen & Fuel Cell Technology RD&D
- Wind Hybrid Systems
- Solar Fuels Production
- Bio-fuels and Products
- Offshore Energy Harvesting
- Geological Hydrogen
- Manufacturing & Industrial Decarbonization

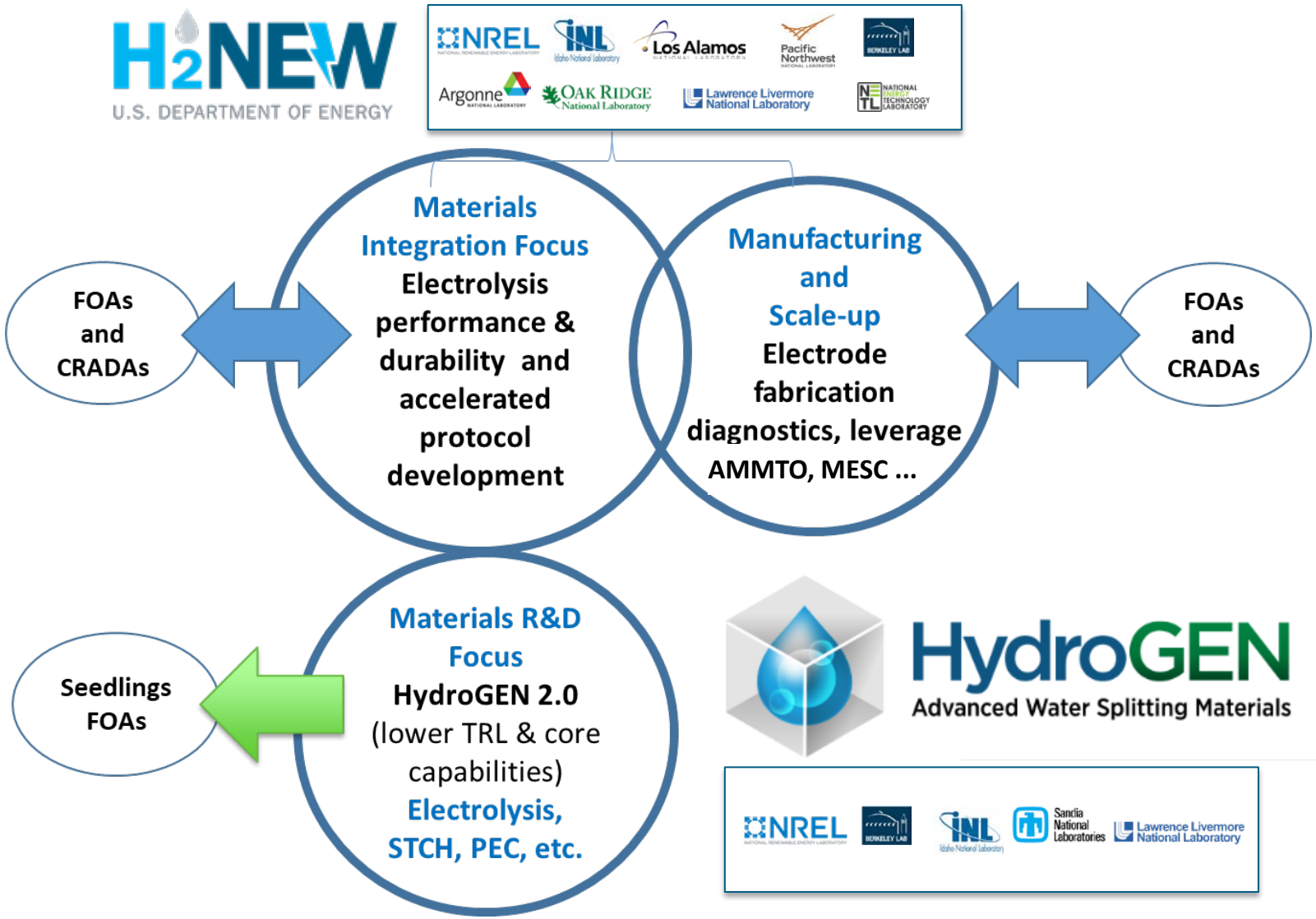
Today
$4-6/kg clean H_2 scenarios*

2026
BIL target: $2/kg clean H_2

2031
H2 Shot target: $1/kg clean H_2

*across multiple renewable energy scenarios

Integrated Consortia Approach – Water-Splitting Example



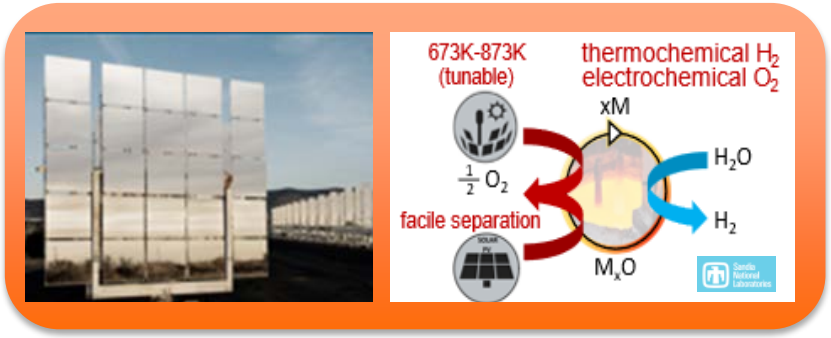
H2NEW Consortium

- *Addressing performance/durability barriers through components & integration*
- *Enabling high-volume production of MW-scale electrolyzers & components*

HydroGEN Consortium

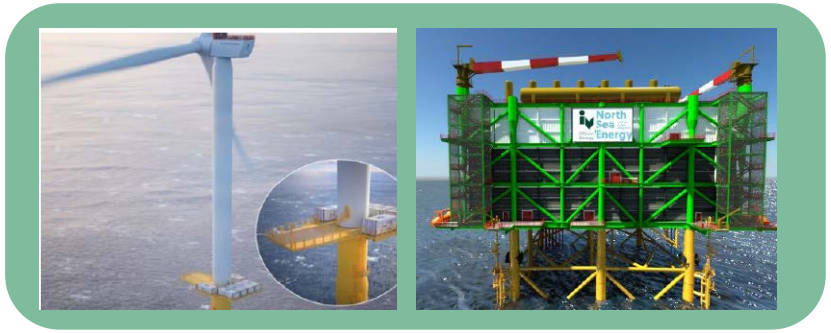
- *Accelerating foundational R&D of innovative materials for AWS technologies*
- *Fosters cross-cutting innovation using theory-guided applied materials R&D*

Focus on Renewable Integration - Examples



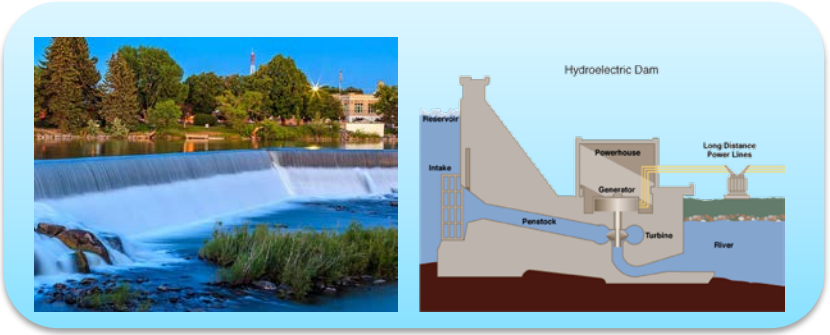
- **Solar water splitting using liquid metal RedOx cycles promoted by electrochemistry – *with SETO***

SETO003



- **Wind to hydrogen RD&D, including offshore wind – *with WETO, HFTO***

WETO001



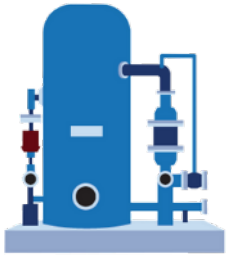
- **Hydropower-Based H_2 Production Analysis – *with WPTO***

WPTO001

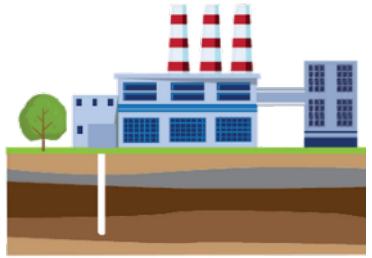
IntraAg: Wed. AM

Office of Fossil Energy and Carbon Management: Strategic Vision

Justice, Labor, and Engagement



Technologies that Lead to Sustainable Energy Resources

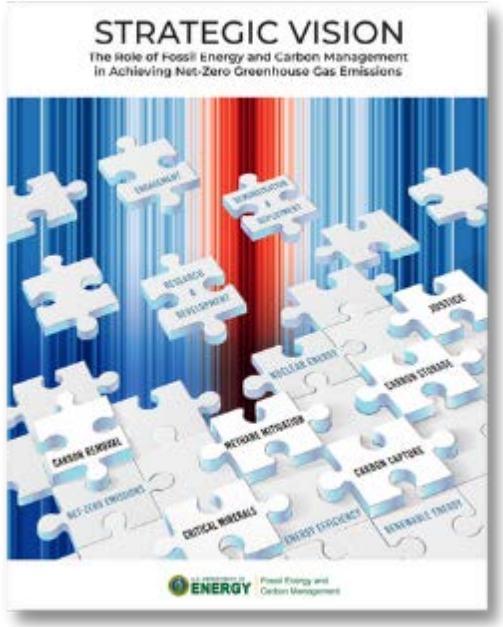


Carbon Management Approaches toward Deep Decarbonization

IntraAg: Tues. AM, PM

FECM Role in Achieving Net-Zero Greenhouse Gases

FECM's *Strategic Vision* will enable DOE to make strategic carbon management decisions to ensure that fossil fuel usage is put into proper context with climate change and is designed for a future that achieves and maintains net-zero greenhouse gas emissions.



Read FECM's Entire Strategic Vision by Scanning the Code Above

Pre-Commercial.. H_2 Generation (TRL 6+)

Advanced CCS Systems for SMR

Svante VeloxoTherm™ solid adsorbent at Linde SMR H_2 plant

- ~1,100,000 tonnes/year net CO_2 capture
- 90% Capture Efficiency
- Production of lower carbon H_2 with 99.97% purity

Gen 1 CCS technology at Phillips 66 refinery in Rodeo, California

- Separate & store ~190,000 tons/year net CO_2 from hydrogen production unit with >90% carbon capture efficiency

Advanced CCUS + for ATR

Tallgrass MLP Operations, LLC

CO2 Capture Unit at Tallgrass MLP Operations LLC's Planned Blue Bison ATR Plant Douglas, WY

- Separate and store 1.66 million tonnes/year of 95% pure CO_2 with >97% carbon capture efficiency
- System combining carbon capture, H_2 production (220 MMSCFD at 99.97% purity), and H_2 combustion in auxiliary burners

Subsurface Hydrogen Storage

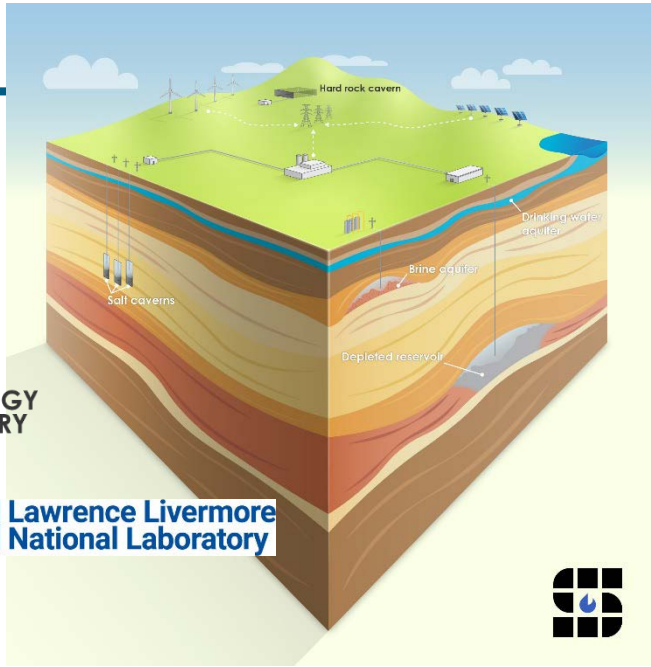
SHASTA
Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

Current Status

- Subsurface hydrogen storage is domestically limited to salt cavern storage facilities.
- Expanding the footprint for subsurface storage to different geologies and geographies.

Goals & Objectives

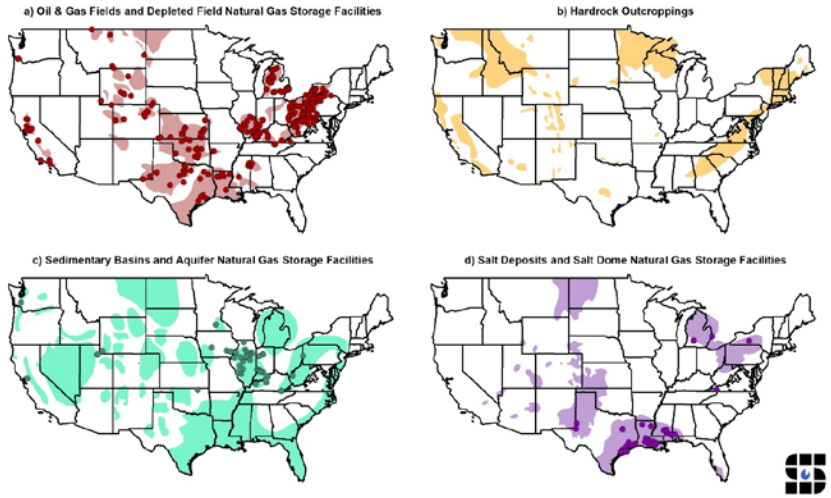
- Identify and address key technological hurdles
- Develop tools and technologies
- Subsurface geologic characterization efforts to demonstrate storage permanence and risk management.
- Determine viability, safety, and reliability



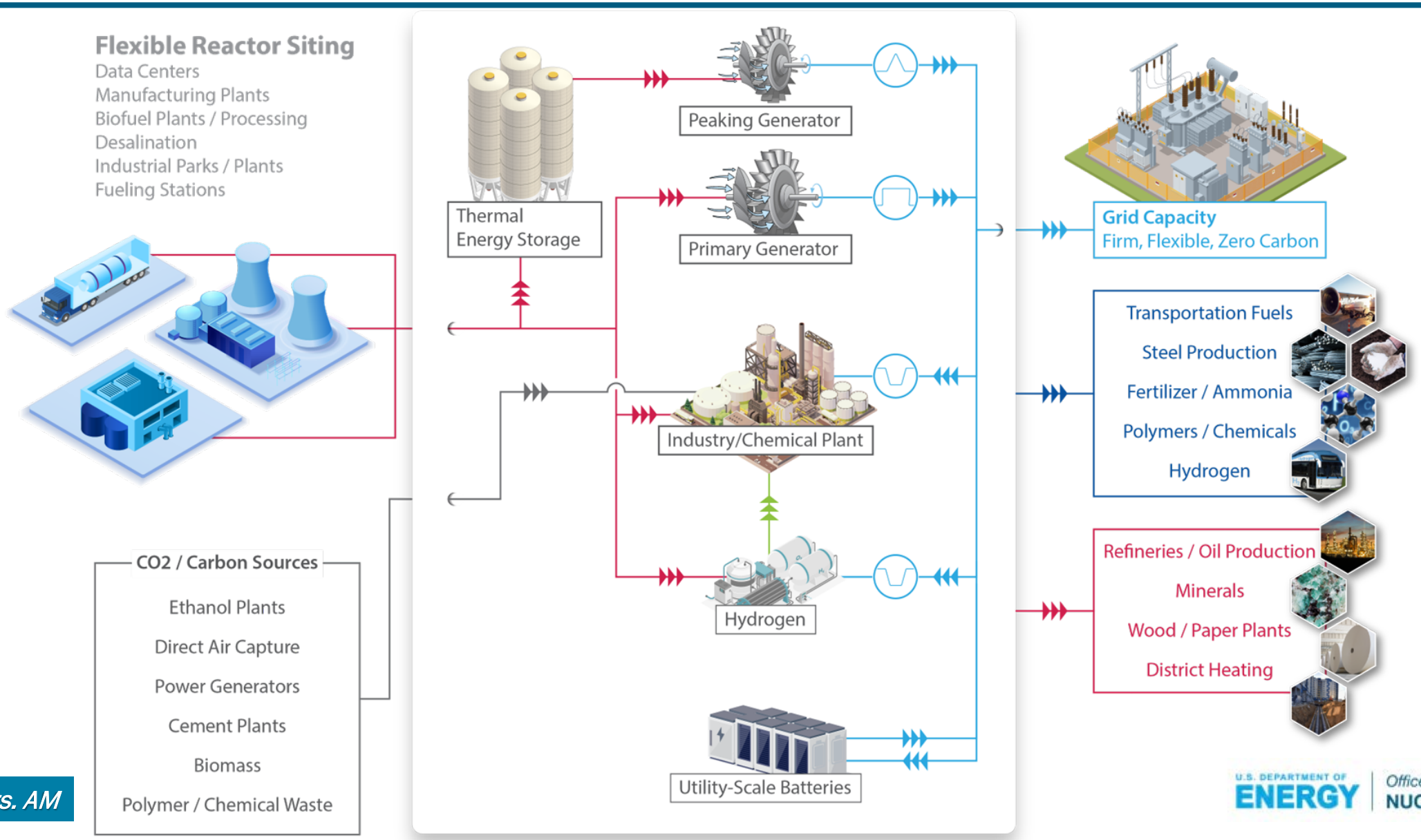
NATIONAL ENERGY TECHNOLOGY LABORATORY

Pacific Northwest NATIONAL LABORATORY

Lawrence Livermore National Laboratory



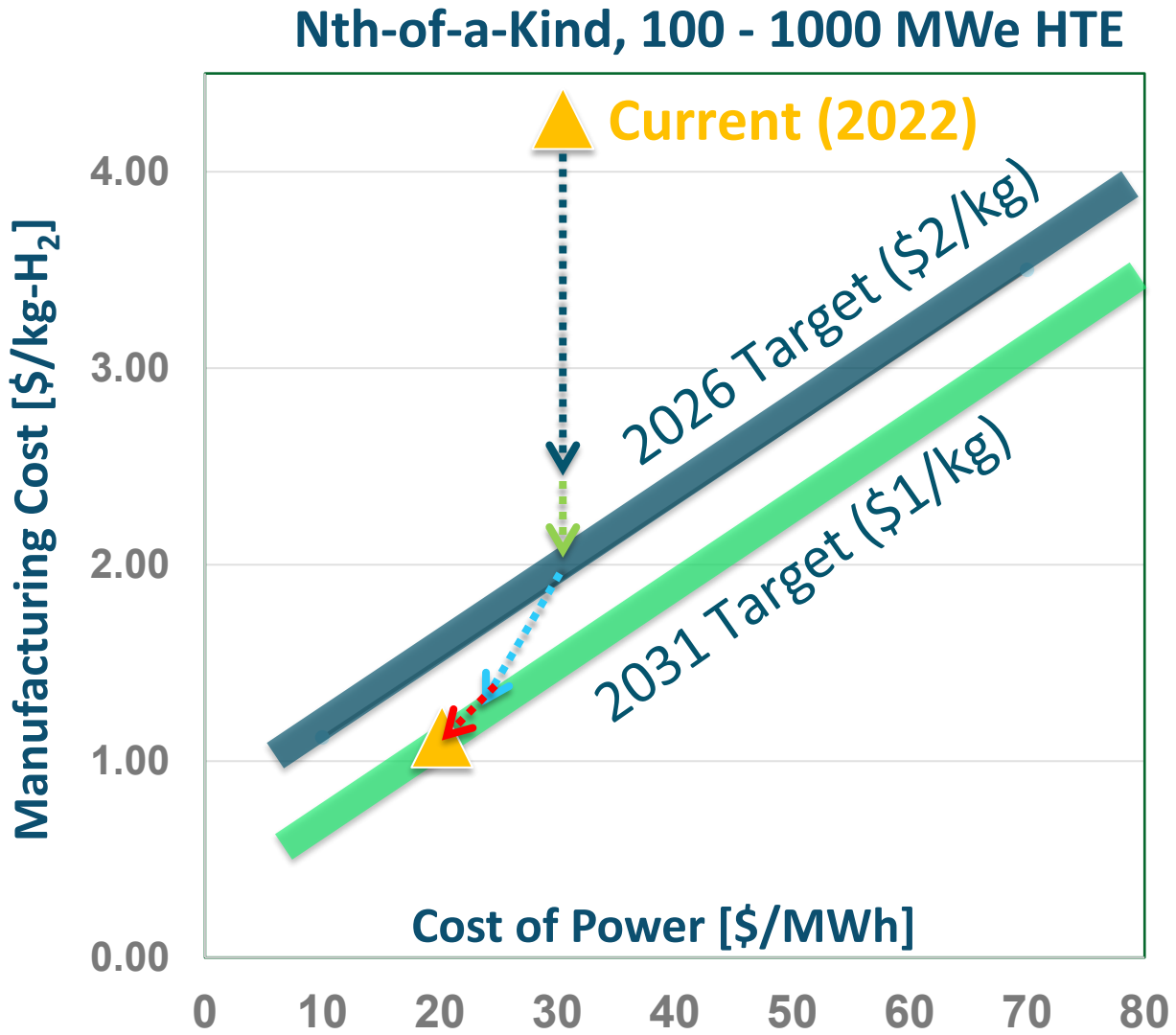
Nuclear Integrated Energy System Concept



IntraAg: Thurs. AM

U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Joint NE - EERE path to Earthshot Goal of $1/kg-H2



- *HFTO R&D improves electrolysis performance and durability*
- *NE reduces cost of power production*
- *Production Tax Credit incentivizes early adoption*
- *Early adoption helps reach achieve high volume manufacturing*

U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Pilot Plant Hydrogen Production Demonstration Projects

Constellation: Nine-Mile Point Plant

- H_2 production began March 2023
- NEL Hydrogen Proton Electrolyte Membrane electrolysis module

Energy Harbor: Davis-Besse Plant

- H_2 production beginning in 2024
- 2 MW_{eDC} Cummins Proton Electrolyte Membrane electrolysis module

Xcel Energy: Prairie Island Plant

- H_2 production beginning in 2024
- Bloom Energy high temperature solid-oxide electrolysis modue

U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Q&A

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Hydrogen

From your perspective, what are key challenges and RD&D opportunities for meeting the clean hydrogen cost targets of $2/kg (2026) and $1/kg (Hydrogen Shot)?

Distinguished Panelists

Vivien Lecoustre
Support Contractor
Tech/T2M-SETA
ARPA-E

Hannah Murdoch
Senior Advisor
(Contractor)
Market Analysis
OTT

Dinesh Mehta
Deputy Director
Loan Originations
LPO

Crystal Farmer
Program Manager
Office of Clean Energy Demonstrations

Advanced Research Projects Agency – Energy: Overview

REDUCE imports

REDUCE emissions

IMPROVE efficiency

IMPROVE energy infrastructure resilience

IMPROVE radioactive waste management

arpa·e
CHANGING WHAT'S POSSIBLE

2007

Rising Above the Gathering Storm **Published** - warning policymakers that U.S. advantages in science and technology had begun to erode

America COMPETES Act **Signed** – authorizing the creation of ARPA-E

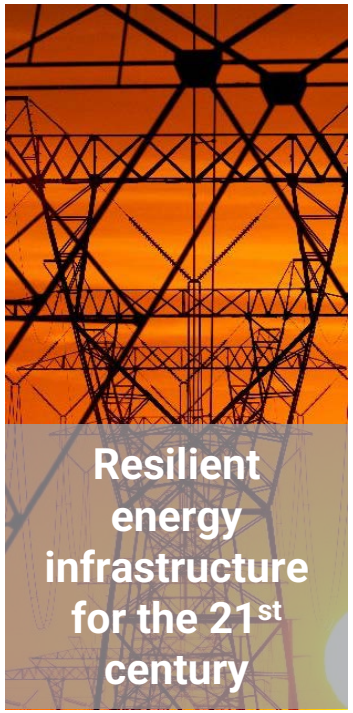
2009

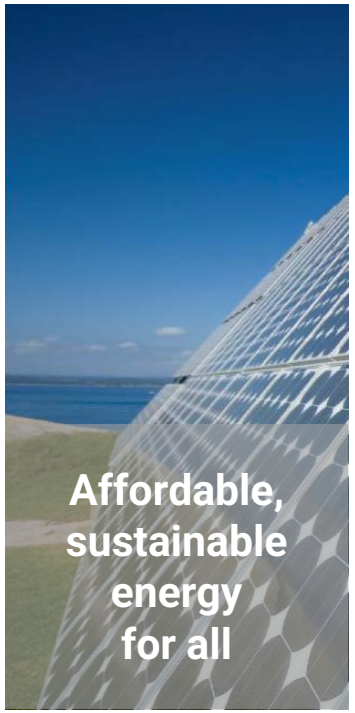
American Recovery & Reinvestment Act **Signed** – Providing ARPA-E its first appropriations of $400 million, which funded ARPA-E's first projects

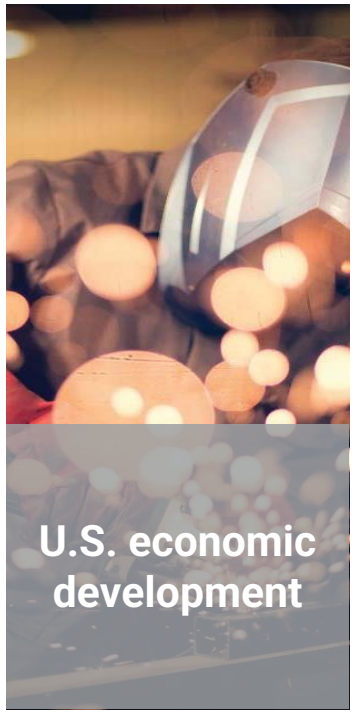
2023

1,468+ Awards
69+ Programs

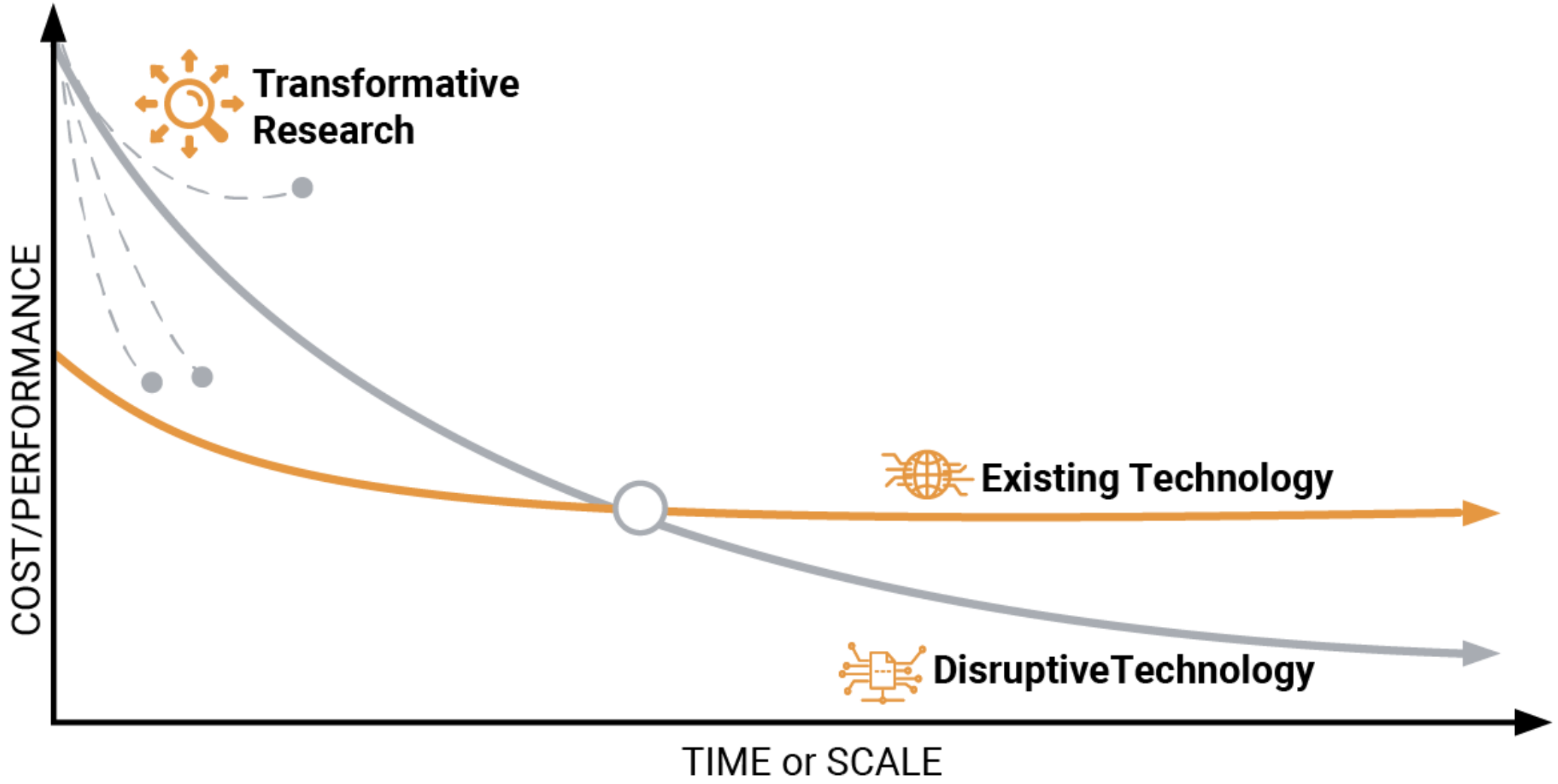
Current Funding: **$470M** (FY23)







Creating New Learning Curves – High Risk, High Reward



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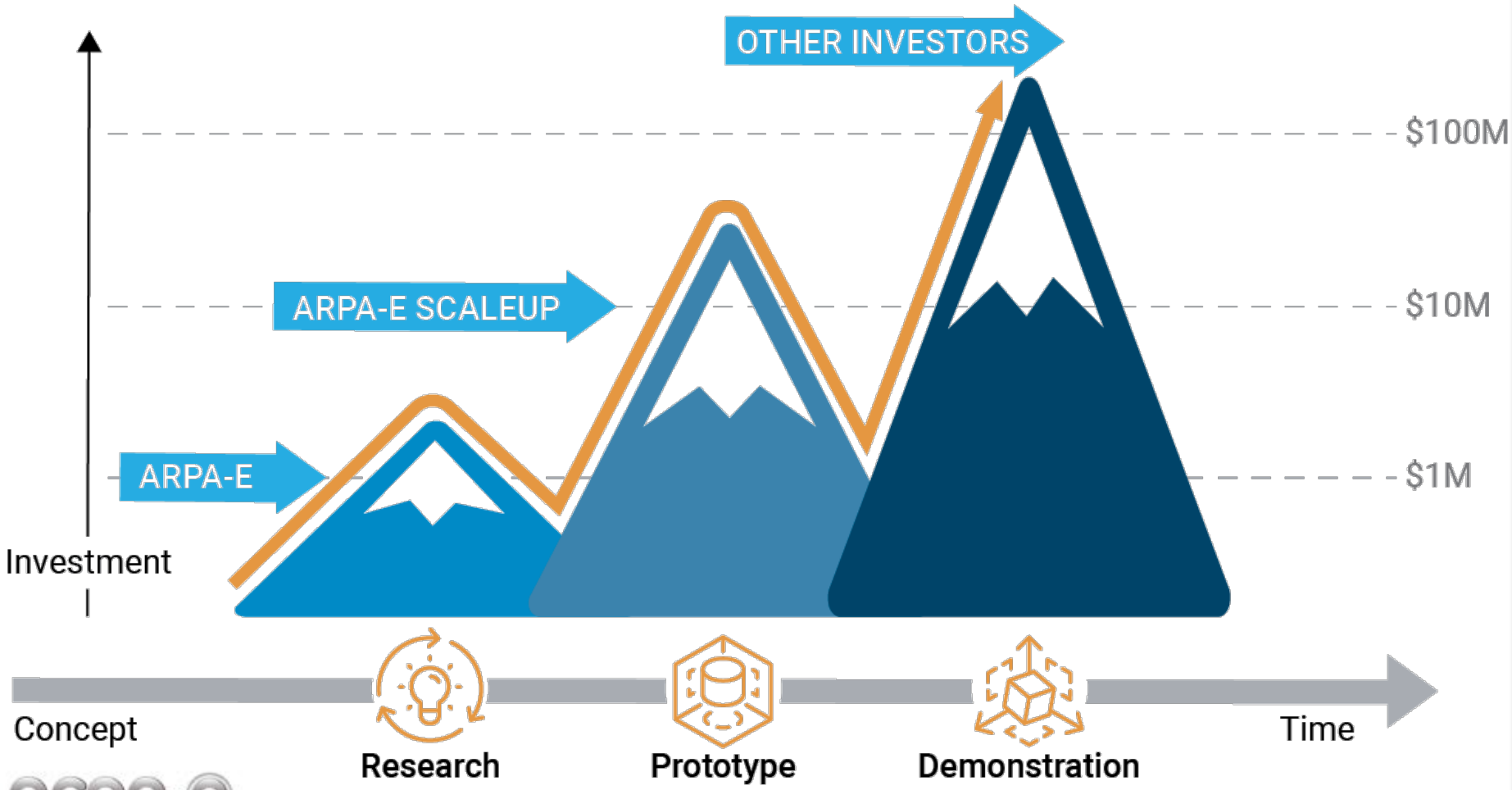
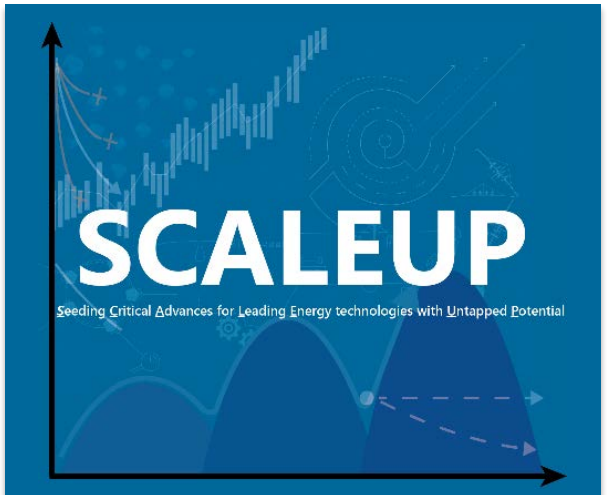
CHANGING WHAT'S POSSIBLE

ARPA-E Creates a *Mountain Of Opportunity* for Energy Technology





Supports previously funded ARPA-E technologies to commercial viability

*

Enables further technology de-risking of pre-production prototypes

*

Encourages small business, company, and industry participation

*

SCALEUP 2019
10 Awardees - $70+ million

*

SCALEUP 2021
8 Awardees - $100 million

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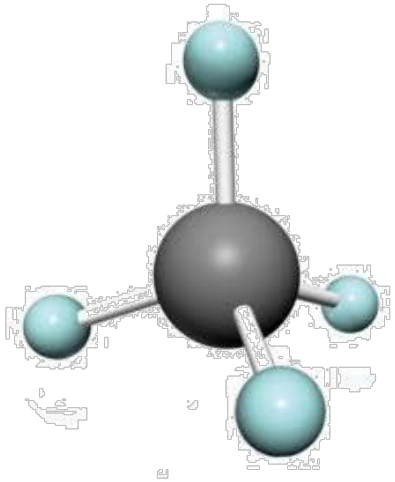
CHANGING WHAT'S POSSIBLE

Methane Pyrolysis Cohort: OPEN 2018 & 2019 ET FOA

$CH_4 \rightarrow 2\ H_2 + C\ (s)$, *lowering the cost of H_2 production while producing high value carbon*



750 - 1200°C

Gaseous hydrogen

+

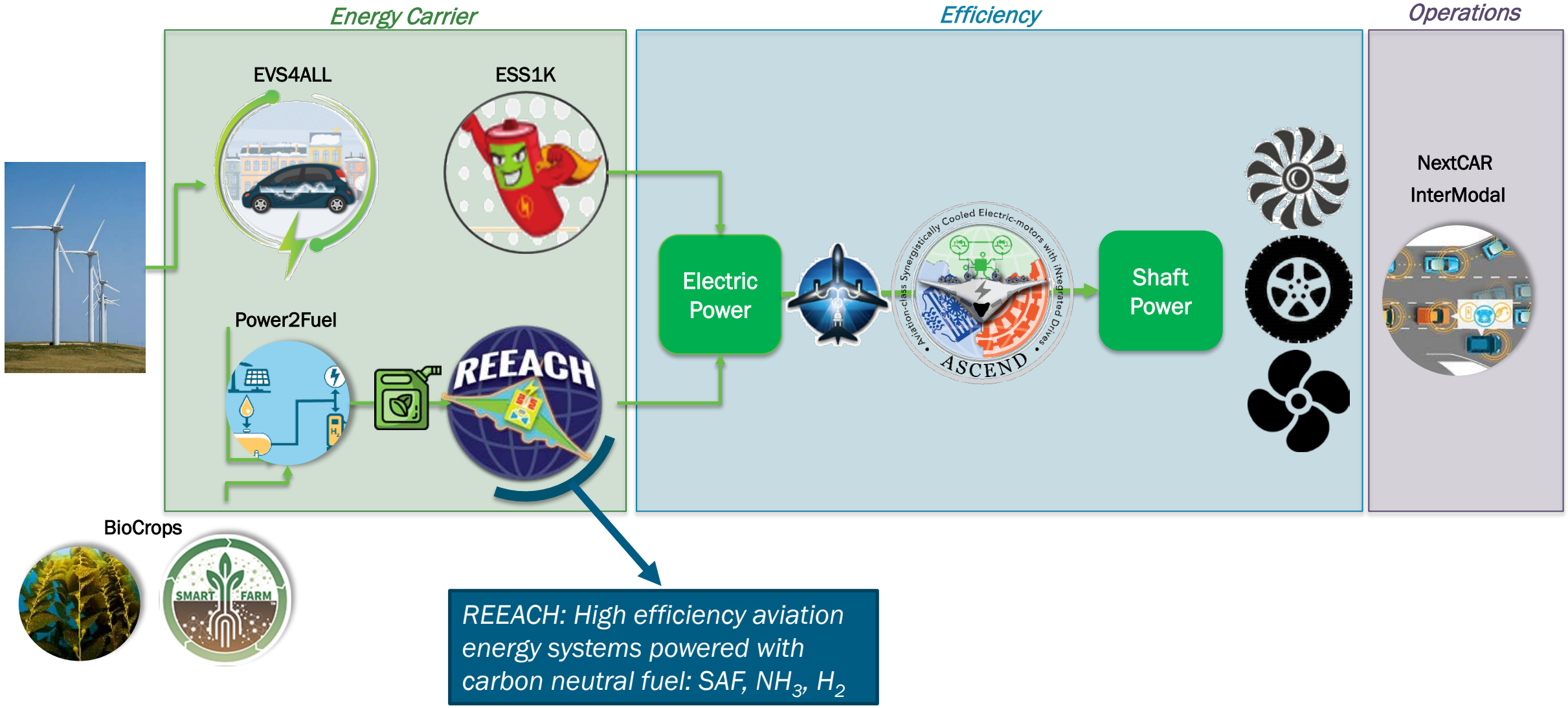
Solid carbon

8 projects
$21M in federal funding

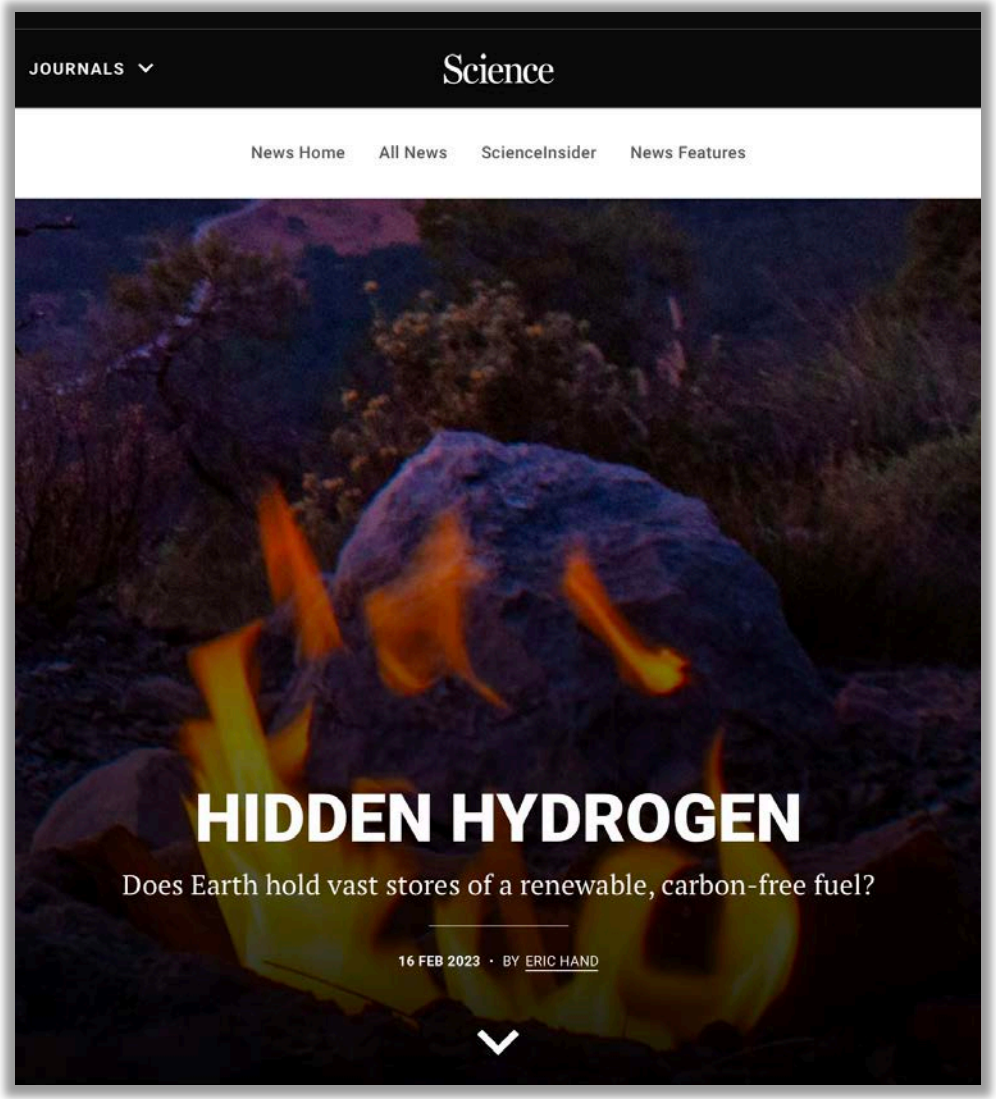
Methane Pyrolysis – Opportunity for Two Valuable Products

High Efficiency in Transportation

Climate-Friendly Commercial Aviation



Geologic H_2 – Stimulating a New Primary Energy Source



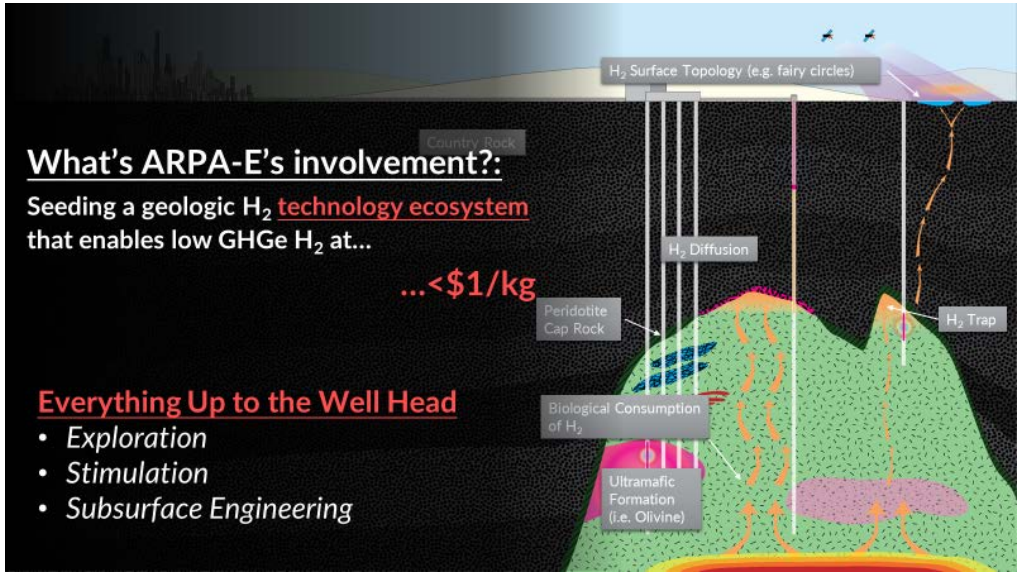
Dr. Doug Wicks
Program Director

The Opportunity is MASSIVE

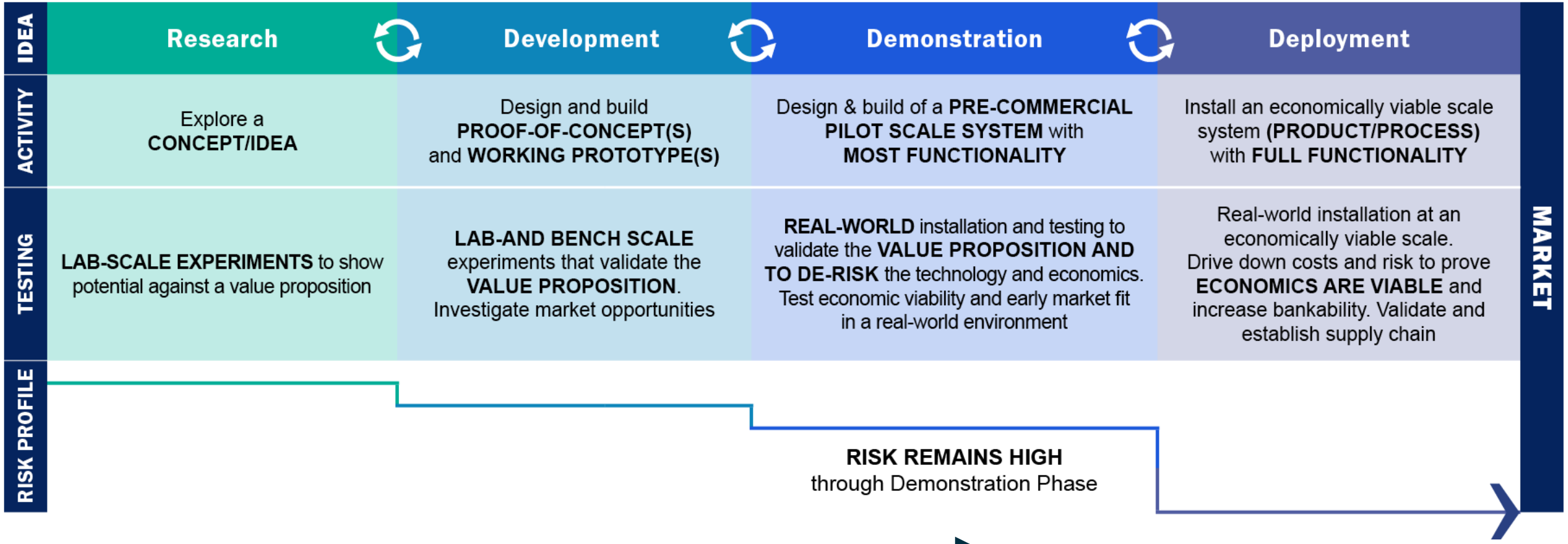
150 trillion tonnes of hydrogen potential under our feet

1 trillion (0.7%)
Would power US economy for **1,000 years**

arpa·e
CHANGING WHAT'S POSSIBLE



OTT OVERVIEW



OTT's Mission

"to expand the commercial impact of the research investments of the Department" & to drive private sector uptake of clean energy technologies

Steward commercialization across the DOE

OTT HIGHLIGHTS

Liftoff Reports

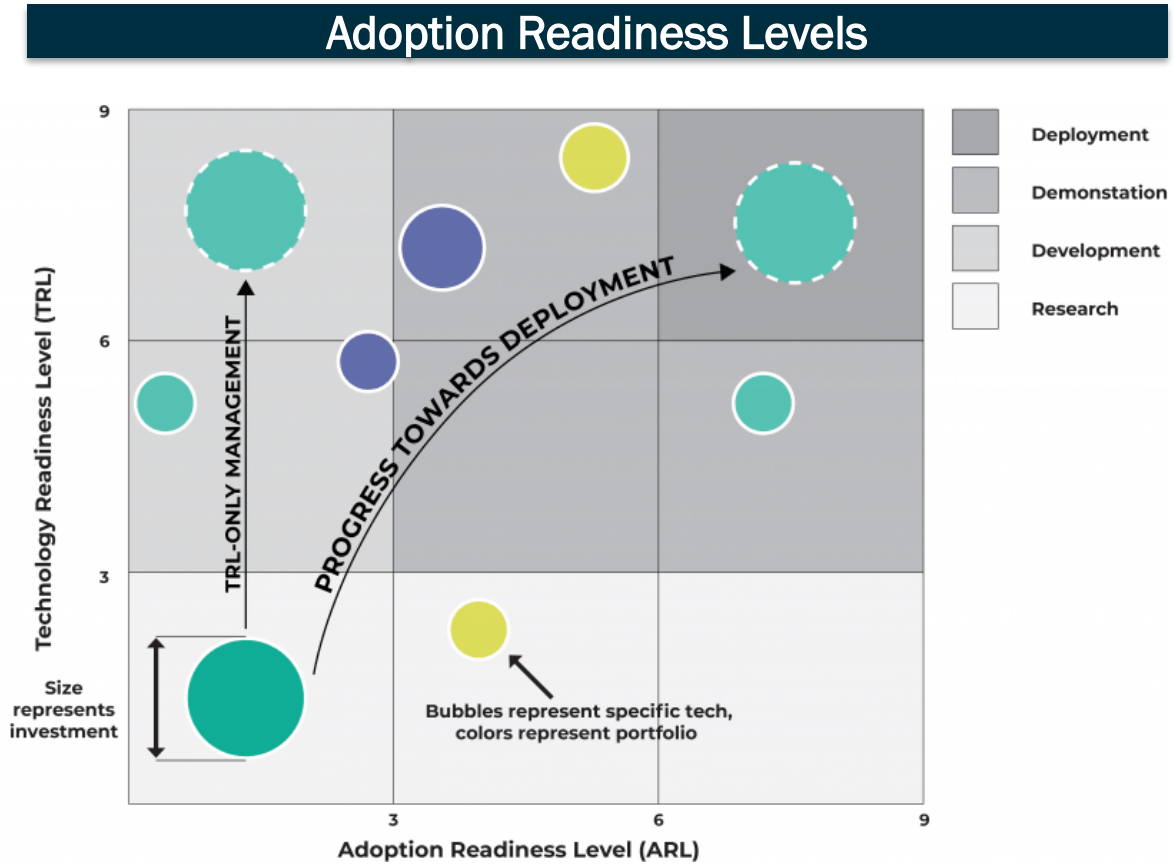
4 reports live – including Clean Hydrogen
60+ external interviews
2000+ comments
30+ working group members across DOE + National Labs

Technology Commercialization Fund

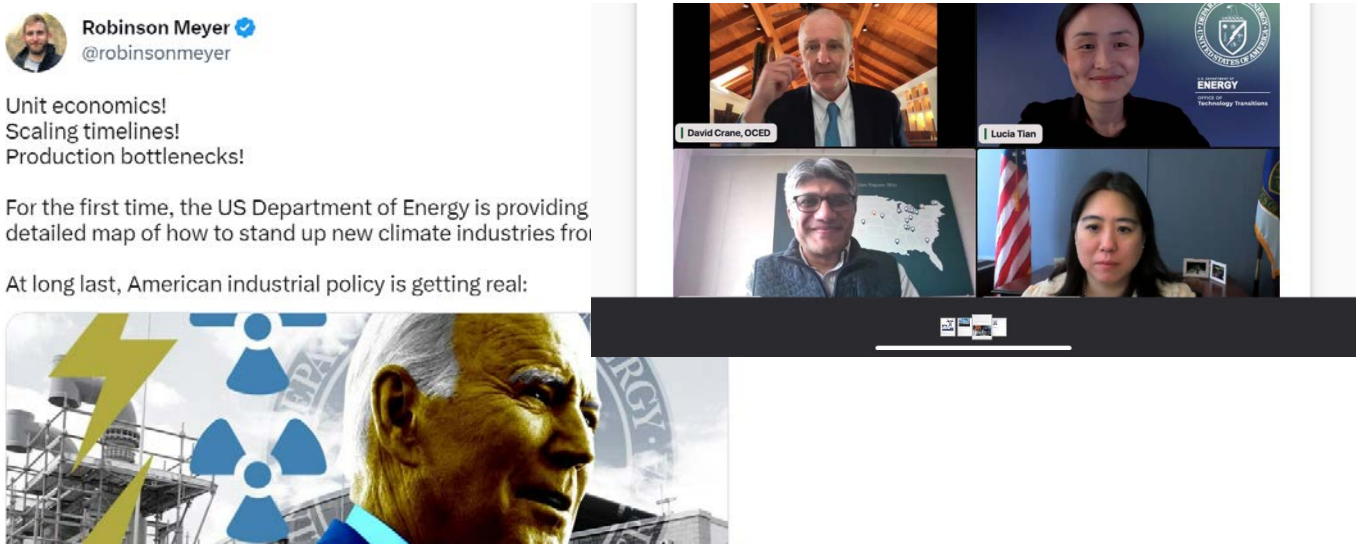
Base Annual Appropriated: OTT-led CLIMBR
BIL: CACTI Lab Call (H2 topic), MAKE IT prize (soon),
MRV lab call (selections announced!)

Lab Partnering Service

Adoption Readiness Levels



Messaging & Media Coverage



Secretary Jennifer Granholm: This effort will "help drive engagement between government and industry to unlock exciting new opportunities and ensure America is the global leader in the next generation of clean energy technologies."

Robinson Meyer: "The most detailed guide yet to how the Biden administration plans to conduct industrial policy for the most advanced — and the most fledgling — energy technologies in its arsenal."

From Politico's EnergyWire: "Developed in part for private investors, the three reports lay out the chief barriers for the three technologies along with possible solutions and rough timelines for their emergence in the 2020s and beyond."

We will continue a steady drumbeat of communications highlighting key insights from reports already released, announcing the release of new reports, and through industry events.

Liftoff Report Topics

Currently released on liftoff.energy.gov:

Clean Hydrogen

Long Duration Energy Storage (LDES)

Advanced Nuclear

Carbon Management

What's next:

- **Industrial decarbonization:**
  - **Cross-cutting** report (Pulp/Paper, Glass, Steel, Food/Bev)
  - **Chemicals & Refining**
  - **Cement**
- Grid (VPPs, other topics)
- Other topics TBC

Liftoff Reports Evaluate the Path to Near-term Deployment - Including How Entire Clean Energy Value Chains Will Emerge

2030 costs across the value chain if advances in distribution and storage technology are commercialized[1]

Industry | Gas replacement | Transport

Upstream: Hydrogen production

- **Reformation-based production**
  - w/ $0.75/kg PTC: LCOH = $0.4-0.85/kg
- **CO2 transport/ sequestration**
- **Water electrolysis**
  - w/ $3/kg PTC: LCOH ≤ $0.4/kg[3]

Midstream: Hydrogen distribution and storage assuming state-of-art technology at scale[2]

Commercialized, best-in-class gas compression	$0.2-0.4/kg at 500 bar, 10 tpd (tank storage, truck distribution) $0.1/kg at 80-120 bar, 50 + tpd (pipeline, co-located electrolysis)	
Salt cavern storage	$0.1/kg at 80 bar for 7 days, 600 tpd	H2 pipeline: $0.1/kg at 600 tpd, 300 km, 12" OD $0.1/kg at ~5000 tpd, 1000 km, 42" OD
Compressed gas tank storage	$0.8 / kg at 500 bar for 7 days	Gas phase trucking: $0.7-1.5/kg at 10 tpd, 250 km
Liquefaction	$2.7/kg at 50 tpd	Liquid hydrogen storage: $0.2/kg for 7 days, 50 tpd scale Liquid hydrogen trucking: $0.2-0.3/kg at 50 tpd, 250 km

- **Next generation fuel dispensing at high utilization[6]**: $1 -3.6/kg, ≥700 kg/day, 700 bar

Downstream: End use applications

End use willingness to pay[4]

Ammonia	$0.9-2.3/kg
Refining	$1-1.3/kg
Steel	$1.25-2.3/kg
Chemicals	$0.9-2.3/kg
NG blending	$0.4-0.5/kg
Industrial heat	$0.7-1.5/kg
Power gen. (high-capacity firm)	$0.4-0.5/kg
Aviation and maritime fuels[5]	$0.7-3/kg
HDMD road transport	$4-5/kg

1. See appendix for calculation details
2. Data based on cost-downs shared from leading-edge companies who have deployed at demonstration scale (or larger)
3. Range based on varying renewables costs and electrolyzer sizes/technologies
4. Defined as the price an off-taker will pay for clean hydrogen
5. Represents delivery of hydrogen to aviation and maritime fuel production facilities
6. Greater than or equal to 70% utilization, assumes line fill at high pressure

Sources: HDSAM, Argonne National Laboratory; DOE National Hydrogen Strategy and Roadmap, Hydrogen Council

Readers should sum (1) Upstream costs and (2) Midstream costs to arrive at a potential delivered cost of clean hydrogen, based on production pathway and storage/distribution method selected. Hydrogen production costs shown take an upper bound of production costs (~2MW (450 Nm3/h) PEM electrolyzer with Class 9 NREL ATB wind power) and then subtract the PTC at point-in-time. A wider range of LCOH values, without the PTC credit applied, are described in Figures 11 and 12 in the Clean Hydrogen Liftoff report.

Building the Bridge to Bankability

Providing financing for technologies to go the last mile to reach full market acceptance

What LPO Offers Borrowers

The unique value of working with LPO for clean energy technology project financing

LPO loans and loan guarantees are differentiated in the clean energy debt capital marketplace in **three primary ways:**

Access to Patient Capital

that private lenders cannot or will not provide.

Flexible Financing

customized for the specific needs of individual borrowers.

Committed DOE Partnership

offering specialized expertise to borrowers for the lifetime of the project.

Innovative Clean Energy - 1703 ICE

Loan guarantees for the deployment of innovative energy projects at commercial scale

Eligibility

The Title 17 program can consider innovative clean energy projects that:

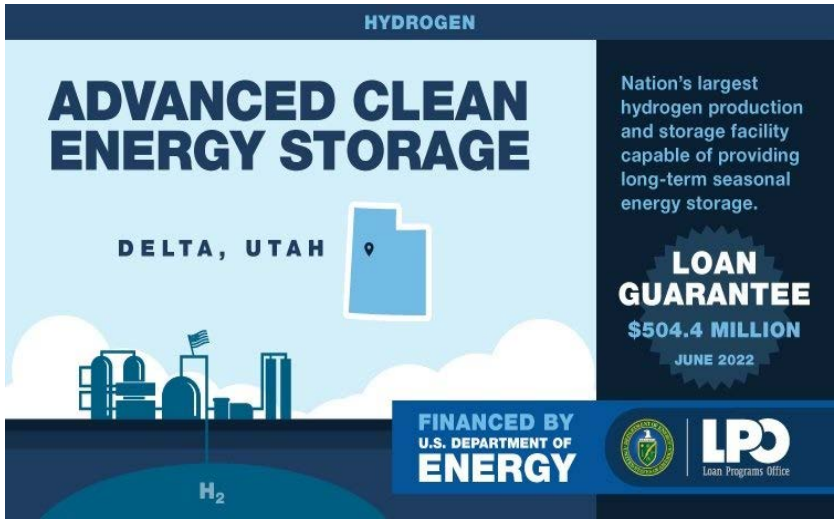
1. Use innovative technology.
2. Reduce, avoid, or sequester greenhouse gas emissions or air pollutants.
3. Are located in the U.S.
4. Provide reasonable prospect of repayment.

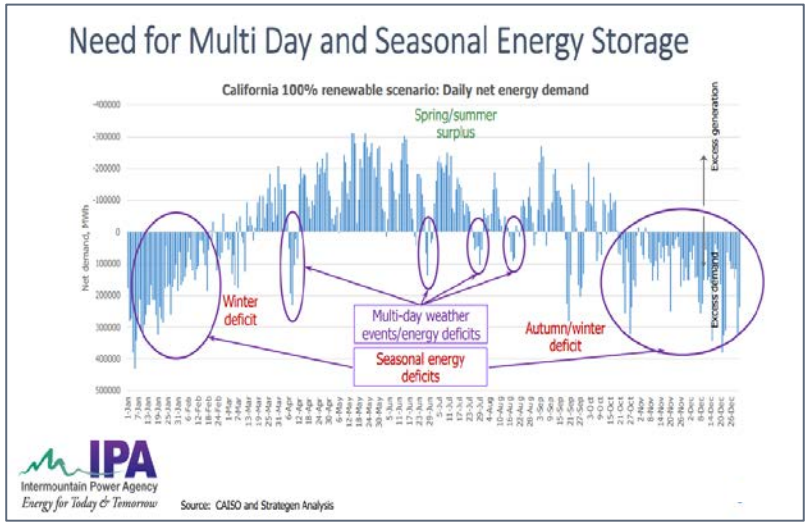
Loan Guarantee Features

- LPO can offer 100% guarantee of U.S. Treasury's Federal Finance Bank (FFB) loans or partial guarantees of commercial loans.
- Senior secured debt priced competitively with commercial rates.
- DOE can serve as sole lender or as a co-lender.
- Structures may include project finance, structured corporate, corporate or warehousing lines.

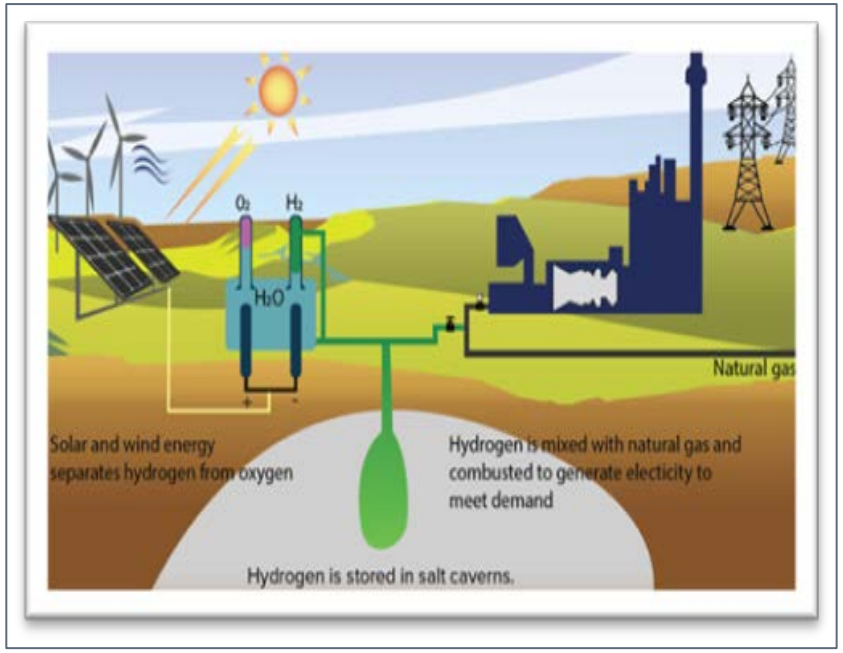
Advanced Clean Energy Storage (ACES)

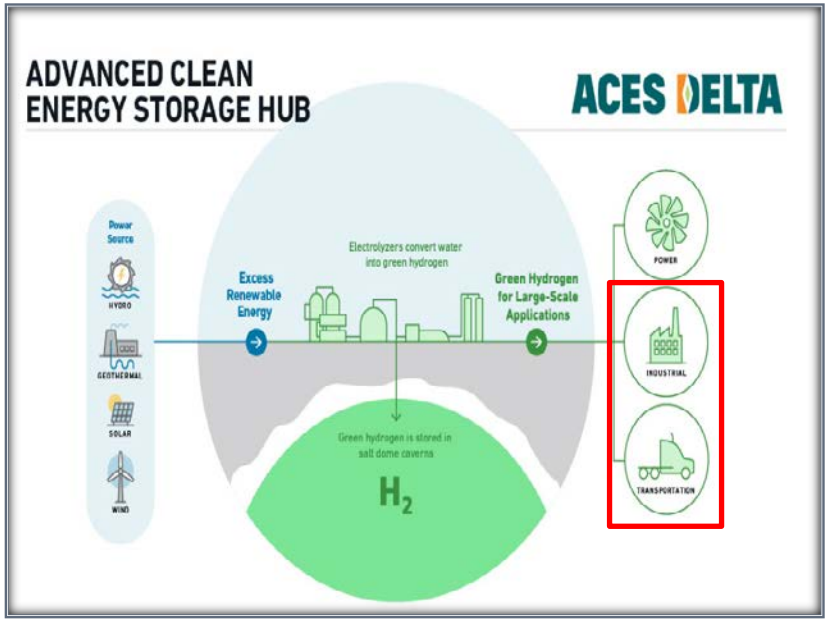
LP0001: Tues. 4:45 PM





- ✓ Commercial scale-up of technology
- ✓ Bellwether project for the U.S. Hydrogen sector
- ✓ Reliable long duration (seasonal), grid-scale storage of excess renewable energy





Office of Clean Energy Demonstrations

THE OFFICE OF

CLEAN ENERGY DEMONSTRATIONS

Hydrogen Hubs

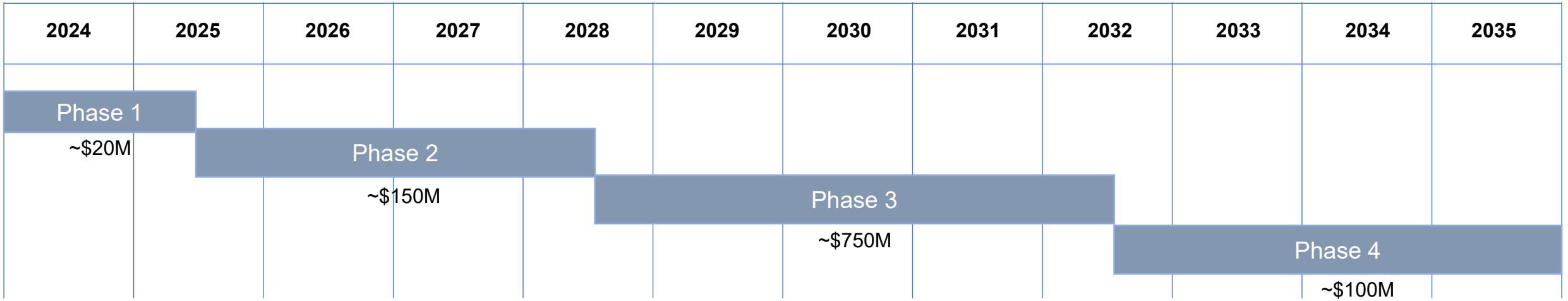
Hydrogen Hubs

- Hydrogen Hubs funding will accelerate the U.S. clean hydrogen market through a focus on new sectors, increasing hydrogen production and reducing cost
- $8B allocated to the development of hubs

Vision: Hydrogen Hubs Liftoff

2023-2026	2027-2034	2035+	2050+
Focus on industrials/chemicals e.g., ammonia production and oil refining	Focus on economies of scale to reduce costs. Emphasis on adoption in new sectors, greater number of producers, offtakes, distribution and storage networks and support of Justice40.	Focus on a sustained commercial market of 10 MMTpa per year supporting 100% clean electricity goal	Successful transition to hydrogen demand of 50 MMTpa per year supporting net zero emissions goal

Hub's Project Schedule



Phase 1:
Detailed Project Planning
Up to $20M
50% minimum cost share
12-18 months

Phase 2:
Project Development, Permitting and Financing
Up to 15% of total DOE funding
50% minimum cost share
2-3 years

Phase 3:
Installation Integration and Construction
50% minimum cost share
2-4 years

Phase 4:
Ramp Up and Sustained Operations
50% minimum cost share
2-4 years

Q&A

From your perspective, what are key challenges and priorities for achieving clean hydrogen commercial liftoff?


Special thanks to all our
Panelists, & our Audience
- Have a Wonderful AMR!