## DOE Hydrogen Shot Strategy Panel

### PROGRAM & PANELISTS

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<td>David Peterson (HFTO)</td>
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<td>Viviane Schwartz (SC-BES)</td>
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<td>Advancing DEI and EEEJ</td>
<td>Kendall Parker (HFTO)</td>
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### PANEL Q&A

June 7th, 2022
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
Responses to: What are the greatest barriers preventing public acceptance of widespread H₂ in the US?

- Public awareness/understanding: 17%
- Cost to end user: 22%
- Need for technology advancements: 11%
- Need for sufficient infrastructure: 19%
- Lack of government support for R&D: 5%
- Safety perceptions: 6%
- Lack of incentives for companies: 8%
- Competing technologies: 6%
- Lack of suitable end uses: 5%

https://www.energy.gov/eere/fuelcells/hydrogen-shot-summit
Leveraging Diverse Domestic Clean H₂ Options

Energy Sources
- Renewables
- Nuclear
- Fossil with CCUS

Pathways and Status
- Electrolysis
  - Cost: ~$5/kg H₂ (at low volume)
- Thermal Conversion (e.g., NG)
  - Cost: $1.50/kg but high emissions
- Advanced Pathways >$10/kg H₂/TBD

Targets
- Hydrogen Shot
  - 1 for 1 in 1 decade
  - $1 1 kg clean H₂ in 1 decade

Use Cases
- Enabling a Clean Grid
- Biofuels, Synfuels, Aviation
- Heavy Duty Trucks
- Chemicals, Fertilizer
- Blending with Natural Gas
- Steel, Iron, Cement Manufacturing

Impact
- Decarbonization
- Equity, Inclusion
- Reliability, Resiliency
- Exports
- Jobs
- Long Duration Energy Storage

Energy Earthshots
U.S. Department of Energy
Hydrogen
All Pathways Contribute to the Mission

**ELECTROLYSIS**
Critical path to sustainable clean H₂ production at scale

- Reduce capital cost of integrated electrolyzer systems (stacks and BOP) at GW scales to <$150/kW
- Optimize integration of electrolyzer systems with renewable and nuclear power to leverage on-site electricity costs <$200/MWh

**THERMAL CONVERSION**
Decarbonization through industrial retrofits

- Improve performance and cost of integrated systems for natural gas reforming with CCUS achieving emissions targets
- Develop diverse options such as gasification of waste feedstocks & pyrolysis of natural gas

**ADVANCED PATHWAYS**
Innovative approaches offering cross-cutting benefits

- Develop advanced H₂O-splitting systems with solar-to-H₂ conversion efficiencies >30%
- Develop robust microbial processes and systems to produce affordable clean H₂ from diverse bio- and waste-feedstocks

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**Expand Production Capacity**
**Adapt Current Production**
**Explore Promising Alternatives**
## DOE All-Hands-On-Deck Effort

**The DOE Hydrogen Program* aligns with the Hydrogen Shot and H2@Scale initiatives, & supports National clean energy priorities**


### EERE HYDROGEN

**Feedstocks:**
- Renewable Energy and Water

**Technologies:**
- Electrolysis – Low- and High-Temperature
- Advanced Water Splitting – Solar/High-Temp Thermochemical, Photoelectrochemical
- Biological Approaches

### FECM HYDROGEN

**Feedstocks:**
- Fossil Fuels – Natural Gas and Solid Wastes

**Technologies:**
- Gasification, Reforming, Pyrolysis
- Advanced Approaches – Co-firing and Modular Systems
- Natural Gas to Solid Carbon plus Hydrogen

### NE HYDROGEN

**Feedstocks:**
- Nuclear Fuels and Water

**Technologies:**
- Electrolysis Systems for Nuclear
- Advanced Nuclear Reactors
- Systems Integration and Controls – LWRs and Advanced Reactors

### Areas of Collaboration

- Reversible Fuel Cells, Biomass, Municipal Solid Waste, Plasctics, Polygeneration including Co-Gasification with Biomass, High-Temperature Electrolysis, Systems Integration

### Cross-Cutting DOE Offices including SC, ARPA-E, LPO, OCED...

Foundational research and innovation; user facilities and tools, materials and chemical processes, artificial intelligence/machine learning, databases and validation, high risk-high impact R&D, hubs, loans, and other crosscutting activities

*coordinate through the EERE Hydrogen and Fuel Cell Technologies Office
Comprehensive RDD&D Approach

Leveraging DOE-wide collaborations and coordination to advance technologies and achieve cost targets and scale

Foundational & applied research
- DOE Program Offices Core R&D
- BIL 816 & 815 R&D:
  - Electrolysis & clean H₂ manufacture/recycle
- DOE Consortia & Collaborations include:
  - HydroGEN, ElectroCat, H-Mat, X-Mat ...
  - H2-related Innovation Hubs & Centers

Demos, manufacturing & scaleup
- DOE Program Offices Core RD&D
- BIL 816 & 815 RD&D:
  - Electrolysis & clean H₂ manufacture/recycle
- DOE Consortia & Collaborations include:
  - H2NEW, M2FCT Consortia
  - H2@Scale demos (nuclear H₂, etc.)
  - Manufacturing Institutes

Commercial-scale deployments
- BIL 813. Regional Clean H₂ Hubs
  - Supporting development of at least 4 regional hubs nationwide
- Collaborations & Coordination include:
  - DOE-wide coordination
  - Regional, state, and local agencies
  - Safety, workforce, EJ40, etc.

Collaborations & Coordination include:
- DOE-wide coordination
- Regional, state, and local agencies
- Safety, workforce, EJ40, etc.

Leveraging DOE-wide collaborations and coordination to advance technologies and achieve cost targets and scale

RDD&D CYCLE

next-generation technologies near-commercial technologies established technologies
Focus on Bridging Innovation with End-Use

H₂ INNOVATORS

CLEAN H₂ INDUSTRIES

technical, economic, & environmental analyses

hydrogen shot

Programmatic Focus

<table>
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<th>Programmatic Focus</th>
<th>Key Priorities</th>
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<tr>
<td>Hydrogen Shot Management</td>
<td>Provide guidance and oversee activities &amp; progress</td>
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<tr>
<td>DOE Advisory Groups</td>
<td></td>
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<tr>
<td>Core Analysis</td>
<td>Refine tools, and develop advanced models</td>
</tr>
<tr>
<td>TEA, LCA, Resource, Markets</td>
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<tr>
<td>Data and Analytics</td>
<td>Update databases with project results and analyze trends</td>
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<tr>
<td>Informatics on All Pathways</td>
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<tr>
<td>Metrics &amp; Targets</td>
<td>Refine targets based on evolving tehnoeconomic landscapes</td>
</tr>
<tr>
<td>SMART Technology Goals</td>
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<tr>
<td>Project Portfolio</td>
<td>Develop R&amp;D&amp;D portfolio and actively manage projects</td>
</tr>
<tr>
<td>Aligned with Goals &amp; Targets</td>
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<tr>
<td>Progress Tracking</td>
<td>Assess progress toward goals &amp; course-correct as needed</td>
</tr>
<tr>
<td>Cost, Emissions, &amp; EJ40</td>
<td></td>
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<tr>
<td>Portfolio Optimization</td>
<td>Adjust priorities based on project outcomes and policy factors</td>
</tr>
<tr>
<td>RDD&amp;D Prioritization</td>
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Off to a Good Start – *exciting times ahead!*

**recurring events include stakeholder listening sessions, H2IQ webinars, etc.**

**FY21 Q4**
- S1 Launch of H2 Shot
- H2 Demo RFI
- BES H2 Round Table
- Clean Ammonia WS

**FY22 Q1**
- H2 Shot Summit
- HBCU Joint FOA
- Power Electronics WS
- Off-Road H2 WS

**FY22 Q2**
- H2 Shot Fellowship
- BIL / H2 Hubs RFIs
- Liquid Alkaline WS
- Bulk H2 Storage WS

**FY22 Q3**
- H2 Shot Strategy Document*
- Clean H2 / BIL FOA NOI
- PEM Electrolyzer WS
- Manufacture & Recycle WS

**FY22 Q4**
- FOA Announcements
- H2 Matchmaker
- H2 Incubator
- High-T Electrolysis WS
- Post-Doc Award at AMR

**Completed**

*Feedback from recent RFIs and the AMR being incorporated in strategy*

Ongoing cross-office and stakeholder engagements to inform H2 Shot directions; and to ensure alignment with clean energy and EEEJ priorities, while maintaining good stewardship of taxpayer dollars.

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*FY22 Q4* and beyond
Hydrogen Shot Strategic Vision

- **Leverage the DOE Hydrogen Program core RDD&D** to address materials, component, and systems integration challenges relevant to production pathways.

- **Leverage deployment of BIL regional clean hydrogen hubs** to advance scale up and associated cost reductions in mature and early-commercial systems.

- **Leverage clean $H_2$ manufacturing and recycling projects** under BIL to advance business propositions for all commercial and viable next-generation technologies.

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The Hydrogen Shot 1,1,1 goal for affordable clean hydrogen at scale is a key enabler of the DOE National Clean Hydrogen Strategy addressing pressing clean energy, climate, and EEEJ priorities.
Water Electrolysis Overview

Water electrolyzer cell configuration (H⁺ Conductor):
Anode: $2\text{H}_2\text{O} \rightarrow \text{O}_2 + 4\text{H}^+ + 4\text{e}^-$
Cathode: $4\text{H}^+ + 4\text{e}^- \rightarrow 2\text{H}_2$

Electrolyzer technologies differentiated by electrolyte conducting species and temperature:
- Proton Exchange Membrane (PEM)
- Alkaline Exchange Membrane (AEM)
- Liquid Alkaline Electrolyte (LA)
- Proton Conducting-Solid Oxide Electrolyzer (P-SOEC)
- Oxide Conducting-Solid Oxide Electrolyzer (O-SOEC)

Temperature (°C)
Overview of Electrolyzer Technologies

- **Current generation at high TRL** (LA, PEM, O-SOEC) ready for commercialization
- **Next generation at lower TRL** needed to achieve performance and cost targets to meet $1/kg H₂

<table>
<thead>
<tr>
<th>Technology</th>
<th>Advantages</th>
<th>Development Needs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Alkaline (LA)</td>
<td>Most mature, Low-cost materials, Long lifetime</td>
<td>Improved performance, Dynamic operation capability</td>
</tr>
<tr>
<td>Proton Exchange Membrane (PEM)</td>
<td>High performance, dynamic operation capable</td>
<td>Lower cost materials (e.g., reduced PGMs)</td>
</tr>
<tr>
<td>Oxide-ion conducting Solid Oxide (O-SOEC)</td>
<td>High efficiency, thermal energy integration</td>
<td>Improved lifetime, intermittent operation</td>
</tr>
<tr>
<td>Alkaline Exchange Membrane (AEM)</td>
<td>Low-cost materials, High performance and dynamic operation potential</td>
<td>Improved lifetime, Supporting electrolyte required?</td>
</tr>
<tr>
<td>Proton-conducting Solid Oxide (P-SOEC)</td>
<td>High efficiency potential, thermal integration, Lower cost materials</td>
<td>Improved lifetime and Faradaic efficiency</td>
</tr>
</tbody>
</table>

Lower-TRL Next generation (AEM, P-SOEC) have the potential to achieve performance and cost targets needed to meet $1/kg H₂, but further development is required.
Electrolysis Cost Reduction

McKenzie Hubert
ORISE Fellow
DOE-EERE-HFTO
Analysis efforts identify possible cost reduction strategies†

Key factors for cost reductions

- High electrical efficiency
- Increased durability/lifetime
- Low-cost capital equipment
- Low-cost manufacturing processes at GW-scale
- Low-cost clean electricity

Achieving economies of scale alone will not meet cost targets, also need to develop advanced technologies & integrated systems with clean electricity

† Reference case: Wind to H2 example pathway to achieve target cost, but not the only pathway. See next slide for underlying assumptions.
* DOE Hydrogen and Fuel Cells Program Record #20004, Sept 2020
Cost Reduction Pathways – LTE Example (different targets for HTE)

### Technical targets under development - LTE example

<table>
<thead>
<tr>
<th>Key Cost Parameters</th>
<th>2020 Status* ($5/kg H₂)</th>
<th>2026 Target ($2/kg H₂)</th>
<th>2031 Target ($1/kg H₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>System efficiency</td>
<td>55 kWh/kg</td>
<td>51 kWh/kg</td>
<td>46 kWh/kg</td>
</tr>
<tr>
<td>Stack lifetime</td>
<td>60,000 hr</td>
<td>80,000 hr</td>
<td>100,000 hr</td>
</tr>
<tr>
<td>System capital cost</td>
<td>$1500/kW</td>
<td>$250/kW</td>
<td>$150/kW</td>
</tr>
<tr>
<td>Manufacturing volume</td>
<td>~100 MW/yr</td>
<td>~1 GW/yr</td>
<td>~1 GW/yr</td>
</tr>
<tr>
<td>Plant size</td>
<td>Distributed (1,500 kg/day nameplate)</td>
<td>Central (50,000 kg/day nameplate)</td>
<td>Central (50,000 kg/day nameplate)</td>
</tr>
<tr>
<td>Energy supply†</td>
<td>Grid-connected ($51/MWh, 80% operating capacity factor)</td>
<td>Clean Energy PPA (e.g., $25/MWh, 50% operating capacity factor)*</td>
<td>Direct Integration (e.g., $12/MWh, 50% operating capacity factor)*</td>
</tr>
</tbody>
</table>

* Reference case: Wind to H₂ scenario, but not the only pathway to achieve target

† DOE Hydrogen and Fuel Cells Program Record #20004, Sept 2020

### Capital cost levers - PEM example

Data from Mayyas, et al. August 2019. NREL/TP-6A20-72740

### Improved clean-electricity integration options

- Catalyst-coated Membrane
- Porous Transport Layers
- Frame
- Bipolar Plates
- Assembly & End Plates
- Balance of Stack
- Power Supplies
- Deionized Water Circulation
- Hydrogen Processing
- Cooling
- Miscellaneous

† Reference case: Wind to H₂ scenario, but not the only pathway to achieve target

* DOE Hydrogen and Fuel Cells Program Record #20004, Sept 2020
Manufacturing & Supply Chain

Paul Syers
Technology Manager
DOE-EERE-AMO
Hydrogen Supply Chain, Today vs 2050

To meet 2050 decarbonization goals, clean H$_2$ technologies need to significantly grow!

Today’s Hydrogen Market
- ~10 MMT/yr in the U.S.
- 65-100 MMT/yr globally
- Almost none of that is electrolytic

2050 Projected Hydrogen Market
- >100 MMT/yr in the U.S.
- >500 MMT/yr globally

To meet that demand with net zero emissions, U.S. manufacturing would need to reach:
- 300 GW/yr of fuel cells
- 1,000 GW/yr of electrolyzers (vs. ~0.17 GW today)

### Growing & Strengthening the Supply Chain

Key U.S. vulnerabilities & opportunities for growing electrolytic hydrogen & fuel cell production:

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<th>Vulnerabilities</th>
<th>Opportunities</th>
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<tr>
<td>Electrolytic prod. &amp; util. technologies are not cost competitive</td>
<td>Reduce production costs, increase commercialization</td>
</tr>
<tr>
<td>Insufficient emission reduction incentives</td>
<td>Develop competitive application</td>
</tr>
<tr>
<td>Insufficient codes &amp; standards</td>
<td>Develop more codes &amp; standards</td>
</tr>
<tr>
<td>Insufficient electricity generation capacity</td>
<td>Expand electric grid capacity</td>
</tr>
<tr>
<td>Electrolyzers are not fully utilized for excess grid energy use</td>
<td>Improve bulk hydrogen storage</td>
</tr>
<tr>
<td>Insufficient infrastructure</td>
<td>Utilize existing nat. gas infrastructure</td>
</tr>
<tr>
<td>Materials supply &amp; manufacturing capacity not sufficient to meet projected demand</td>
<td>Increase domestic materials supply &amp; mfg capacity</td>
</tr>
<tr>
<td>Industry has energy &amp; environmental justice issues</td>
<td>Lead on EEJ issues</td>
</tr>
<tr>
<td>Mismatch in workforce supply &amp; demand</td>
<td>Export Hydrogen</td>
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Wind - Hydrogen Strategy

Optimized, Cost competitive, Scalable, Modular, and Integrated Wind – H₂ Systems

**INTEGRATED WIND HYBRID GENERATION**
- Optimized Wind / Solar / Storage Hybrid Electricity Generation - matching H₂ use demand profile
- Direct Wind-Electrolyzer Connection: Shared Components / Control
- Overbuilt, paired electrolyzer plant to enable full, dedicated electricity utilization (no curtailment losses)

**OPTIMIZED H₂ PRODUCTION**
- H₂ production: Near collocated (reduced delivery - potential direct pipeline) to user
- Reduced storage requirements: continuous real time generation
- Potential option to eliminate Grid connected equipment & Grid connection constraints

**COST COMPETITIVE CLEAN H₂ ACROSS SECTORS**
- Industrial: Green Steel, Green Cement, Green Ammonia, Green Chemicals
- Transportation: Green Fuels – Marine, Aviation, Heavy trucking
- Target: Cost competitive – without subsidization
Nuclear Hydrogen Opportunities

Jason Marcinkoski
Program Manager
DOE-NE
Nuclear Integrated Energy System Concept

Flexible Scale Reactors

Thermal Storage

Primary Generator

Peaking Generator

Industrial/Chemical Plant

Hydrogen Production

Battery

Firm, Flexible, Zero-Carbon Grid Capacity

Flexible generation enables more renewable power to the grid

Flexible Reactor Siting

Data centers
Manufacturing plants
Biofuel plants/processing
Desalination
Industrial parks/plants
Fueling Stations

Transportation Fuels
Steel Production
Fertilizer / Ammonia
Polymers/ Chemicals
Hydrogen

Refineries/Oil Production
Minerals
Wood/Paper plants
District Heating

CO₂/ Carbon Sources
- Ethanol plants
- NG generators
- Cement plants
- Biomass
- Polymer/Chemical Waste
Thermal Conversion Pathways

Eva Rodezno
Program Manager
DOE-FECM
# Thermal Conversion Pathways

<table>
<thead>
<tr>
<th>Industrial Process</th>
<th>Carbon Capture Method</th>
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<tr>
<td>Steam Methane Reforming</td>
<td>Pre &amp; Post Combustion Capture</td>
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<tr>
<td>Autothermal Reforming</td>
<td>Pre-Combustion Capture</td>
</tr>
<tr>
<td>Partial Oxidation</td>
<td>Pre-Combustion Capture</td>
</tr>
<tr>
<td>NG Pyrolysis</td>
<td>Solid Carbon Product</td>
</tr>
<tr>
<td>Coal &amp; Biomass Gasification</td>
<td>Pre-Combustion Capture</td>
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Source: [https://netl.doe.gov/energy-analysis/details?id=ed4825aa-8f04-4df7-abef-60e564f636c9](https://netl.doe.gov/energy-analysis/details?id=ed4825aa-8f04-4df7-abef-60e564f636c9)
Thermal Conversion Cost Reduction Strategies

**R&D Needs**
- Process Intensification to improve efficiency and reduce CAPEX
- Improved CO₂ sorbents
- Improved sorbent separation technology
- High-temperature H₂/CO₂ separation membranes
- Advanced catalysts to lower system energy requirements and reduce cost

**SMR + CCS**
- 3-9 kg CO₂e/kg H₂ 100-GWP

**ATR + CCS**
- 4-10 kg CO₂e/kg H₂ 100-GWP

**Cost Reduction Strategies**
- Sharing CO₂ transport and storage costs with other emitters
- CO₂/carbon valorization
- Location selection
- Plant Scaling
- Integrated energy systems
- Byproduct sales (argon, carbon black, sulfur, slag)
Thermal Conversion:
Flexible Feeds & Products

William Gibbons
Technology Manager
DOE-EERE-HFTO
Thermal Conversion - Gasification + CCS

The gasification process converts organic or fossil-based carbonaceous materials at high temperatures (>700°C) without combustion into hydrogen, carbon monoxide, and carbon dioxide; typically with a controlled amount of oxygen and/or steam. The carbon monoxide can then react with water to form carbon dioxide and more hydrogen via a water-gas shift reaction.

Opportunities:
- Feedstock flexibility, leveraging regional resources: *biomass-, fossil-, and waste- feedstocks*
- Tunable value-add co-products
- Valorization of waste streams (MSW, plastics, etc.)
- Potential for net negative carbon emissions
- Novel smaller/modular gasification systems enable distributed operation

Research Needs:
- Feedstock pre-treatment & transport cost reduction
- Feedstock variability and contamination
- Optimal feedstock blending
- Process intensification
- Add/leverage/adapt existing carbon capture technology
Thermal Conversion - Novel Integrated Systems

Innovative integrated systems benefit from component-level advances as well as operation optimization.

Opportunities:
- Feedstock flexibility, leveraging regional resources
- Polygeneration of H₂ + value-add co-products
- Integrated & optimized carbon management
- Hybridization allows for regional tuning & max. ROI

Research Needs:
- Analysis of novel configurations
- Component technology advances (durability, efficiency, and cost)
- System level optimization & cost reduction (complexity vs benefit)
- Optimized operations for varied inputs (feedstock and electricity costs in real time)

Cracking Methane: Two Product Process

\[ CH_4 \rightarrow 2H_2 + C(s) \]

- Gaseous hydrogen
- Solid carbon

750 - 1200°C

\( \frac{1}{4} \) weight \( H_2 \)
\( \frac{1}{2} \) energy

3 X weight \( H_2 \)
Methane Pyrolysis Cohort.. **2018 OPEN & 2019 FOA**

- **H2 Generation**
  - Johns Hopkins University
    - Ni / NiCl2
  - parc
    - Molten Zn

- **C Generation**
  - C Zero
    - Molten Salt
  - nanocomp
    - Miralon (CNTR & H2 Process)
  - Rice University
    - Fe Catalyst
  - Stanford University

- **C Upgrading**
  - Johns Hopkins University
    - Joule Heating

- **C Utilization**
  - Carbon House
Observations

• **Hydrogen-centric processes could be competitive with SMR and PEM/AEM electrolysis**
  • Need $0.5-1/kg carbon price for parity with H₂-only processes
  • Requires very large carbon market (cement, asphalt, soil, sequestration)
  • Less sensitive to natural gas price than SMR
  • Electrically heated processes remain competitive with electrolysis in an all-electric future

• **Carbon-centric processes**
  • Generally target smaller-volume/higher-value markets
  • Hydrogen co-product could be used captively as fuel vs sale
Technology Commercialization

Jonah Wagner
Senior Advisor
DOE-LPO
**Path to Commercial Scale for Clean H2**

### Barriers to scaling clean hydrogen

<table>
<thead>
<tr>
<th>High unit costs for production</th>
<th>Lack of common infrastructure</th>
<th>Lack of commercial debt</th>
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<tbody>
<tr>
<td>• Current prices at $4-5/Kg serving narrow set of use cases, though recent high NG prices narrow gap</td>
<td>• Currently only <del>1,600 miles of H2 pipelines in the U.S., with high capex cost (</del>$3M per mile)</td>
<td>• Debt allows for scaling and replicability of clean H2 business models</td>
</tr>
<tr>
<td>• Sub-scale domestic electrolyzer manufacturing capacity</td>
<td>• Other transport options (e.g., truck, ship) can add significant cost</td>
<td>• Current market funded by private equity, while commercial debt limited by tech risk and bankability</td>
</tr>
<tr>
<td>• Multiple deployments will lower the cost of existing clean hydrogen technologies (i.e., $1/kg Earthshot)</td>
<td>• On-site production an option for certain uses</td>
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### Paths to scale

| Contracted medium/long-term offtake for clean H2 to create a stable demand signal and enhance bankability |
| Regional hubs with shared infra costs for common infrastructure supporting multiple developers and offtakers |
| LPO lending supporting early stages of commercial scale up by taking early deployment risk |

Sources: IEA, FCHEA Hydrogen Roadmap, BNEF
Emerging Business Models LPO is Seeing

Business models

- Methane pyrolysis for clean hydrogen and carbon black
- Hydrogen production and storage facilities for seasonal energy storage
- Distributed H2 production and distribution for transportation and equipment
- Retrofitting of transmission-constrained renewable assets for hydrogen/green ammonia production
- “Anchor tenant” hydrogen hub facilities (e.g., H2-based steel production, ports)

LPO conditional commitments

Monolith materials: ~$1B

- FOAK commercial deployment of methane pyrolysis
- Two revenue sources: green ammonia and carbon black (large, established markets)

Magnum ACES: ~$500M

- Green hydrogen production and storage facility to supply hydrogen-ready NG-power plant
- Offtake from Intermountain Power Agency
- Balance renewable generation and improve transmission utilization
Thermal Integration with CSP

Avi Shultz
Program Manager
DOE-EERE-SETO
Solar Thermochemical Processing

CSP-PV to H2: Concentrating Solar Power (CSP) and Photovoltaic (PV) Hybrids to produce Hydrogen for Solar Thermal Fuels
PI: Mark Ruth

Solar Hydrogen from Water Splitting using Liquid Metal Oxidation/Reduction Cycles Promoted by Electrochemistry
PI: Tony McDaniel

SiC Receiver/Reactor by Additive Manufacturing for Concentrated Solar Thermocatalysis with Thermal Energy Storage
PI: Bradley Brennan
Advanced Pathways

James Vickers
Technology Manager
DOE-EERE-HFTO
Exploring Potential of Advanced Pathways - examples

**Photoelectrochemical Solar Water Splitting (PEC)**

**Solar Thermochemical Water Splitting (STCH)**

**Fermentation with Microbial Electrolysis of Waste Streams**

### STCH Boundary Study

- **Active Material Productivity**: 700, 200, 100 (amol H2/g)
- **Active Material Life**: 40, 10, 4 (years)
- **Active Material Cost**: 3.0, 4.0, 6.0 ($/kg)
- **Solar to Hydrogen Eff.**: 25, 21, 17 (%)

<table>
<thead>
<tr>
<th>Hydrogen Production Cost ($/kgH2)</th>
<th>1.00</th>
<th>2.00</th>
<th>3.00</th>
<th>4.00</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PEC Example Cost Reduction Pathway</strong></td>
<td>PECEfficiency improved to 25%</td>
<td>panel cost reduced to $200/m2</td>
<td>lifetime extended to 20 years</td>
<td>interim target</td>
</tr>
<tr>
<td><strong>Installed Capital Cost</strong></td>
<td>75%, 100%, 125%</td>
<td></td>
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<tr>
<td><strong>Feedstock $/dry mt</strong></td>
<td>$57, $75, $94</td>
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<tr>
<td><strong>Broth Concentration</strong></td>
<td>300, 175, 100 g/L</td>
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<tr>
<td><strong>Generator Efficiency</strong></td>
<td>95%, 90%, 85%</td>
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<tr>
<td><strong>H2 PSA Recovery</strong></td>
<td>96%, 88%, 80%</td>
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<tr>
<td><strong>Reaction Time</strong></td>
<td>24, 74, 74 hours</td>
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</table>
**Advacned Pathways – Progress and Impacts**

**Important Progress in PEC Solar Water Splitting**

**Notable Progress in Photocatalytic Aqueous H₂ Production**

JCAP has identified a range of integrated device architectures that allow for efficient operation and scalable deployment of intrinsically safe solar-hydrogen systems. It was demonstrated a >10% and sustained (>40 hours) unassisted solar-driven water-splitting using a fully integrated, membrane-based, wireless prototypes systems that comprised of tandem junction photoabsorbers and earth-abundant electrocatalysts.


**IMPACTS OF ADVANCED PATHWAY RESEARCH:**

- Offers efficient direct conversion of clean energy sources into solar fuels
- Potential for breakthrough levels of solar to hydrogen conversion efficiency (e.g., >30% with PEC, STCH)
- Cross-over knowledge developed for catalysts, interfaces, and complex materials systems
- Training a new generation of hydrogen technology experts

_Brahmachari et al..Photosynthesis Research 143:183–192 (2020)_
Advancing Science & Technology

Viviane Schwartz
Program Manager
DOE-SC-BES
Advancing Science

Innovative Tools and Scientific Advances:

• Data Science coupled with theory and experimental tools
• In-situ and Operando characterization methods

Materials Project: Combination of high-throughput calculations, state-of-the-art electronic structure methods as well as novel data mining algorithms for surface, defect, electronic and finite temperature property predictions -- to yield an unparalleled materials design environment.

Workforce Development:

Primarily done by supporting undergraduates, graduate students, and postdoctoral researchers through research and development awards at universities and at the DOE national laboratories.

https://science.osti.gov/wdts


Neutron User Facilities: Neutron scattering can track the dynamic changes of materials composed of low-atomic-weight elements in operating environments. Schematic of operando small-angle neutron scattering of an operating fuel cell and representative scattering data showing evolution of the structure of the fuel cell membrane with cell current.
Advancing Technology—Recent Roundtable on Carbon-Neutral H₂ Technologies

Priority Research Opportunities for a BES research agenda:

Discover and Control Materials and Chemical Processes to Revolutionize Electrolysis

- How do we co-design multiple components that work together to enable stable, efficient electrolysis for the carbon-free production of hydrogen from water?

Manipulate H₂ Interactions to Harness the Full Potential of H₂ as an Energy Carrier

- How do we acquire fundamental insights across the entire range of energies to allow selective tuning of hydrogen interactions with molecules and materials?

Elucidate the Structure, Evolution, and Chemistry of Complex Interfaces for Energy and Atom Efficiency

- How can co-existing and evolving interfaces be tailored at multiple length scales to achieve energy-efficient, selective processes and enable carbon-neutral hydrogen technologies?

Understand and Limit Degradation Processes to Enhance the Durability of Hydrogen Systems

- How do we identify and understand the complex mechanisms of degradation to obtain foundational knowledge that enables the predictive design of robust hydrogen systems?

BES convened a Roundtable in August 2021 chaired by Morris Bullock (PNNL) and Karren Moore (ORNL)

https://science.osti.gov/bes/Community-Resources/Reports
Advancing Energy Equity & Environmental Justice (EEJJ)

Kendall Parker
ORISE Fellow
DOE-EEERE-HFTO
How do we transform our energy system while ensuring it becomes more equitable and just?
**DOE Justice40 Policy Priorities for Disadvantaged Communities**

<table>
<thead>
<tr>
<th>Priority</th>
<th>Description</th>
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<tbody>
<tr>
<td>Energy burden</td>
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<tr>
<td>Environmental exposure and burdens</td>
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<tr>
<td>Parity in clean energy technology access and adoption</td>
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<td>Access to low-cost capital</td>
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<td>Clean energy enterprise creation for MBE/DBE</td>
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<td>Clean energy job pipeline and job training</td>
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<tr>
<td>Energy resiliency</td>
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<tr>
<td>Energy democracy</td>
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</table>
Examples of DEI and EEEJ-Related Activities

- **H2 Matchmaker** to facilitate hydrogen hub teaming and stakeholder identification
- **H2EDGE** for workforce training in the hydrogen economy
- **Center for Hydrogen Safety** to provide educational resources on hydrogen safety
- **Fellowships** to support the next generation of hydrogen and fuel cell leaders
- **IPHE Early Career Network** to connect young professionals interested in hydrogen
- **HBCU-OMI FOA** for university training and research at minority serving institutions
- **H2 Twin Cities** to build global partnerships that deploy clean hydrogen solutions
Exciting Fellowship Opportunities

Seeking Diverse Candidates

The U.S. Department of Energy (DOE) is looking for talented, bright, early career professionals to partner with DOE Hydrogen Program Managers working to achieve the Hydrogen Energy Earthshot goal of $1 per 1 kilogram in 1 decade (“1 $1”).

Are you graduating soon or just starting your career in hydrogen?

Do you want to help make clean hydrogen affordable for all?

The Hydrogen Shot Fellowship might be the opportunity you’re looking for!

Apply today at: www.zintellect.com Keyword: Hydrogen Shot
Thanks to All Our Panelists!
From your perspective, what is one key priority for meeting the ambitions 1,1,1 Hydrogen Shot goal, and on a scale of 1 to 10, how confident are you we'll meet it within a decade?
Thank You!

https://www.energy.gov/eere/fuelcells/hydrogen-shot