Transporting Hydrogen:

Understanding the Processes and Costs to Transport Hydrogen Including Compressed, Liquid, Ammonia and LOHC in Pipelines, Trailers, Trains and Ships

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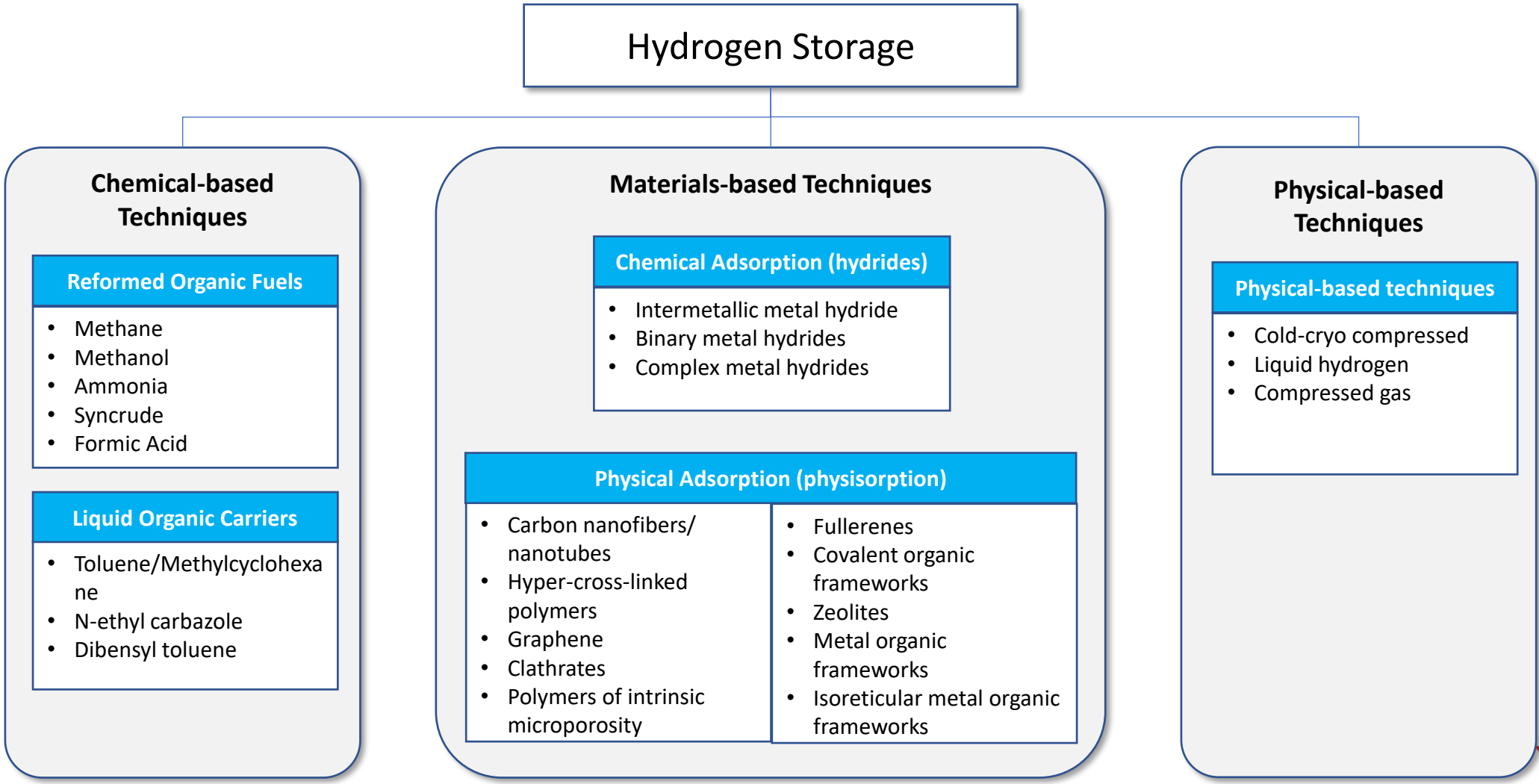
Today's Agenda

- Approximately 95% of all hydrogen produced in the world is consumed in the same place it is produced. Transporting hydrogen is notoriously challenging.
- According to the IEA, the global hydrogen market is expected to grow from 80 million tons per year to an expected 290 million tons per year in their net zero 2050 scenario.
- Realizing this phenomenal growth in green hydrogen requires connecting low-cost production with high value markets. Hydrogen hubs are being designed around the world in locations with significant land area with wind and solar resources. Billions of dollars of investment are depending on the ability to connect these hydrogen hubs to markets around the world.
- This webinar is going to review the various methods being deployed to transport hydrogen, including gaseous, liquid, ammonia and LOHC.

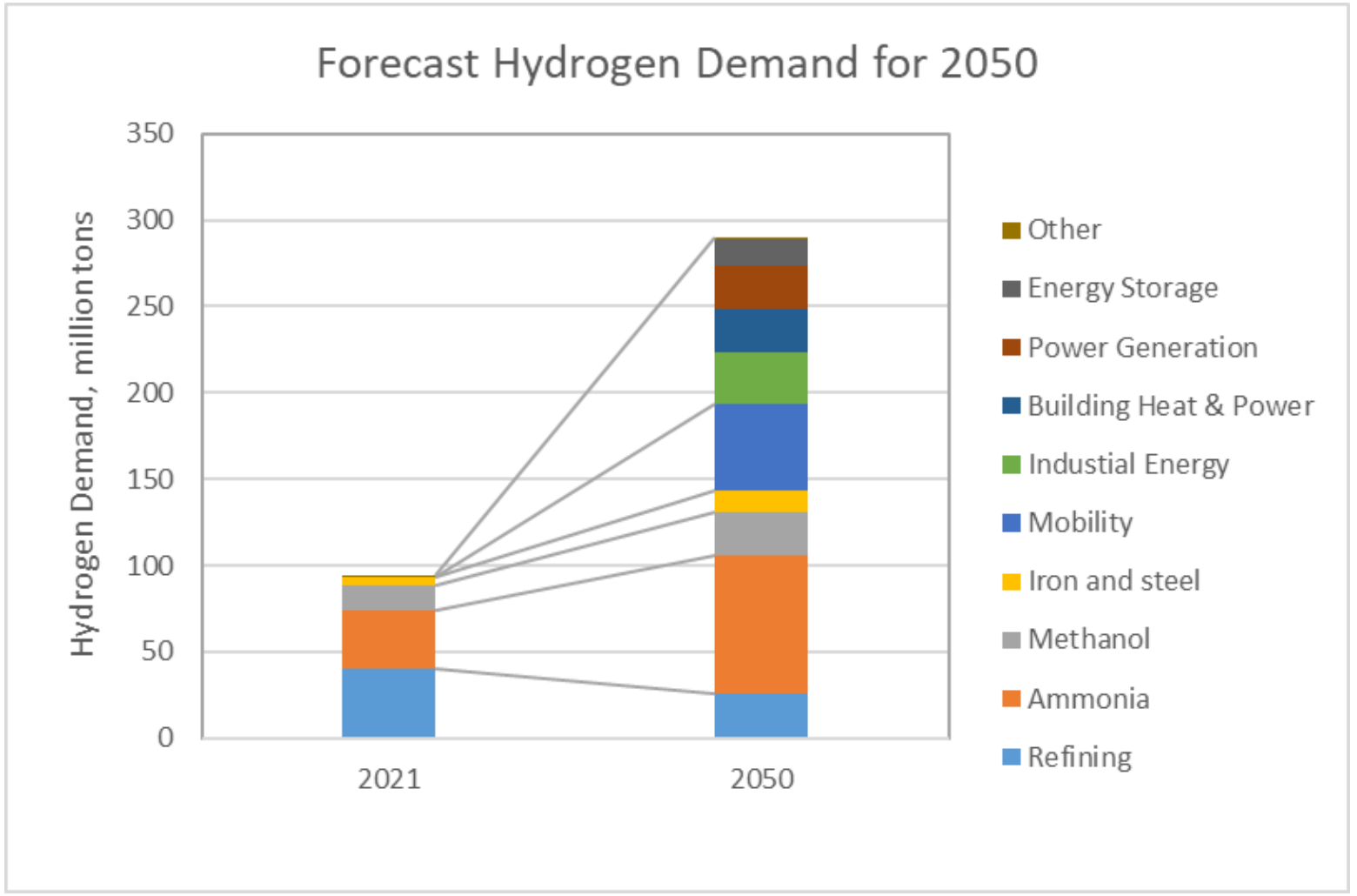
There are many approaches being pursued for hydrogen storage, used for both stationary storage and for transporting hydrogen



Today, we are focusing on the most common hydrogen storage forms for transporting hydrogen

- Liquid Hydrogen
  - Trucks
  - Ships
- LOHC
  - Ships
- Gaseous Hydrogen
  - Trucks
  - Pipelines

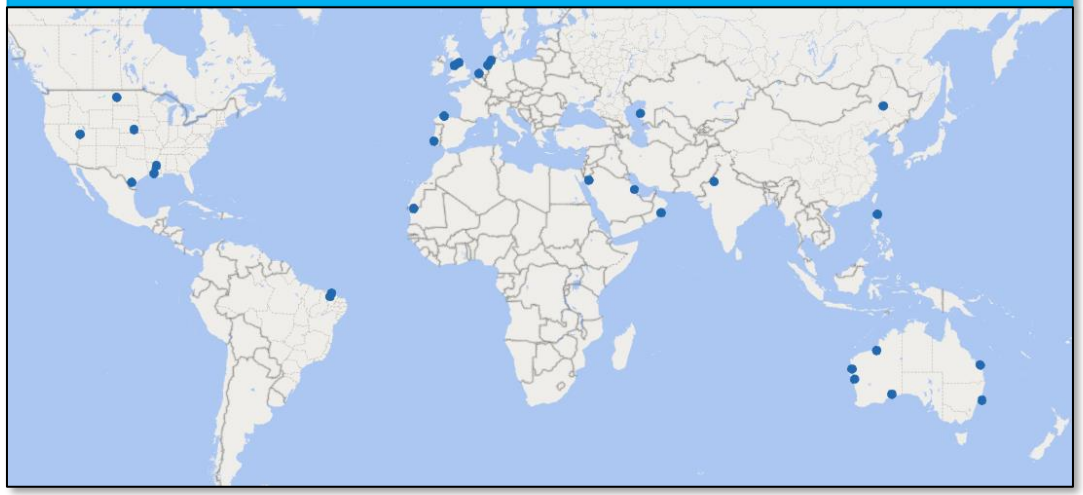
Estimates of future demand for hydrogen vary widely, although significant growth dominates every forecast with new end-uses in transportation, power generation, energy storage and heat energy



Source: IEA, Hydrogen Council, Velerity

Thirty largest announced hydrogen hub in the world have the capacity to produce an estimated 53 million tons per year of hydrogen

30 Largest Announced Hydrogen Hubs



Potential global production of green ammonia is very ambitious

- If 90% of the 24 largest green hydrogen projects produce ammonia, ammonia production will be 238 million tons per year
- Current global ammonia production is about 180 million tons per year
- Current global trade in ammonia is about 18 million tons per year

Source	Hydrogen Production (million TPY)	Percentage of Hydrogen Produced	Number of Projects	Average Hydrogen Production (million TPY)
Natural Gas	4.91	9.3%	5	0.98
Petroleum	1.00	1.9%	1	1.00
Renewable Energy	46.79	88.8%	24	1.95
Total	52.69	100.0%	30	1.76

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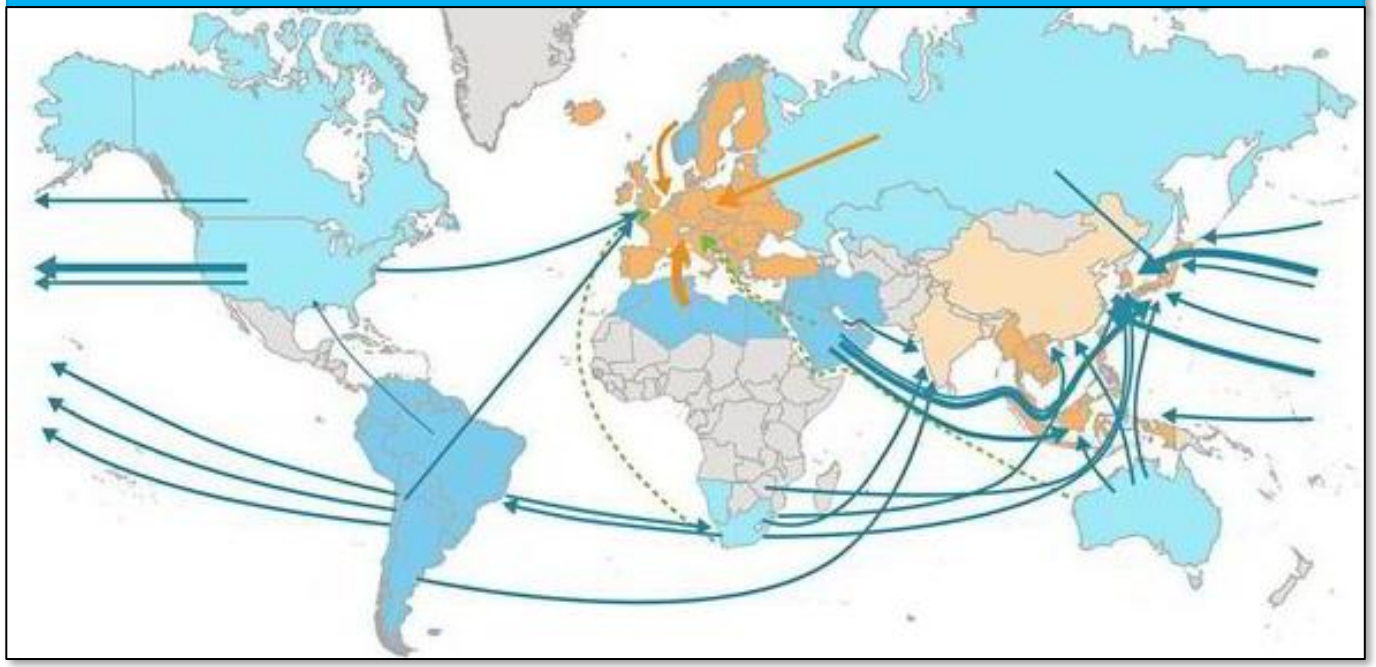
A vast network of long-distance shipping and pipeline routes are expected to be built by 2050 for the trading of just over 60% of the world's hydrogen supply

Major Flows of Hydrogen and Derivatives in 2050



Source: Hydrogen Counsel, McKinsey

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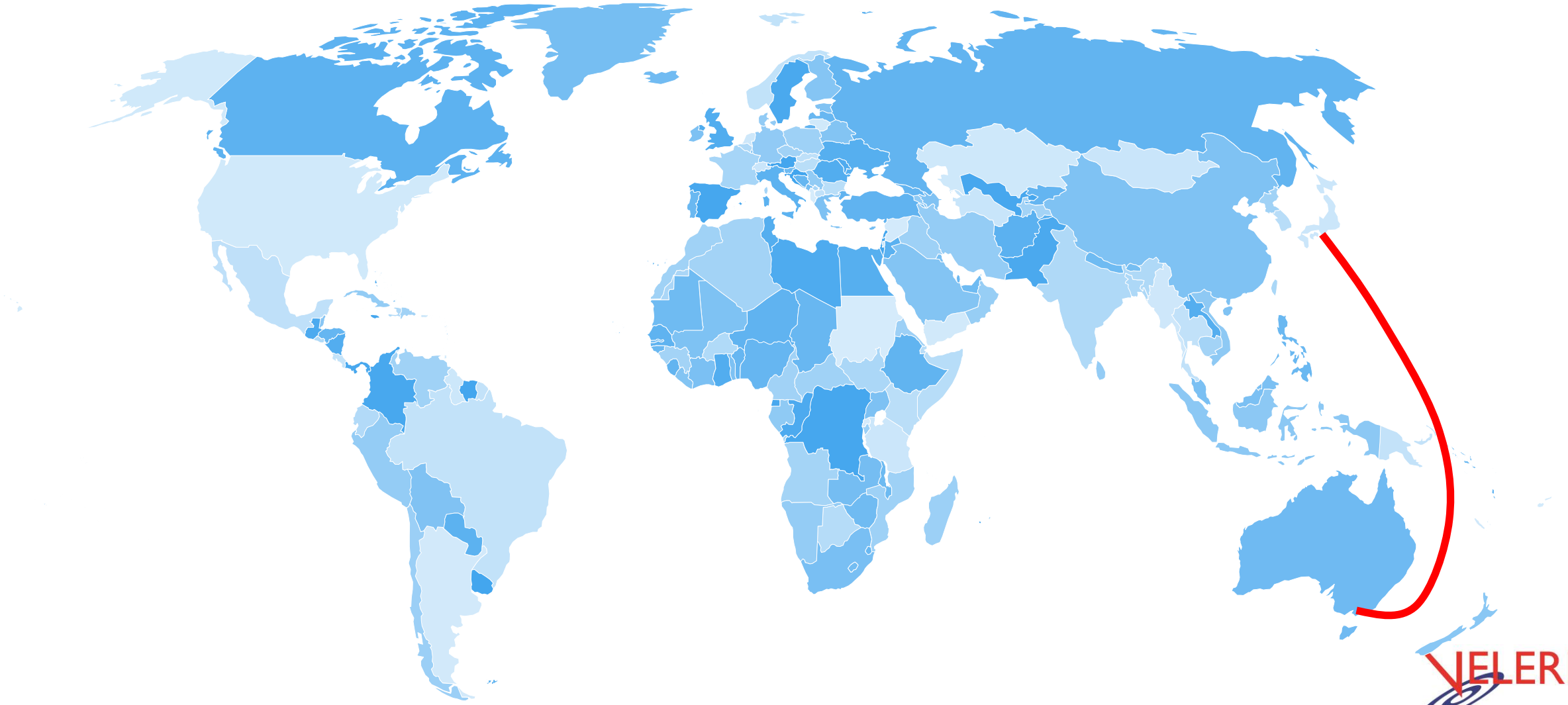
Liquid hydrogen shipped via the Suiso Frontier from the Port of Hastings in Australia to Kobe, Japan, 9,000 kilometers



Although unfortunately green hydrogen, the world's first liquid hydrogen transport ship was built and is in operation to ship hydrogen 9,000 km from Australia to Japan

Latrobe Brown Coalfields	Brown coal gasification/H2 Refining System	High Pressure Gas Trailer	H2 liquefaction/ Loading Terminal	LH2 Carrier	LH2 Loading Terminal
					
AGL Energy Limited	Construction・Operation : J-POWER	Construction : KHI Operation : Iwatani		Construction : KHI Operation: Shell Japan (STASCO)	Construction : KHI Operation: Iwatani
Australia : Victoria's Latrobe Valley		Approx. 150km	Victoria State Hastings	Approx. 9000km	Japan : Kobe

※HySTRA business supported by NEDO(New Energy and Industrial Technology Development Organization) is written in red.
※Consortium business supported by Commonwealth of Australia and Victoria State Government is written in white.
※KHI=Kawasaki Heavy Industries, Ltd.
※STASCO=Shell International Trading and Shipping Company Limited

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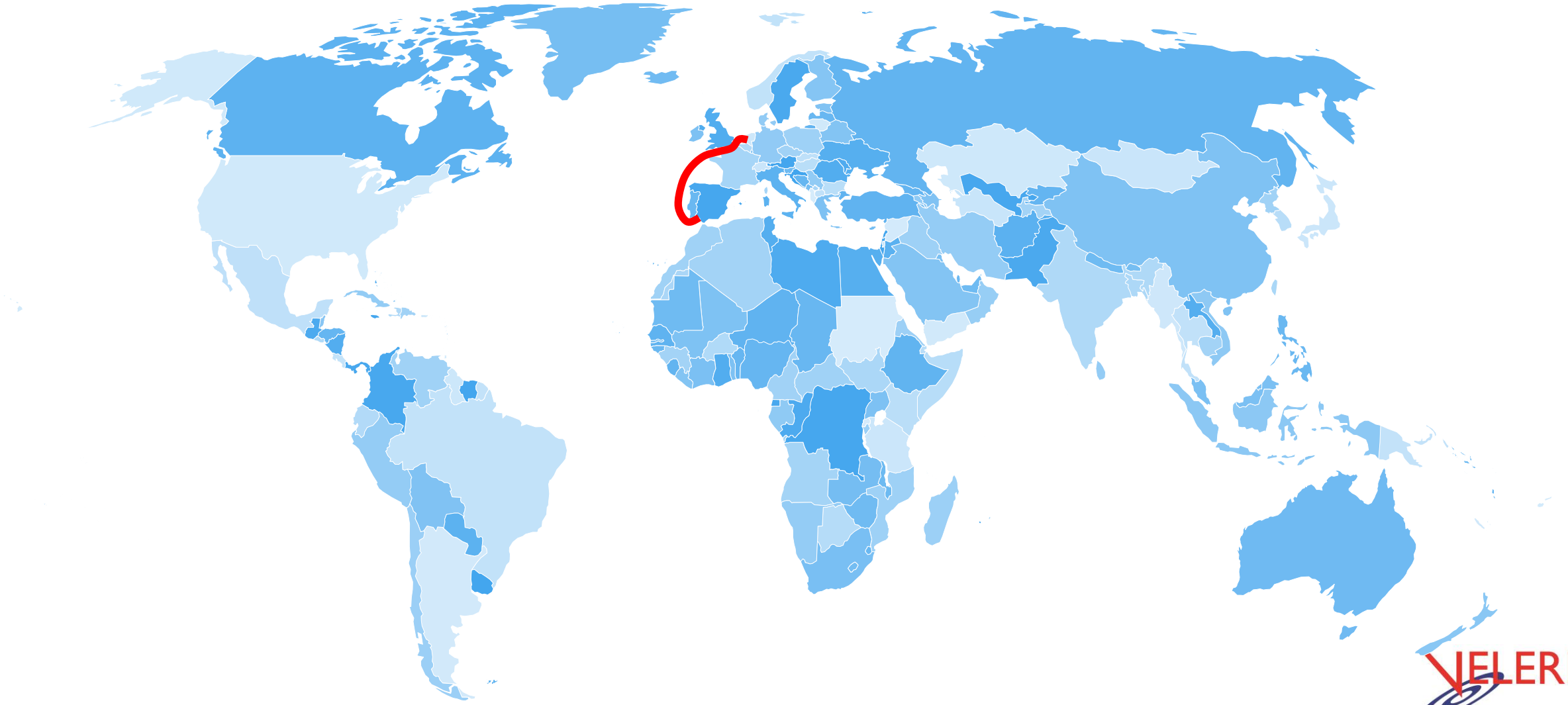
The hydrogen goes through many processes before arriving in Japan

- **Latrobe Valley facility**
  - Operated by J-Power
  - Gasification and refining
  - Loaded into tube trailers for 80 km transport to Port of Hastings
- **Port of Hastings plant**
  - 0.25 ton per day liquefaction capacity.
  - Has a 41m3 LH2 storage container.
- **Suiso Frontier**
  - The specialized marine carrier has a ship tank capacity of 1,250m3 and successfully made the first shipment in early 2022
  - Gross tonnage - 8,000 ton
  - Top speed - 13 knots
  - Trip duration – 2 weeks
  - Storage - 1,250-cubic-metre storage tank
  - A commercial-scale HESC project is expected to produce 225,000 tons of liquid hydrogen annually with carbon capture and storage

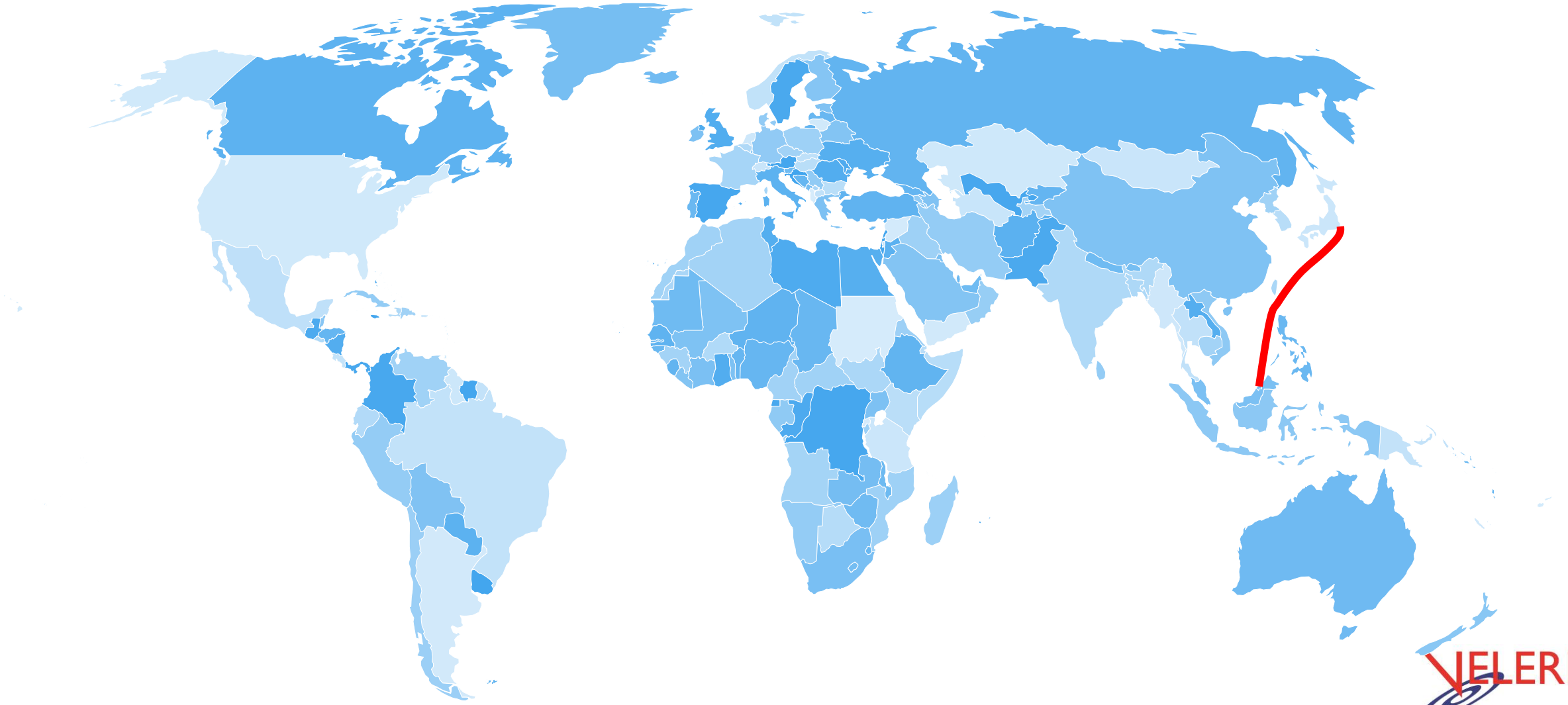
Andalusia, Spain to the Port of Rotterdam, Netherlands – Producing and transporting ammonia 1,595 miles from the south of Spain to the Port of Rotterdam



Yara is partnering with Cepsa to produce and transport green ammonia from Spain to the Netherlands

- The alliance incorporates Yara Clean Ammonia as the newest partner of the Andalusian Green Hydrogen Valley, where Cepsa plans to build a new green ammonia plant at its energy park in San Roque, Cádiz, near the port of Algeciras, with a 1-billion-euro investment and the creation of 3,300 jobs.
- The agreement includes a 1 GW electrolyzer
- It will be the largest green ammonia project in Europe with an annual production capacity of up to 750,000 tons, which will prevent up to 3 million tons of CO2 from being emitted
- The initiative expands the largest green hydrogen project in Europe from 1 to 2 GW of electrolysis capacity, expected to be operational in 2027
- The plant will use green hydrogen generated by Cepsa and EDP at the 1 GW plant in Campo de Gibraltar for its feedstock

Brunei, Darussalam to Kawasaki City, Japan, Liquid Organic Hydrogen Carrier, 5,000 kilometers



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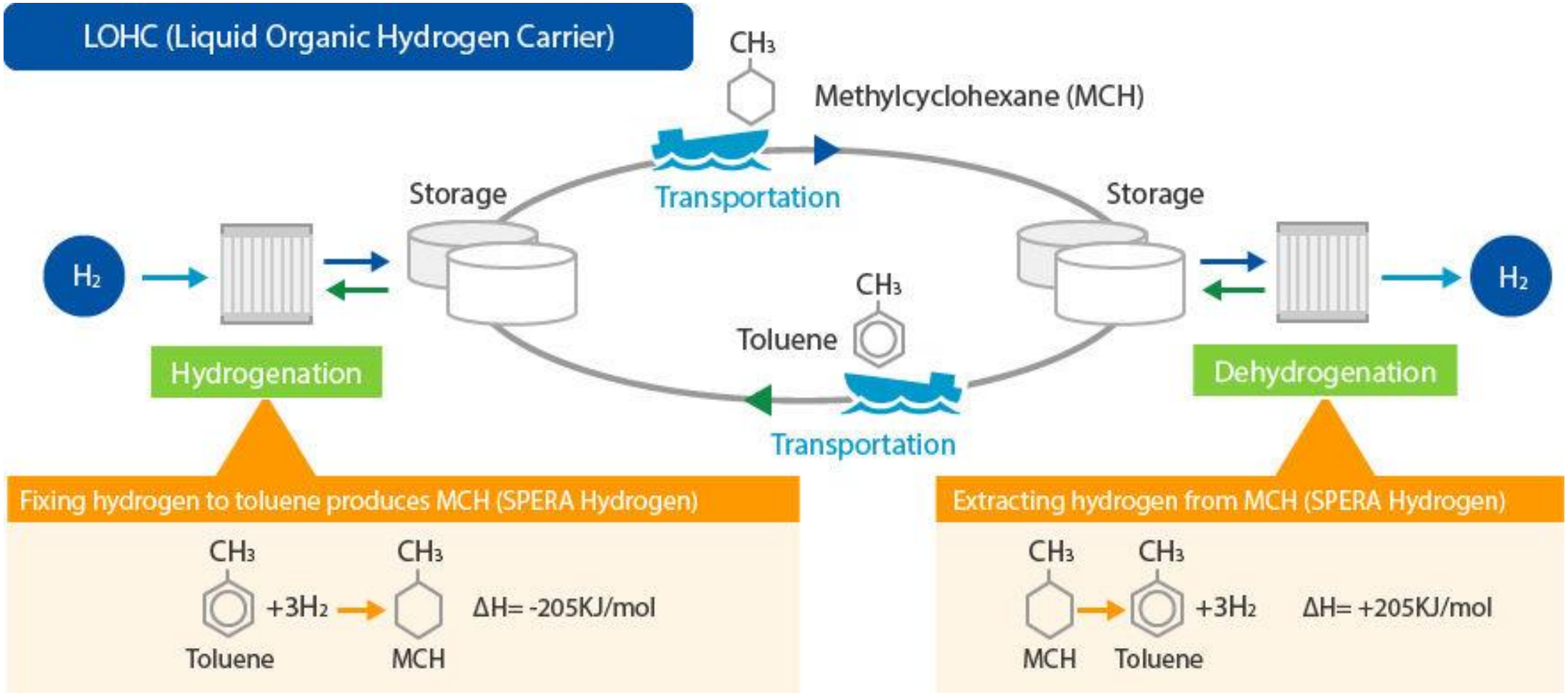
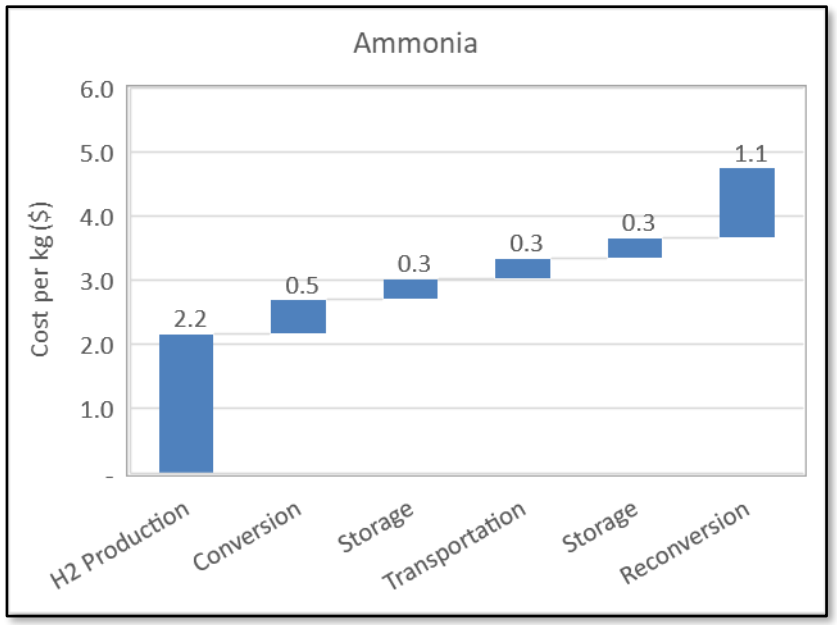
Brunei LOHC project

- Project has maximum 210 mt/year hydrogen supply capacity. Hydrogen produced from processed gas at Brunei LNG. Transporting hydrogen at normal temperature, pressure.
- The project uses the organic chemical hydride method to produce hydrogen by steam reforming processed gas from the Brunei LNG liquefaction process. The hydrogen is converted by hydrogenation reaction using toluene into methylcyclohexane (MCH), which is a liquid at ambient temperature and pressure, meaning existing facilities can be used for storage and transport.
- The MCH is shipped to Tokyo Bay, where the hydrogen is extracted using a new dehydrogenation plant at the 70,000 b/d Keihin refinery in Tokyo Bay, operated by Toa Oil, a subsidiary of Idemitsu Kosan. Toluene from the process is then transported back to Brunei for re-use in the hydrogenation process.
- The project supplies about 100 mt of hydrogen for power generation at the Mizue plant in Japan
- The project supplies separated hydrogen from the dehydrogenation plant and blends it with byproduct gas for to fuel gas turbines at the Mizue power station inside the Keihin refinery with a subsidy from the state-owned New Energy and Industrial Technology Development Organization, or NEDO

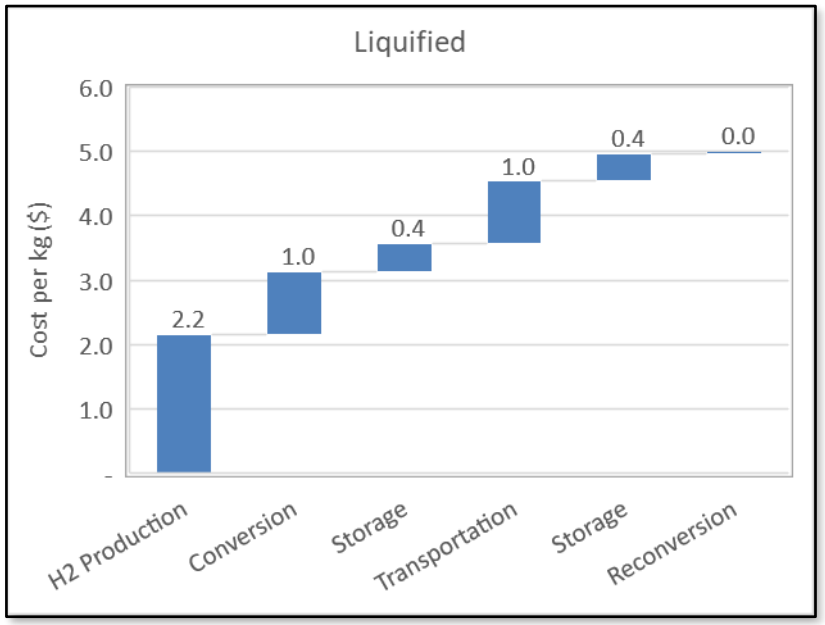
The Brunei LOHC process



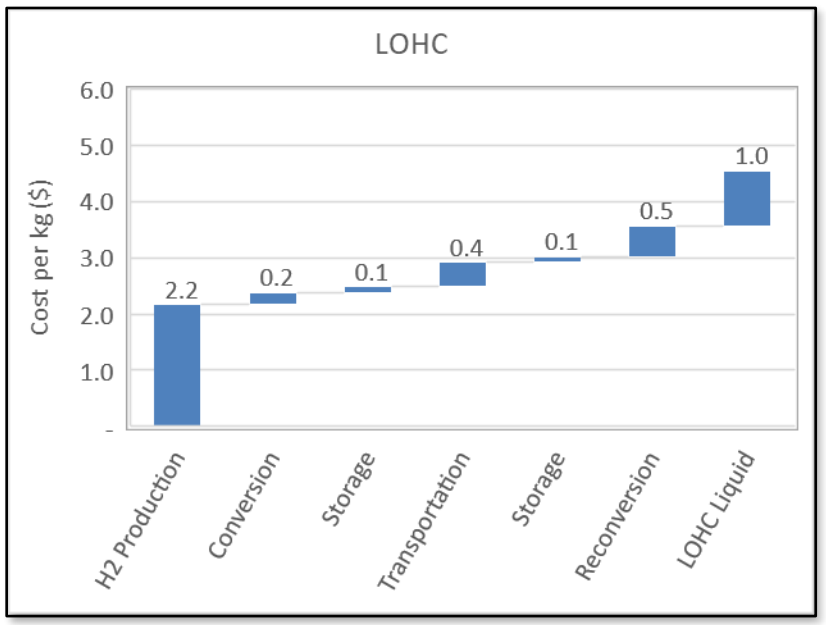
Comparative economics for transporting hydrogen via ammonia, liquid and LOHC



Ammonia LCOH - $4.6/kg



Liquid LCOH - $5.2/kg



LOHC LCOH - $4.5/kg

The costs are specific to each use case
Mileage – 12,000 km
H2 Volume – 73,000 tpy
Source: Roland Berger

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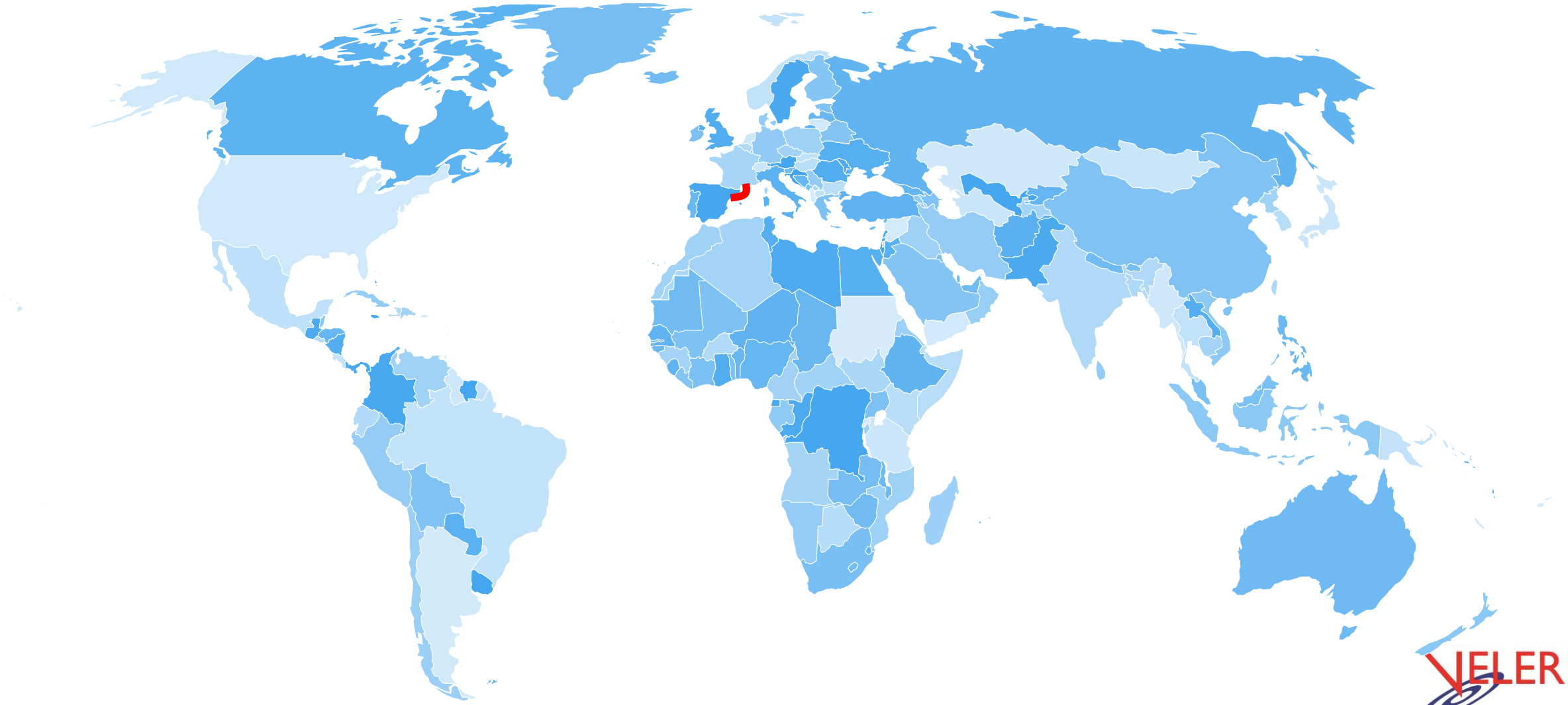
European Hydrogen Backbone

- The European Hydrogen Backbone, by 2040, is expected to have a total length of about 53,000 km, consisting of approximately 60% repurposed existing infrastructure and 40% of new hydrogen pipelines.
- The proposed network would meet 1,640 TWh of annual hydrogen demand in Europe by 2040
- The total investment costs are expected to range from €80 to €143 billion
- Annual operating costs are estimated to be between €1.6 and €3.2 billion

One example: H2MED

€ 2.5 billion undersea pipeline between Barcelona, Spain and Marseille, France which will carry 2 million tons per year of hydrogen



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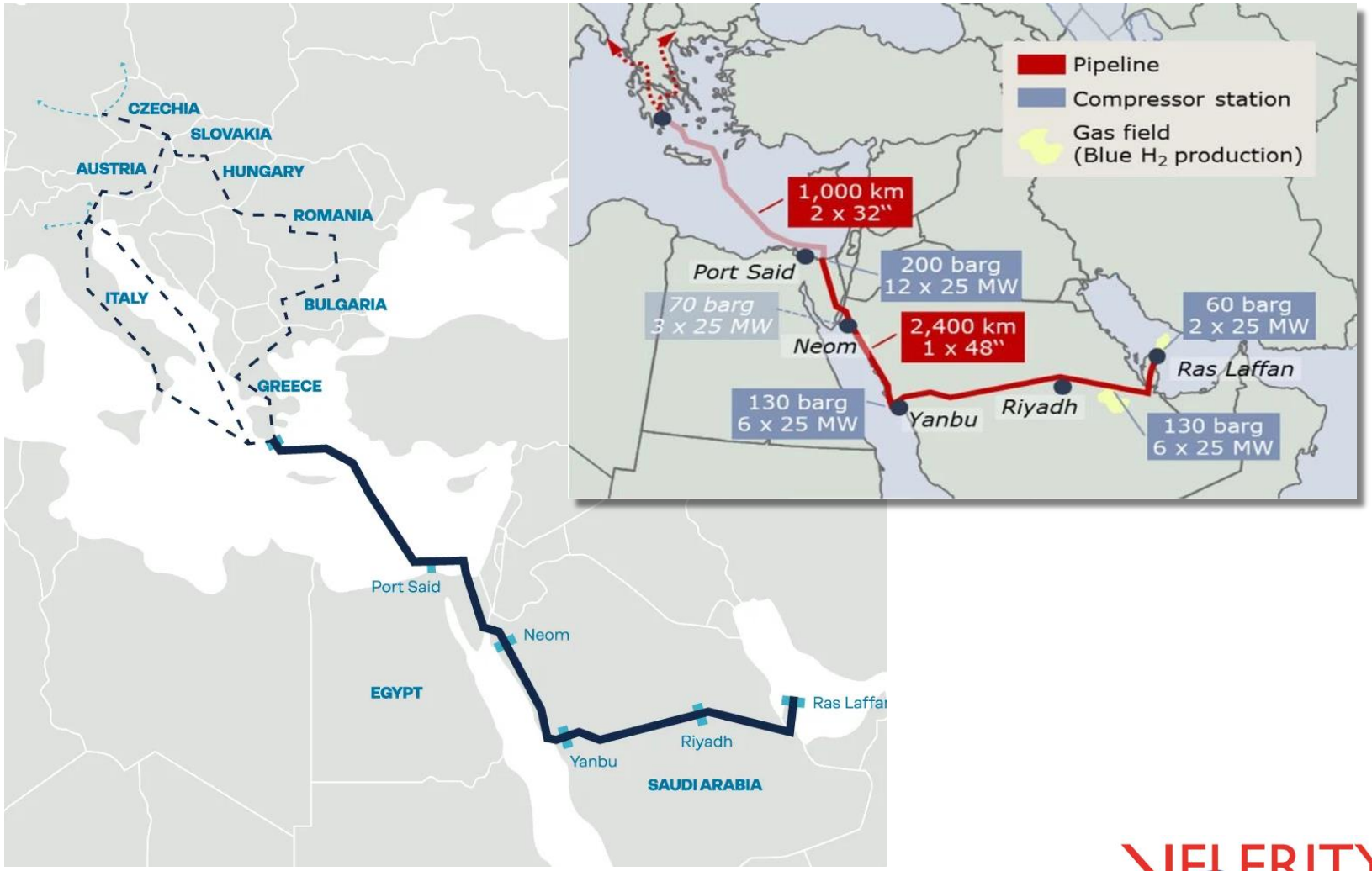
A 3,400 km hydrogen pipeline connecting Qatar, Saudi Arabia, Egypt, and traversing the Mediterranean Sea to Europe

- Hydrogen pipeline connecting Qatar, Saudi Arabia, Egypt, and traversing the Mediterranean Sea to Europe
- Pipeline could transport 100 TWh or approximately 2.5 million tons of hydrogen per year.
- The cost of transporting hydrogen through this pipeline is initially seen at approximately €1.2/kg H2.
- The Gulf countries, in turn, could supply green and blue hydrogen to the economic hub of Europe at Levelised Costs Of Delivered Hydrogen (LCODH) of around €2.7/kg starting from the 2030s, decreasing to around €2.3/kg in the longer term.



Over land transport of hydrogen

- Steel Tube Trailer
  - Capacity 300 – 380 kg
  - Pressure – 180 (~2,600 psi) to 250 bar ~3,600 psi)
  - Steel cylinders
  - Capacity constrained by the weight of the cylinders
  - 4-6 kWh/kg for compression
- Composite Tube Trailer
  - Capacity - 800 – 1,300 kg
  - For 1,000 kg - 517 bar (7500 psi)
  - 6–8 kWh/kg for compression
- Liquid hydrogen trailer
  - Capacity 4,000 kg
  - Hydrogen Temperature -253° centigrade
  - Energy cost to liquefy 10-12 kWh/kg H2
  - Large liquefaction plant – 50 tpd – 6 kWh/kg H2

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Comparison of over land hydrogen transportation alternatives