1-1. Reducing High Marine Transportation and Onshore Distribution Costs

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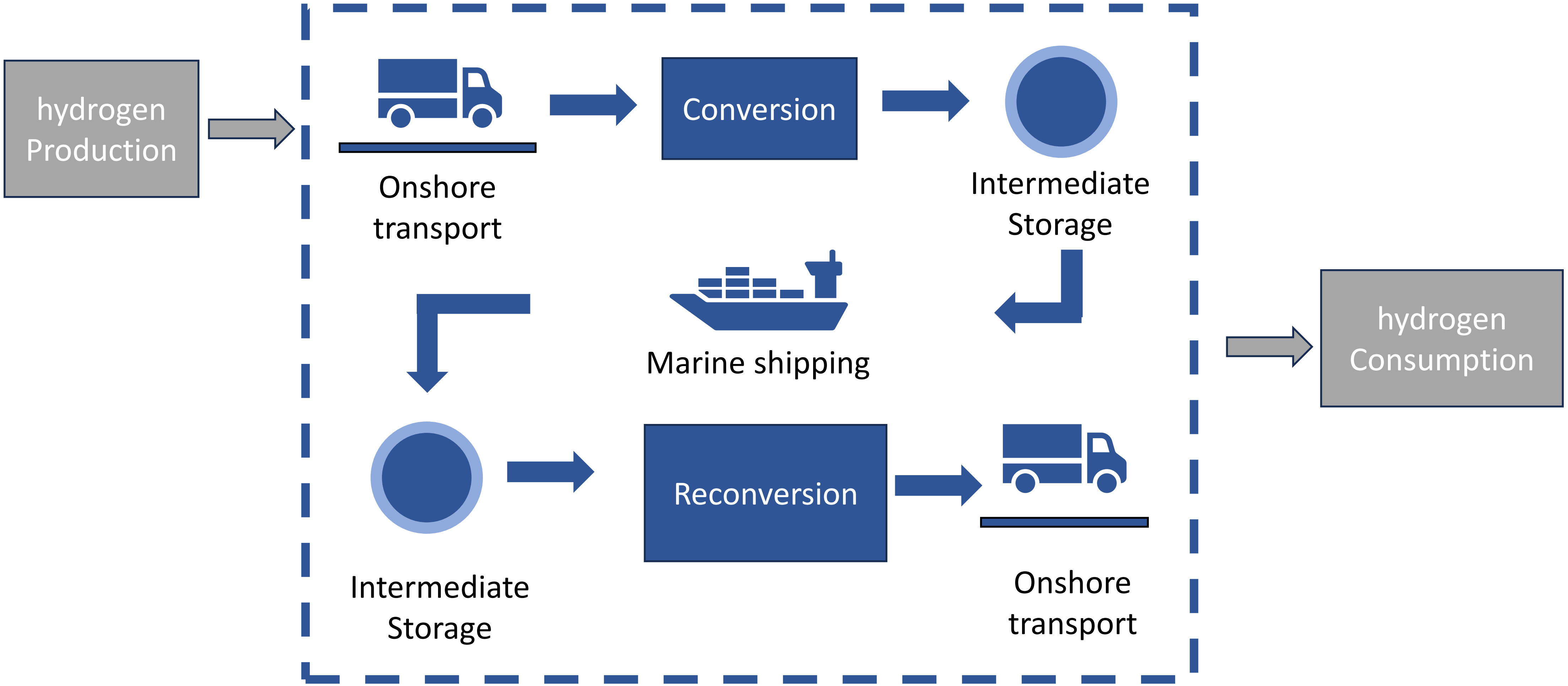
Reaching end-use hydrogen consumers efficiently is challenging



- Most of the hydrogen is produced and consumed on-site (85%), while the rest is transported via pipelines or compressed trailer trucks for distances less than 300 km.
- To achieve a carbon neutrality scenario, a large gap in investment exists in hydrogen transport and distribution.

Comparison between hydrogen carriers

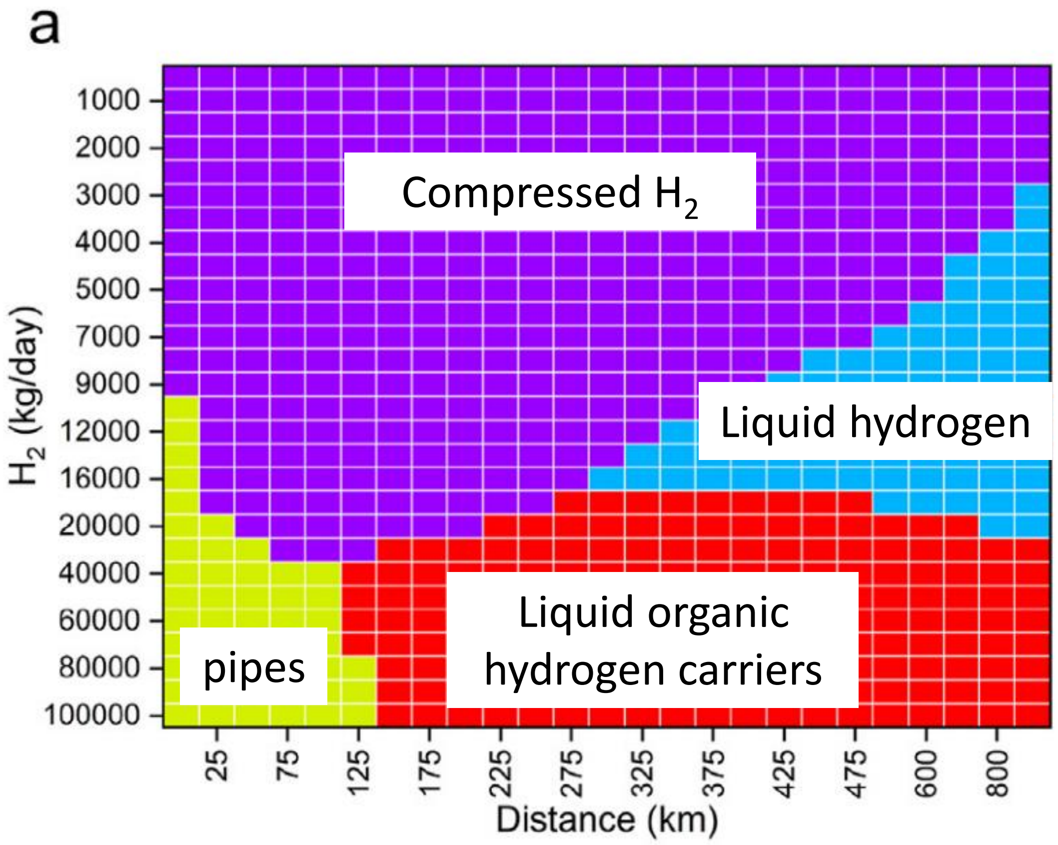
Properties	Unit	H_2 (gas)	H_2 (liquid)	CH_3OH	NH_3	MCH
Storage Method	-	Compression	Liquefaction	Ambient	Liquefaction	Ambient
Temperature	°C	25	-259.9	25	25	25
Storage Pressure	MPa	20	0.1	0.1	0.99	
Density	kg/m^3	14.1	70.8	792	600	770
Explosive Limit in Air	%Vol	4-75	4-75	6.7-36	15-28	1.2-6.7
Gravimetric Energy Density (LHV)	MJ/kg	120	120	20.1	18.6	7.4(*)
Volumetric Energy Density (LHV)	MJ/l	1.692	8.49	15.8	12.7	5.69(*)
Gravimetric H_2 content	wt%	100	100	12.5	17.8	6.16
Volumetric H_2 content	kg-H_2/m3	14.1	70.8	99	121	47.4
H_2 release	-	Pressure release	Evaporation	Catalytic decomposition T > 200 °C	Catalytic decomposition T > 400 °C	T > 200 °C
Energy to Extract H_2	kJ/mol-H_2	-	0.907	16.3	30.6	68.3

Volumetric energy density of diesel is 34.6 MJ/l. Lower volumetric density implies more trips to transport the same amount of energy if the same vessels are used.

(*) Assuming the energy in the H2 content in MCH

Different requirements of transportation may use different hydrogen carrier

- Different conditions require different solutions:
  - Short distance (<350km) and less that 0.4 PJ demand (approx. 10 tonnes of hydrogen/day) , transport through trucks is more competitive.
  - Liquid hydrogen becomes competitive if more demand growth, and distances are long enough, however, boil-off losses (0.5- 5% vol/day) can make its use difficult in trips that take several days. In comparison Ammonia boil-off losses are smaller fraction (0.025% vol/day)
  - Other hydrogen carriers have a space at long distance and high hydrogen demand.



Source: Techno-economic analysis of hydrogen storage and transportation from hydrogen plant to terminal refueling station (Rong et al., 2024)

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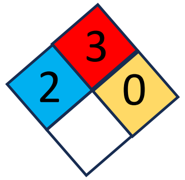
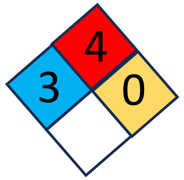
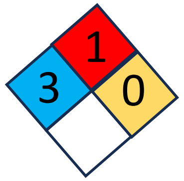
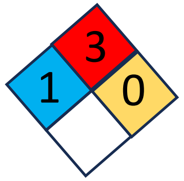
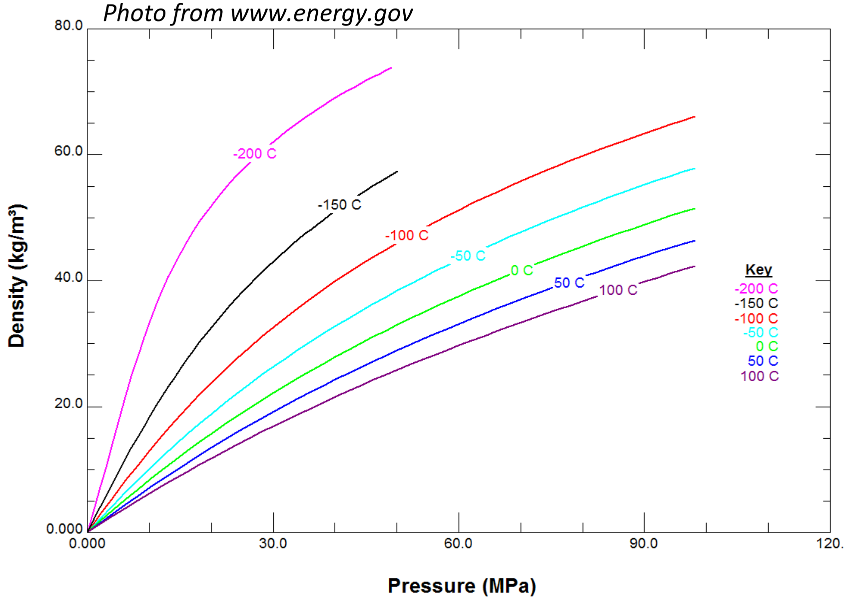
NFPA Diamond of Hydrogen Carriers

H2 Carrier	Diamond	Description
Toluene		Can cause temporary incapacitation or residual injury. Can be ignited under almost all ambient temperature conditions. Normally stable, even under fire conditions
Liquid Hydrogen		Can cause serious or permanent injury. Burns readily. Rapidly or completely vaporizes at atmospheric pressure and normal ambient temperature. Normally stable, even under fire conditions
Ammonia		Can cause serious or permanent injury. Must be preheated before ignition can occur. Normally stable, even under fire conditions.
Methylcyclohexane		Can cause significant irritation. Can be ignited under almost all ambient temperature conditions. Normally stable, even under fire conditions.

Source: https://cameochemicals.noaa.gov/chemical/3919

Transport via trucks

Photo from www.energy.gov



Source: H2tools.org

- Hydrogen transport via trucks will play the most important role during the early phase of the development of the hydrogen industry as distances as volumes may not be high enough to justify bigger investment.
- To be transported via trucks, hydrogen needs to be compressed from 30 bar to 200 bar. Compressing Hydrogen is energy intensive and can consume around 10% of the energy content in hydrogen.
- Transportation of gases at this or higher levels of pressure is under strict regulation. New hydrogen trucks have a capacity of 1 tonne (USA) or 1.3 tonne (Europe). The energy content is 120 to 150 GJ. Cm of type II vessel is 1.5%, for the most advanced type IV vessel is a 5.5%.
- A typical fuel tank trailer can hold 7000 gallons of diesel or 22.5 tonnes. The energy content is 953 GJ.

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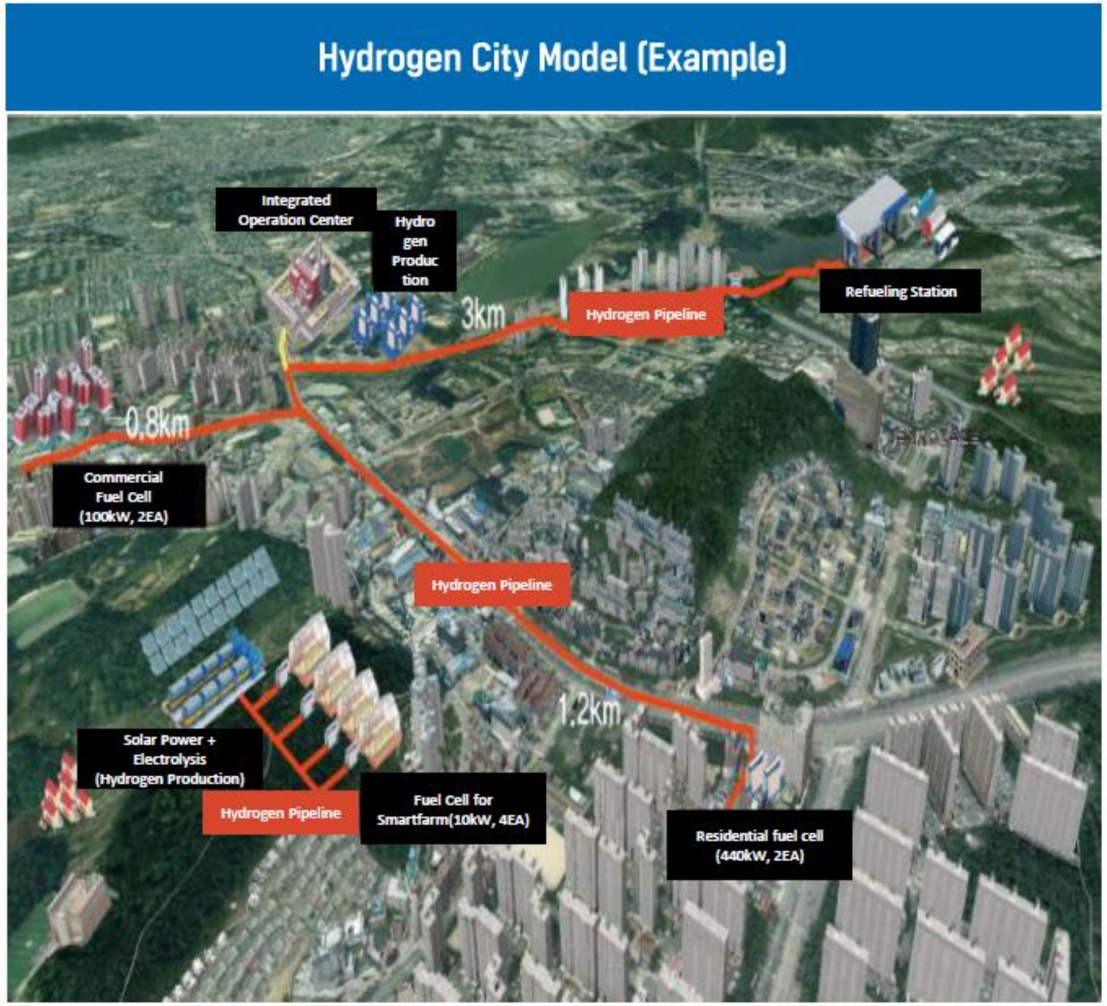
Transport via Pipelines

- Today there are 5000 km of hydrogen pipelines mostly inside industrial areas. Dedicated new pipelines can become attractive for large volumes of hydrogen.
- Pipeline capacity must be carefully chosen as small capacity may constraint demand growth.
- Korea is installing several kilometers of pipelines to power hydrogen cities in several pilot projects.
- Blending hydrogen with natural gas has a limit of 20% (V/V) due to technical constraints. This option reduces the amount of energy per unit of volume (14%) and reduces emission by 6.7% per unit of energy.



Source: Strategies for Realizing Hydrogen Cities in Korea (Ministry of Land, Infrastructure and Transport, 2023)

Distribution and Transport (long distance demand)

- Long distance requires a conversion to other hydrogen carrier: compressed and liquified hydrogen may not be competitive. Because of boil off requires bigger tanks
- Liquefy hydrogen consumes around 36 MJ/kg H_2.
- Methanol and Ammonia have the advantage of being able to be used directly without reconversion, however, direct burning of Ammonia releases NOx.
- Conversion to Ammonia and reconversion to hydrogen consumed more than 42 MJ/kg H_2.
- Although there are experiences trading ammonia and methanol, they are considered extremely dangerous chemicals.

Press Release on December 2023:

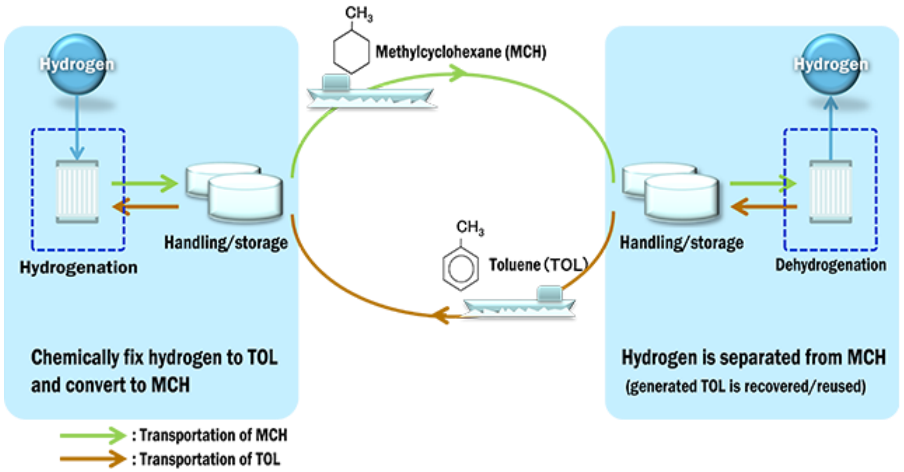
Maersk Tankers, one of the world's largest tanker operators, sets out to offer seaborne transportation of clean ammonia, leveraging its close to 100-year experience of operating tanker and gas vessels.

Source: https://maersktankers.com/newsroom/maersk-tankers-to-pioneer-transportation-of-clean-ammonia

Long distance transportation projects in APEC

APEC has experience with long distance transport: AHEAD ,that uses methylcyclohexane (MCH), and HESC, that uses liquefied hydrogen. Transportation did not use clean fuels.

Advanced Hydrogen Energy Chain Association for Technology Development (Brunei Darussalam-Japan)



Source: https://www.ahead.or.jp/en/research.html

In December 2020, the AHEAD project announced the successful transport of 100 tonnes of hydrogen over 10 months, using MCH as hydrogen carrier. The hydrogen was used in a gas turbine in Keihin refinery in Japan.

Hydrogen Energy Supply Chain (Australia-Japan)

Source: https://www.hydrogenenergysupplychain.com/about-the-pilot/supply-chain/the-suiso-frontier/

The pilot was successfully completed in February 2022 with the arrival of the Suiso Frontier, the World's first liquified hydrogen carrier, in Kobe, Japan with liquefied hydrogen from Australia. Suiso Frontier has a capacity of 1250 m^3 of liquid hydrogen (-253 °C)

Project Haru Oni-Porsche & HIF

Chile has started exports of methanol to UK. The first 2600 liters were already shipped at the beginning of 2023

Source: https://www.siemens-energy.com

Costs

- There are still uncertainties and assumptions may affect results:

Source	Route	Cost USD/kg H_2
IEA (The Future of Hydrogen)	Truck (gas H_2) 500 Km	1.8
IEA (The Future of Hydrogen)	Truck (gas H_2) 200 Km	1
IEA (The Future of Hydrogen)	pipeline (100 tpd) 500 Km	0.9
IEA (The Future of Hydrogen)	Shipping liq-H_2 5000 Km	3
IEA (The Future of Hydrogen)	Shipping NH_3 5000 Km	1.2
IEA (The Future of Hydrogen)	Shipping LOHC 5000 Km	1.4
Collis & Schomäcker (2022)	Trucking (gas H_2) 300Km	1.1
Collis & Schomäcker (2022)	Shipping NH_3 7000 Km	3-4
Collis & Schomäcker (2022)	Shipping LOHC 7000 Km	2.5-2.8
Collis & Schomäcker (2022)	Shipping liq-H_2 7000 Km	5.2
Allard Castelein (2nd World H_2 Summit 2021)	Shipping NH_3 South America-Rotterdam	3
Allard Castelein (2nd World H_2 Summit 2021)	Shipping liq-H_2 South America-Rotterdam	4
Allard Castelein (2nd World H_2 Summit 2021)	Shipping MCH South America-Rotterdam	3
Allard Castelein (2nd World H_2 Summit 2021)	Shipping CH_3OH South America-Rotterdam	6

Summary

- Transport of hydrogen represents one of the biggest challenges that requires attention as it may hinder the development of a future hydrogen economy.
- Several hydrogen carriers have been proposed. The conversion of produced hydrogen to these carriers requires energy additional energy, reducing the efficiency of hydrogen as an energy carrier.
- Even though some proposed hydrogen carriers have been used in industry, such as ammonia or ethanol, they are also very toxic and difficult to manage. Adaptation of safety regulations will be required to allow these chemical to be handled.
- The energy required to transport hydrogen or hydrogen carriers can easily “dirty” clean hydrogen. It is important not to considered just the emission intensity of hydrogen production but also the process of transportation and distribution.

Thank you.

https://aperc.or.jp