Hydrogen Storage

A brief overview of hydrogen storage options

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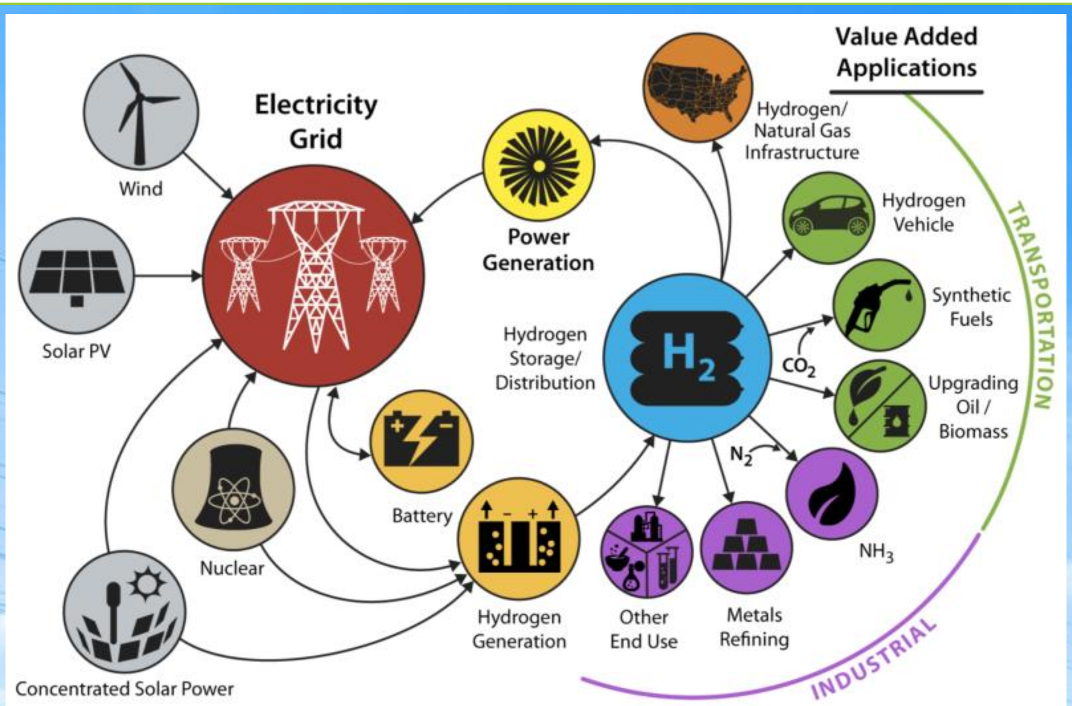


Ref:(https://www.greencarcongress.com/2016/09/20160911-doe.html)

2nd workshop on Thermal, Mechanical and Chemical Energy Storage

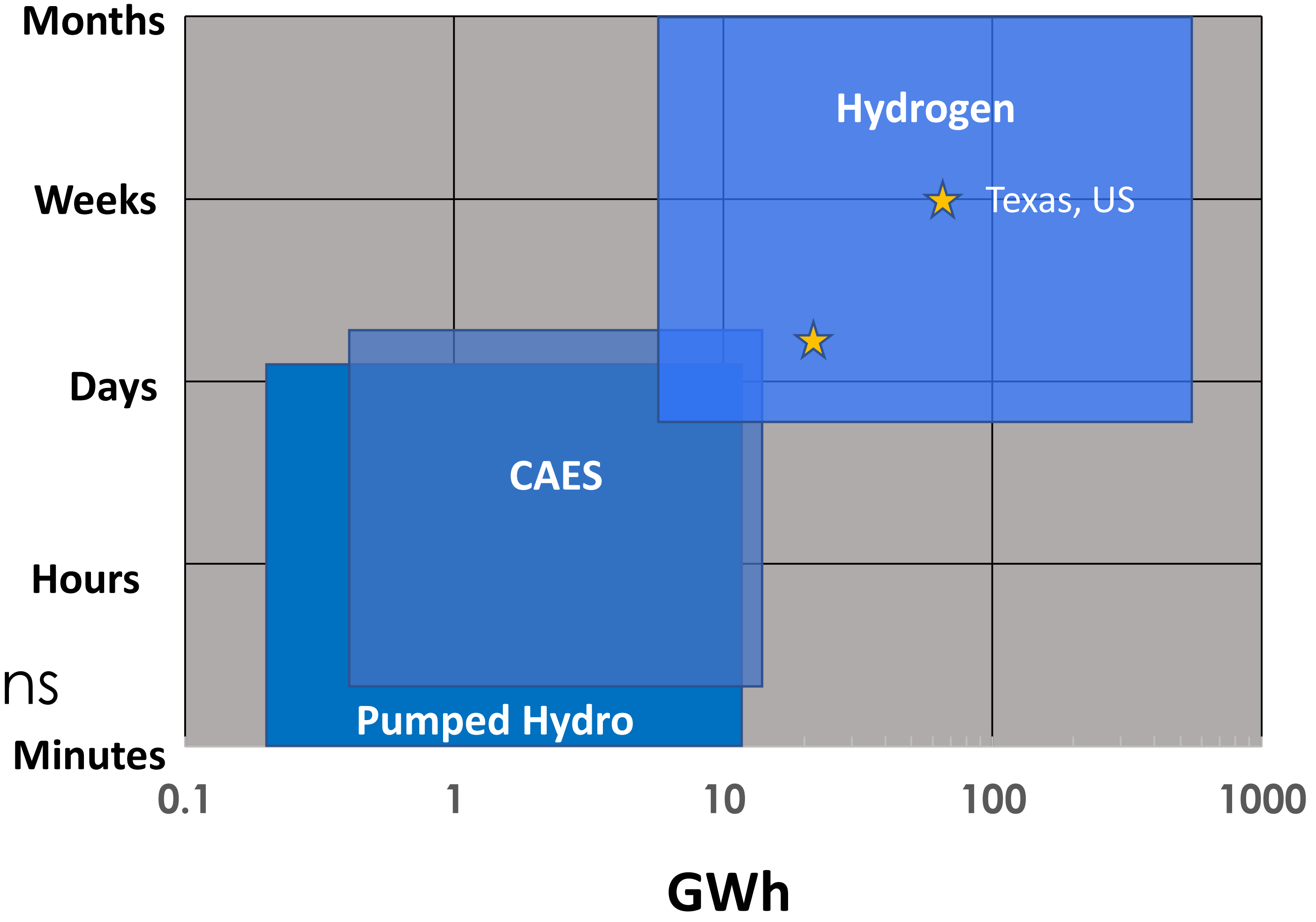
Omni William Penn; Pittsburgh PA; February 4, 2020

Sponsored by Elliot Group; Co-organized with SwRI and NETL

Presentation Outline

Small-scale to large-scale hydrogen storage provides attractive options

- H_2 physical properties
- Overview H_2 production, transportation & utilization
- H_2 storage technologies
  - Compressed storage
  - Liquid storage
  - Materials based storage
  - Chemical hydrogen storage
  - Vehicle & portable applications
  - Storage in NG pipelines
- Summary



Ref:
1. Crotogino F, Donadei S, Bu¨ nger U, Landinger H. Large-scale hydrogen underground storage for securing future energy supplies. Proceedingsof 18thWorld Hydrogen Energy Conference (WH2C2010), Essen, Germany;May 16e21, 2010. p. 37e45.
2. Kepplinger J, Crotogino F, Donadei S, Wohlers M. Present trends in compressed air energy and hydrogen storage in Germany. Solution Mining Research Institute SMRI Fall 2011 Conference, York, United Kingdom; October 3e4, 2011.

Physical Properties of H_2 vs CH_4

H_2 has a very low density and energy density, and a high specific volume

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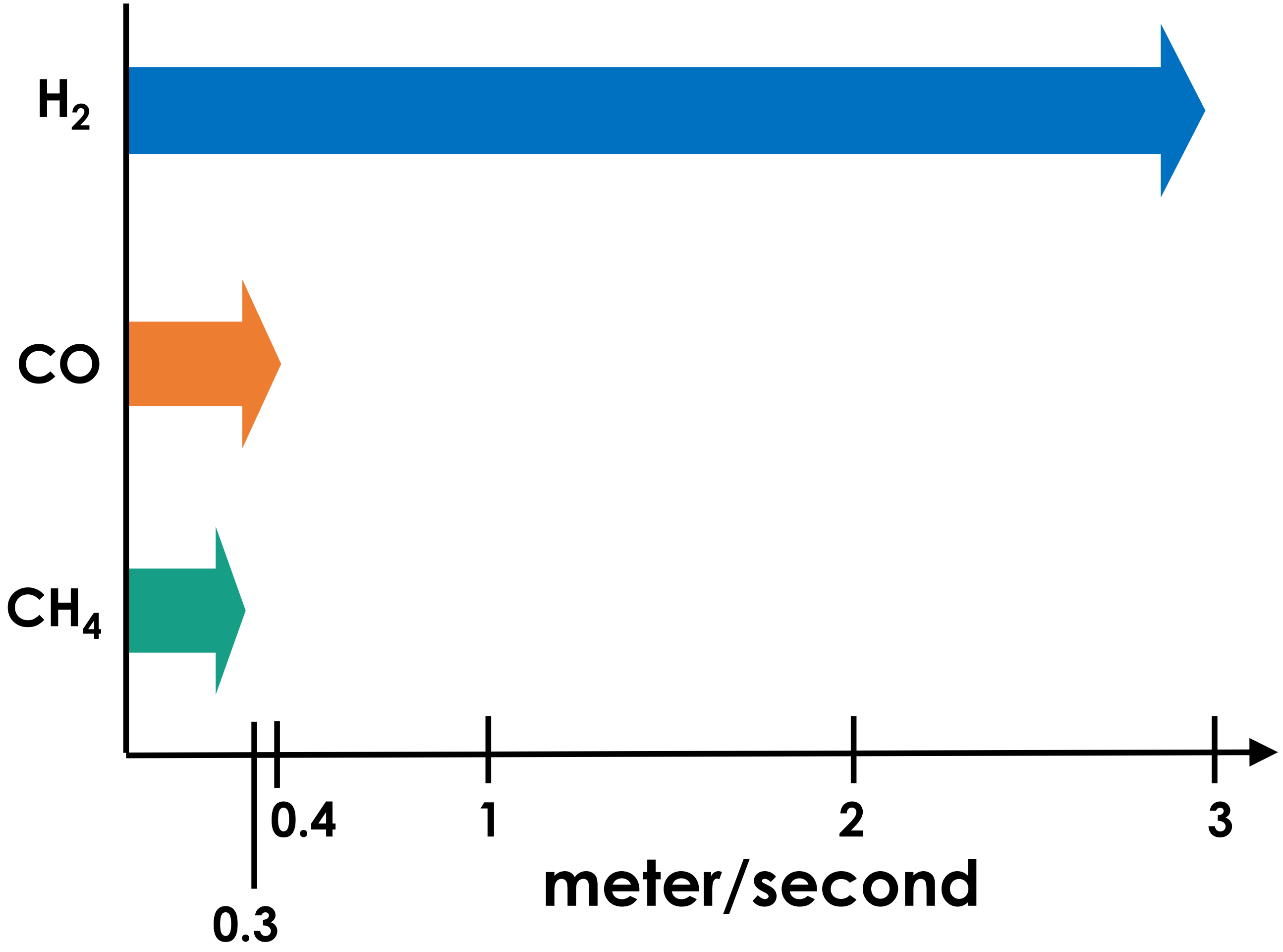
Property	Density (kg/m^3)	Lower Heating Value (kJ/kg)	Specific Volume m^3/kg	Energy Density kJ/m^3
Hydrogen	0.085	120	11.98	10,050
Methane	0.65	50	1.48	32,560
	1 atm,15°C	1 atm, 25°C	1 atm, 21°C	1 atm, 25°C

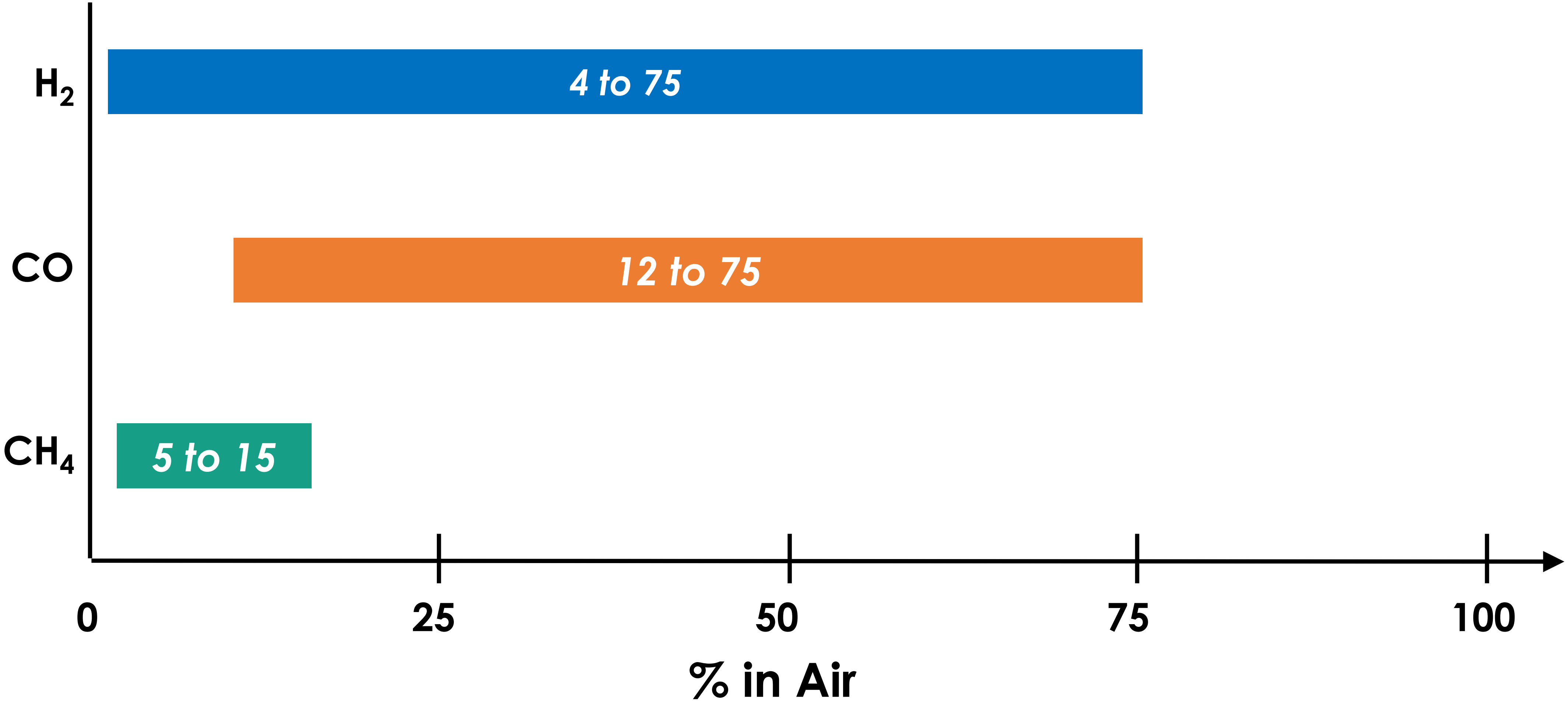
Laminar Flame Speeds

Hydrogen burns ten times as fast as methane



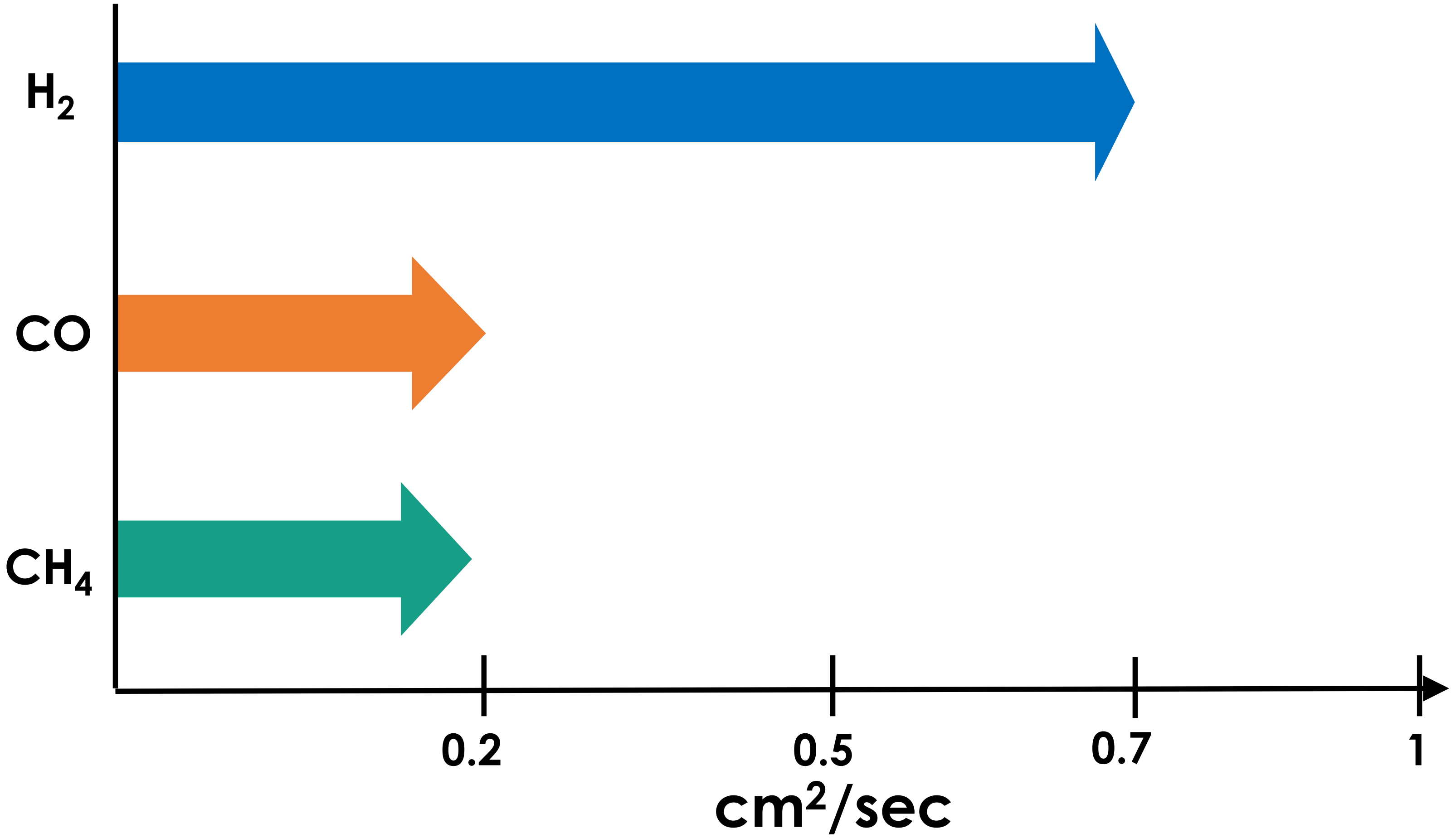
Flammability Limits In Air

Hydrogen has broad flammability limits compared to methane



Diffusivity in Air

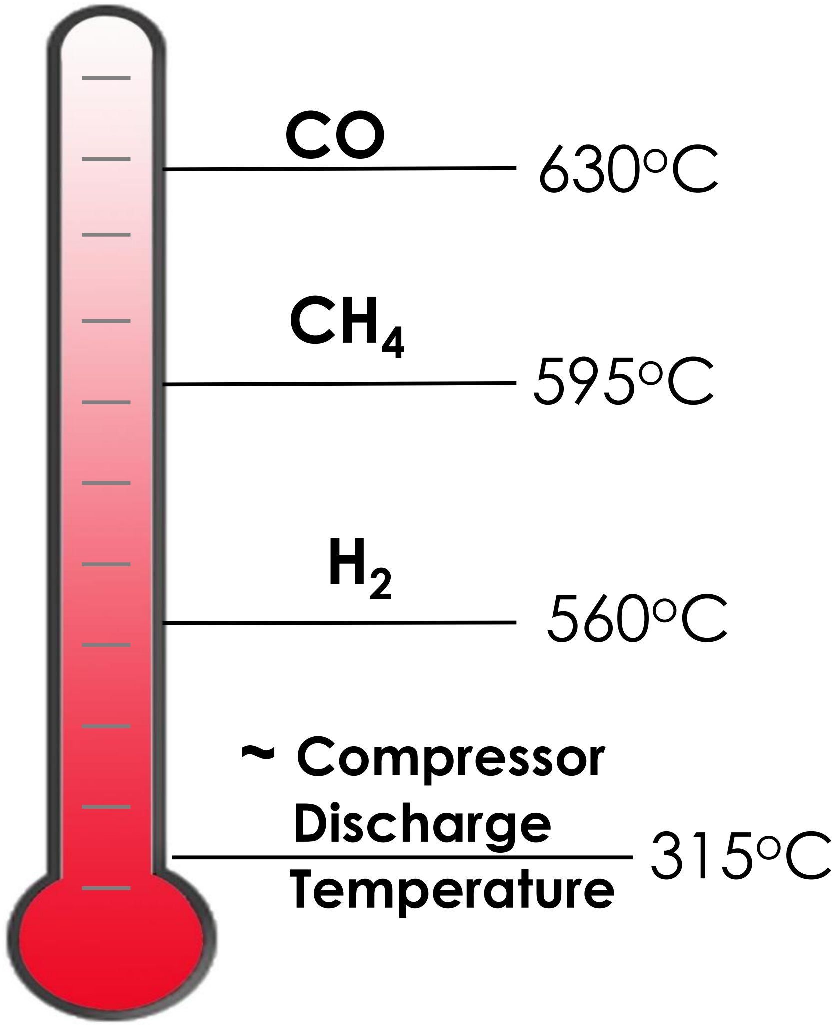
In air, hydrogen diffuses over three times as fast compared to methane



Ref: Vargaftik, N. B., Vinogradov, Y. K., and Yargin, V. S. (1996) *Handbook of Physical Properties of Liquids and Gases*, 3rd Ed., Begell House, Inc., New York.

Auto Ignition Temperature & Minimum Ignition Energy

H_2 auto ignition temp. safely higher than compressor exit temperatures



Minimum Ignition Energy (mJ)

CO	0.3 (2)
CH_4.............	0.3 (1)
H_2...............	0.017 (1)
Coffee.........	160 (1)

References
1. Babrauskak, V. (2003) Ignition Handbook, Fire Science Publishers, Issaquah WA
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Overview of Hydrogen Technologies

Production, Transportation and Utilization

Hydrogen Production

- Produced using domestic resources – water, natural gas and coal
- DOE supports R&D for a wide range of H_2 production technologies
  - Electrolytic – electrolyzers to split water into H_2 and O_2
  - Thermochemical - NG reforming (SMR, SOEF, etc.)
  - Solar – use light energy to split water into H_2 and O_2
- Challenge – Cost & Efficiency

Hydrogen Transport

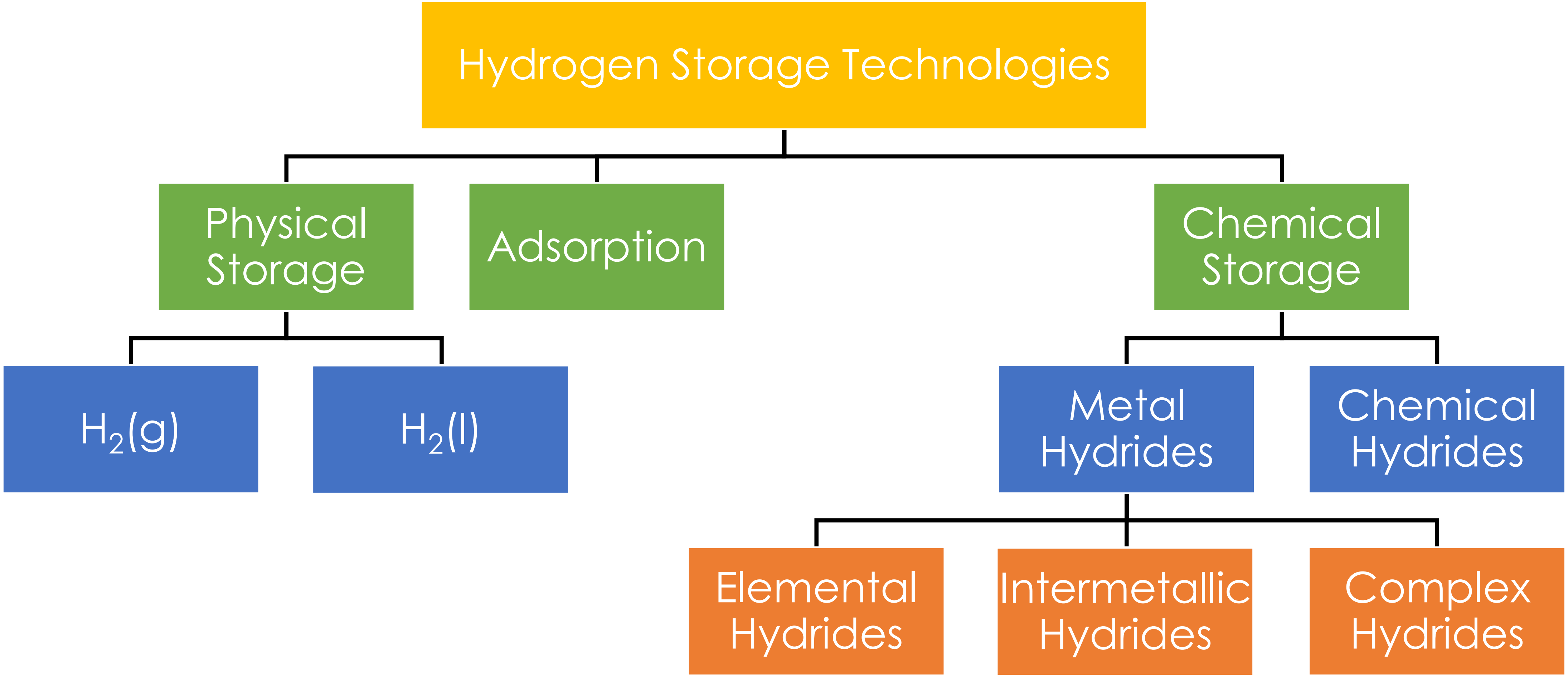
- Develop infrastructure to deliver H_2 from points of production to end-use
- Mixed into the natural gas pipe line system
- Pressurized and delivered as a compressed gas or liquefied
- DOE supports R&D to develop H_2 transport technologies and reduce costs
- *Challenges* –delivery cost, purity, compression efficiency, reduce leakage

Hydrogen Utilization

- Develop technologies to utilize H_2 as an energy source
  - Combustion turbines, fuel cells, other heat engines, domestic appliances
- *Challenges* – H_2 fuel properties: low energy density, broad flammability limits, high flame speed, low ignition energy
- DOE supports R&D to improve the understanding of H_2 combustion and develop advanced H_2 utilization technologies

Hydrogen Storage Technologies

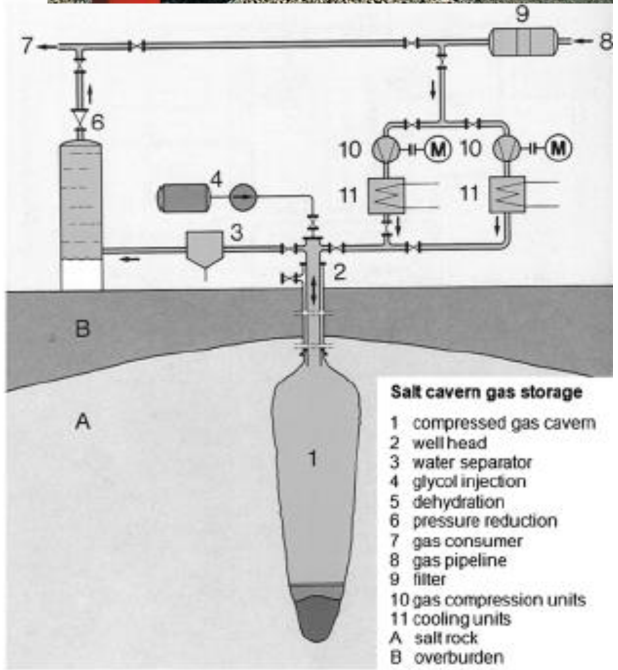
Generalized groups of hydrogen storage technologies



Ref: Andersson, J. and S. Gronkvist, 2019, "Large-scale storage of hydrogen." International Journal of Hydrogen Energy, Vol. 44.

Physical Storage - Gaseous hydrogen

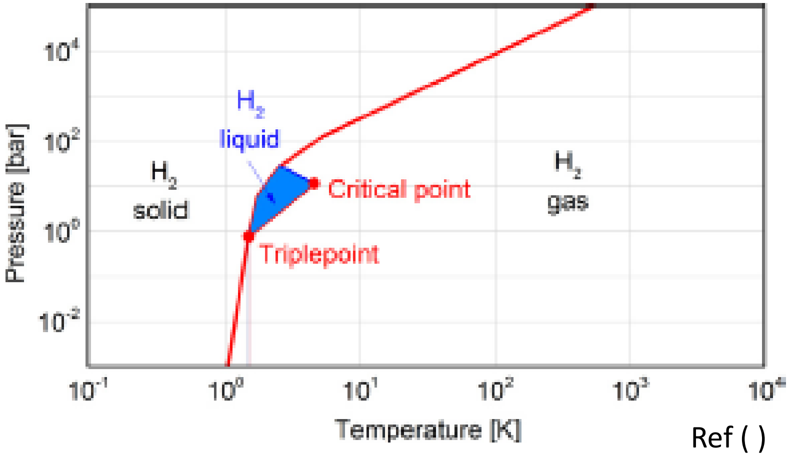
- Spherical pressure vessels (20 bar)
- Pipe storage (100 bar)
  - Common for industrial use
- Underground
  - Salt caverns
    - Several in use at full industrial scale
    - Not applicable in all geographic regions
    - Many advantages: Low construction costs, low leakage rates, fast withdrawal and injection rates, low cushion gas requirements, minimal H_2 contamination
  - Depleted oil/gas reservoirs
    - Low cyclability
    - Potential leakage issues
- Large gaseous storage volumes can have high investment costs but typically lower operating costs
  - Primarily compression and storage vessels



Ref: Salt Cavern Image: KBB. Untertagespeicher. Kavernen Bau und Betriebs GmbH; 1988.

Physical Storage - Liquid hydrogen

- High storage density (70kg/m^3 at 1 bar)
- Utilized in the space industry
- Energy intensive (BP: -253°C @1 bar, does not cool during throttling above -73°C
- Expensive containment vessels
- Boil-off is an issue
  - mitigated if stored near liquefaction plant
- Installations exist globally (355 tpd capacity)



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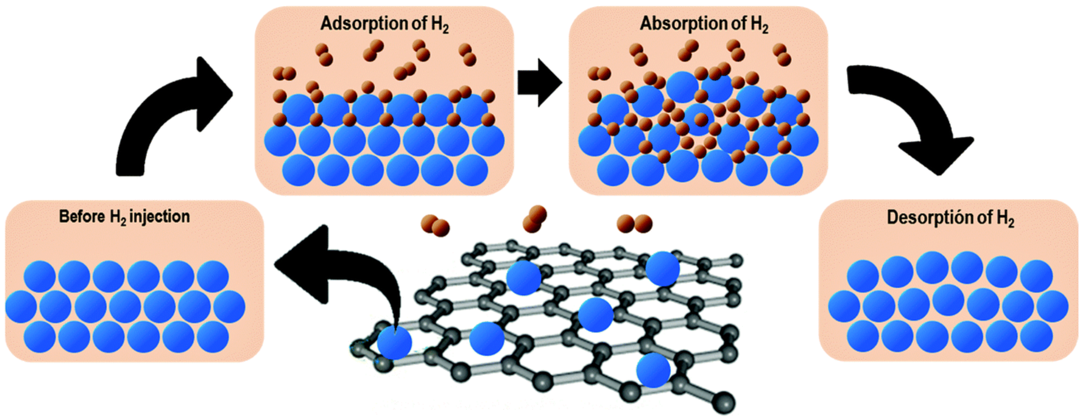
Adsorption

- Van der Waals forces bond H_2 to materials with large specific surface area
- Adsorbents
  - Porous carbon-based materials
  - Metal-organic frameworks
  - Porous polymeric materials
  - Zeolites
- Low temperatures and elevated pressures are typically required to promote VWF
- Exothermic process, heat management necessary
- Lab-scale only, low TRL
- Storage capacity likely limited to 40 – 50 kg/m^3 at – 196 °C



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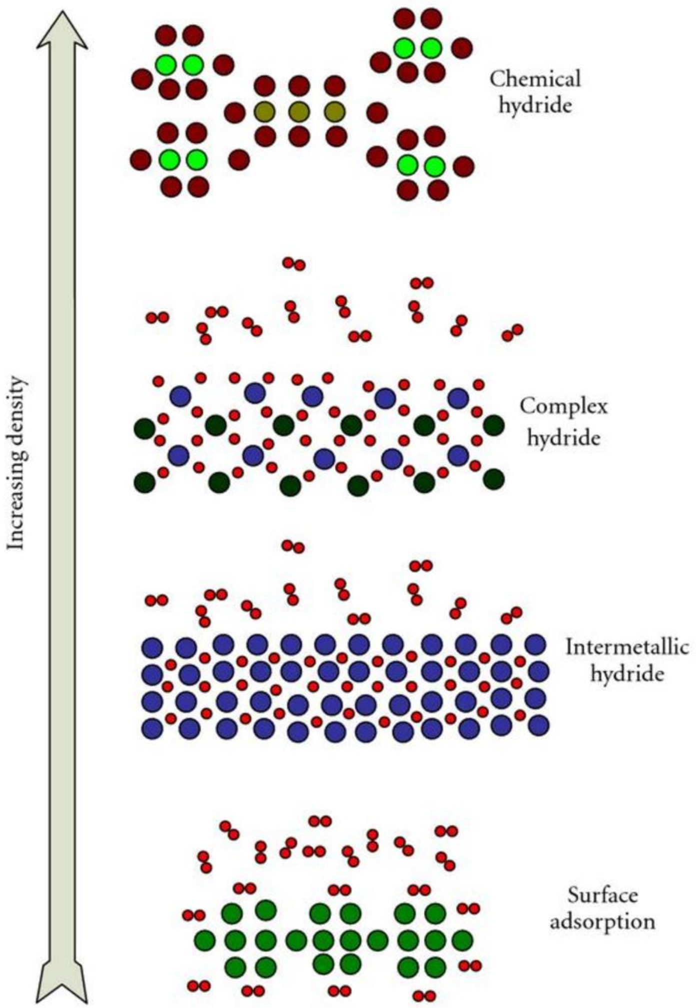
Chemical Storage – Metal Hydrides

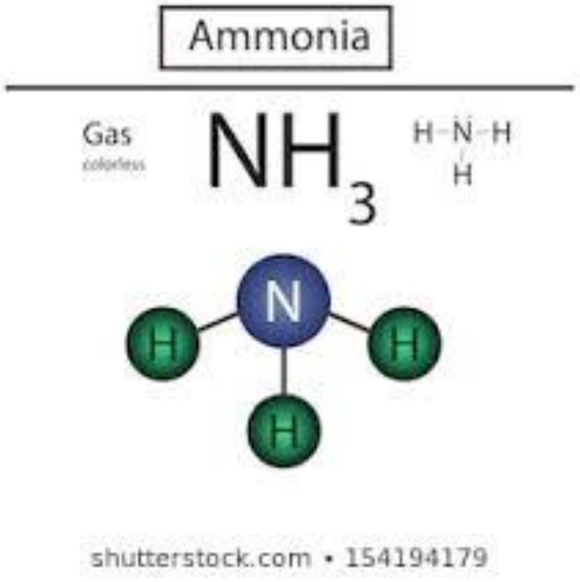
- H_2 chemically bonds with the material
- Wide range of available materials
  - Elemental (magnesium, aluminum)
  - Intermetallic
  - Complex metal
- H_2 is released with:
  - Water (hydrolysis, exothermic, irreversible)
    - $NaBH_4$
  - Heating(thermolysis, endothermic, reversible)
    - MgH_2 and AlH_3
- Issues
  - Heat management
  - Dehydrogenation energy
  - Costly materials
- A popular choice for vehicle applications
  - MgH_2 storage capacity ~ 86 kg /m^3



Ref: Andersson, J. and S. Gronkvist, 2019, "Large-scale storage of hydrogen." International Journal of Hydrogen Energy, Vol. 44.

Chemical Storage - Chemical hydrides

- Highest energy density of all chemical storage methods
- Formic acid (53 kg/m^3)
  - Low hydrogen storage density
  - Easily dehydrogenated
- Methanol (99 kg/m^3)
  - Can be dehydrogenated with steam reforming
  - Synthesized from CO_2 and hydrogen, (also stores CO_2)
- Ammonia(123 kg/m^3 at 10 bar)
  - High hydrogen storage density
  - Requires high heat to completely dehydrogenate
- Liquid organic hydrogen carriers
  - Remain liquid at ambient conditions in both hydrogenated and dehydrogenated states



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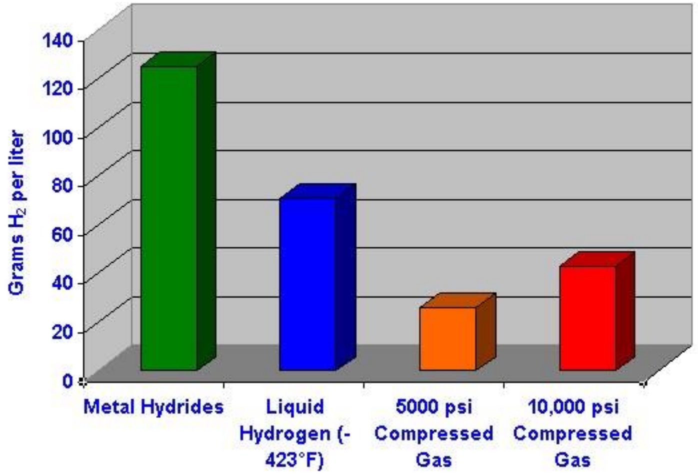
Hydrogen Storage for Vehicle Applications

- Primary solution: High pressure cylinders
- Vehicles have different storage characteristics than large scale storage:
  - compact, light, stable, quick charging/discharging, strict delivery conditions
- Large scale storage would require:
  - Low energy and capital costs
  - Low leakage/loss rates
- Research for vehicle H_2 storage has driven material development
  - Similar to battery development
  - Metal hydrides could be the answer to density for vehicles, but weight is an issue



Natural Gas Pipeline System as Storage Capacity

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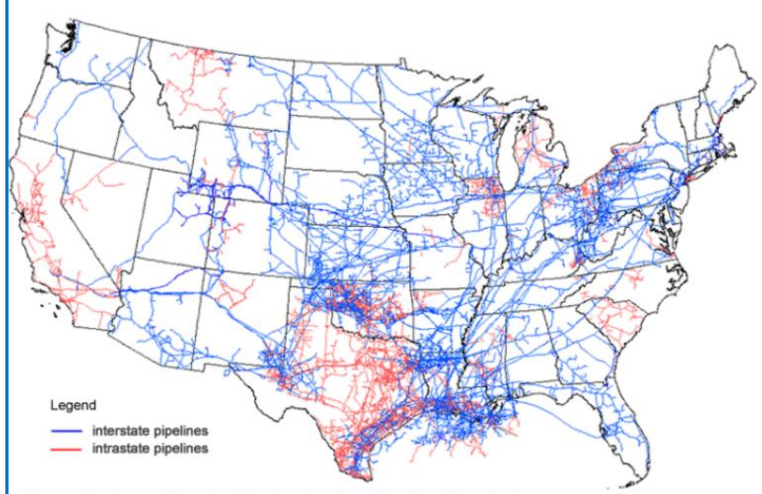
- 3 million miles of natural gas pipeline in the US: Vast potential for immediate H_2 storage
- Mixing10-20% hydrogen in natural gas pipelines could be possible today
- Combustion apparatus can handle some amount of H_2/CH_4 fuel blending
  - Appliances: 10-20% (depending on appliance) with no issues
  - Turbines: can handle 10% blending with no modifications or up to 30% with minor alterations

Map of U.S. interstate and intrastate natural gas pipelines



Source: U.S. Energy Information Administration, *About U.S. Natural Gas Pipelines*

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1. *Energy Information Administration (EIA), 2020, "Natural gas explained." https://www.eia.gov/energyexplained/natural-gas/natural-gas-pipelines.php*
2. McDonell, V. et al., 2019, "Implications of Increase Renewable Natural Gas on Emissions and Stability Behavior of Appliances." Presentation, CEC Grant PIR-16-017, October 23, 2019.
3. ETN Global, "Hydrogen Gas Turbines: The Path Towards a Zero-Carbon Gas Turbine."

Operating Costs of H_2 Storage Technologies

	Storage Process				Release Process	
Storage Technology	Heat (kWh/kg H_2)	Temp (°C)	Pressure (bar)	Electricity (kWh/kg H_2)	Heat (kWh/kg H_2)	Temp (°C)
Gas 100 bar	-	-	100	1	-	-
Gas 200 bar	-	-	200	1.2	-	-
Gas 700 bar	-	-	700	1.6	-	-
Liquid Hydrogen	-	-253	-	6	-	-
Adsorption	-	-176	40	6.7	-	-
AlH_3	54	<70	-	10	1	100
MgH_2	-	300	30	0.7	10.3	350
Intermetallic Hydride	-	<80	50	0.8	~2-6	<80
Formic Acid	64	100-180	105	6.7	4.3	<100
Ammonia	-	400	250	2-4	4.2	>425
Methanol	-	250	50	1.3-1.8	6.7	250

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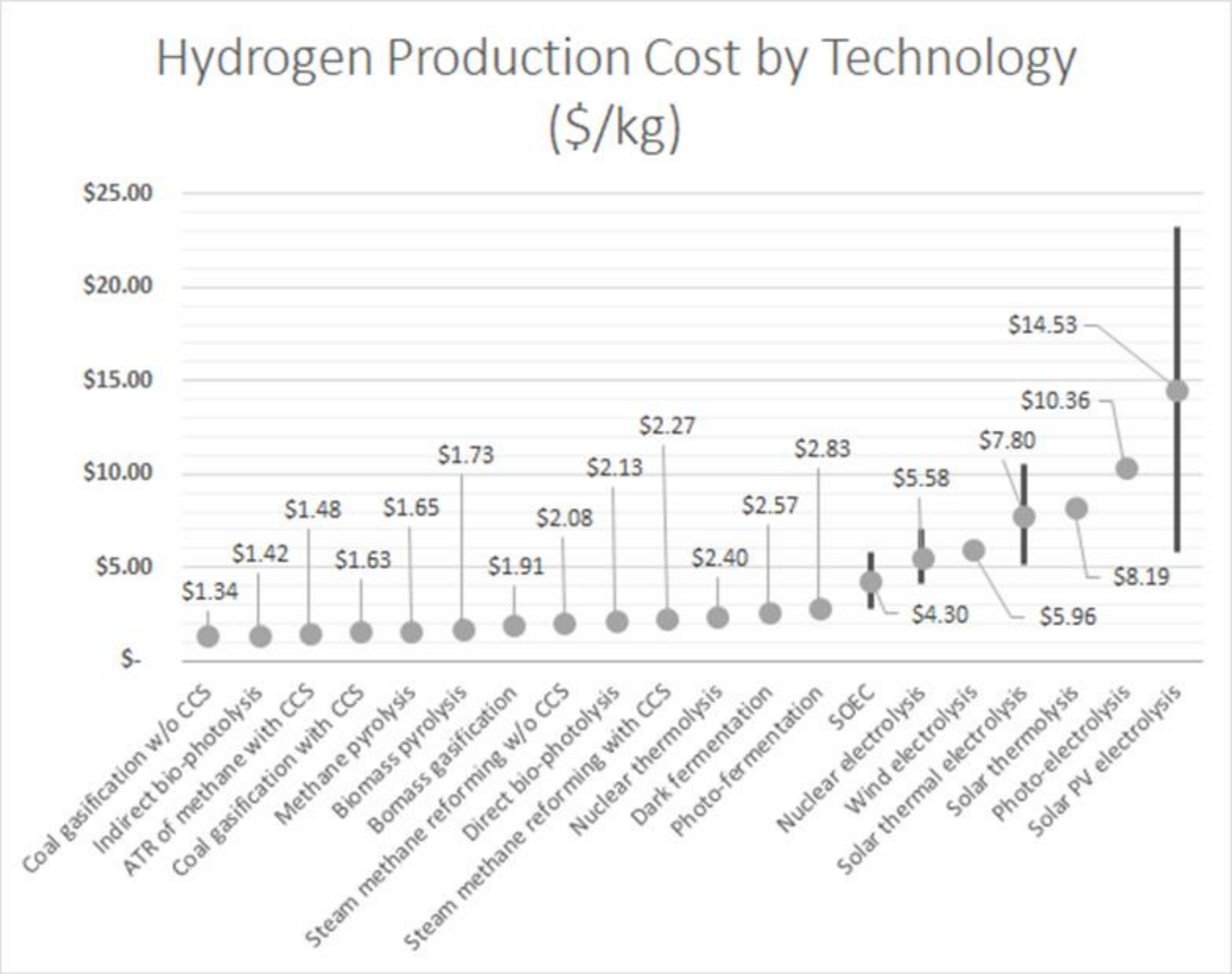
Summary

Hydrogen a potential carbon free energy ecosystem

- H_2 is a challenging fuel compared to methane
- Utilizing H_2 as an energy source can be carbon free
  - Need CCS for FE based; Renewable or NE electricity for electrolysis
- H_2 storage offers a long term / high capacity ES option compared to other methods (CAES, pumped hydro, batteries)
- The existing NG pipeline system could accommodate storage now
  - In part decarbonizing NG
- H_2 could provide for a carbon free energy ecosystem (production, storage, distribution and use) and leverage existing assets while allowing future technology development and insertion



Ref: https://www.sciencedirect.com/topics/engineering/hydrogen-production-cost and https://www.hydrogen.energy.gov/pdfs/16014_h2_production_cost_solid_oxide_electrolysis.pdf

World's Largest Renewable Energy Storage Project Announced in Utah

- *Grid-scale energy storage with renewable hydrogen production and utilization forms core of Advanced Clean Energy Storage project in central Utah*
- SALT LAKE CITY– (May 30, 2019) Mitsubishi Hitachi Power Systems (MHPS) and Magnum Development today joined The Honorable Gary Herbert, Governor of Utah, to announce an initiative to launch the Advanced Clean Energy Storage (ACES) project in central Utah. In the world's largest project of its kind, the ACES initiative will develop 1,000 megawatts of 100 percent clean energy storage, thereby deploying technologies and strategies essential to a decarbonized future for the power grid of the Western United States.