



Transporting Hydrogen

Part of the Hydrogen Tech Brief Series

Issues Transporting Hydrogen

By Tanker

- Hydrogen is very voluminous gas requiring compacting to transport an appreciable quantity in a reasonable volume
 - High compression
 - Liquefaction
 - Creating hydrogen compounds which reduce the volume and pressure needed
 - Nitrogen to make ammonia
 - Liquid Organic Hydrogen Carrier (LOHC)

By Pipeline

- Hydrogen is a tiny molecule
 - More prone to leakage than other gases
- Hydrogen can cause “embrittlement” of steel
 - Requiring the use of stainless steel or polymers with metal layer.

Ways Reduce Hydrogen Volume

Liquid Organic Hydrogen Carriers

- Hydrogen is combined with an industrial oil such as toluene
- Store 7x the hydrogen per volume at ambient temperature & pressure

Liquefaction

- Hydrogen chilled and compressed into liquid form
- Store 5x the hydrogen per volume at -259°C

Ammonia

- Combine H_2 with nitrogen (N) from the air to make NH_3
- Store 7 to 8.5x the hydrogen per volume at 10 bar & ambient temperature.

Converting Hydrogen Requires Infrastructure

- Conversion loss
 - Energy is lost in converting hydrogen to a more compact form and then back to hydrogen
 - The cost of conversion loss may be less than the cost to transport or store gaseous hydrogen
- Cost
 - Infrastructure & energy.

Moving Hydrogen With Tankers

Liquid Organic Hydrogen Carriers (LOHC)

- Compounds that can absorb and release hydrogen through chemical reactions
 - Readily available industrial oils
 - Hydrogenation is carried out using a catalyst, pressure and heat
 - Dehydrogenation takes place using a catalyst and heat
- LOHC's are stable at ambient temperature and pressure
 - Could use existing gas & diesel tankers and fuel station tanks
 - Hydrogenated and dehydrogenated LOHC's are non-flammable
 - Stores 0.2158 kg Hydrogen per gallon of LOHC

Liquid Organic Hydrogen Carriers (LOHC)

LOHC without
Hydrogen

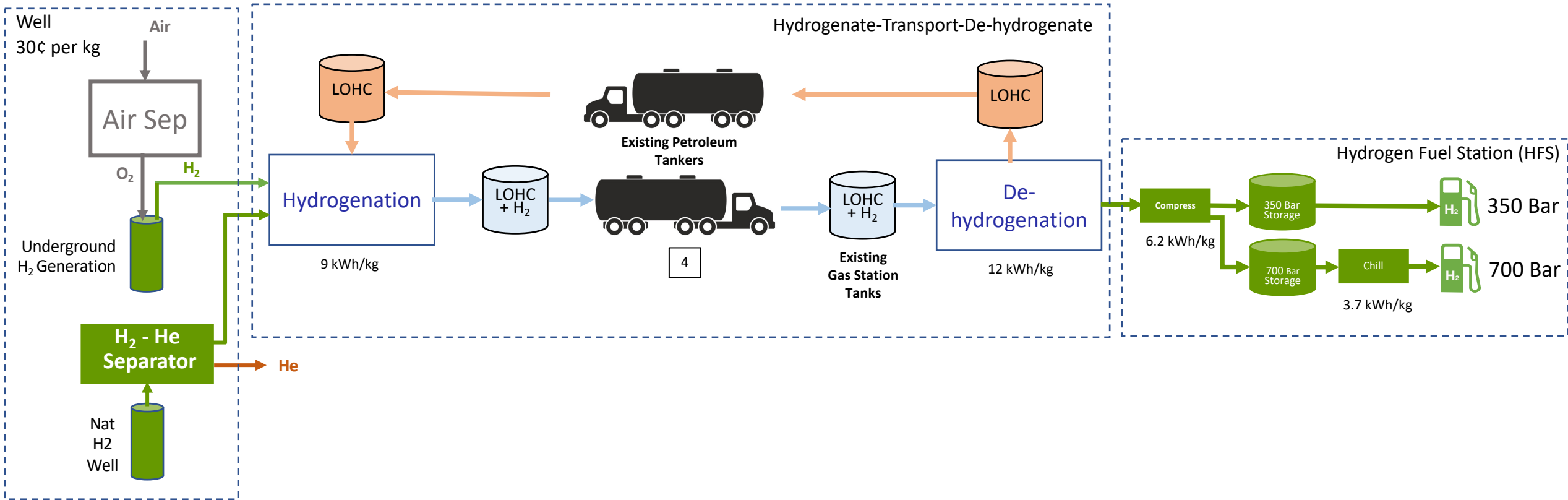


LOHC saturated with Hydrogen.
Compound is Non-flammable.

- Liquid Organic Hydrogen Carrier (LOHC) suppliers
 - www.chiyodacorp.com/en/service/spera-hydrogen/
 - www.hydrogenious.net

Safely Store and Transport Hydrogen at Ambient Temperature and Pressure

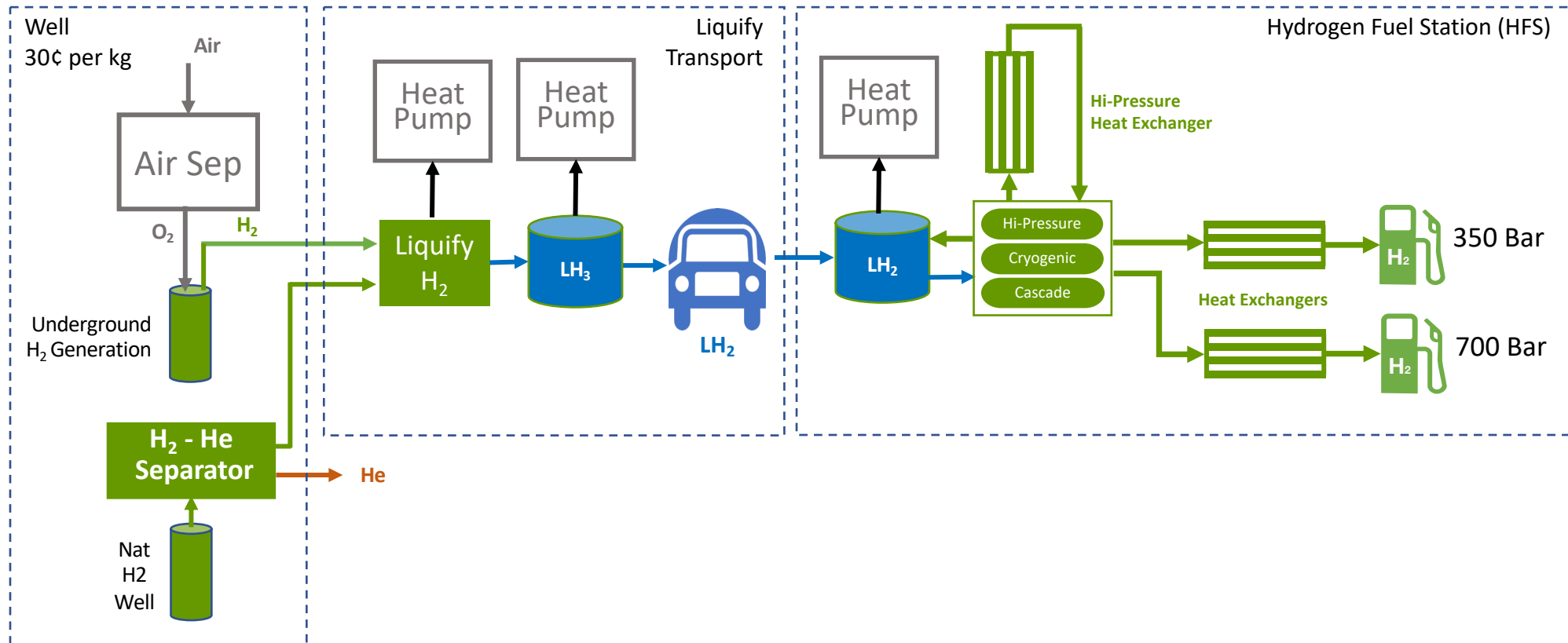
Moving Hydrogen Using Liquid Organic Hydrogen Carrier (LOHC)



Hydrogen Liquefaction

- Liquefaction through compression and chilling
- Liquid hydrogen (LH₂) requires constant refrigeration to prevent boil-off
- Transfer of LH₂ between vessels requires refrigeration

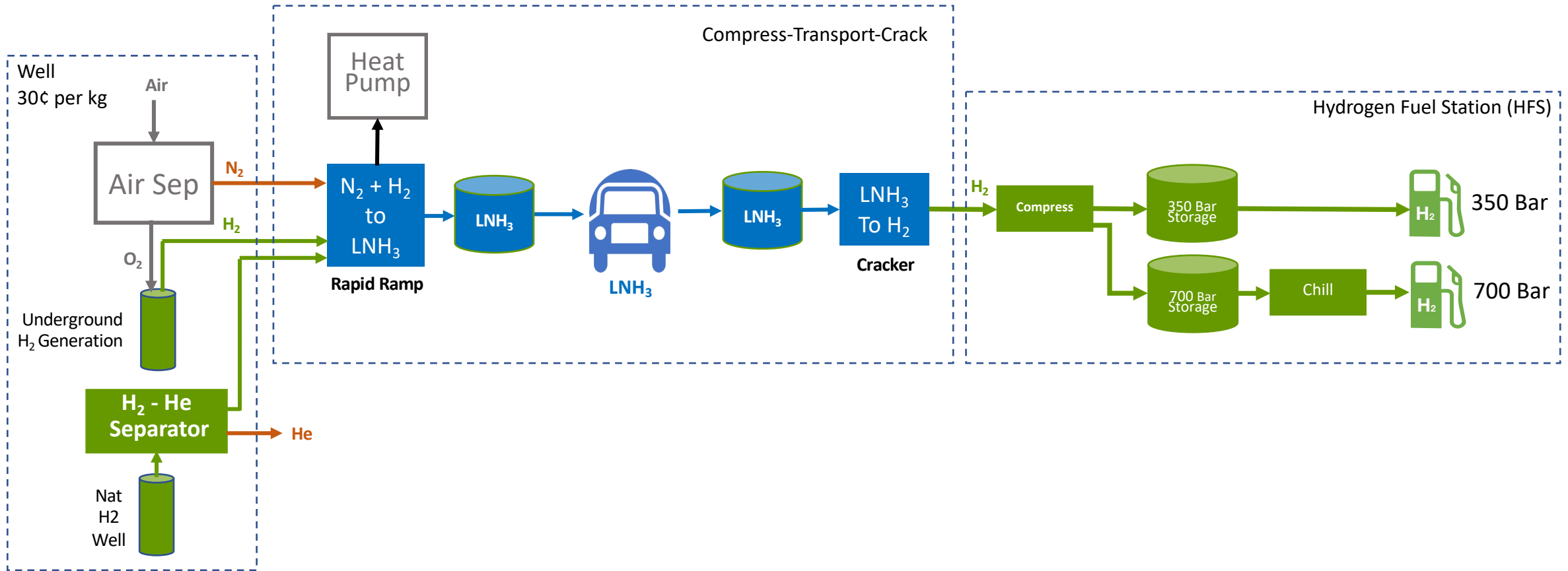
Moving Hydrogen as a Liquid – Self Pressurizing



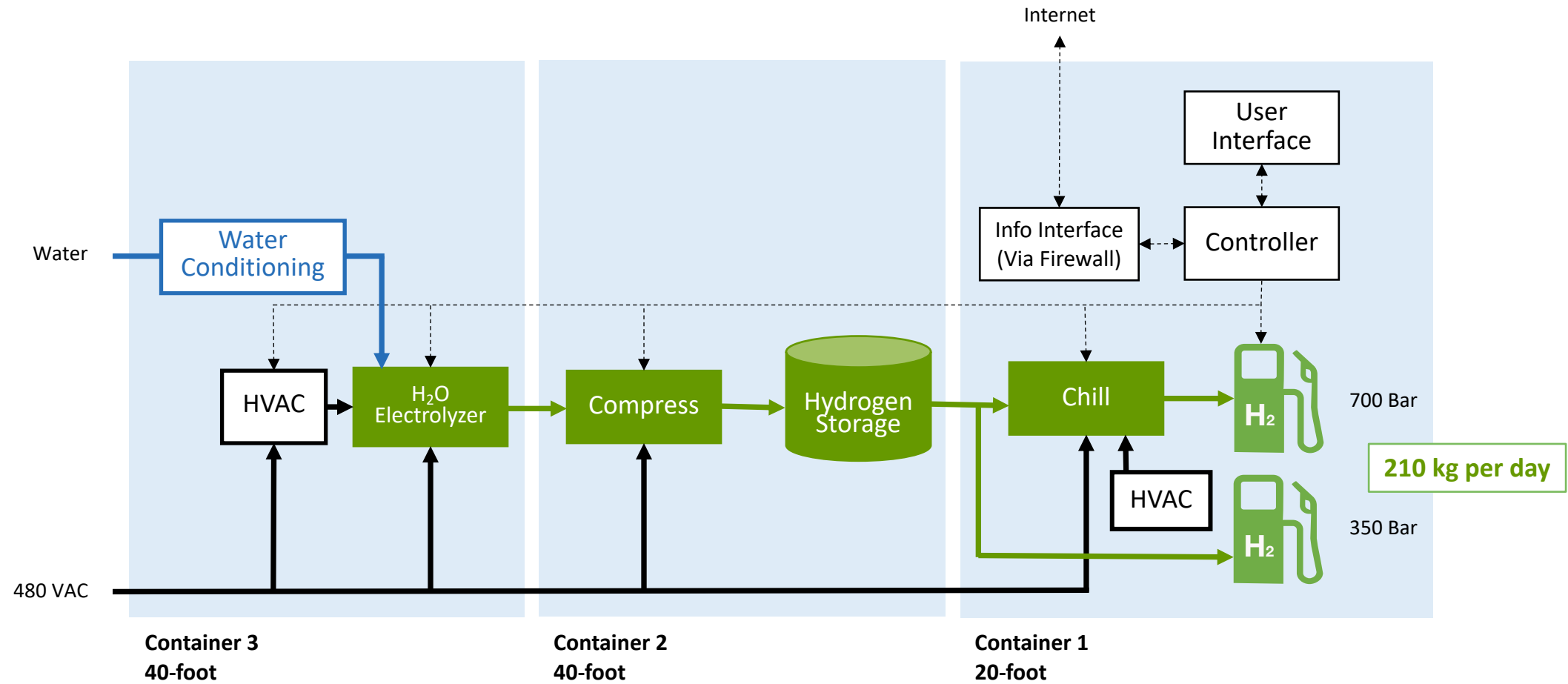
Ammonia

- Hydrogen can be combined with nitrogen from the air to form ammonia (NH₃)
- Liquid ammonia can be stored at ambient temperatures and around 150 PSI (10 bars) of pressure
 - 7 times the hydrogen per volume than compressed hydrogen gas
- Conversion loss
 - Energy is lost in converting hydrogen-to-ammonia and ammonia-to-hydrogen
 - The cost of conversion loss may be less than the cost to transport or store gaseous hydrogen.

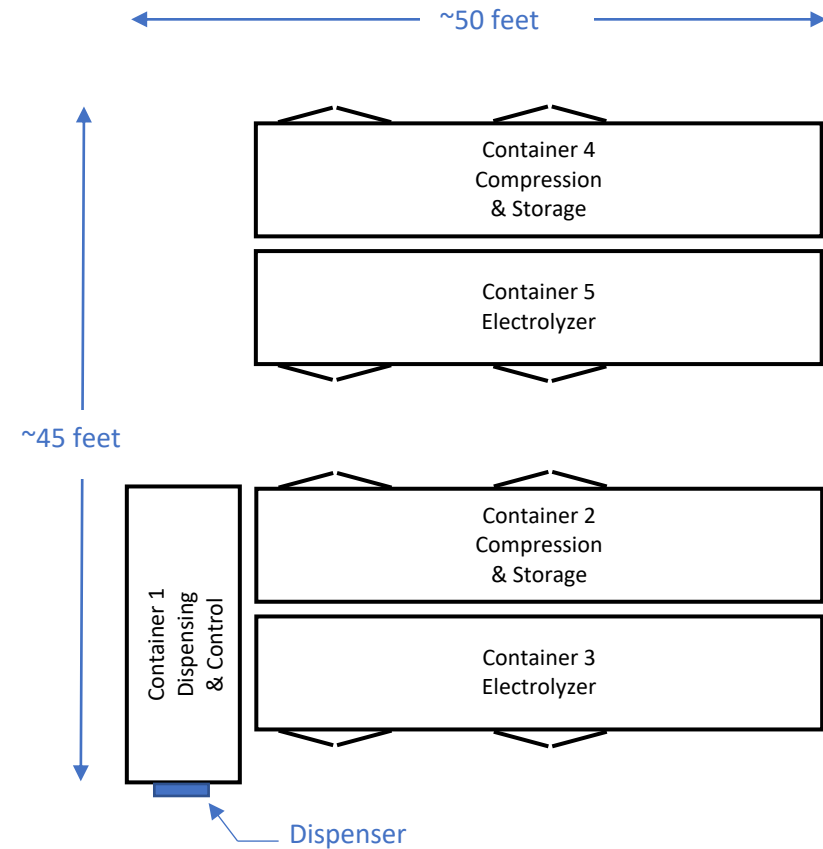
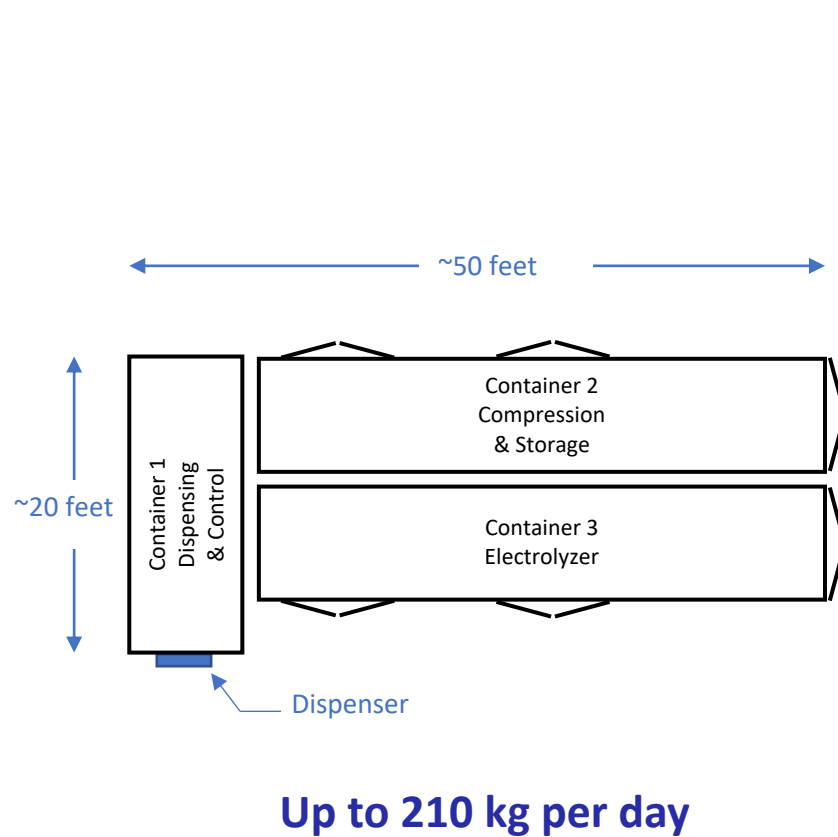
Moving Hydrogen as Ammonia



On-Site H₂ Generation 210 kg/day



On-site Hydrogen Fuel Station Footprints



Gasoline & Diesel Replacement H₂ Price Target

- Goal: Price hydrogen at the same or better cost-per-mile as petroleum
 - To entice users to switch from petroleum to hydrogen vehicles
- Cost-per-mile is based on vehicle efficiency
 - Hydrogen vehicles are more efficient than petroleum . . . but that varies by Class
- Energy Economy Ratio (EER)
 - Ratio of MPKg-to-MPG
 - For similar size and weight vehicles

Class	LD/MD Gas	LD/MD Diesel	HD Diesel Local	HD Diesel Highway
Petrol. \$/gal	\$3.50	\$4.00	\$4.00	\$4.00
EER	2.5	1.9	1.5	1.1
Target Price \$/kg	\$8.75	\$7.60	\$6.00	\$4.40

Price Per kg is Highly Dependent on Vehicle Class and Comparison to Gasoline vs Diesel

Cost to Transport Hydrogen

50-mile delivery	CAPEX	CAPEX debt service (\$/kg)	OPEX (\$/kg)	Transport Cost	H2 Cost at well	Total Cost (\$/kg)
LH ₂ Delivered	\$3.8 M	\$2.40	\$2.04	\$4.44	\$0.30	\$4.74
LOHC Delivered	\$4.3 M	\$2.73	\$3.13	\$5.87	\$0.30	\$6.17
Ammonia Delivered	\$7.0 M	\$4.43	\$2.78	\$7.21	\$0.30	\$7.51
On-Site Electrolysis	\$3.2 M	\$4.23	\$4.52			\$8.75

Estimate to A Rough Order Of Magnitude

Cost-Price Comparison

Hydrogen Target Price				
Class	LD/MD Gas	LD/MD Diesel	HD Diesel Local	HD Diesel Highway
Petrol. \$/gal	\$3.50	\$4.00	\$4.00	\$4.00
EER	2.5	1.9	1.5	1.1
Target Price \$/kg	\$8.75	\$7.60	\$6.00	\$4.40



Cost-Price Comparison

✓ = Price ≥ Cost	LD/MD Gas	LD/MD Diesel	HD Diesel Local	HD Diesel Highway
	\$8.75	\$7.60	\$6.00	\$4.40
LH ₂	\$4.74	✓	✓	✓
LOHC	\$6.17	✓	✓	(✓)
Ammonia	\$7.51	✓	✓	
Electrolysis	\$8.75	✓		

Cost for Transport and Generation					
50-mile delivery	Transport CAPEX debt service (\$/kg)	Transport OPEX (\$/kg)	Transport Total Cost	H ₂ Cost at well	Total Cost (\$/kg)
LH ₂ Delivered	\$2.40	\$2.04	\$4.44	\$0.30	\$4.74
LOHC Delivered	\$2.73	\$3.13	\$5.87	\$0.30	\$6.17
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Cost (\$/kg)

**To Compete With Petroleum
Hydrogen Needs to Cost Less Than 30¢ per kg at the Source**



Moving Hydrogen Via Pipeline

Natural Gas Replacement

- Goal: Price hydrogen at the same cost-per-BTU as natural gas (CH₄)

Item	Value (at H ₂ Source)
CH ₄ cost per 1,000 SCF	\$9.60
BTU per 1,000 SCF	922,740
BTU per kg H ₂ (LHV)	23,418
kg H ₂ equiv. to 1,000 SCF CH ₄	39.4
Cost per kg H₂ equiv. to CH₄	\$0.24

- Natural gas is available “at the curb”, but hydrogen will need delivery pipelines adding around 20¢ per kg (small pipe, 10 miles point-to-point)

Hydrogen Source Cost + Pipeline Transport Needs to Equal Less Than 24¢ Per kg

Pipeline Technology

- SmartPipe Technologies is a manufacturer of continuous lengths of polymer pipe in the field
- Pipe can be manufactured with a metallic layer which acts as a barrier to hydrogen
- Transferring renewable energy as hydrogen through pipelines can be an alternative to building new electrical transmission lines



Take-Aways

Hydrogen can compete with petroleum for transportation

- On-site electrolysis is competitive with light-duty gasoline
- For other classes of vehicles
 - Other sources of 30¢ per kg hydrogen is needed
 - Natural hydrogen wells
 - Generated Underground (GU) Hydrogen using petroleum reservoirs
 - Liquid hydrogen transport is the lowest cost

Hydrogen for industry & utilities

- H₂ source cost of 30¢ per kg plus 20¢ pipeline cost (50¢ per kg total) makes it difficult to hit price target of 24¢ per kg

HydrogenNowCast
2/9/24
2/23/22