U.S. DEPARTMENT OF ENERGY

Hydrogen Program
2022 Annual Merit Review and
Peer Evaluation Meeting


DOE Hydrogen Shot Strategy Discussion


June 7, 2022

DOE Hydrogen Shot Strategy Panel

PROGRAM & PANELISTS	
Hydrogen Shot Strategy Introduction	*Eric Miller (HFTO)*
Electrolysis Pathways	*David Peterson (HFTO)*
Electrolysis Cost Reduction Strategies	*McKenzie Hubert (HFTO)*
Manufacturing, Recycling & Supply Chain	*Paul Syers (AMO)*
Wind-to-Hydrogen Opportunities	*Jian Fu (WETO)*
Nuclear-Produced Hydrogen and Use	*Jason Marcinkoski (NE)*
Thermal Conversion Pathways	*Eva Rodezno (FECM)*
Flexible Feeds and Products	*William Gibbons (HFTO)*
Methane Pyrolysis Opportunities	*Jack Lewnard (ARPA-E)*
Technology Commercialization	*Jonah Wagner (LPO)*
Thermal Integration with CSP	*Avi Shultz (SETO)*
Advanced Pathways	*James Vickers (HFTO)*
Advancing Science & Technology	*Viviane Schwartz (SC-BES)*
Advancing DEI and EEEJ	*Kendall Parker (HFTO)*
PANEL Q&A	

June 7th, 2022

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Hydrogen

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

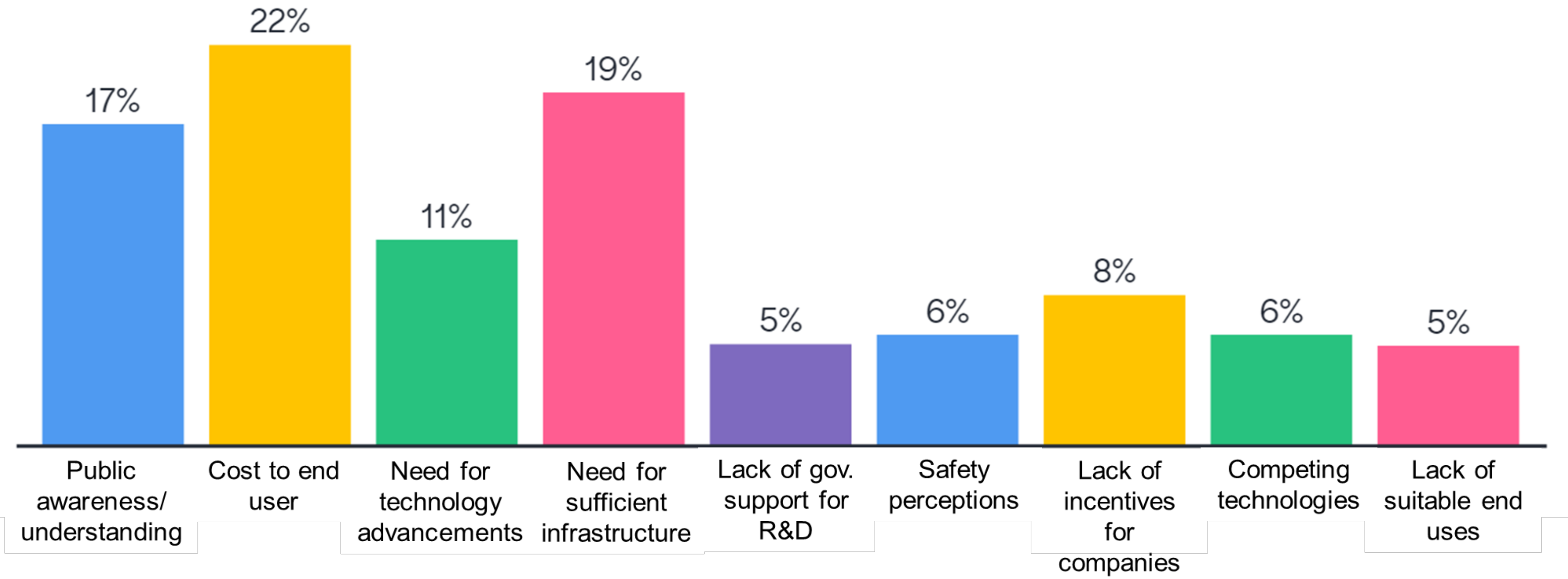
Hydrogen Shot Summit Stakeholder Feedback

4,900+ total registrants, 3,200+ participants in Plenary, 33 countries + USA

Speakers included:

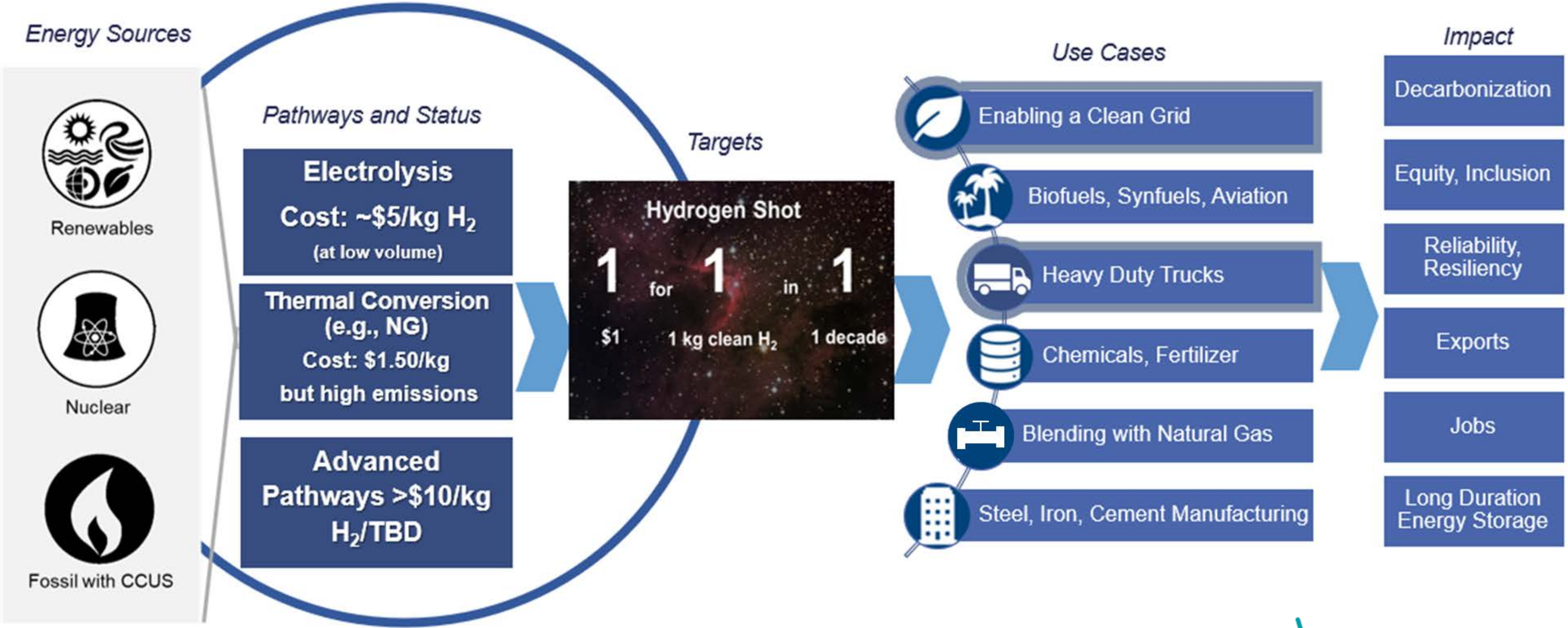
- **Secretary Granholm, DOE Leadership across offices**
- **Sec. John Kerry**
- **Bill Gates**
- Industry CEOs, VPs Congressional Members, Labs, Research and Academic Experts

Responses to: What are the greatest barriers preventing public acceptance of widespread H_2 in the US?



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

Leveraging Diverse Domestic Clean H_2 Options



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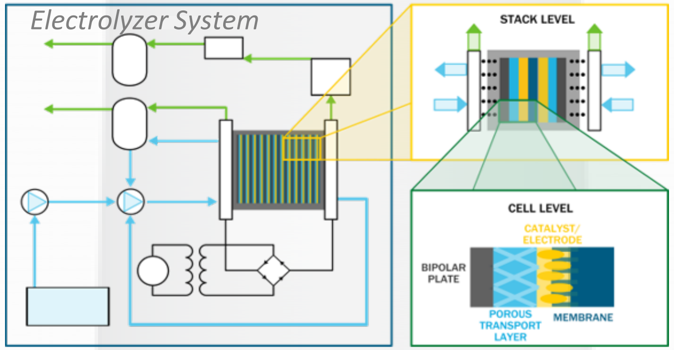
All Pathways Contribute to the Mission

ELECTROLYSIS

Critical path to sustainable clean H_2 production at scale

Reduce costs to achieve scale



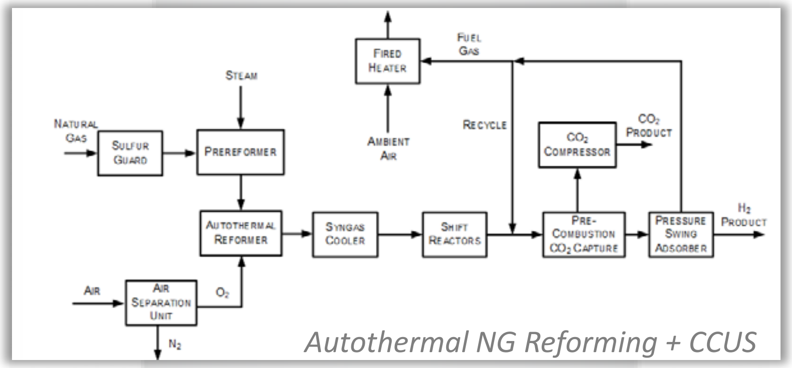
- Reduce capital cost of integrated electrolyzer systems (stacks and BOP) at GW scales to <$150/kW
- Optimize integration of electrolyzer systems with renewable and nuclear power to leverage on-site electricity costs <$200/MWh

Expand Production Capacity

THERMAL CONVERSION

Decarbonization through industrial retrofits

Add CCUS to reduce emissions



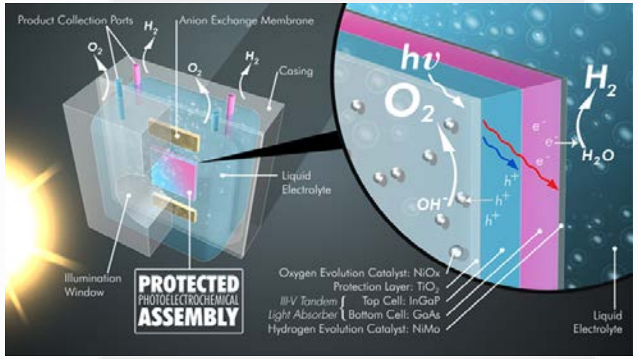
- Improve performance and cost of integrated systems for natural gas reforming with CCUS achieving emissions targets
- Develop diverse options such as gasification of waste feedstocks & pyrolysis of natural gas

Adapt Current Production

ADVANCED PATHWAYS

Innovative approaches offering cross-cutting benefits

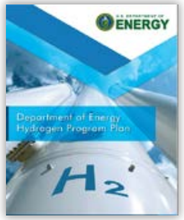
Achieve high-impact breakthroughs



- Develop advanced H_2O-splitting systems with solar-to-H_2 conversion efficiencies >30%
- Develop robust microbial processes and systems to produce affordable clean H_2 from diverse bio- and waste-feedstocks

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

https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

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, Plastics, 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

Technology Readiness Level

Foundational & applied research

- DOE Program Offices Core R&D
- BIL 816 & 815 R&D:
  - *Electrolysis & clean H_2 manufacture/recycle*
- DOE Consortia & Collaborations include:
  - *HydroGEN, ElectroCat, H-Mat, X-Mat …*
  - *H2-related Innovation Hubs & Centers*

tech handoff

data & feedback

Demos, manufacturing & scaleup

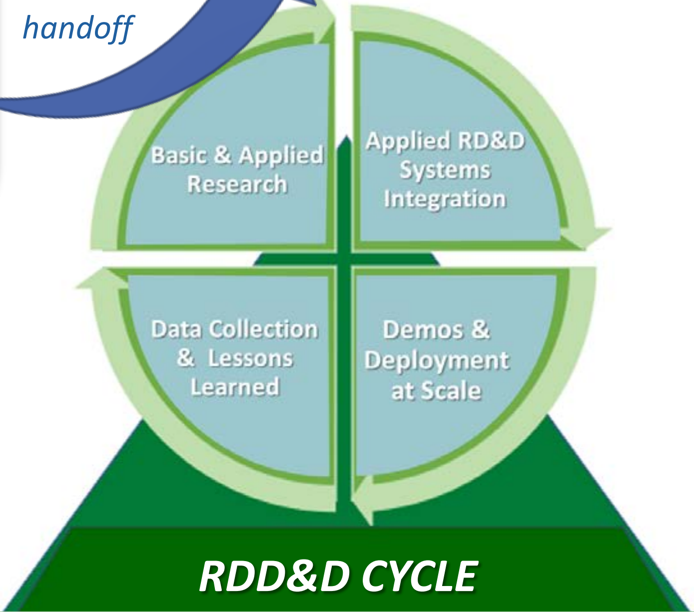
- DOE Program Offices Core RD&D
- BIL 816 & 815 RD&D:
  - *Electrolysis & clean H_2 manufacture/recycle*
- DOE Consortia & Collaborations include:
  - *H2NEW, M2FCT Consortia*
  - *H2@Scale demos (nuclear H_2, etc.)*
  - *Manufacturing Institutes*

tech handoff

data & feedback

Commercial-scale deployments

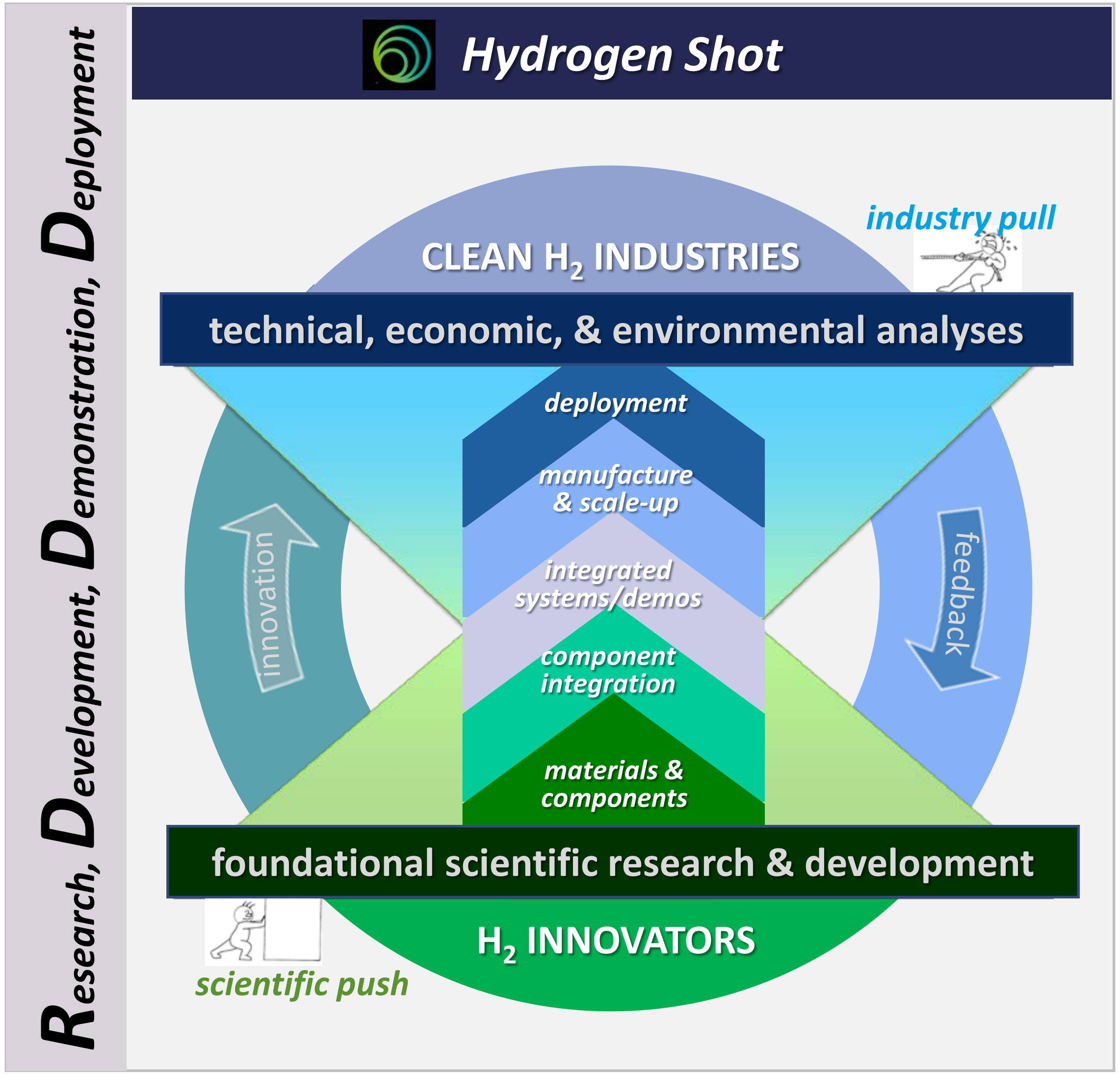
- BIL 813. Regional Clean H_2 Hubs
  - *Supporting development of at least 4 regional hubs nationwide*
- Collaborations & Coordination include:
  - *DOE-wide coordination*
  - *Regional, state, and local agencies*
  - *Safety, workforce, EJ40, etc.*



Technology Investment Stage

next-generation technologies | *near-commercial technologies* | *established technologies*

Focus on Bridging Innovation with End-Use



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

Off to a Good Start – *exciting times ahead!*

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

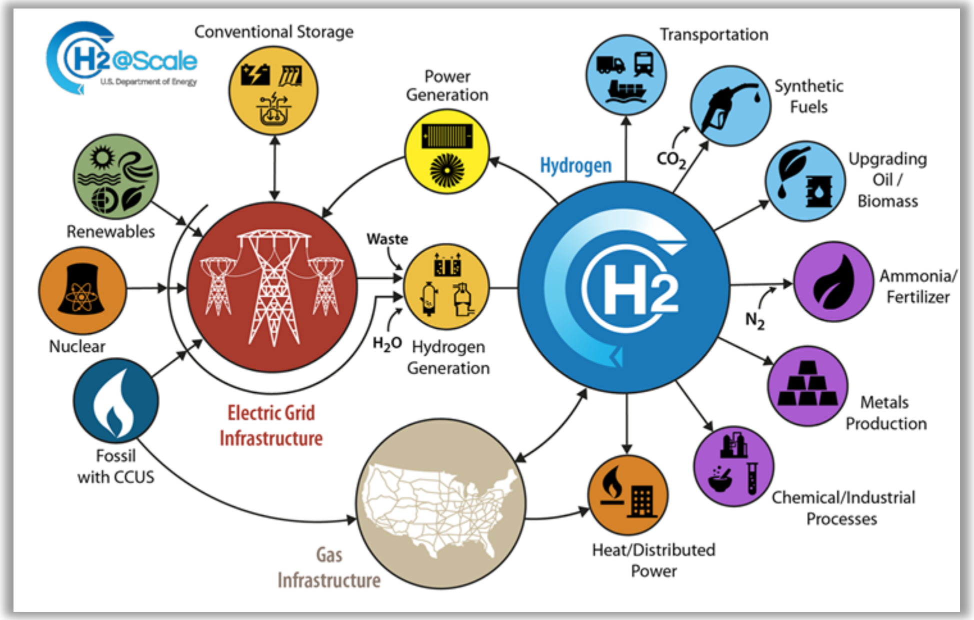
	FY21 Q4	FY22 Q1	FY22 Q2	FY22 Q3	FY22 Q4	*and beyond*
IMPORTANT MILESTONES	S1 Launch of H2 Shot ✓	H2 Shot Summit ✓	H2 Shot Fellowship ✓	H2 Shot Strategy Document*	FOA Announcements	
RFIs, FOAs & LAB CALLS	*H2 Demos RFI* ✓	*HBCU Joint FOA* ✓	*BIL / H2 Hubs RFIs* ✓ *H2 Matchmaker* ✓	*Clean H2 / BIL FOA NOI* ✓ *H2 Incubator* ✓		*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*
WORKSHOPS & MEETINGS	*BES H2 Round Table* ✓ *Clean Ammonia WS* ✓	*Power Electronics WS* ✓ *Off-Road H2 WS* ✓	*Liquid Alkaline WS* ✓ *Bulk H2 Storage WS* ✓ *High-T Electrolysis WS* ✓	*PEM Electrolyzer WS* ✓ *Manufacture & Recycle WS* ✓ *Post-Doc Award at AMR* ✓		

✓ *Completed*

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

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

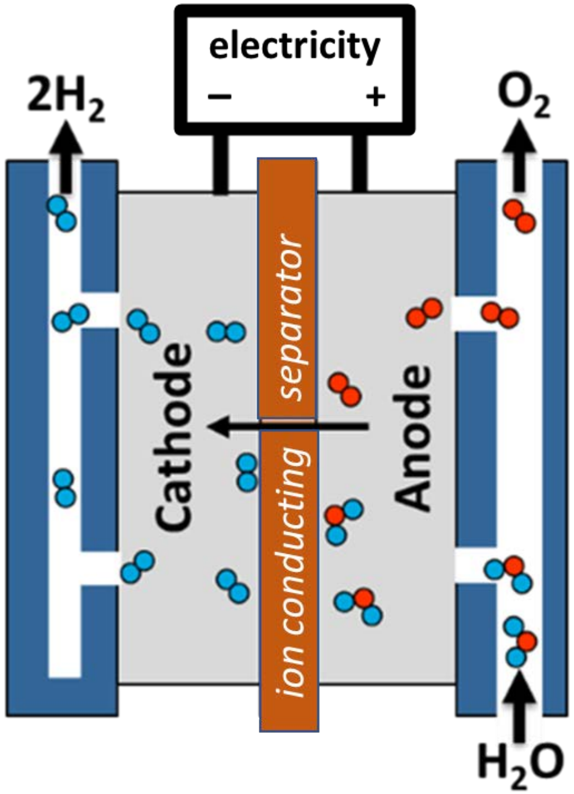


The Hydrogen Shot 1,1,1 goal for affordable clean hydrogen at scale is a key enabler of the DOE National Clean Hydrogen Strategy addressing pressing clean energy, climate, and EEEJ priorities

Electrolysis Pathways

David Peterson
Technology Manager
DOE-EERE-HFTO

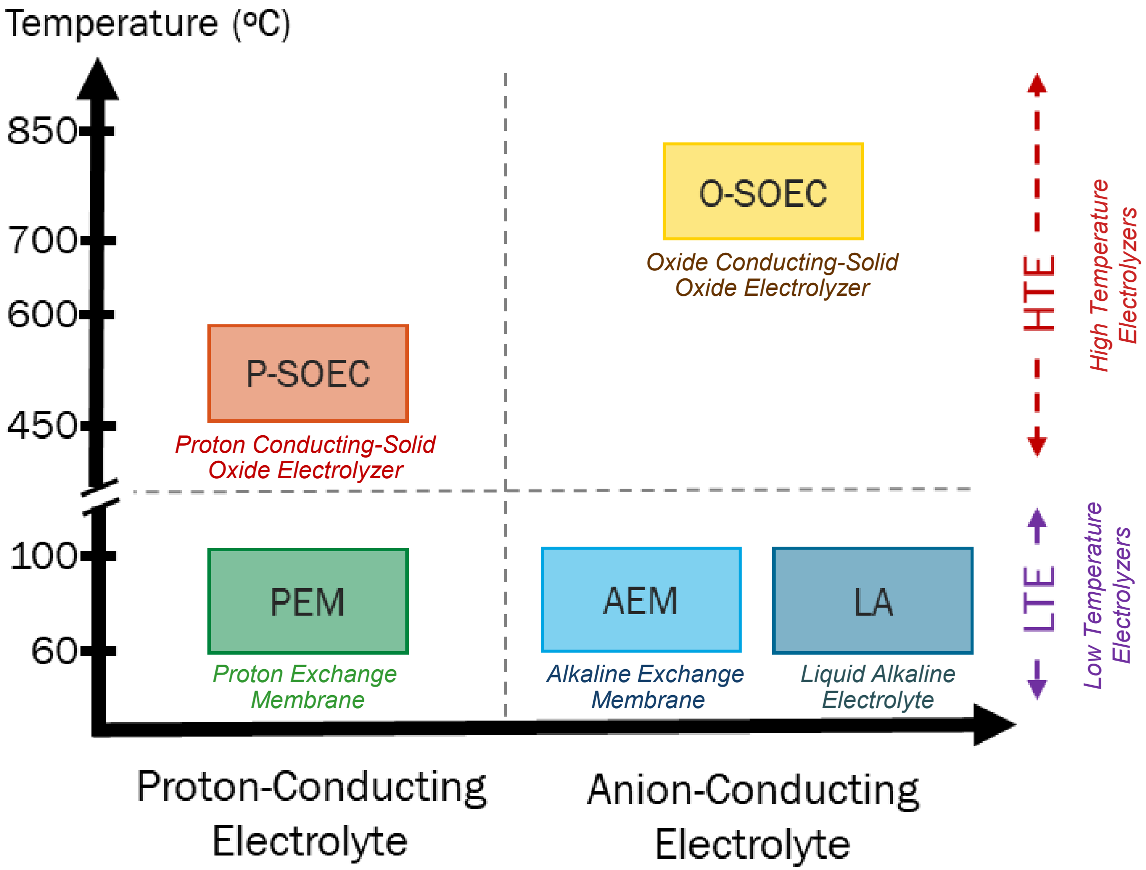
Water Electrolysis Overview



Water electrolyzer cell configuration (H^+ Conductor):

Anode: $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$

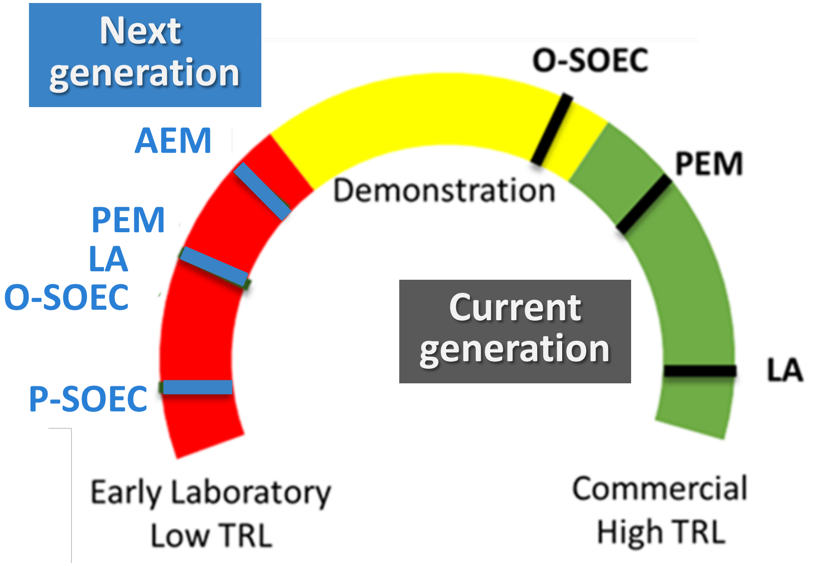
Cathode: $4H^+ + 4e^- \rightarrow 2H_2$



Electrolyzer technologies differentiated by electrolyte conducting species and temperature

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 H_2



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

Lower-TRL Next generation (AEM, P-SOEC) have the potential to achieve performance and cost targets needed to meet \$1/kg H_2, but further development is required

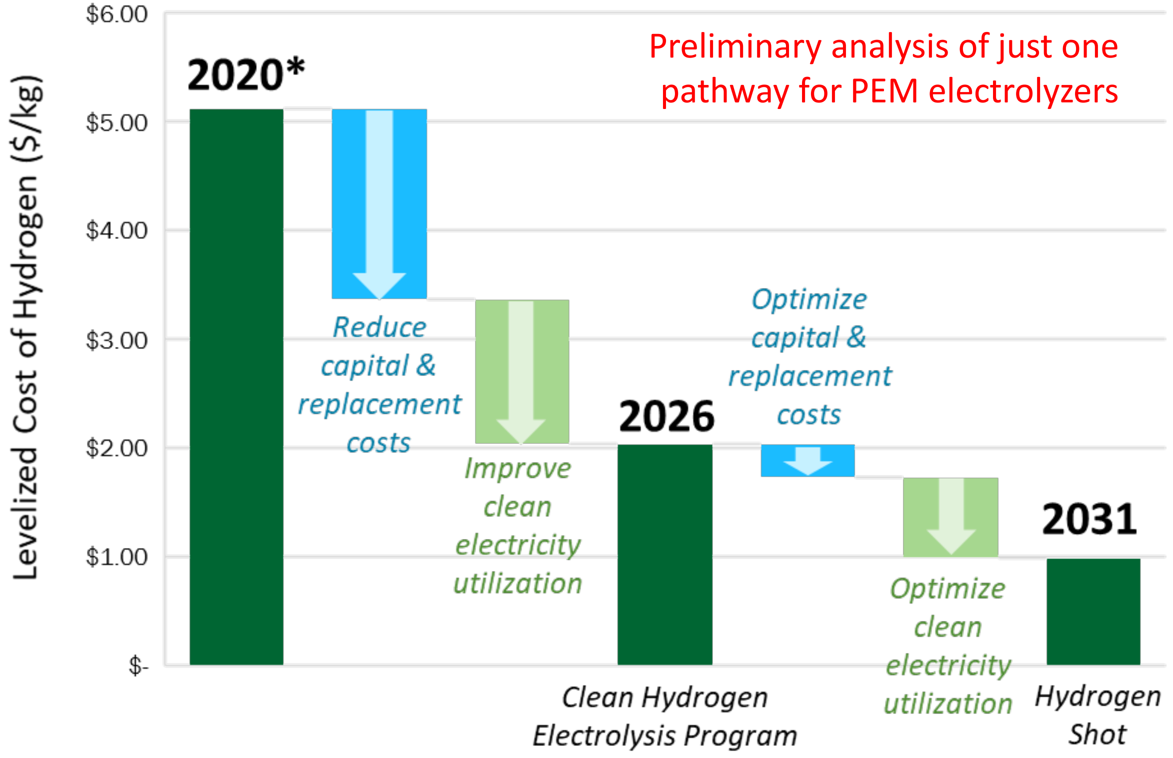
Electrolysis Cost Reduction

McKenzie Hubert
ORISE Fellow
DOE-EERE-HFTO

Cost Reduction Strategy- *PEM Example* *(similar analysis for LA & SOEC)*

Potential pathways for achieving $2/kg and $1/kg targets: Comprehensive approach targeting cost, efficiency, durability

Analysis efforts identify possible cost reduction strategies†



† Reference case: Wind to H_2 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

Key factors for cost reductions

Key factors	
High electrical **efficiency** Increased **durability/lifetime**	**Technology Advancements**
Low-cost **capital equipment** Low-cost **manufacturing** processes at GW-scale	**Domestic Manufacturing**
Low-cost **clean electricity**	**Demonstrations**

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

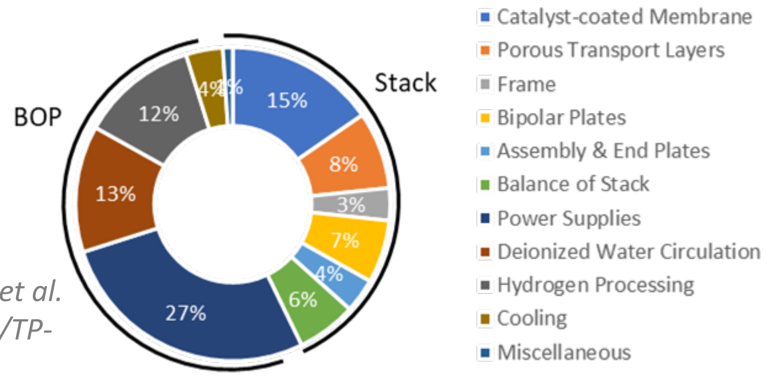
Cost Reduction Pathways – *LTE Example* *(different targets for HTE)*

Technical targets under development - *LTE example*

Key Cost Parameters	2020 Status* ($5/kg H_2)	2026 Target ($2/kg H_2)	2031 Target ($1/kg H_2)
System efficiency	55 kWh/kg	51 kWh/kg	46 kWh/kg
Stack lifetime	60,000 hr	80,000 hr	100,000 hr
System capital cost	$1500/kW	$250/kW	$150/kW
Manufacturing volume	~100 MW/yr	~1 GW/yr	~1 GW/yr
Plant size	Distributed (1,500 kg/day nameplate)	Central (50,000 kg/day nameplate)	Central (50,000 kg/day nameplate)
Energy supply†	Grid-connected ($51/MWh, 80% operating capacity factor)	Clean Energy PPA (e.g., $25/MWh, 50% operating capacity factor)†	Direct Integration (e.g., $12/MWh, 50% operating capacity factor)†

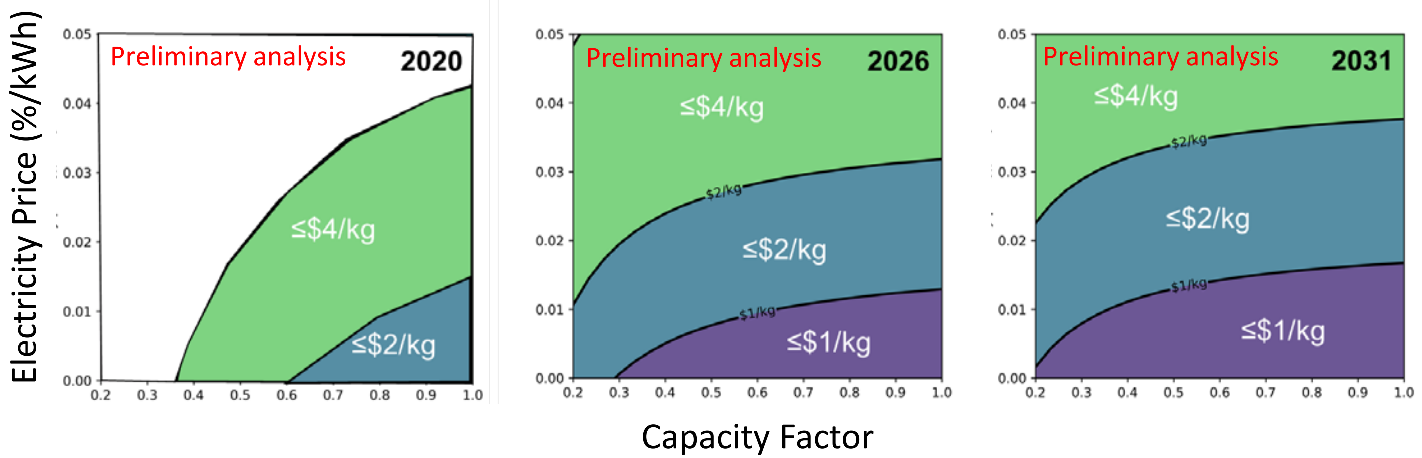
† Reference case: Wind to H_2 scenario, but not the only pathway to achieve target
** DOE Hydrogen and Fuel Cells Program Record #20004, Sept 2020*

Capital cost levers - *PEM example*



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

Improved clean-electricity integration options



Manufacturing & Supply Chain

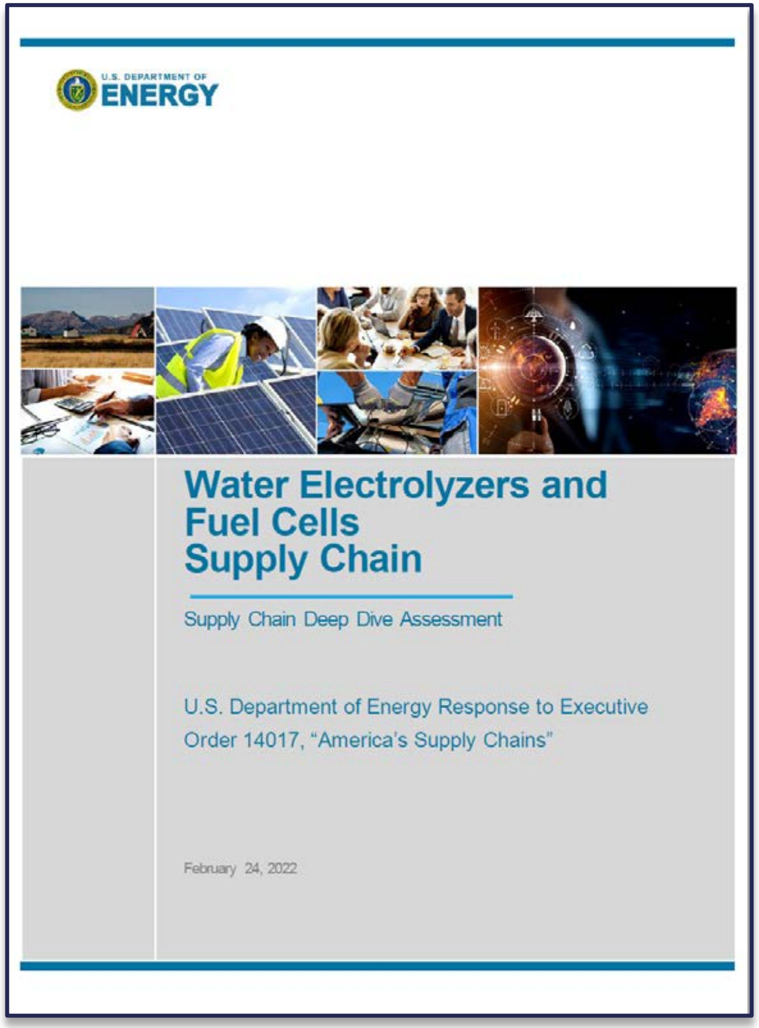
Paul Syers

Technology Manager

DOE-EERE-AMO

Hydrogen Supply Chain, Today vs 2050

To meet 2050 decarbonization goals, clean H_2 technologies need to significantly grow!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Water Electrolyzers and Fuel Cells Supply Chain

Supply Chain Deep Dive Assessment

U.S. Department of Energy Response to Executive Order 14017, "America's Supply Chains"

February 24, 2022

Today's Hydrogen Market

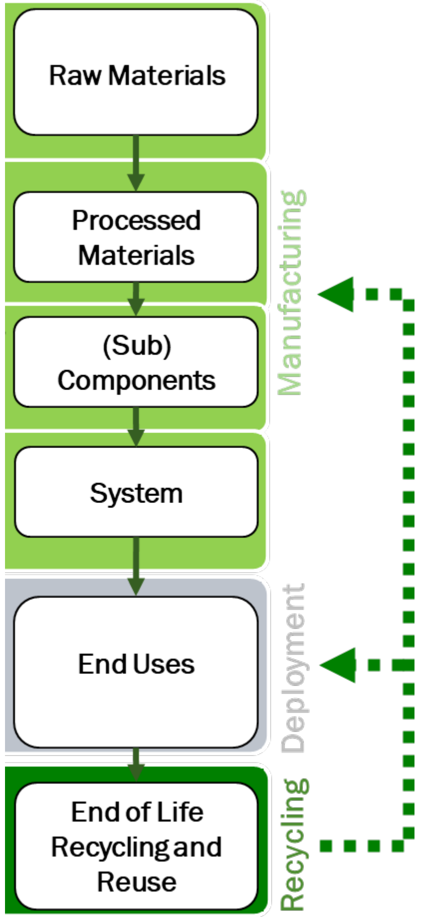
- ~10 MMT/yr in the U.S.
- 65-100 MMT/yr globally
- Almost none of that is electrolytic

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:

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

More information: www.energy.gov/eere/fuelcells/water-electrolyzers-and-fuel-cells-supply-chain-deep-dive-assessment

Wind to Hydrogen Opportunities

Jian Fu
Program Manager
DOE-EERE-WETO

Wind -Hydrogen Strategy

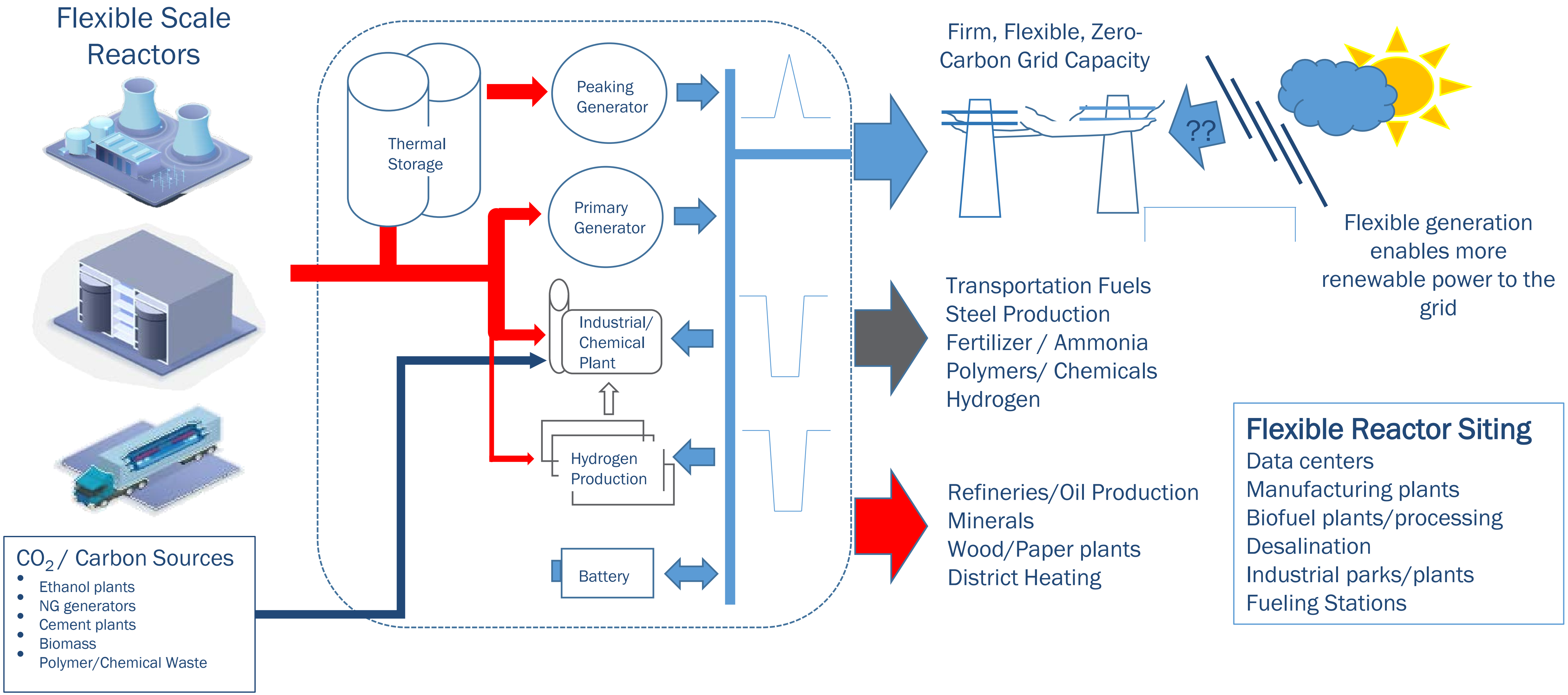
Optimized, Cost competitive, Scalable, Modular, and Integrated Wind – H_2 Systems

INTEGRATED WIND HYBRID GENERATION +	OPTIMIZED H_2 PRODUCTION +	COST COMPETITIVE CLEAN H_2 ACROSS SECTORS
Optimized Wind / Solar / Storage Hybrid Electricity Generation - matching H2 use demand profile	H_2 production: Near collocated (reduced delivery - potential direct pipeline) to user	Industrial: Green Steel, Green Cement, Green Ammonia, Green Chemicals
Direct Wind-Electrolyzer Connection: Shared Components / Control	Reduced storage requirements: continuous real time generation	Transportation: Green Fuels – Marine, Aviation, Heavy trucking
Overbuilt, paired electrolyzer plant to enable full, dedicated electricity utilization (no curtailment losses)	Potential option to eliminate Grid connected equipment & Grid connection constraints	Target: Cost competitive – without subsidization

Nuclear Hydrogen Opportunities

Jason Marcinkoski
Program Manager
DOE-NE

Nuclear Integrated Energy System Concept



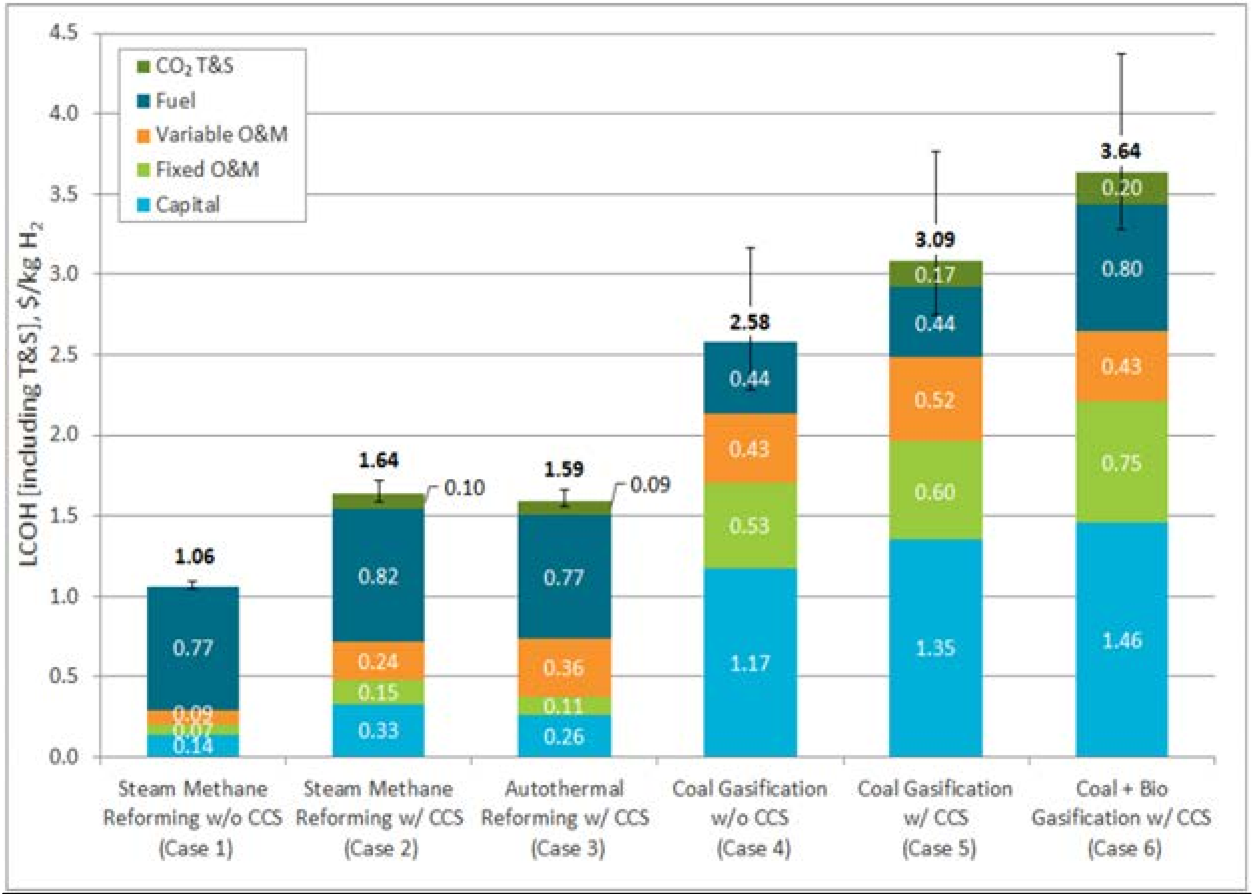
Thermal Conversion Pathways

Eva Rodezno
Program Manager
DOE-FECM

Thermal Conversion Pathways

$H_2 + CO_2$ (or C)

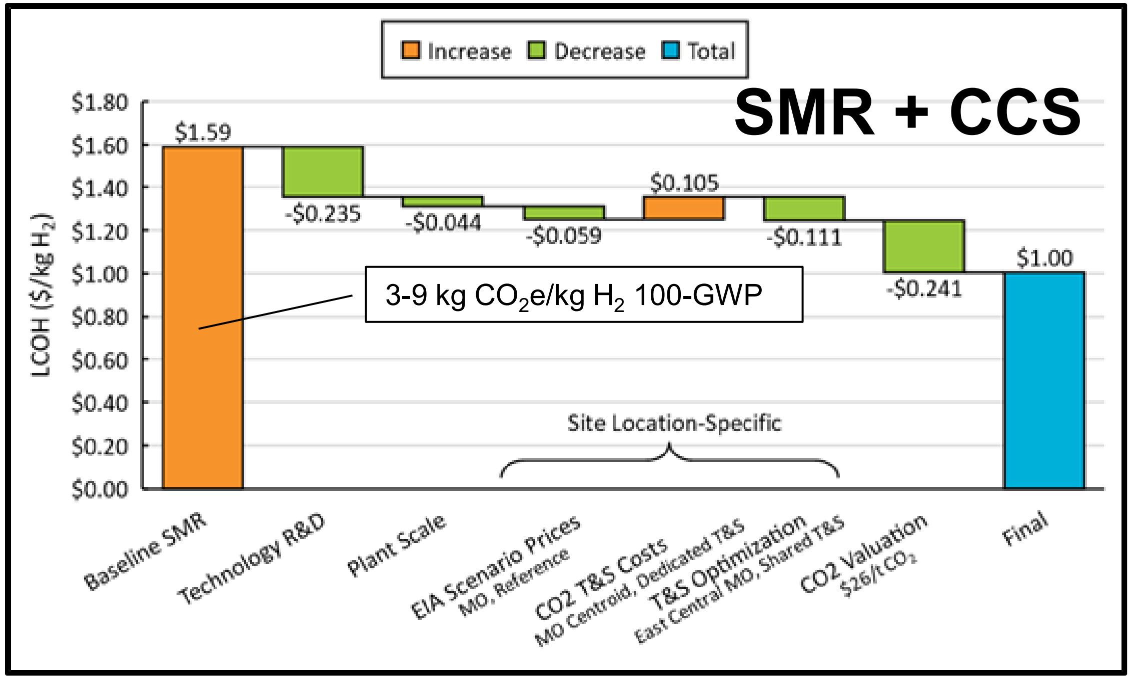
Industrial Process	Carbon Capture Method
Steam Methane Reforming	Pre & Post Combustion Capture
Autothermal Reforming	Pre-Combustion Capture
Partial Oxidation	Pre-Combustion Capture
NG Pyrolysis	Solid Carbon Product
Coal & Biomass Gasification	Pre-Combustion Capture



Source: https://netl.doe.gov/energy-analysis/details?id=ed4825aa-8f04-4df7-abef-60e564f636c9

NATIONAL ENERGY TECHNOLOGY LABORATORY

Thermal Conversion Cost Reduction Strategies

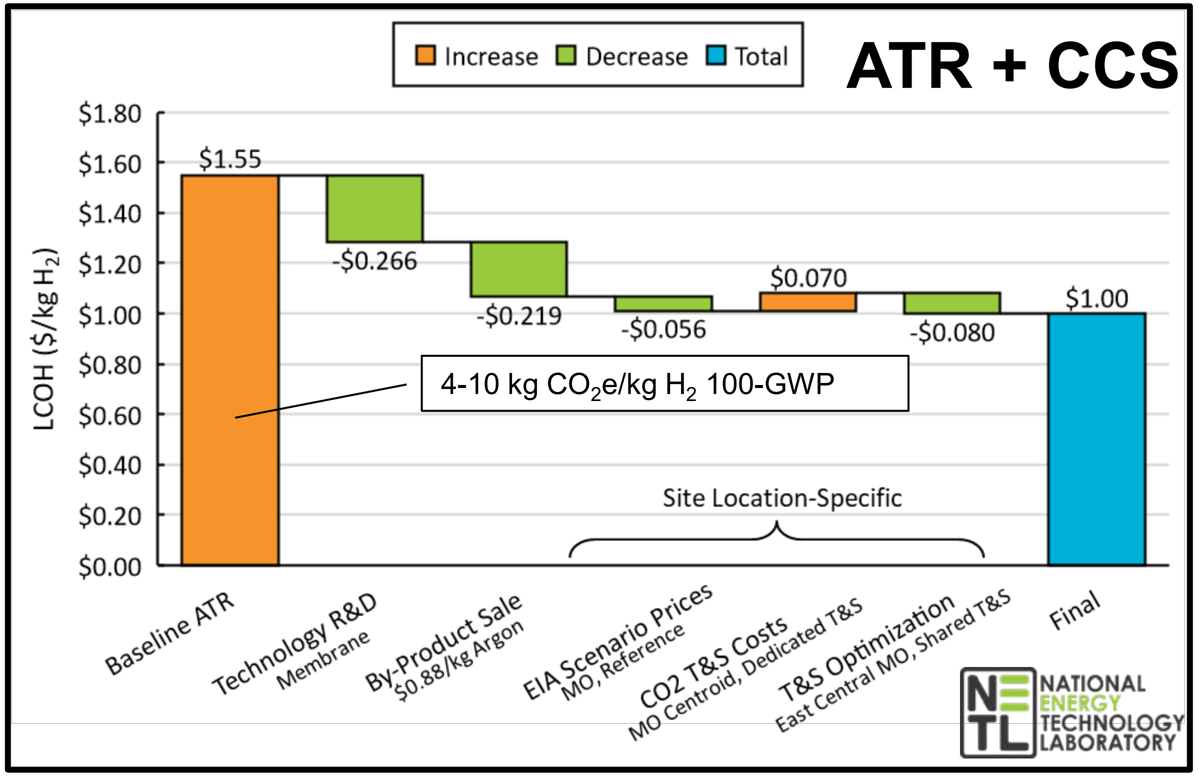


Cost Reduction Strategies

- Sharing CO_2 transport and storage costs with other emitters
- CO_2/carbon valorization
- Location selection
- Plant Scaling
- Integrated energy systems
- Byproduct sales (argon, carbon black, sulfur, slag)

R&D Needs

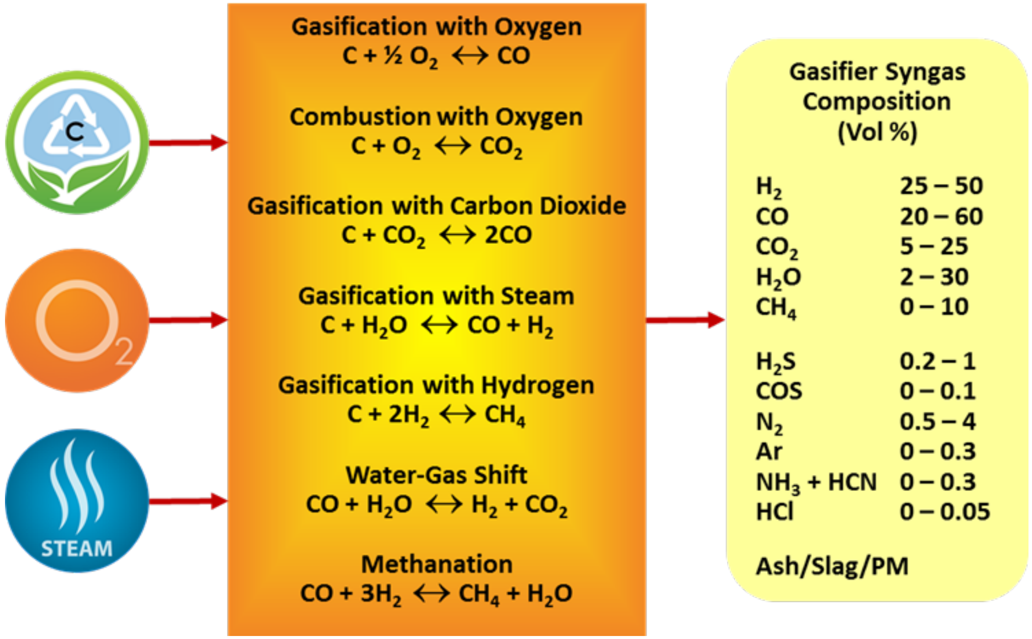
- Process Intensification to improve efficiency and reduce CAPEX
- Improved CO_2 sorbents
- Improved sorbent separation technology
- High-temperature H_2/CO_2 separation membranes
- Advanced catalysts to lower system energy requirements and reduce cost



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:

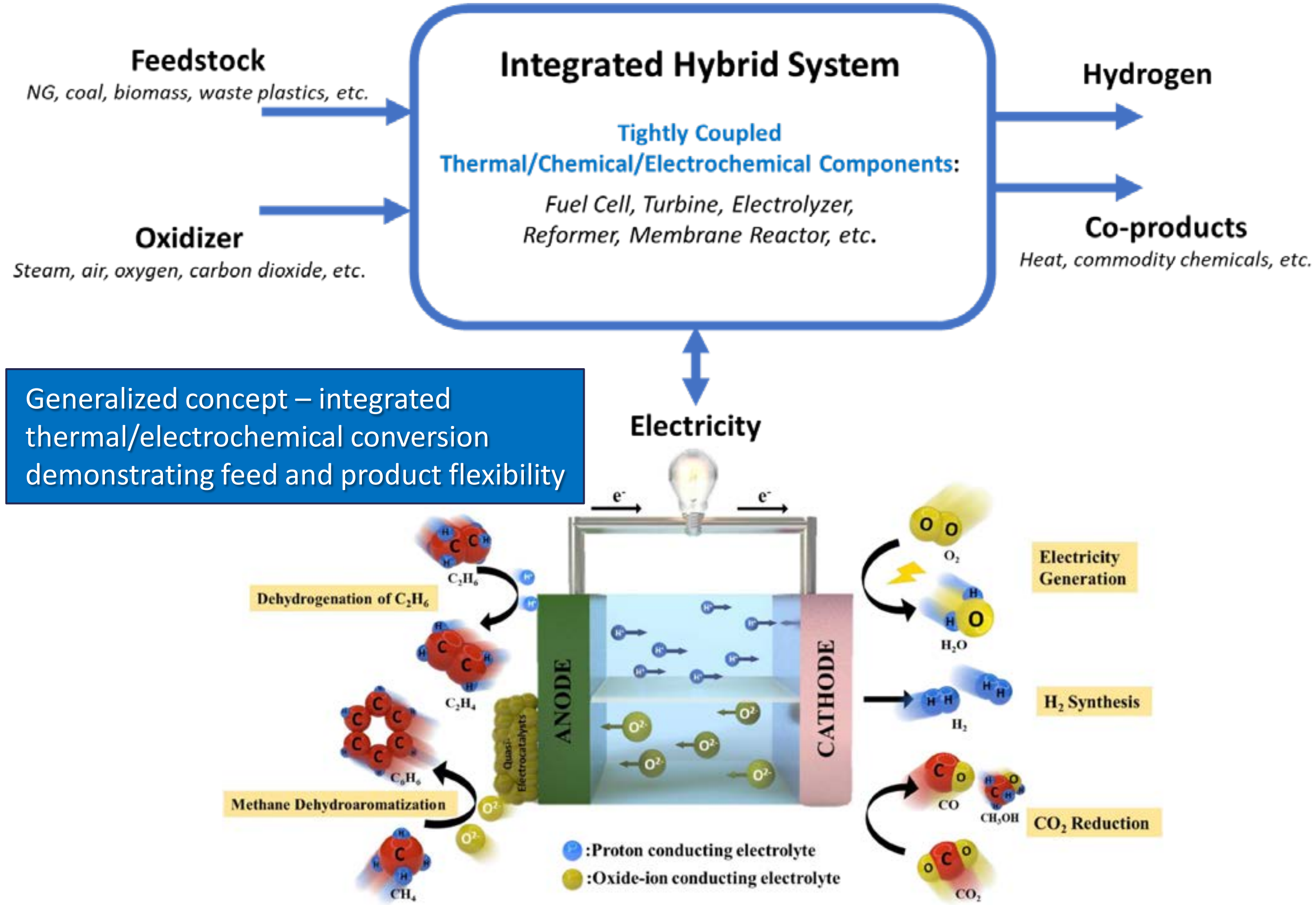
- Feedstock flexibility, leveraging regional resources: *biomass-, fossil-, and waste- feedstocks*
- Tunable value-add co-products
- Valorization of waste streams (MSW, plastics, etc.)
- Potential for net negative carbon emissions
- Novel smaller/modular gasification systems enable distributed operation

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



Generalized concept – integrated thermal/electrochemical conversion demonstrating feed and product flexibility

Opportunities:

- Feedstock flexibility, leveraging regional resources
- Polygeneration of H_2 + value-add co-products
- Integrated & optimized carbon management
- Hybridization allows for regional tuning & max. ROI

Research Needs:

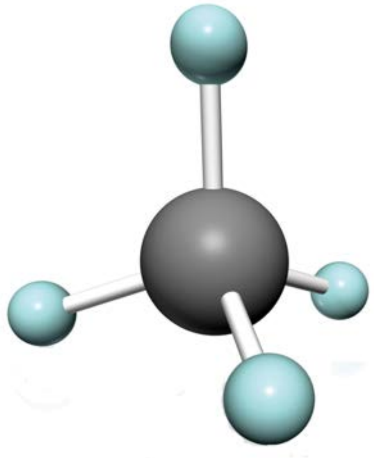
- Analysis of novel configurations
- Component technology advances (*durability, efficiency, and cost*)
- System level optimization & cost reduction (*complexity vs benefit*)
- Optimized operations for varied inputs (*feedstock and electricity costs in real time*)

Source (INL review): https://www.sciencedirect.com/science/article/pii/S1388248121001521

Methane Pyrolysis

Jack Lewnard
Program Director
DOE ARPA-E

Cracking Methane: *Two Product Process*



750 - 1200°C

Gaseous hydrogen

+

Solid carbon

$$CH_4 \longrightarrow 2\,H_2 + C\,(s)$$

$2\,H_2$

¼ weight

½ energy

C (s)

3 X weight H_2

Methane Pyrolysis Cohort.. *2018 OPEN & 2019 FOA*

H2 Generation

- Johns Hopkins University — Ni / NiCl2
- parc (A Xerox Company) — Molten Zn

C Zero — Molten Salt

C Generation

- nanocomp Technologies, Inc. (A Huntsman Company) — Miralon
- RICE — CNT & H2 Process
- Stanford University — Fe Catalyst

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 H_2-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		Paths to scale
High unit costs for production	• Current prices at $4-5/Kg serving narrow set of use cases, though recent high NG prices narrow gap • Sub-scale domestic electrolyzer manufacturing capacity • Multiple deployments will lower the cost of existing clean hydrogen technologies (i.e., $1/kg Earthshot)	**Contracted medium/long-term offtake** for clean H2 to create a stable demand signal and enhance bankability
Lack of common infrastructure	• Currently only ~1,600 miles of H2 pipelines in the U.S., with high capex cost (~$3M per mile) • Other transport options (e.g., truck, ship) can add significant cost • On-site production an option for certain uses	**Regional hubs with shared infra costs** for common infrastructure supporting multiple developers and offtakers
Lack of commercial debt	• Debt allows for scaling and replicability of clean H2 business models • Current market funded by private equity, while commercial debt limited by tech risk and bankability	**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)

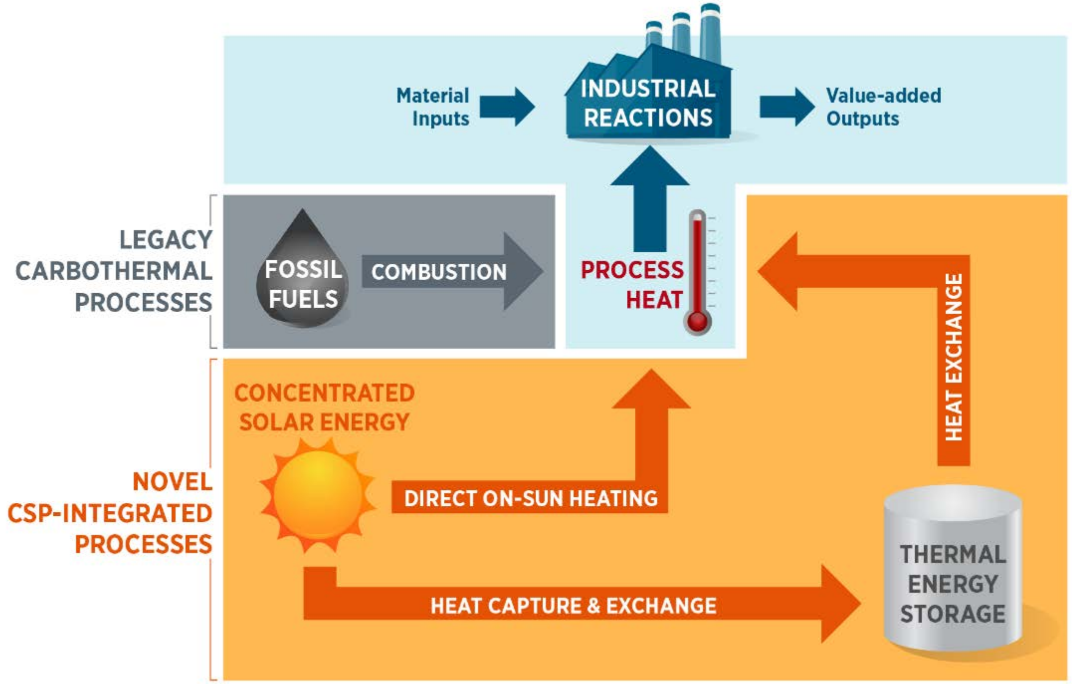
Magnum ACES: ~$500M

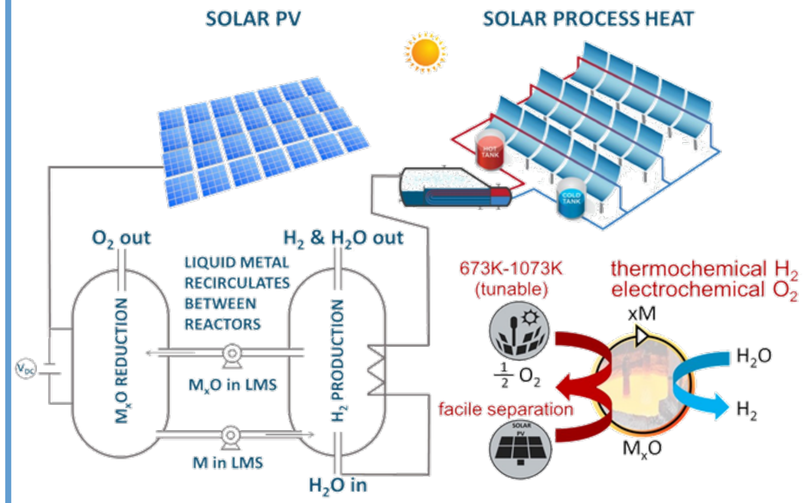
- Green hydrogen production and storage facility to supply hydrogen-ready NG-power plant
- Offtake from Intermountain Power Agency
- Balance renewable generation and improve transmission utilization

Thermal Integration with CSP

Avi Shultz
Program Manager
DOE-EERE-SETO

Solar Thermochemical Processing



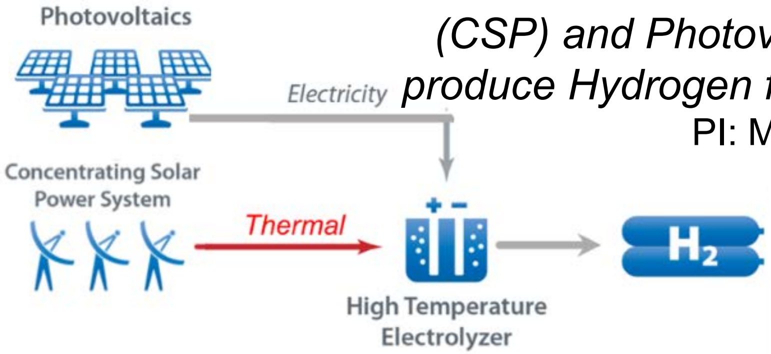


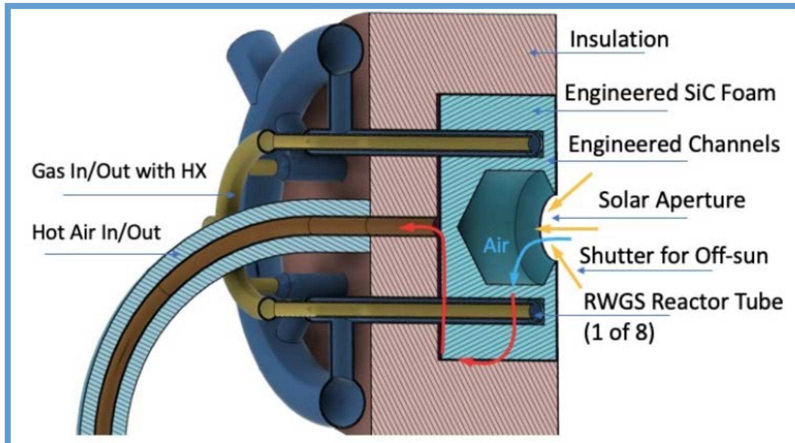
Solar Hydrogen from Water Splitting using Liquid Metal Oxidation/Reduction Cycles Promoted by Electrochemistry

PI: Tony McDaniel

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

PI: Mark Ruth





SiC Receiver/Reactor by Additive Manufacturing for Concentrated Solar Thermocatalysis with Thermal Energy Storage

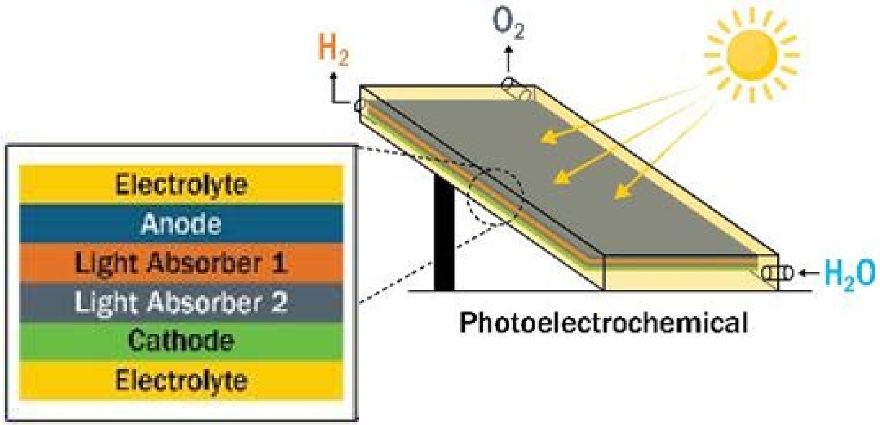
PI: Bradley Brennan

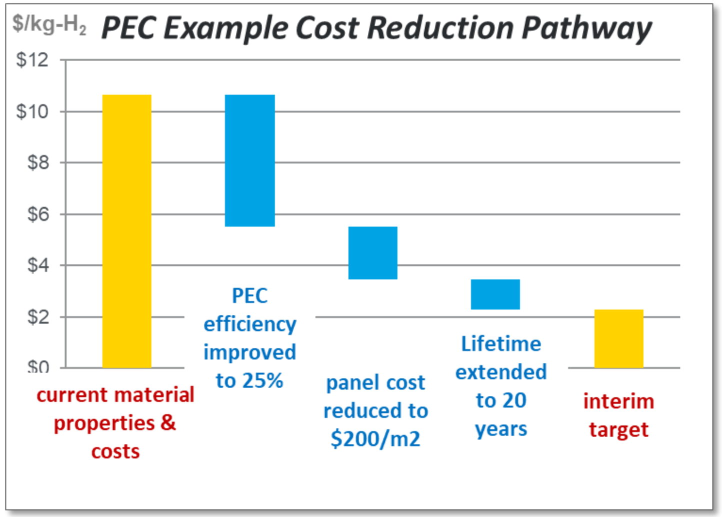
Advanced Pathways

James Vickers
Technology Manager
DOE-EERE-HFTO

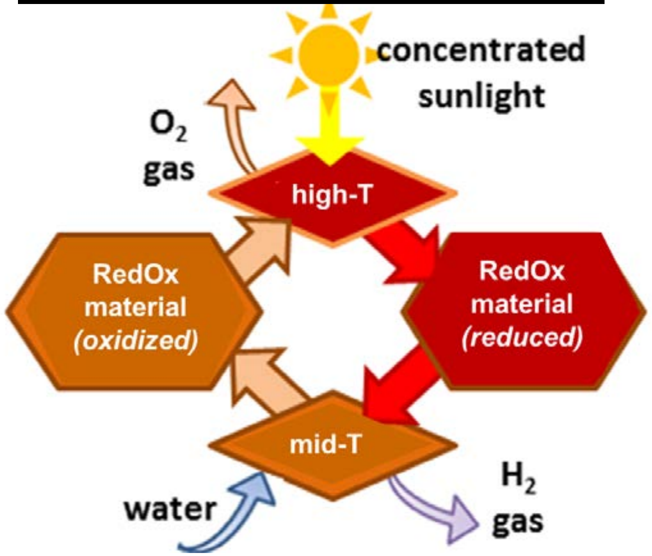
Exploring Potential of Advanced Pathways - *examples*

Photoelectrochemical Solar Water Splitting (PEC)

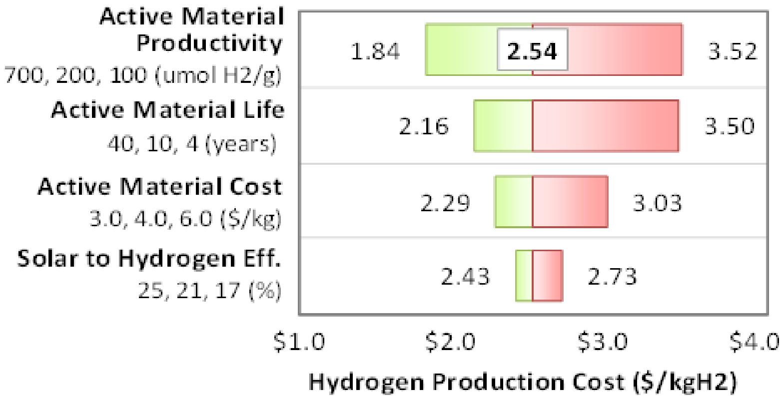




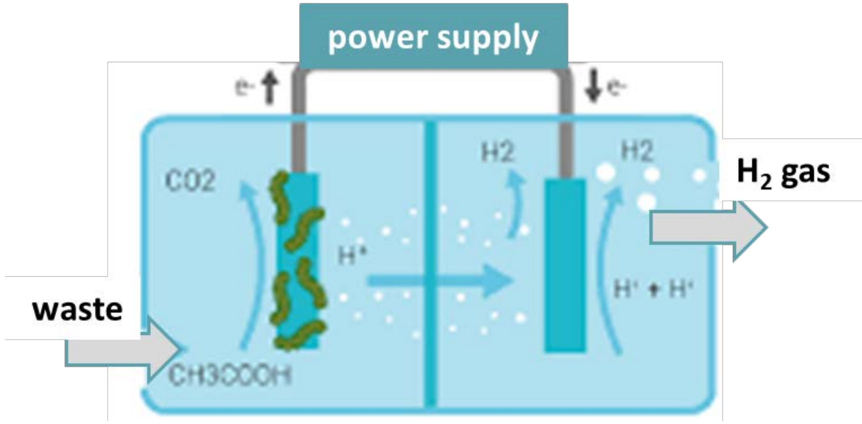
Solar Thermochemical Water Splitting (STCH)



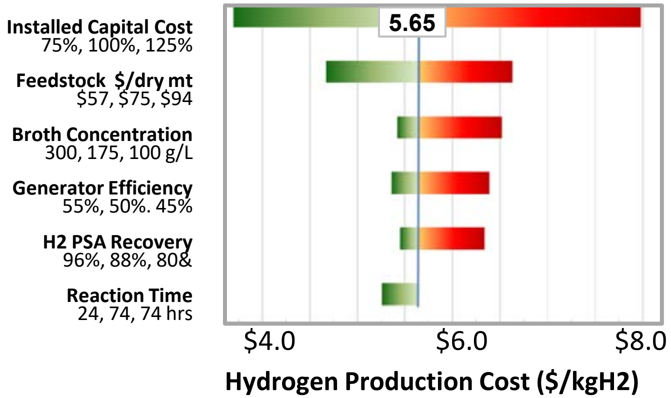
STCH Boundary Study



Fermentation with Microbial Electrolysis of Waste Streams

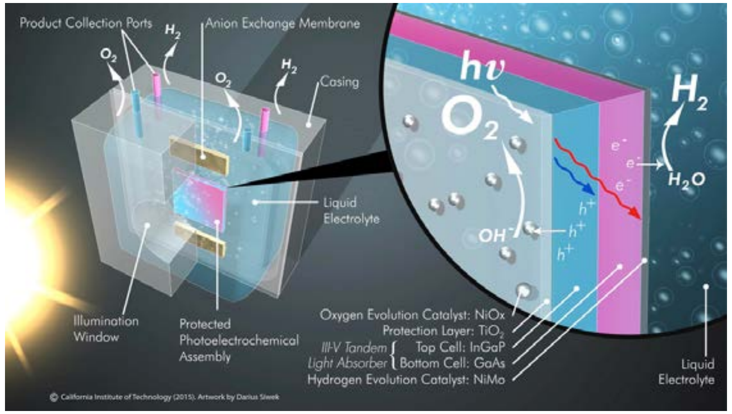


Fermentation Boundary Study



Advanced Pathways – *Progress and Impacts*

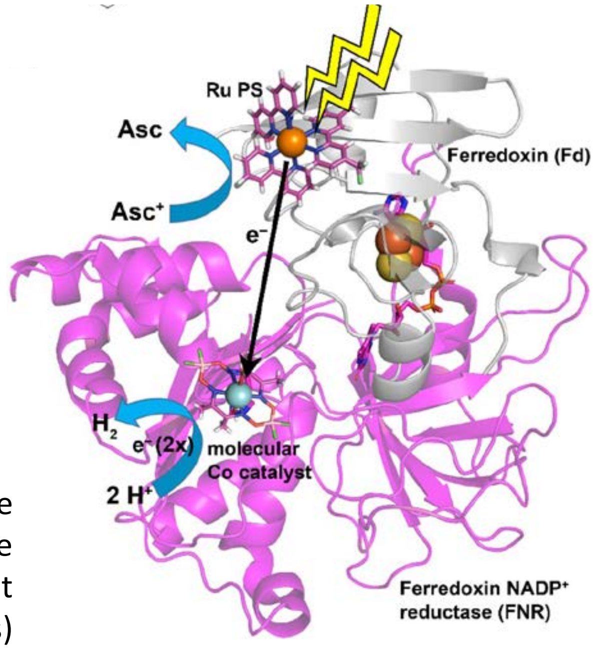
Important Progress in PEC Solar Water Splitting



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

E. Verlage,. et al. E&ES, DOI: 10.1039/C5EE01786F (2015)

Notable Progress in Photocatalytic Aqueous H_2 Production



2-protein biohybrid system produces hydrogen in aqueous solutions via light-induced interprotein electron transfer reactions. The native electron shuttle protein ferredoxin (Fd) is used as a scaffold for binding of a ruthenium photosensitizer and H2 catalytic function is imparted to its partner protein, ferredoxin-NADP+-reductase (FNR), by attachment of cobaloxime molecules.

Brahmachari et al..Photosynthesis Research 143:183–192 (2020)

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**

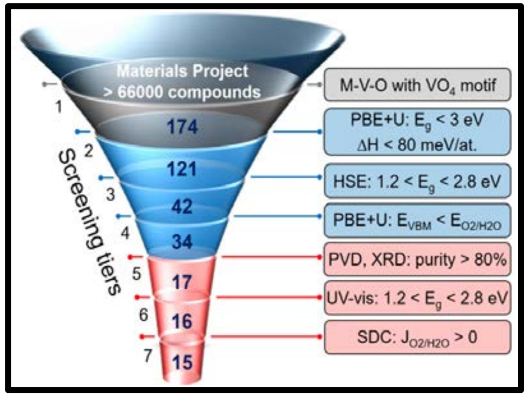
Advancing Science & Technology

Viviane Schwartz
Program Manager
DOE-SC-BES

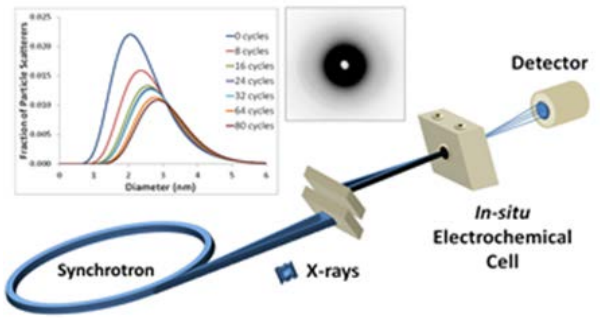
Advancing Science

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.

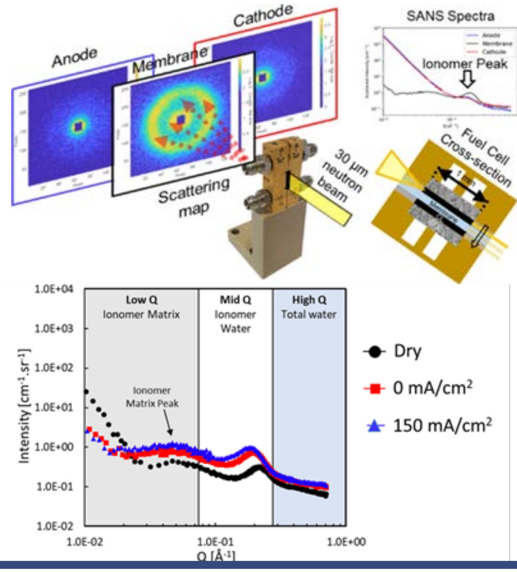


X-ray User Facilities: Studies combining X-ray Scattering with X-ray Spectroscopy provide mechanistic insight into the process of electrocatalyst degradation. Schematic of operando synchrotron X-ray scattering, representative scattering data, and evolution of platinum electrocatalyst nanoparticle size distribution derived from X-ray scattering data as a function of potential cycling.

Workforce Development:

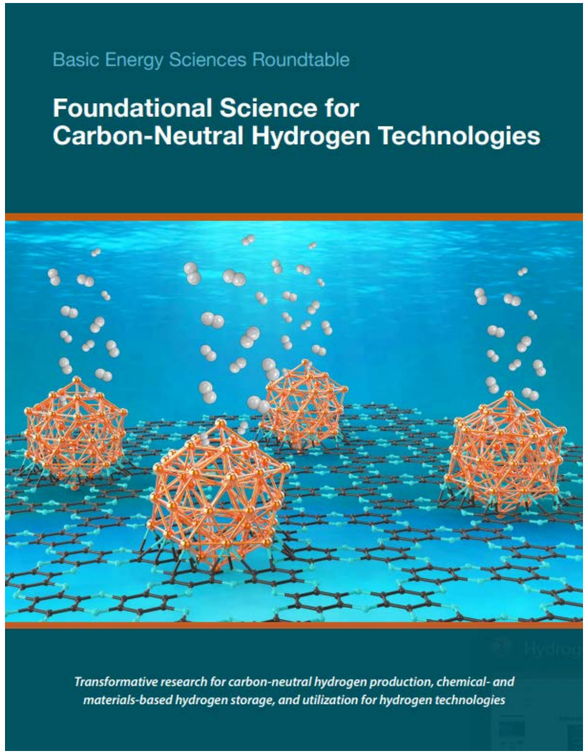
Primarily done by supporting undergraduates, graduate students, and postdoctoral researchers through research and development awards at universities and at the DOE national laboratories.

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 H_2 Technologies



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

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 H_2 Interactions to Harness the Full Potential of H_2 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?*

https://science.osti.gov/bes/Community-Resources/Reports

Advancing Energy Equity & Environmental Justice (EEEJ)

Kendall Parker

ORISE Fellow

DOE-EERE-HFTO

How do we transform our energy system while ensuring it becomes more equitable and just?

DOE Justice40 Policy Priorities for Disadvantaged Communities

↓	Energy burden
↓	Environmental exposure and burdens
↑	Parity in clean energy technology access and adoption
↑	Access to low-cost capital
↑	Clean energy enterprise creation for MBE/DBE
↑	Clean energy job pipeline and job training
↑	Energy resiliency
↑	Energy democracy

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

H2 TWIN CITIES

CENTER FOR Hydrogen SAFETY

An AIChE Technical Community • A Global Resource On Hydrogen Safety

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Hydrogen Fellows

IPHE Early Career Network

Christine Watson
Chair

Gaurav Shukla
Co-Chair

Kendall Parker
Co-Chair

IPHE.net | IPHE | IPHE | @The_IPHE

Exciting Fellowship Opportunities

Seeking Diverse Candidates

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Hydrogen

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 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

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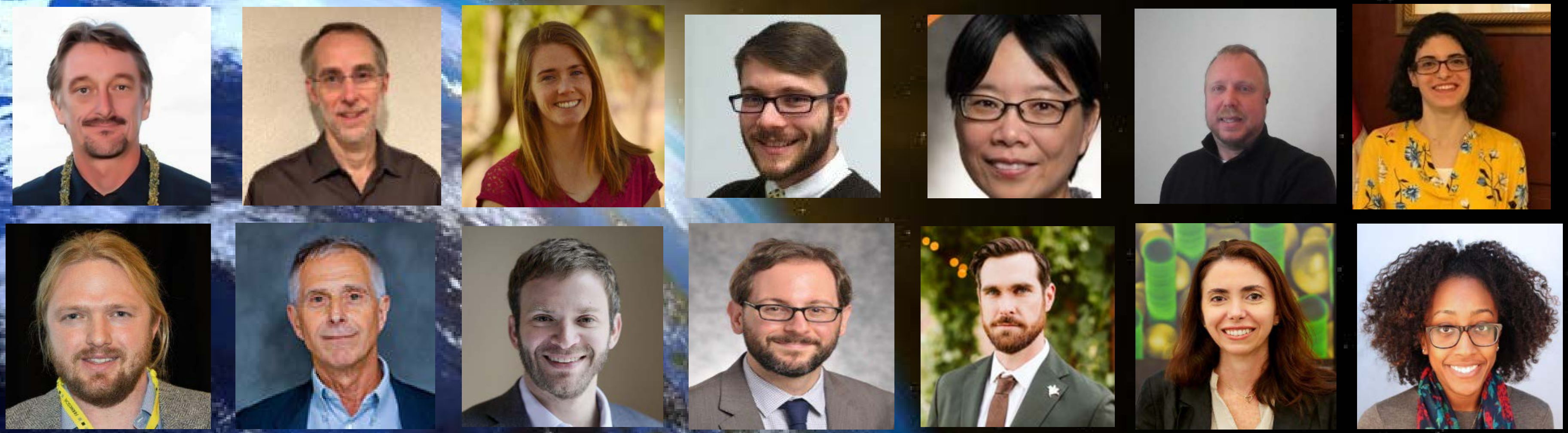
Thanks to All Our Panelists!



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Panel Q&A

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?

Moderator
Eric Miller
DOE-EERE-HFTO

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Thank You!

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