NREL Fuel Cell and Hydrogen Systems Research

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Georgia Tech University Webinar
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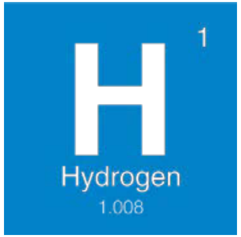
Hydrogen at a glance



WHAT IS HYDROGEN?

- One of the most abundant elements in the Universe
- Consists of only one proton and one electron
- Hydrogen is an energy carrier rather than energy source (stores and delivers energy)
- Found in many substances in nature, but must be extracted for end use
  - i.e., Fresh/sea water, biomass, hydrogen sulfide, and fossil fuels

WHY STUDY HYDROGEN?

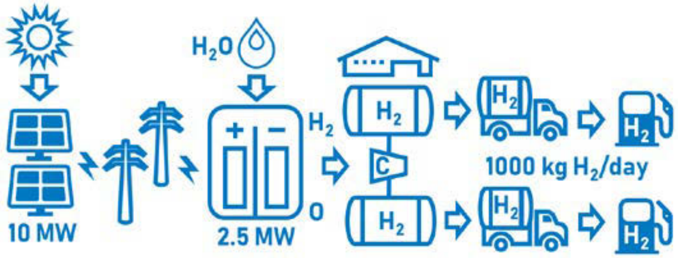
- Utilized in fuel cells to generate power using a chemical reaction rather than combustion, producing only water and heat as byproducts.
  - Used in vehicles, stationary power, portable power, etc.

HOW HYDROGEN PRODUCTION WORKS

- Hydrogen can be produced using diverse, domestic resources
  - Fossil fuels (natural gas and coal), nuclear energy, and other renewable energy sources, such as biomass, wind, solar, geothermal, and hydro-electric power—using a wide range of processes.

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

Hydrogen Facts

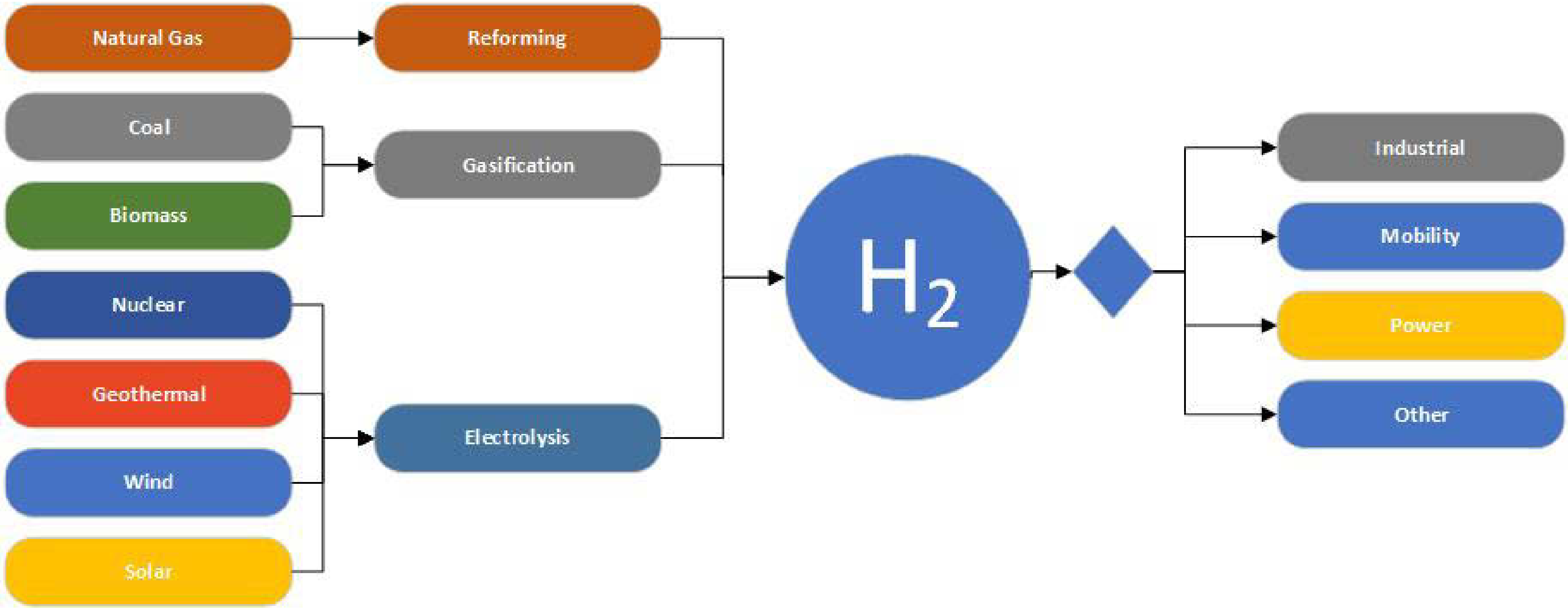


FACTS

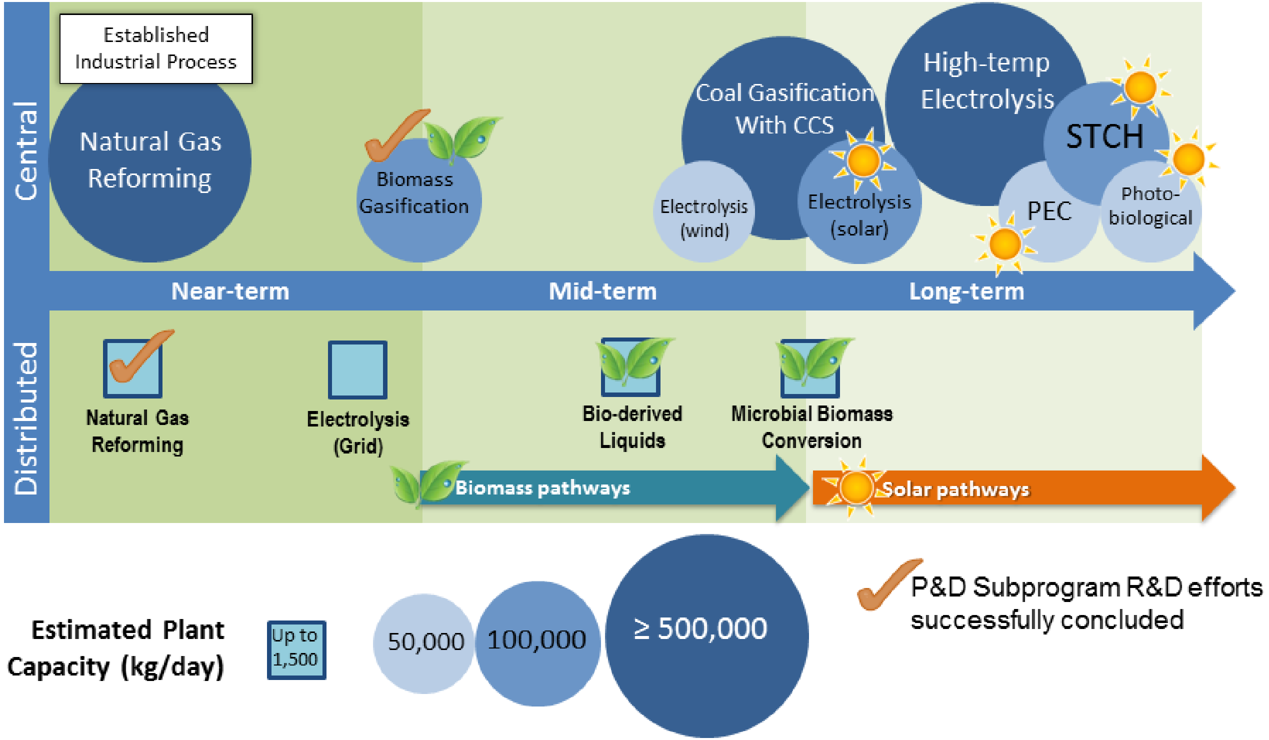
- Over ten million metric tons of hydrogen are currently produced in the United States every year (95% of which is via centralized reforming of natural gas)
  - Other approaches include hydrogen production from water splitting, such as electrolysis, photoelectrochemical cells, or solar thermochemical systems.
- The primary uses of hydrogen today are in the oil refining and ammonia industries.
- Other applications include fuel cell vehicles, metals refining, and synthetic natural gas production.
- Hydrogen can be produced:
  - At or near the site of use (distributed production)
  - At large facilities and then delivered to the point of use (central production)
  - At intermediate scale facilities located in close proximity (25–100 miles) to the point of use (semi-central production).
- 1 Kg of Hydrogen (gas) = 1 gallon Gasoline equivalent

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

Methods for Making Hydrogen



Hydrogen Production Pathways



The objective of the U.S. Department of Energy and the National Renewable Energy Laboratory is conduct R&D into the production of economical and environmentally friendly hydrogen by leveraging a diverse set of technologies.

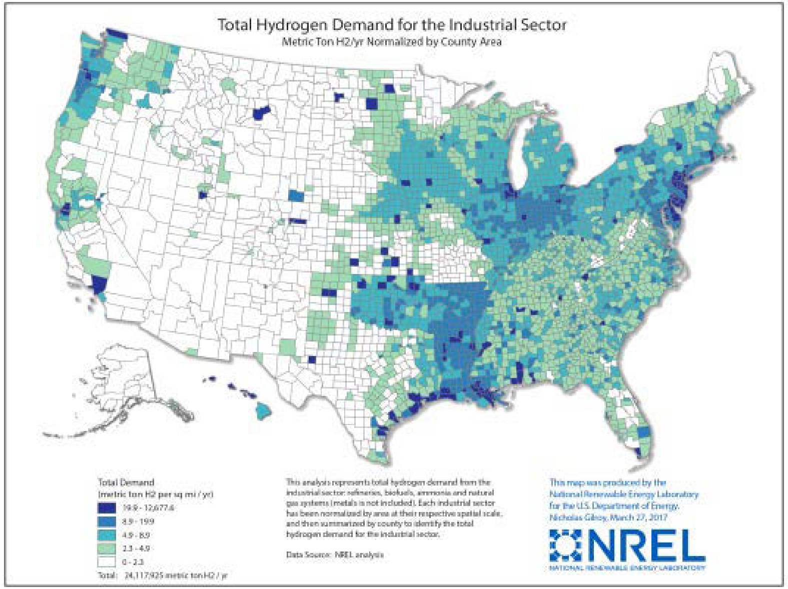
https://www.energy.gov/eere/fuelcells/hydrogen-production-pathways

Hydrogen Production Methods

Fossil fuel reforming	Biofuel reforming	Coal and biomass gasification	Thermochemical method	Water electrolysis	Photoelectrochemical method	Biological method
Critical challenges						
High capital costs	High capital costs	High reactor costs	Cost effective reactor	Low system efficiency	Effective photocatalytic material	Efficient microorganisms for sustainable production
Design	High operation and maintenance costs	System efficiency	Long-term technology	High capital costs	Low system efficiency	Optimal microorganism functionality
High operation and maintenance costs	Design	Feedstock impurities	Effective and durable materials	System integration	Cost effective reactor	Reactor material selection
	Feedstock quality	Carbon capture and storage		Design issues	Long-term technology	Long-term technology
Major R&D Needs						
Efficiency and cost	Hydrogen yield and efficiency	Low cost and efficient purification	Robust, low cost materials	Durable and cheap materials	Durable and efficient photocatalyst	Microorganism functionality
Low cost and efficient purification	Low temperature production	Co-fed gasifiers	Ease of manufacture and application	Corrosive-resistant membranes	Low cost materials	New organisms
Feedstock pre-treatment	Low cost and efficient purification	Carbon capture and storage	System optimization	Durable, active, and cheap catalysts	Active, stable, and cheap supporting materials	Inexpensive methods
Optimization	Optimization	Hydrogen quality	High volume, low cost, flexible system design	Large scale applications	High volume production	Low cost and durable material
Automated process control	Regional best feedstock	Cost of feedstock preparation	Efficient heat transfer	Storage and production rate	System control	System optimization
Reliability	Feedstock pre-treatment	Tolerance for impurities	Reliability	Reliability	Power losses	High capacity and low cost systems
Key benefits						
Most viable approach	Viability	Low cost syngas production	Clean and sustainable	No pollution with renewable energy sources	Low operation temperature	Clean and sustainable
Lowest current cost	Existing infrastructure	Abundant and cheap feedstock	Recycled chemicals	Existing infrastructure	Clean and sustainable	Tolerant of diverse water conditions
Existing infrastructure				Integration with fuel cells		Self sustaining

https://www.sciencedirect.com/science/article/pii/S0360319914034119

Potential Hydrogen Demand



Total market potential: 60 MMT/yr

Industrial Use	Market potential (million metric tonne H_2 / year)
Refineries & CPI§	8*
Metals	5
Ammonia	5
Natural Gas	7
Biofuels	4
Light Duty Vehicles	28
Other Transport	3
Total	**60**

§ CPI: Chemical Processing Industry not including metals, biofuels, or ammonia

* Current potential used due to lack of consistent future projections

Light duty vehicle calculation basis: 190,000,000 light-duty FCEVs from http://www.nap.edu/catalog/18264/transitions-to-alternative-vehicles-and-fuels

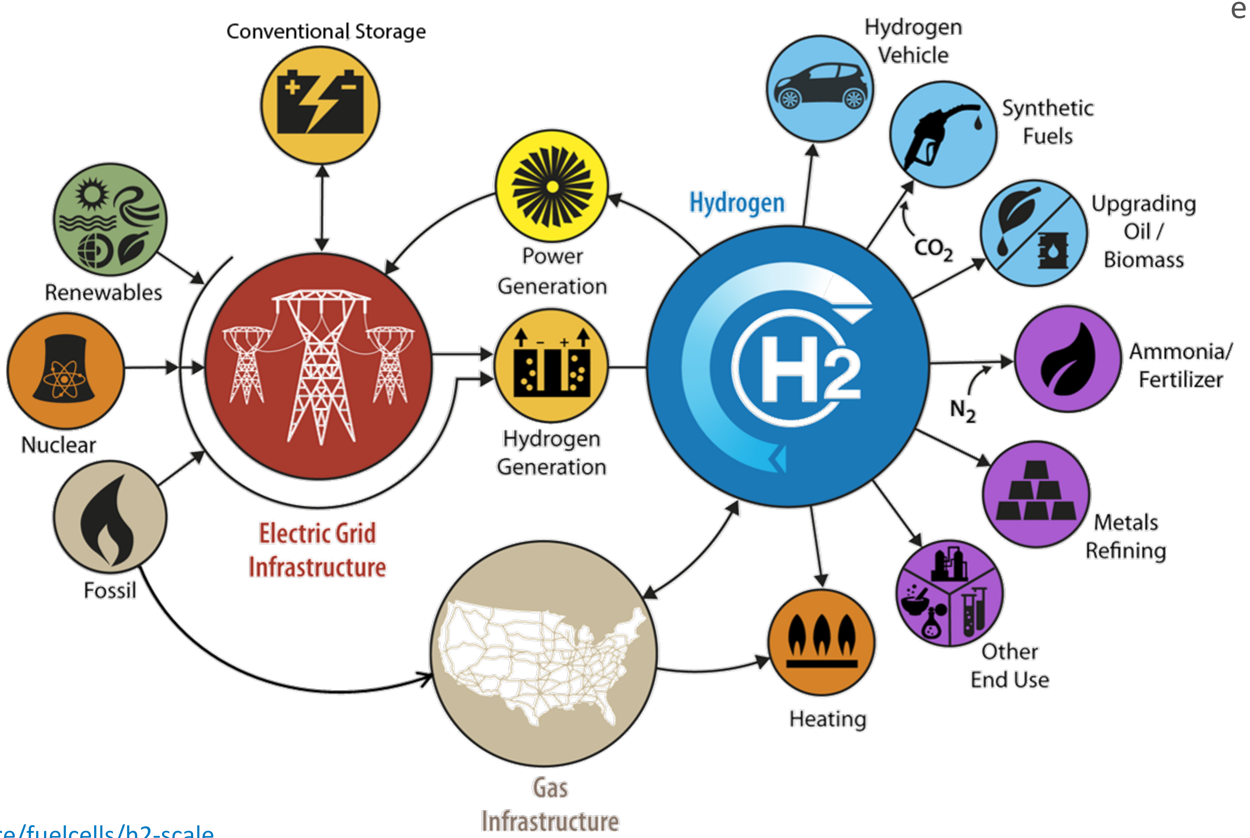
1. Global hydrogen Generation Market by Merchant & Captive Type, Distributed & Centralized Generation, Application & Technology- Trends & Forecasts (2011-2016)

Why Hydrogen?

- Over half of U.S. CO_2 emissions come from the industrial and transportation sectors
- Hydrogen can enable affordable, reliable, clean, and secure energy across sectors
  - Large-scale, clean, cross-sector energy
  - Energy system flexibility, resiliency, and hybridization
  - Economic, security, and environmental benefits

H2@Scale

Hydrogen integrated with multiple U.S. energy sectors



https://www.energy.gov/eere/fuelcells/h2-scale

Controllable electrolyzers addressing renewable generation challenges

Curtailment

- Integrated renewable-electrolysis systems have the potential to reduce curtailment in current and future power systems.

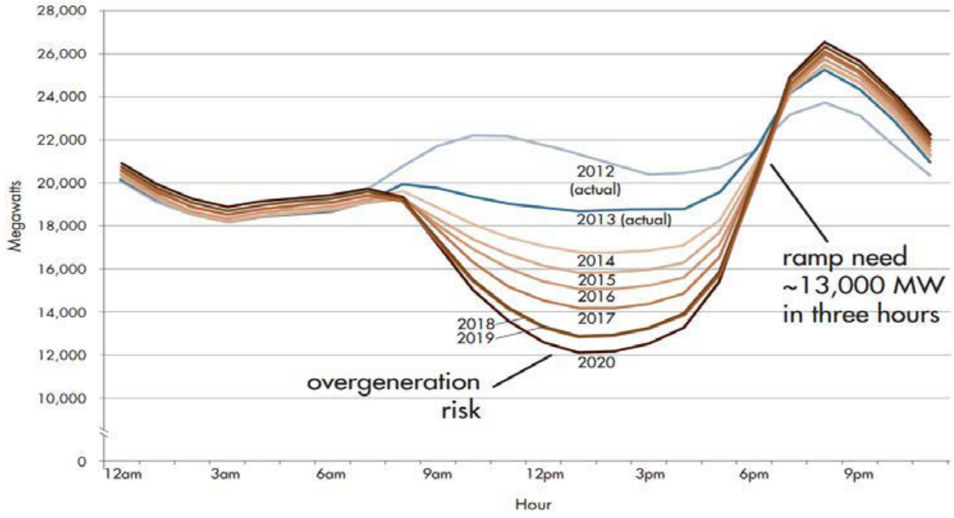
Electricity prices

- The flexibility of renewable-electrolysis systems enables access to low-cost electricity for hydrogen production and higher value markets for renewable electrons.

Electricity markets

- Electrolyzers can participate in different electricity markets, including energy and ancillary services for grid balancing and reliability, as well as capacity for resource adequacy.

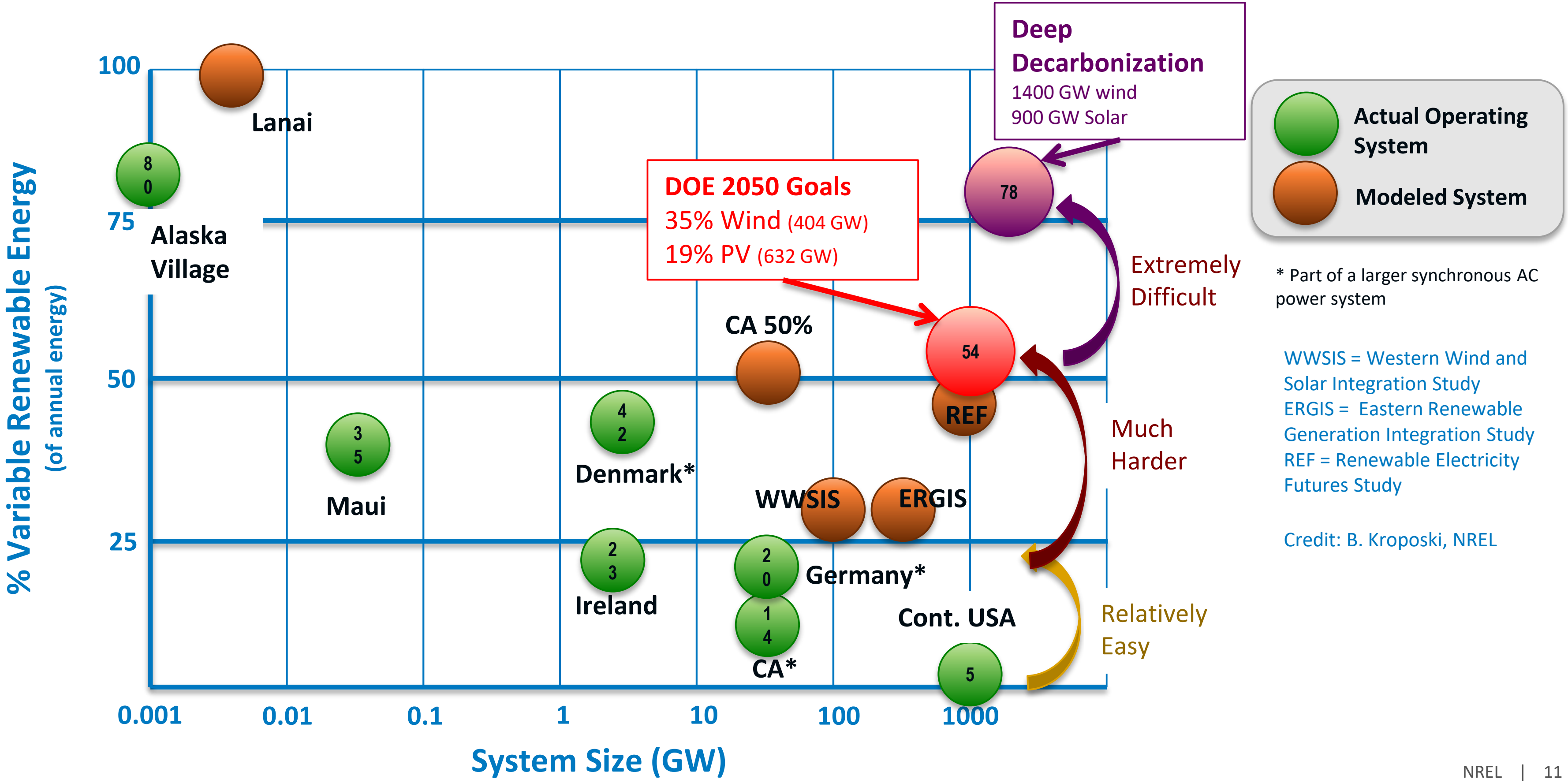
The “Duck” Curve



Source: www.caiso../Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf

Renewables over-generate power in times of low demand and under-generate during times of high demand causing grid resiliency issues. Lack of energy storage solutions result in curtailment of renewables.

What is at scale?



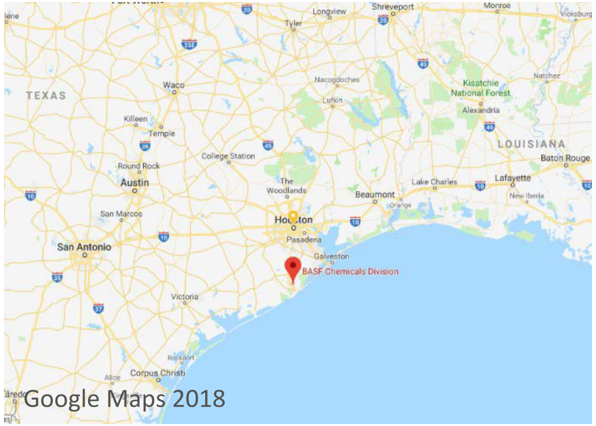
* Part of a larger synchronous AC power system

WWSIS = Western Wind and Solar Integration Study
ERGIS = Eastern Renewable Generation Integration Study
REF = Renewable Electricity Futures Study

Credit: B. Kroposki, NREL

Real-World H2@Scale Examples

Integration of 10-MW of electrolysis with Rheinland Refinery Complex (Germany)
(2018; Shell)



750,000 tonne/year ammonia plant using by-product hydrogen opens in Freeport, TX
(2018; Yara, BASF)

Steam-Methane Reforming

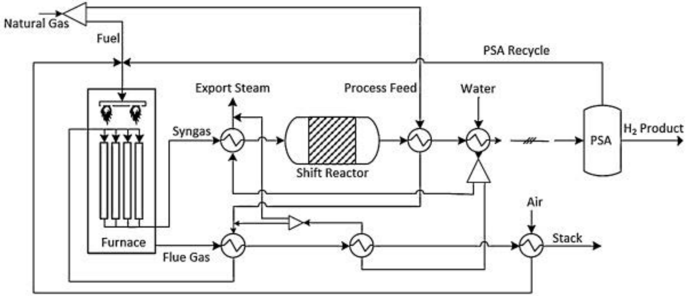
- The most economical and common form of H_2 production today (in the United States) is by steam-methane reformation
- High-temperature steam (700°C–1,000°C) is used to produce H_2 from a methane source (i.e., natural gas)
- Reacts with steam under 3–25 bar pressure in the presence of a catalyst to produce H_2, CO, and CO_2
- Endothermic

Steam-methane reforming reaction

$CH_4 + H_2O$ (+ heat) → $CO + 3H_2$

Water-gas shift reaction

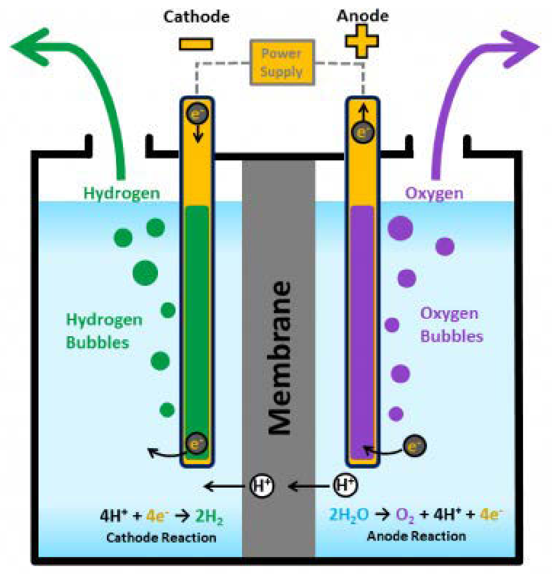
$CO + H_2O$ → $CO_2 + H_2$ (+ small amount of heat)



Electrolysis

Process of using electricity to split water into hydrogen and oxygen

- Types:
  - Proton exchange membrane (PEM) (H^+ transport)
  - Solid oxide (O^{2-} transport)
  - Alkaline (OH^- transport)
- Tied to renewable and/or non-greenhouse-gas-emitting forms of electricity for green H_2 production
  - Primarily wind and nuclear
- Temperature range: 20°C–100°C
- Efficiency range: 60% – 70%
- R&D needs:
  - Cost reduction, increased efficiency, and integrated compression
- High temperature electrolysis for future R&D

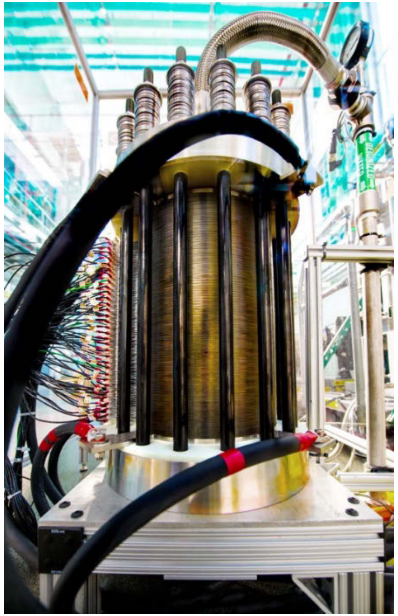


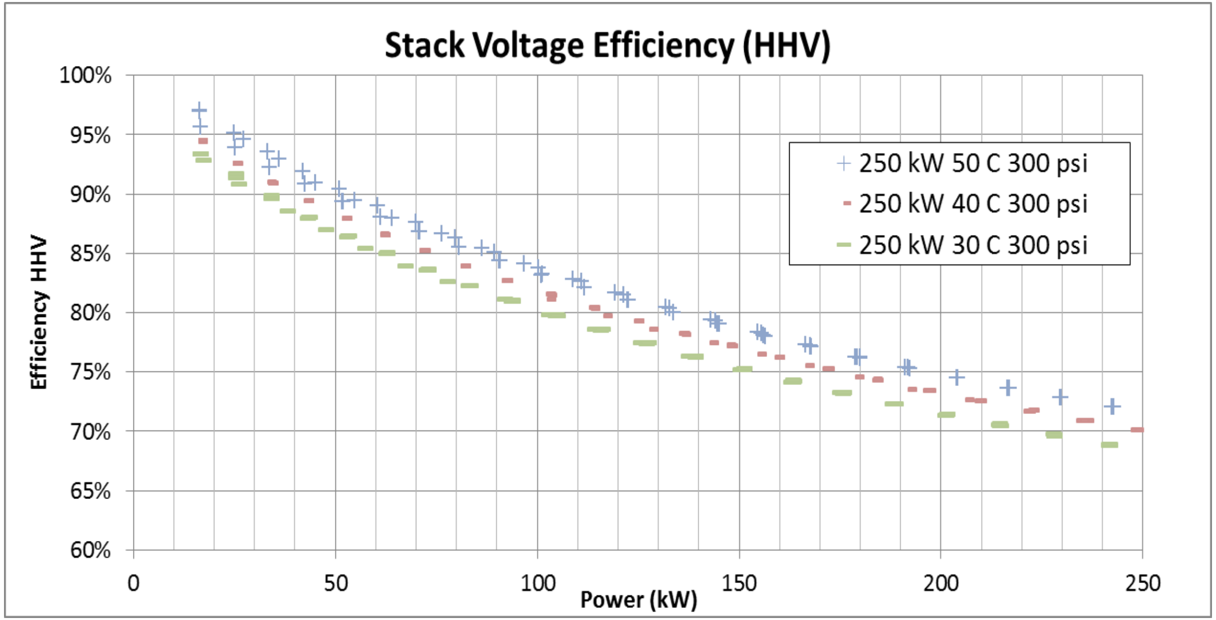
Anode Reaction: $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$

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

https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis

Electrolysis Efficiency

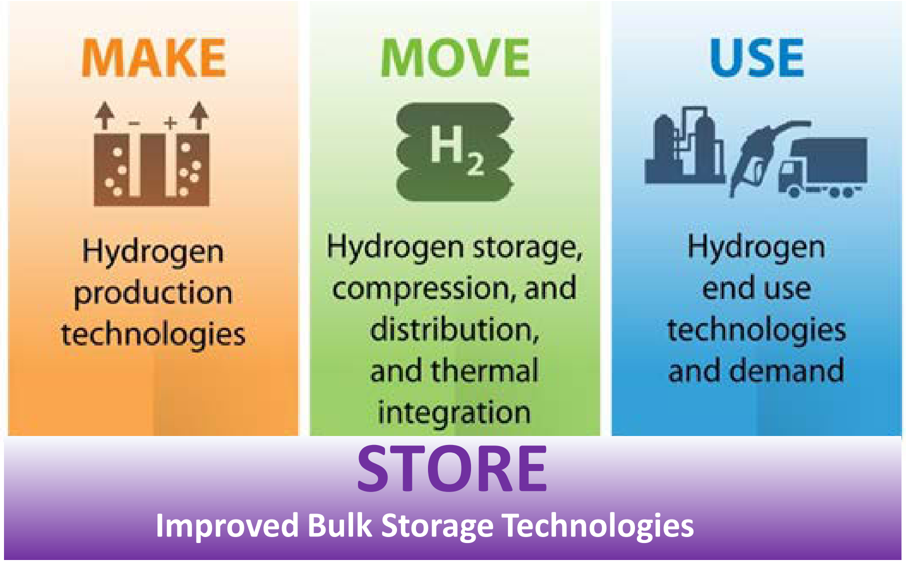


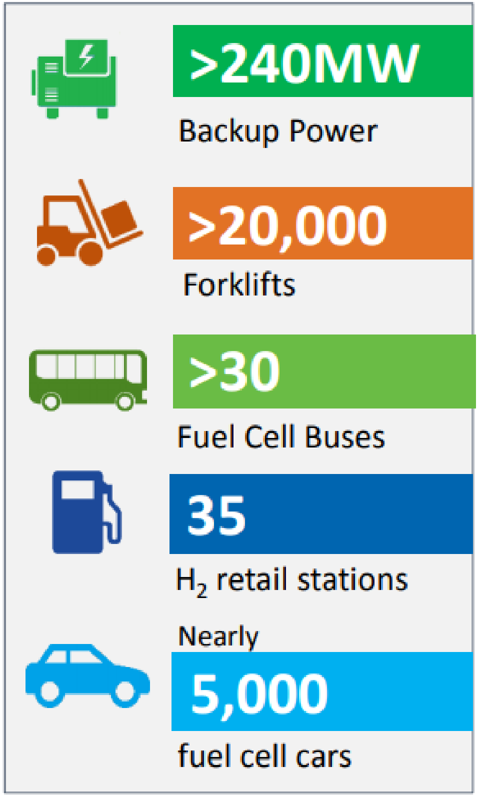


https://www.hydrogen.energy.gov/pdfs/review17/tv031_hovsapian_2017_o.pdf

- Electrolysis efficiency increases with higher temperature
- High temperature electrolysis is an emerging and potentially breakthrough technology
- Innovations and R&D are needed for high temperature electrolysis. Scalability, novel materials, durability, and reliability remain a challenge.

Key Focus Areas and End Uses



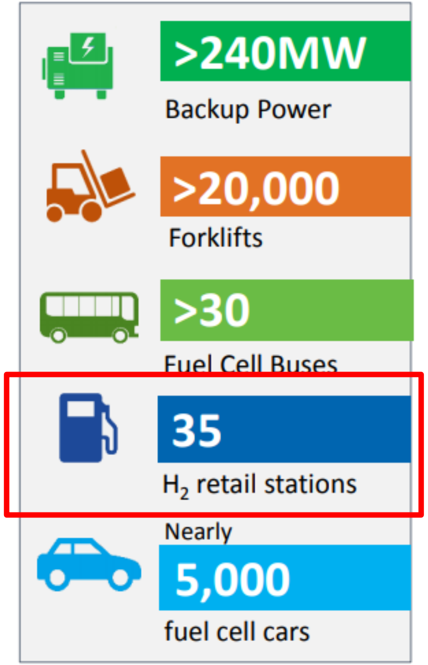


Hydrogen Production

U.S. Snapshot and States with Growing Interest

CA
- Up to 200 stations planned
- Over 35 public stations open

HI, OH, SC, NY, CT, MA, CO, UT, TX, MI, and others with interest
- 12–25 stations planned in the Northeast
- 4 non-retail stations operating



Hydrogen Stations

- 700 bar (10,000 psi) gaseous onboard storage chosen by the original equipment manufacturers (OEMs) for commercial passenger cars
- 350 bar (5,000 psi) gaseous was chosen for buses and lift trucks (i.e., forklifts)
- SAE J2601 standard dictates the protocols for fills

Source: https://www.energy.gov/eere/fuelcells/dispensing-hydrogen-fuel-vehicles

350 bar

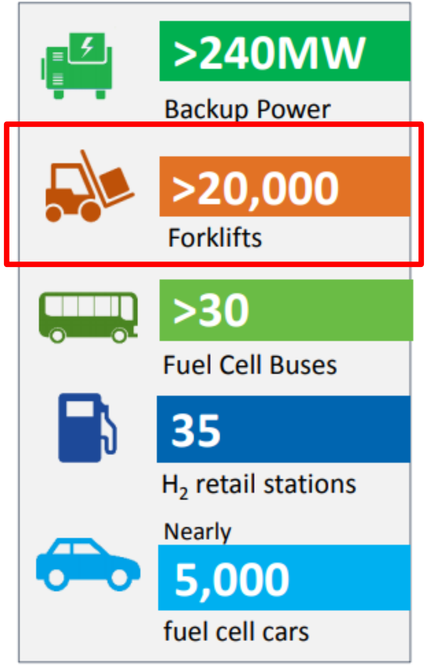
700 bar

https://www.weh.us/refueling-systems-hydrogen.html/

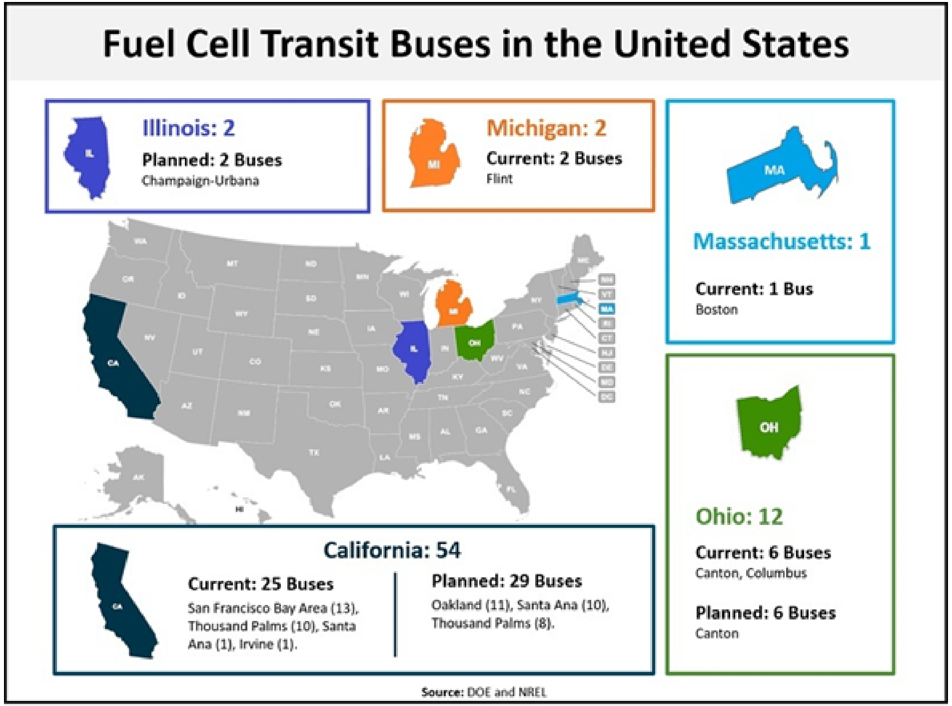
Material Handling

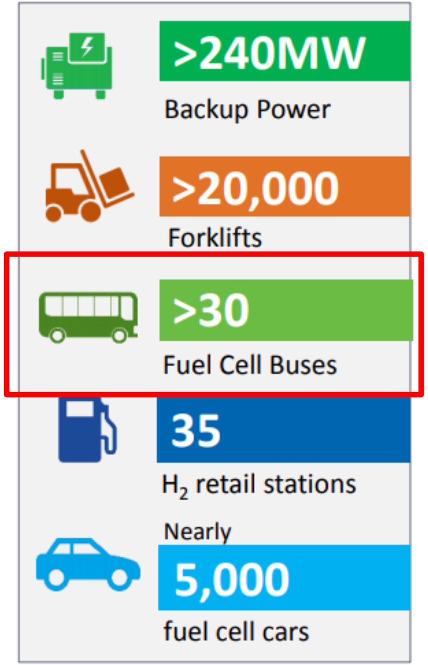
More than 20,000 fuel cell forklifts utilized across the United States

- Amazon, BMW, Fed-Ex, H-E-B, Kroger, Nissan, UPS, Walmart, Wegmans, Whole Foods warehouses
- Over 12 million refueling
- Targeting airport and warehouse tugs



Fuel Cell Bus and Heavy Duty





FCEBs in operation by year
2010 – 13
2017 – 25
2018 – 34 (estimate)

https://www.nrel.gov/hydrogen/fuel-cell-bus-evaluation.html

Fuel Cell Bus and Heavy Duty

Toyota's Project Portal hydrogen fuel cell Class 8 truck. (Photo: Toyota)

Nikola Two electric fuel cell truck. (Photo: Nikola Motor)

- Target market for FCEV technology
- Range, performance, and efficiency

Commercial Fuel Cell Electric Vehicles (FCEVs)

https://ssl.toyota.com/mirai/fcv.html

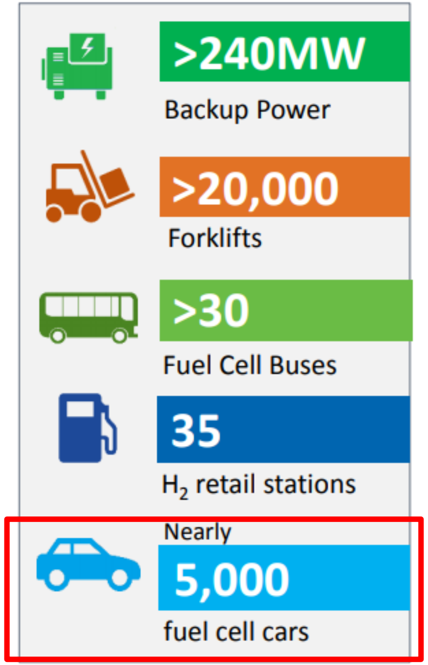
Toyota Mirai (2016–Present)
Power: 114 kW (153 hp)
Torque: 335 Nm (247 lbf·ft)
Fuel Economy: 66 mpg-e combined
Range: 312 miles
H_2 Capacity: 5 Kg
Buy/Lease: $349/month for 36 mos. and 3 years/$15K in H_2 fuel or $58,365 with 3 years/$15K H_2 fuel

https://automobiles.honda.com/clarity-fuel-cell

Honda Clarity FCV (2017–Present)
Power: 103 kW (174 hp)
Torque: 335 Nm (221 lbf·ft)
Fuel Economy: 68 mpg-e combined
Range: 366 miles
H_2 Capacity: 5.46 Kg
Lease Only: $369/month for 36 mos. and 3 years/$15K in H_2 fuel

Hyundai Nexo (2018 Pre-Production 2019 Release)
Power: 135 kW (160 hp)
Torque: 395 Nm (291 lbf·ft)
Fuel Economy: 60 mpg-e combined
Range: 370 miles
H_2 Capacity: 6.3 Kg
Lease: $369/month for 36 mos. and 3 years/$15K in H_2 fuel

https://www.hyundainews.com/models/hyundai-nexo-2019-nexo/overview



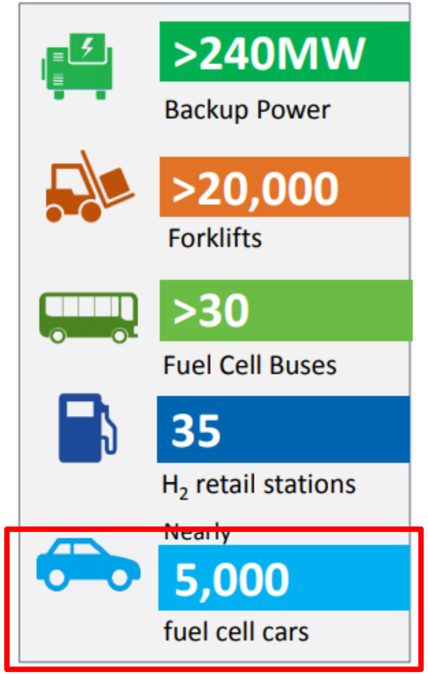
Commercial Fuel Cell Electric Vehicles (FCEVs)

Mercedes-Benz GLC F-Cell (Anticipated early 2019)
Power: TBD (PHEV with fuel cell hybrid powerplant)
Torque: TBD
Fuel Economy: TBD
Range: 30 miles electric and 271 miles total (hybrid)
H_2 Capacity: TBD
Buy/Lease: Available early 2019 for fleets only

https://www.mercedes-benz.com/en/mercedes-benz/vehicles/passenger-cars/glc/the-new-glc-f-cell/

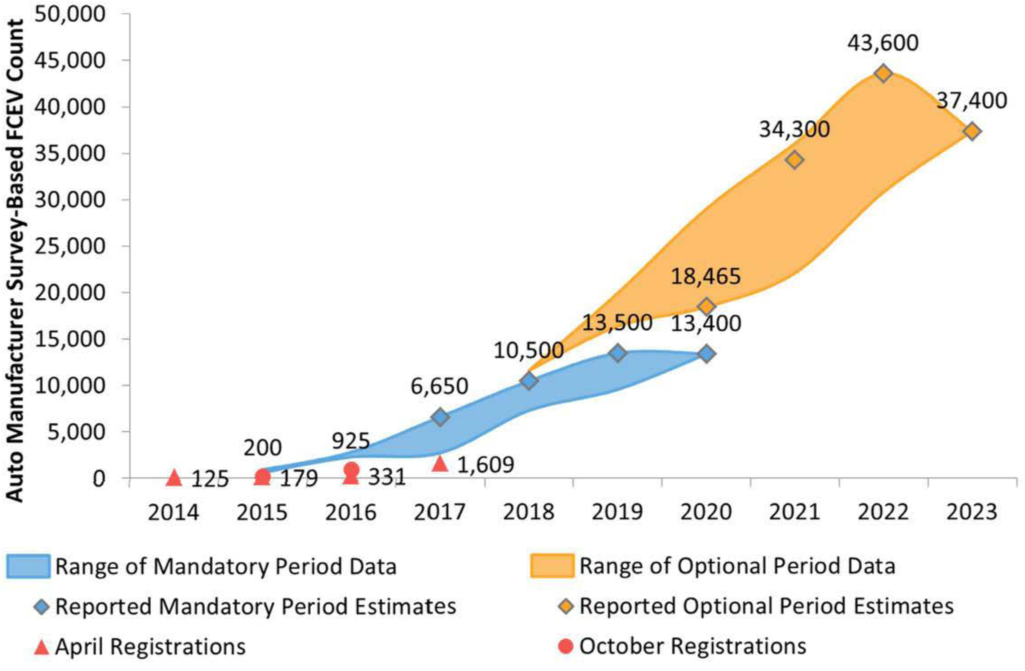
General Motors Colorado ZH2 (2016)
Power: Not disclosed (based on GM FCEV models)
Torque: Not disclosed
Fuel Economy: Not disclosed
Range: Not disclosed
H_2 Capacity: Not disclosed
Lease Only: Military demonstration only (TARDEC)

https://www.motortrend.com/news/gm-u-s-army-unveil-chevrolet-colorado-zh2-fuel-cell-truck/



California FCEV Deployment

Figure ES4: Current and Projected On-Road FCEV Populations and Comparison to Previously Collected and Reported Projections[2]



Source: https://www.arb.ca.gov/msprog/zevprog/ab8/ab8_report_2017.pdf

Increasing on-road FCEV counts are driving increased demand for hydrogen fueling

New Applications and Opportunities

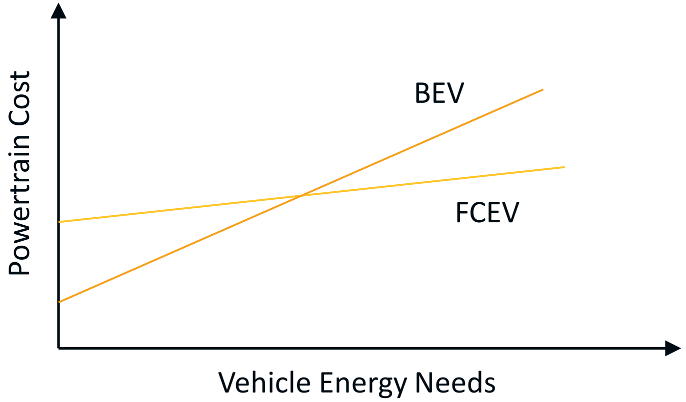
Leverage performance and economics of automotive fuel cell technology advances for new applications like a carbon-free data center with distribution fuel cell IT power.

Daimler media 11/10/17 – non-transportation fuel cell systems

Source: https://www.sciencedirect.com/science/article/pii/S1464285917304273

Have Batteries Won?

- Complex energy issues require multiple technology options where the system requirements drive system solutions
- Integrated energy sectors need economically viable, performance based solutions with optimization for duration and size
- A portfolio of mobility solutions ensures technologies that meet specific needs and operational profiles



FCEVs offer extended range, fast refueling time, electric drivetrain, and scalable.

NREL Fuel Cell and Hydrogen Research

National Laboratories

The United States Department of Energy National Laboratories and Technology Centers are a system of facilities and laboratories overseen by the United States Department of Energy for the purpose of advancing science and technology to fulfill the DOE mission.

https://science.energy.gov/laboratories/

17 National Labs

- 10 Office of Science
- 4 DOE
- 3 NNSA

NREL at a Glance

1,800

Employees,
plus more than
400
early-career researchers and visiting scientists

World-class
facilities, renowned technology experts

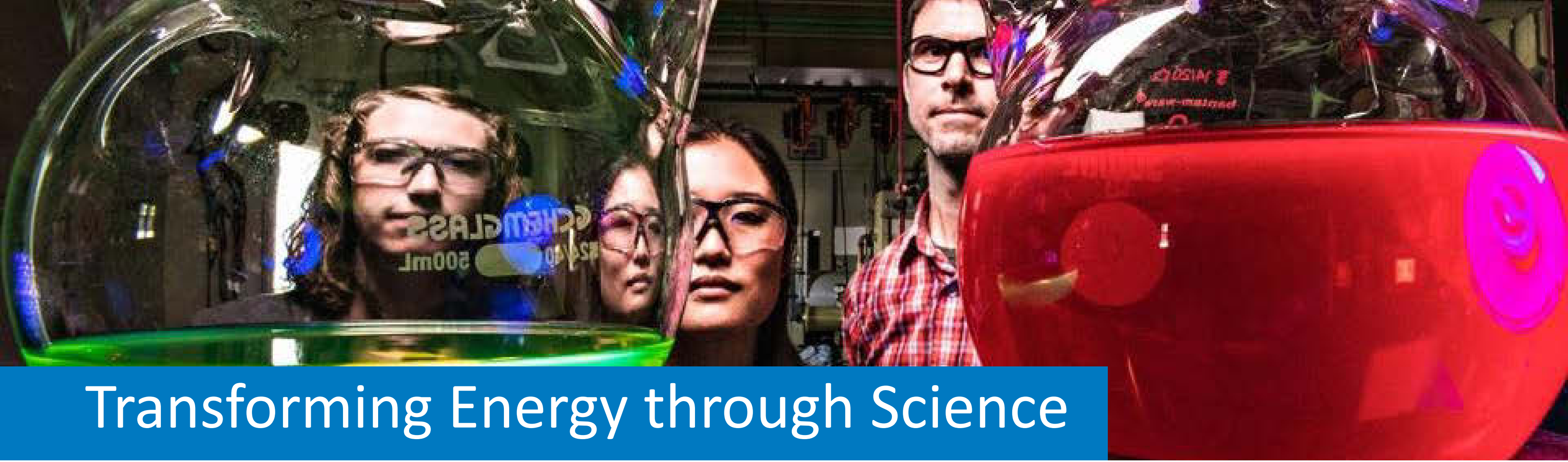
nearly 750

Partnerships
with industry, academia, and government

Campus
operates as a living laboratory

$872M annually

National economic impact



Transforming Energy through Science

NREL advances the science and engineering of **energy efficiency**, **sustainable transportation**, and **renewable power technologies** and provides the knowledge to **integrate and optimize energy systems**

NREL's Science Drives Innovation

Renewable Power

Solar

Wind

Water

Geothermal

Sustainable Transportation

Bioenergy

Vehicle Technologies

Hydrogen

Energy Efficiency

Buildings

Advanced Manufacturing

Government Energy Management

Energy Systems Integration

High-Performance Computing

Data and Visualizations

Connecting Renewables and Mobility

Renewables	Production	Distribution	Fueling	Mobility
Curtailed renewable electricity	Hydrogen production via electrolysis	Hydrogen storage and distribution via liquid, truck, pipeline	Hydrogen fueling cars, trucks, buses, and forklifts	Zero-emission mobility for people and goods

Fuel Cell and Hydrogen Technologies

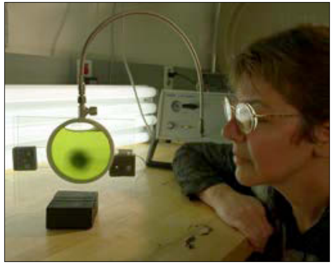
Major Research Topics

- Hydrogen production
- Delivery/H2FIRST
- Storage
- Fuel cells
- Fuel cell manufacturing R&D
- Technology validation
- Market transformation
- Safety, codes and standards
- Systems analysis

H2FIRST: Hydrogen Fueling Infrastructure Research and Station Technology

Hydrogen Production

- Photoelectrochemical (PEC) water splitting
- Photobiological water splitting (concluded)
- Fermentation of biomass
- Solar thermochemical water splitting
- Renewable electrolysis
- Pathway analysis (H2A)



Aerial view of facility

HydroGEN: Advanced Water Splitting Materials (AWSM)

HydroGEN
Advanced Water Splitting Materials
Core Labs

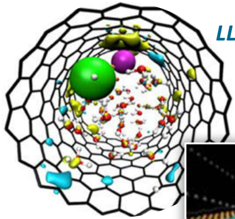
NREL · Berkeley Lab · Sandia National Laboratories · INL Idaho National Laboratory · Lawrence Livermore National Laboratory · SRNL

Accelerating discovery and development of innovative materials critical to advanced technologies for sustainable H_2 production, including:

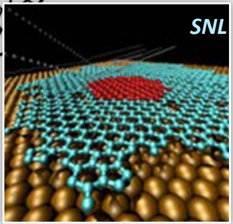
- ***Advanced high- and low-temperature electrochemical conversion***
- ***Direct photoelectrochemical solar water splitting***
- ***Direct solar thermochemical water splitting***

Comprising more than 80 unique, world-class capabilities/expertise in materials theory/computation, synthesis, characterization & analysis

Materials Theory/Computation

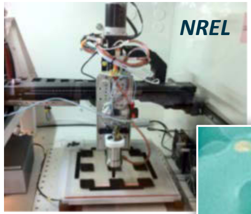


Bulk & interfacial models of aqueous electrolytes

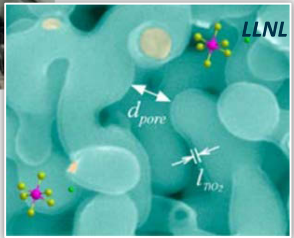


LAMMPS classic molecular dynamics modeling relevant to H_2O splitting

Advanced Materials Synthesis



High-throughput spray pyrolysis system for electrode fabrication



Conformal ultrathin TiO_2 ALD coating on bulk nanoporous gold

Characterization & Analytics

Stagnation flow reactor to evaluate kinetics of redox material at high-T

TAP reactor for extracting quantitative kinetic data

Website: https://h2awsm.org

Photoelectrochemical (PEC) H_2 Production: New World Record

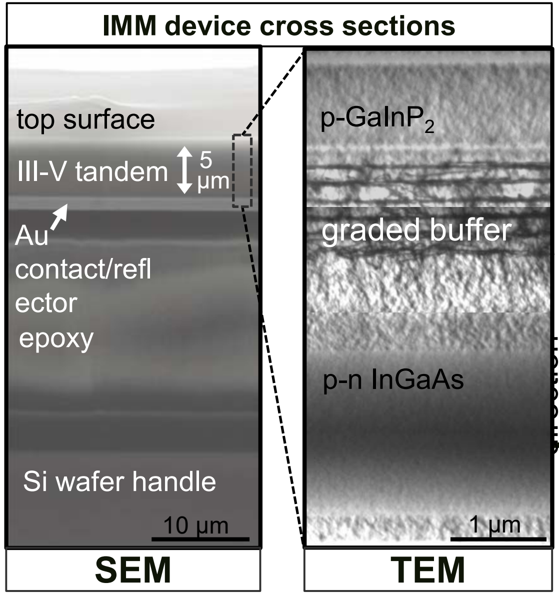
Technology

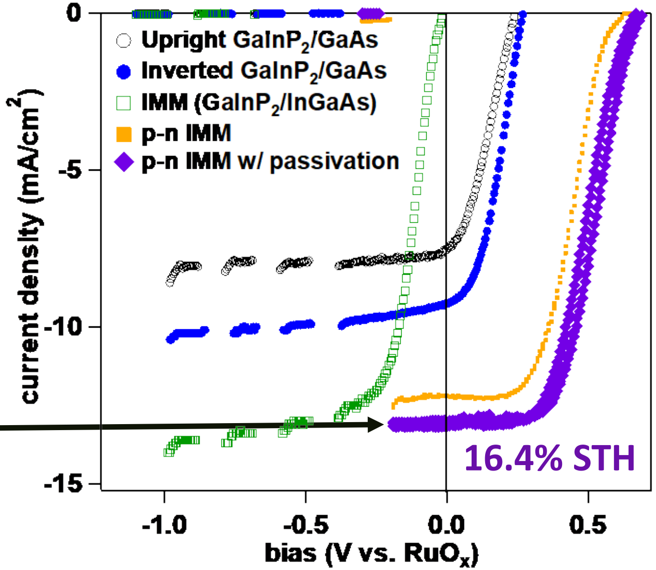
- **Inverted metamorphic multijunction (IMM) PEC** device enables more ideal bandgaps
- Grown by **organometallic vapor phase epitaxy**
- Incorporates **buried p/n $GaInP_2$ junction** and **AlInP passivation layer**

Solar-to-Hydrogen Efficiency

16.4%

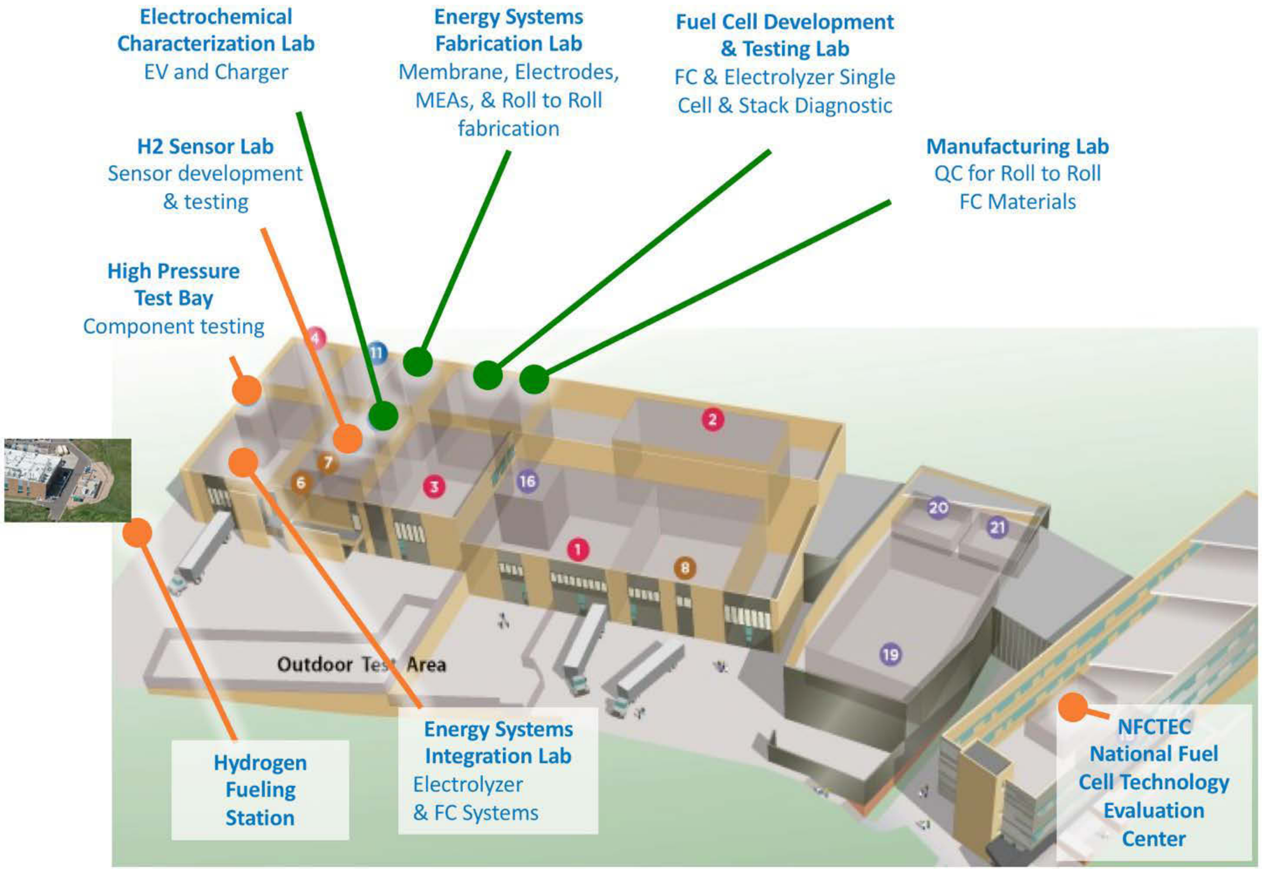
Benchmarked under outdoor sunlight at NREL





H_2
Production,
Compression,
Storage
Labs
High Performance
Data Center
Offices
Energy Systems Integration Facility (ESIF)

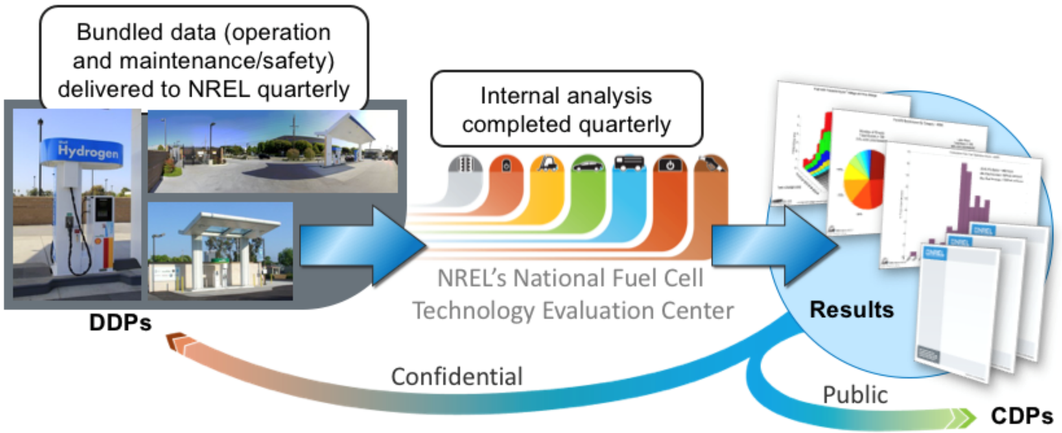
ESIF Layout



Electrochemical Characterization Lab
EV and Charger
Energy Systems Fabrication Lab
Membrane, Electrodes, MEAs, & Roll to Roll fabrication
Fuel Cell Development & Testing Lab
FC & Electrolyzer Single Cell & Stack Diagnostic
H2 Sensor Lab
Sensor development & testing
Manufacturing Lab
QC for Roll to Roll FC Materials
High Pressure Test Bay
Component testing
Outdoor Test Area
Hydrogen Fueling Station
Energy Systems Integration Lab
Electrolyzer & FC Systems
NFCTEC National Fuel Cell Technology Evaluation Center

National Fuel Cell Technology Center (NFCTEC)

- Independent, secure analysis
- Industry collaboration and benchmarking
- Confirmation of component and system technical targets
- Technology validation
- Evaluation, optimization, and demonstration in integrated energy systems and real-world operation
- Security of proprietary data

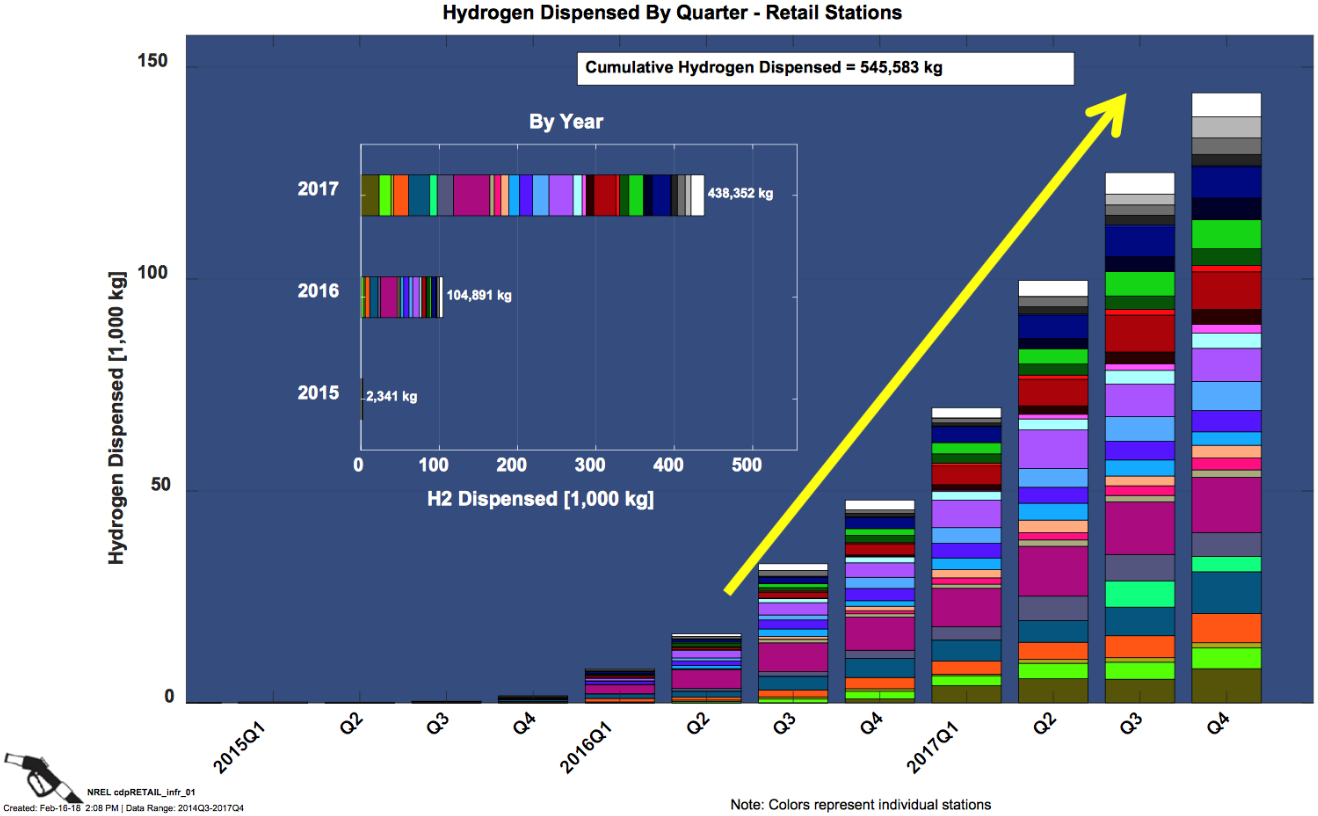


Detailed Data Products (DDPs)
- Individual data analyses
- Identify individual contribution to CDPs
- Only shared with partner who supplied data every 6 months[1]

Composite Data Products (CDPs)
- Aggregated data across multiple systems, sites, and teams
- Publish analysis results without revealing proprietary data every 6 months[2]

1) Data exchange may happen more frequently based on data, analysis, and collaboration
2) Results published via NREL Tech Val website, conferences, and reports

Hydrogen Dispensing

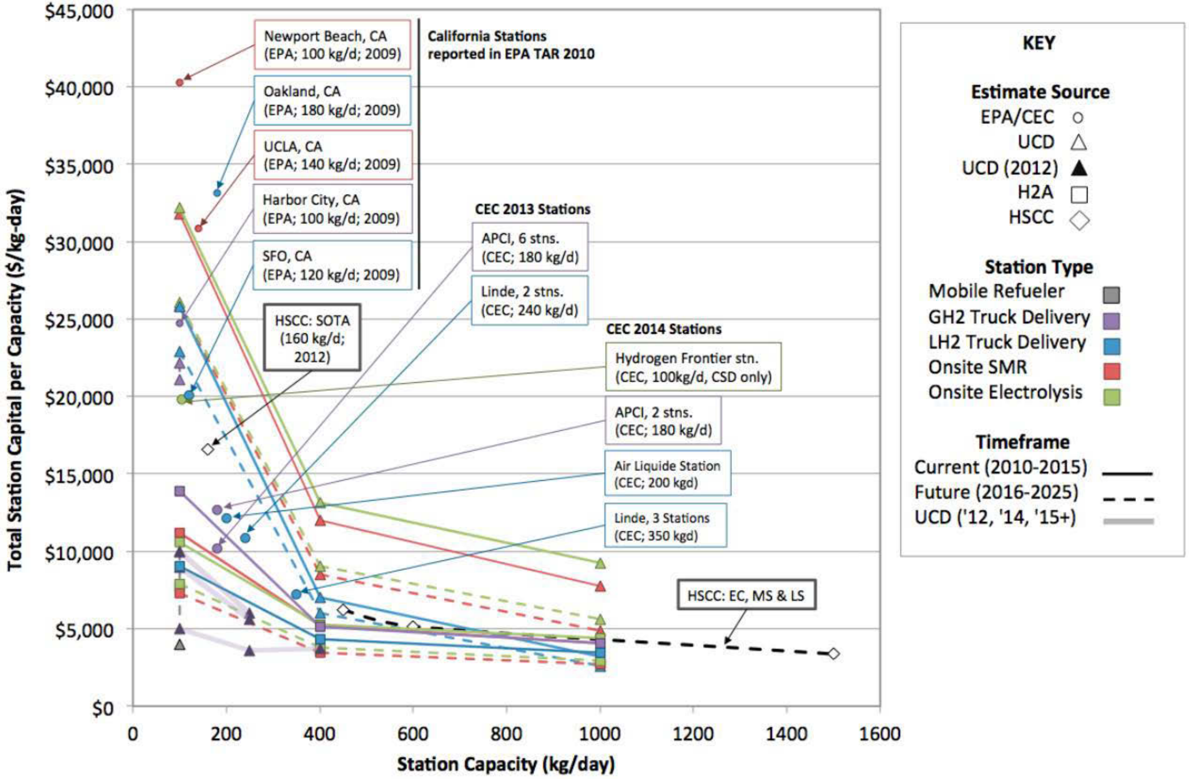


Average dispensing per station >50 kg/day

Average price is $16.31/kg

https://www.nrel.gov/hydrogen/infrastructure-cdps-retail.html

Capital Cost – H_2 Retail Stations



- Progress – 2009 100 kg/day stations >$20,000 kg/day
- <$3,000/kg for 1,000 kg/day station = $3 million

Source: NREL, https://www.nrel.gov/docs/fy13osti/56412.pdf

NREL Electrolyzer Experimental Setup

- Stack test bed at NREL's Energy Systems Integration Laboratory (ESIL)
  - Fully controllable AC-DC power supplies capable of 4,000 ADC and 250 VDC (1 MW)
  - All balance of plant equipment
  - Flexible platform with growing capability to test multiple electrolyzers at one time
  - Individual cell monitoring
  - Production to research hydrogen station

Image of electrolyzer hardware-in-the-loop, NREL

Electrolyzers as Controllable Loads

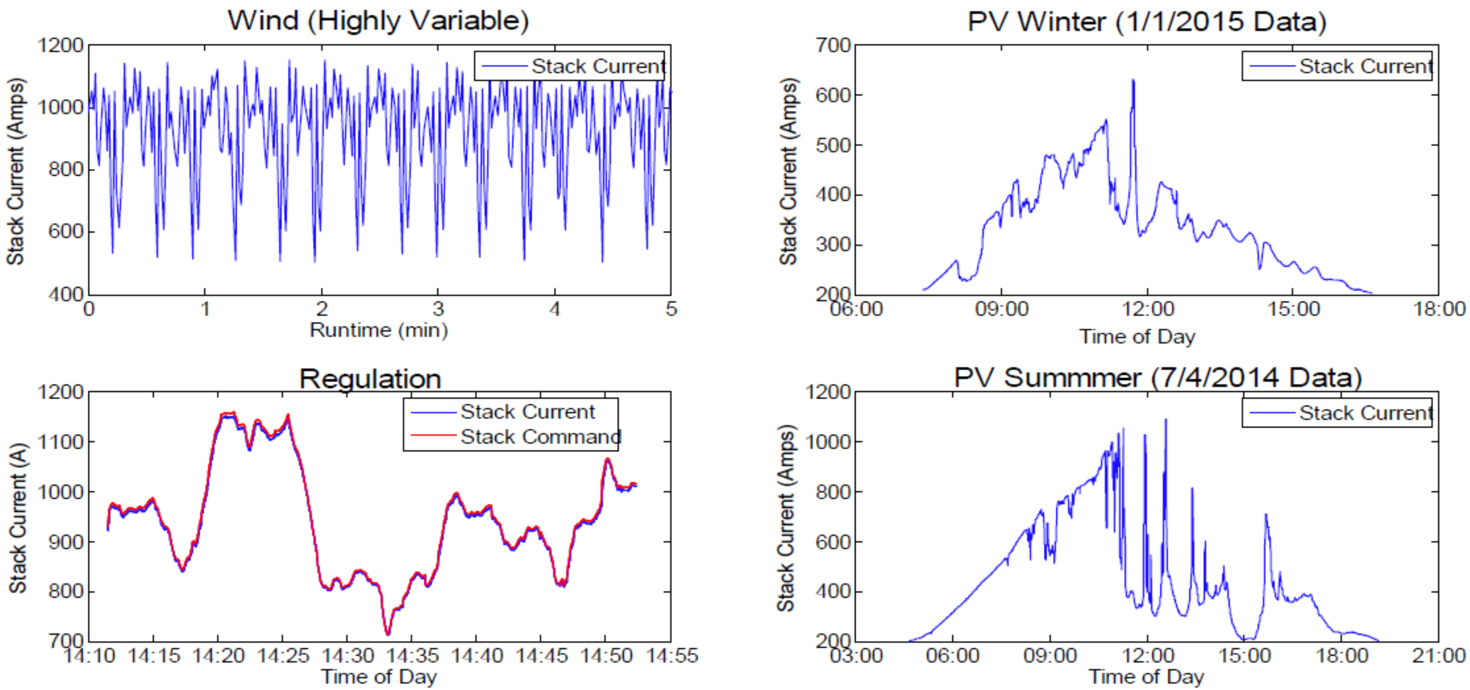
Real time dynamic operation

- Validating performance and benefits
- Verifying the communications and controls
- Optimizing balance of plant components
- Quantifying stack characterization and degradation
- Evaluating use case scenarios of electrolyzers providing grid services with hydrogen production

Image of electrolyzer hardware-in-the-loop, NREL

Renewable Hydrogen Production via Electrolysis

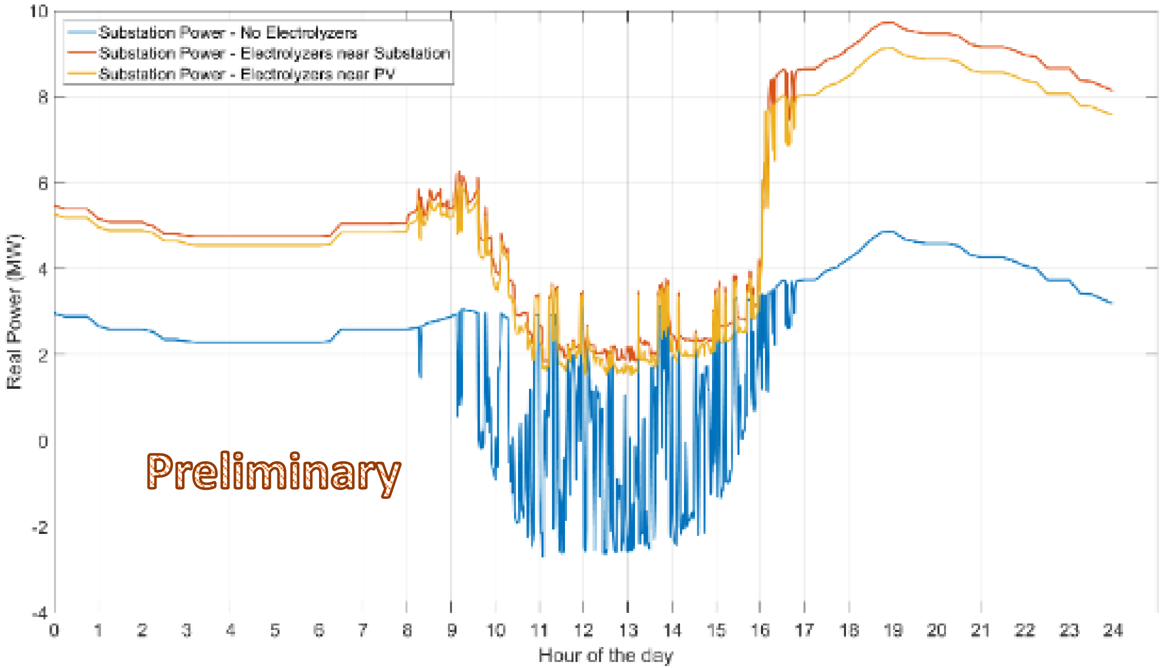
Electrolyzers can provide grid services **and** renewably generated hydrogen for mobility with fast response time as a controllable load.



Source: NREL

Electrolyzers Avoid Curtailed Renewable Generation with Hydrogen Production

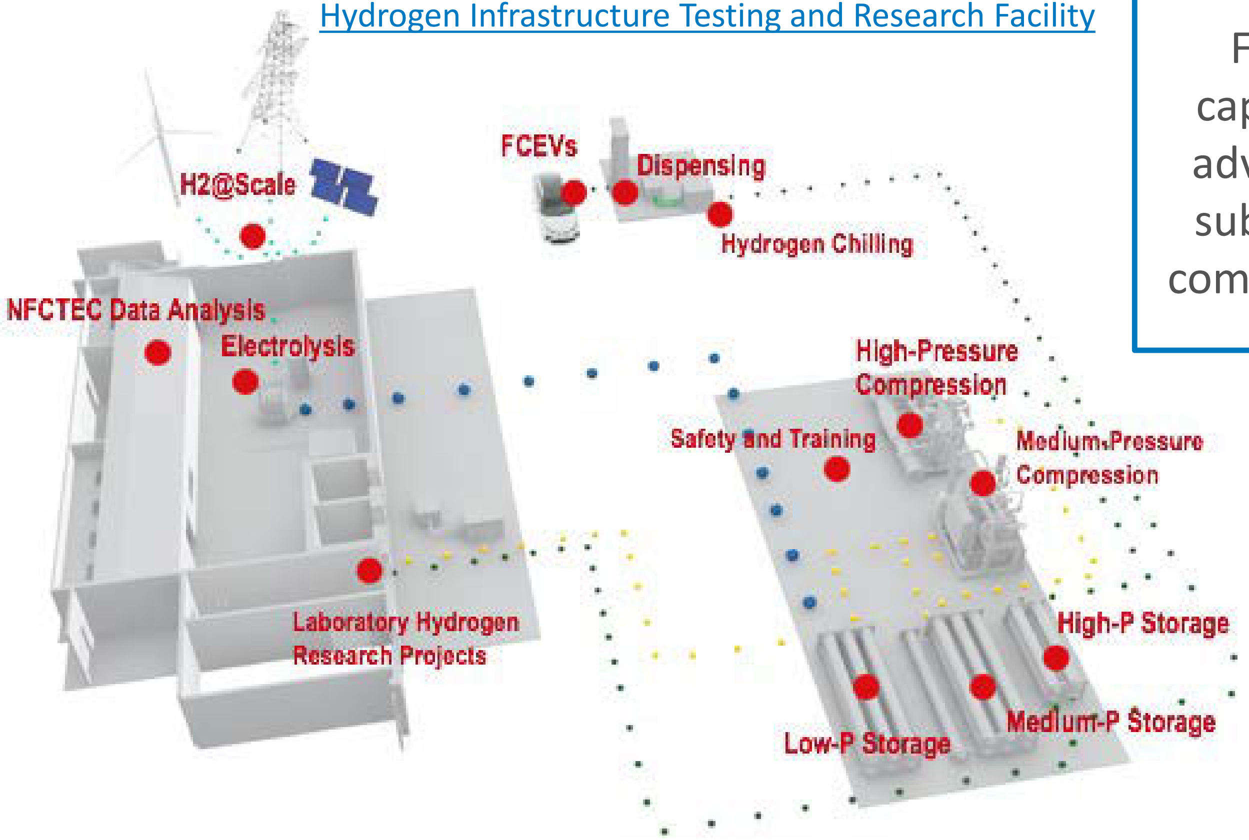
Electrolyzers are operated at nearly steady state until PV generation, then the electrolyzer network operates during PV transients to dampen impacts of variable generation on a distribution feeder, utilize what would have been curtailed PV generation, and produce high-value hydrogen.



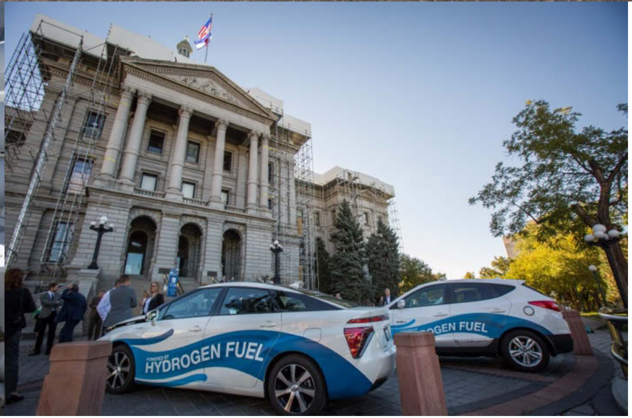
Source: NREL

Hydrogen Infrastructure Research at NREL

Hydrogen Infrastructure Testing and Research Facility

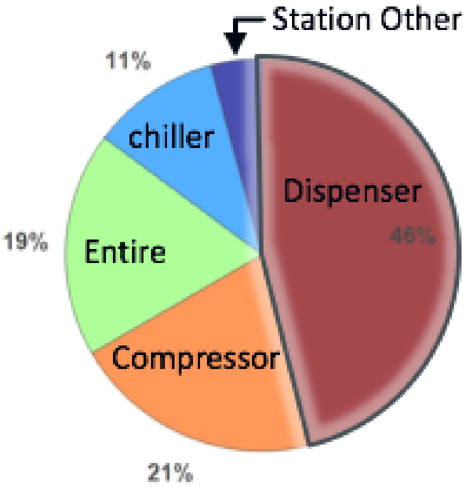


Fully integrated system capable of experiments on advanced components and subsystems and innovative component/system concepts.



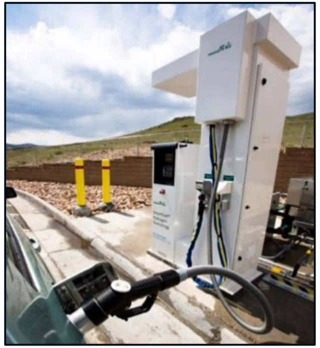
Dispensing, compression and storage, safety, control/operational strategies, production and delivery, outreach

Benchmarking Dispenser Reliability



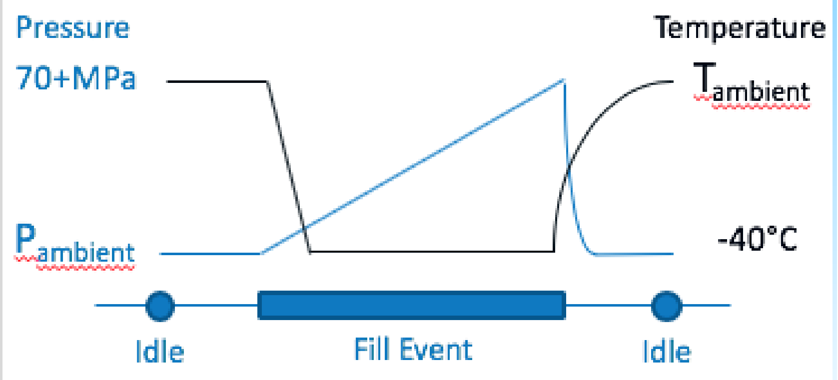
Maintenance by Equipment Type
Retail Stations
Total Events: 4,663
Dispenser: 46% of Events

NREL cdpRETAIL_infr_21



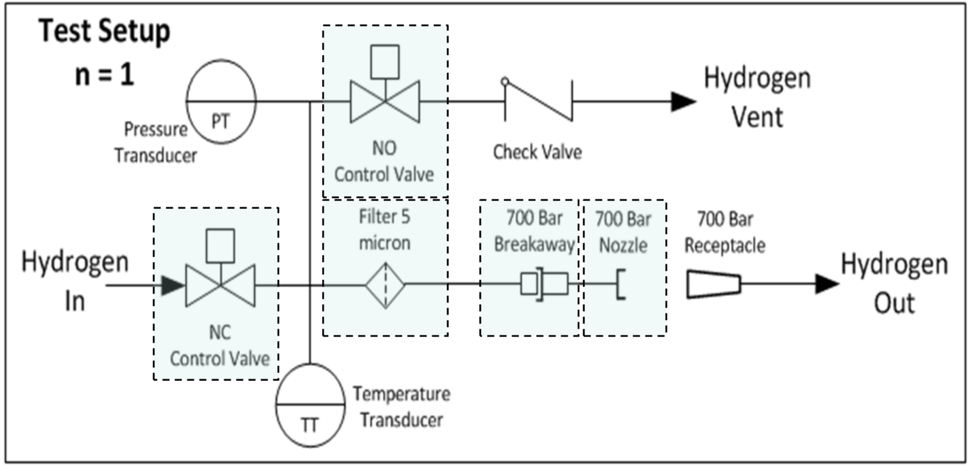
Major dispenser components:

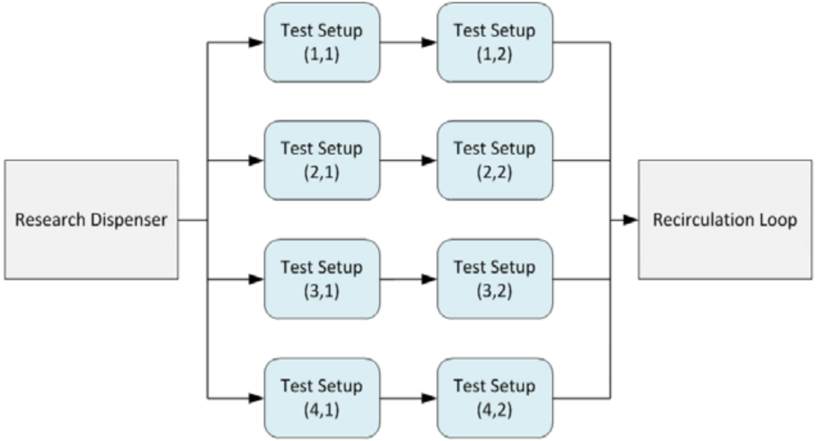
Breakaway
Hose
Nozzle
Block/Bleed Valves
Filters



Simplified Dispenser Cycle

Component Reliability Based On Temperature





- Gather statistical failure data for dispenser components
  - Number of fill events to failure
  - Mass of hydrogen dispensed to failure
- Sensitivity of component failures to controlled and uncontrolled variables

  T_{H_2} = -40°C, -20°C, 0°C $\qquad T_{ambient} \qquad RH$
- Inform industry with results to improve future component performance

Component Reliability Based On Use

Hose reliability project objectives:

- Replicate failures seen in the field
- Develop accelerated lifetime testing
- Identify methods for early prediction of failure
- Identify solutions for improved reliability

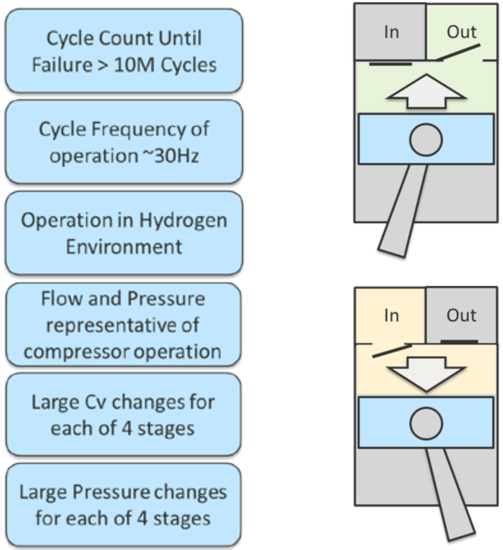
Nozzle freeze lock project objectives:

- Repeatable characterization in varying ambient conditions for temperature and humidity, diagnosis of cause, and recommended mitigation strategies for nozzle freeze lock events

Improving Hydrogen Compression

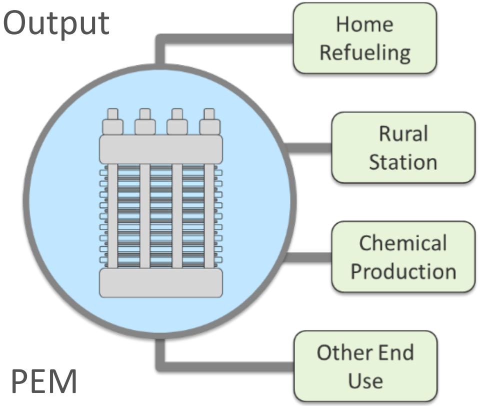
Compressor reed valve lifetime project objectives:

- Design a test apparatus capable of attaining valve failures representative of field operation



Electrochemical compression project objectives:

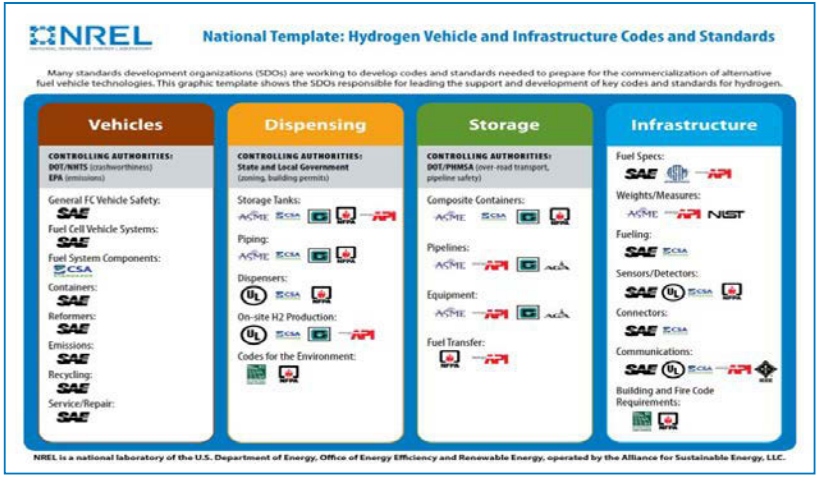
- Benchmark and validate system
- Identify potential market opportunities for project partner



Combined PEM Electrolysis and Compression System

Safety, Codes and Standards

- Guidance on safe operation, handling, and use
- Safety testing and sensors
- Vehicle, equipment, and building codes and standards



Top and middle photos by Keith Wipke, NREL; bottom photo by Dennis Schroeder

Thank you

www.nrel.gov

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