COLORADO HYDROGEN NETWORK

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.

COLORADO HYDROGEN NETWORK

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.

COLORADO HYDROGEN NETWORK

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 then the cost to transport or store gaseous hydrogen
- Cost
  - Infrastructure & energy.

COLORADO HYDROGEN NETWORK

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

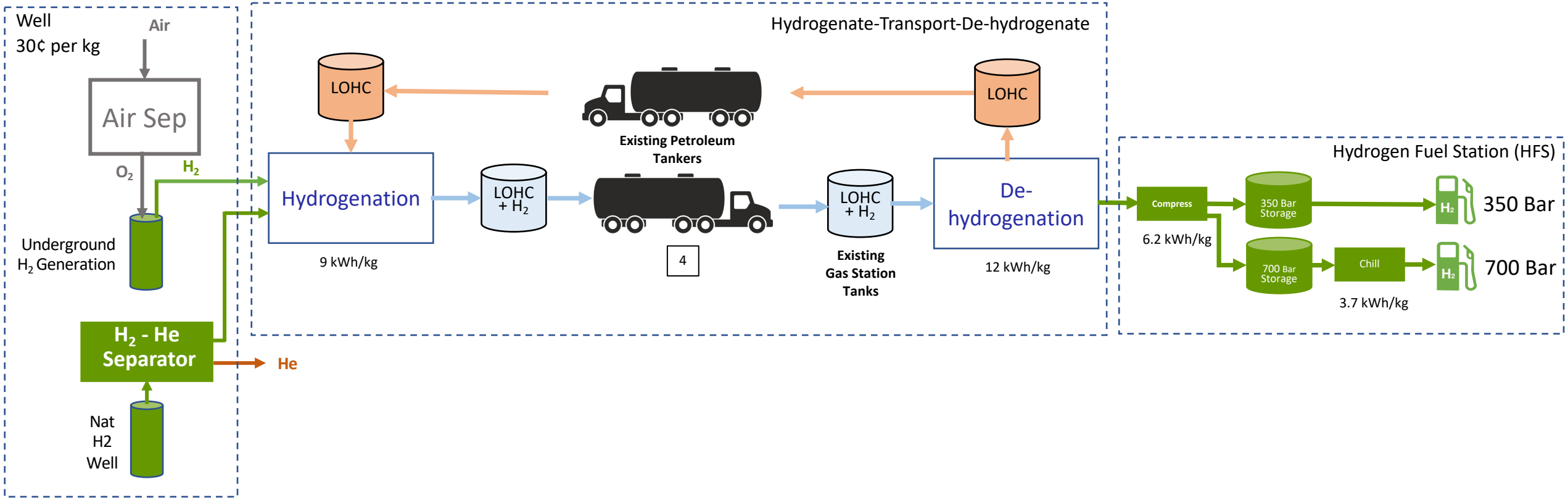
LOHC saturated with Hydrogen. *Compound is Non-flammable.*

- 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

COLORADO HYDROGEN NETWORK

Moving Hydrogen Using Liquid Organic Hydrogen Carrier (LOHC)

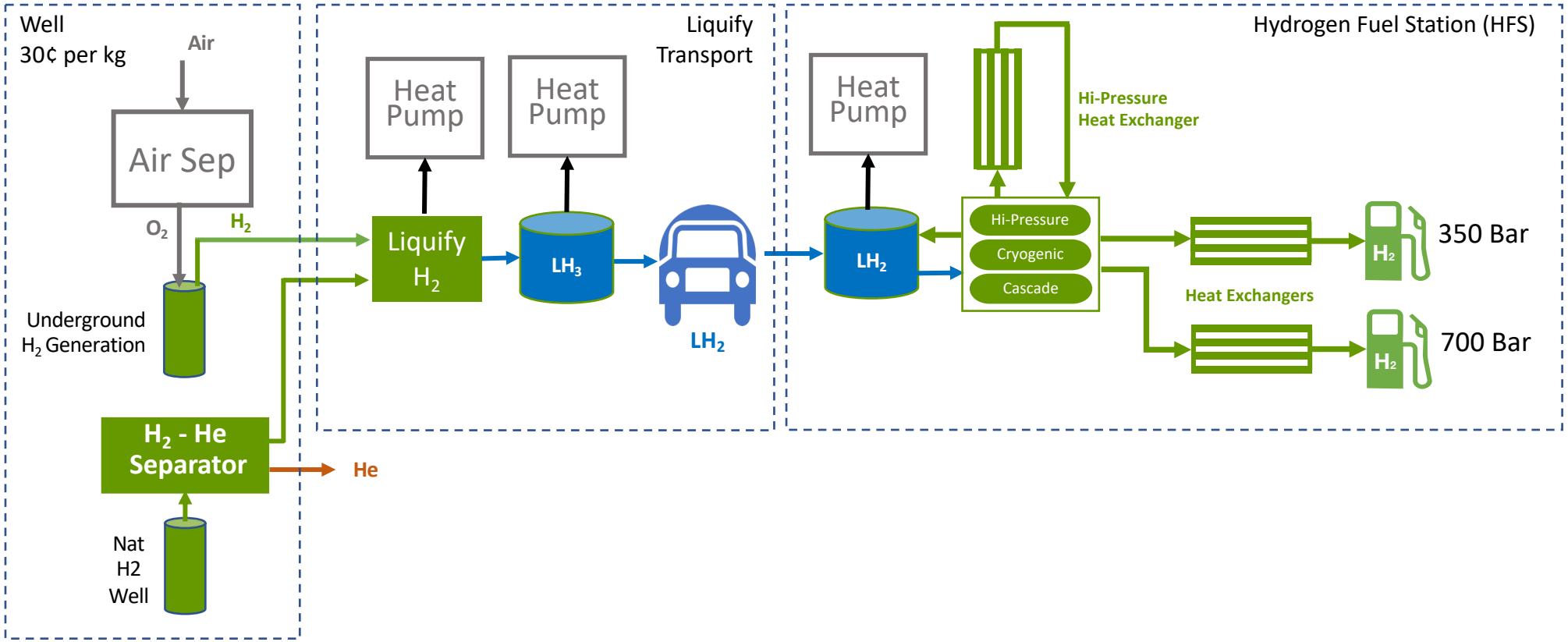


COLORADO HYDROGEN NETWORK

Hydrogen Liquefaction

- Liquification through compression and chilling
- Liquid hydrogen (LH_2) requires constant refrigeration to prevent boil-off
- Transfer of LH_2 between vessels requires refrigeration

Moving Hydrogen as a Liquid – Self Pressurizing

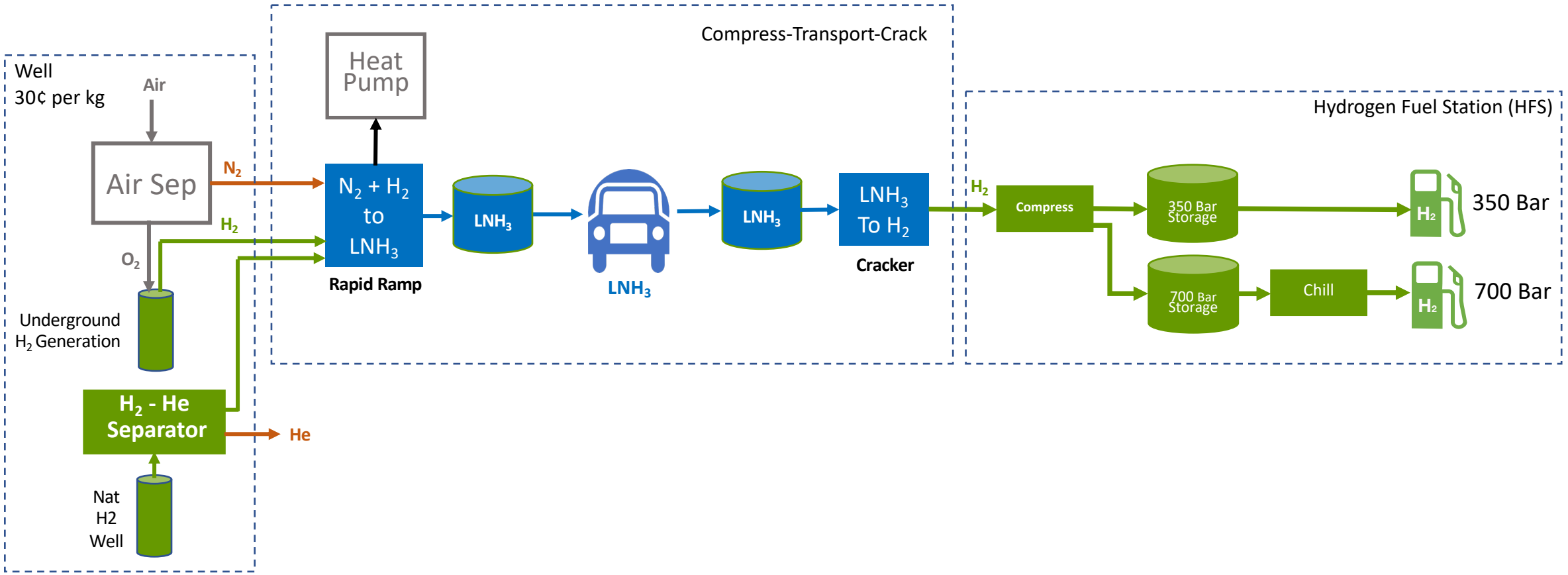


COLORADO HYDROGEN NETWORK

Ammonia

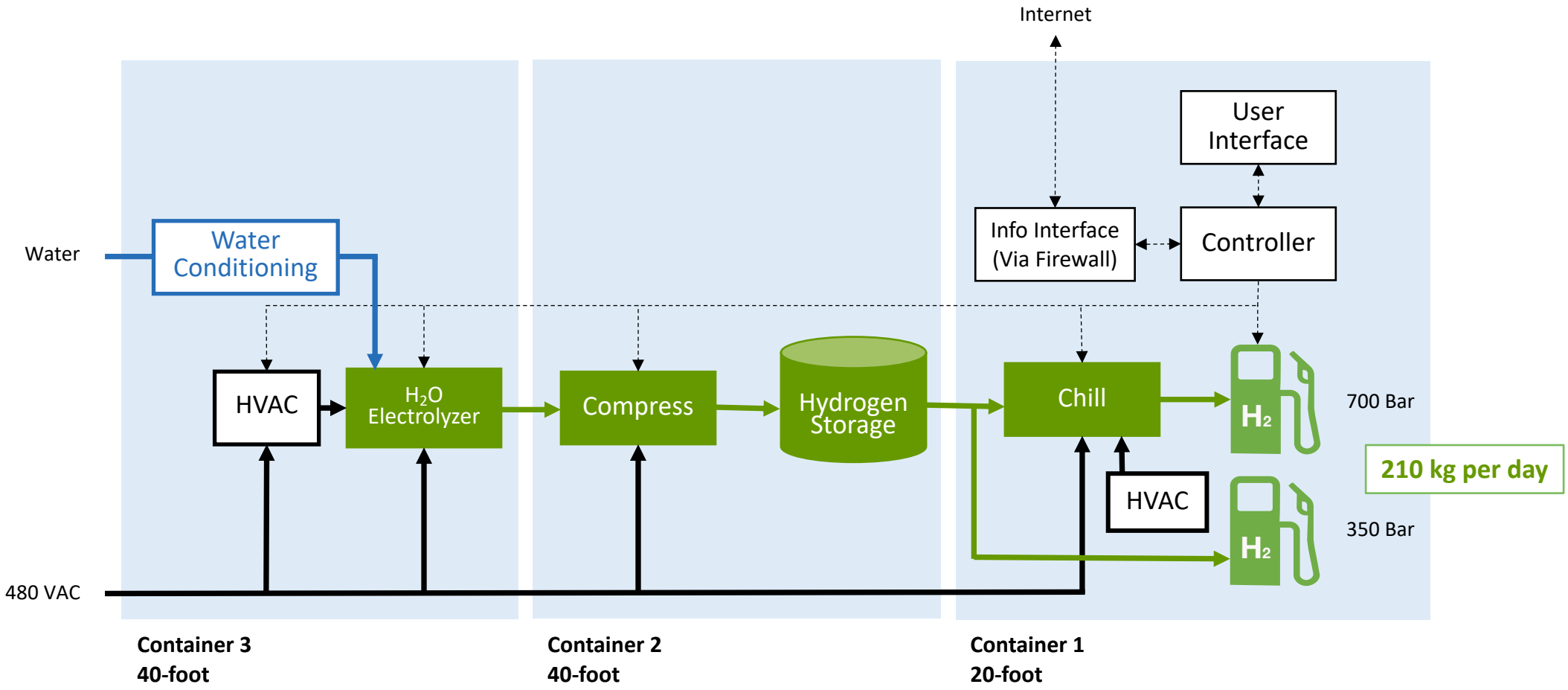
- Hydrogen can be combined with nitrogen from the air to form ammonia (NH_3)
- Liquid ammonia can be stored at ambient temperatures and around 150 PSI (10 bars) of pressure
  - 7 times the hydrogen per volume than compressed hydrogen gas
- Conversion loss
  - Energy is lost in converting hydrogen-to-ammonia and ammonia-to-hydrogen
  - The cost of conversion loss may be less then the cost to transport or store gaseous hydrogen.

Moving Hydrogen as Ammonia

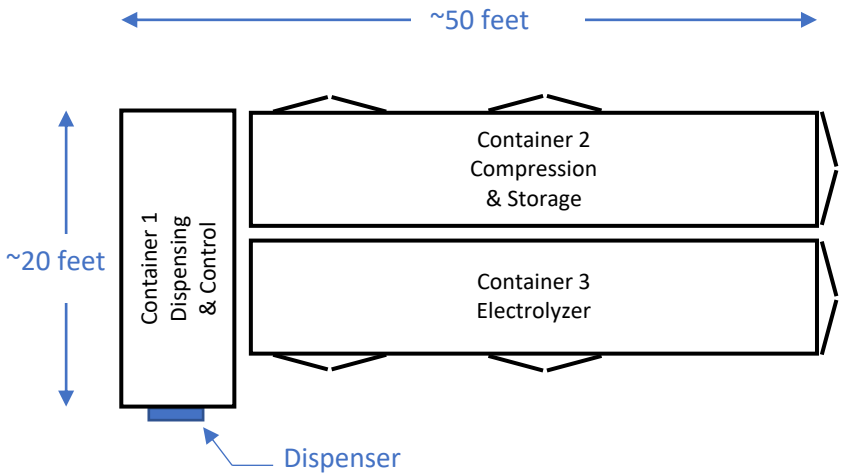


COLORADO HYDROGEN NETWORK

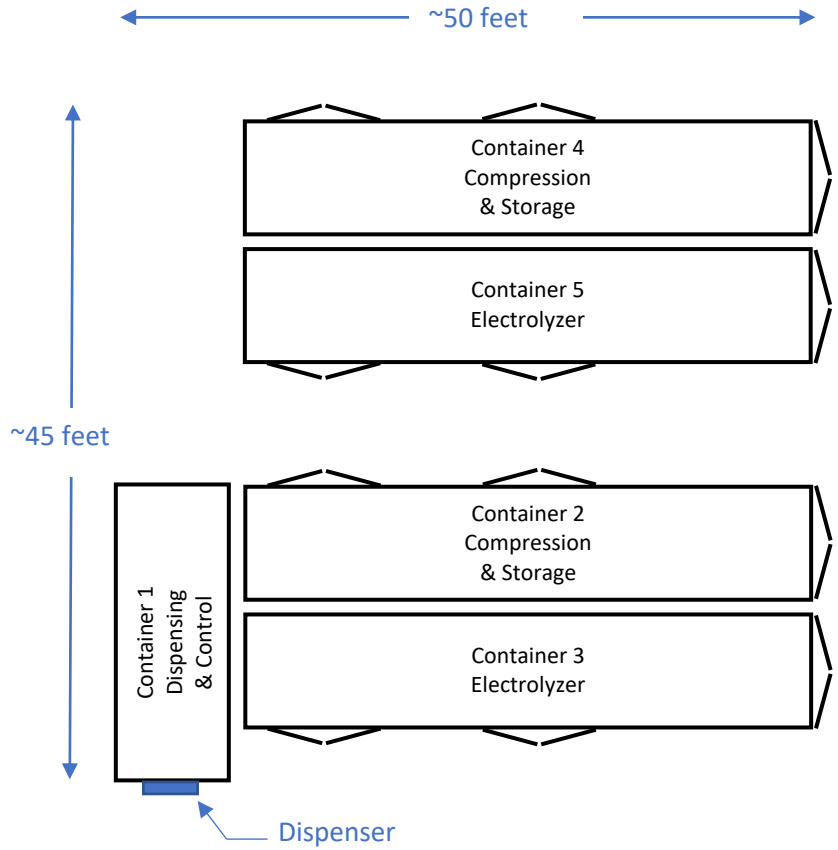
On-Site H2 Generation 210 kg/day



On-site Hydrogen Fuel Station Footprints



Up to 210 kg per day



Up to 420 kg per day

COLORADO HYDROGEN NETWORK

Gasoline & Diesel Replacement H_2 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

COLORADO HYDROGEN NETWORK

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

COLORADO HYDROGEN NETWORK

Cost-Price Comparison

Hydrogen Target Price				
Classc	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 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**
Ammonia Delivered	$4.43	$2.78	$7.21	$0.30	**$7.51**
On-Site Electrolysis	$4.23	$4.52			**$8.75**

Cost ($/kg)			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**	✓			

To Compete With Petroleum

Hydrogen Needs to Cost Less Than 30¢ per kg at the Source

COLORADO HYDROGEN NETWORK

Moving Hydrogen Via Pipeline

- Goal – Price hydrogen at the same cost-per-BTU as natural gas (CH_4)
- Natural gas is available “at the curb”, but hydrogen will need delivery pipelines
  - Adding around 20¢ to 80¢ per kg (small pipe, 10 miles point-to-point)
- Goal – Price hydrogen at the same cost-per-BTU as natural gas (CH_4)

COLORADO HYDROGEN NETWORK

Natural Gas Cost-Price Comparison

Price Target	
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)	114,887
kg H_2 equiv. to 1,000 SCF CH_4	8.03
Price per kg H_2 equiv. to CH_4	**$1.20**

Cost Analysis	
Item	**$ per kg**
Hydrogen Cost at source	$0.30
Pipeline cost OPEX + ROI	$0.20 to $0.80
Total cost per kg	**$0.50 to $1.10**

Cost less than target price

Hydrogen Can Compete With Natural Gas if the Source is Priced at 30¢ to 40¢ per kg

COLORADO HYDROGEN NETWORK

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

SMARTPIPE TECHNOLOGIES

https://smart-pipe.com

COLORADO HYDROGEN NETWORK

Take-Aways

Hydrogen can compete with petroleum for transportation

- On-site electrolysis is competitive with light-duty gasoline
- For other classes of vehicles
  - 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 can compete with Nat. Gas for industry & utilities

- With a hydrogen source cost of 30¢ per kg
- And 20¢ to 80¢ per kg pipeline cost

COLORADO HYDROGEN NETWORK