U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Hydrogen and Fuel Cell Program Overview

Dr. Sunita Satyapal, Director - Fuel Cell Technologies Office

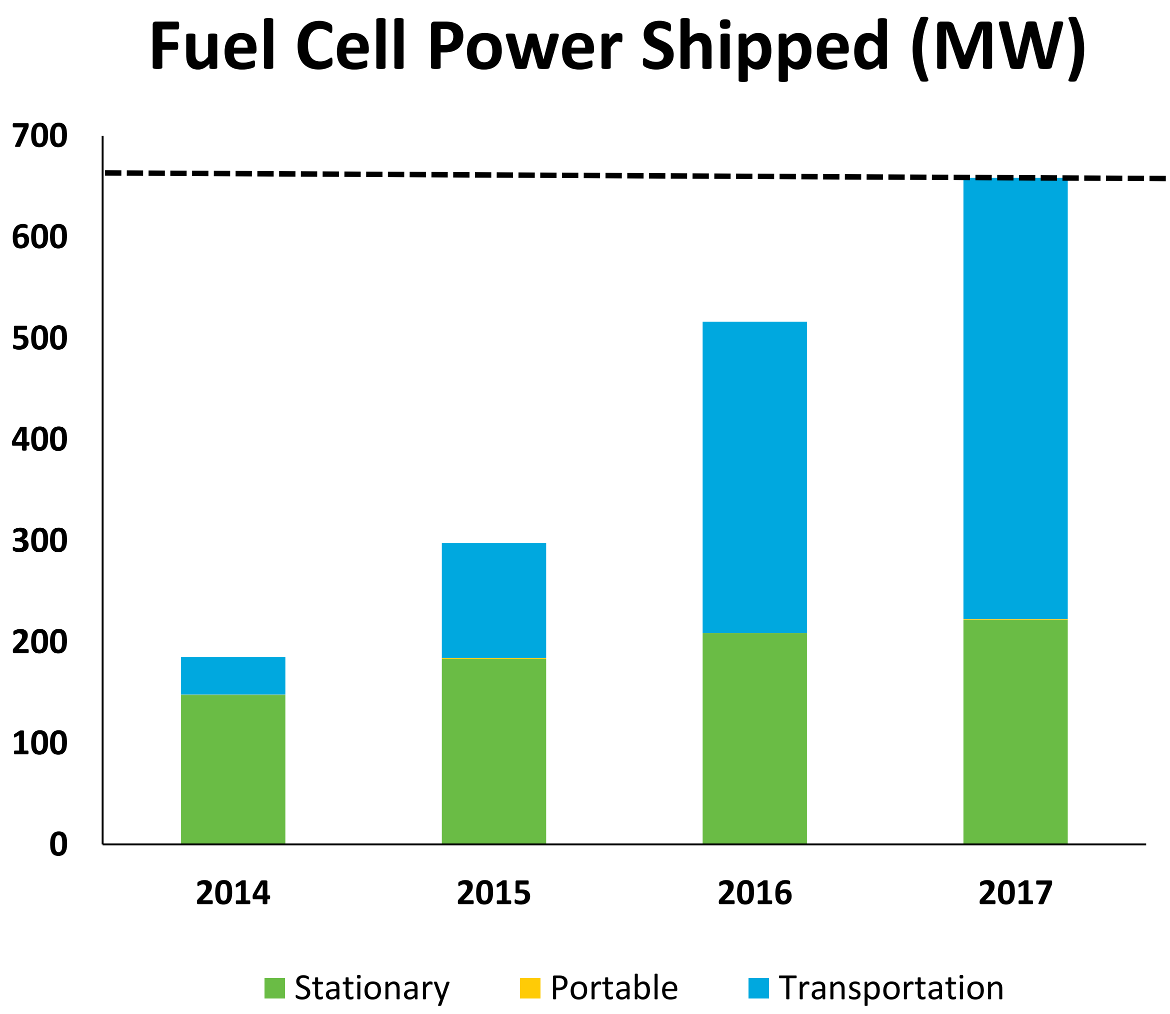
2018 Annual Merit Review

Washington D.C. - June 13, 2018



Exciting time for hydrogen & fuel cells

Fuel Cell Shipments - Growth by Application



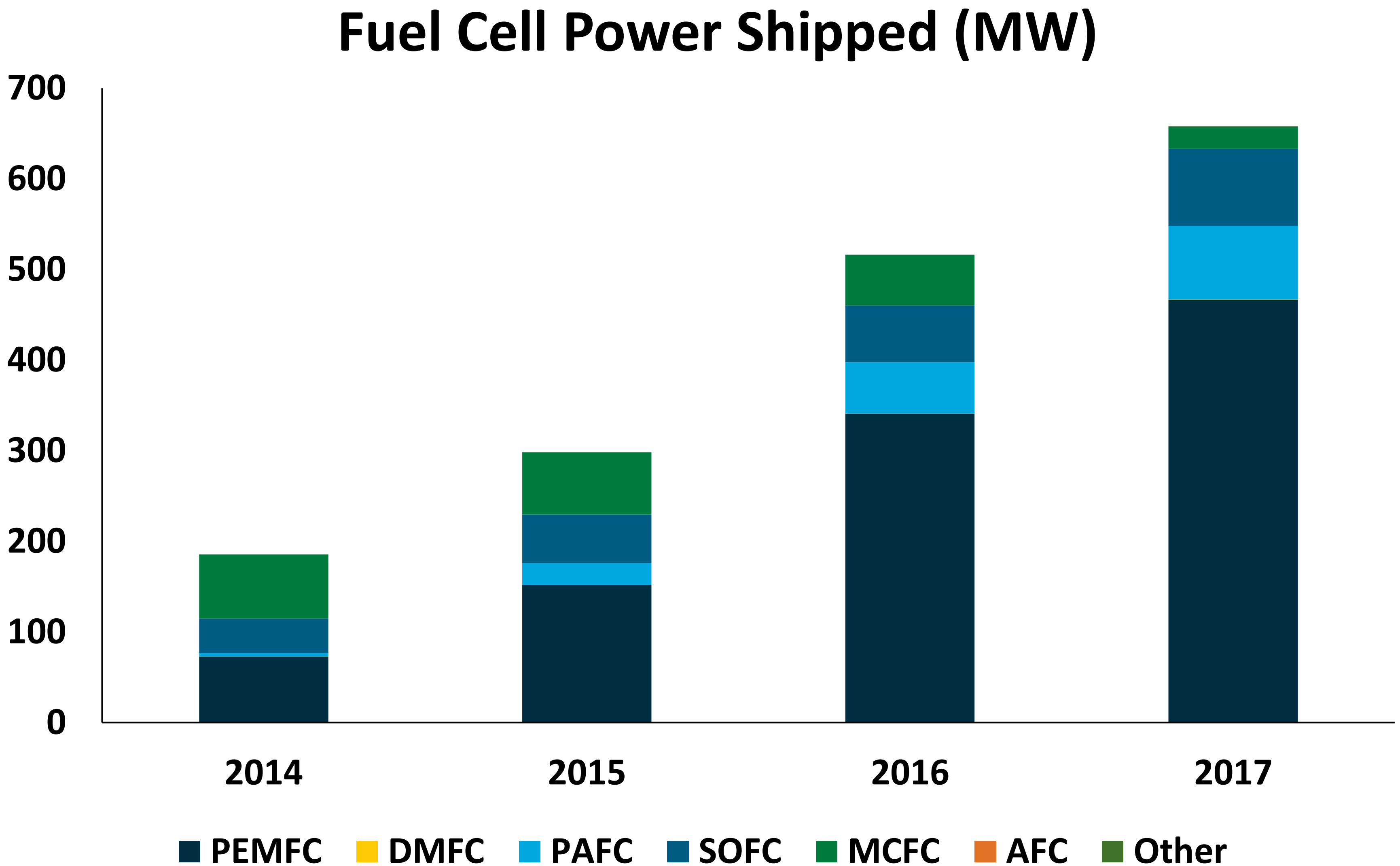
650 MW
fuel cell power
shipped worldwide

70,000
fuel cell units
shipped worldwide

Approximately
$2 Billion
fuel cell revenue

Source: DOE and E4Tech

Growth by Fuel Cell Type



Source: E4Tech

2018 U.S. Snapshot

Nearly **5,000 fuel cell cars**

in the U.S. since 2015

2018 U.S. Snapshot

More than **20,000 forklifts**

Over **12 million refuelings**

2018 U.S. Snapshot

2018 U.S. Snapshot

35 retail stations open today

Over 200 planned

Hydrogen and Fuel Cell Applications in the U.S.

U.S. Snapshot

>240MW
Backup Power

>20,000
Forklifts

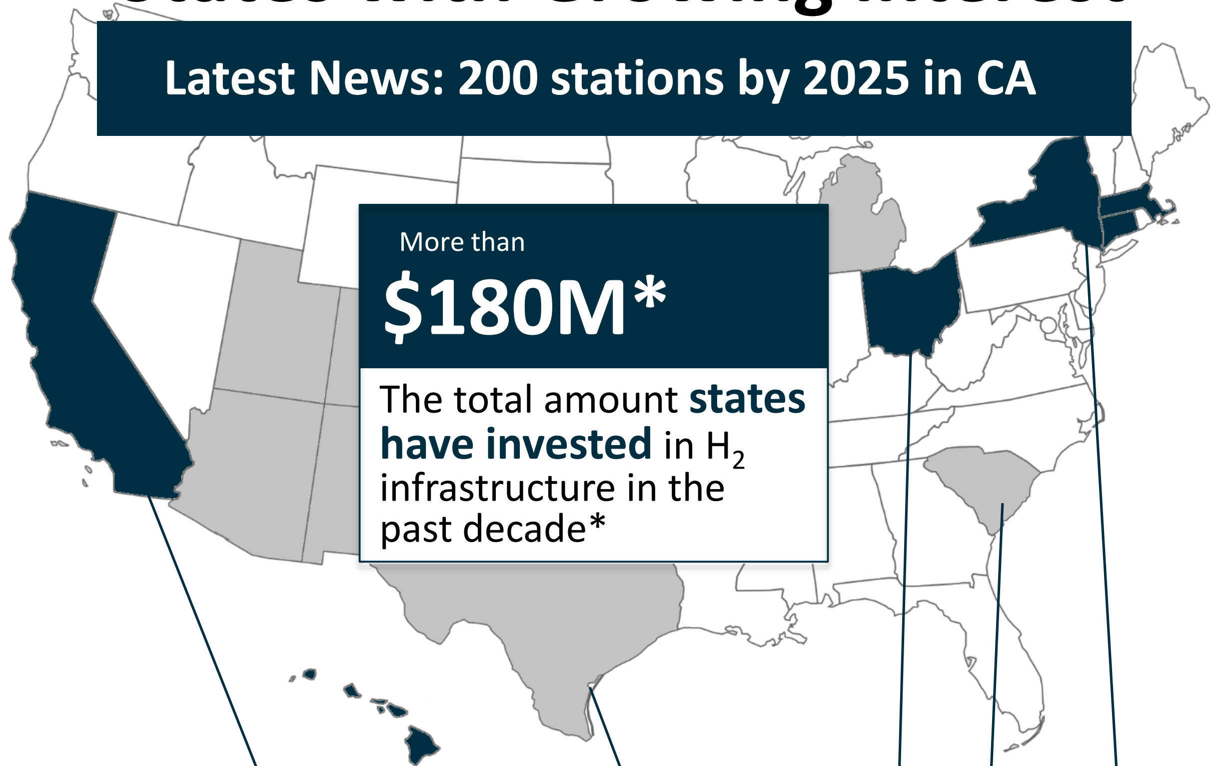
>30
Fuel Cell Buses

35
H_2 retail stations

Nearly
5,000
fuel cell cars

States with Growing Interest

Latest News: 200 stations by 2025 in CA



More than
$180M*
The total amount **states have invested** in H_2 infrastructure in the past decade*

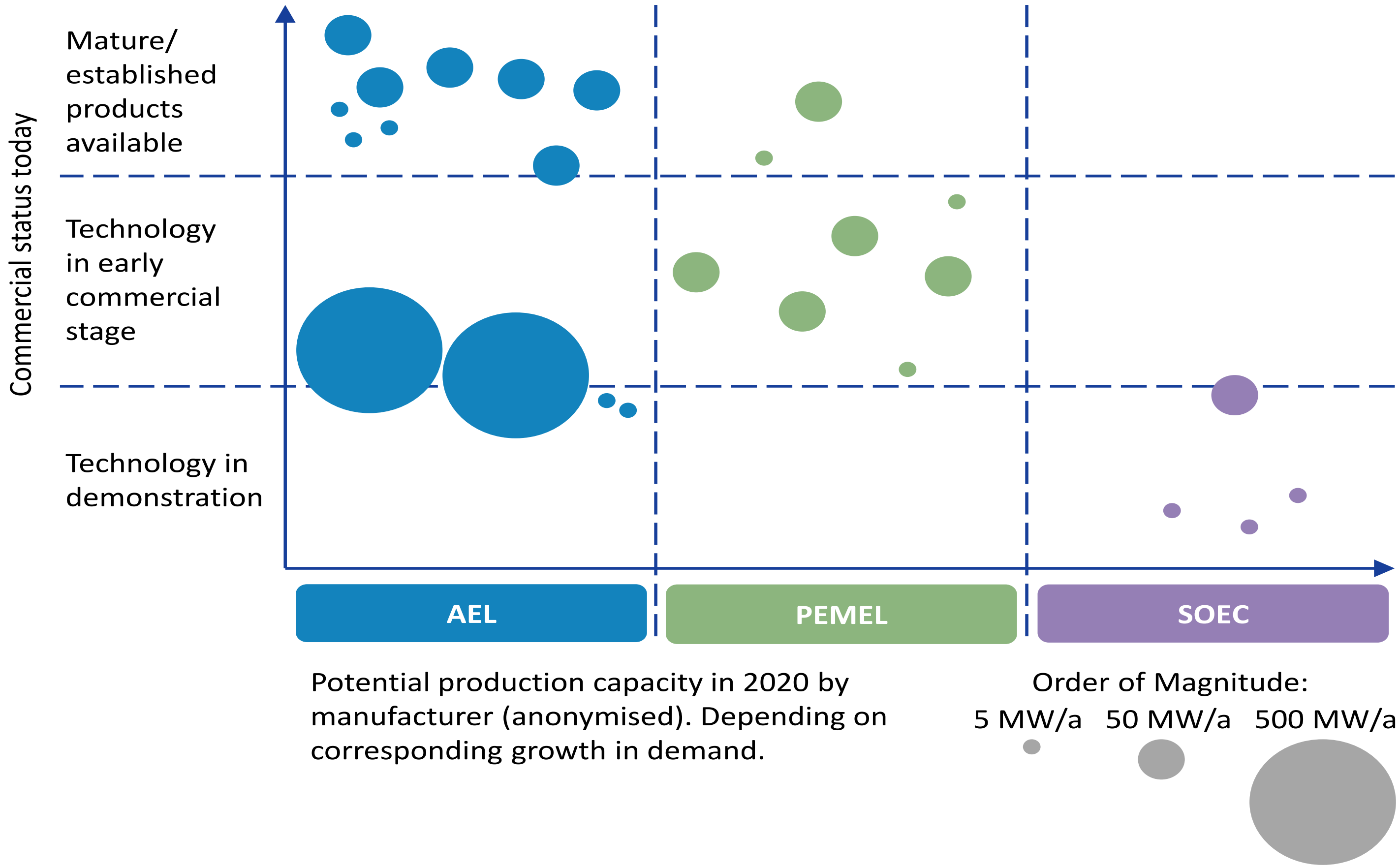
CA
- 200 stations planned
- Over 30 public stations open
- $150M invested
- $235M announced in 2018

HI, OH, SC, NY, CT, MA, CO, UT, TX, MI, and others with interest
- Over $27M invested
- 12-25 stations planned in the NE

*Excludes recent announcement from CA to invest $235M in electric vehicles

Electrolyzers

Global sales estimated at 100 MW/year*

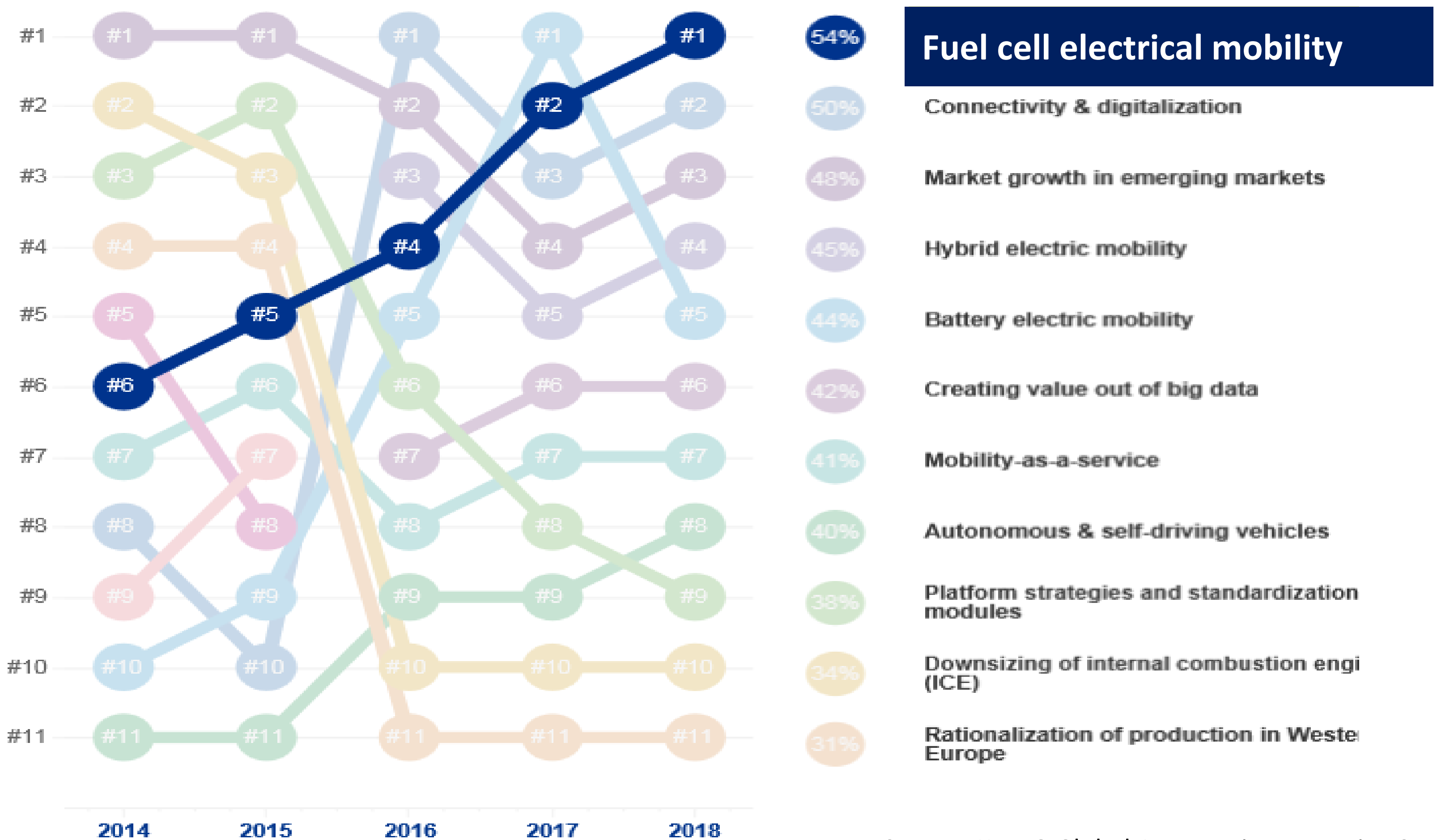


***Courtesy of NOW, E4tech and partners: A collaborative effort to assess electrolyzer market potential**

Bundesministerium für Verkehr und digitale Infrastruktur | PtJ Projektträger Jülich Forschungszentrum Jülich | NOW Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie | E4tech Strategy | Energy | Sustainability | Fraunhofer IPA | Fraunhofer ISE

Automotive Executives Survey Results

First time fuel cell electric mobility ranks #1 trend among automotive executives



Source: KPMG Global Automotive Executive Survey 2018

Program Overview

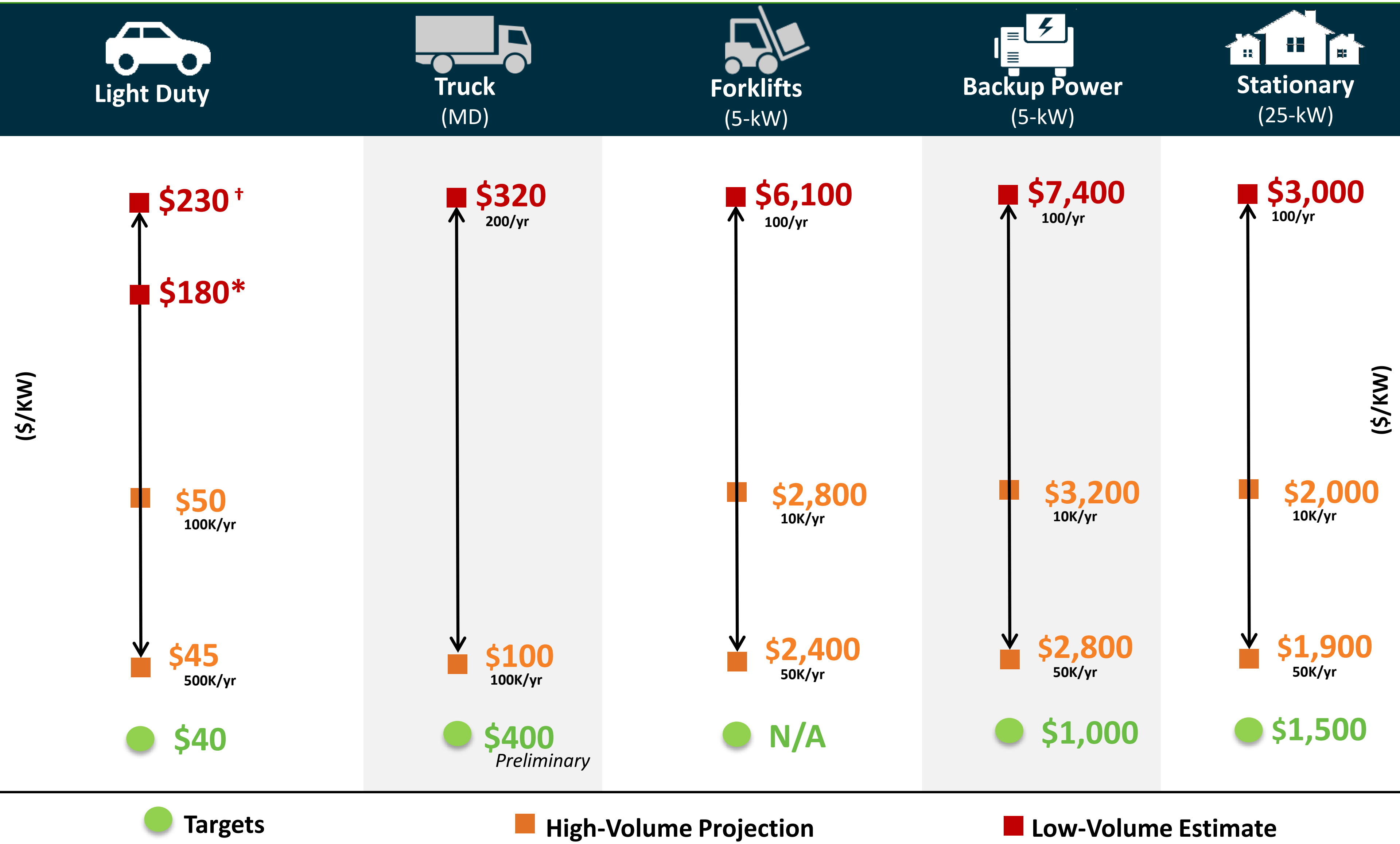
Strategy

R&D and innovation to enable affordable and reliable hydrogen and fuel cell technologies.

Increase focus on infrastructure.

Targets Guide R&D

DOE fuel cell system cost vs. targets

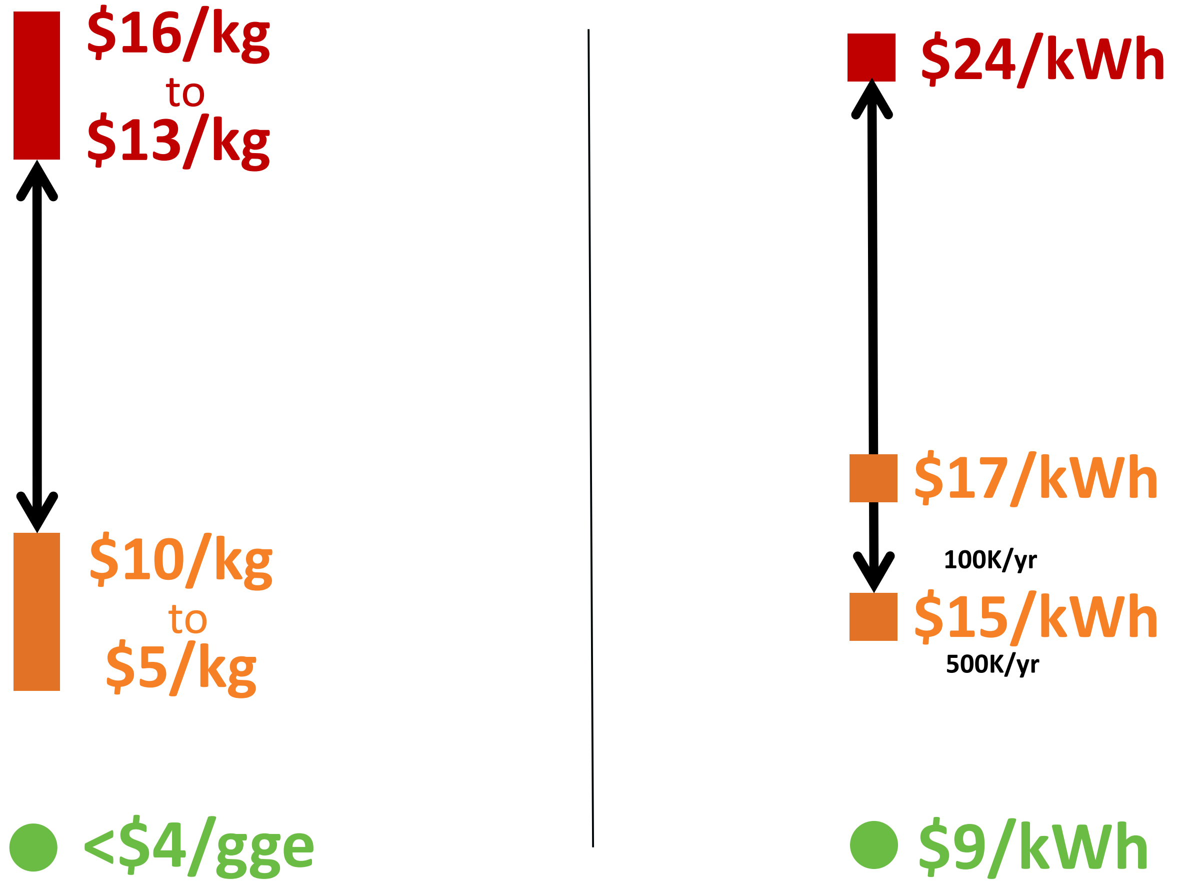


†Based on commercially available FCEVs †Based on state of the art technology

Note: Graphs not drawn to scale and are for illustration purposes only.

Hydrogen fuel cost vs. targets

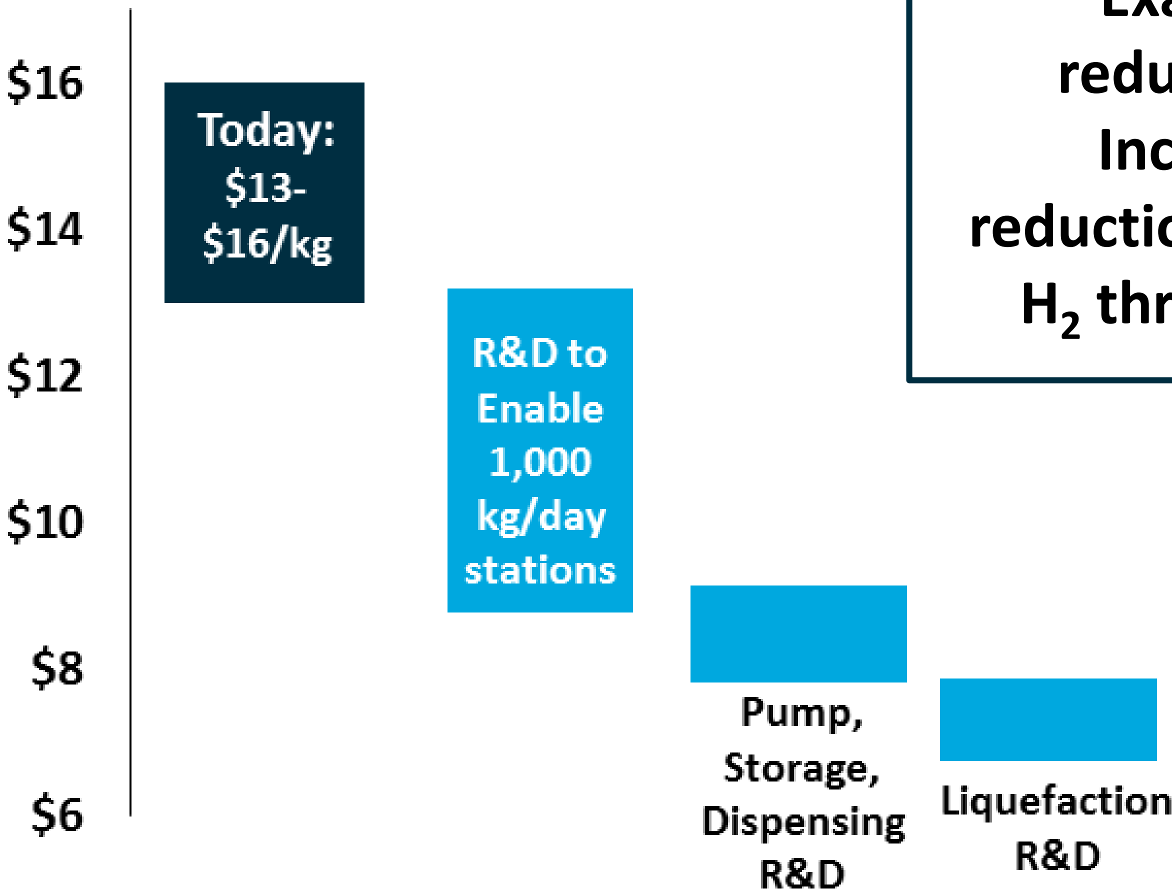
Production, Delivery & Dispensing	On-board Storage *(700-bar compressed system)*



Targets High-Volume Projection Low-Volume Estimate

Note: Graphs not drawn to scale and are for illustration purposes only.

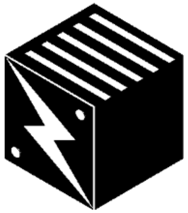
Cost reduction strategies based on analysis



Examples of cost reduction strategies Include footprint reduction to enable higher H_2 throughput stations

Target: $7/kg.
by 2025

Key Program Early R&D Focus Areas - FY18



Fuel Cells

- PGM- free catalysts
- Durable MEAs
- Electrode performance

PGM = Platinum group metals
MEA = Membrane Electrode Assembly

Hydrogen Fuel

- Production
- Delivery (including dispensing)
- Storage

Program Mission and Strategies

Early R&D Focus

Applied research, development and innovation in hydrogen and fuel cell technologies leading to:

- Energy security
- Energy resiliency
- Strong domestic economy

Early R&D Areas

Fuel Cells	Hydrogen Fuel	Infrastructure R&D
• PGM- free catalysts • Durable MEAs • Electrode performance	• Production Pathways • Advanced materials for storage	• Safety • Manufacturing • Delivery components • Others

PGM = Platinum group metals

MEA = Membrane Electrode Assembly

New in FY19 Budget Request

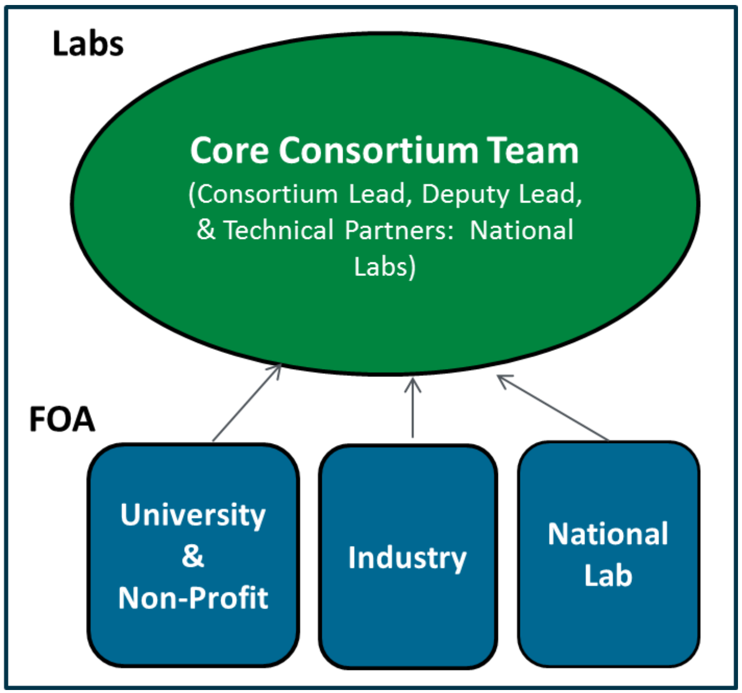
Enabling

H2@Scale
U.S. Department of Energy

Strategy: Leveraging National Labs and Partners

Consortium Approach

Multi-lab core capabilities with steady influx of new partners



Energy Materials Network
U.S. Department of Energy

Consortia Launched

Improved PEM fuel cells

FCPAD
FUEL CELL PERFORMANCE AND DURABILITY

PGM-free catalysts

ElectroCat
Electrocatalysis Consortium

Advanced H_2 materials storage

HyMARC
Hydrogen Materials Advanced Research Consortium

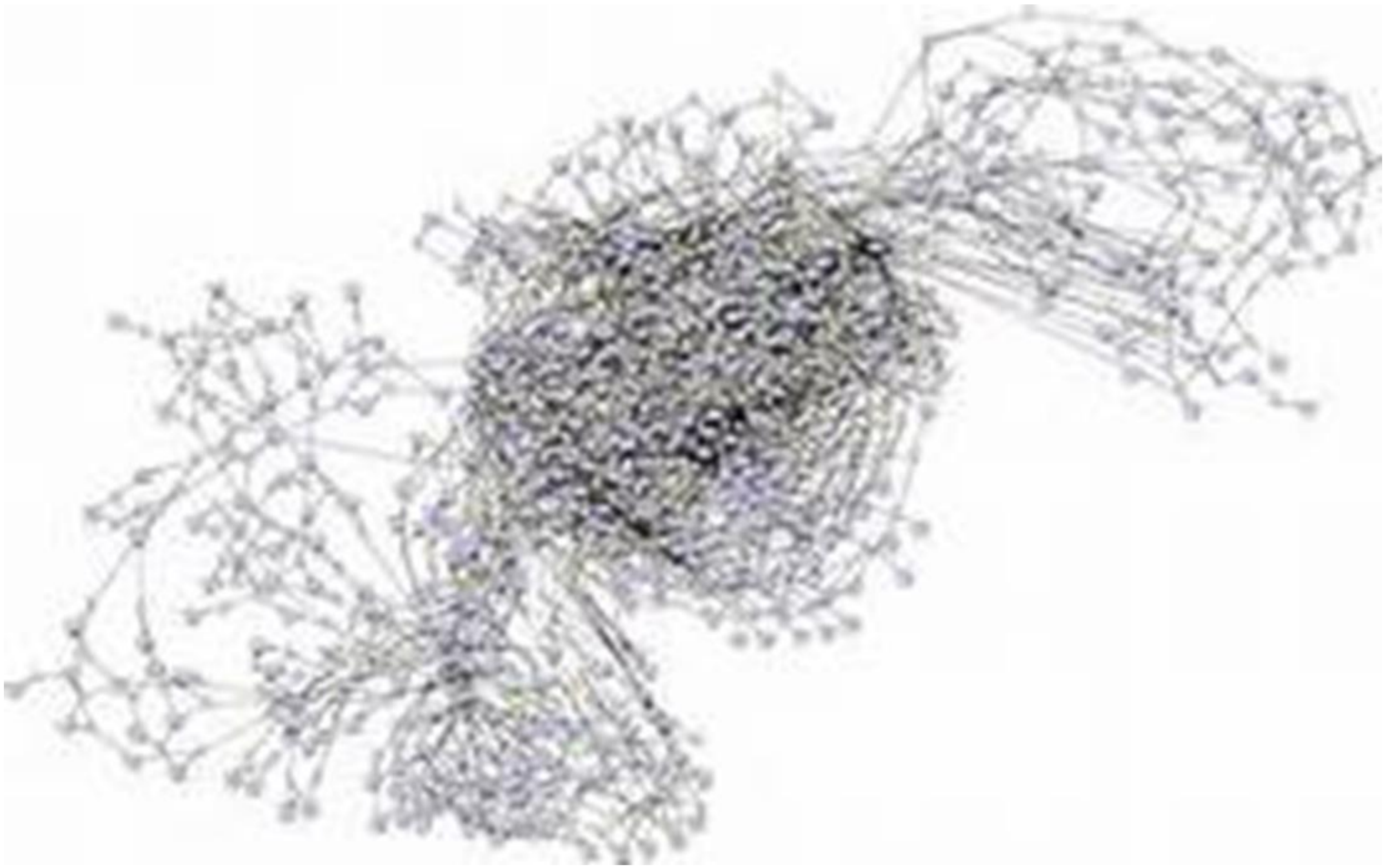
Materials for renewable H_2 production

HydroGEN
Advanced Water Splitting Materials

New Consortium: H-MAT

HMat
Hydrogen Materials Consortium

A $\longrightarrow$ **B**



A

B

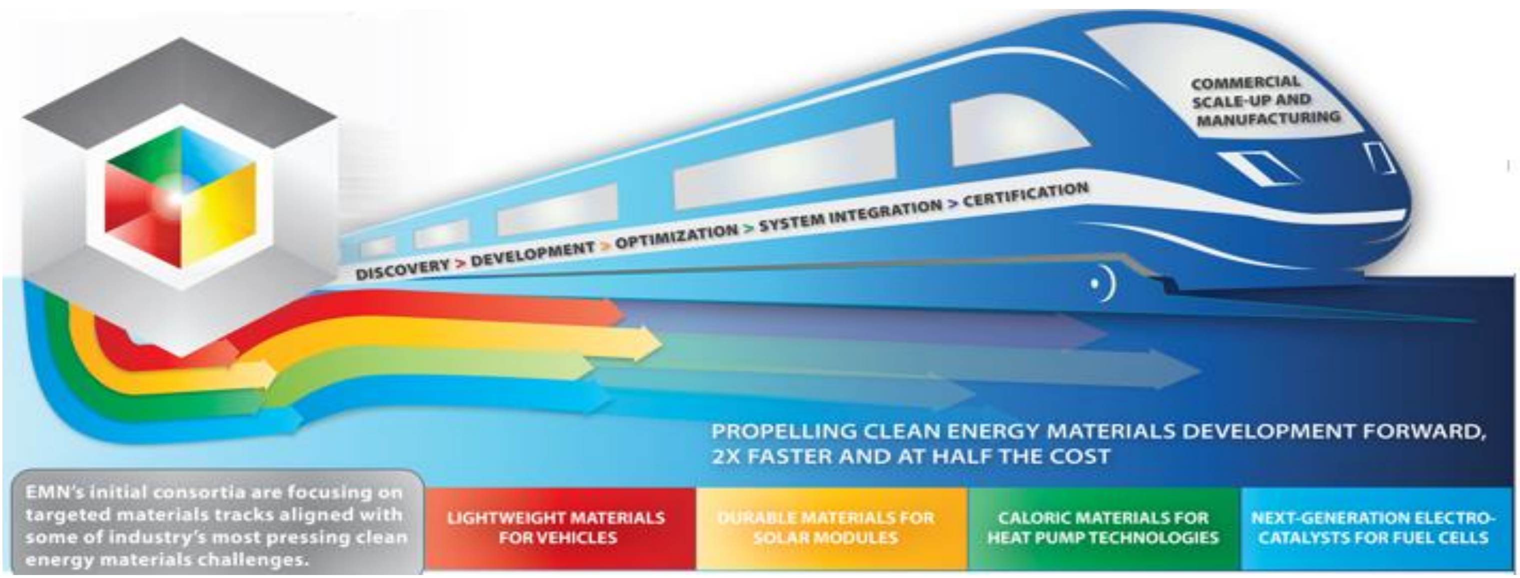
EMN: A Platform for Accelerated Materials R&D

Energy Materials Network
U.S. Department of Energy

Research Capabilities & Core Principles guiding EMN

Predictive Simulation Across Scales	Synthesis & Characterization	Rapid Screening	End Use Performance
Process Scalability	Process Control	Real-time Characterization	Reliability Validation

Data Management & Informatics



Technical Accomplishments

DOE Program Impact - Examples

Innovation

Approx. **730** H_2 and fuel cell **patents** enabled by FCTO funds

Approx. **35%** of H_2 and fuel cell patents come from National Labs

Market Impact

More than **30** **Technologies** commercialized by private industry

and over **65** **with potential** to be commercial in the next 3-5 years

can be traced back to FCTO R&D

Examples of Progress enabled by DOE FCTO in the last decade

Fuel Cell R&D

Reduced cost 60%

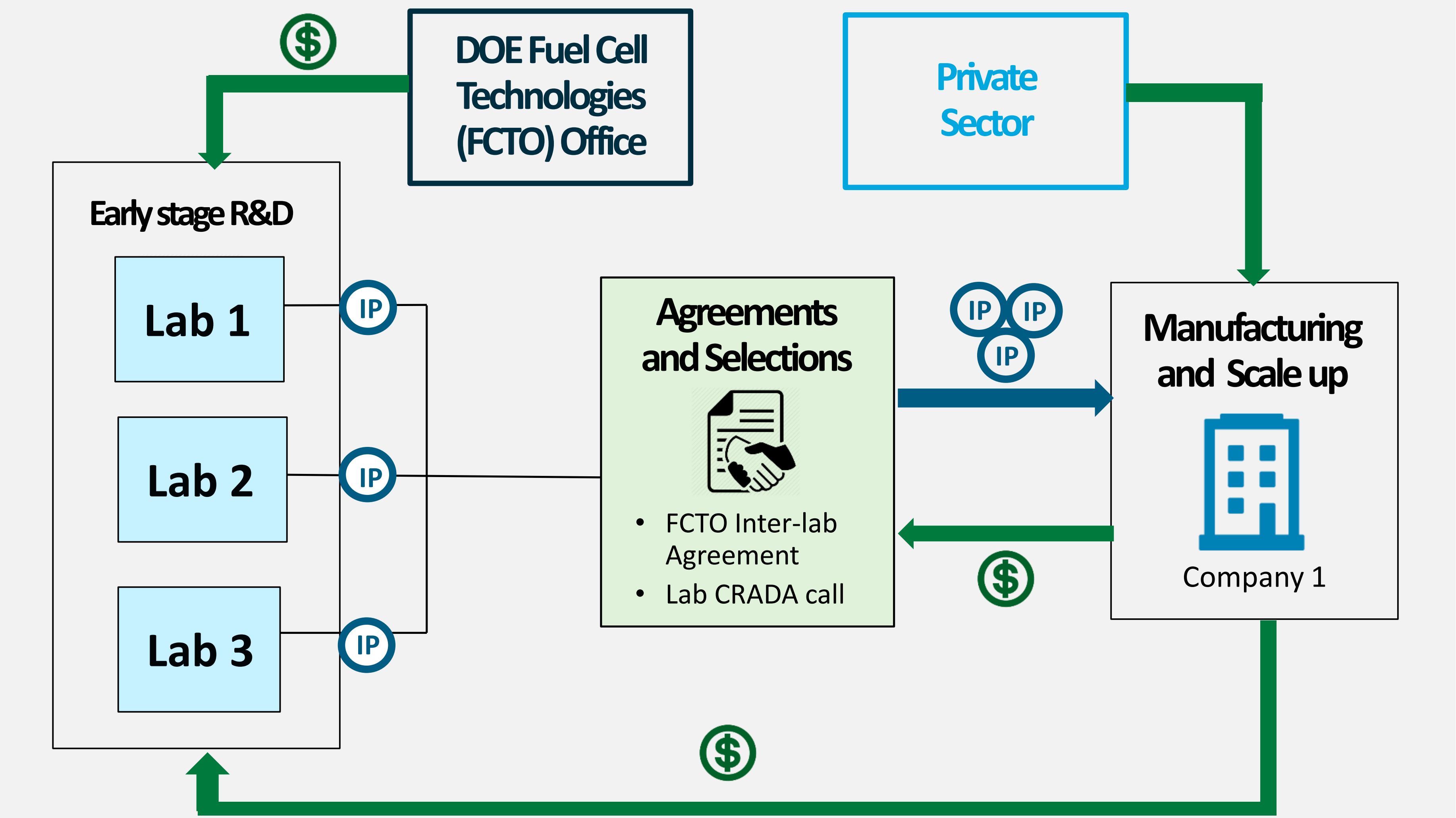
Quadrupled durability

H2 Production R&D

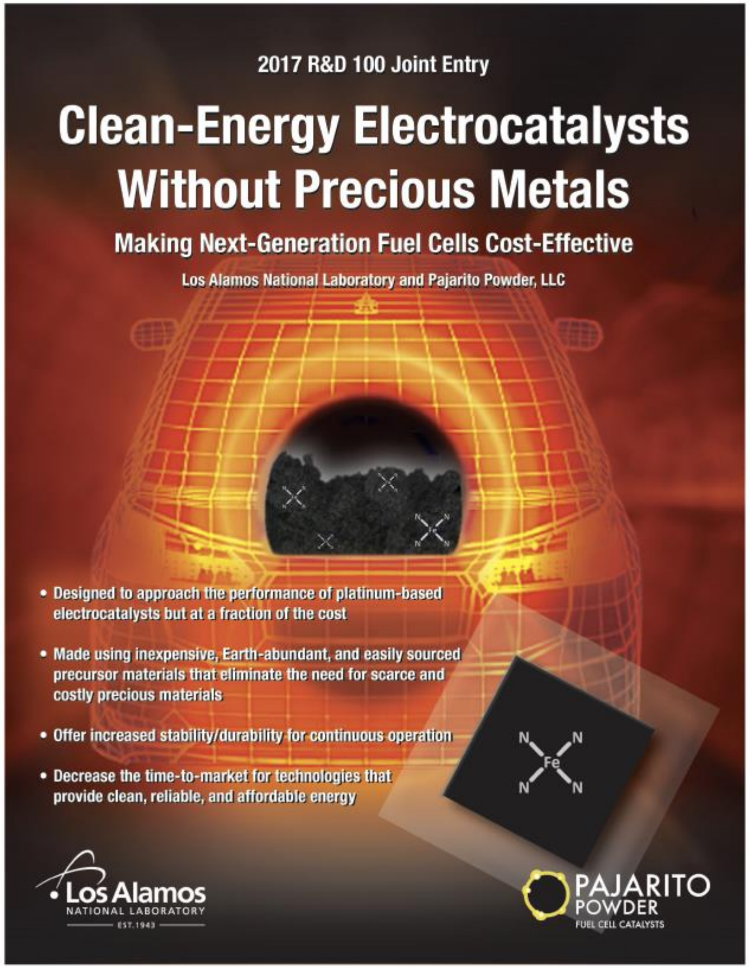
Cut electrolyzer costs 80%

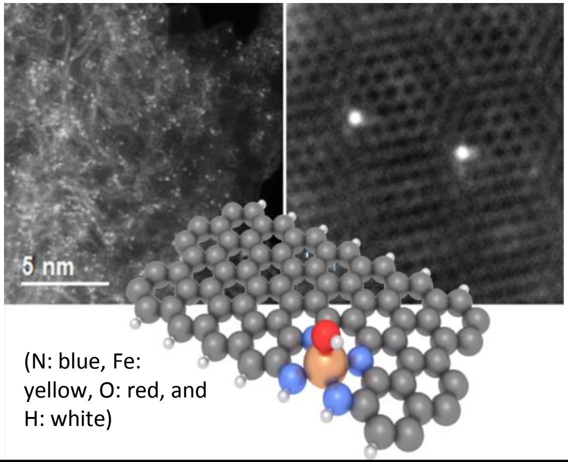
Leverage Private Sector to Accelerate Lab IP to Market

L'Innovator= "Lab Innovator" FCTO Pilot



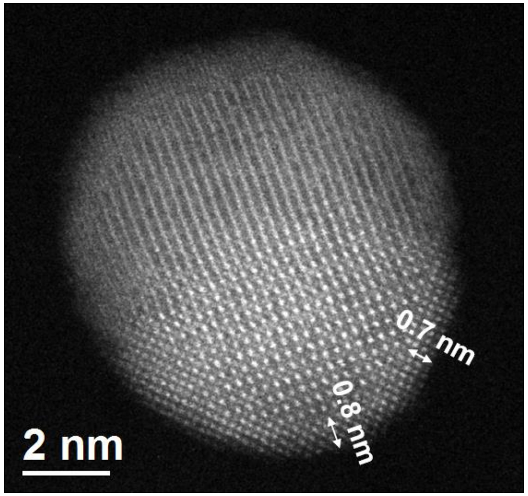
Examples: R&D 100 Awards and more





Science Paper (LANL, ORNL)

Active site(s) in PGM-free Fe-N-C



Ordered core (PtCo) remains intact even after 30K cycles (AST)

(LANL, Brown University, ORNL)

Journal of the Electrochemical Society: Focus Issue on PEM Fuel Cell Durability

Guest Editors: Jean St-Pierre, Debbie Myers, Rod Borup, over 40 papers, many FC-PAD authors

Focus Areas

Emphasize high-throughput + modeling for catalyst R&D

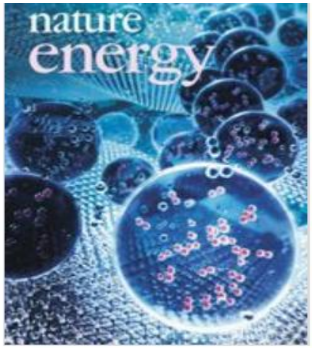
Increase focus on innovative membranes

HydroGEN: High-Impact Computational Research in Catalysis

nature energy

ARTICLES

PUBLISHED: 31 JULY 2017 | VOLUME: 2 | ARTICLE NUMBER: 17127



Self-optimizing, highly surface-active layered metal dichalcogenide catalysts for hydrogen evolution

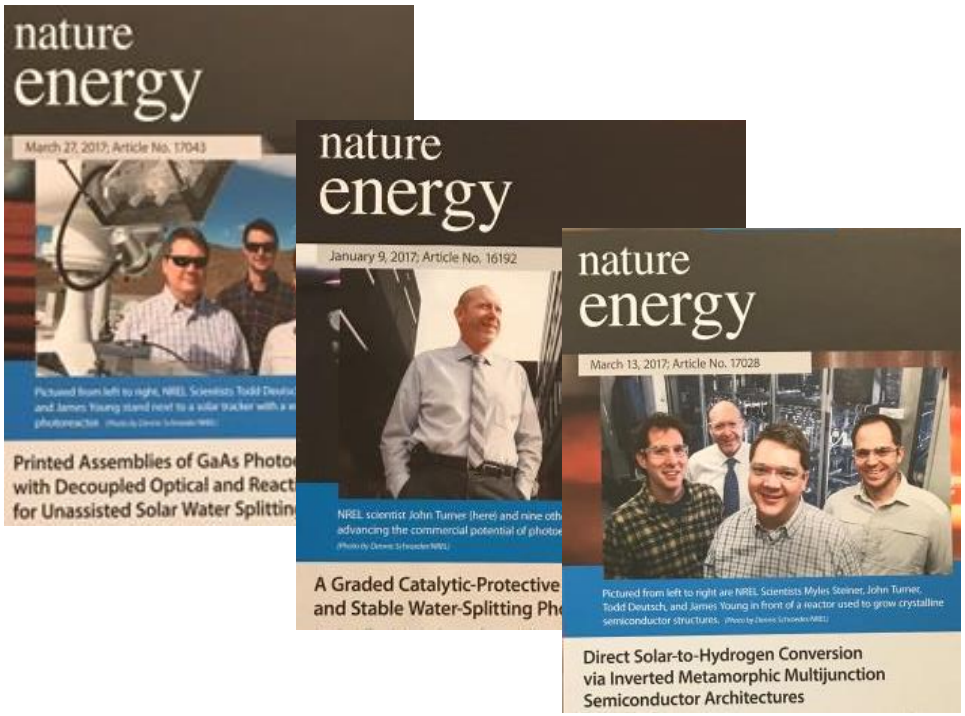
Yuanyue Liu[1†‡], Jingjie Wu[1‡], Ken P. Hackenberg[1‡], Jing Zhang[1], Y. Morris Wang[2], Yingchao Yang[1], Kunttal Keyshar[1], Jing Gu[3], Tadashi Ogitsu[2], Robert Vajtai[1], Jun Lou[1], Pulickel M. Ajayan[1], Brandon C. Wood[2*] and Boris I. Yakobson[1*]

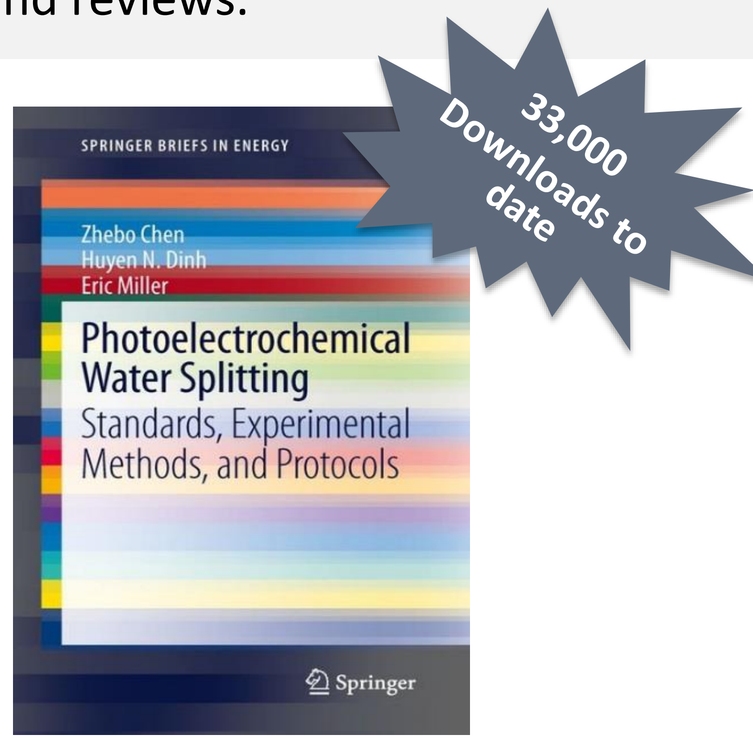
Steering Committee Member (Tadashi) owns a FCEV and chooses a unique license plate

HydroGEN:
High-Impact Research in Photoelectrochemistry

Achieving Record Performance
NREL set new record with III-V semiconductor PEC tandem cell: 3 *Nature Energy* publications.

Addressing Benchmarking Needs
Technology advancement by publishing standards, protocols and reviews.





PEC World Record Benchmarked at >16% STH

Technology Standards to Facilitate Research Progress

Focus Areas

Emphasis on water-splitting

Raising the Tide: R&D Test Protocols for Water-Splitting

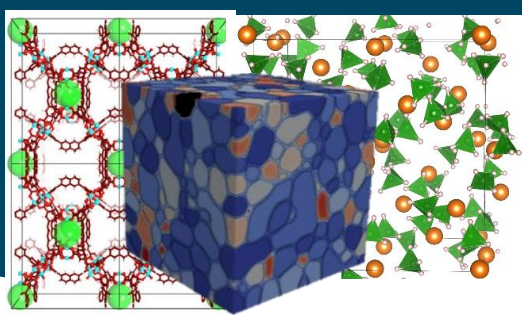
HyMARC Advanced Hydrogen Storage Materials

Provides **foundational understanding** of thermodynamics and kinetics to advance solid-state hydrogen storage materials

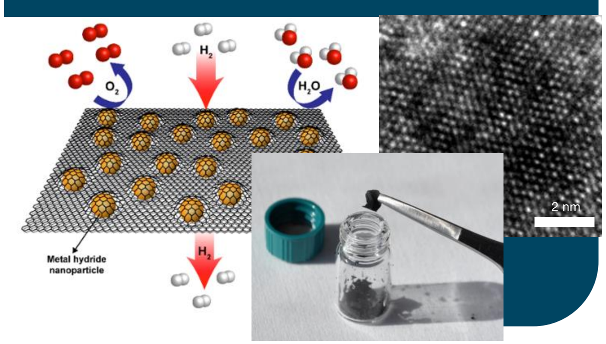
Delivers **community tools and capabilities:**

- High-throughput materials screening
- Surface, bulk, soft X-ray, synchrotron
- Probing nanoscale phenomena

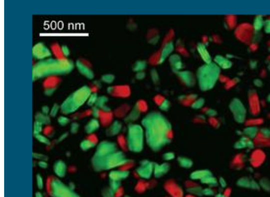
Theory, simulation, & data

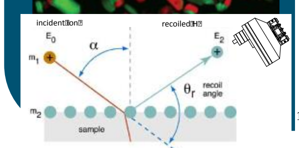


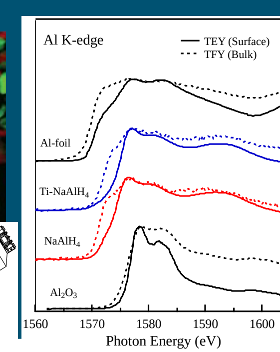
Controlled synthesis



In situ characterization





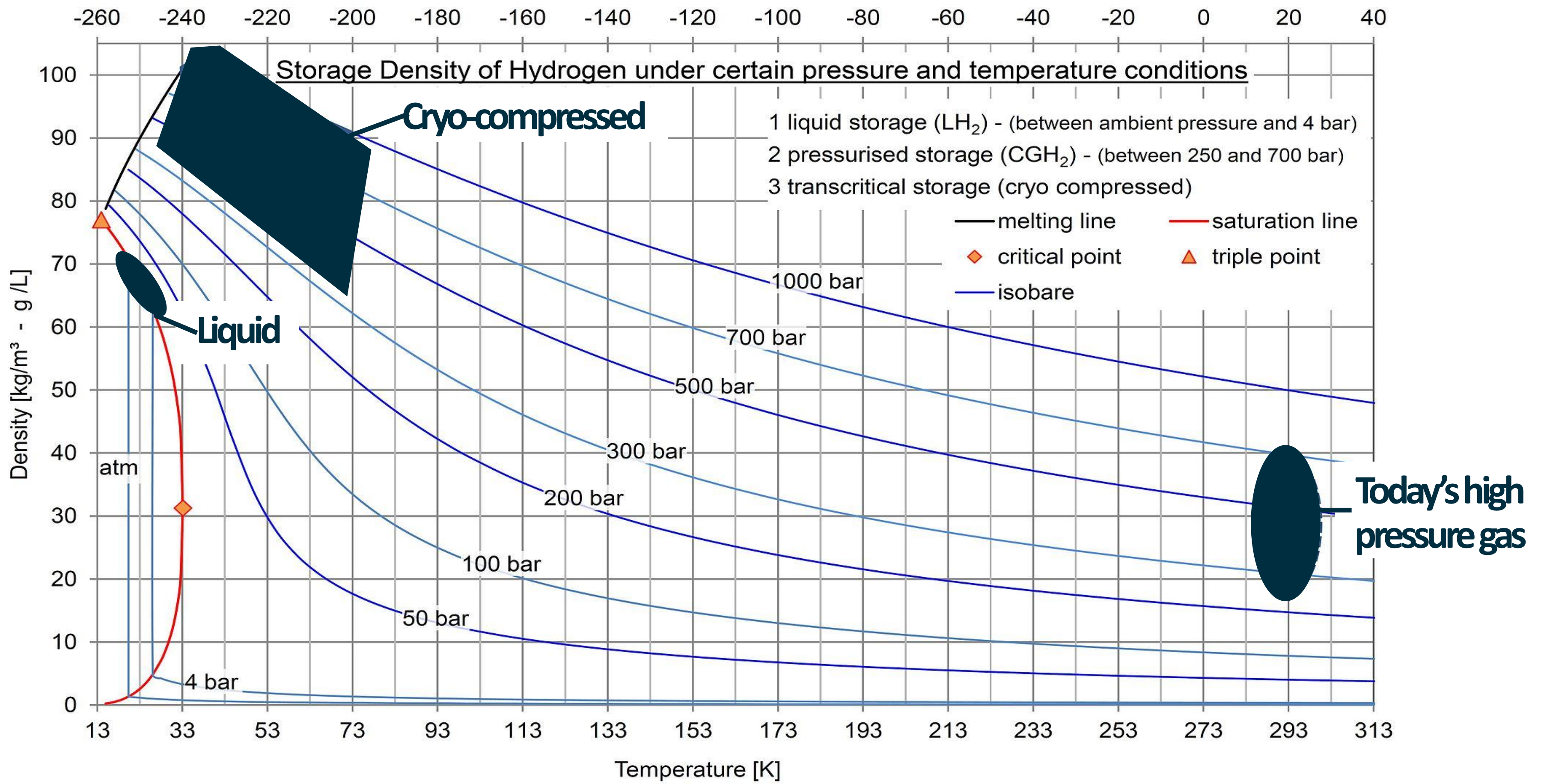


Focus Areas

Adding H_2 Carriers R&D to HyMARC

Example of Innovation- potential for heavy duty?

Cryo-compression can offer densities higher than liquid hydrogen



ANL analysis (preliminary) shows potential for:

90-200% storage capacity increase	25% less cost (at 5,000 units/yr)	46% less carbon fiber composite

Potential Opportunities for Larger Vehicles/Long Range

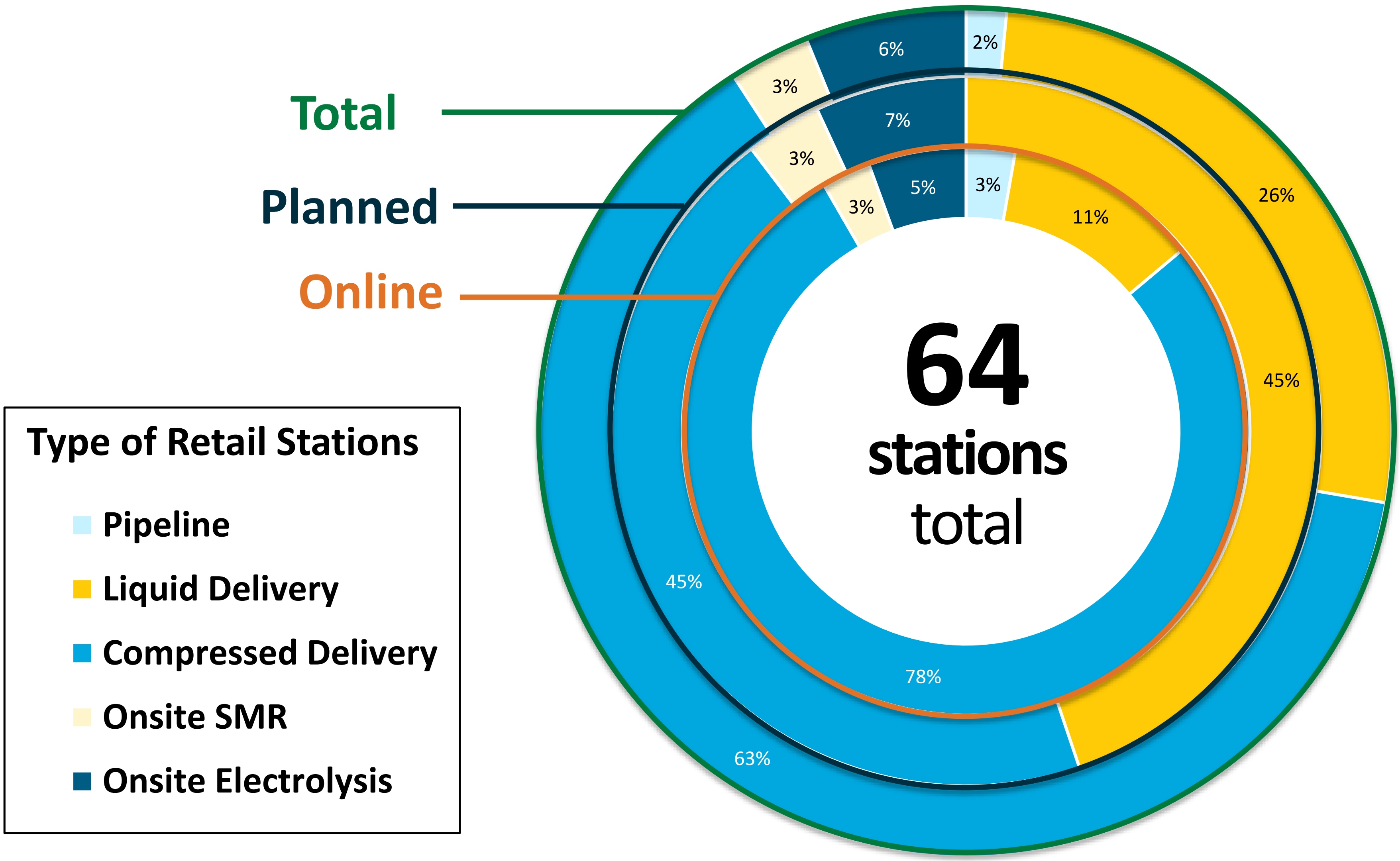
FCEVs : Lower cost for large size classes and longer driving range

Year 2040: FCEV minus BEV-X Total Cost of Ownership
Green shows where FCEVs are more cost effective

	50 mi.	100 mi.	150 mi.	200 mi.	250 mi.	300 mi.	350 mi.
Two-seaters	$0.05	$0.01	-$0.03	-$0.07	-$0.11	-$0.15	-$0.19
Minicompacts	$0.05	$0.02	-$0.01	-$0.04	-$0.07	-$0.10	-$0.13
Subcompacts	$0.05	$0.02	-$0.01	-$0.04	-$0.07	-$0.11	-$0.14
Compacts	$0.04	$0.01	-$0.02	-$0.05	-$0.09	-$0.12	-$0.15
Midsize Cars	$0.05	$0.01	-$0.03	-$0.06	-$0.10	-$0.13	-$0.17
Large Cars	$0.04	$0.01	-$0.02	-$0.06	-$0.09	-$0.12	-$0.16
Small Station Wagons	$0.05	$0.01	-$0.03	-$0.07	-$0.11	-$0.15	-$0.19
Pass Van	$0.03	-$0.01	-$0.06	-$0.11	-$0.15	-$0.20	-$0.24
SUV	$0.03	-$0.02	-$0.08	-$0.14	-$0.19	-$0.25	-$0.30
Small Pickup	$0.06	$0.02	-$0.02	-$0.07	-$0.11	-$0.15	-$0.19

Preliminary DOE Market Segmentation Study

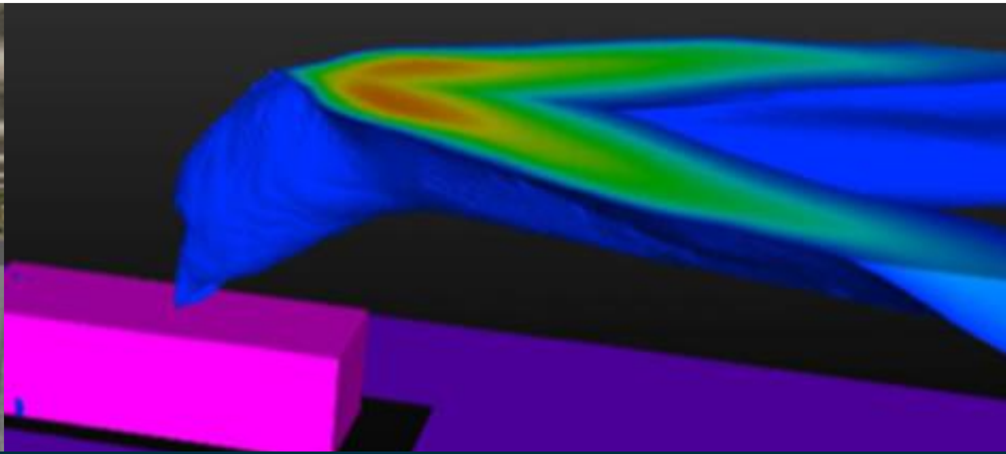
More liquid stations planned



Based on data from NREL

Safety R&D Accomplishments enabling Infrastructure

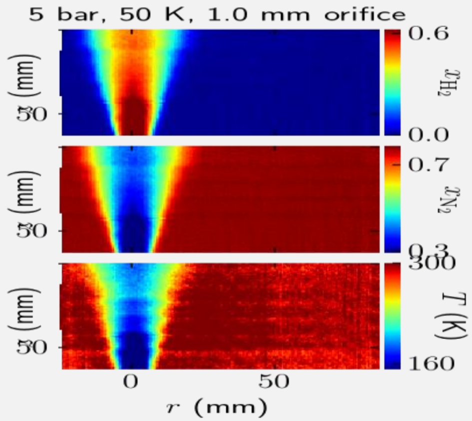
Tunnel Safety R&D and Modeling

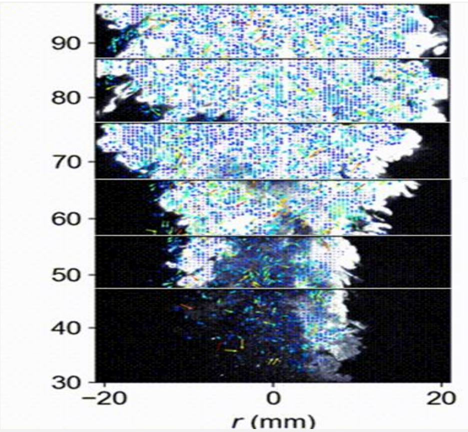


Relief vent fire doesn’t have a significant impact on tunnel structure elements

Validation of release models

First ever nearfield measurement and validation of temp., concentration and velocity of cryogenic plumes at 50K





Infrastructure R&D related progress- Examples

2017 R&D 100 WINNER

LANL, LLNL, and H2Frontier R&D 100 award for H2 safety sensor (available for commercialization)

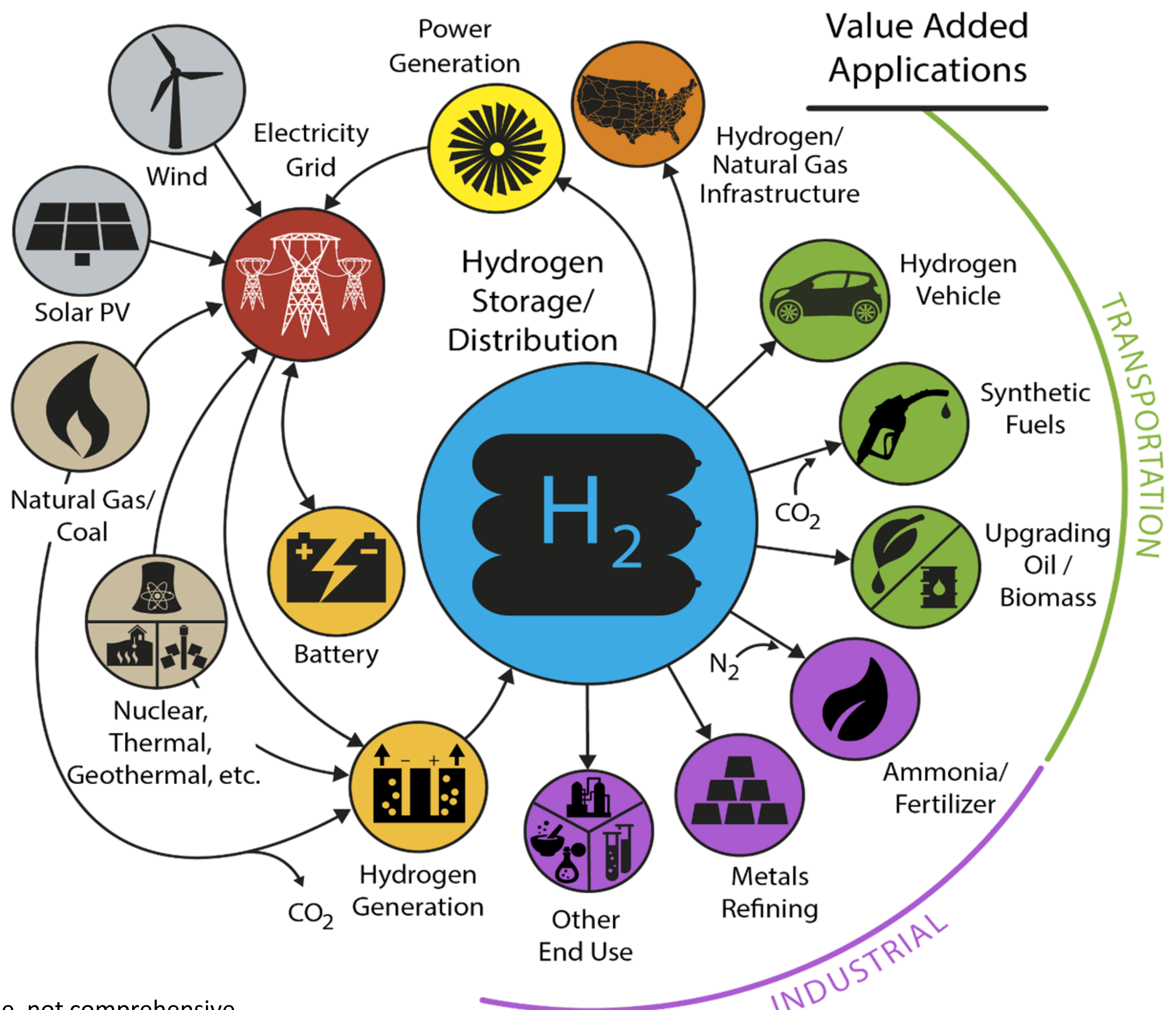
LANL contamination detector (HCD) to alert - in real time - fuel station operator if conditions for potential poor hydrogen fuel quality exist.

H2@Scale

Vision

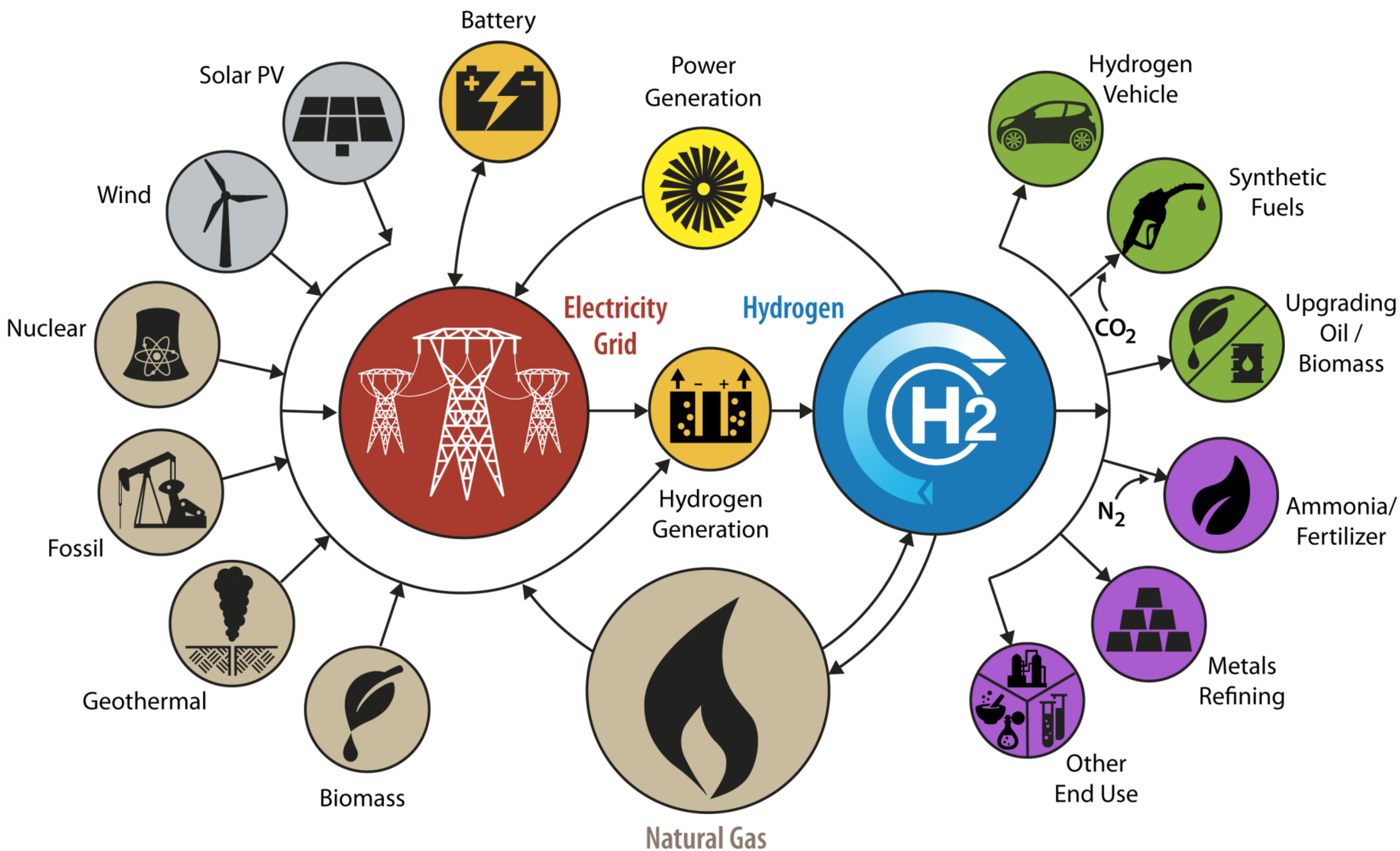
H2@Scale: Enabling affordable, reliable, clean and secure energy across sectors

H_2@Scale System



*Illustrative example, not comprehensive
Source: NREL

H_2@Scale: Linking Natural Gas, Electric and H_2 Grids

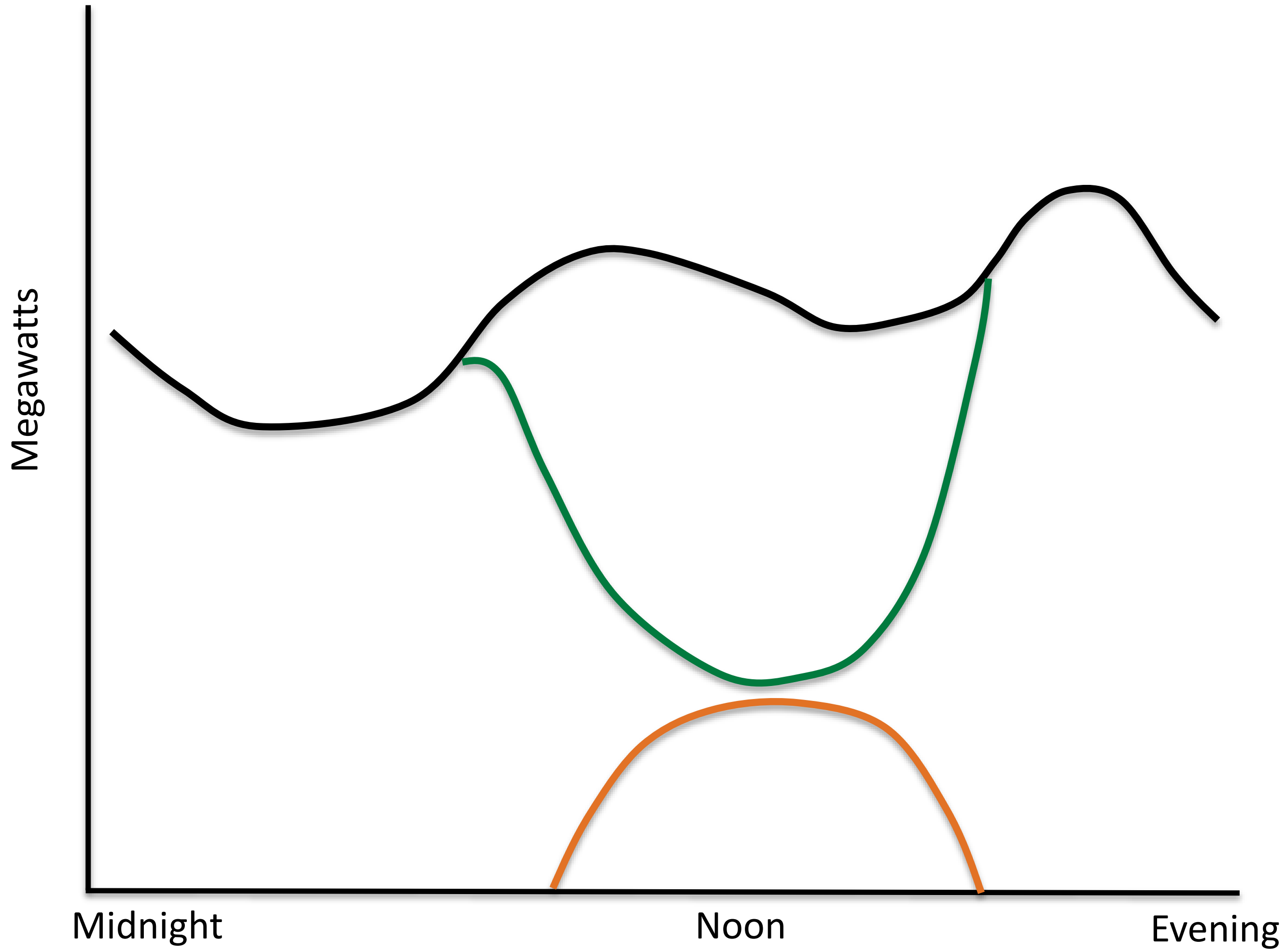


Versatility

Volume

Value Proposition

The Duck Curve 101 - Example

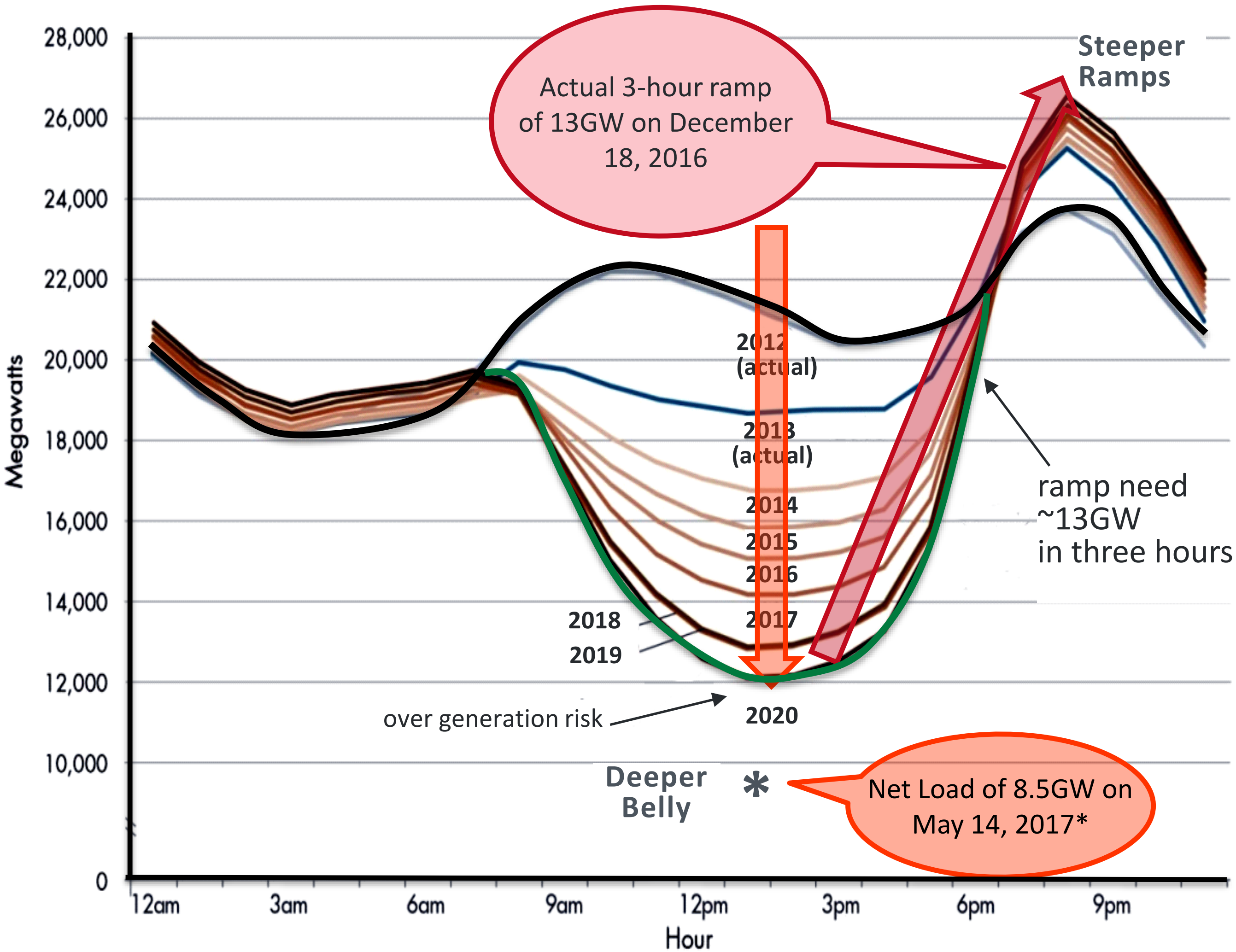


Total Load (demand)

Load (net) on commercial utility grid (duck belly forms)

Solar Production

The Duck's belly is getting bigger



Source U.S. DOE Solar Energy Technologies Office

*Real example from California

Two Concerns:

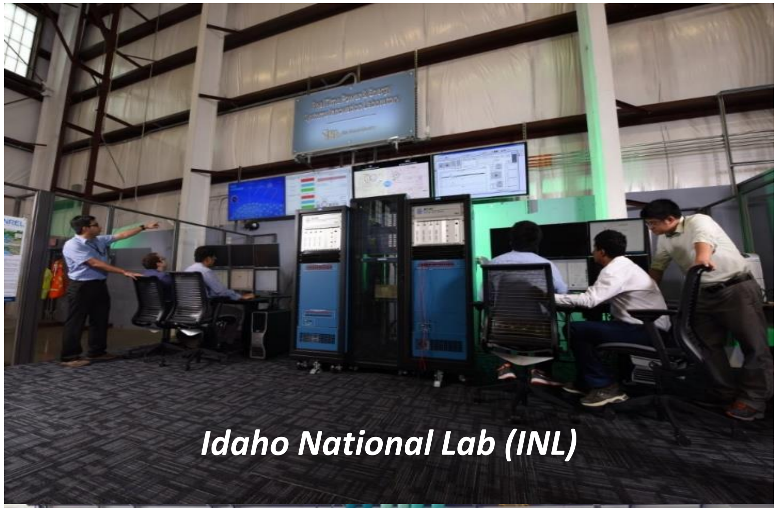
- **Low Net Load:** flexibility to reduce baseload generation resources is limited
- **High Ramp Rates in Evening:** flexibility of other generation to ramp up is limited

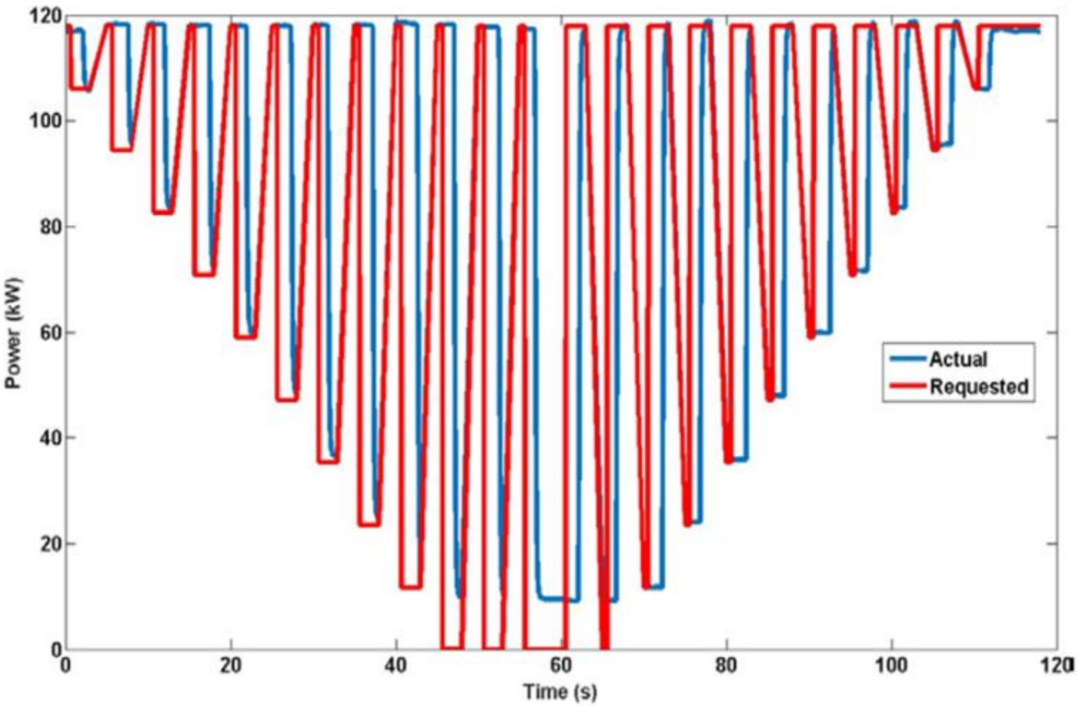
Can be addressed by

H2@Scale
U.S. Department of Energy

Lab testing shows value of electrolyzers for ancillary services

First Ever Validation of Frequency Regulation with Electrolyzers





Lab testing shows dynamic response within seconds and potential for grid services

Scale: Simple Example

How much hydrogen for 1 car?

$$\frac{\textbf{12,000 miles}\text{ per year}}{\textbf{60 miles}\text{ per kilogram}} = \textbf{200 kg}\text{ per year} \textbf{ or } \textbf{0.2 tonnes}\text{ per year}$$

How much hydrogen for many cars?

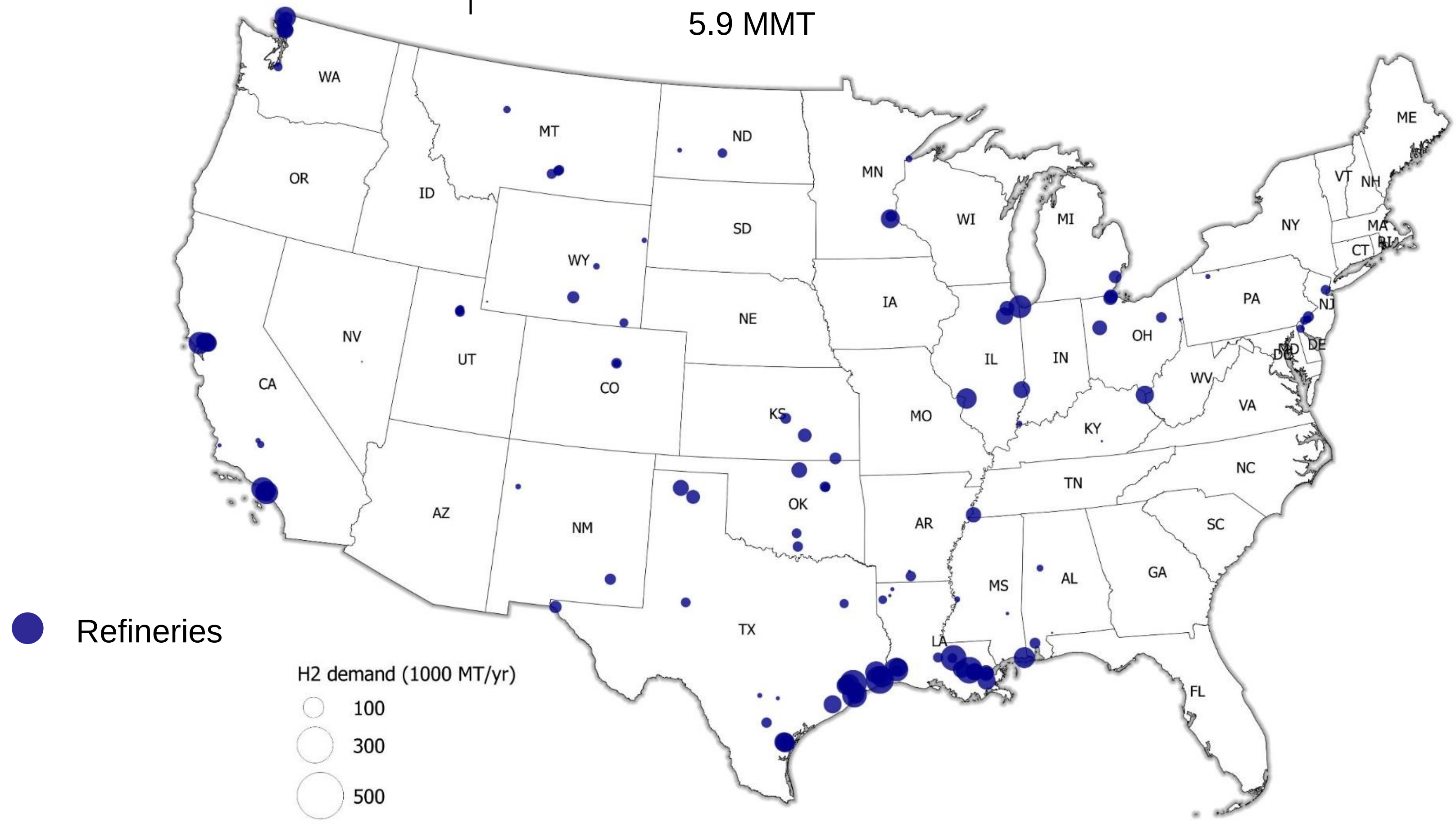
100 M cars	**20M tons** H_2 per year
= 10M cars	**20 B kg** H_2 per year

Refineries: Where is the H_2 demand today?

2017

H_2 Demand

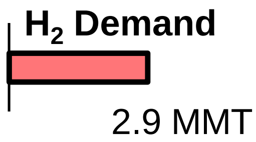
5.9 MMT

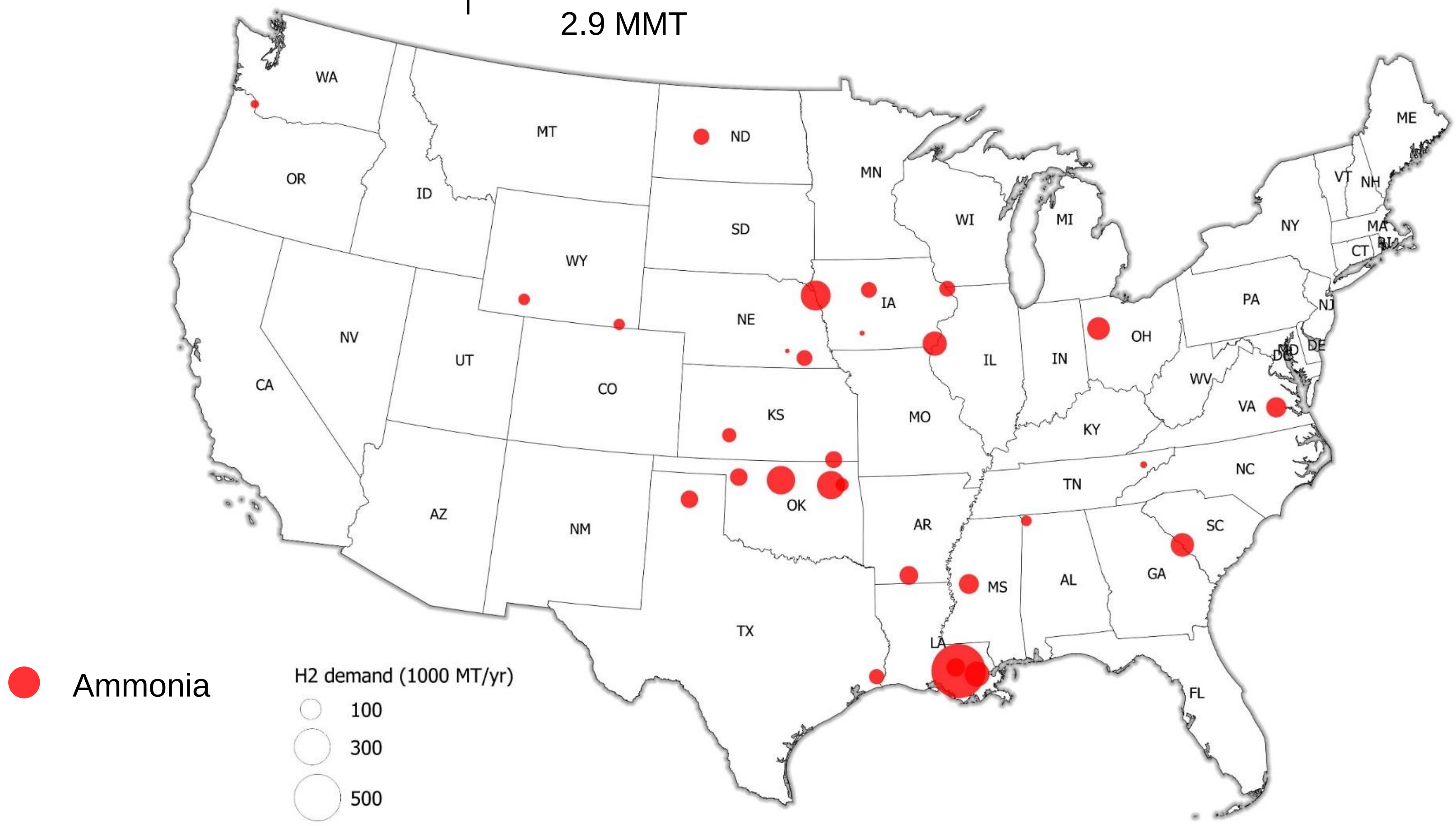


Source: Elgowainy, et al, ANL

Ammonia: Where is the H_2 demand today?

2017

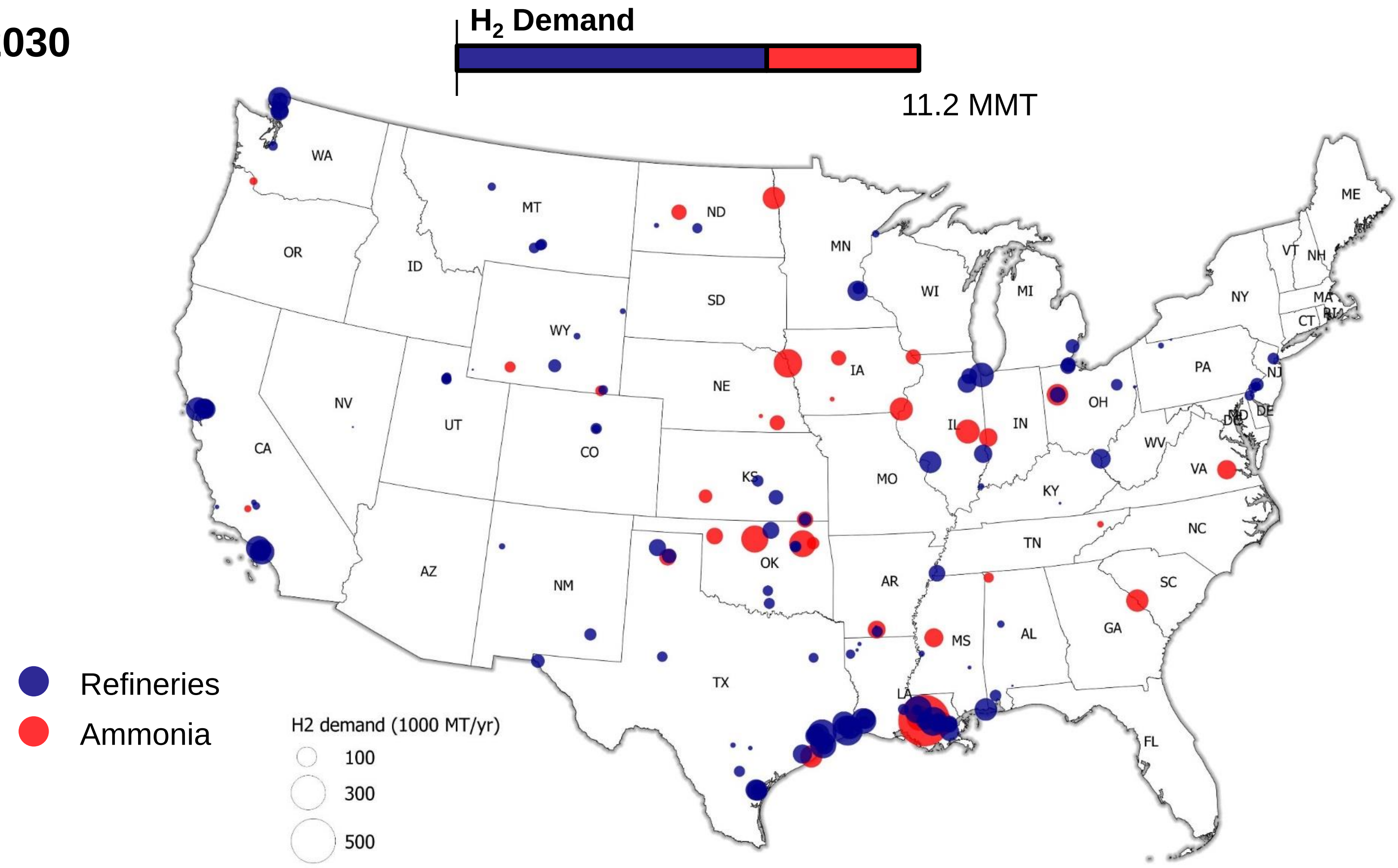




Source: Elgowainy, et al, ANL

Ammonia & Refineries and Potential H_2 Demand

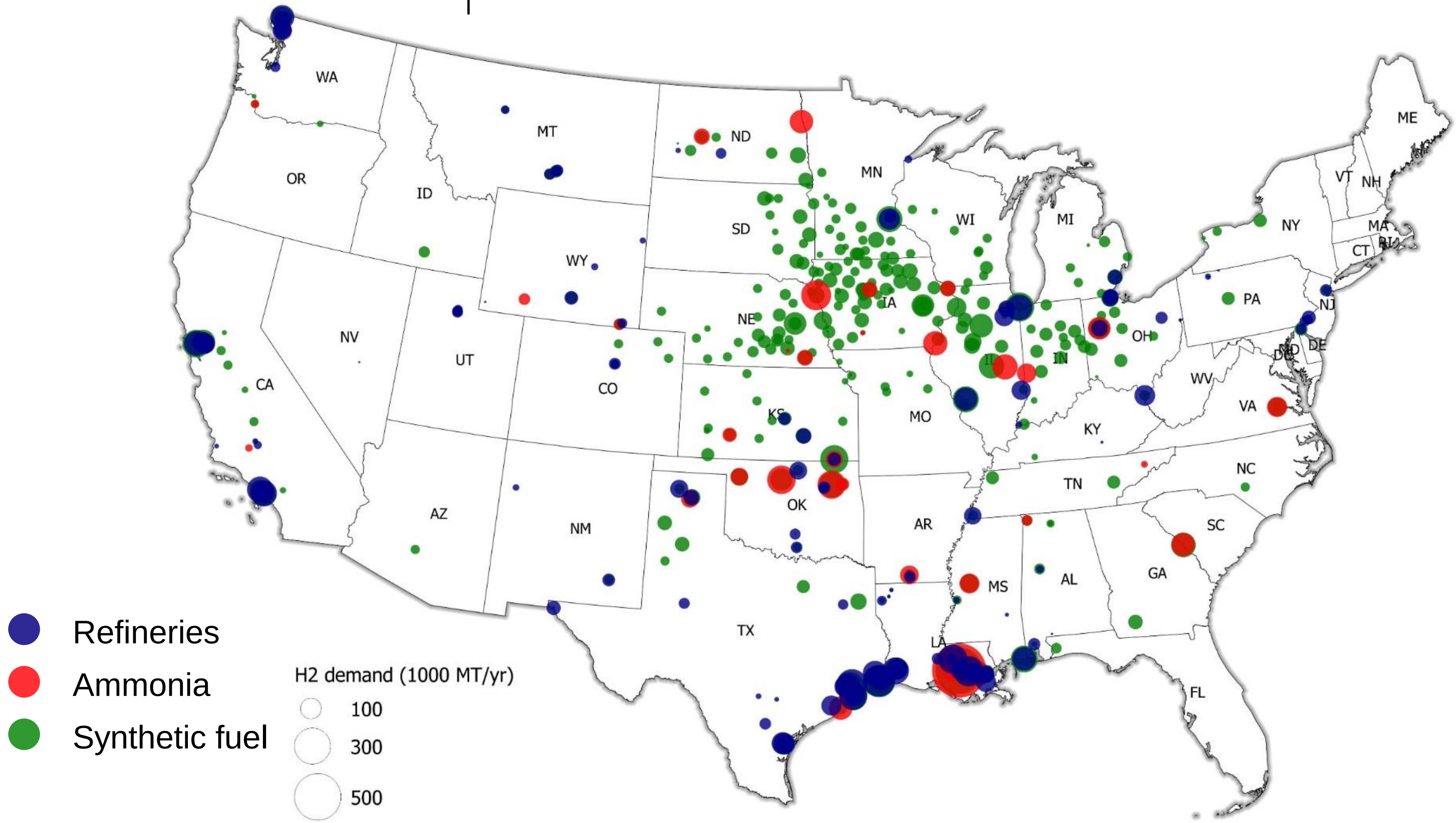
2030



Source: Elgowainy, et al, ANL

Plus demand from synthetic fuel production…

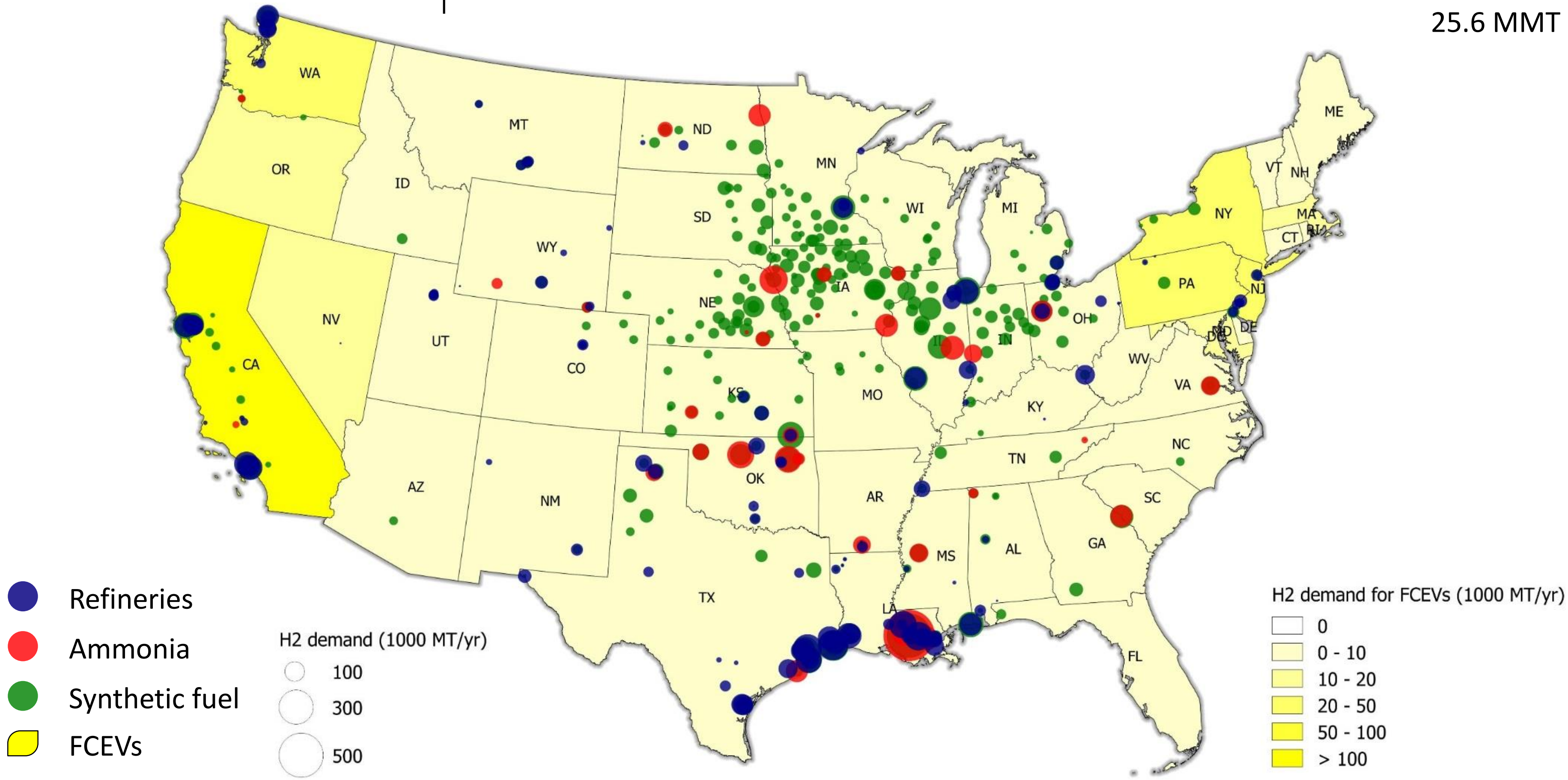
2030



Source: Elgowainy, et al, ANL

Hydrogen Demand Potential

2030



Nearly 30 million metric tons of potential hydrogen demand in the U.S.

Source: Elgowainy, et al, ANL

H_2@Scale: Value to industrial processes?

Electrical power plant cooling

- **Over 16,000 H_2 cooled generators** worldwide
- **Less delivery logistics, inventory management, 1-2 yr payback and improved efficiency**
- **Potential $2B addressable market**

Source: Proton

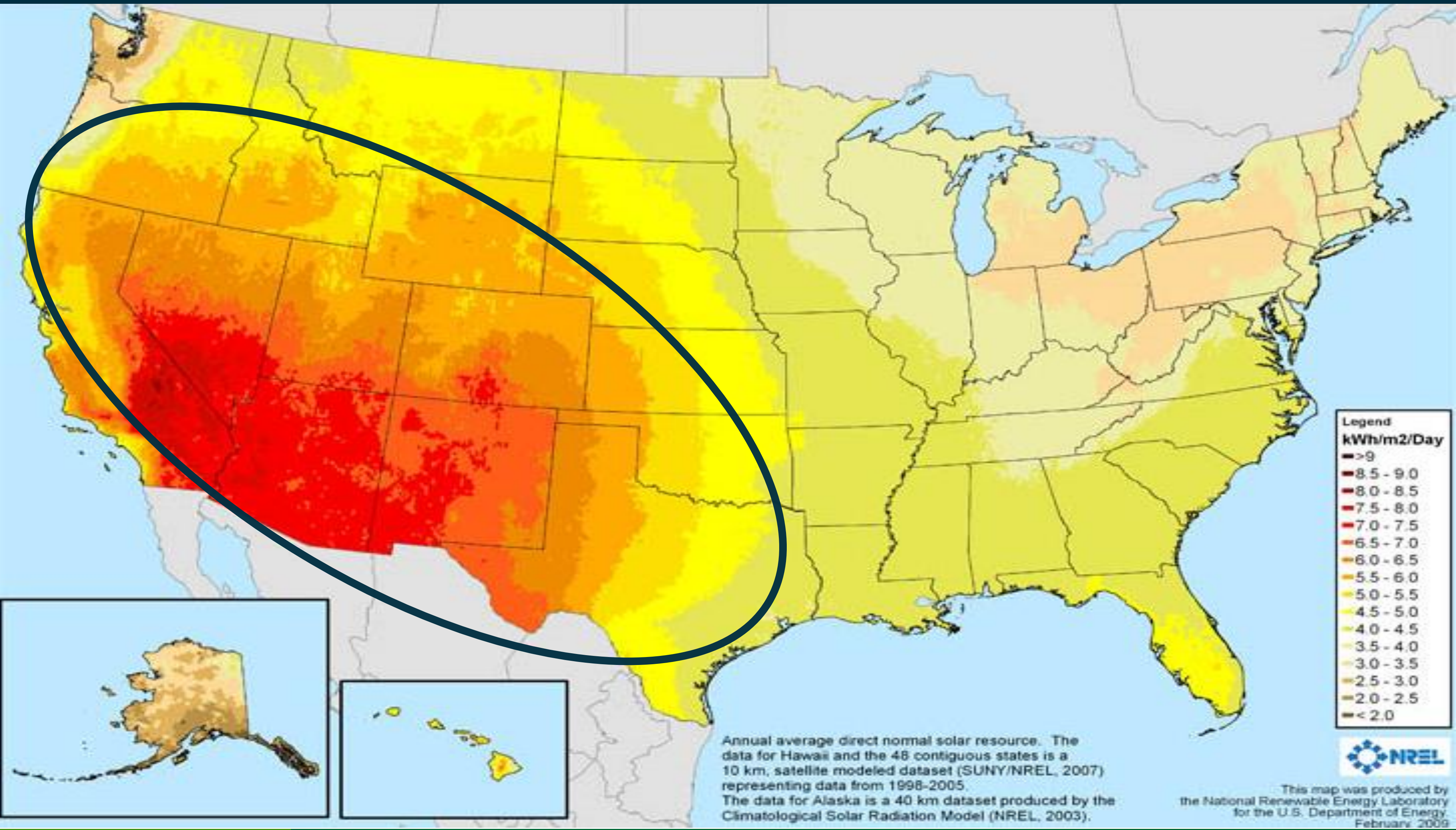
Iron Refining, Steel manufacturing

- **More energy efficient when hydrogen used** as reductant at high temperatures
- **Potential annual savings of over $100,000** for a 100,000 ton/year plant

Source: EERE Advanced Manufacturing Office, Berry Metal

H_2@Scale: Enabling renewable energy transport?

Where we find abundant solar and wind energy

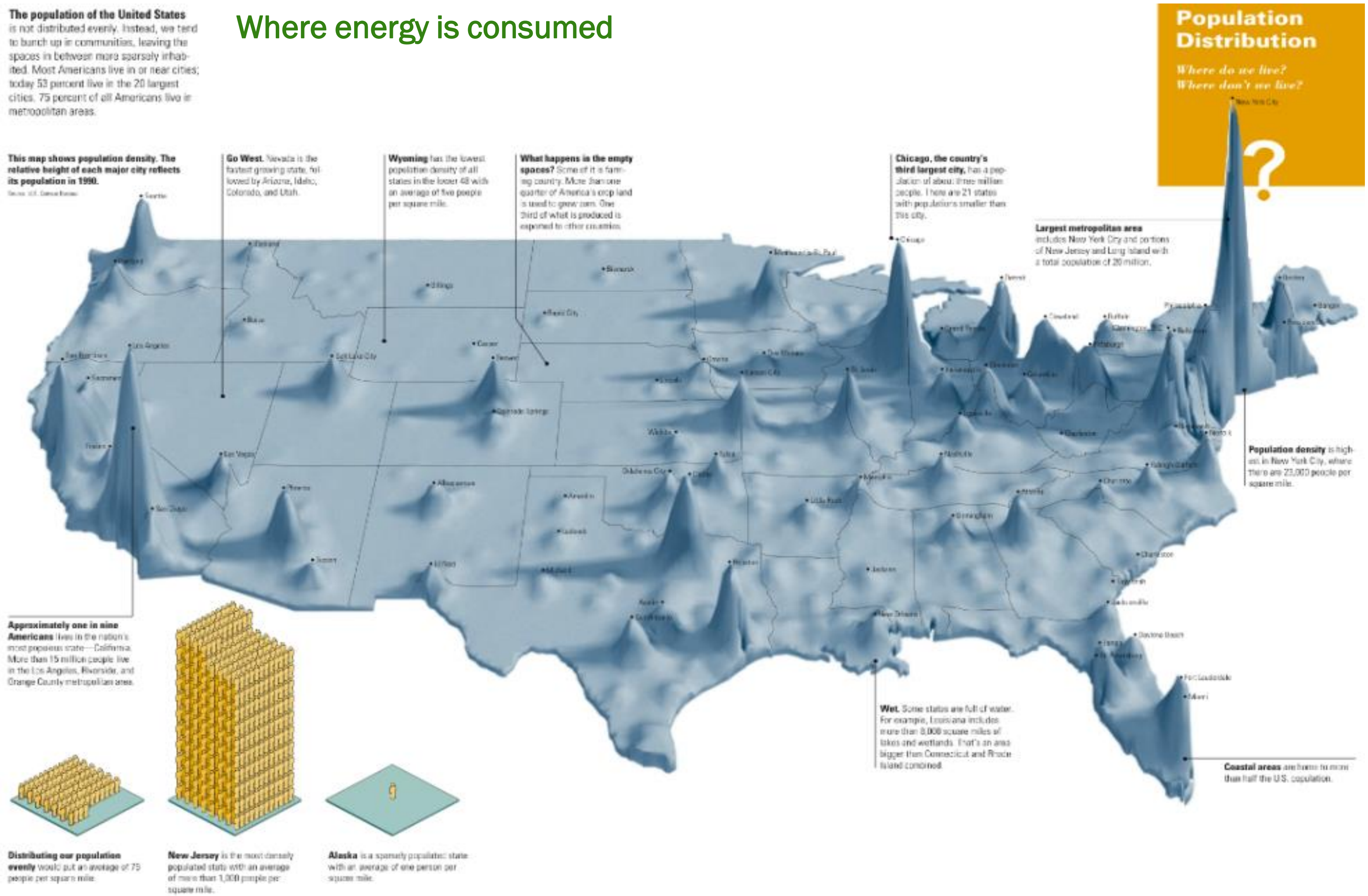


H_2@Scale: Enabling renewable energy transport?

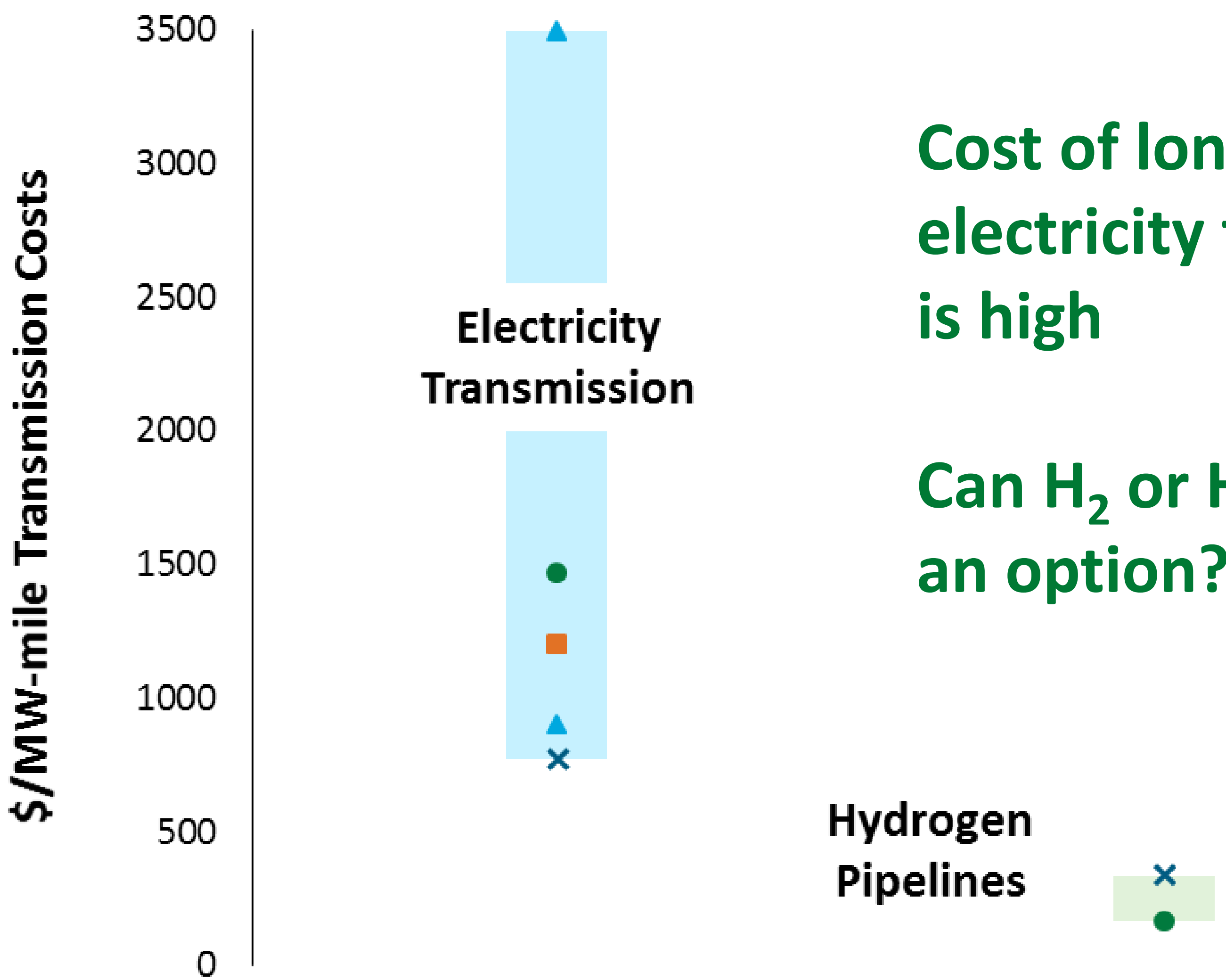
Where we find abundant solar and wind energy

…and deliver it or co-locate distributed generation with demand for certain applications

Where energy is consumed



Preliminary analysis underway to guide future plans

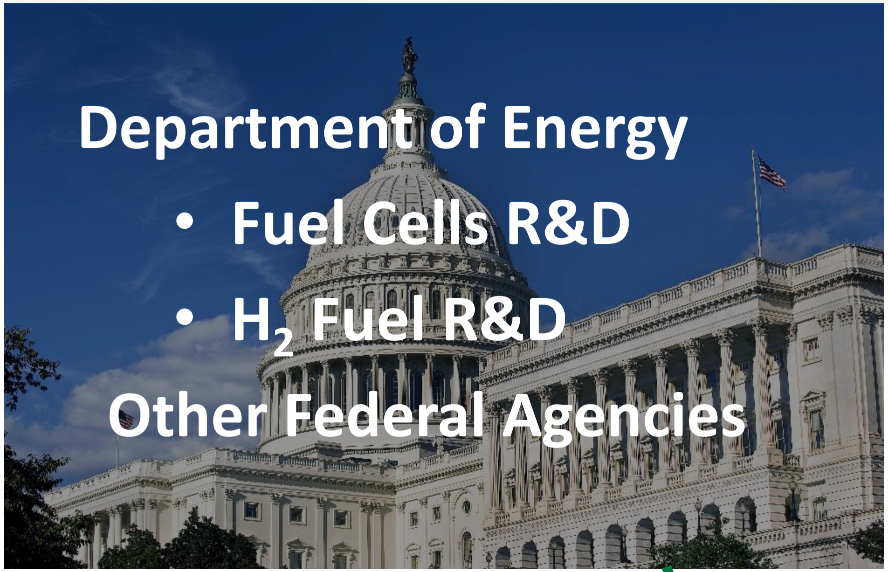


Cost of long distance electricity transmission is high

Can H_2 or H_2 carriers be an option?

Strategy: Partnerships to enable H_2@Scale

Early- Stage R&D



Demonstration, Deployment & Commercialization

H2@Scale
U.S. Department of Energy

H_2@Scale Consortium

H_2@Scale Stakeholder Feedback – Examples

Hundreds of stakeholders engaged
6 DOE Offices engaged
(EERE, FE, NE, OE, SC, ARPA-E)

2016 Session at Intermountain Energy Summit
Idaho Falls, ID

2017 Session at Fuel Cell Seminar
Long Beach, CA

Planned: 2018 Kickoff
Chicago, IL

2017 Session at FCTO's Annual Merit Review
Washington, D.C.

Planned: 2018 AMR
Washington, D.C.

2017 Workshop
Houston, TX

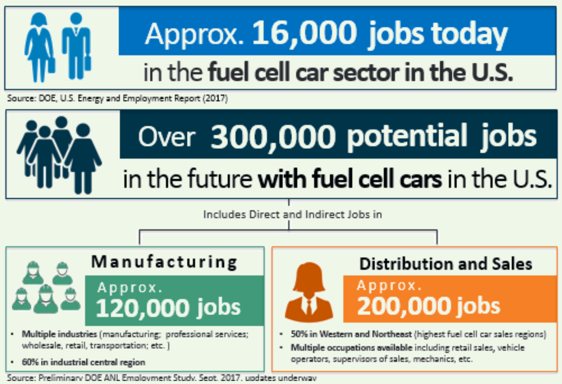
2016 Workshop
Golden, CO

Examples of additional presentations:

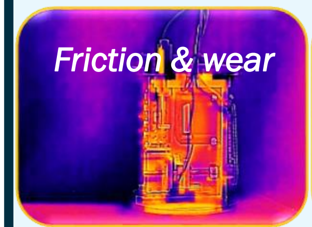
- Utah (2017)
- Michigan (2017)
- Minnesota (2017)
- Germany (2017, 2018)
- Japan (2018)

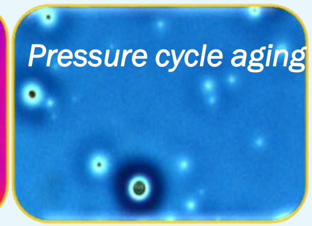
H_2@Scale R&D Lab Capabilities– Examples

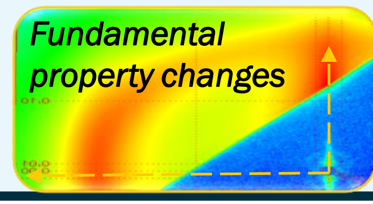
Techno economic Modeling and Analysis



Hydrogen Materials R&D

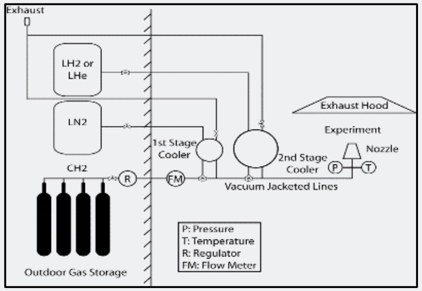






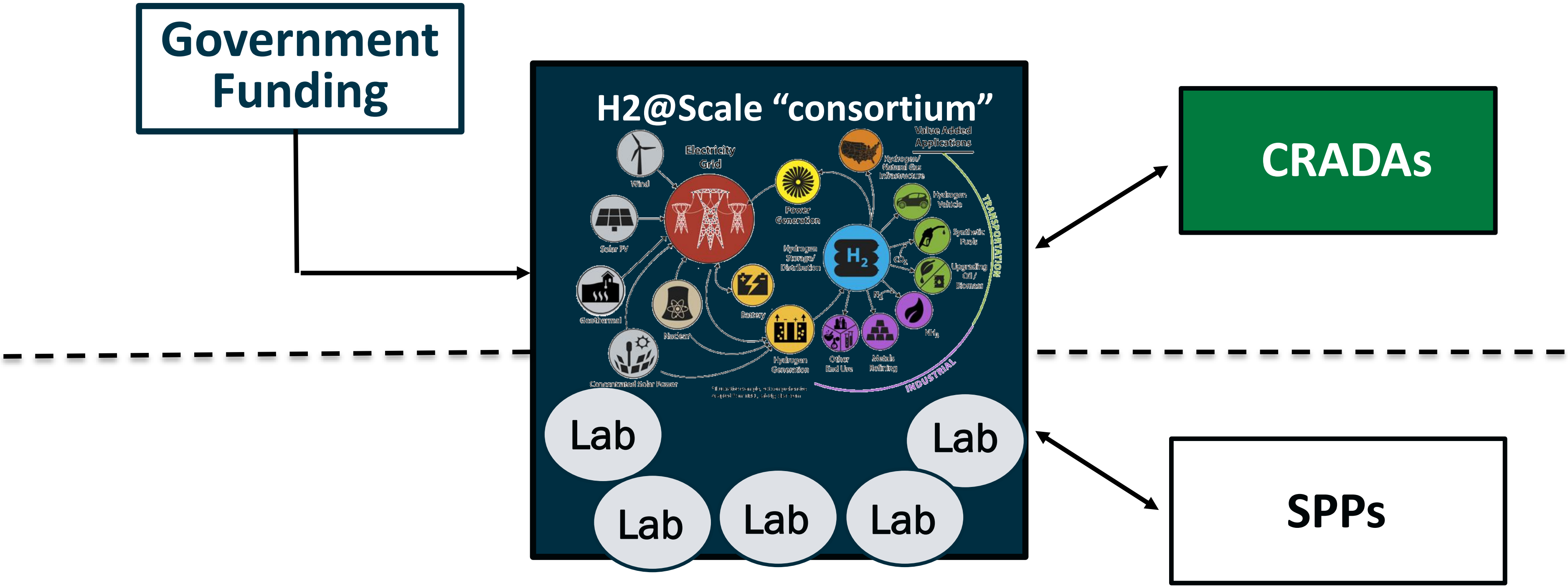
Grid simulation and Testing R&D

Safety and Infrastructure R&D



H_2@Scale – Lab CRADAs

- **Leverages Lab capabilities and expertise to address challenges- materials R&D, analysis, safety R&D, etc.**
- **Round 1 in 2017.**



CRADA = Cooperative Research and Development Agreement
SPP- Strategic Partnership Project ('Work for Others')

H_2@Scale 2017 CRADA call selections

HYDROGEN QUANTITATIVE PERFORMANCE ANALYSIS AND OPERATION R&D

- Air Liquide
- California Energy Commission
- Connecticut Center for Advanced Technology
- PDC Machines
- Quong & Associates, Inc.

HYDROGEN DISTRIBUTION COMPONENT DEVELOPMENT R&D

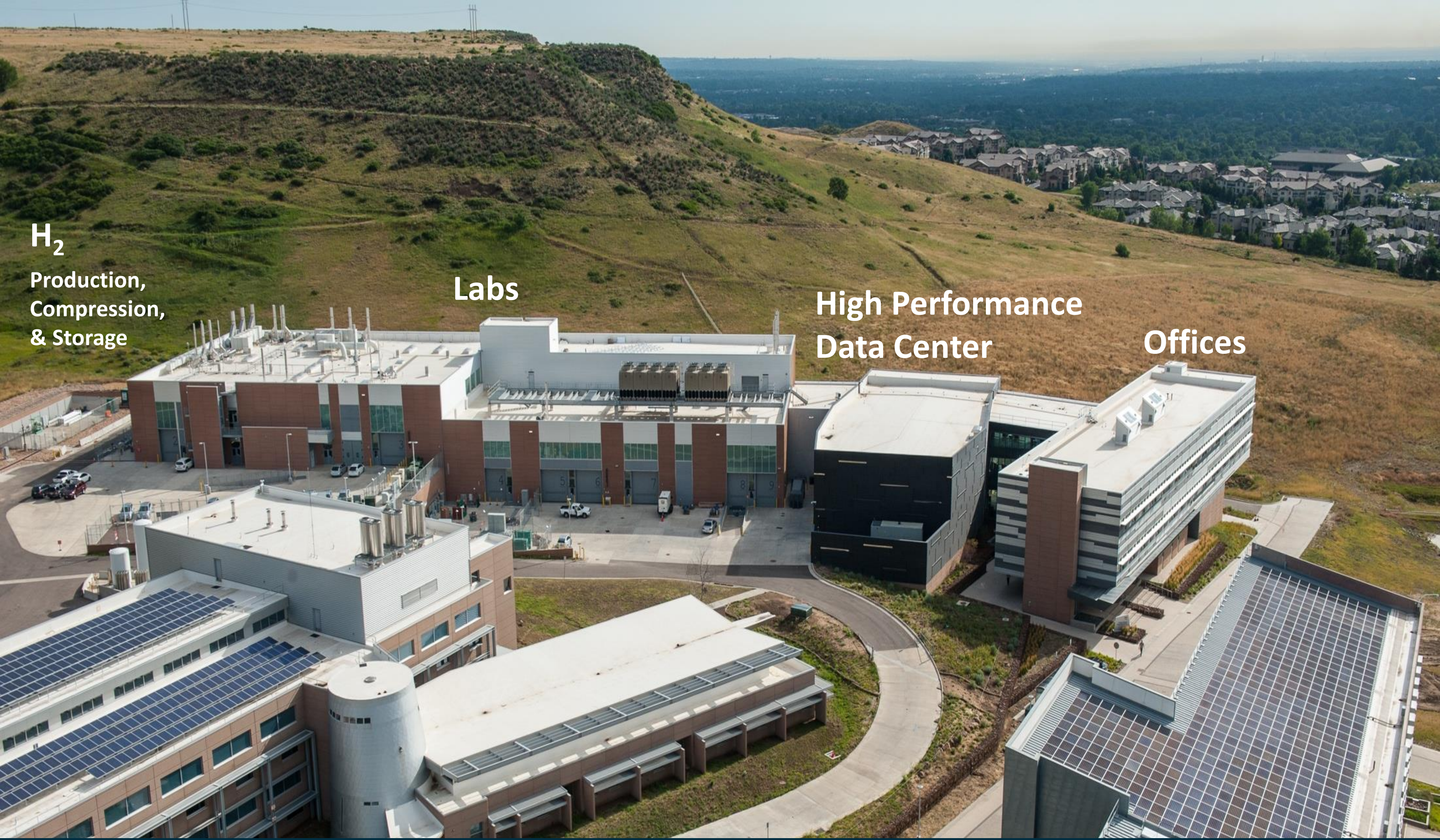
- California Go-Biz Office
- Frontier Energy
- HyET
- Honda
- NanoSonic
- RIX
- Tatsuno

ADVANCED HYDROGEN PRODUCTION CONCEPTS R&D

- Honda
- C4-MCP, Inc.
- GinerELX
- GTA, Inc.

HYDROGEN INTEGRATION WITH ENERGY GENERATION R&D

- Electric Power Research Institute
- Exelon
- Southern Company / Terrestrial Energy
- Nikola Motor
- Pacific Gas & Electric
- TerraPower



Energy Systems Integration R&D, NREL
Coordinating with INL, SNL and other labs
For H2@Scale

Example of End Use & Industry Partnership with Labs

Production of natural gas using H_2

- **Utilizes H_2+ CO_2 and salts to generate pipeline quality natural gas** (> 97% CH_4)
- **Biocatalyst used in the process** - Methanothermobacter thermautotrophicus
- **Industry and lab partners:** Southern California Gas Company, NREL and Electrochaea

Biomethanation Process:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

NREL Fuel Cell Data Center

First time automotive fuel cell is integrated to a data center

H_2@Scale Future Plans: Focus Areas

MAKE	MOVE	USE
Increased Low Cost Hydrogen Production	More Efficient Hydrogen Transmission	Low Cost Value-added Applications

STORE

Improved Bulk Storage Technologies

August 1

H2@Scale Kickoff Meeting Planned

Chicago

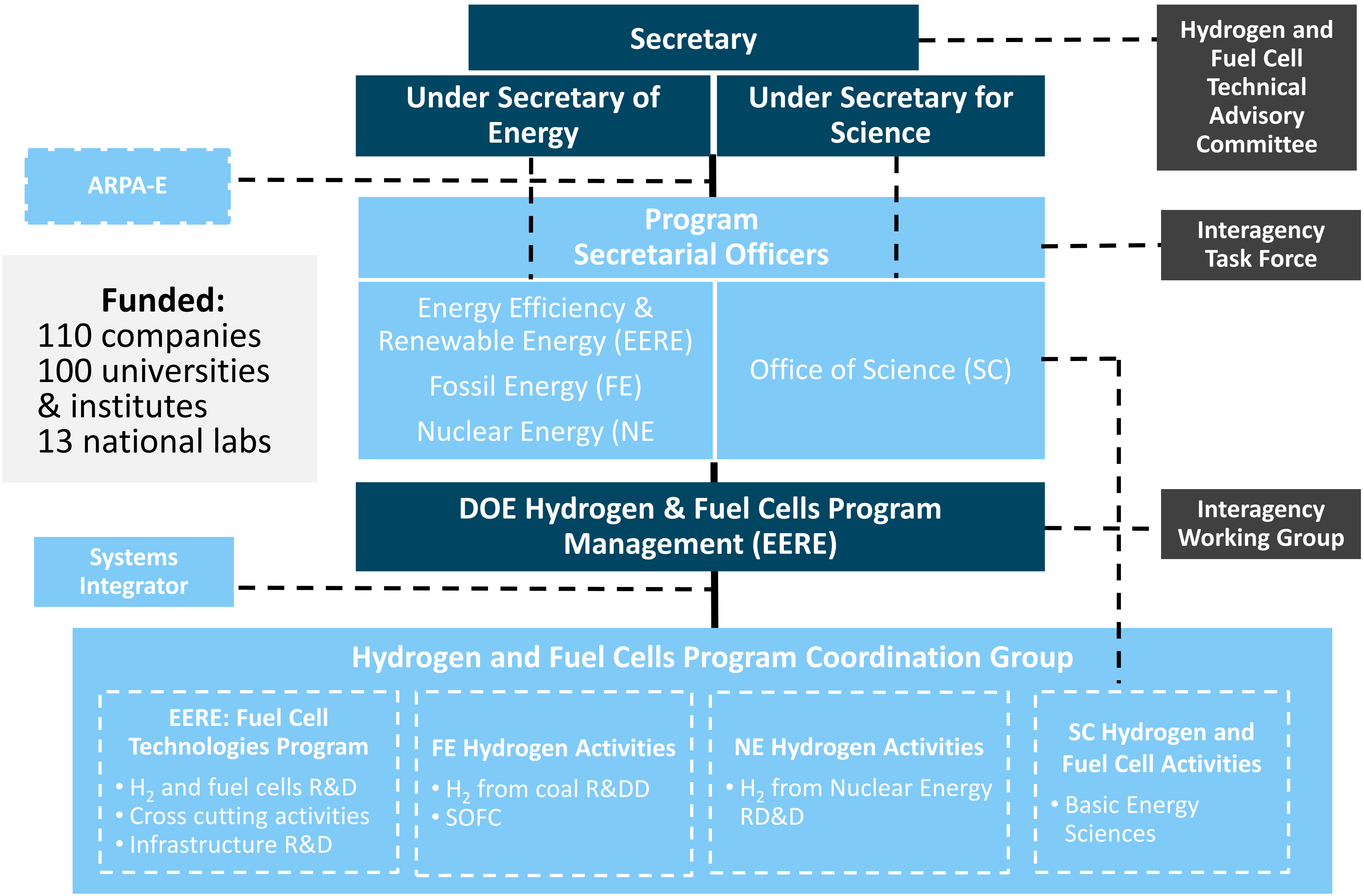
Roadmap Planned

Collaboration

and

Program Funding

The H_2 and Fuel Cells Program spans other DOE offices



DOE Program Funding

DOE-wide Hydrogen and Fuel Cells Funding[1]

Office	FY 2017 ($ in thousands)
EERE	101,000
ARPA-E	47,000
Science	22,000
Fossil Energy	30,000
Nuclear	2,000
Total	**202,000**

EERE – Fuel Cell Technologies Office

Key Activity	FY 2017	FY 2018
	($ in thousands)	
Fuel Cell R&D	32,000	32,000
Hydrogen Fuel R&D	41,000	54,000
Systems Analysis	3,000	3,000
Technology Acceleration	18,000	19,000
Safety, Codes and Standards	7,000	7,000
Total	**101,000**	**115,000**

[1] 2017 DOE Hydrogen and Fuel Cells Program Annual Progress Report

Coordination across Offices- Examples

DOE/EERE AMO
- Prototyping of emerging NG reforming options
- Innovative manufacturing for electrolyzer systems, R2R
- WBS institute: power electronics for H_2 BOP

DOE/EERE BETO
- Bio-waste-stream utilization options for H_2
- H_2 options for bio-fuel synthesis

DOE/EERE SETO
- Concentrator BOP for solar-thermochemical H_2
- CSP-based solar NG reforming
- Solar to fuels

DOE/EERE Wind
- Wind-electrolysis integration R&D

DOE/EERE FCTO

Foundational Early-Stage R&D and H2@Scale

- Hydrogen production, delivery and storage R&D; fuel cell R&D (PEM, MCFC, PAFC, DMFC, etc.- non SOFC)
- Consortia on hydrogen production, storage, fuel cell catalysts, H2@Scale
- Technology acceleration (manufacturing R&D, technology validation, market transformation, safety codes and standards)
- Infrastructure R&D
- Systems analysis to guide R&D

NSF
- Academia-based fundamental research relevant to Hydrogen and Fuel Cell R&D (coordination with FCTO consortia)

NIST, DOT DOD, NASA, etc.
- Examples: Standards in H_2 materials & services; next-generation military and space, buses, rail, marine, etc. applications

DOE/SC
- Fundamental processes of energy & matter relevant to H_2 manipulations
- Synergies with EFRCs & ongoing projects

DOE/FE
- Innovative large-scale coal and NG H_2 options + SOFC

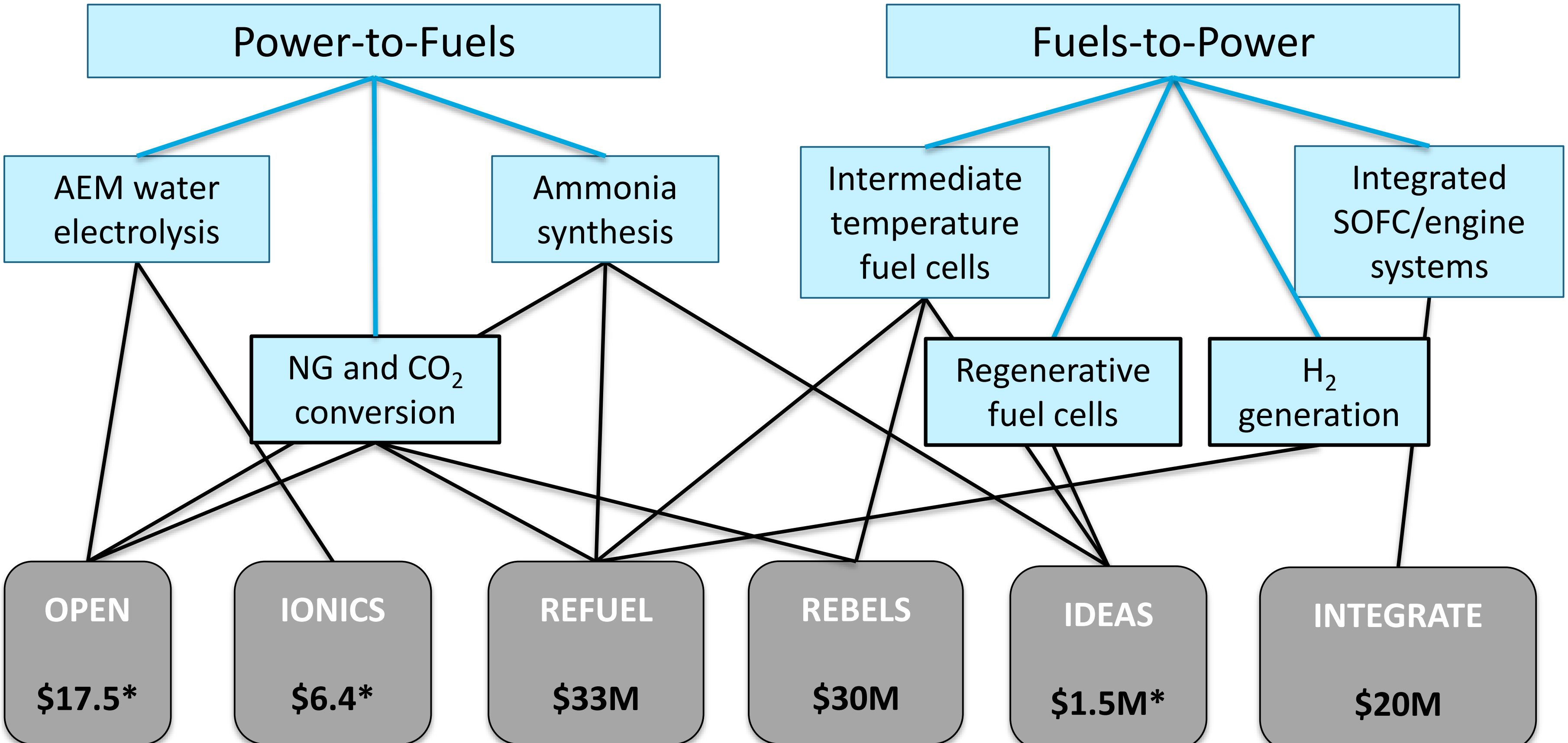
DOE/NE
- Integrated and hybrid systems for nuclear H_2

DOE/OE
- H_2 for energy storage & grid ancillary services

DOE/ARPA-E
- Innovative and disruptive concepts related to hydrogen and fuel cells

ARPA-E Hydrogen and Fuel Cells Activities

ARPA-E Programs in Fuel Cells/Electrolyzers for Energy Conversion and Storage



Source: ARPA-E

* - related to FC/electrolyzers/H_2

Online Resources - we need your help!

Spread the word on H_2 Safety Lessons Learned!

Share at regular team meetings

Provide feedback to FCTO and stakeholders

Find lessons learned at **H2tools.org**

Collaboration: Announcing New H_2 Safety Partnership

Leverages new partnership to promote collaboration on safety

Pacific Northwest
NATIONAL LABORATORY

AIChE

CENTER FOR
Hydrogen
SAFETY

HYDROGEN
Safety Panel

HYDROGEN
Emergency Response
Training Resources

U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

IPHE: International Partnership for H_2 and Fuel Cells in the Economy

- **Share** information on H_2 and fuel cells, lessons learned, best practices
- **Increase** international **collaboration to accelerate progress**

U.S. elected as Chair

May 2018

- Australia
- Austria
- Brazil
- Canada
- China
- European Commission
- France
- Germany
- Iceland
- India
- Italy
- Japan
- Republic of Korea
- Norway
- Russian Federation
- South Africa
- United Kingdom
- United States

Launched 2003 and includes 18 countries and the European Commission

Save the Date

Thank You

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energy.gov/eere/fuelcells

DOE Collaboration: H_2 & Fuel Cell Working Group

DOE Program Managers collaborate on hydrogen and fuel cell activities

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