NREL
Transforming ENERGY





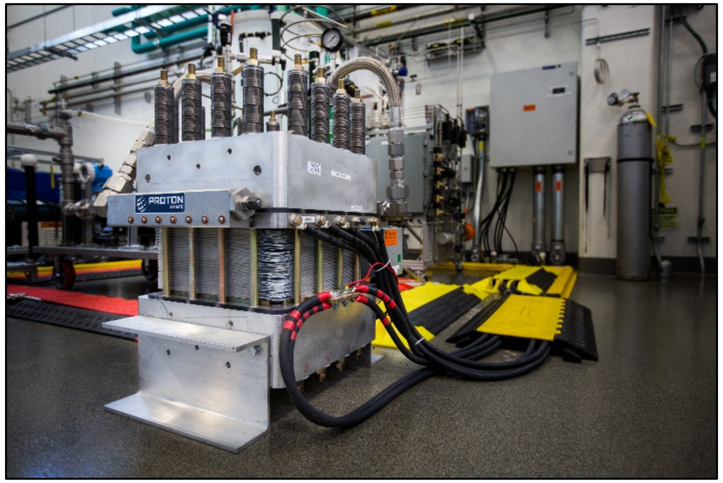
Hydrogen as an Energy Carrier

Jacob Thorson February 17th, 2021

Images: NREL

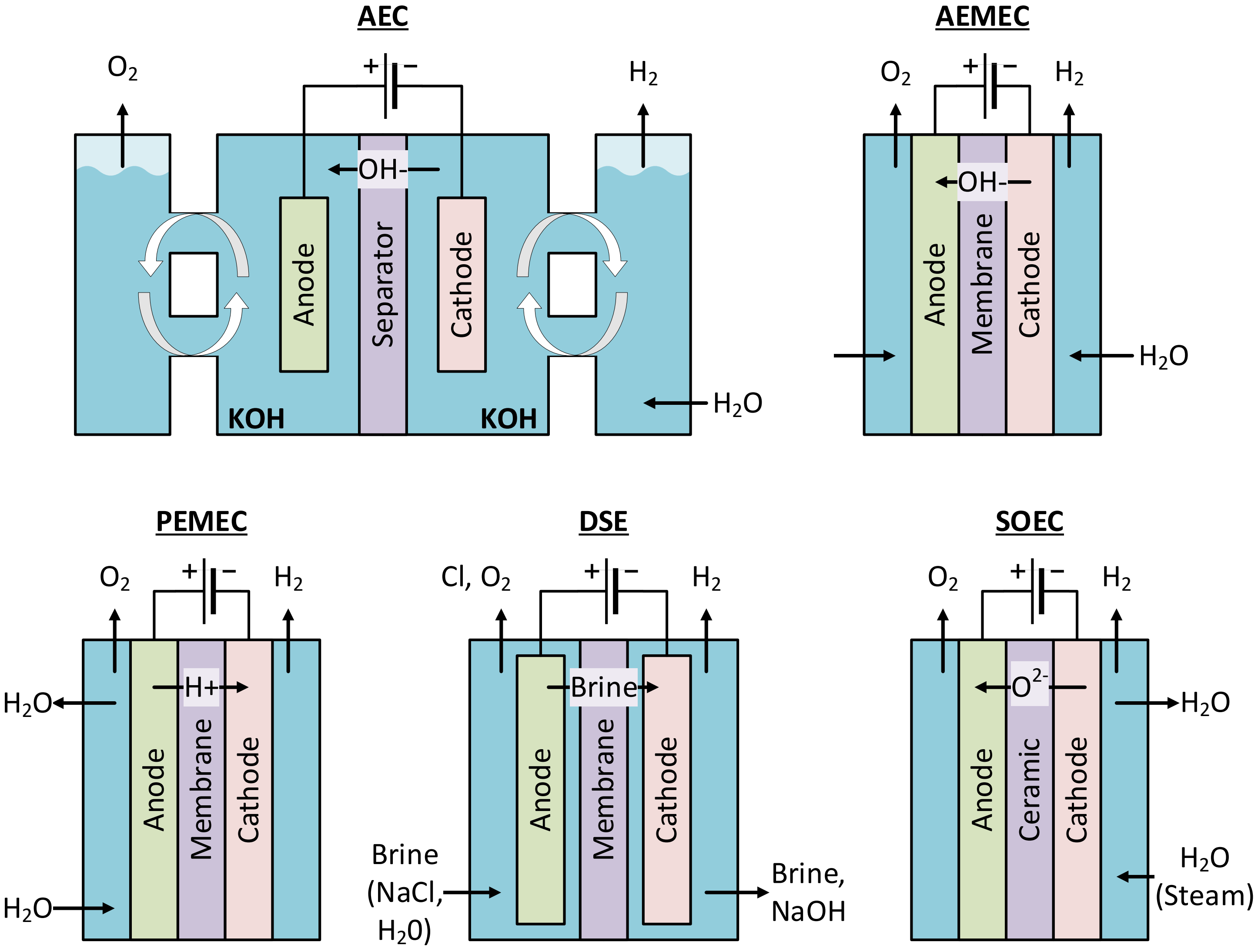
Making Hydrogen with Electrolysis

- Alkaline electrolysis cell (AEC)
- Anion exchange membrane electrolysis cell (AEMEC)
- Proton exchange membrane electrolysis cell (PEMEC)
- Direct seawater electrolysis (DSE)
- Solid oxide electrolysis cell (SOEC)



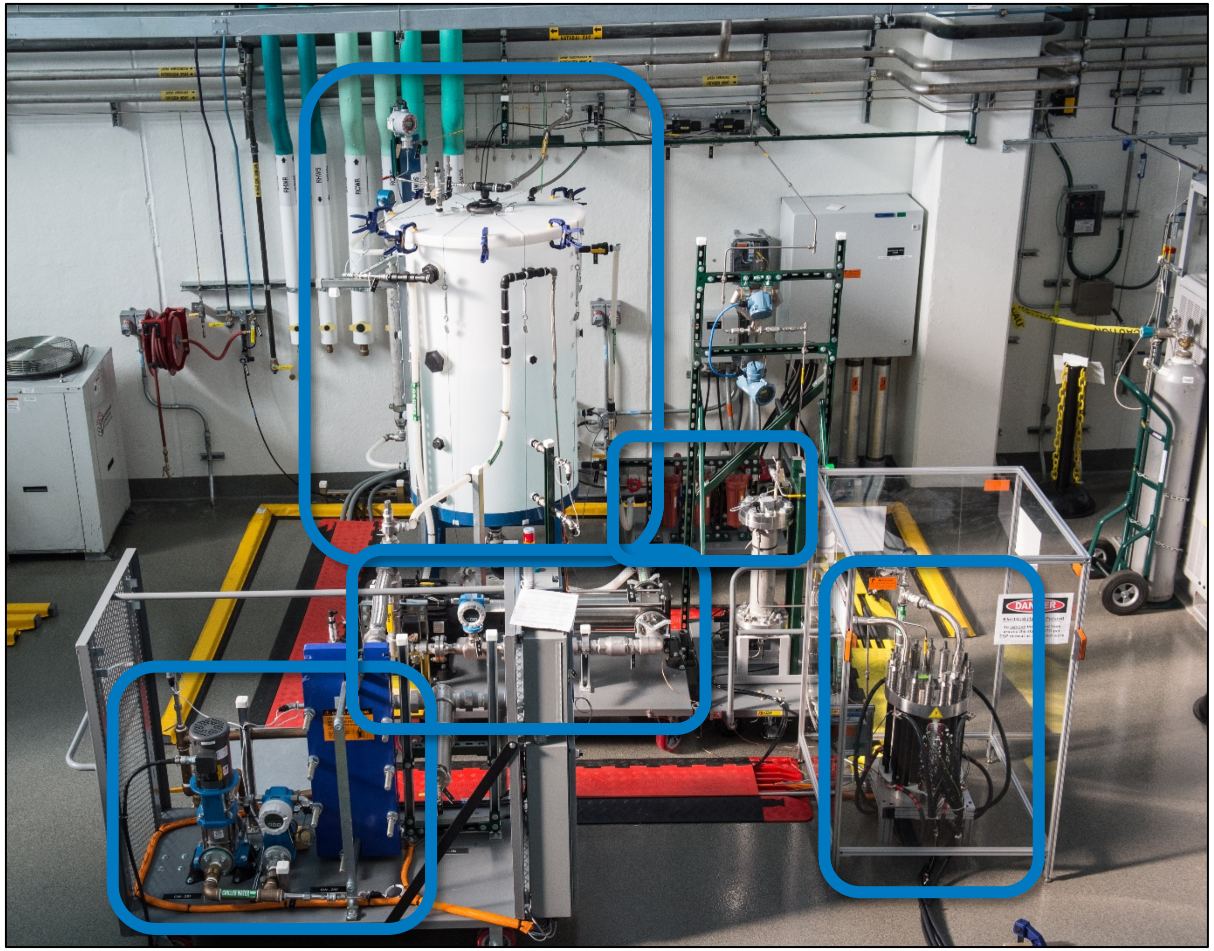
PEM Electrolyzer at NREL

Image: NREL



Adapted from Schmidt, O. 2017. "Future Cost and Performance of Water Electrolysis: An Expert Elicitation Study." International Journal of Hydrogen Energy, October, 23.

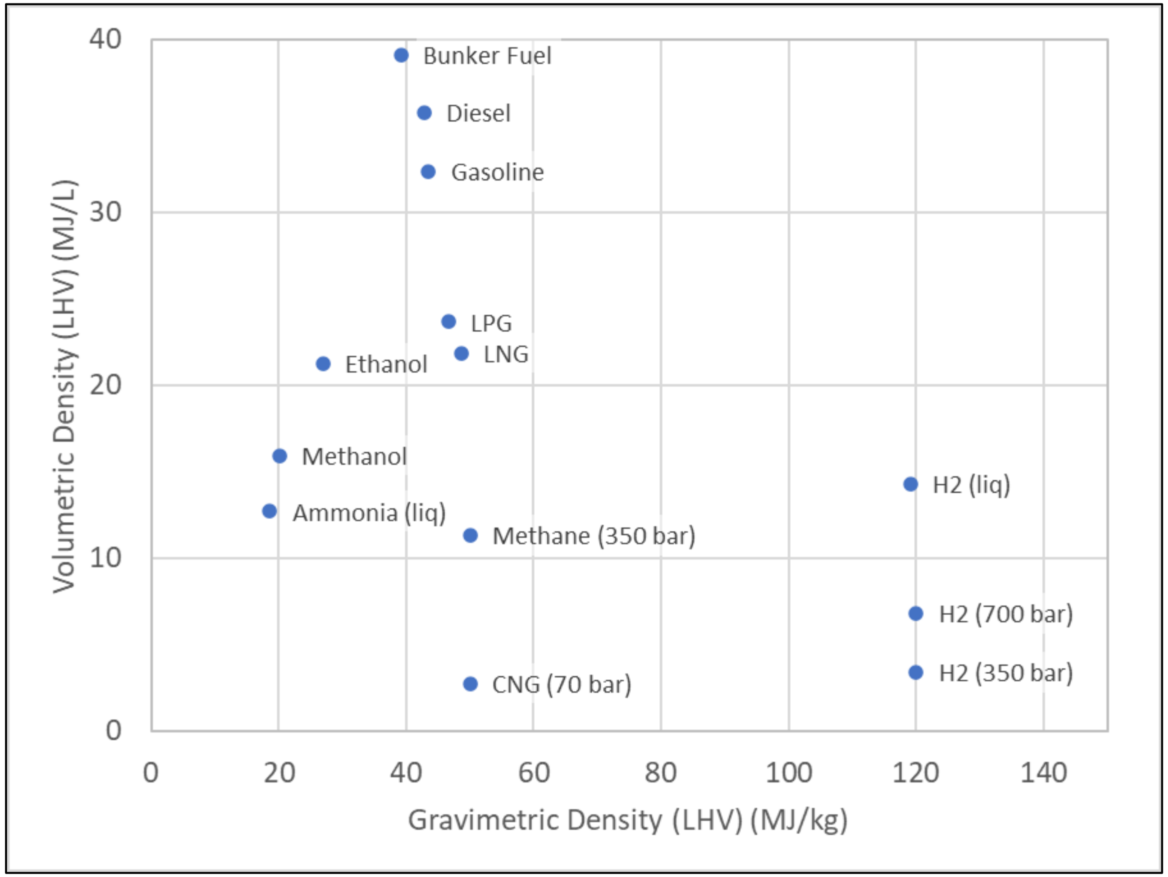
Supporting Equipment for Hydrogen Production and Storage



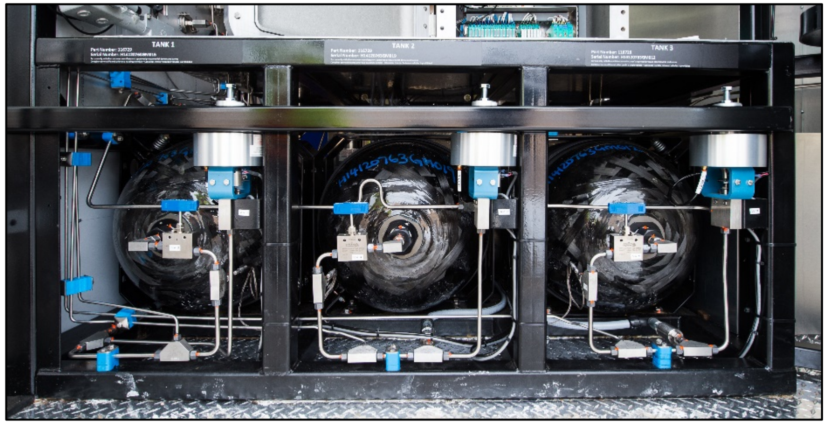
Images: NREL

Storing Hydrogen

- Physical: Compressed, liquified
- Material: Chemical (NH_3, CH_3OH, etc.) & Reversible (metal hydrides, adsorption)

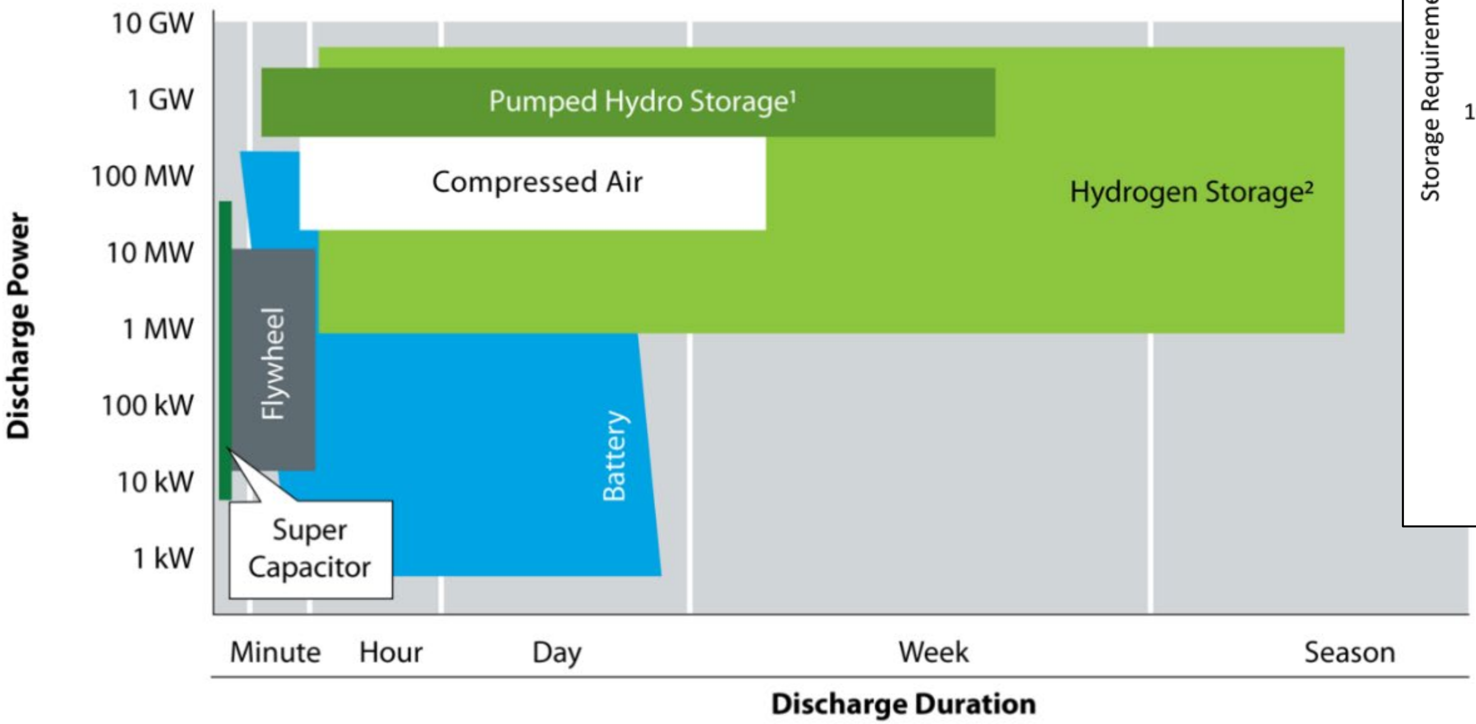


Data from GREET and REFPROP

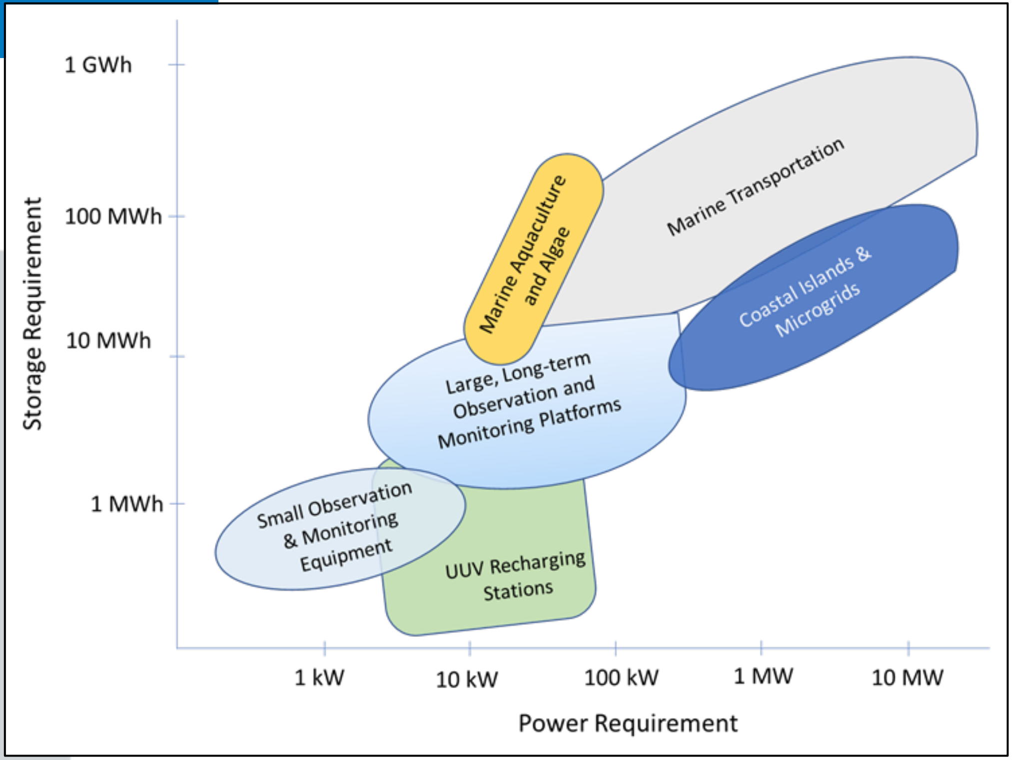


Images: NREL

Using Complementary Energy Storage Technologies to Meet Storage and Power Requirements



[1] Pumped hydro capacity is limited due to geographic constraints. Estimated maximum potential is <1% of U.S. electrical energy demand
[2] As hydrogen, ammonia, or synthetic natural gas



Ruth, Mark F., Jadun, Paige, Gilroy, Nicholas, Connelly, Elizabeth, Boardman, Richard, Simon, A. J., Elgowainy, Amgad, and Zuboy, Jarett. *The Technical and Economic Potential of the H2@Scale Hydrogen Concept within the United States*. United States: N. p., 2020. Web. doi:10.2172/1677471.

So, Why Hydrogen?

- Like electricity, hydrogen is an energy vector
- Hydrogen is flammable but nontoxic and dissipates quickly in the atmosphere
- Electrolyzers can utilize highly variable power and have been demonstrated at a range of scales
- Hydrogen fuel cells produce electricity with zero local emissions and low noise
- Fast-fueling supports existing logistics and operations
- Hydrogen has a very high energy density [energy/mass] (but low volumetric density [energy/volume])
- Hydrogen can be used as a renewable feedstock for alternative fuels and other industrial products





Thank you!

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Storage Characteristics

Technology	Pressure	Water Volume	Mass Stored	Cost Estimate		Technology Status	Deployment
	(MPa)	(m^3)	(kg-H_2)[a]	(\$/kWh)[b]	(\$/kg-H_2)		
Steel Tank (Type I)	1 – 100	0.7	32	45	900	Current	Onshore
Pre-stressed Concrete	0.7 – 87.5	22	1000			Large LNG Systems	Onshore
Wrapped Steel Tank (Type II, II-S)	0.7 – 87.5	0.77	35.4			Current	Onshore
Pipeline Storage	0.7 – 10	6,100	50,000	25.8	516	Current/ Natural Gas	Onshore/ Underwater
Undersea Inflatable	0.6 – 8	35,705	22,500			Air prototype 29.5 m[c]	Underwater
Undersea Concrete Lined [c]	0.7 – 87.5	22	1000			Future	Underwater
Underground, Lined Cavern	1 – 23	40,000	672,000	3.6	72	Future	Onshore
Underground Salt Cavern	5.5 – 15.2	566,000	6,000,000	1.75	35	Current	Onshore
Spherical Vessels	0.1 – 1	32,000	27,000			Natural Gas	Onshore
Aquifer Storage	15 – 17	4,141,000	54,000,000			Natural Gas	Onshore
Cryogenic Storage	2	3,400	230,000			Current	Onshore

Data collected from (FIBA 2021; Penev 2013; Pimm, Garvey, and de Jong 2014)

Electrolysis Technologies

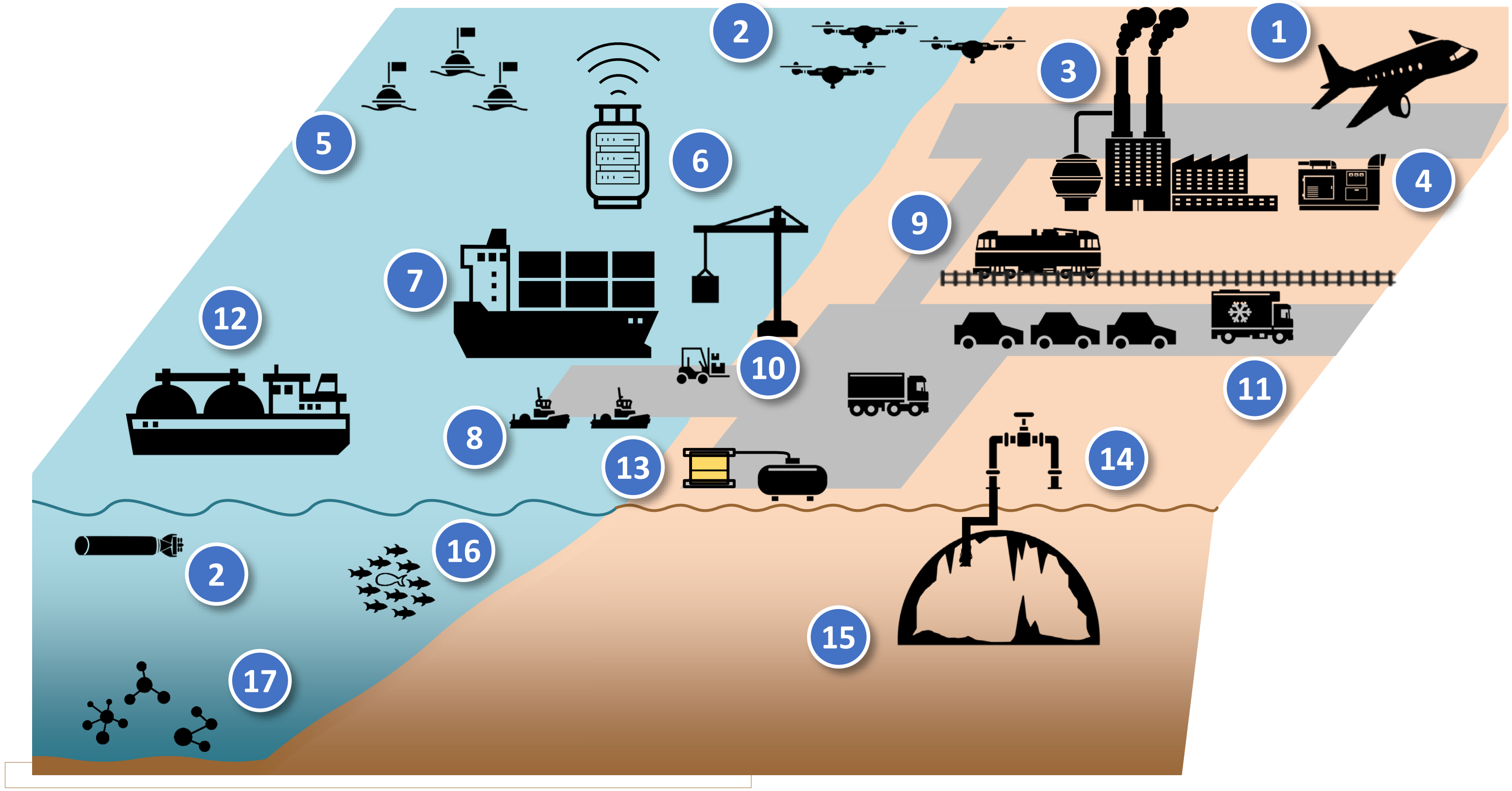
Technology:	Alkaline	PEM	SOEC	AEM	DSE
Operating Temperature	60°-100°C	50°-90°C	650°-1000°C	40°-60°C	TBD
Typical Outlet Pressure	< 435 psi (3 MPa)	< 2900 psi (20 MPa)[a]	< 363 psi (2.5 MPa)	< 508 psi (3.5 MPa)	-
System Electrical Conversion (kWh/kg)[b]	50-79	50-83	39.8-50[c]	57-69	-
Dynamic Response Speed	Seconds	Milliseconds	Seconds	Milliseconds	-
Electrolyte	Aqueous alkaline electrolyte	Polymer membrane	Ceramic membrane	Polymer membrane	Seawater
Demonstrated Stack Durability	60,000-90,000 hr	20,000-80,000 hr	< 35,000 hr	> 5,000 hr	-
Produced H_2 Gas Purity (%)	> 99.3	> 99.9	> 99.9	> 99.9	-
Cold Start Time (min)	< 60	< 20	< 60 - 600	< 20	-
Lower Dynamic Range (%)	10–40	0–10	30	5	-
System Capital Cost ($/kW)	~500-1,600	~450-2,800	~500-2,400+	-	-

[a] High pressure PEM electrolysis, >70 MPa outlet pressure has been demonstrated (Martin et al. 2019)

[b] The HHV and LHV of hydrogen is 39.4 kWh/kg and 33.3 kWh/kg respectively

[c] Additional thermal energy usage of 5 to 12 kWh/kg

Examples Applications at a Hydrogen Hub Port



Icons from Noun Project with Credit to:
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1. Air transport
2. Unmanned vehicles
3. Chemical processing
4. Backup/Auxiliary power
5. Remote monitoring and Navigational aids
6. Underwater computing
7. Marine vessel auxiliary power
8. Marine vessel primary power
9. Rail transport
10. Material handling
11. Heavy duty vehicles
12. Liquid fuel production
13. Local H_2 production
14. Pipeline injection
15. Underground storage
16. Aquaculture
17. Ocean mineral extraction