Gutierrez Energy
Management Institute
C. T. Bauer College of Business

Hydrogen's Potential Role in the Energy Transition

KAUST Hydrogen Seminar Series: Building Hydrogen Infrastructure

November 22, 2022

Why Hydrogen?

"I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable."

Jules Verne – The Mysterious Island (1874)

Hydrogen is a unique element

- Hydrogen is the most abundance element in the earth's biosphere
  - the smallest and lightest of all elements
  - Not found "free" in nature in any significant quantities – contained in water and chemical compounds (including hydrocarbons)
- H_2 is not an energy source except from nuclear fusion (i.e., on the sun)
- Hydrogen combustion produces only heat and water
- Its high specific energy content (3X gasoline by wt.) makes it potentially valuable as a energy carrier (in parallel to electricity) and storage medium
- Hydrogen can be produced by electrical energy and visa versa
  - Electrolysis (Hydrogen Production) – convert water and electricity to hydrogen and oxygen
  - Fuel Cell (Hydrogen Use)– convert hydrogen and oxygen to electricity and water
- Hydrogen use has been traditionally limited by a high cost of production and lack of distribution infrastructure and limited end uses outside industrial applications.
- However, issues around sustainability, climate change and environmental protection have sparked interest in hydrogen as a clean and sustainable energy option

Hydrogen could play a large role in a low-zero carbon world

Source Pathways

- *Zero carbon (green)* pathways including water electrolysis with renewable power (including conversion of excess electricity to hydrogen during times of oversupply)
- *Low carbon (blue)* production from fossil fuels (steam methane reforming or coal gasification with carbon capture)

Energy Transportation and Storage

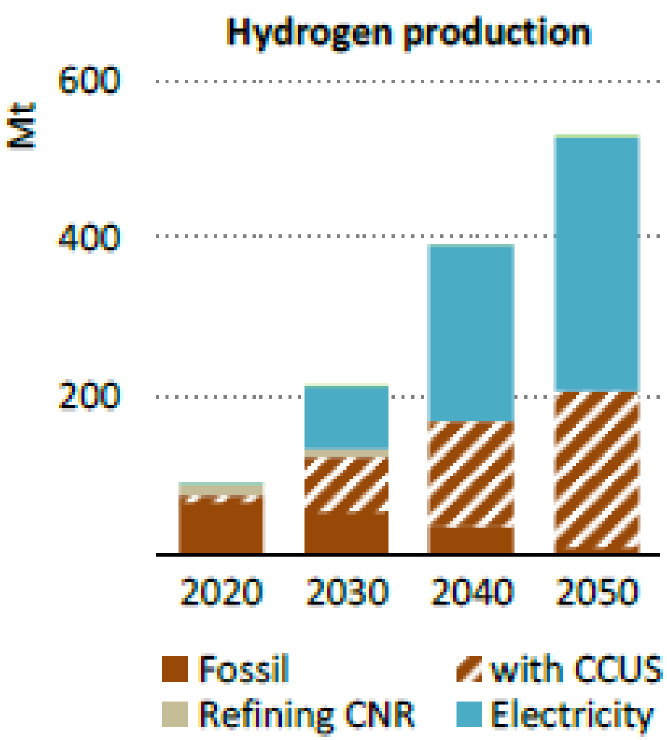
- Multiple forms and modes of energy transport
  - Different physical forms of hydrogen (liquid or gas)
  - Hydrogen-derived energy carriers (ammonia, methanol, liquid organic hydrogen carriers)
- Large scale, long term energy storage (15-20% of global energy demand is currently held in storage in the form of fossil fuels as the primary energy system buffer)
  - Physical based (compressed gas, cryo-compressed, liquid hydrogen, salt caverns)
  - Material based (adsorbents, metal hydrides, chemical hydrogen)

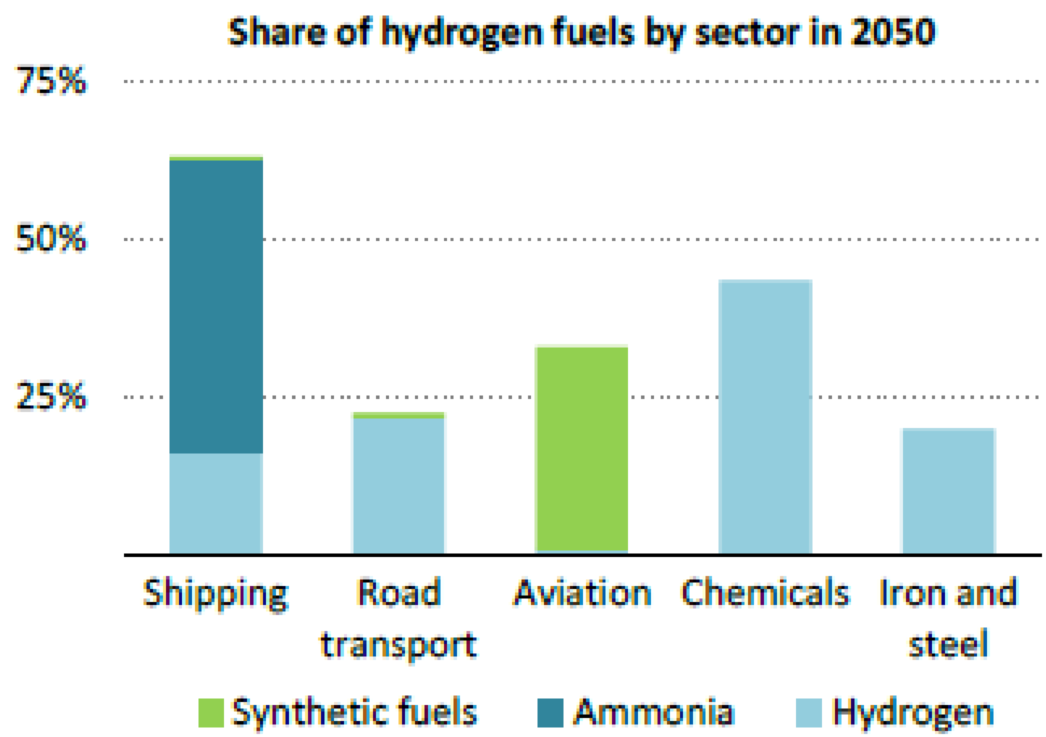
Hydrogen could play a large role in a low-zero carbon world (continued)

Zero-carbon end uses

- Transportation
  - Fuel cells -long distance, heavy duty transport (heavy duty trucks, non-electrified trains, small scale shipping)
  - Drop-in synfuels – combine hydrogen with captured CO2 for large scale, long distance shipping and aviation
- Residential and Commercial
  - Centralized or decentralized source of heat and electric power for buildings
  - Blended in existing natural gas systems (15-20%) to decarbonize the gas grid
- Industrial
  - High grade industrial heat
  - Steel production (direct iron reduction)
  - Chemical feedstock
  - Refinery process use
- Power Generation

The IEA's Net Zero Scenario increases hydrogen production by 5X with significant shares in transport and industry





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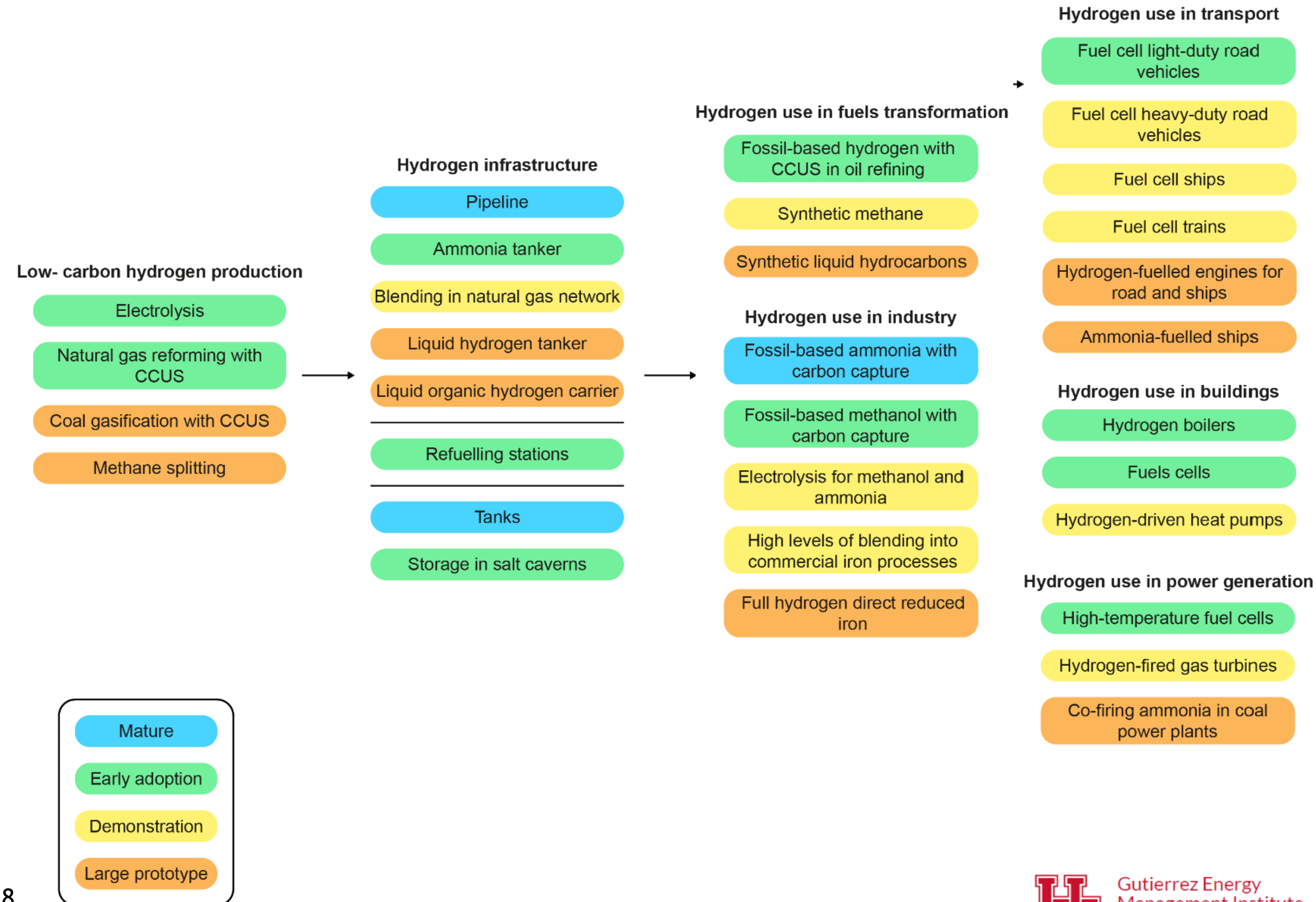
Some key hydrogen-related technologies have been around for many years

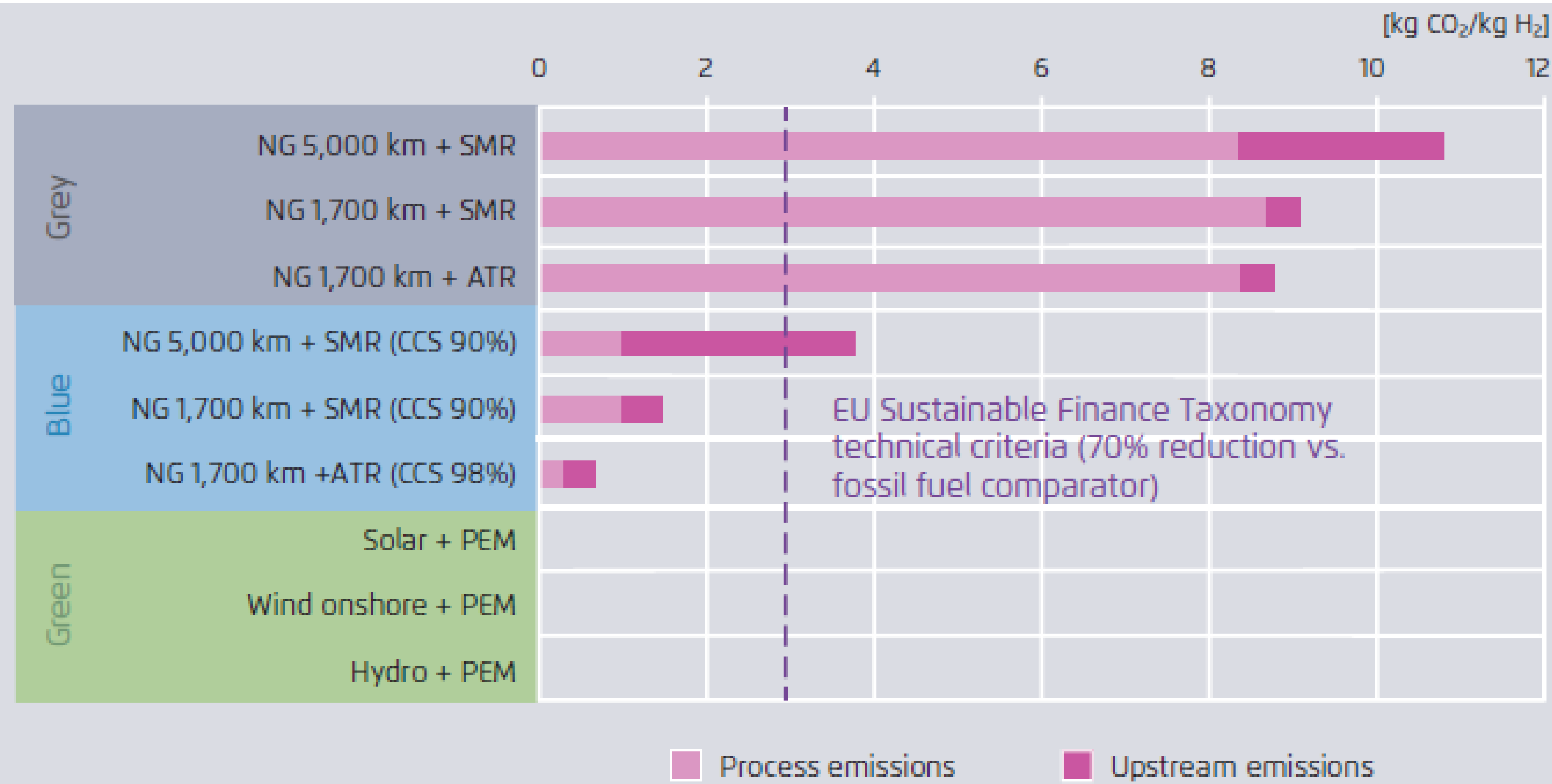
Technology	Year
Electrolyzer	1800
H2-fueled Internal Combustion Engine	1807
Fuel Cell	1839
Liquid H2	1898
Photovoltaic Cell	1940

To realize hydrogen’s full potential in the transition, many technologies will need to mature



Production

Carbon intensity will become more important



Source: 12 Insights on Hydrogen - Agora

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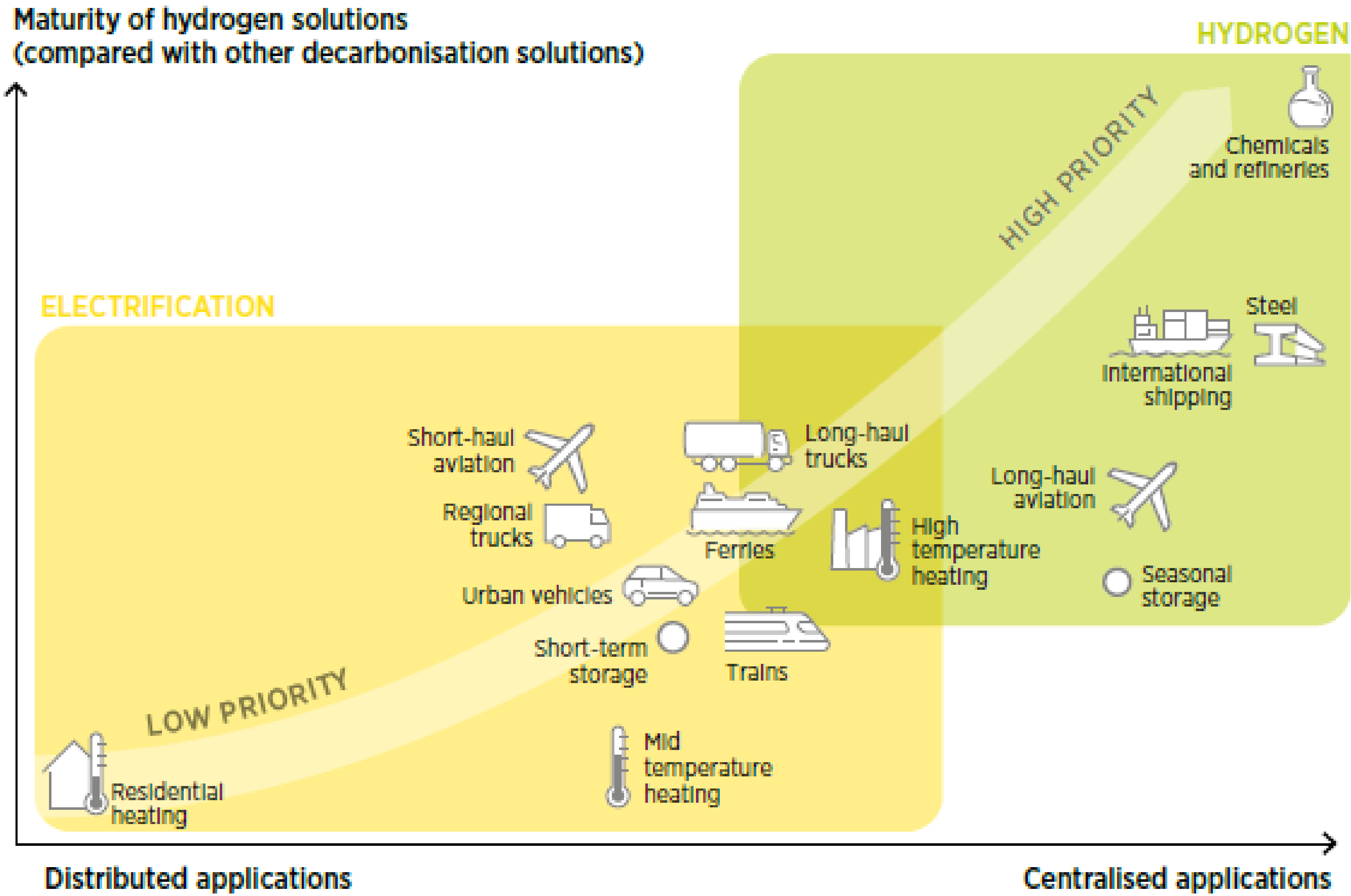
Recent analysis suggests that green hydrogen costs could ultimately be very low with large scale adoption

Year	$/MWH Green Electricity	Electrolyser capacity implied (GW)	Electrolyzer capital expenditure ($/KW)	Cost of H2 ($/kg)
2010	360	-	1500	24
2021	30-45	0.3	950	4.0-5.5
+5 years	20-35	25	330	2.0-3.0
+10 years	15-27	50	270	1.5-2.0
Large scale adoption	10-13	>50	170	<1

Source: The Hydrogen Revolution (Alvera, 2021)

Hydrogen will find its best markets in more centralized applications where it will be advantaged versus electricity

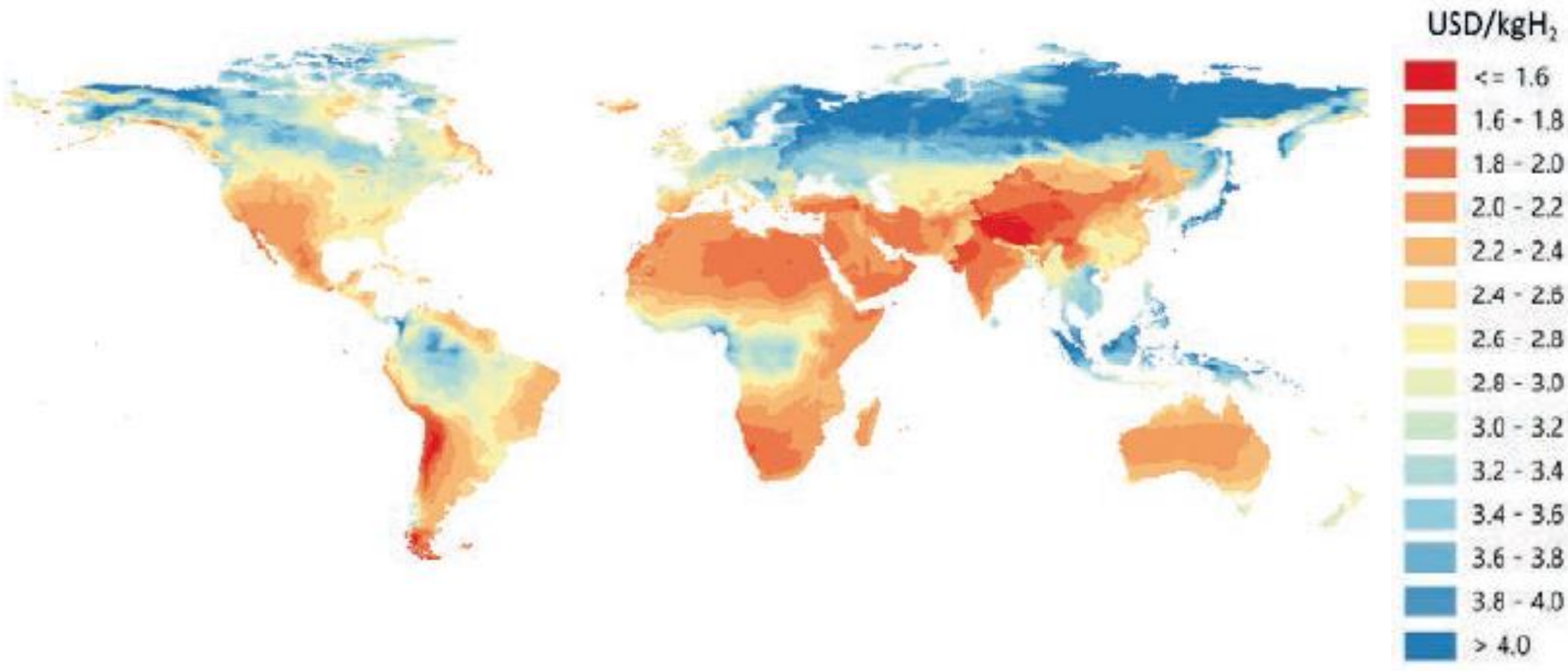


Source: IRENA 2022

Hydrogen penetration will be greatest in heavy duty transportation and industrial sectors

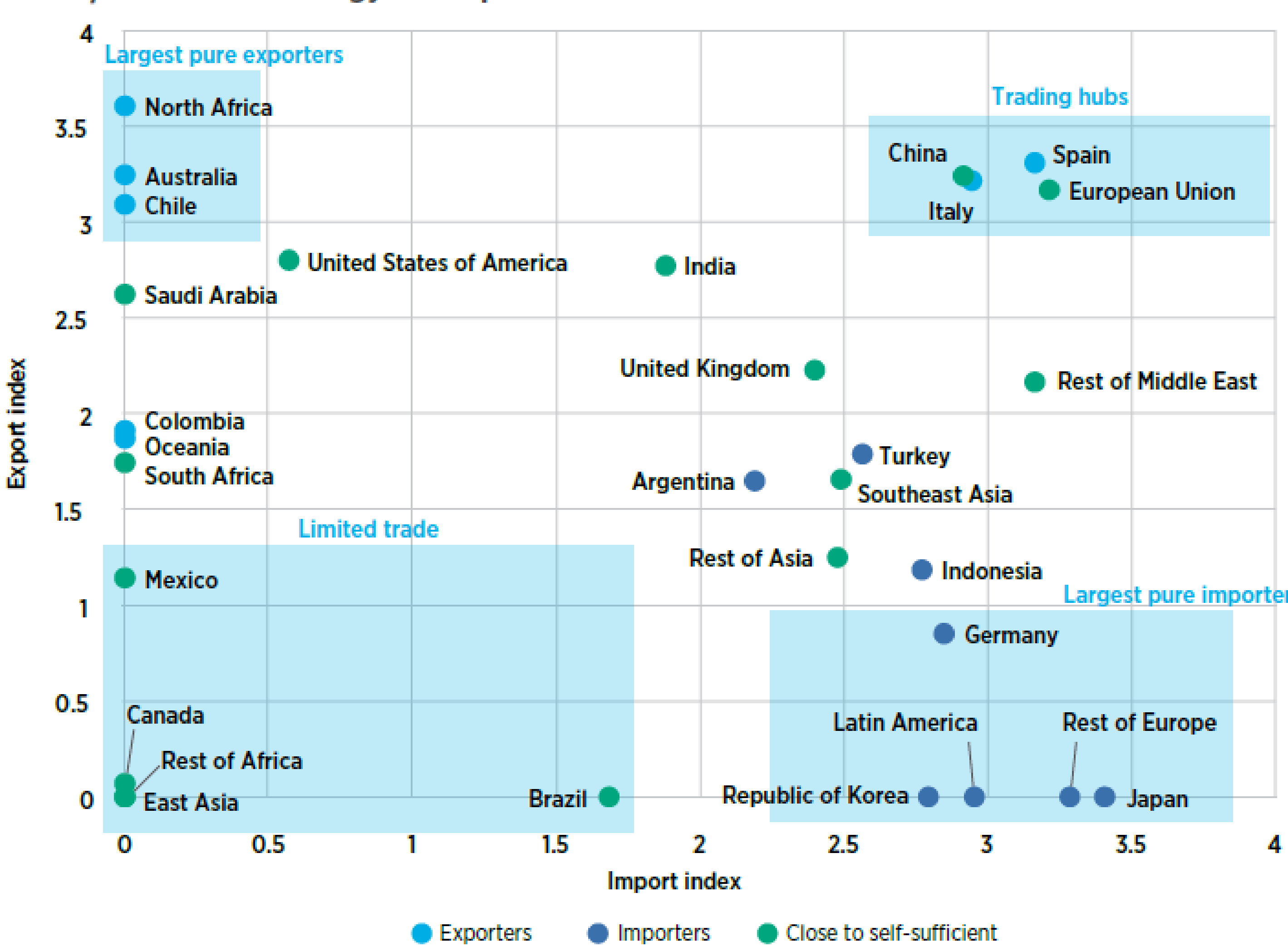
- Hydrogen use in buildings is limited by the need to replace natural gas based equipment and infrastructure which has limited H2 tolerance
- In light duty transport, hydrogen is limited by its poor efficiency versus battery electric vehicles
- Hydrogen-powered heavy duty trucks have considerably lower payload loss than battery trucks and hence today have a lower cost of ownership at longer vehicle ranges
- Ammonia (produced from green hydrogen) is expected to have the lowest TCO of zero carbon fuels for large ships
- Aviation posed the biggest transportation challenge with even short-haul battery powered jet flights requiring nearly 200% of the takeoff weight for the energy source versus 10% for traditional jet fuel
- Hydrogen has advantages in the hard-to-abate industrial sectors requiring high heat levels including steel, plastics, and cement

Regions with low potential hydrogen costs and smaller populations will be in a position to export hydrogen



On hydrogen trade, countries will sort into self-sufficient, importers and exporters

Volumes of H2 Exports and Imports in 2050



Source: IRENA Global Hydrogen Trade 2022 (Optimistic)

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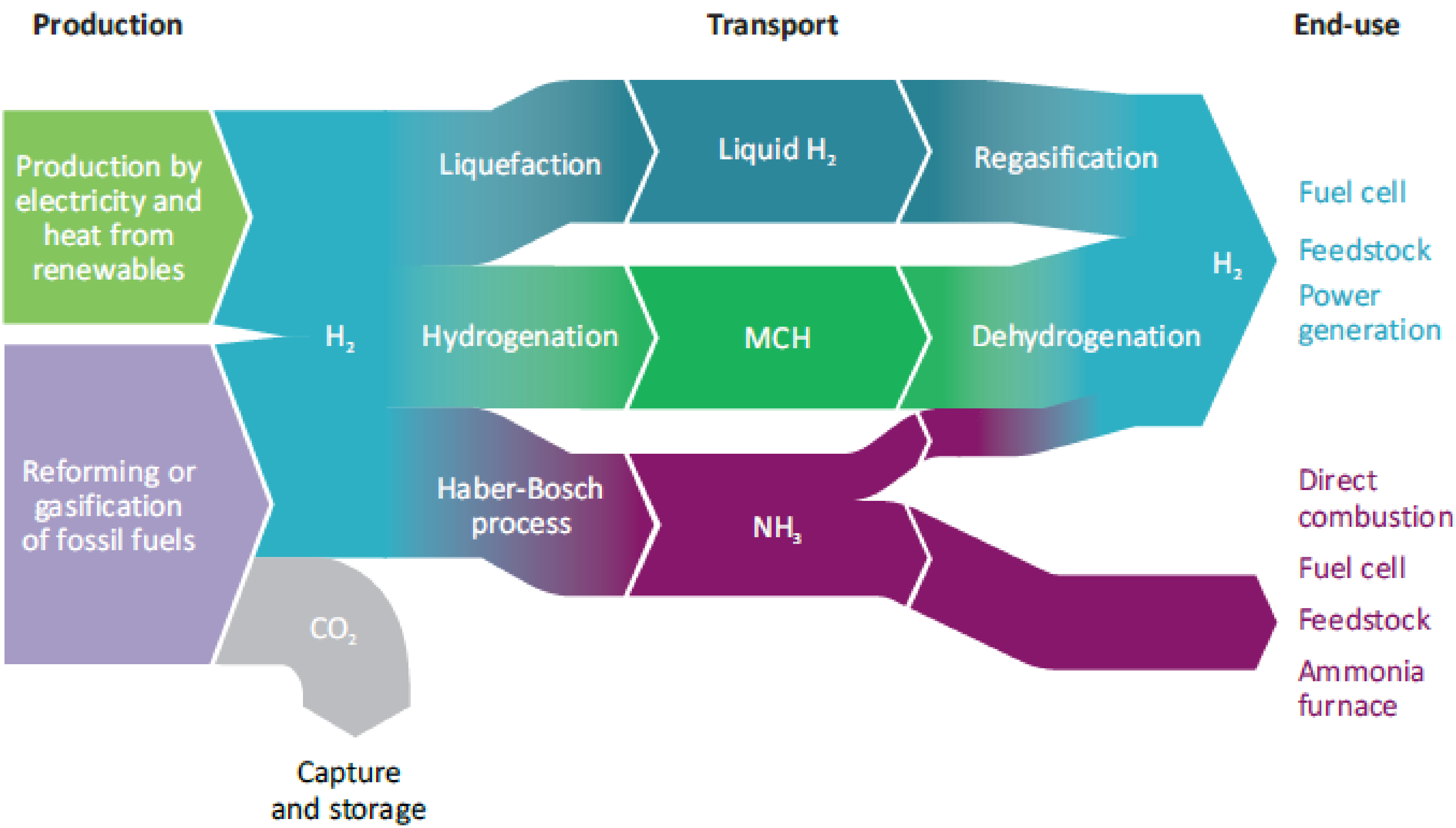
There are three main paths for hydrogen as an energy carrier and storage medium



MCH – methylcyclohexane, one of several potential Liquid Organic Hydrogen Carriers (LOHC)

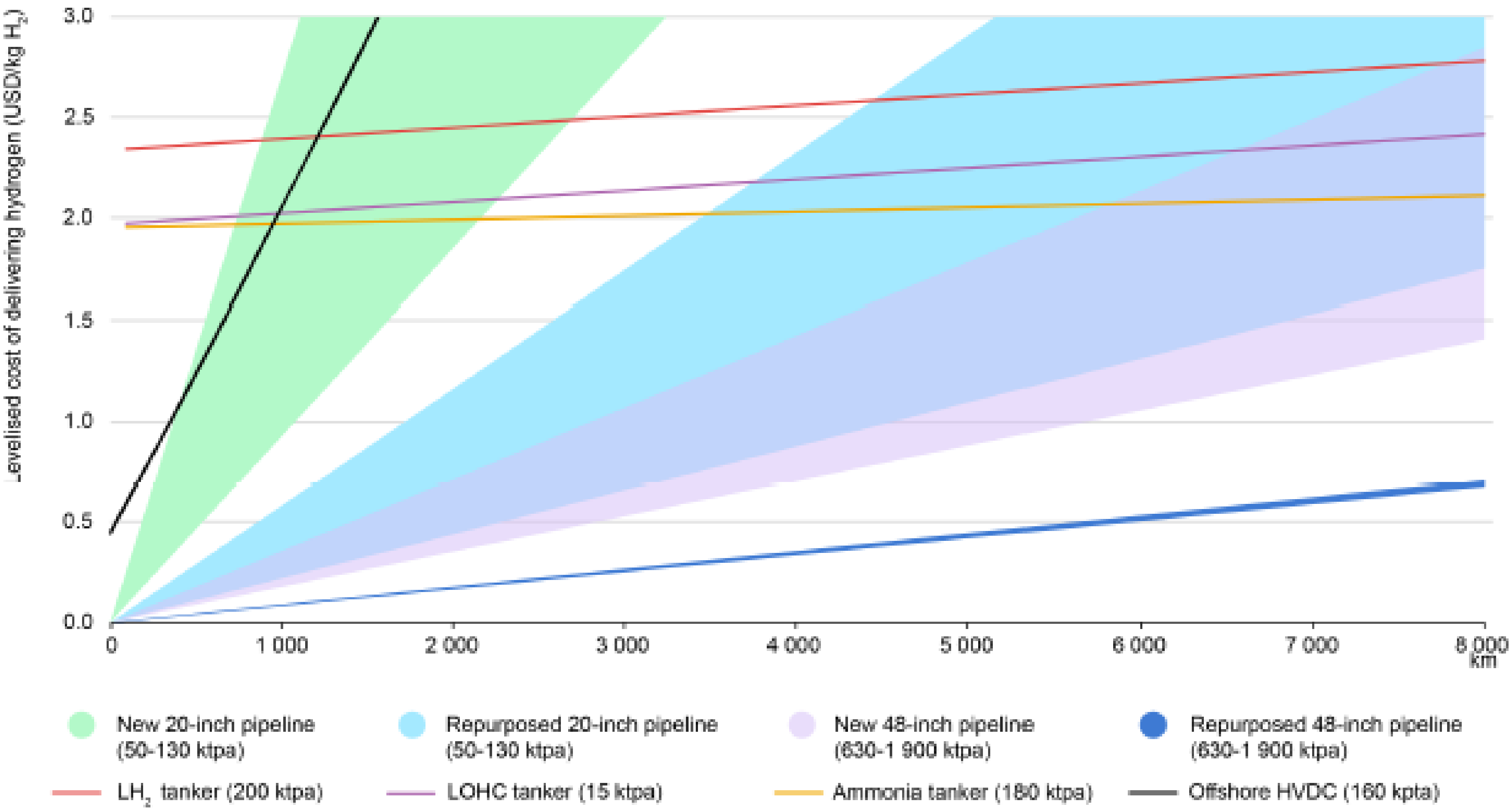
IEA World Energy Outlook 2018

Each carrier has different advantages and challenges

CHARACTERISTICS	LIQUID	TOLUENE-MCH	AMMONIA (NH_3)
Challenges	• Requires very low temperature (about −250 °C) • High energy requirement for cooling/liquefaction • Demands cost reduction for liquefaction • Liquefaction currently consumes about 45% of the energy brought by H_2 • Difficult for long-term storage • Requires boil-off control (0.2%–0.3% d^{-1} in truck) • Risk of leakage	• Requires high-temperature heat source for dehydrogenation (higher than 300 °C, up to 300 kilopascal) • The heat required for dehydrogenation is about 30% of the total H_2 brought by MCH • As MCH with molecular weight of 98.19 gram per mol^{-1} only carries three molecules of H_2 from toluene hydrogenation, the handling infrastructure tends to be large • Durability (number of cycles)	• Lower reactivity compared to hydrocarbons • Requires treatment due to toxicity and pungent smell • Treatment and management by certified engineers • Consumes very high energy input in case of dehydrogenation (about 13% of H_2 energy) and purification
Advantages	• High purity • Requires no dehydrogenation and purification	• Can be stored in liquid condition without cooling (minimum loss during transport) • Existing storing infrastructure • Existing regulations • No loss	• Possible for direct use • Potentially be the cheapest energy carrier • Existing NH_3 infrastructure and regulation

The cost of delivery varies by choice of carrier and transport mode

2030 Levelized Cost of Delivery ($/kg)



Source: IEA Global Hydrogen Review 2022

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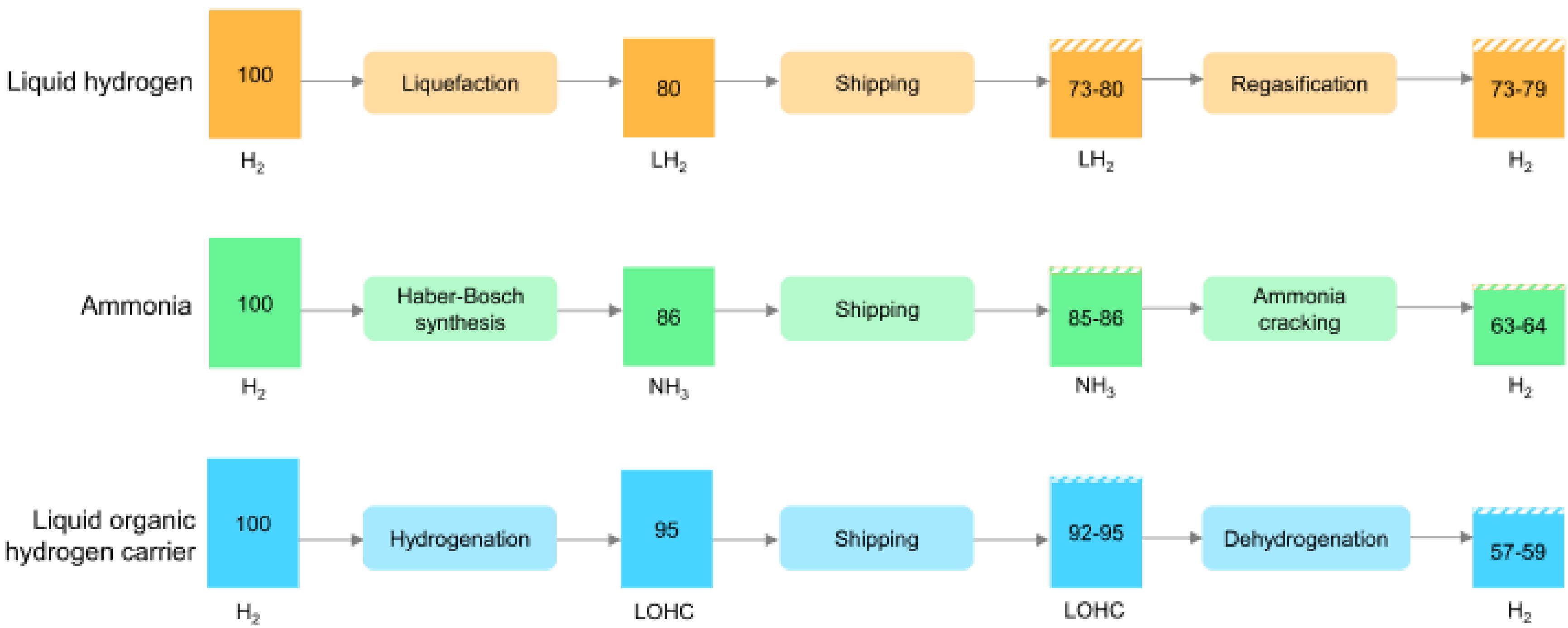
The final use will also influence carrier choice as transportation and conversion losses vary by carrier

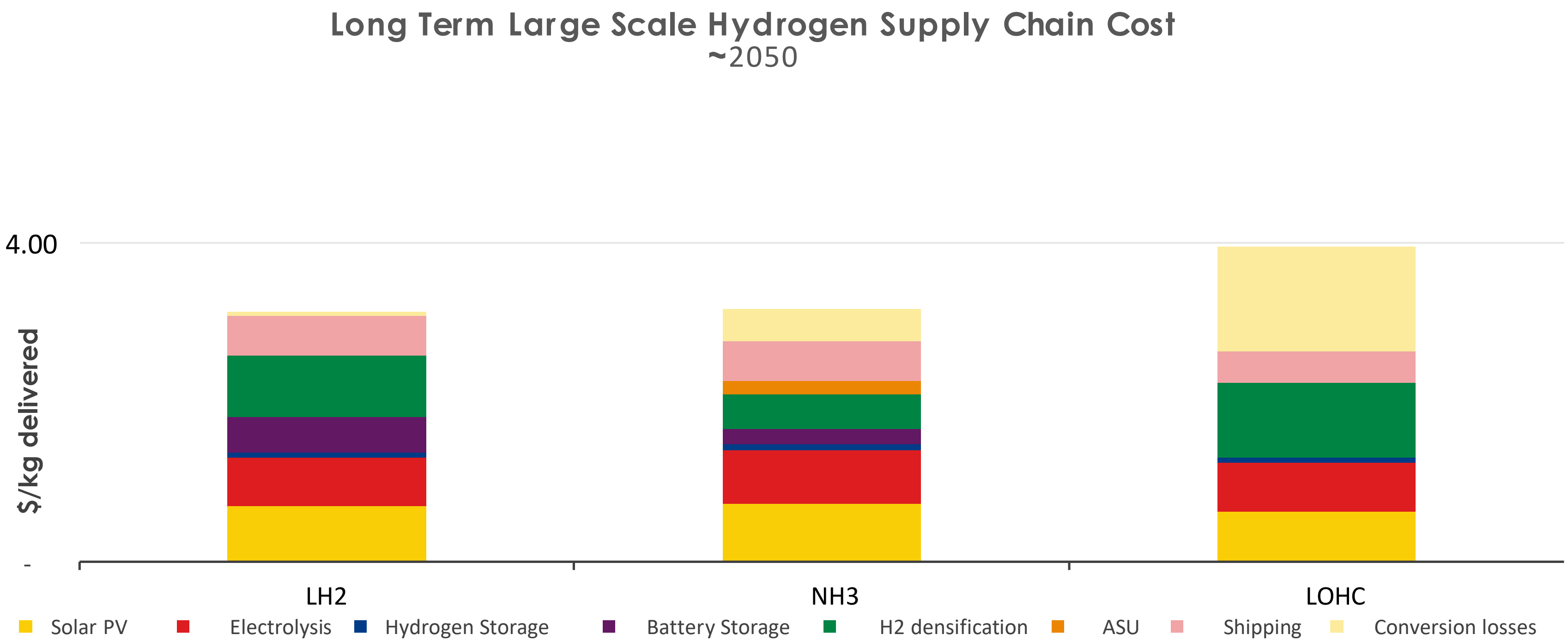
2030 Energy available after transportation and conversion



Note: Assumes 8000km shipping distance

Source: IEA Global Hydrogen Review 2022

Many companies such as Shell, believe there is significant potential reduction in the cost of delivered hydrogen

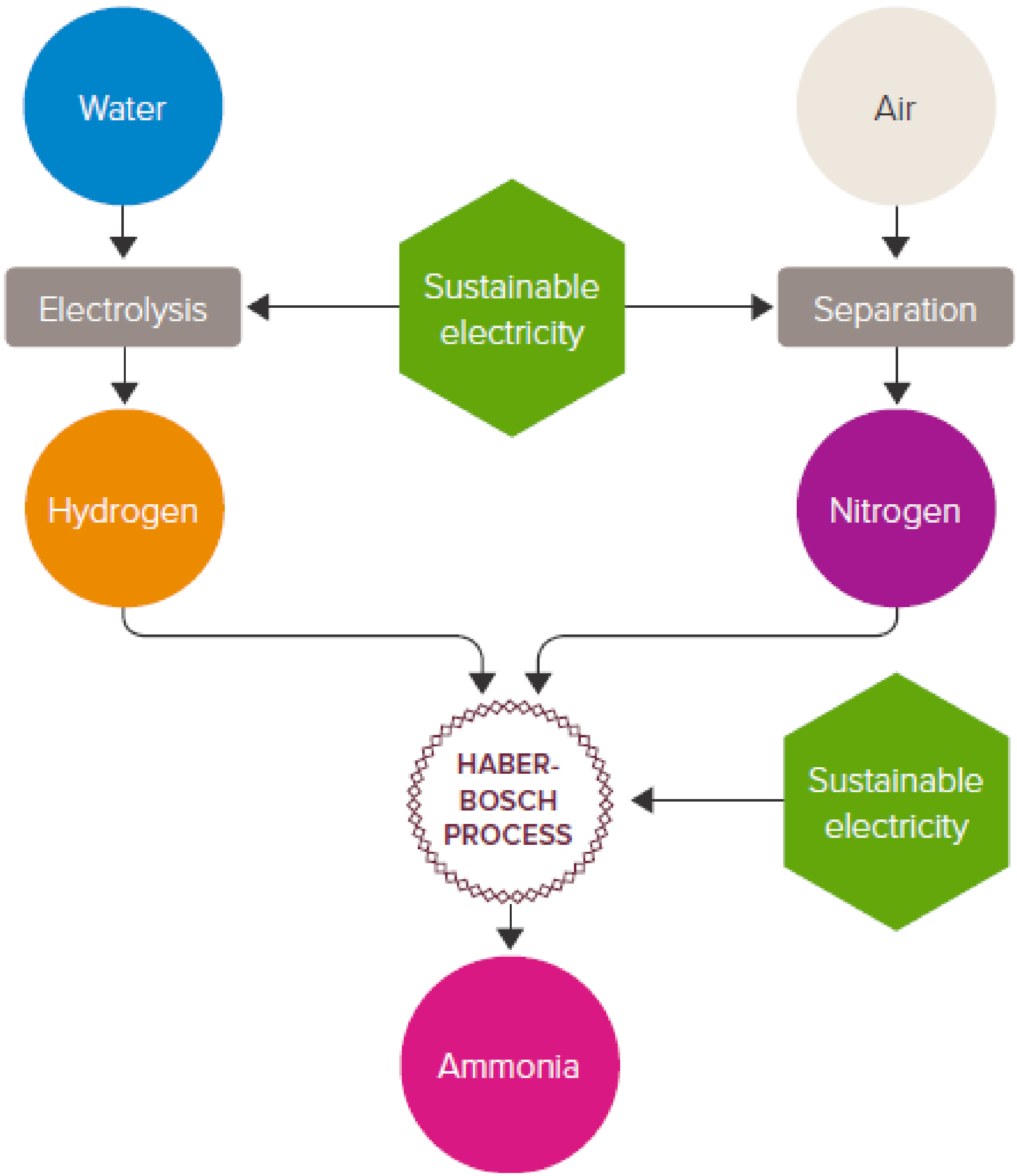


Notes:

1. Production large scale electrolysis using renewable energy
2. Shipping costs lower for LOHC as it uses conventional chemical tanker.
3. Conversion losses represents thermodynamic energy loss due to cracking, and is applicable also for the cases of direct use applications

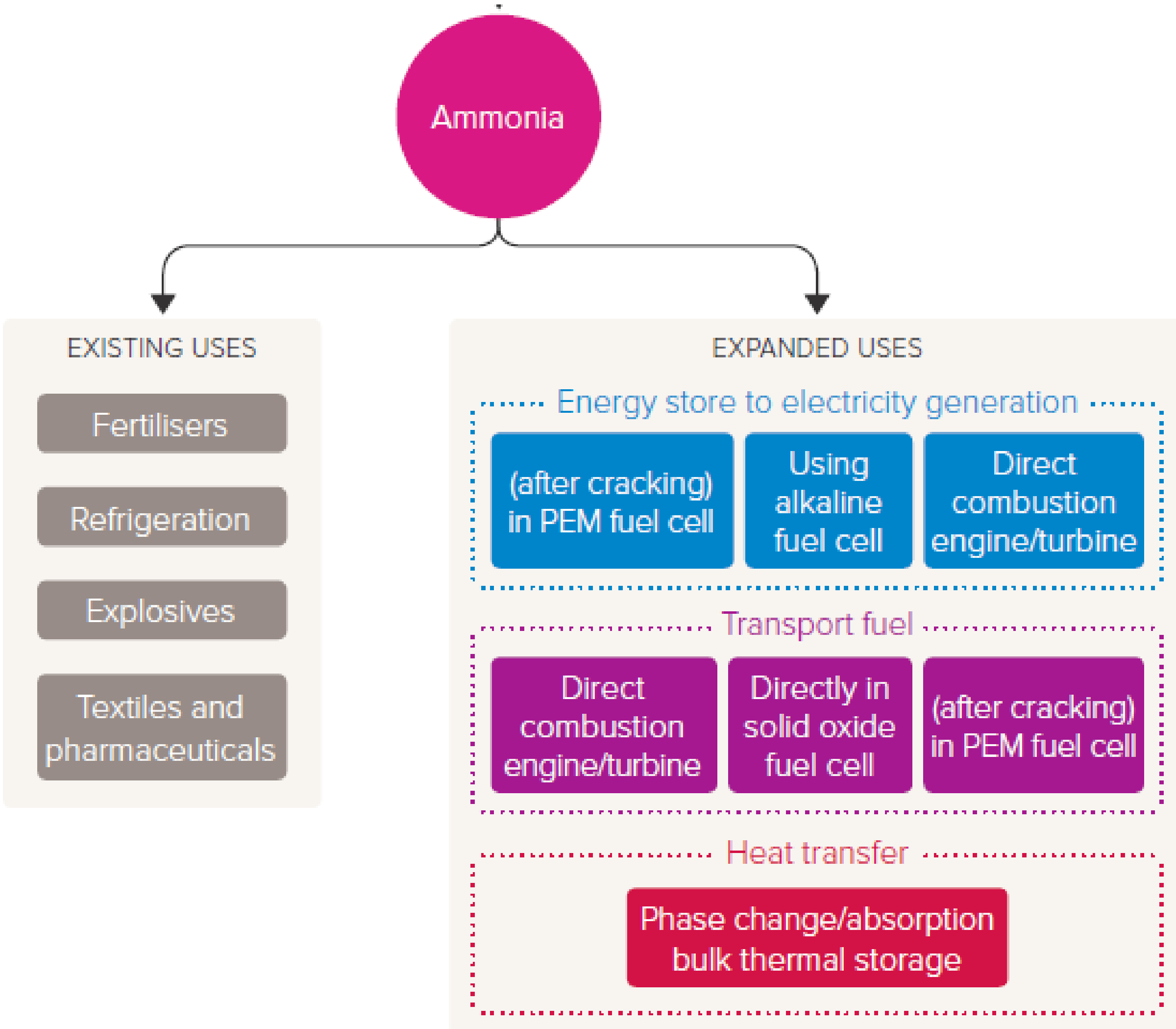
Shell International March 2019

"Green" ammonia is made using zero-carbon hydrogen in the traditional process using zero-carbon electricity



- Ammonia production in the SDS in 2070 is 130 million tonnes, 70% from natural gas with CCS and 30% from electrolysis
- Producing green ammonia requires 23,000 GWH per tonne with 90% of that consumed in electrolysis
- The overall energy efficiency of the process is about 50%
- Ammonia's toxicity requires special care in handling

Green ammonia can go into traditional uses as well as energy transport, storage, and power generation



Ammonia versus Methane

- Significantly higher boiling point, similar to propane (easier to transport)
- More existing shipping and storage infrastructure

but

- Combustion produces NOx (requiring SCR to convert to N2)

and

- Lower volumetric and gravimetric energy density than LNG

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In the IEA 's NZ205 scenario, ammonia and hydrogen capture over 60% of the marine fuel market

Category		2020	2030	2050
Road transport				
Share of PHEV, BEV and FCEV in sales:	cars	5%	64%	100%
	two/three-wheelers	40%	85%	100%
	bus	3%	60%	100%
	vans	0%	72%	100%
	heavy trucks	0%	30%	99%
Biofuel blending in oil products		5%	13%	41%
Rail				
Share of electricity and hydrogen in total energy consumption		43%	65%	96%
Activity increase due to modal shift (index 2020=100)		100	100	130
Aviation				
Synthetic hydrogen-based fuels share in total aviation energy consumption		0%	2%	33%
Biofuels share in total aviation energy consumption		0%	16%	45%
Avoided demand from behaviour measures (index 2020=100)		0	20	38
Shipping				
Share in total shipping energy consumption:	Ammonia	0%	8%	46%
	Hydrogen	0%	2%	17%
	Bioenergy	0%	7%	21%

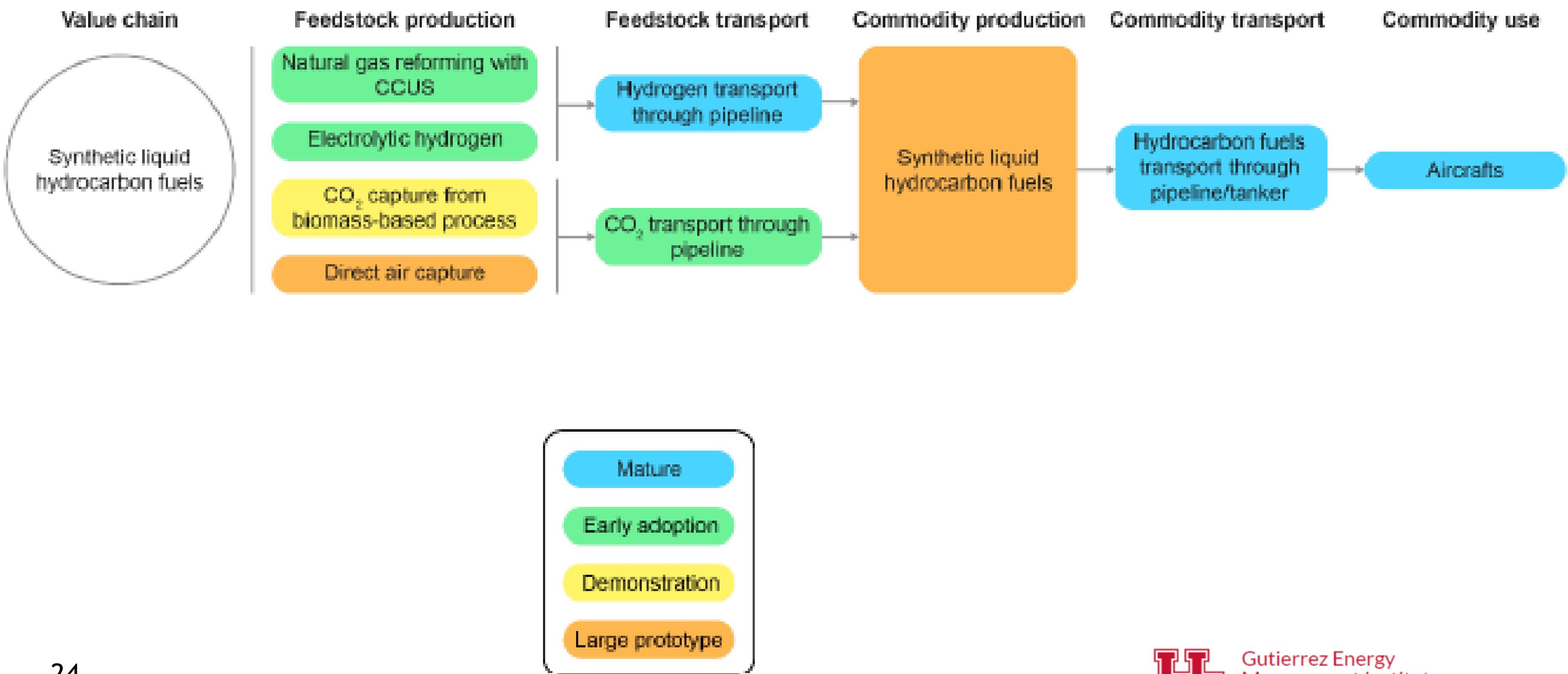
IEA Net Zero by 2050

Synthetic hydrocarbons can be produced from hydrogen and a carbon source

- Hydrogen can be a significant contributor to captured CO_2 utilization by producing long chain hydrocarbons which can be upgraded into usable fuels and chemical products
- Hydrogen can be combine with captured CO_2 to produce fuels (synthetic kerosene/jet fuel, synthetic gasoline and diesel, dimethyl ether, and methanol)
- Hydrogen can also be combined with captured CO_2 to produce chemicals (methanol and then urea, formic acid, formaldehyde)
- The captured CO_2 can come from combustion, biofuel production, or direct air capture

However, the relatively high cost of synthetic hydrocarbon fuels will largely limit their use to aviation fuels where alternatives are limited

The least mature components of a synthetic jet fuel value chain are direct air capture and the production reaction



In the IEA's NZ205 scenario, synthetic liquid hydrocarbon fuels capture one third of the aviation market

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IEA Net Zero by 2050

Methanol is an energy carrier, fuel, and chemical feed that could be produced from captured CO2 and green H2

- Methanol is a broadly used primary chemical with chemical and fuel uses
- Large scale production of methanol from coal and natural gas Is well developed, has often been an economic way to create value from remote natural gas or coal resources
- The methanol industry spans the entire globe, with production in Asia, North and South America, Europe, Africa and the Middle East.
- While the majority of methanol demand is for chemicals, there is a growing market for methanol as a fuel, primarily in China where it is made from coal

Via Captured CO2 and H2 from Electrolysis

Reverse Water Gas Shift

$CO2 + H_2 \rightarrow CO + H_2O$

Methanol Production

$CO + 2H_2 \rightarrow CH_3OH$

Via Traditional Steam Methane Reforming

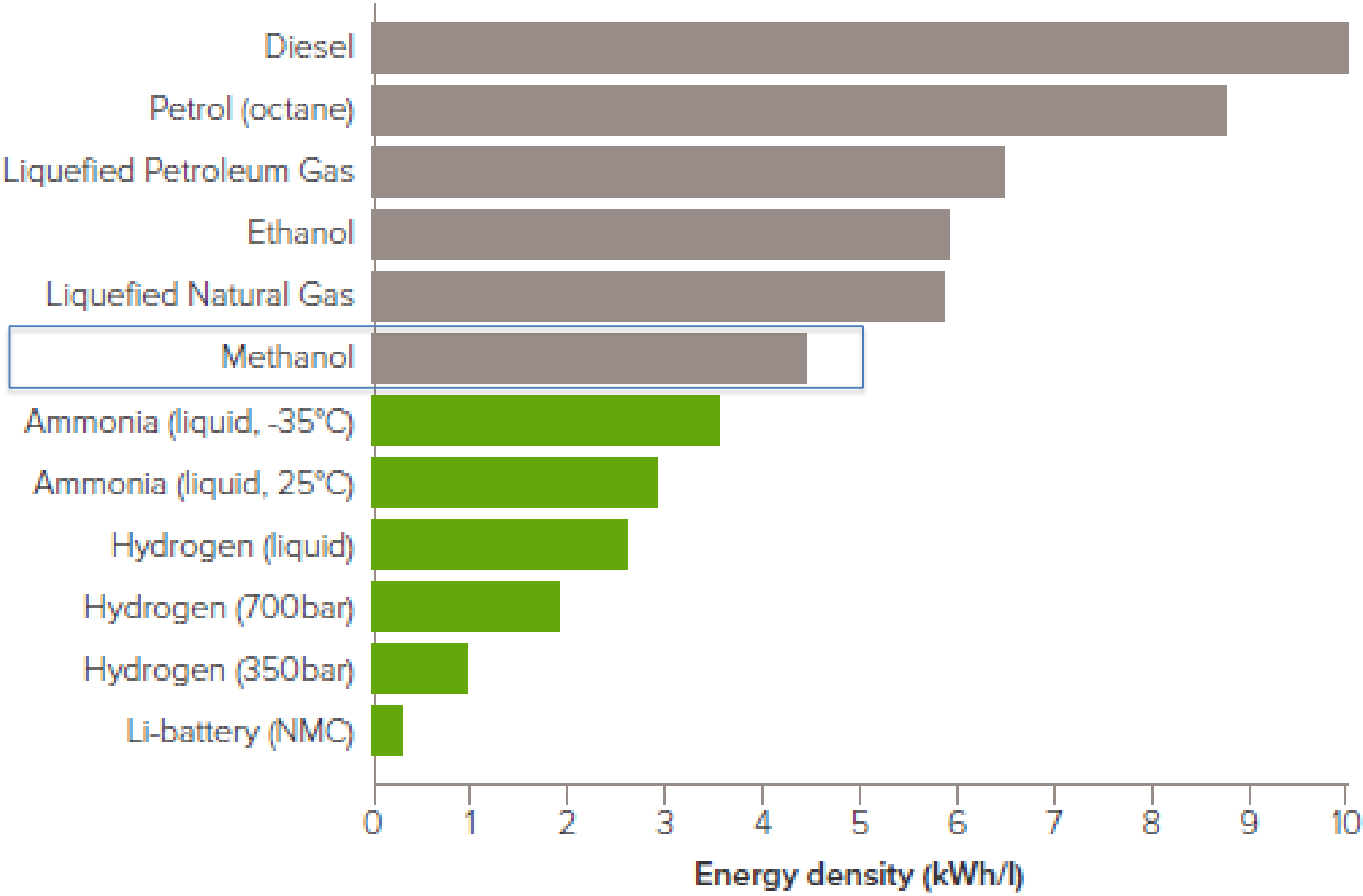
Steam Methane Reforming

$CH_4 + H_2O \rightarrow CO + 3H_2$

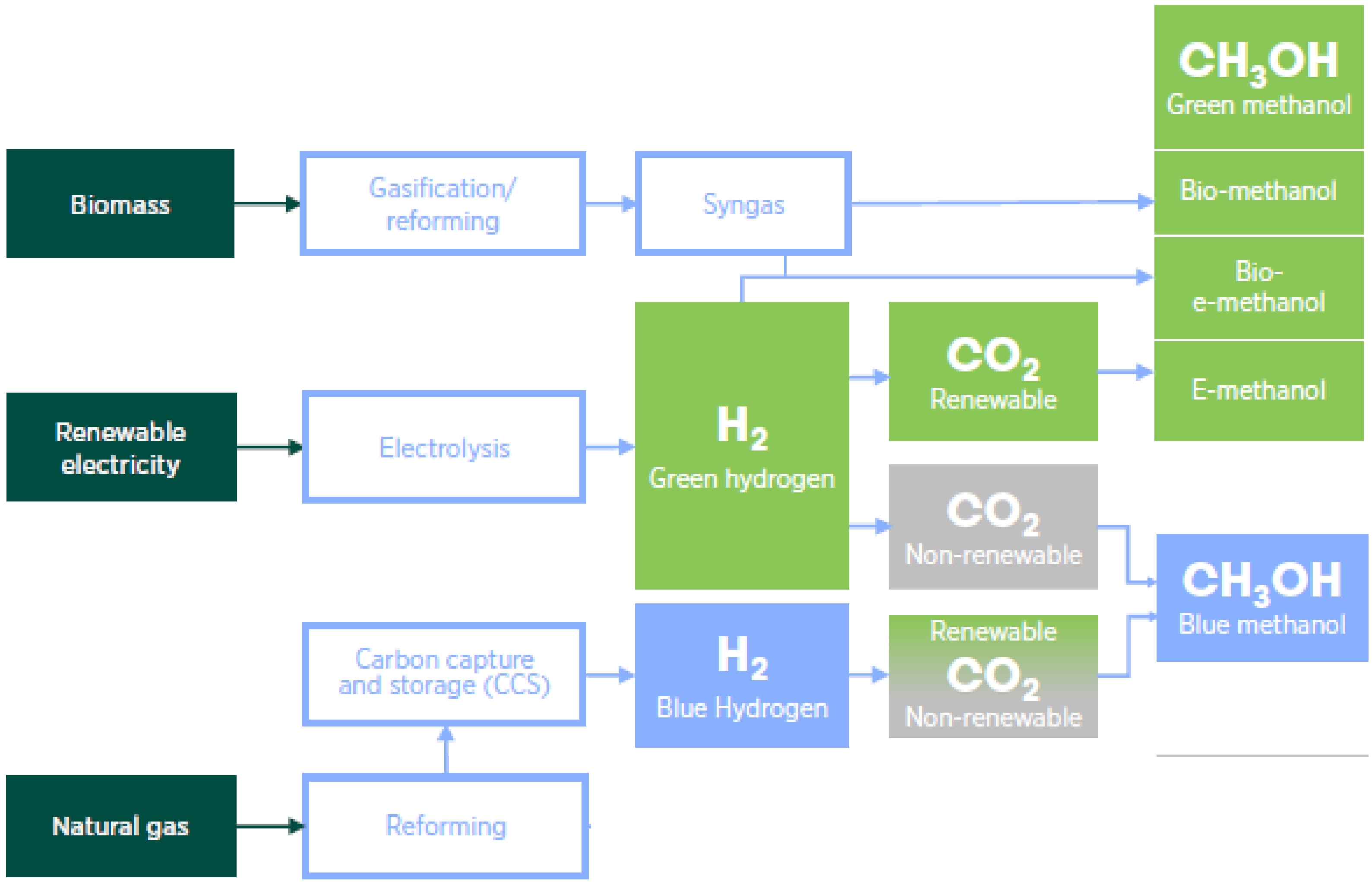
Methanol Production

$CO + 2H_2 \rightarrow CH_3OH$

Methanol has the highest volumetric energy density of the hydrogen derived compounds



Green methanol requires biomass-derived CO2 and green hydrogen feedstocks



Summary

- Hydrogen could play a large role in a low-zero carbon world
- The IEA's Net Zero Scenario increases hydrogen production by 5X with significant shares in transport and industry
- To realize hydrogen's full potential in the transition, many technologies will need to mature
- Regions with low potential hydrogen costs and smaller populations will be in a position to export hydrogen
- There are three main paths for hydrogen as an energy carrier and storage medium
- Ammonia and hydrogen could capture over 60% of the marine fuel market
- Synthetic liquid hydrocarbon fuels could capture one third of the aviation market
- Methanol is an energy carrier, fuel, and chemical feed that could be produced from captured CO_2 and green H_2