Plug Power: The Mobility Sector and Refueling Technologies

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Green Hydrogen at Work™

The most operational experience in emerging hydrogen markets

1+ billion Hours of operation	**60,000+** Systems in service	**25 years** Of innovation
99%+ Hydrogen availability	**220+** Private fueling stations	**40+ tons** Hydrogen dispensed daily

Largest PEM supply chain volume (common to fuel cells and electrolyzers)

- Most PEM fuel cell sales in the world
- Largest membrane electrode assembly manufacturer in the N. America
- Building GW scale manufacturing center in New York state

Plug Power Innovation of cryogenic infrastructure

- Operator of the world's largest hydrogen refueling station fleet
- Unparalleled ability to offer a comprehensive, cryogenic infrastructure solution

Comprehensive product offerings and support

- Hydrogen liquefaction and transportation technology
- Engineering support for broad end-use applications

Source: Plug internal analysis (2023)

Overview of context and objectives for this study

Context

- The hydrogen economy is in a state of rapid expansion fueled by accelerating industry interest, maturing decarbonization technologies, rapidly approaching targets, and government investments.
- The next 3-5 years will be critical to realizing the development and role out of technologies and applications that will allow us to successfully decarbonize a range of industries, particularly hard to abate ones.

Objectives

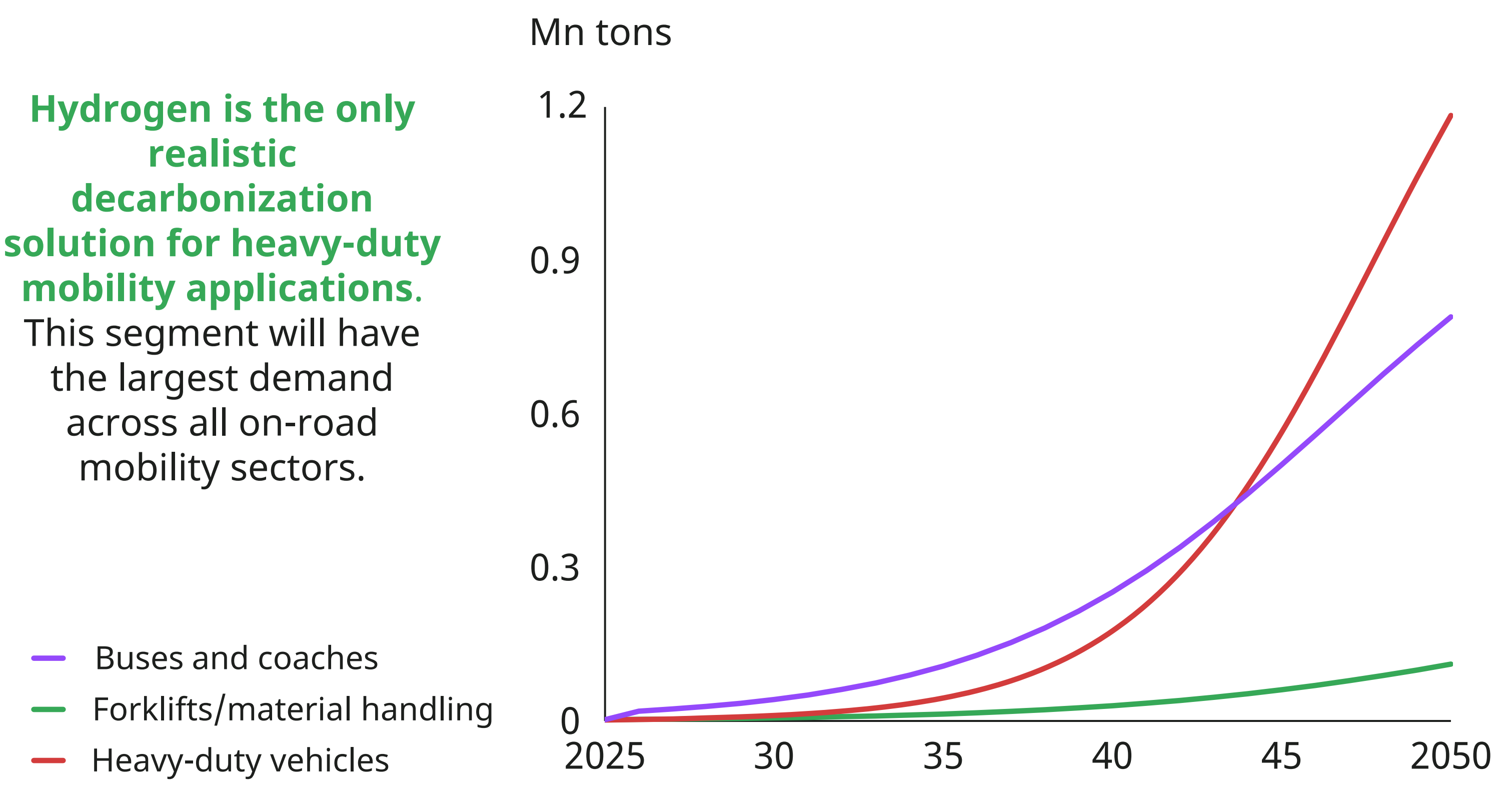
To describe the current state of the landscape with respect to hydrogen refueling infrastructure and the critical needs/capabilities/pain points as they are presently understood:

- **Review** feedback from the industry, government, and working groups on **application/technology timing**
- **Breakdown the various types of refueling infrastructure that will be needed**
- **Discuss some of the critical technology gaps** which are currently recognized
  - Make projections about where pain points could exist

Yearly baseline demand is interpolated for mobility applications

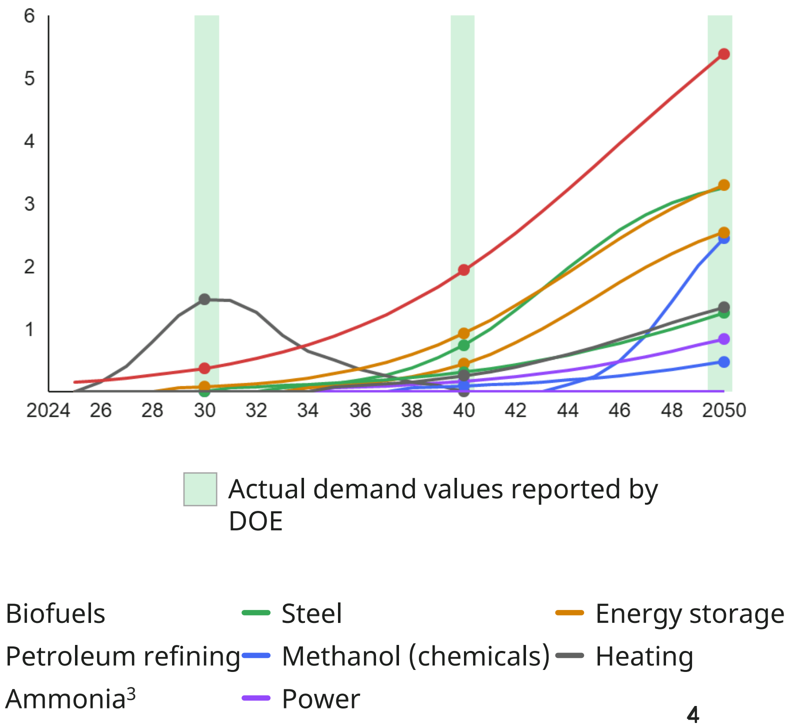
Breakdown of hydrogen demand for mobility

Hydrogen is the only realistic decarbonization solution for heavy-duty mobility applications. This segment will have the largest demand across all on-road mobility sectors.



Interpolated baseline demand curves by end-use sector

Green hydrogen demand, Mn tons



1. Logistic function (A+(A+B)/1+C/x)^n) is applied where A=forecasted minimum demand, B=forecasted maximum demand, x=individual year, n=curvature number
2. Threshold calculated based on the smallest project with 2025 Commercial Operation Date, Niagara Liquid Green Hydrogen (~6 ktpa); demand for each end-use is then assumed to pick up after it exceeds ~10x the size of this smallest viable hydrogen project
3. Ammonia demand for 2040 is adjusted up to account for 35% of total green hydrogen demand across end uses for curve fitting

Source: Plug Power analysis, DOE Liftoff report, National Hydrogen Strategy & Roadmap

Core Questions for Mobility

It is critical that we accurately identify the required technologies to satisfy an application

The application sets the core performance needs:

1) **How much Energy** does the application need?
2) **How fast** does it need to get it on-board?
3) **How often** will the station refill a platform?

Critical KPIs
Storage Medium
Dispense Quantity
Fueling Rate
Station Utilization
Efficiency

} $\$/kg_{dispensed}$

Application

The energy required for regular operation dictates the on-board storage and/or operational protocol (i.e. how long before refueling)

On-Board Storage

Refueling Solution

The on-board storage and station utilization will dictate the refueling station capabilities and specifications.

On-Board Storage: H_2 Density

Higher-density storage will ultimately be required…

Usually a closed ecosystem. Short ranges allow for “low” quantities of energy stored on-board. GH_2 at 350-Bar is a good solution.

Commercially Viable Present Day

On-Board Capacity: 1-20 kg H_2
HRS Fill Times: 2-15 minutes (1.0-3.6 kg/min)
HRS Utilization: 0.5 – 1.5 tons-H_2/day

- Material Handling
- Some Ground Support Equipment
- Some Buses/Short Range Trucking

Low Power/ Short Range Mobility

High Power/ Long Range Mobility

- **On-Board Capacity:** 20-500 kg-H_2 **HRS Fill Rate:** (10-20 min) 5-20 kg/min
- **HRS Utilization:** 4-8+ tons-H_2/day

Commercially Realized 2027-2029

- Heavy/Long Distance Trucking
- Agriculture
- Mining
- Construction
- Short Range Maritime (i.e., Ferries)

The fueling solution for each of these segments will be unique…

Aerospace

- **On-Board Capacity:** Platform-specific
- **HRS Fill Rate:** (30-40 min) 50-200 kg/min
- **HRS Utilization:** 10+ tpd

Commercially Realized 2035+

Maritime

- **On-Board Capacity:** ?
- **HRS Fill Rate:** ?
- **HRS Utilization:** ?

Commercially Realized 2035+?

Not commercially ready. Applications have significant energy demands. Multiple gaps currently exist:

- Supply Chain
- On-board Storage (GH_2 will not be viable)
- Codes & Standards
- Fuel Cells/Combustion

Ecosystem Fueling Infrastructure

A variety of fueling solutions will be required to support a multi-faceted site (i.e., airports and ports)

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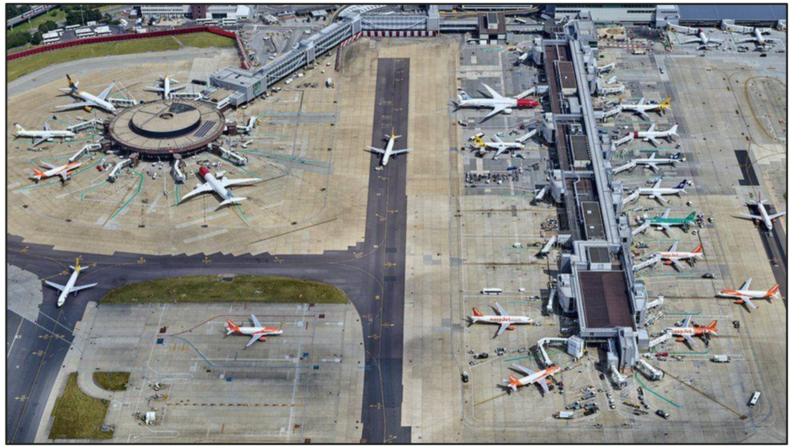
Mobile and Stationary fueling infrastructure will be required

Mobile Fuelling Infrastructure
- 350-Bar GH_2 — *GSE; Early Adoption*
- 700-Bar GH_2 — *GSE; Stationary MD Equipment*
- sLH_2/CcH_2 — *Aircraft; Stationary/Stranded HD Equipment*

Stationary Fuelling Infrastructure
- 350-Bar GH_2 — *Mobile GSE; Buses*
- 700-Bar GH_2 — *Mobile GSE; Buses/MD Trucks*
- sLH_2/CcH_2 — *HD Trucks; OGVs, Aircraft, Rail*



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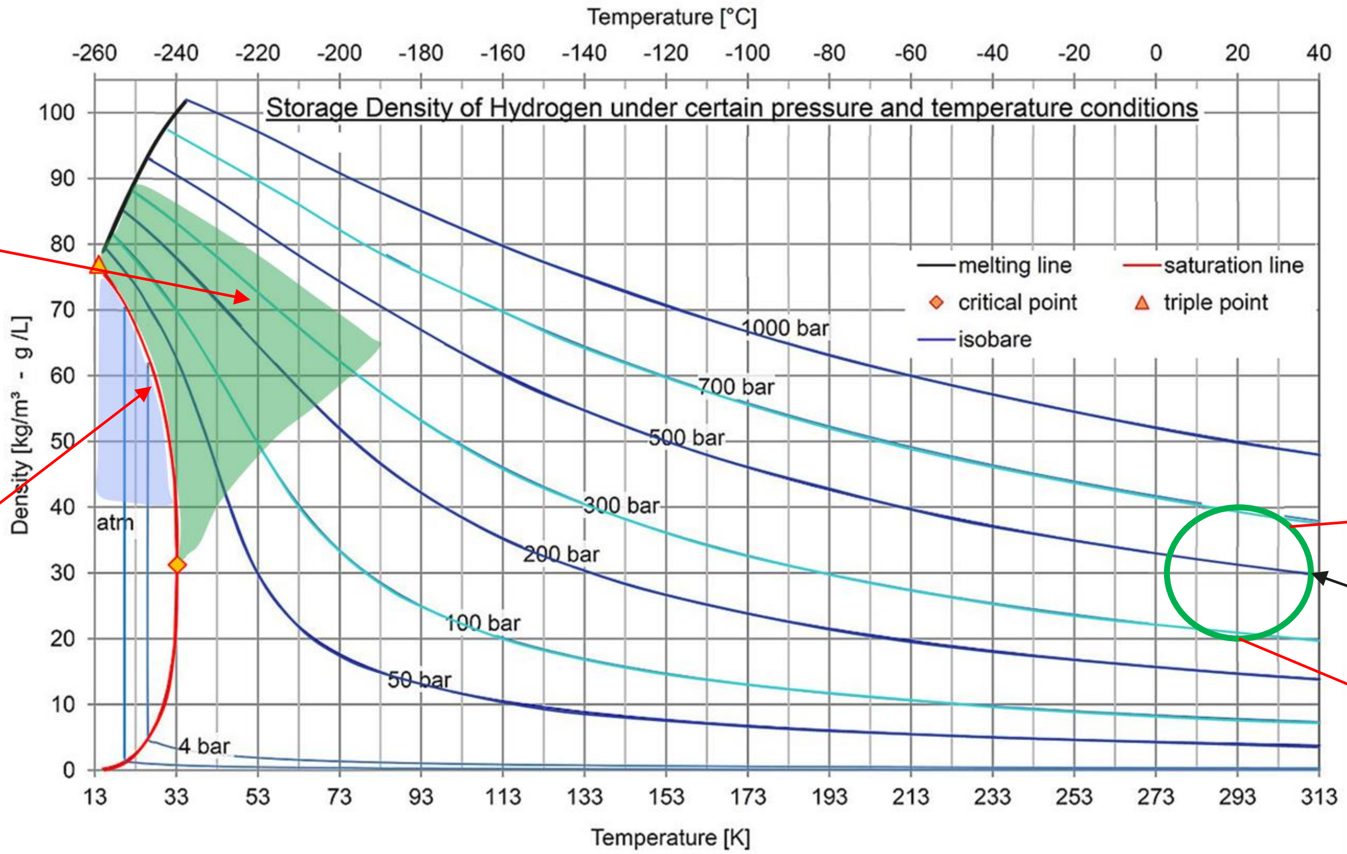
On-Board Storage: H_2 Density

Higher-density storage will ultimately be required…

The mobility industry will require higher density forms of storage. The most mature methods with regards to TRL are cryogenic techniques. Long term, cryo-absorbed/absorptive methods may be viable (2035+)

CcH_2
70-80 g/L
40-80K, 150-350-Bar

Sub-Cooled LH_2
50-60 g/L
~26K, 16-Bar



Each LH_2 solution has clear advantages and disadvantages…

700-Bar: 39.69 g/L

GH_2 Storage Range

350-Bar: 23.65 g/L

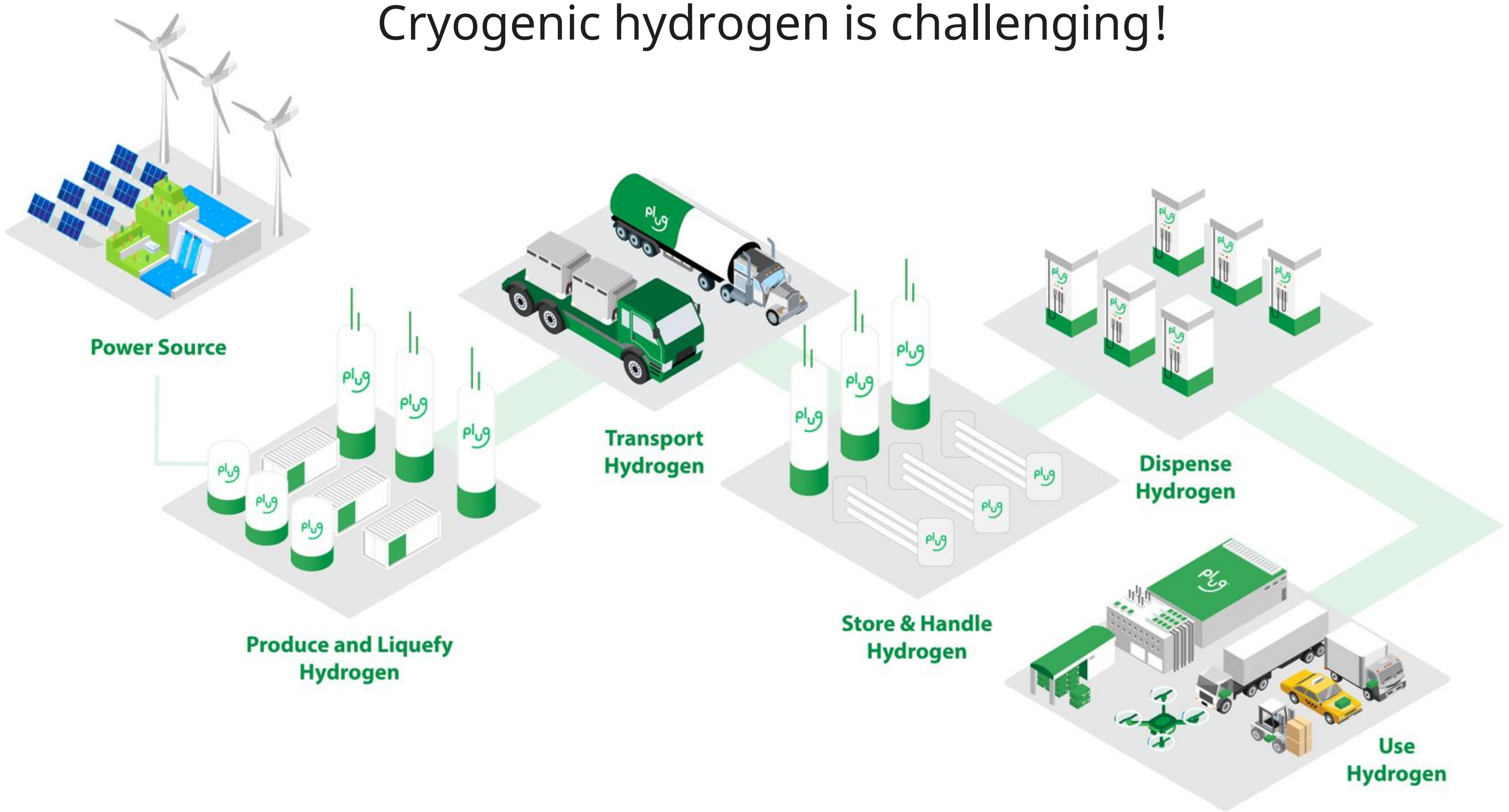
1 In the near term, 700-bar on-board storage will be a critical transitory technology.

2 Long term, cryogenic based solutions will be required for more mature market penetration and near-diesel parity.

Thermodynamic Optimization

Thermal optimization across the liquid supply chain is a critical gap…

Cryogenic hydrogen is challenging!



To realize the DOE performance targets set, **the entire supply chain must be optimized.** It cannot be treated as discrete elements any longer

Plug is building an end-to-end green hydrogen ecosystem, from production, storage and delivery to energy generation.

This affords us the unique ability to understand exactly how different parts of the hydrogen lifecycle impact a refueling station performance.

Hydrogen Refueling

Current Challenges…

- Safety Concerns, Challenges, & Considerations
- Transfer Operations
- Heavy Machinery
- Vapor Management
- Misc.

Plume Studies & Venting Releases

More research is needed on how plumes disperse in different meteorological conditions, particularly as release scenarios get bigger. This will be the case at airports, maritime ports, and large-scale storage sites. The lack of knowledge here creates difficulties in siting and implementing appropriate safety margins.
In addition, more complex site configurations must be studied and understood. This includes sites with multiple large liquid storage tanks or mobile refuelers. Considerations for scenarios that may occur need to be studied as well:

1. Venting from a mobile refueler near an aircraft intake
2. Cryo/near-cryogenic conditions
3. Mega-installations/complex site plumes and venting
4. Better integration into the code

Material Selections:

Future sites will require long and complex piping runs. Piping is needed which can be welded on and still be suitable for pressurized hydrogen service. At present, most piping available possess a heat treatment which will be degraded when welded. This prevents long piping runs from being utilized and increases the cost, complexity, and efficiency as junctions and fittings must be utilized instead.

Boil-Off Management

The number one problem with liquid, and barrier to adoption, is the belief that it will just boil away after you have invested in it. We get around it through frequent use, this is not something the majority of the market can guarantee (at this point). Zero-boil off storage techniques, at the large and small scale are critical. The current calls are still not addressing this issue in ways that will make changes. The economics of a ZBO system and the desired storage performance need to be taken into account. There needs to be a maturation pathways for zero-boil off storage.

Leak Detection:

Leak detection is generally considered challenging at best. It is almost impossible to detect a wide area thereby requiring a significant number of sensors to be deployed over a wide area to detect all leaks. Ultrasonic approaches do not seem to work well yet.

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PSM Limits

The current OSHA PSM limit is 10,000 lbs. This is an arbitrary number which needs to be less arbitrary. There needs to be more rationale behind the threshold at which different levels of safety studies are done.

Hydrogen Flame Radiation

There is a misapplication of radiation from hydrocarbon flames that is not necessarily appropriate for hydrogen flames. There are no radiating condensed phases in hydrogen flames. There need to be better guidelines for the industry for ignited plume radiation calculations.

Cryogenic Flow Meters

Metering liquid hydrogen is inaccurate at best. The best method to monitor at present is via scales weighing the downstream tank. This is impractical for higher volume applications (high flow rates, greater quantities, or greater frequency of fills). Turbine flow meters can be used but questions remain about the ultimate accuracy and longevity. This is also important for custody transfers of liquid hydrogen, both at the IGC level and during trucking filling operations.

Cryogenic Pump Reliability

Liquid hydrogen cryogenic pumps are still at an early stage of development with high costs and marginally sufficient performance at best. They are the biggest maintenance item at a refueling site, significantly impacting site efficiency, liquid tank performance, and hydrogen losses.
More reliable pumps are needed (specifically cold end improvements)

Transfer Pumps

This is a critical need to enable high utilization of liquid hydrogen in various applications as well as eliminate boil-off associated with differential pressure transfers. High flow rate, high volume pumps will be required, and they do not currently exist. Consideration also needs to be given for submersible pumps. The challenges with servicing them have prevented their adoption so far. Submersible pumps which were easily maintained or had exceptional reliability would be a key enabler.

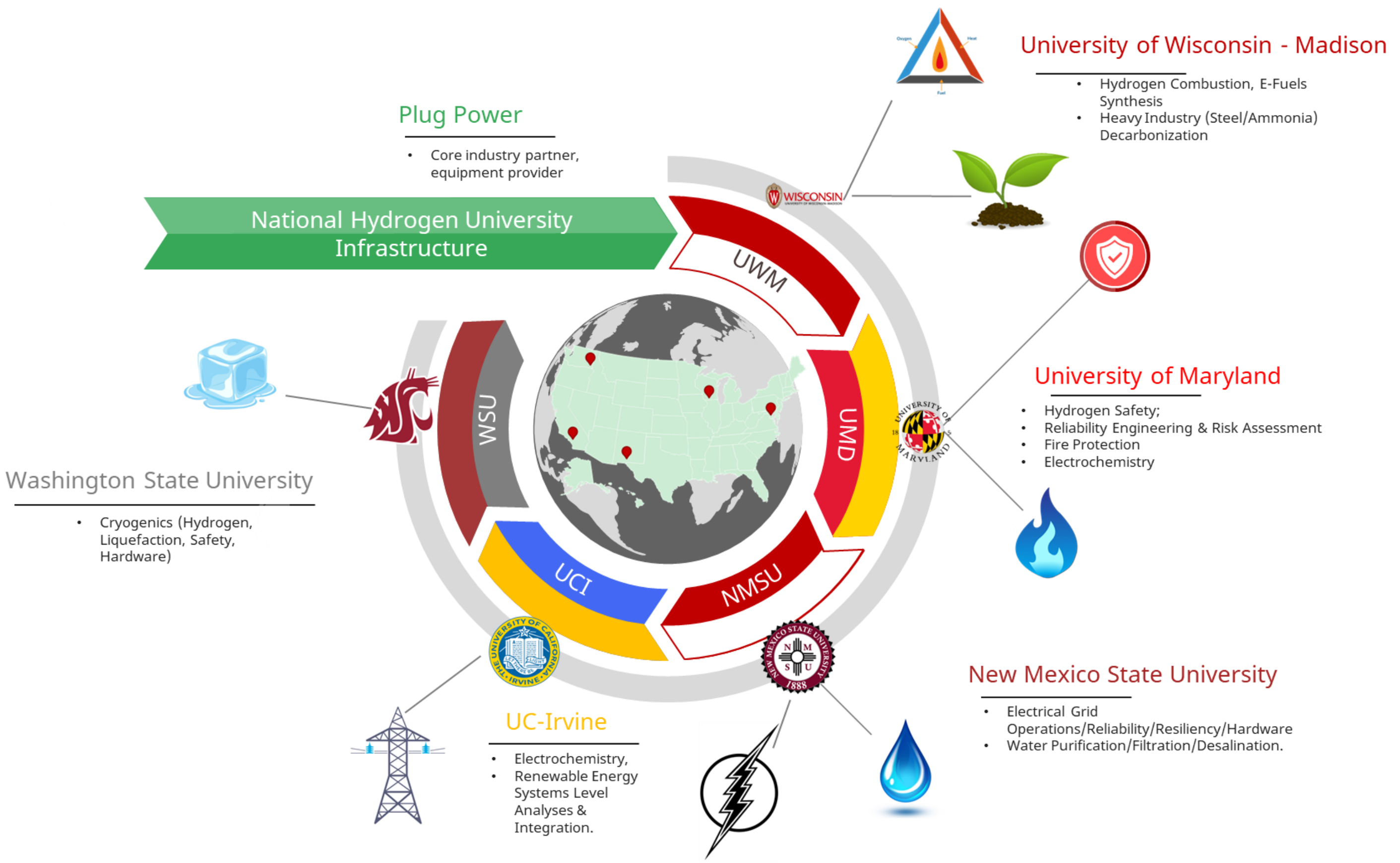
Workforce Development is Key

The availability of a trained, relevant workforce will quickly become one of the rate limiting factors with regards to the growth, maturation, and adoption of the hydrogen economy…

Overview: Plug is collaborating with key university partners across the country to enable to creation of unique, critically needed, workforce development programs. These centers would provide five things:

1) The means to provide students with hands-on hydrogen experience in a controlled, safe, and highly relevant manner thereby accelerating workforce development.
2) Support DE&I and EJ efforts in the local community.
3) Promote education and greater awareness of clean energy and green hydrogen.
4) Enable adoption of hydrogen powered applications and serve as a pivot to support further expansion.
5) Serve as a backbone to support further research and development interests.

Each university has been identified for their unique capabilities and relevancy to the clean hydrogen economy.



Workforce development is a critical need across the hydrogen landscape.

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