Utilising hydrogen by-product to create carbon free transportation

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12th International Chlor-Alkali Technology Conference & Exhibition

13-15 May 2025
Barcelona - Spain

AGENDA

Chart has more than 12‘000 experts in 115 locations across the globe

- **Introduction**
- **Hydrogen Liquefaction**
- **Supply Chain Economics**

Current hydrogen use

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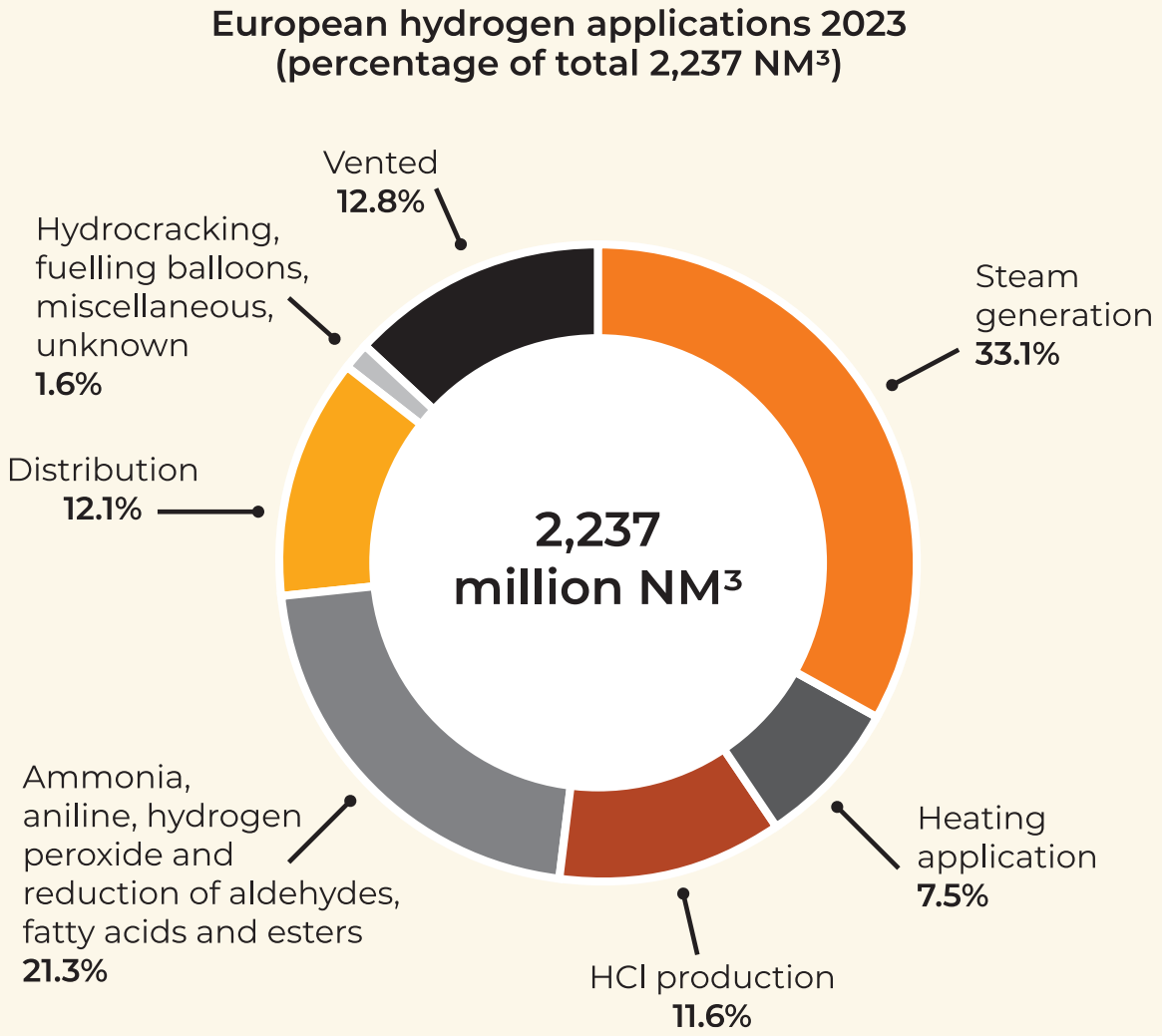
Hydrogen use in European Chlorine Production

- 53,4 % of the hydrogen is either vented or thermally used
- This corresponds to about 294 tpd
- If only plants with more than 5 tpd hydrogen are considered, then 260 tpd are remaining
- HCl has a very low commercial value
- Mobility market pays 18-24 €/kg H_2
- Equivalent of 4,3 Mio € per day. (@10 €/kg)
- A liquefaction supply chain is paid back (ROI) < 3 years



Principal Products Manufactured In-house

Liquefaction Plants

Gas Compressors

Refuelling Stations

Cryogenic Storage Tanks

Heat Exchangers

Transport Trailers

Carbon Capture

Cryogenic Railcars

On-Board Fuel Tanks

Cryogenic ISO Containers

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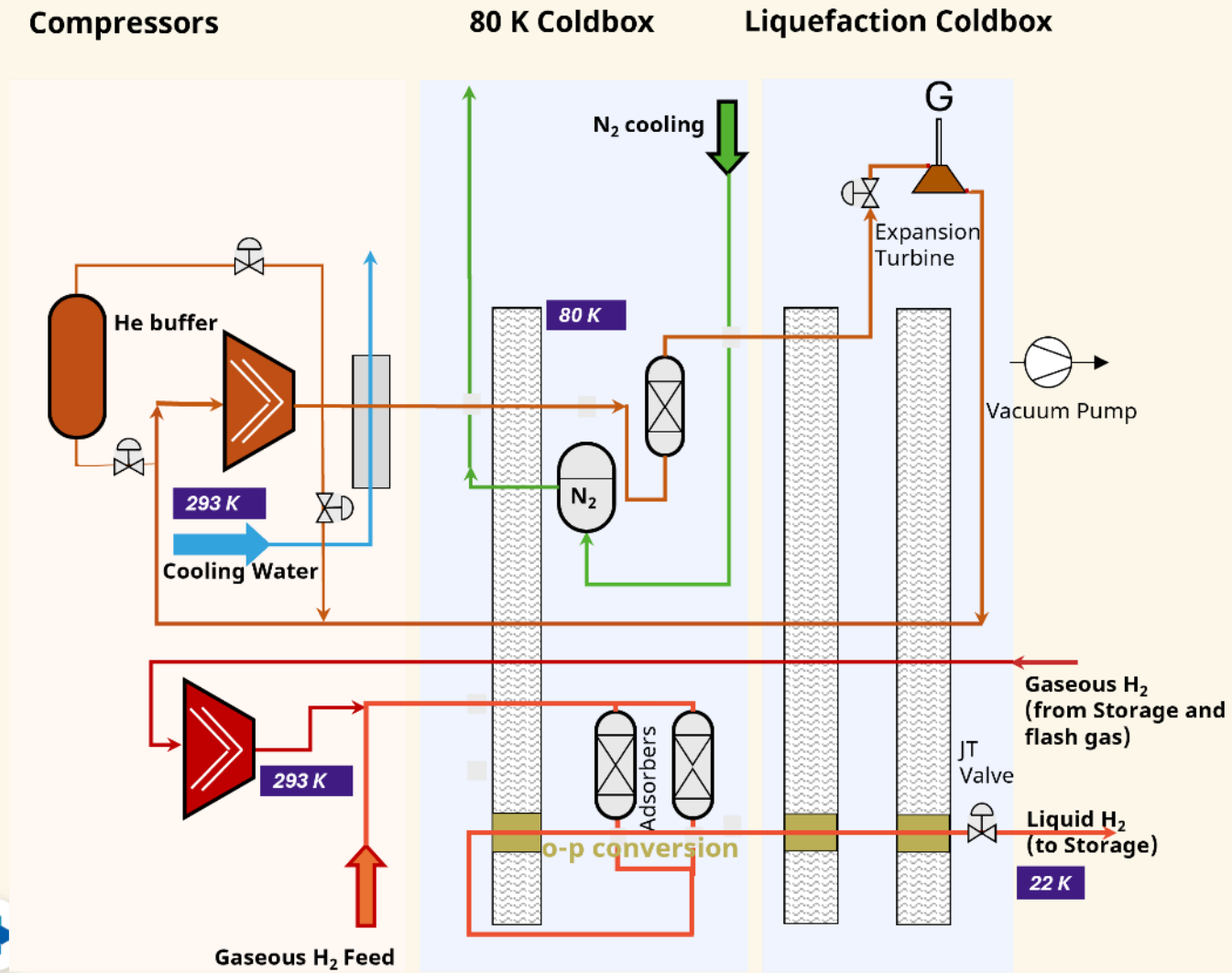
Hydrogen Liquefaction Process

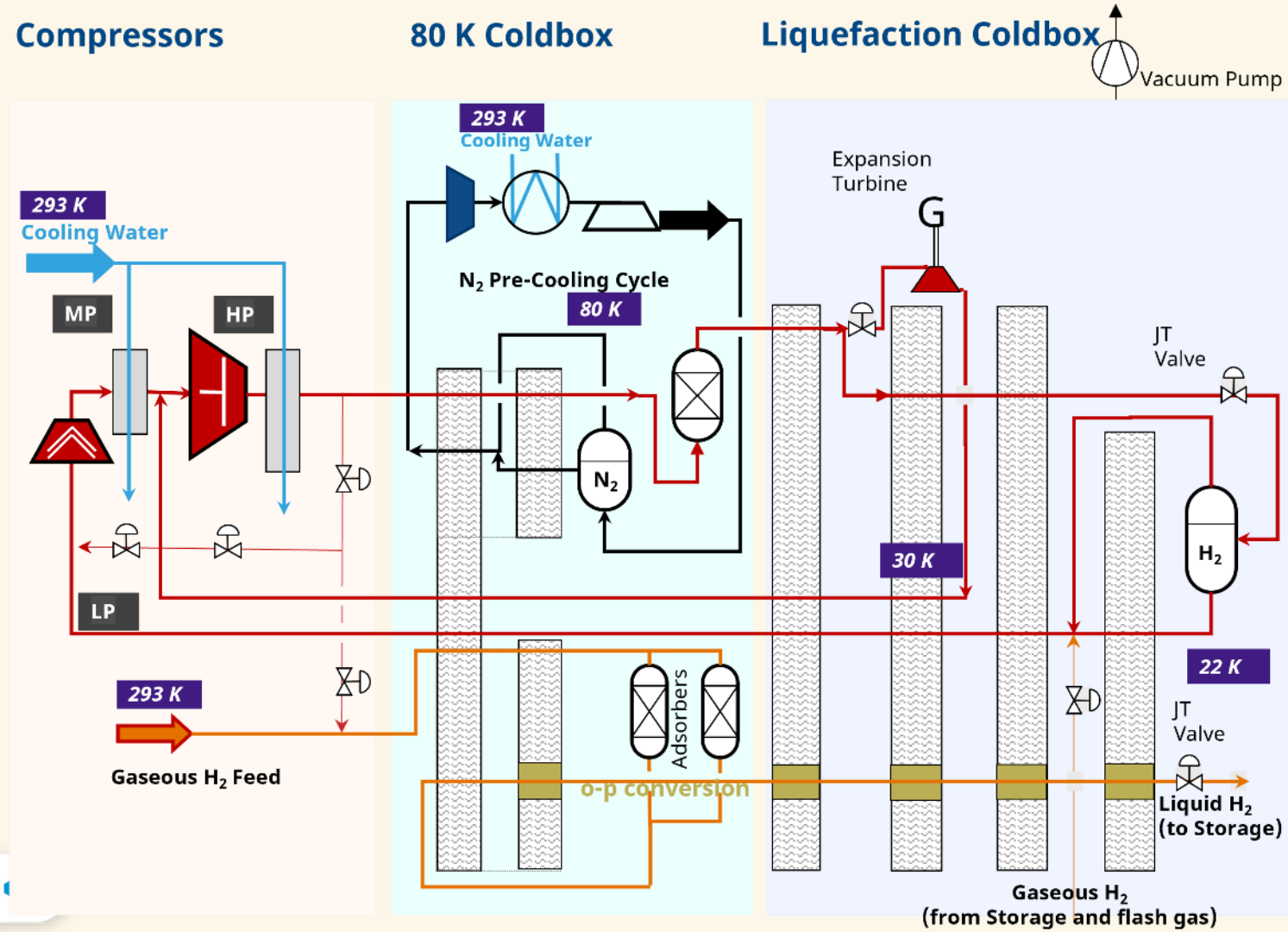
Helium as main refrigerant (Brayton Cycle, simplified)



- Brayton Cycle commonly used for small scale liquefaction (typically 1-2 to per day)
- Sacrificial Nitrogen (reduced CAPEX)
- Turndown with frequency variators or floating pressure concept
- Helium is sourced from natural gas
- Integrated o-p conversion
- Feed gas pressure >15 bara
- Specific energy demand: 15-19 kWh/kg LH_2 (including LIN)
- Adsorbers in alternating operation for removal of impurities

Hydrogen Liquefaction Process

H_2 as main refrigerant (Claude Cycle, simplified)



- Claude Cycle commonly used for liquefaction (5-30 to per day)
- Closed loop nitrogen precooling (>10 tpd)
- Turndown with floating pressure concept
- Hydrogen is used as refrigerant
- Integrated o-p conversion
- Feed gas pressure >15 bara
- Specific energy demand: 9-11 kWh/kg LH_2 (including LIN cycle)
- Adsorbers in alternating operation for removal of impurities
- Integrated boil-off gas compression

Hydrogen Liquefaction Process

Required Hydrogen Purification

- At 21 K (boiling atmospheric H_2) , all gases except for helium and hydrogen are solids
- If impurities freeze out in the refrigerating heat exchangers, performance suffers
- Capex for impurity removal is lowest at atmospheric conditions

- **Presence of oxygen in a hydrogen process is a major safety risk**
- Feed gas to liquefaction must be less than 1 ppmv O_2
  - Deoxo unit may need to be prolongated
  - Removal of other impurities (case by case)
- Condensation of air: Oxygen condenses first

Hydrogen Liquefaction Process (10 tons/day)

Oxygen (optional)
- O_2 liquefaction Cold Box
- LOX Storage Tank

Hydrogen
- H_2 pre-cooling Cold Box
- H_2 liquefaction Cold Box
- Refrigerant Compressors
- Expansion Turbines
- Storage Tanks

Trailer Filling System
- Vaporizers
- Vacuum-insulated Pipes

Transport
- Liquid Gas Trailers

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CAPEX and OPEX for H_2 Supply Chain

- Liquefaction Equipment

- Compressor, Coldbox, Expander, Storage Tanks, Filling Stations

CAPEX and OPEX for H_2 Supply Chain

Increasing Density & Payload

Type I Jumbo GH_2 Trailer

Type III & IV HP GH_2 Trailer

Jumbo Liquid Trailer

Liquid Hydrogen Railcar

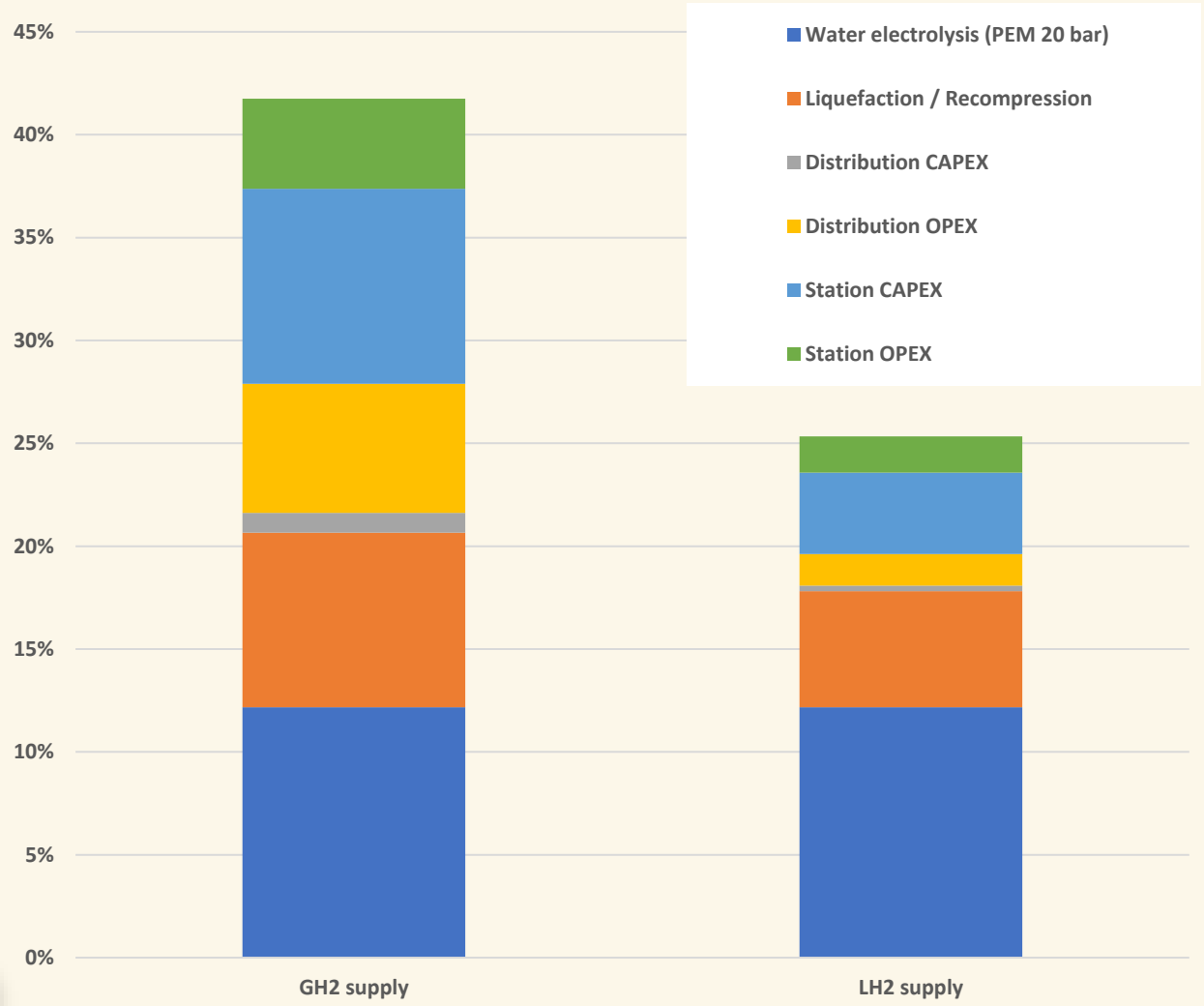
Pressure	165 bar	450-525 bar	7.5-11.5 bar	2.5 -4.0 bar
Density	12-15 g/l	25-40 g/l	70 g/l	70 g/l
Payload	350 kgs	450-1000 kgs	4,400 kgs	8,000 kgs
Capex/kg	100%	146%	52%	28%
+	•Good for low pressure applications at smaller volume	•Good for high pressure applications	•Highest delivered volume by road	•Lowest distribution cost in large volumes
	•Low Maint. & OPEX < 100 km	•Used for cascade deliveries into ground storage	•Low maintenance & OPEX 800 km+ trips typical	•Can be used to connect sources to hub terminals
	•Mature supply chain		•Mature technology	
-	•Requires large footprint	•Higher maintenance	•Higher initial investment	•DOT Permits expired and previous regulations outdated
	•Drop & Swap model -most cost effective	•Large residual volume, when not used in drop & swap	•Potential for losses during deliveries & transfers	•Boil off management required
	•Residual volume remaining			

CAPEX and OPEX for H_2 Supply Chain

- Liquid Hydrogen ISO Containers

ISO Model	UN T75 40 ft ISO		
Capacity (water vol.)	11,300 gal	42,78	m^3
Payload at 90%	6614 lbs	3'000,0	kg
Tare Weight	~12,000 lbs	5'443,1	kg
MAWP	145 psig	10	bar
Length	40’	12,19	m
Width	8’	2,44	m
Height	8’-6”	2,59	m
Hold Time	30+ days	30+ days	

Why the Race to Liquid for H_2 Refueling Stations?



The new Hyundai Nexo drives about 97.8 km/kg of hydrogen (April 2025)

	GH_2 supply	LH_2 supply
Water electrolysis (PEM 20 bar)	12,2%	12,2%
Liquefaction / Recompression	8,5%	5,6%
Distribution CAPEX	1,0%	0,3%
Distribution OPEX	6,3%	1,5%
Station CAPEX	9,5%	3,9%
Station OPEX	4,4%	1,8%
Total Specific Costs per 100 km of a comparable gasoline car	**42%**	**25%**

electricity $ 30,00 per MWh
Depreciation: CAPEX gas systems 15 years, liquid 25 years, liquefier 20 years, capacity **30 tpd**, electrolyzer 15 years (pressure cycles for gas equipment are limited)

THANK YOU

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Cefic sector group

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Chlor-alkali: achieving climate neutrality

References - Liquid H_2 and He Plant (selection)

Plant Type	Scope of Supply	Capacity [mT/D]	Power [kWh / kg]	Country	Year Built	Coldbox Dimensions (Ø/H in m)	Coldbox Weight [mT]	Precooling type	Precooling LIN [mT/D]	Liquefaction refrigerant
LH_2	Compression, Liquefaction, Distribution	30 3 trains	11	USA	Project Awarded 2024	To be determined	To be determined	N_2	Closed loop LIN recycle & Perlite coldbox	Hydrogen
LH_2	Compression, Liquefaction, Distribution	15	11	Canada	Project Awarded 2021	Ø 3.05m x 10.07m PCB: 4.27m x 4.27m x 18.4m	VCB: 26.35 PCB: 67.13	N_2	Closed loop LIN recycle & Perlite coldbox	Hydrogen
LH_2	Compression, Liquefaction, Distribution	15	19.75	USA	2024	Ø 2.44m x 9.77m PCB: 3.66m x 4.27m x 18.4m	VCB: 20.41 PCB: 56.06	N_2	Closed loop LIN recycle & Perlite coldbox	Helium
LH_2	Compression, Liquefaction, Distribution	15	19.75	USA	2023	Ø 2.44m x 9.77m PCB: 3.66m x 4.27m x 18.4m	VCB: 20.41 PCB: 56.06	N_2	Closed loop LIN recycle & Perlite coldbox	Helium
LH_2	Purification, Compression, Liquefaction, Distribution	9,07	15,20	USA	2018	Ø 3.05m x 11.89m H.	28,10	LN_2	71,3	Helium
LH_2	Purification, Compression, Liquefaction, Distribution	9,07	13,02	USA	2016	Ø 3.05m x 11.89m H.	28,10	LN_2	77,29	Helium
LHe	Purification, Compression, Liquefaction, Distribution, Cooling Water System	3,47	25,50	Russia	2018	Ø 3.05m x 10m H.	34,01	LN_2	11,76	Helium
He	Purification	2,75	0,05	Poland	2016	Ø 2.43m x 9.1m H.	12,44	LN_2	3,89	-
LHe	Purification, Compression, Liquefaction, Distribution	4,05	3,69	USA	2012	Ø 3.05m x 10.12m H.	24,95	LN_2	13,12	Helium
LHe	Purification, Compression, Liquefaction, Distribution	2,17	8,73	Poland	2008	Ø 1.82m x 9.14m L.	15,88	LN_2	1,958	Helium
LHe	Purification, Compression, Liquefaction, Distribution	8,16	2,37	USA	2006	Ø 2.36m x 9.32m H.	17,24	LN_2	13,07	Helium

Plant types in bold characters are supplied with hydrogen from chlorine alkaline plants