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

UH Hydrogen Symposium Business Track Scene-Setting

April 17, 2024

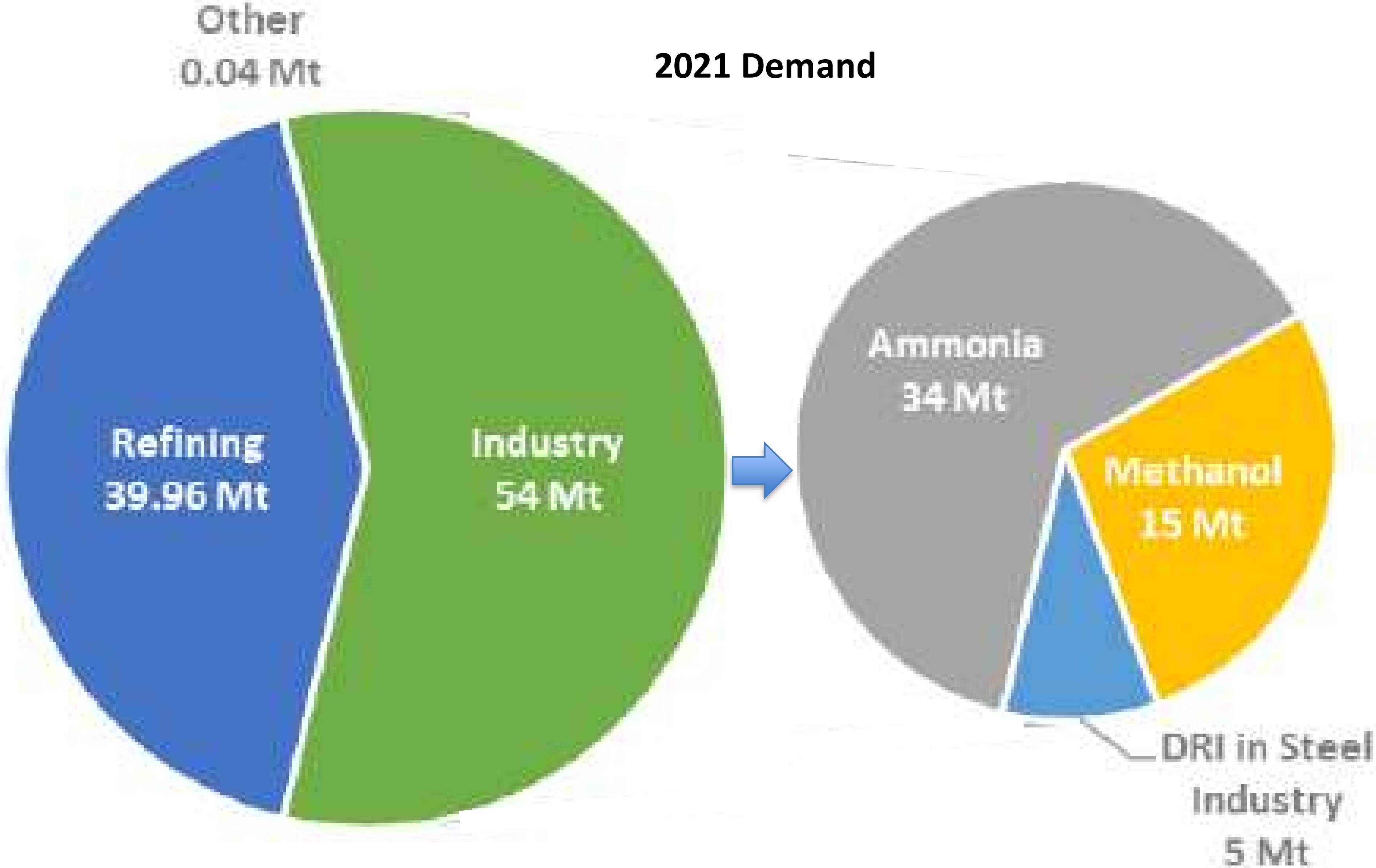
- Current Hydrogen Market

- Hydrogen in a Net Zero by 2050 Scenario

- Development of US Hydrogen Industry

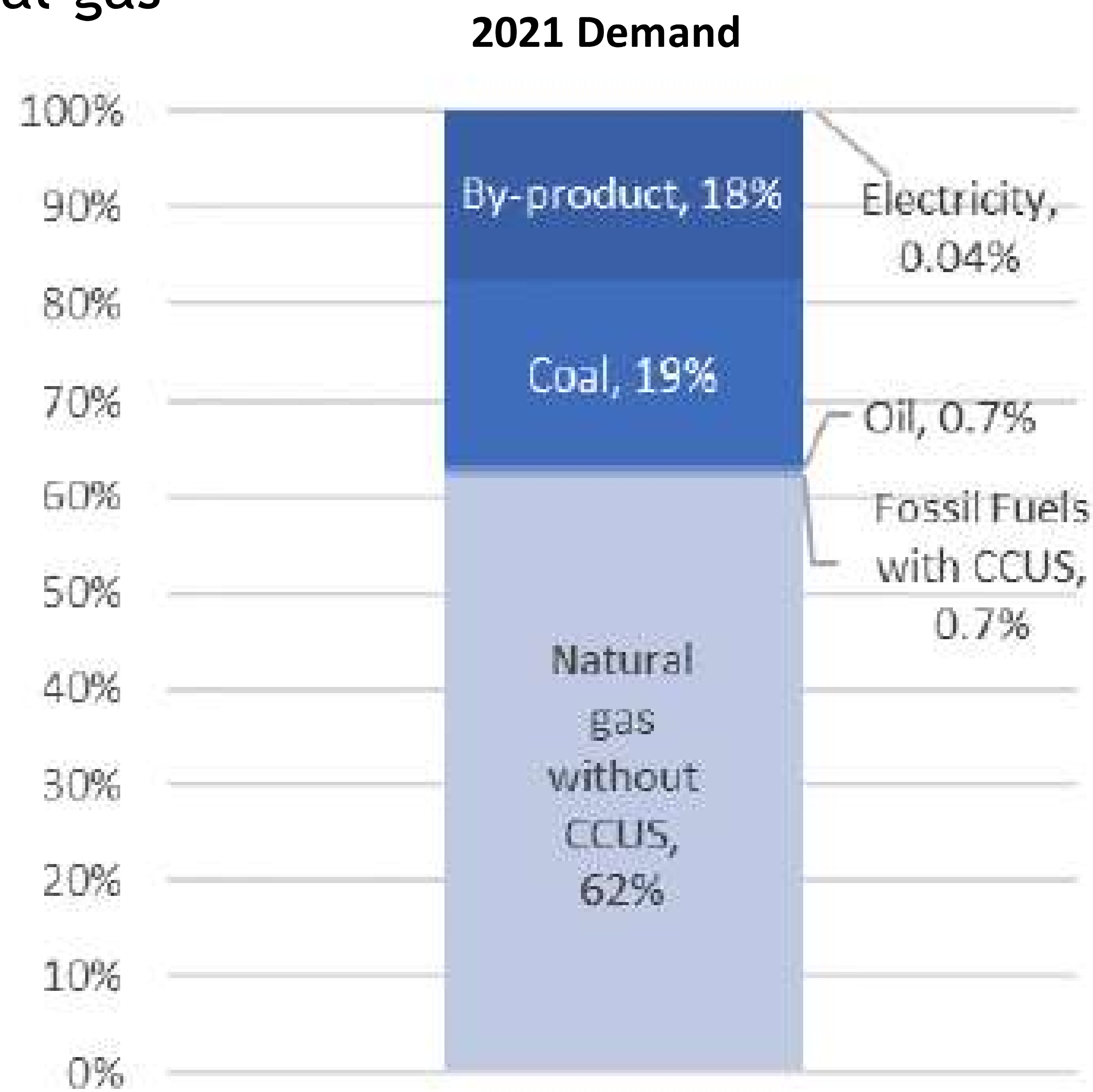
- Development of USGC Hydrogen Industry

Global hydrogen demand today is dominated by the refining and chemicals industry



Source: EFI Foundation Hydrogen Market Formation - An Evaluation Framework (Jan 2024)

Over 80% of hydrogen is produced today by unabated coal and natural gas



Source: EFI Foundation Hydrogen Market Formation - An Evaluation Framework (Jan 2024)

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Regional hydrogen markets today have varying characteristics

Theme	United States	Canada	European Union	United Kingdom	Japan	China
Today's Hydrogen Industry						
Hydrogen production	11.4 Mt, mostly through SMR (natural gas)	3 Mt, mostly through steam methane reforming (SMR) of natural gas	8.6 Mt, mostly using natural gas and coal	<1 Mt, mostly using natural gas	2 Mt, around 50% from fossil gas reforming	33 Mt, 60% through coal gasification
Hydrogen pipelines	1,600 miles	91 miles	Almost 1,000 miles	25 miles	Minimal	62 miles

 Source: EFI Foundation Hydrogen Market Formation - An Evaluation Framework (Jan 2024)

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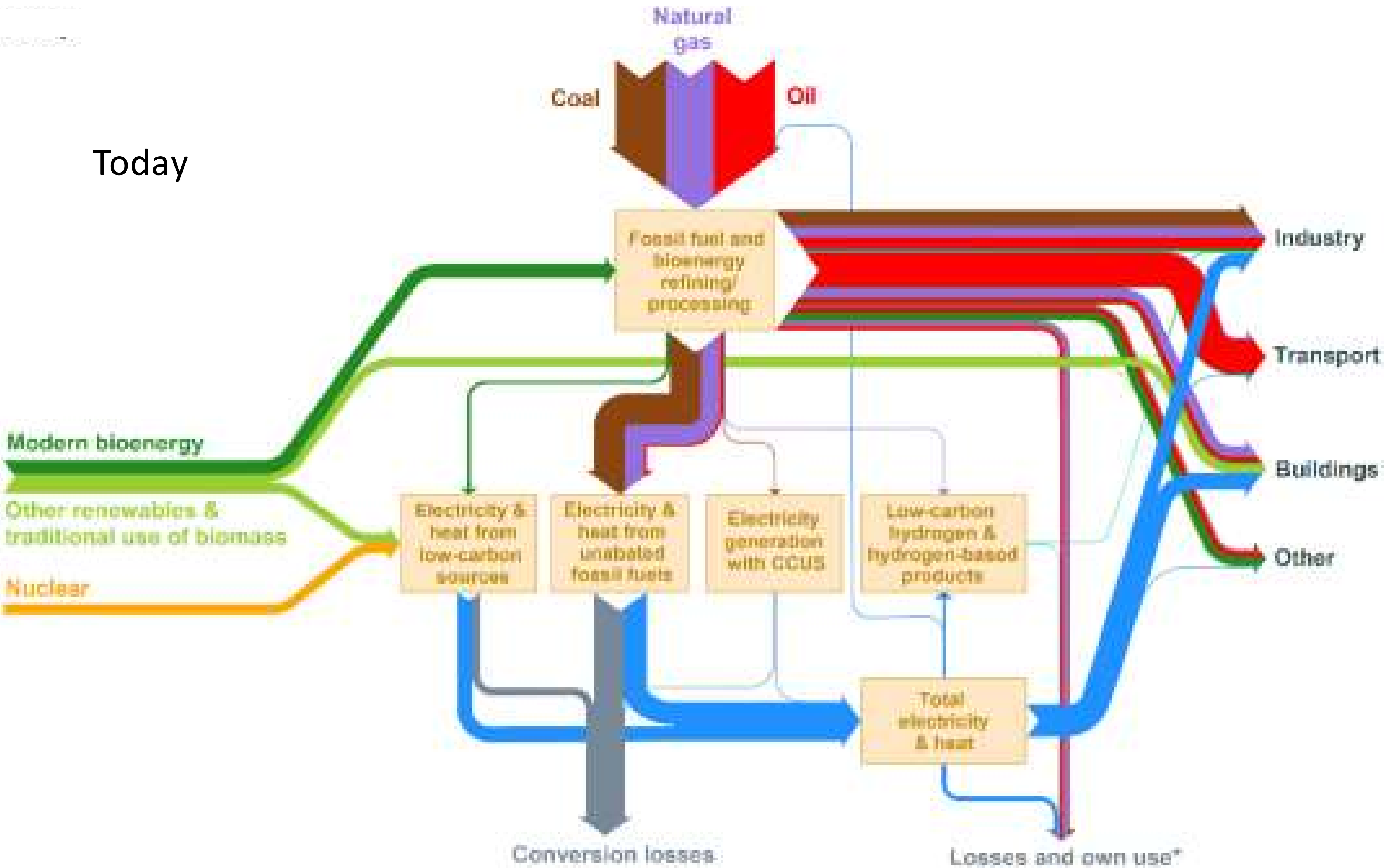
The shift to a more sustainable global energy system is focused on five key goals

- Energy Access
  - provide affordable energy services for the well-being of the 7 billion people today and the 9 billion people projected by 2050
- Energy Security
  - provide uninterrupted supply of vital energy services
- Climate Change
  - reduce global energy systems greenhouse gas emissions to limit global warming to less than 1.5°C above pre-industrial level
- Air Pollution
  - reduce indoor and outdoor air pollution from fuel combustion and its impacts on human health
- Adverse effects and ancillary risks
  - Freshwater use, land use, waste and other impacts associated with some energy systems

Global Energy Assessment - Toward a Sustainable Future

The global energy system shifts from significant final consumption of fossil fuels and fossil-fuel generated

Today



Source: IEA

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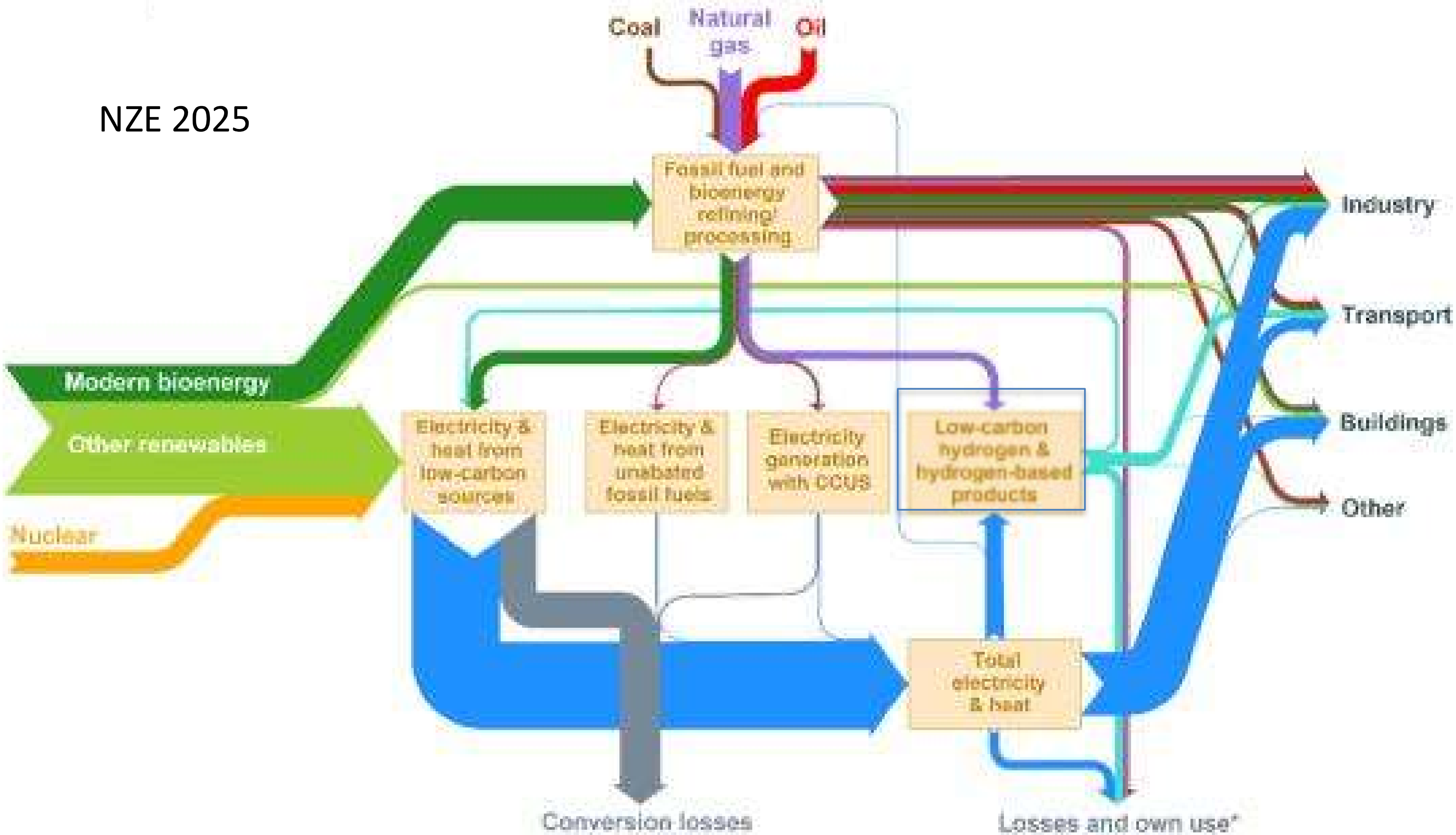
… to a system dominated by renewable-generated power with hydrogen as an important energy carrier

NZE 2025

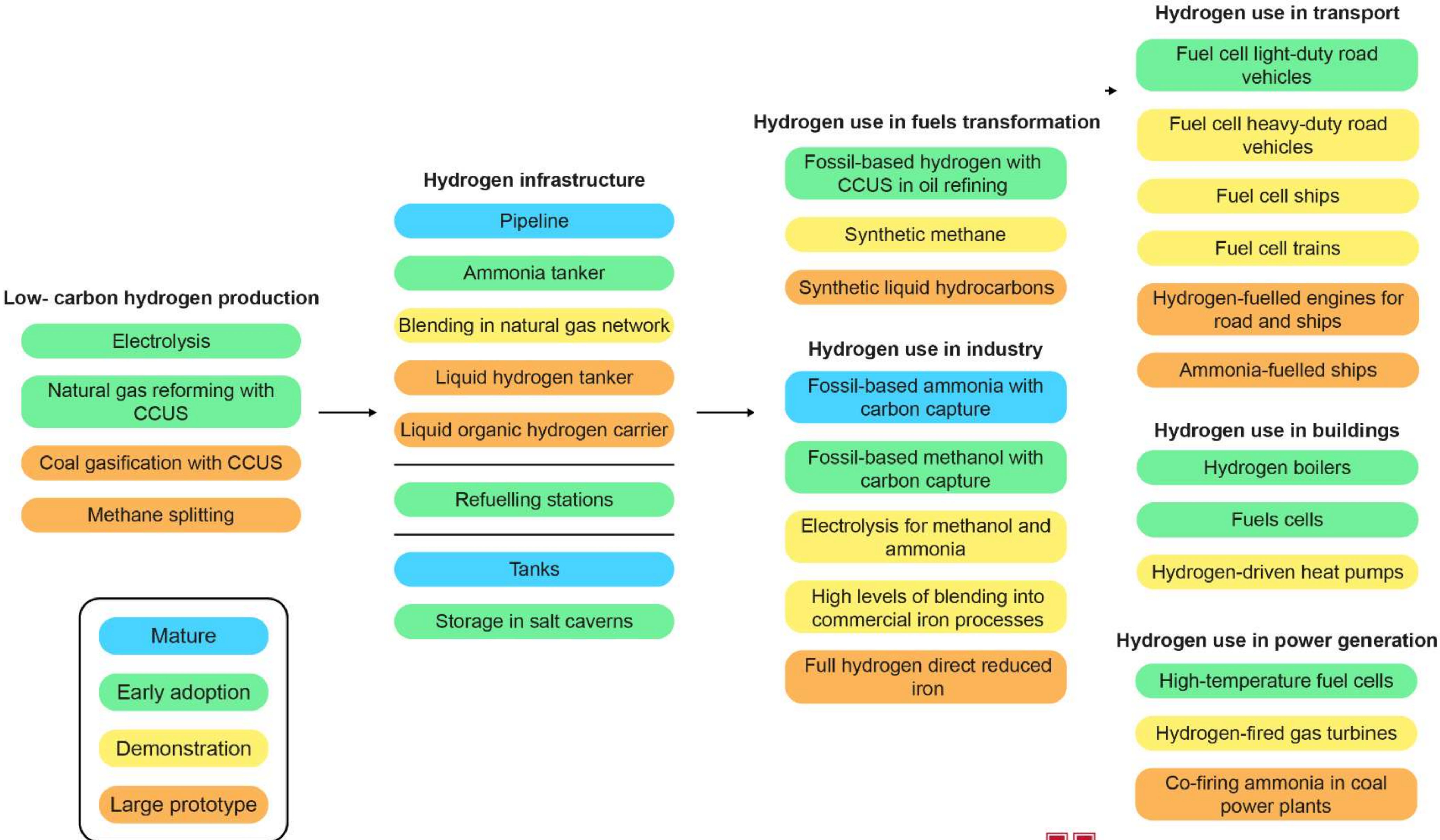


Source: IEA

Building a sustainable low carbon energy system will require overcoming many difficult challenges

- Rapid growth in sustainable energy sources
  - Solar, wind, bioenergy, nuclear, geothermal
- De-carbonization of energy uses
  - Transportation – road transport (light and heavy duty), rail, marine, aviation
  - Industry – steel, cement, refining and chemicals
  - Buildings – space and water heating, space cooling, lighting
- Construction of new energy value chains and associated supply chains for goods and services
  - Low carbon electricity
  - Low carbon hydrogen
  - CO_2 capture, use and storage
  - Low carbon synthetic liquid fuels
  - Advanced biofuels
- Significant increase in energy investment

Costs in a low carbon hydrogen value chain should decrease as technologies mature



Source: IEA Energy Technology Perspective 2020

Electrolysis technology is expected to advance faster than more mature reforming and carbon capture technologies

Process	Input	Units	2023	2030
Electrolysis	Electrolyzer CapEx	$M	$1,263	$202
		$/kW	$1,000	$250
	Electrolyzer Capacity	MW	1,263	809
		kg/day	474,000	474,000
	Efficiency	kWh/kg_{H2}	64	41
	Lifetime	Years	15	15
	Utilization rate	%	Reflects source of electricity	
Steam Methane Reform with Carbon Capture & Sequestration	SMR CapEx	$M	$216	$216
	CCS CapEx	$M	$140	$135
	SMR Capacity	kg/day	500,000	500,000
	Efficiency	$MMBtu_{CH4}/kg_{H2}$	0.171	0.171
	Lifetime	years	15	15
	Utilization rate	%	90%	90%
	Carbon intensity	kg_{CO2}/kg_{H2}	8.5	8.5
	Carbon capture rate	%	90%	90%

Source: Brattle - Emerging Economics of Hydrogen Production and Delivery

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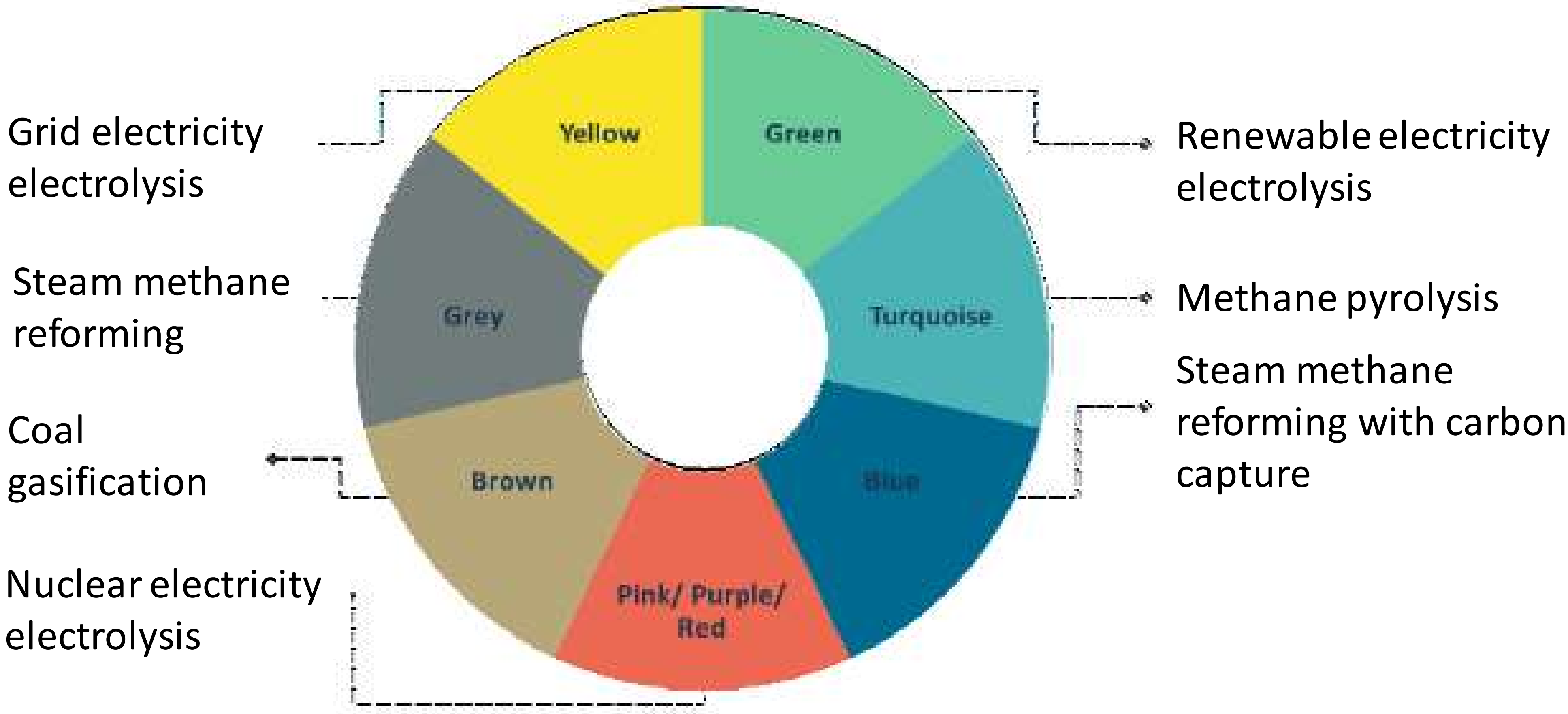
In the future, there could be additional sources of hydrogen



White hydrogen is naturally-occurring hydrogen

Source: Center for Houston's Future: Houston’s Future as a Global Center for Clean Hydrogen Manufacturing, Recycling, and Electrolysis (Dec 2022)

In total, global hydrogen consumption will increase by a factor of five in the IEA's Net Zero by 2050 Scenario

Sector	2020	2030	2050
Total production hydrogen-based fuels (Mt)	87	212	528
Low-carbon hydrogen production	9	150	520
share of fossil-based with CCUS	95%	46%	38%
share of electrolysis-based	5%	54%	62%
Merchant production	15	127	414
Onsite production	73	85	114
Total consumption hydrogen-based fuels (Mt)	87	212	528
Electricity	0	52	102
of which hydrogen	0	43	88
of which ammonia	0	8	13
Refineries	36	25	8
Buildings and agriculture	0	17	23
Transport	0	25	207
of which hydrogen	0	11	106
of which ammonia	0	5	56
of which synthetic fuels	0	8	44
Industry	51	93	187

Note: Hydrogen-based fuels are reported in million tonnes of hydrogen required to produce them.

Source: IEA Net Zero By 2050 (2021)

About 30% of hydrogen production is converted to ammonia and synthetic fuels.

The IEA assumes that 60% will be produced electrolysis and 40% from abated fossil fuels

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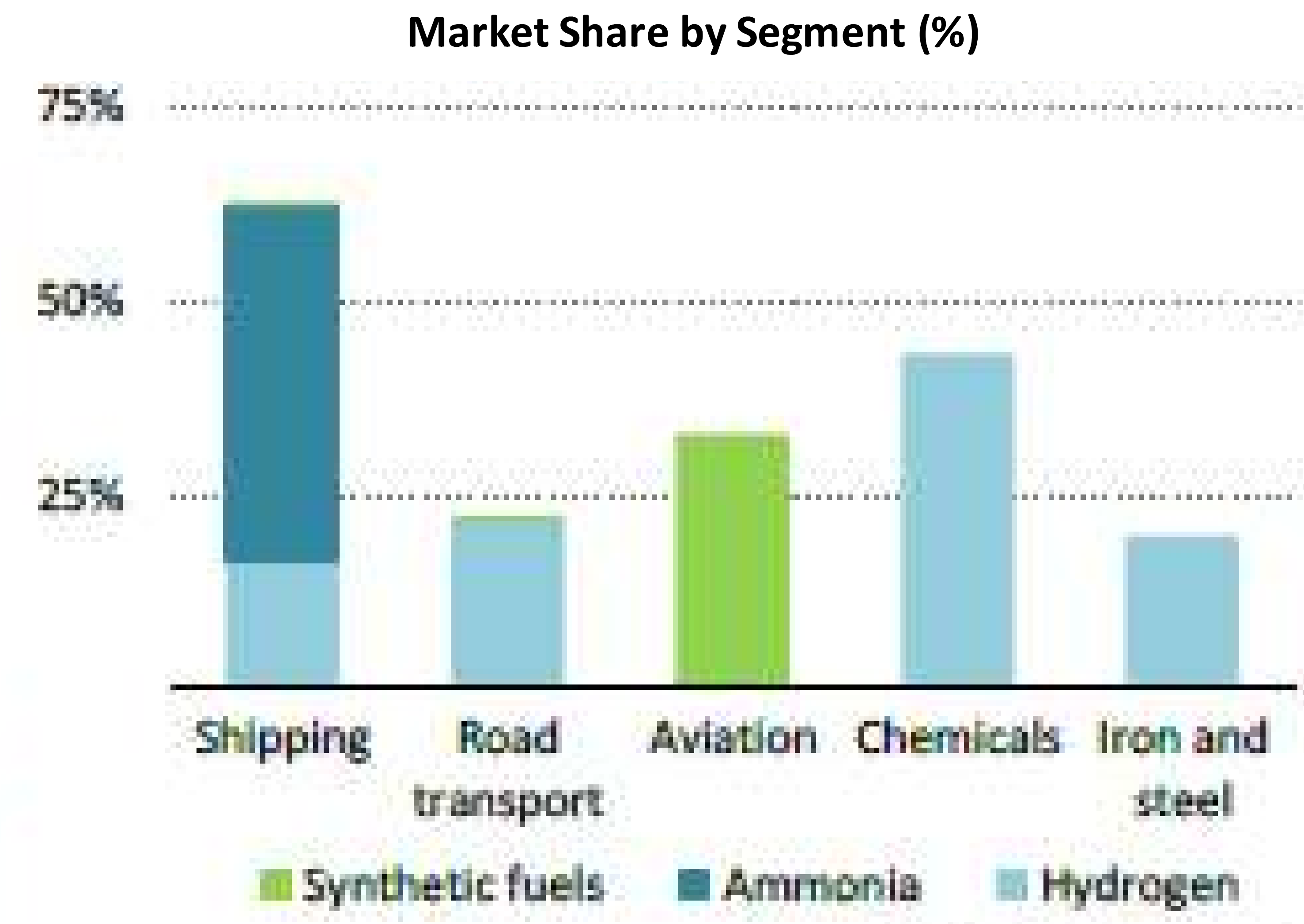
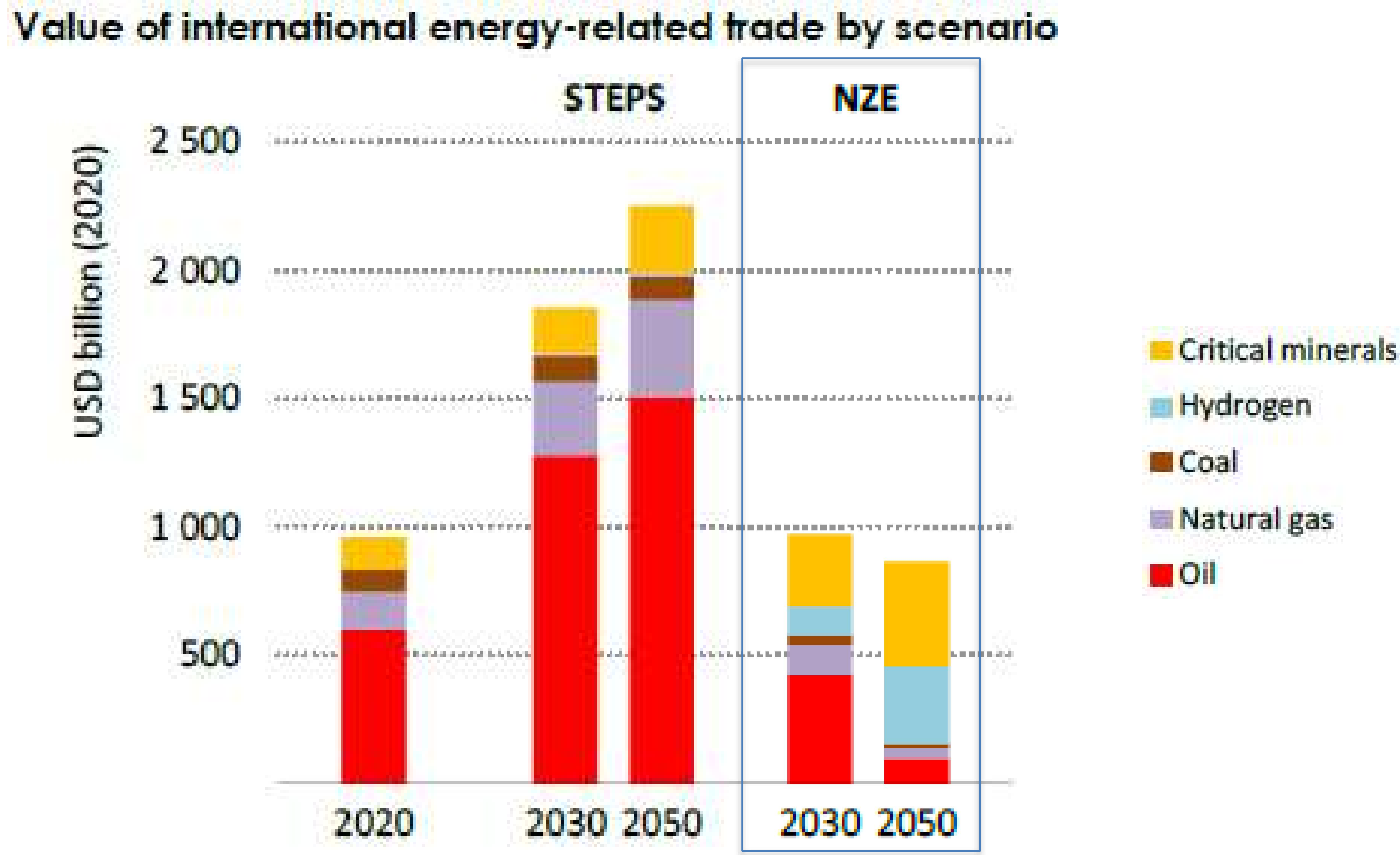
Hydrogen gets a significant share in selected transport and industrial segments by 2050 in the IEA NZE Scenario



Source: IEA Net Zero By 2050 (2021)

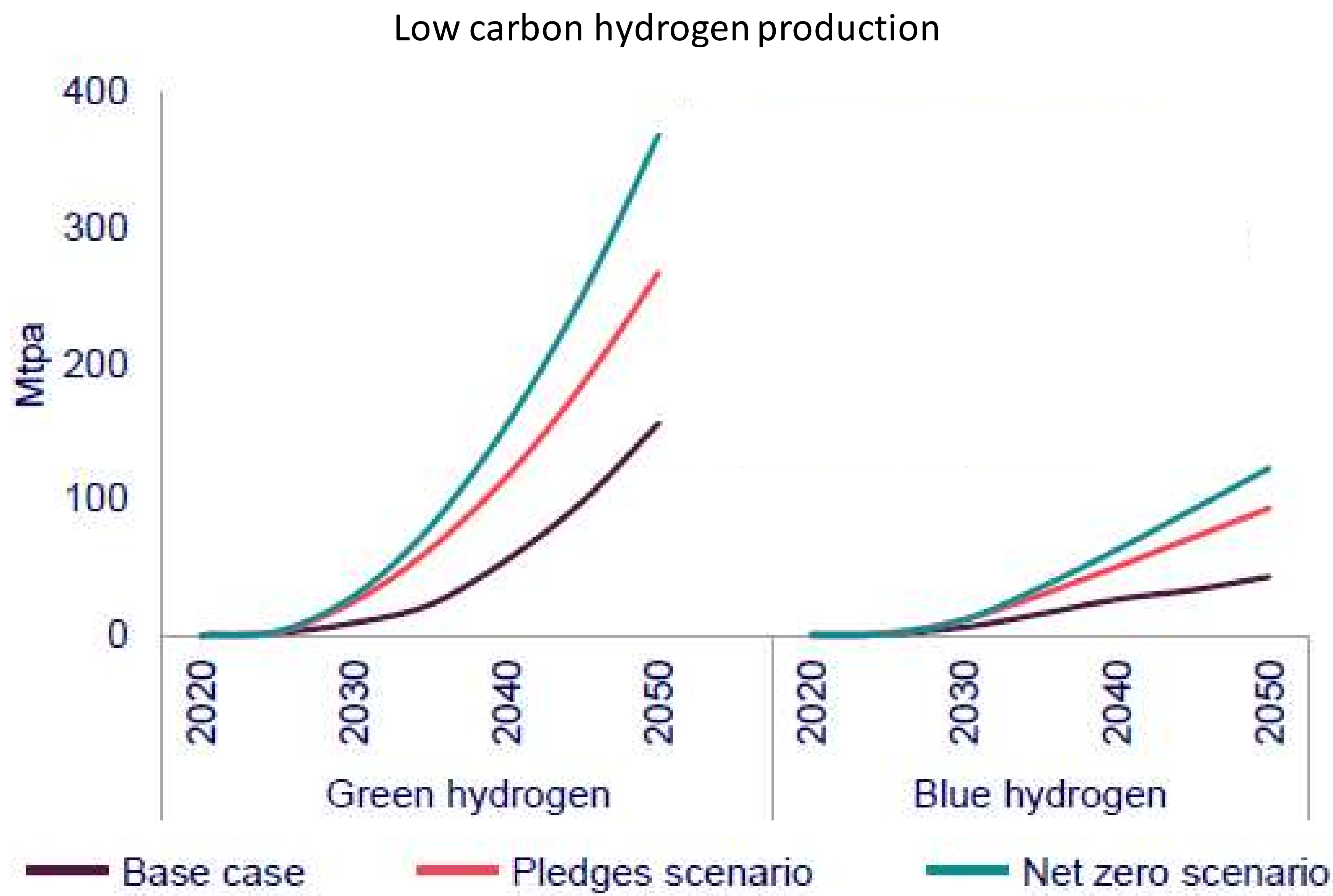
Hydrogen will also be an important component of international energy trade in 2050 in a Net Zero Scenario



Notes: Values for hydrogen trade include volumes for liquid hydrogen, ammonia and synthetic fuels. Values for critical minerals trade include volumes for processed copper, nickel, lithium and cobalt, with assumptions that the ratio of trade value to total demand remains constant.

Source: IEA analysis based on historical critical minerals trade data from UN (2021).

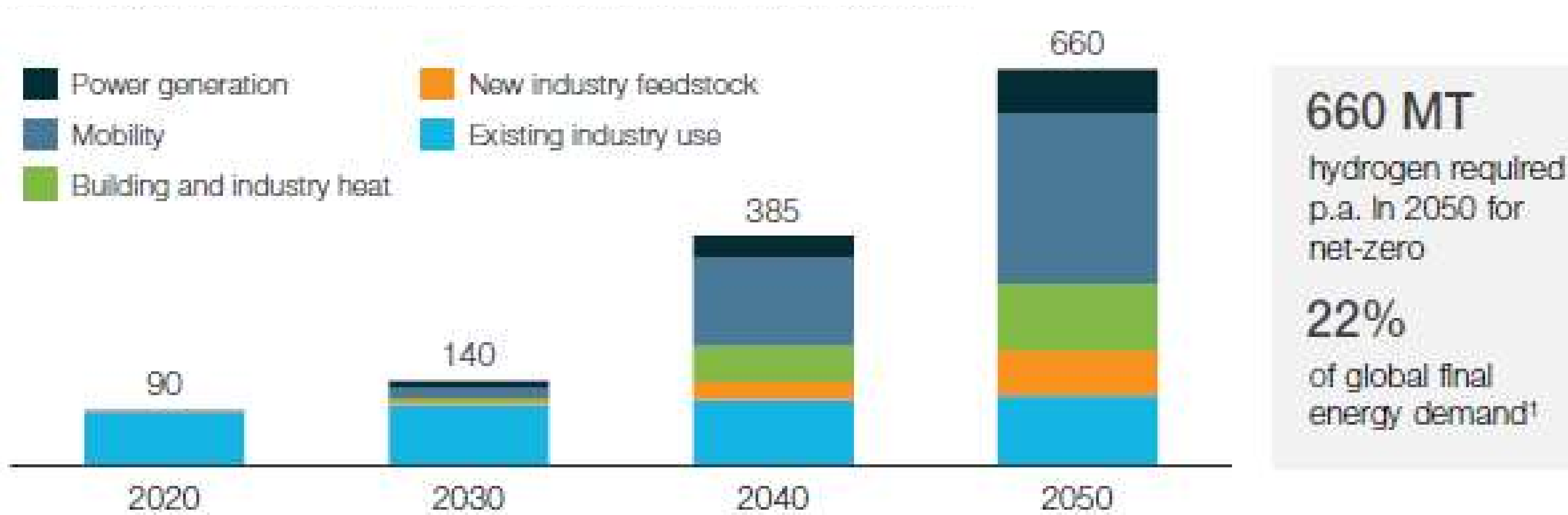
Woodmac assumes a similar market development by 2050 in their NZ Scenario



Source: Woodmac 2023 Energy Transition Outlook Summary (Sept 2023)

The Hydrogen Council has an even more aggressive view of hydrogen demand in a net zero scenario

Hydrogen End-Use Demand by Segment (mmtpa)

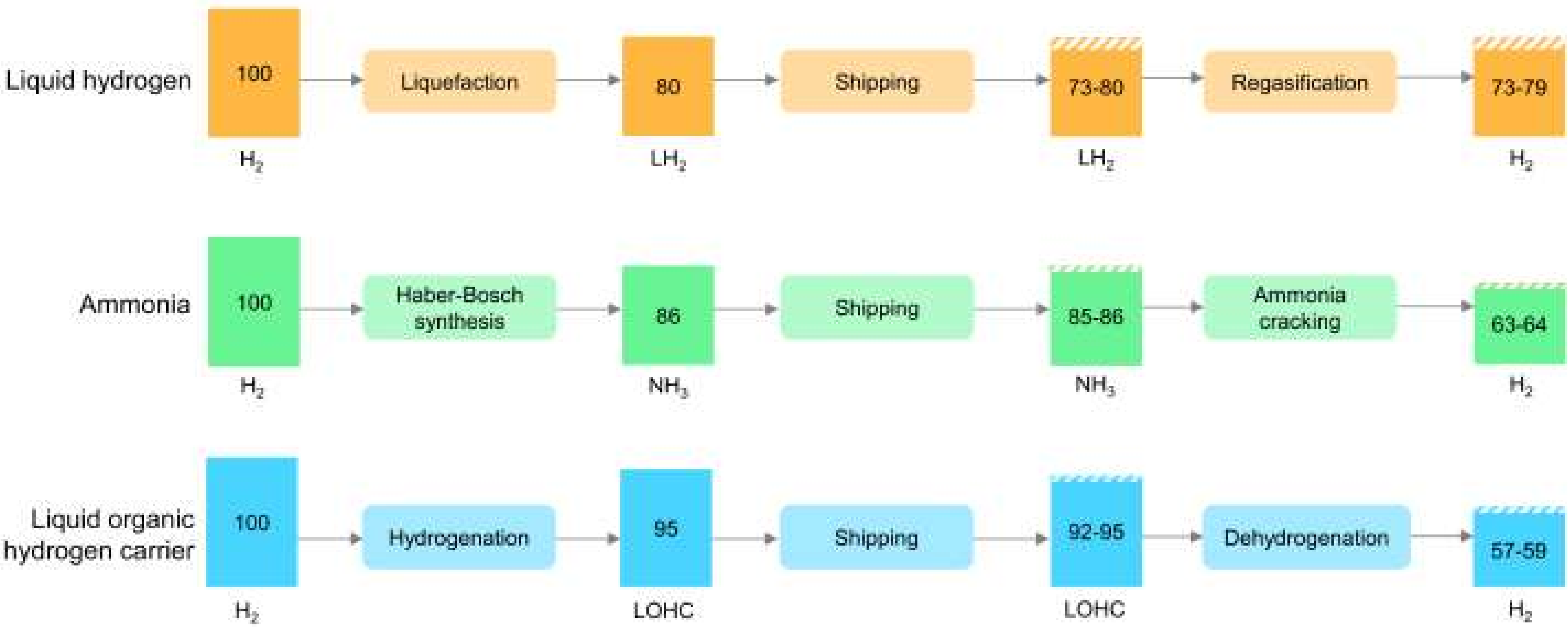


Hydrogen Supply is expected to be 70% from electrolysis and 30% from abated fossil fuels

Source: Hydrogen Council: Hydrogen for Net Zero (Nov 2021)

Of the three main hydrogen carriers, the liquid hydrogen chain is the most energy efficient over long distances…

2030 Energy available after transportation and conversion*



Assumes 8000km shipping distance, excludes electrolyzer energy consumption to produce green hydrogen (approximately 30%)

Source: IEA Global Hydrogen Review 2022

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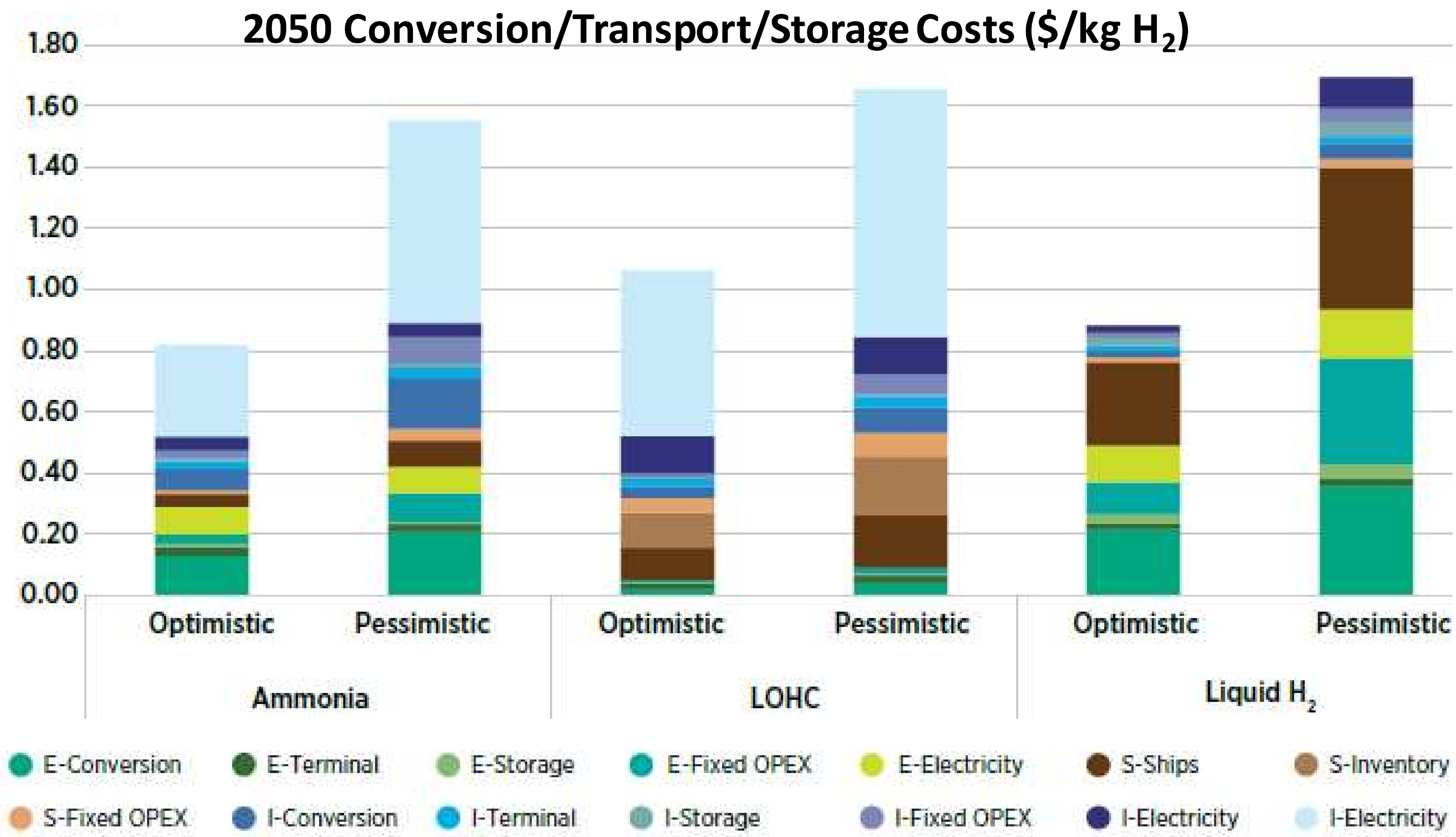
…but projected total conversion, transportation, and re-conversion costs are fairly similar for the three carriers



Notes: Costs are for a 1 MtH2/yr export flow and a distance between ports of 10 000 km. Cost components are divided by part of the value chain: E = exporting country; S = ships; I = importing country

Source: IRENA Global Hydrogen Trade to Meet the I.5°C Target (2022) - Part 2

To accelerate development most regions have initiated hydrogen policy support

Theme	United States	Canada	European Union	United Kingdom	Japan	China
Regional Interest and Support						
Financial support	• Financial incentives (e.g., 45V production tax credit) • Federal funding (for hubs) • Loan Programs Office support	• Financial incentives (e.g., Clean Hydrogen Investment Tax Credit and Carbon Sequestration tax credits) • Federal funding (e.g., Clean Fuels Fund)	• Federal funding (e.g., H2Use and H2Tech) • CfD subsidy schemes (Germany's H2Global and EU Hydrogen Bank's pilot auction)	• Federal funding (e.g., Net-Zero Hydrogen Fund and CCUS Infrastructure Fund) • CfD subsidy scheme • UK Infrastructure Bank	• Federal funding (e.g., Green Innovation Fund) • GX Economy Transition Bonds • CfD subsidy scheme introduced	• Central government and provincial funding
Cost reduction targets	\$2/kg by 2026; \$1/kg by 2031				\$3/kg by 2030, \$2/kg by 2050	

Source: EFI Foundation Hydrogen Market Formation - An Evaluation Framework (Jan 2024)

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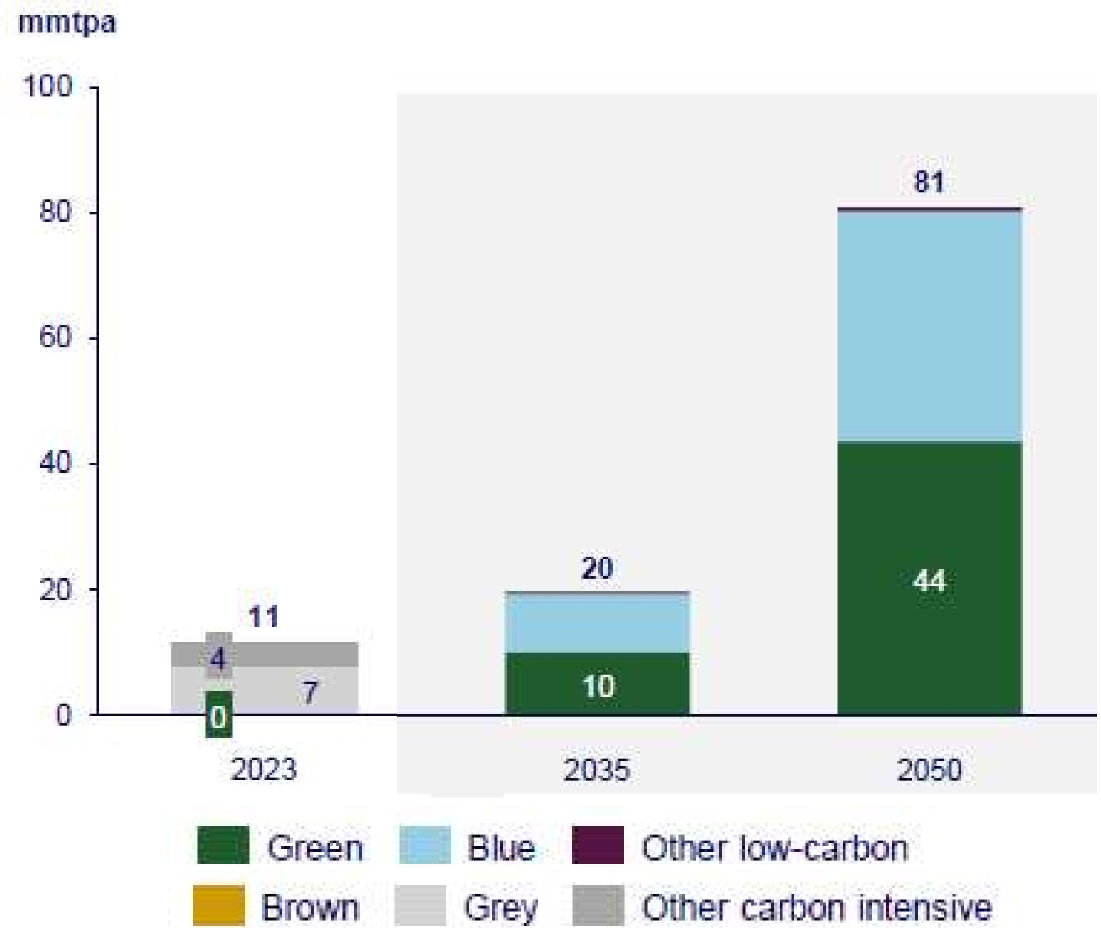
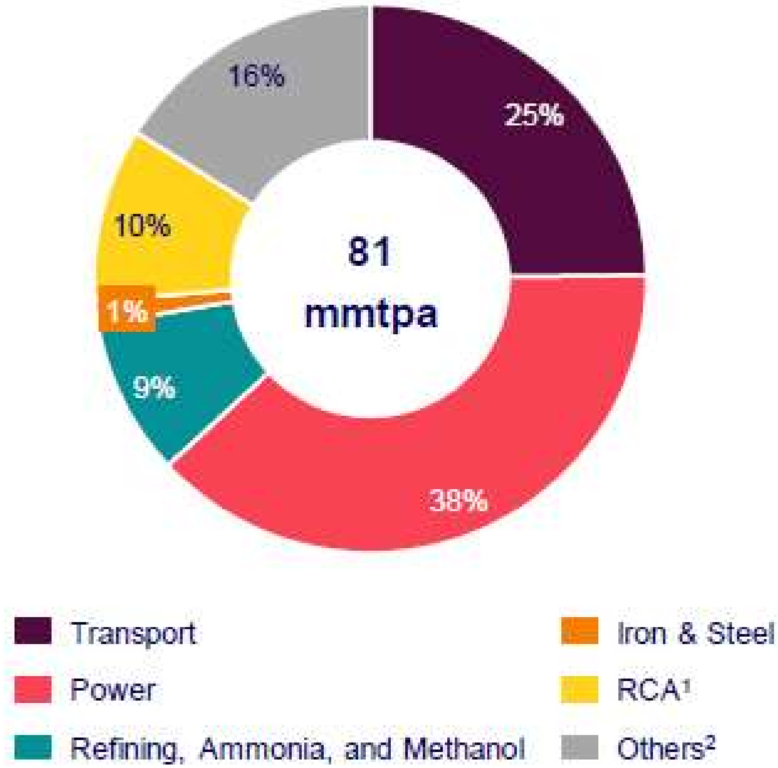
The Woodmac net-zero scenario has 80 mmpta of hydrogen demand in the US by 2050

2050 US Net Zero Production by Type



2050 US Net Zero Demand by Sector



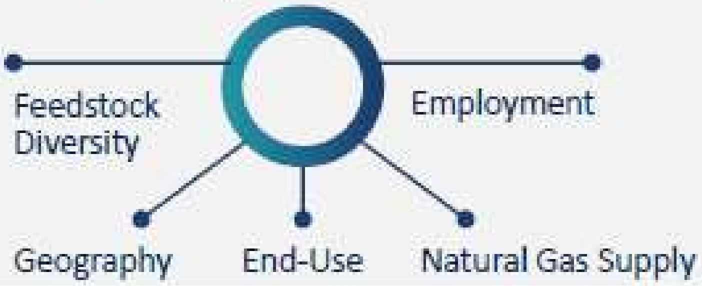
Source: Woodmac Implications of 45V Guidance for the Future of the Green Hydrogen Industry – Executive Summary (Feb 2024)

The US has established significant incentives for investment in hydrogen

Hydrogen Hubs (2021)[1]

Congress appropriated $8 billion to award "networks of clean H_2 producers, consumers, and the connecting infrastructure."

- Part of the Infrastructure Investment Job Act (IIJA)
- DOE is administering the funding in 50% cost-sharing agreements
- Seven hubs selected Oct 2023, each receiving about $1 billion and targeting mix of H_2 feedstock's and end-uses
- An additional $1 billion is targeted for demand-side initiatives.
- DOE expects projects to be executed over 8 to 12 years



Inflation Reduction Act (2022)[2]

Congress introduced major incentives for clean energy production, including expanded tax credits for carbon capture utilization and storage (CCUS) and direct air capture (DAC), and novel tax credits for clean hydrogen production.

Tax Credit	Amount	Description
45V (new)	Up to $3/kg H_2	Production tax credit for "clean" hydrogen, developers allowed to choose between ITC and PTC
45Q (extended and augmented)	Up to $85/t$CO_2$ stored	Production tax credit for capture *and* sequestration; Cannot be stacked with 45V
45Z (new and augmented)	$0.2 to $1/gal. x emission factor $0.35 to $1.75 x emission factor (aviation fuel)	Clean transport. fuel production credit; higher amount available for meeting wage and labor criteria; Cannot be stacked with 45V

Source: Brattle - Emerging Economics of Hydrogen Production and Delivery

The DOE has selected seven US hydrogen hubs for support

	Type of H_2	Target Sectors[a]
Appalachian Hydrogen Hub	Green, Blue, Biohydrogen	Ammonia, chemicals, industrial, heavy-duty transport, mining, data centers, distribution centers, Sustainable aviation fuel (eSAF), gas utility blending, residential fuel cells
California Hydrogen Hub	Green, Biohydrogen	Heavy duty-transport, power generation, port operations
Gulf Coast Hydrogen Hub	Green, Pink, Blue	Ammonia, refining and petrochemicals, industrial, heavy-duty transport, transit authorities, ports, eSAF, marine fuel (eMethanol), power generation
Heartland Hydrogen Hub	Green, Pink, Blue	Fertilizer, industrial, eSAF, power generation, gas LDC blending
Mid-Atlantic Hydrogen Hub	Green, Pink, Blue	Industrial, refineries, heavy-duty transportation, transit authorities
Midwest Hydrogen Hub	Green, Pink, Blue	Agriculture, industrial, manufacturing, heavy-duty transportation, eSAF, gas utility blending
Pacific Northwest Hydrogen Hub	Green	Fertilizer, refiners, industrial, heavy-duty transport, eSAF, marine fuel, long-duration energy storage

Source: Brattle - Emerging Economics of Hydrogen Production and Delivery

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The Gulf Coast region has many advantages in hydrogen

Gulf Coast's Energy Assets

- Broad base of industrial energy customers across multiple demand segments
- Welcoming environment for infrastructure development
- 33% of U.S. hydrogen production capacity
- Highly skilled energy workforce (11% of U.S. energy jobs)
- Large concentration of academic and industry-driven energy innovation: major research universities and a new innovation campus
- Largest energy manufacturing cluster (7000+ establishments)

Production capacity

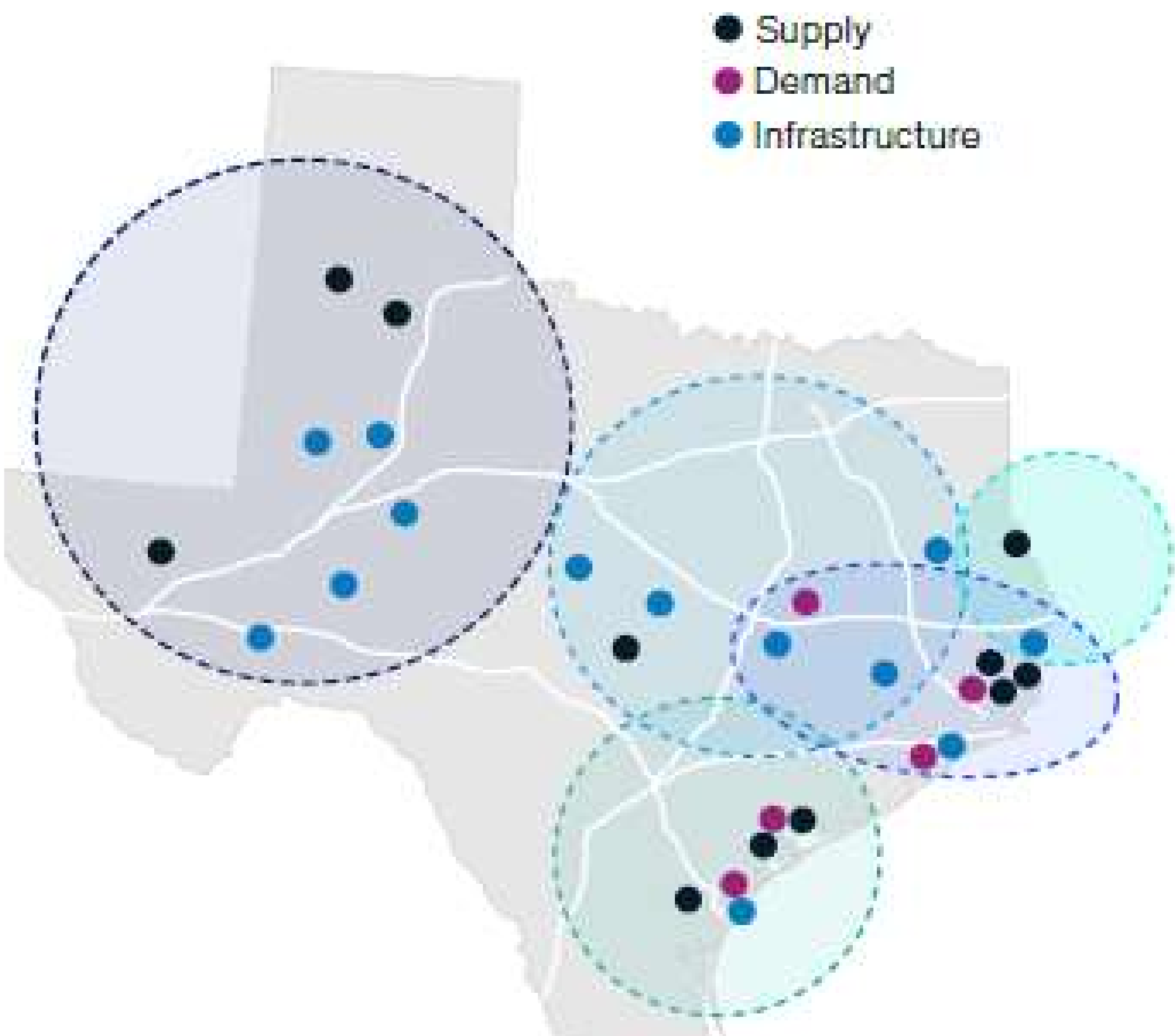
- Largest renewable energy market in the nation (36 GW wind, 15 GW solar)
- 2.4 billion tons of CO_2 storage capacity (10,000x Houston's current CO_2 emissions)
- Access to abundant low-cost natural gas (11.2 Tcf natural gas produced in 2022)

Transportation and storage

- 1000+ miles of hydrogen pipeline – largest networks in the nation
- 3 of the 6 hydrogen storage caverns in the world

Source: DOE Office of Clean Energy Demonstrations Regional Clean Hydrogen Hubs Gulf Coast Regional H2Hub Community Briefing October 2023

A Texas hydrogen hub would likely have a number of clusters



West Texas
- Clean H_2 generation through renewable sources and natural gas coupled with CO_2 storage
- Potential midstream infrastructure including pipeline to East Texas

Texas Triangle and Bay City
- Nuclear or waste-to-hydrogen production
- Fueling network to support transport use cases
- Coalition of enablers, including R&D efforts

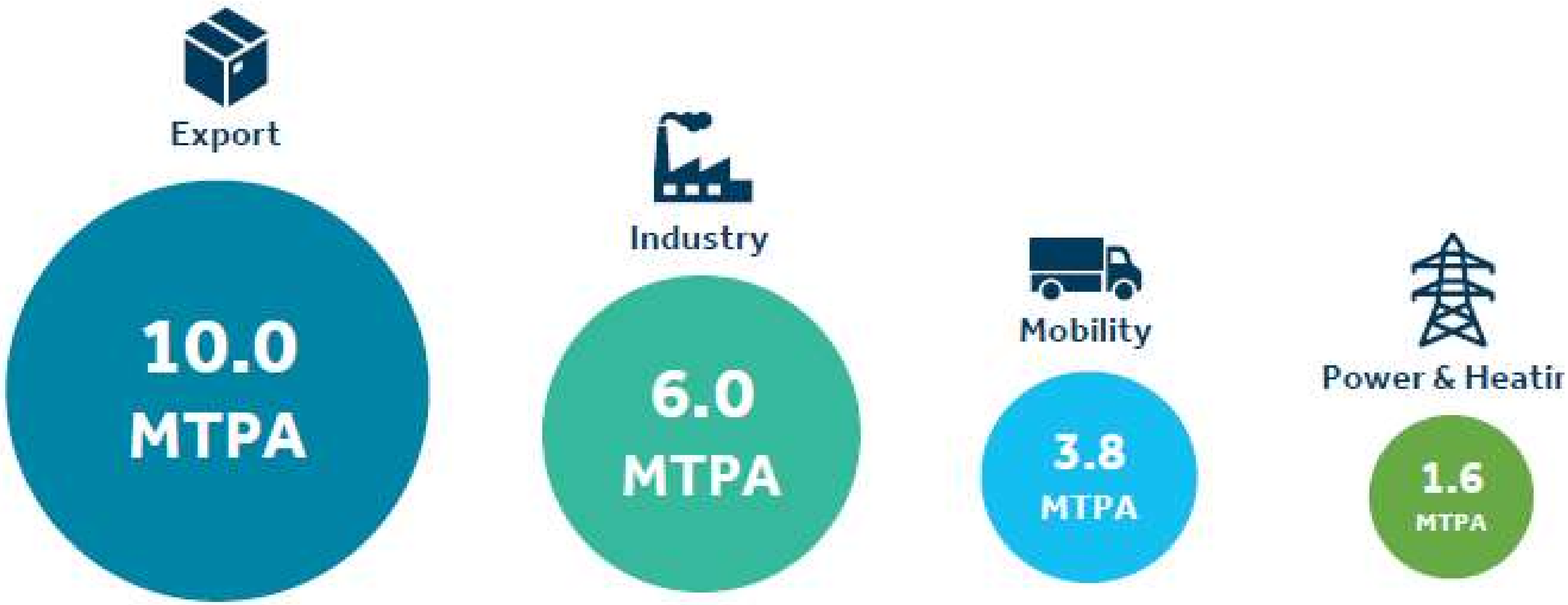
East Texas
- Clean H_2 storage
- Potential offtake from power demonstration

Greater Houston
- Blue H_2 production epicenter with onshore and offshore CO_2 storage
- Potential export and offtake from industrial clusters, including refining and petrochemical producers

Corpus Christi and South Texas
- Clean H_2 production
- Potential export and offtake from industrial clusters including iron and steel producers, petrochemical players

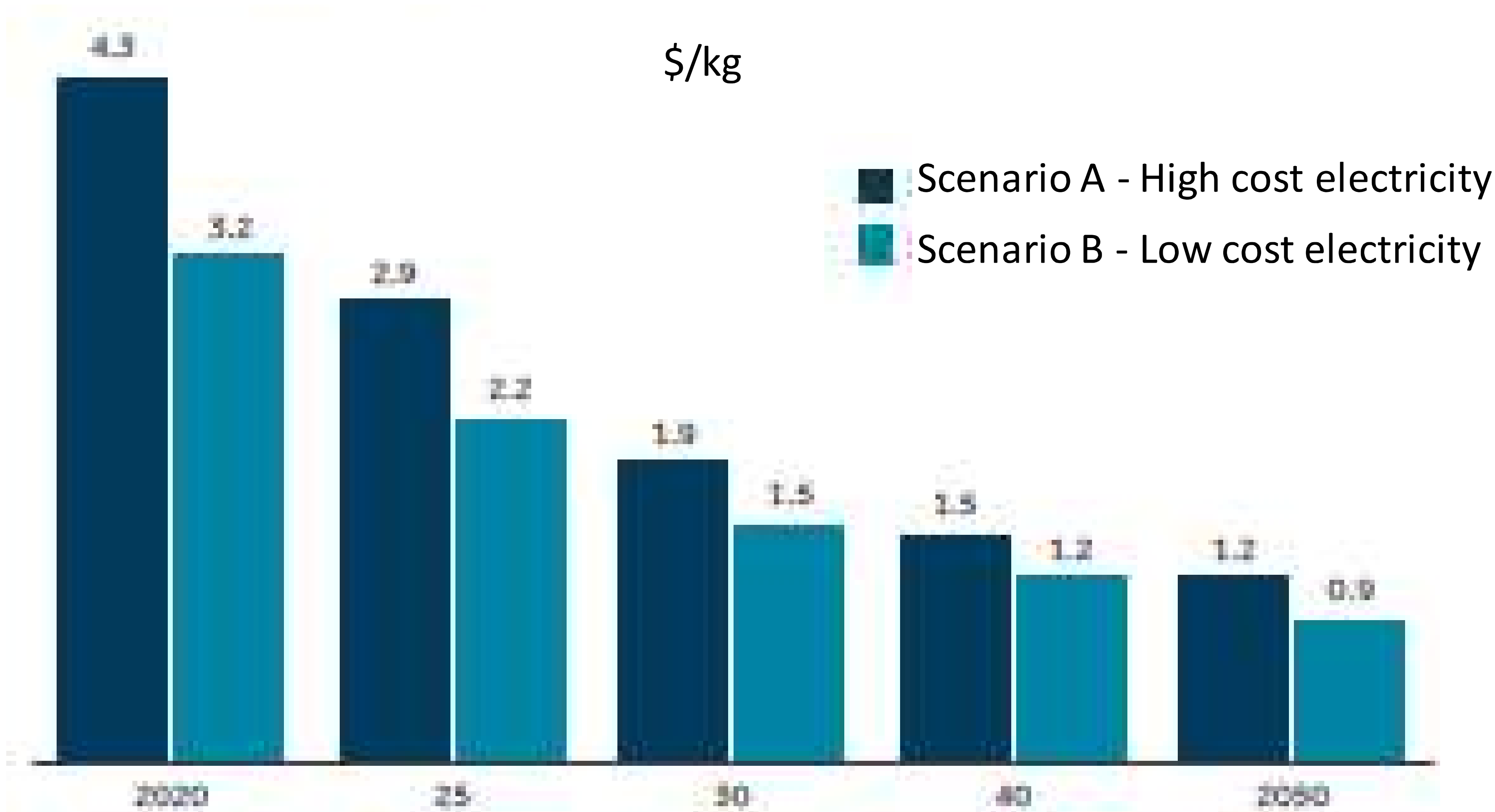
Source: McKinsey Unlocking clean hydrogen in the US Gulf Coast: The “here and now” (Aug 2023)

A Texas hub could reach over 20 mmtpa by 2050 including exports



Source: CHF/GHP :Houston as the epicenter of a global clean hydrogen hub (May 2022)

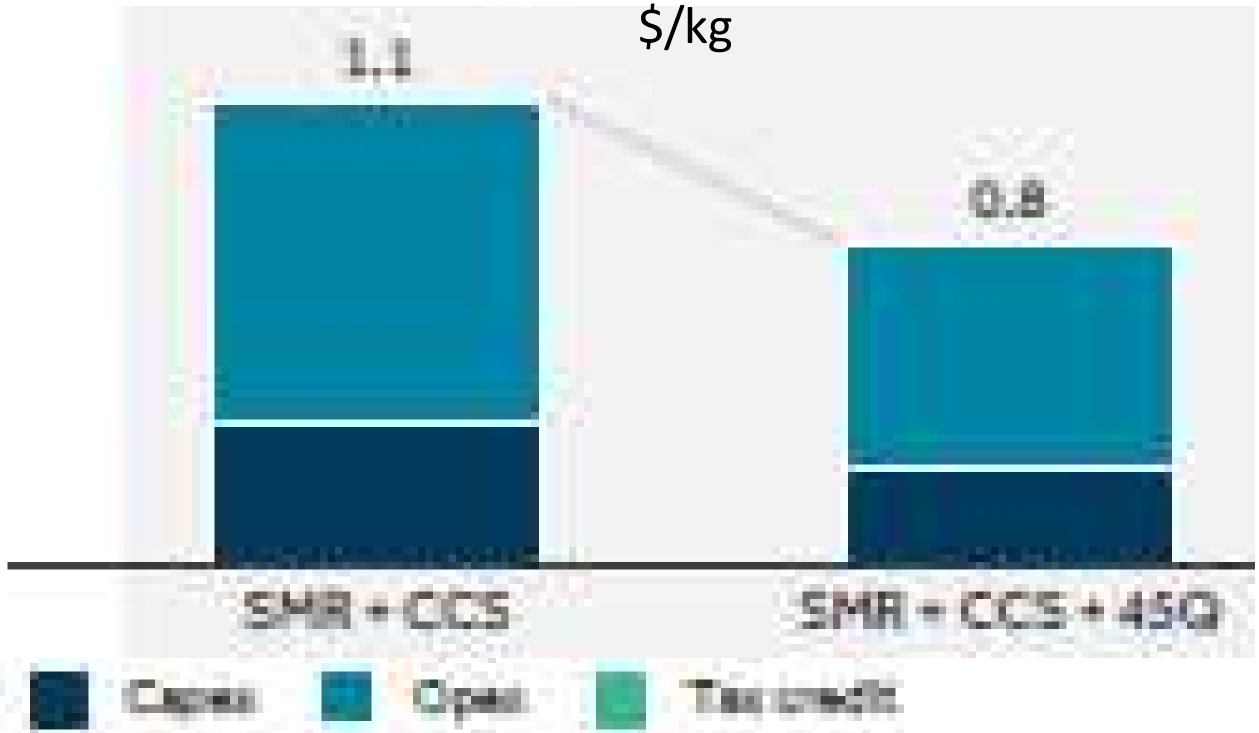
2050 electrolyzer hydrogen production costs in Texas could reach $1/kg with technology development and system scale



Scenario A - LCOE of $37/mwh in 2020 and $26/mwh in 2050
Scenario B - LCOE of $25/mwh in 2020 and $21/mwh in 2050
Electrolyzer system of 2mw in 2020 and 85 mw in 2050

Source: CHF/GHP :Houston as the epicenter of a global clean hydrogen hub (May 2022)

Production cost for SMR with CCS (including 45Q) could be below $1/kg by 2030



- Plant capacity = 100,000 Nm^3/h; natural gas = ~ $2.5-3/MMBtu; greenbuild
- Tax credit of $50/ton captured CO_2; captured CO_2 of ~6 kg CO_2 / kg H_2
- Tax credit = ~$0.3/kg H_2

Source: CHF/GHP :Houston as the epicenter of a global clean hydrogen hub (May 2022)

Finally, repurposing existing fossil fuel assets could accelerate and reduce the cost of a hydrogen hub

Asset Type	Repurpose
Oil and Gas Production Facilities	Solar or wind generation and hydrogen production
Gas Pipelines	Hydrogen, hydrogen blends
Processing Plants	Refineries - hydrogen, ammonia, synthetic hydrocarbon production LNG Plants - ammonia, hydrogen
Storage and Terminal Facilities	Liquids - synthetic hydrocarbons Gas (salt domes) - hydrogen LPG - ammonia LNG - hydrogen, ammonia
Shipping	Refined products - synthetic hydrocarbons LPG - ammonia
Coal and Gas Power Plants	Solar or wind generation and hydrogen production, hydrogen/ammonia co-firing, coal to abated gas

Note: Repurposing here is defined as using a new feedstock or process, producing a new product (i.e., excludes process modifications like adding carbon capture to current hydrogen or power plants)