Role of Hydrogen in Low-Carbon Energy Transition

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MIT Joint Program Global Change

Motu economic & public policy research

Te Tai Ōhanga The Treasury

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THE COLORS OF HYDROGEN

GREEN

Hydrogen produced by electrolysis of water, using electricity from renewable sources like wind or solar. Zero CO_2 emissions are produced.

BLUE

Hydrogen produced from fossil fuels (i.e., grey, black, or brown hydrogen) where CO_2 is captured and either stored or repurposed.

GREY

Hydrogen extracted from natural gas using steam-methane reforming. This is the most common form of hydrogen production in the world today.

PURPLE/PINK

Hydrogen produced by electrolysis using nuclear power.

TURQUOISE

Hydrogen produced by thermal splitting of methane (methane pyrolysis). Instead of CO_2, solid carbon is produced.

BROWN/BLACK

Hydrogen extracted from coal using gasification.

YELLOW

Hydrogen produced by electrolysis using grid electricity from various sources (i.e., renewables and fossil fuels).

WHITE

Hydrogen produced as a byproduct of industrial processes. Also refers to hydrogen occurring in its (rare) natural form.

Applied Economics Clinic

Hydrogen Reasons

Potential to provide **energy** in **all** parts of economy: industry, transportation, residential.

Potential for **remote communities** (with no access to grid).

Can be **stored** in many forms: gas, liquid, solid.

Can be **made** from **various** sources.

Zero emissions of carbon during operation, but only as clean as the technology used to produce it.

Clean if produced by:

Electrolysis using renewables or nuclear
Steam reforming with carbon capture and storage
Based on renewable biomass

Hydrogen Challenges

Expand from the current applications (primarily as a chemical feedstock) to other sectors

Need for integrated solutions to benefit from **economies of scale**

Policy support (low-carbon, hydrogen-targeted)

Cost, infrastructure, and safety

Why do we need low-carbon hydrogen and renewable gas?

An approach "Decarbonize electricity and electrify everything" – has its limits

Need for renewable hydrocarbons in the form of liquid and gaseous fuels

Heavy-duty, long-distance transport (trucks, ships and planes); high temperature industrial heat (food and beverage sector, steel production, glass production); agriculture (renewable fertilizer such as green ammonia and biofertilizer); and chemical production (such as methanol)

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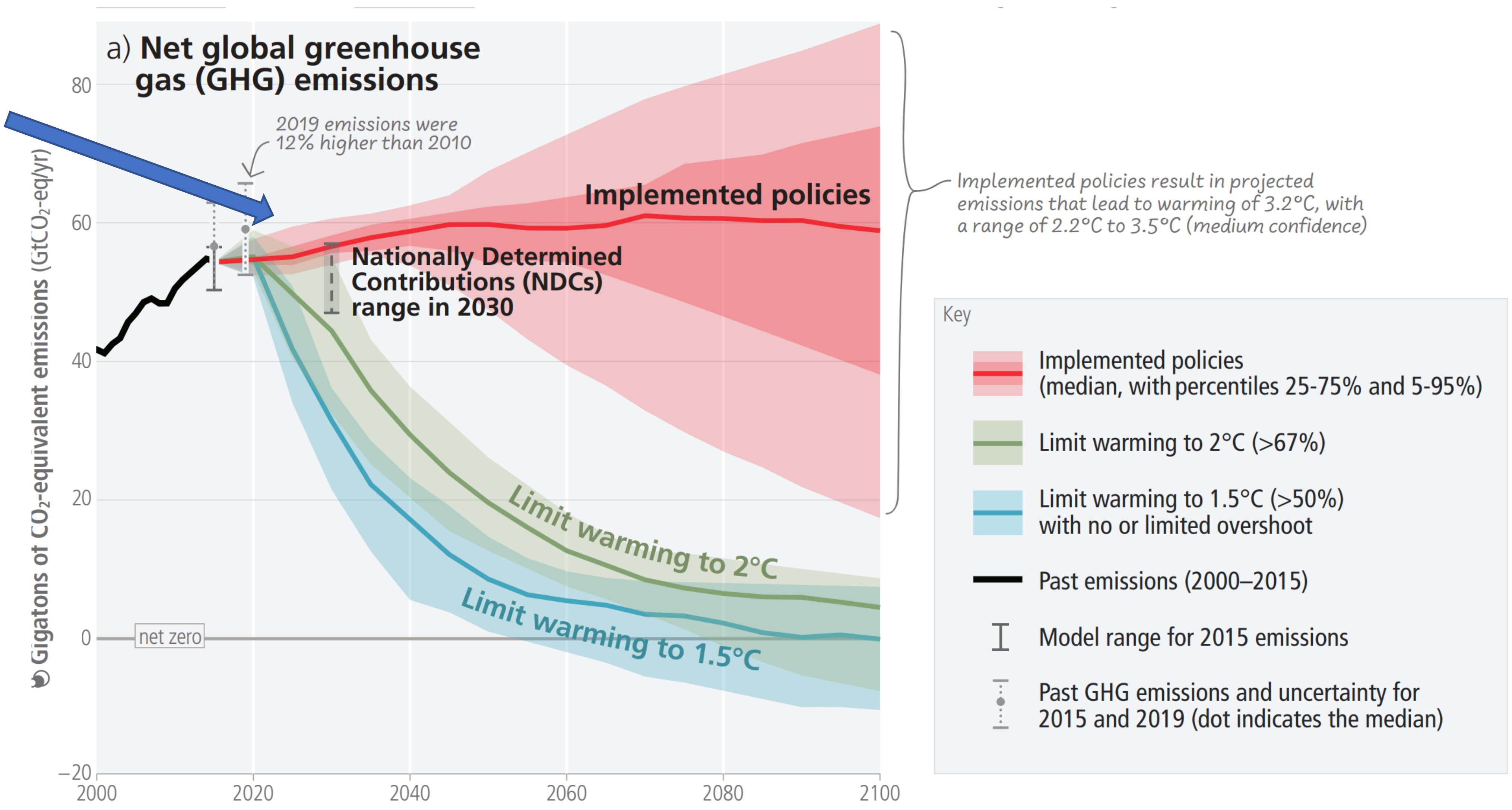
2023 IPCC AR6 Synthesis Report – Global emission pathways

2022 -2023 emissions are outside of the IPCC range



MIT Economic Projection and Policy Analysis (EPPA) Model

Multi-sector, multi-region computable general equilibrium (CGE) model of the world economy for energy, economy and emissions projections

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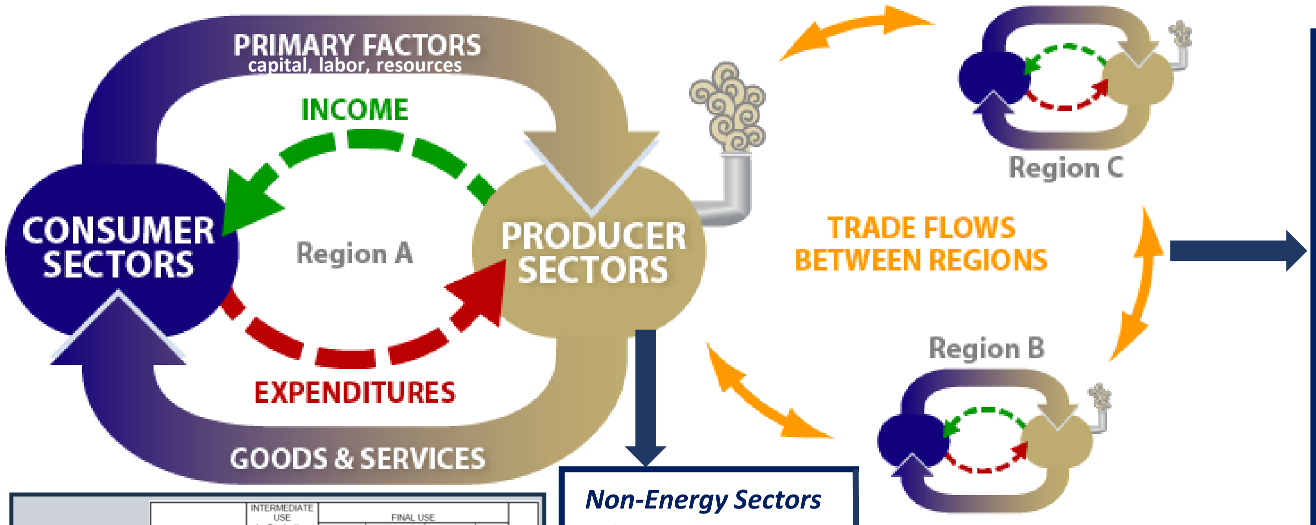
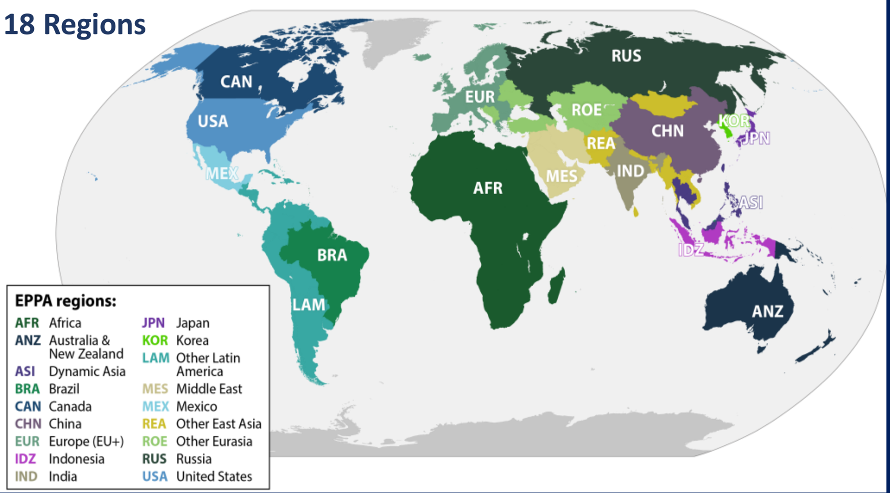
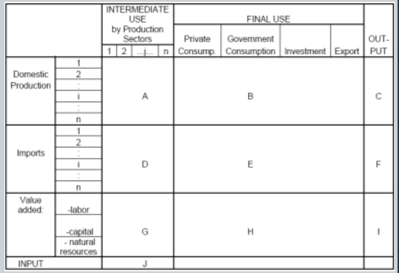


18 Regions



Technical Features
- Written in GAMS using MSPGE
- Based on GTAP Database
- Calibrated to current economic and energy levels based on IMF and IEA
- Documented in peer-reviewed literature
- Publicly Available Version
- 2100+ (in 5-year steps)

Full Input-Output Data for Every Region



Key Inputs
- Policy Assumptions
- Population Growth
- Capital/Labor Productivity Growth
- Energy Efficiency Improvements
- Technology Costs
- Rate of Technology Penetration
- Elasticities of Substitution (related to labor, capital, energy, fuels, etc.)
- Fossil Fuel Resource Availability
- Urban Pollutant Initial Inventories & Trends
- Land Productivity

Non-Energy Sectors
- **Crops**
- **Livestock**
- **Forestry**
- **Food**
- **Energy-Intensive Industry** — Iron & Steel; Cement; Chemicals; Non-Ferrous Metals; *+ low-carbon options*
- **Manufacturing**
- **Service**
- **Commercial Transport**
- **Household Transport** — ICE (gasoline & diesel); Plug-in Electric; Battery Electric; Hydrogen

Energy Sectors
- **Crude Oil**
- **Refined Oil**
- **Liquid Fuel from Biomass** — Current Generation; Advanced Biofuel
- **Oil Shale**
- **Coal**
- **Natural Gas (conv., shale, tight)**
- **Electricity** — Conv. Fossil (coal, gas, oil); Adv. Fossil (NGCC, Adv Coal); Coal with CCS; Coal + Bio Co-firing w/ CCS; Gas with CCS; Gas with Advanced CCS; Nuclear; Advanced Nuclear; Hydro; Solar; Wind; Renewables with Backup; Biomass; Biomass with CCS
- **Synthetic Gas (from Coal)**

New Technologies Continually Added

Regions and sectors can be added for special studies

Key Outputs
- GDP
- Consumption
- Emissions (GHGs, Air Pollutants)
- Primary/Final Energy Use
- Electricity Generation
- Technology Mix
- Commodity and Factor Prices
- Sectoral Output
- Land Use
- **At global and regional levels**

Key Features
- Global Coverage & International Trade
- Economy-Wide Coverage & Inter-Industry Linkages
- Feedbacks Across Regions & Sectors
- Theory-Based (microeconomics with full input-output data)
- Endogenous Prices, Investments & Capital Accumulation
- GDP and Welfare Effects
- Policies (emissions limits/prices, sector/technology regulations…)
- Distortions (taxes, subsidies, etc.)
- Accounting for Physical Quantities (energy, electricity, land)
- **Links to MIT Earth System Model (MESM)**

Key Equations

Firms maximize profit: choose technology, level of output and inputs subject to production functions and costs

Household maximize welfare: choose savings and consumption subject to budget constraint

Equilibrium Conditions: Market-Clearing, Zero-Profit, Income Balance

https://globalchange.mit.edu/research/research-tools/human-system-model

Examples of recent applications of MIT tools: variety of research efforts

Projecting Energy and Climate
Paltsev (2020) Economics of Energy and Env Policy, 9(1), 43-62.

Decarbonizing Hard-to-Abate Sectors
Paltsev et al (2021) Applied Energy, 300, 117322.

Health Co-Benefits of Renewables
Dimanchev et al (2019) Environmental Research Letters, 14(8).

Climate Change Effects on Agriculture
Gurgel et al (2021) Climatic Change, 166(29).

Cost and Value of Variable Renewables
Gurgel et al (2023) Applied Energy, 344, 121119.

Global Electrification of Light-Duty Vehicles
Paltsev et al (2022) Econ of Energy and Env Policy, 11(1), 165-191.

Economics of Bioenergy with CCS (BECCS)
Fajardy et al (2021) Global Environ Change, 68, 102262.

Framework for Assessing Stranded Assets
Chen et al (2023) Climate Change Economics, 14, 2350003.

Transition Scenarios for Financial Risk Analysis
Chen et al (2022) https://globalchange.mit.edu/publication/17757

Climate-Related Financial Stress-Testing
Le Guenedal et al (2023) https://globalchange.mit.edu/publication/18121

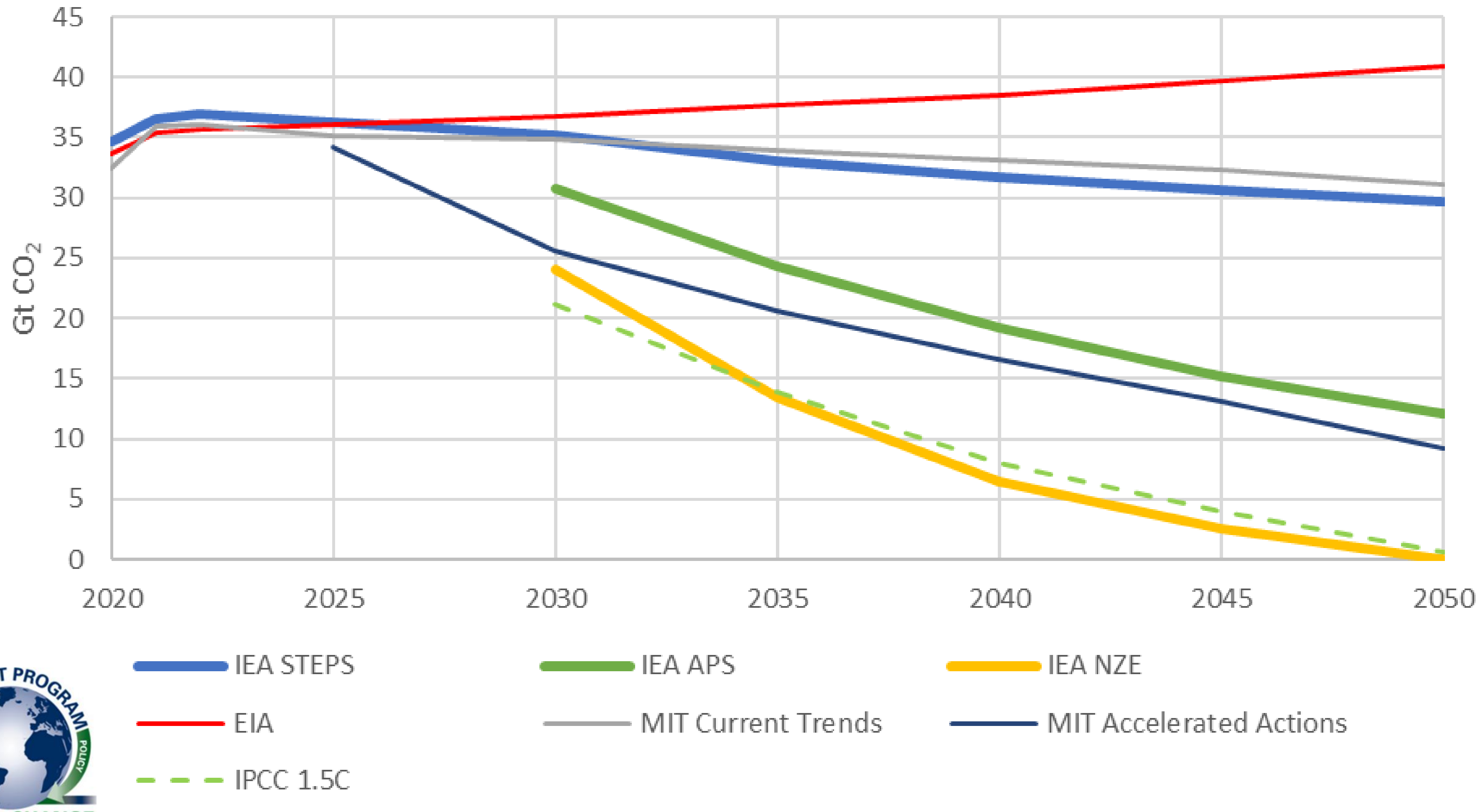
MIT 2023 Global Change Outlook
Charting the Earth's Future Energy, Managed Resources, Climate, and Policy Prospects
https://globalchange.mit.edu

Published every other year.

For current trends, typically, scenarios assess NDCs and other pledges

Since the contributions are determined nationally, countries decide what is “fair” (conditional vs unconditional)

COP-28: “transitioning away from fossil fuels in energy systems, in a just, orderly and equitable manner ... so as to achieve net zero by 2050 in keeping with the science.”



Current Trends: current policies

Ultimately, all countries have to be at “net-zero”

Accelerated Actions by 2050

Advanced economies: 70-80% reduction

Emerging economies: 50-75% reduction

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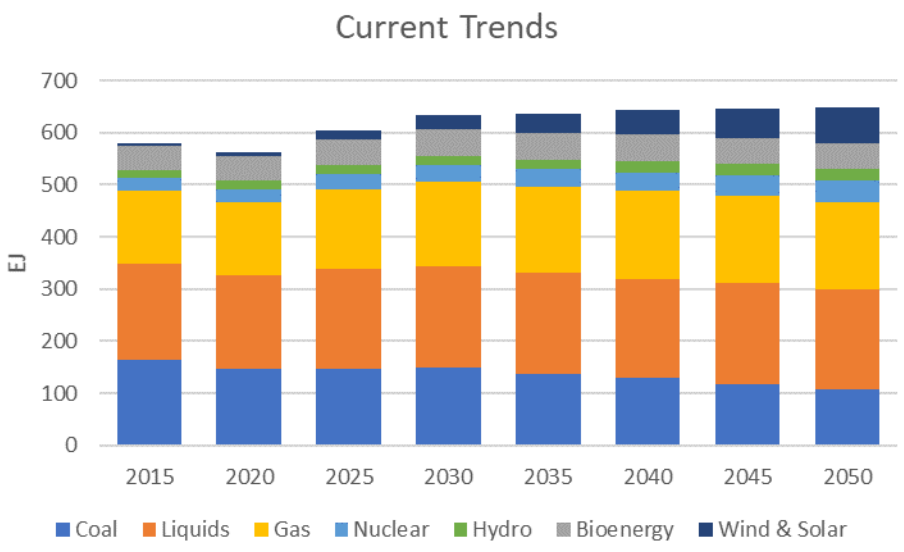
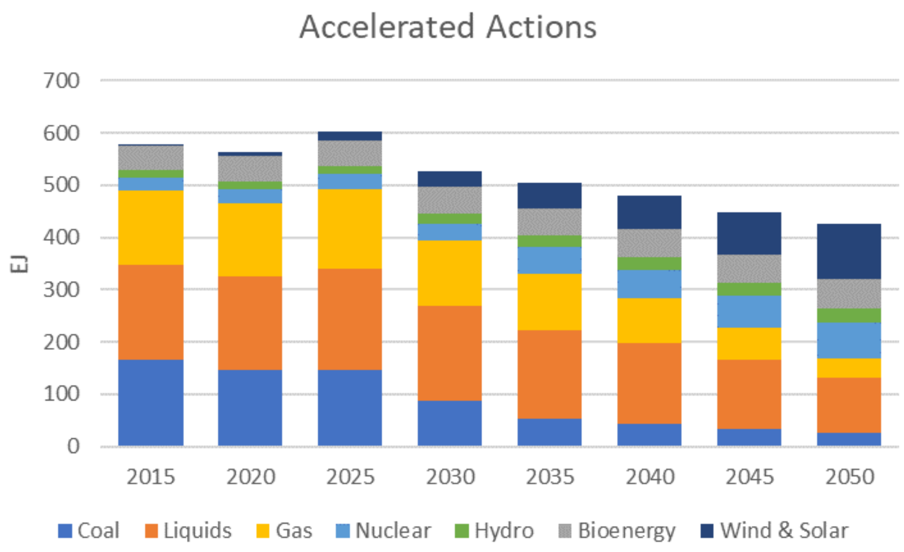
Global Primary Energy

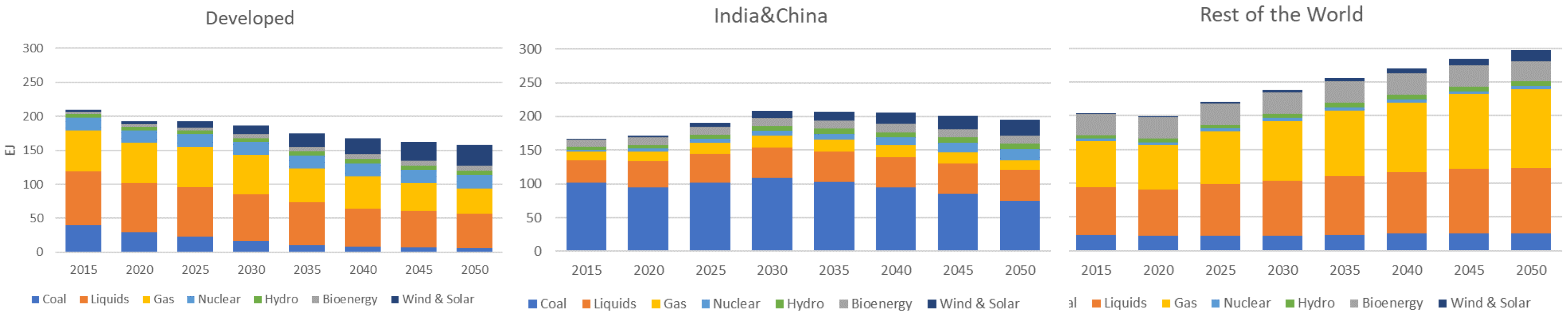




Global primary energy use in the *Current Trends* scenario grows to about 650 exajoules (EJ) by 2050, up by 15% from about 560 EJ in 2020. The share of fossil fuels drops from the current 80% to **70%** in 2050. Wind and solar - **8.6**-fold increase in EJ (from <2% to **11%** share).

In the *Accelerated Actions* scenario, global energy use is reduced due to efficiency and demand response. The fossil fuel share drops to **39%**. Wind and solar energy grow more than **13** times from 2020 to 2050 (to **25%** share).

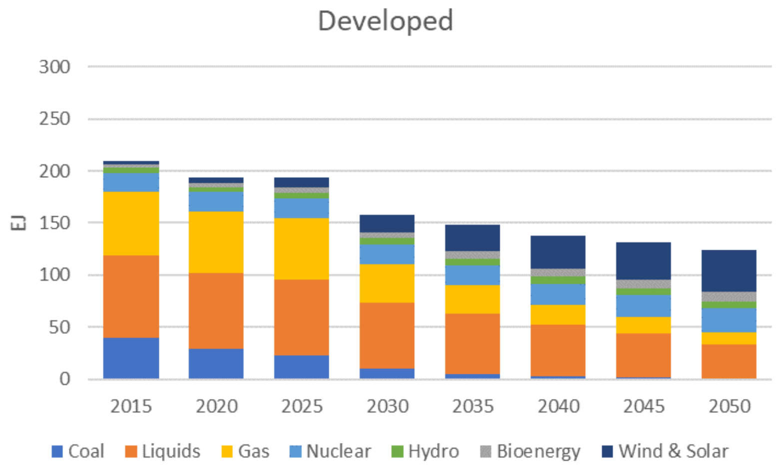
Current Trends: Global Primary Energy by Regional Group

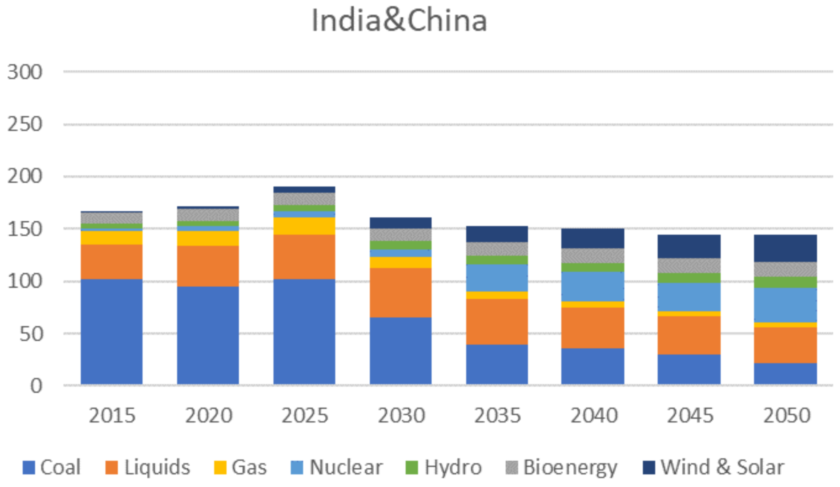


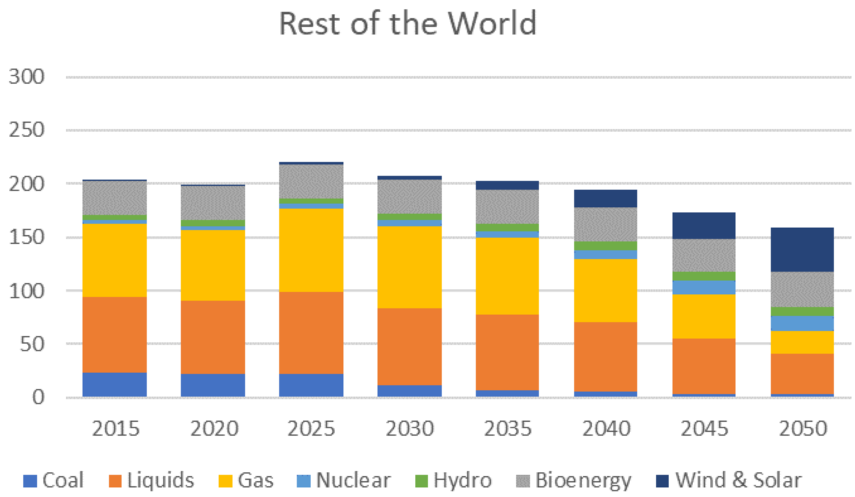
Energy consumption declines by 20% in the Developed region (driven by more aggressive emissions mitigation policies), while growth in energy use is 10% in the India&China region and 50% in the Rest of the World region.

Developed: oil and gas still provide a large share of energy, coal declines, the share of low-carbon sources grows from about 17% in 2020 to about 40% in 2050.
India&China: continue to rely heavily on coal.
Rest of the World: coal does not play a large role, but this region continues to consume large quantities of oil and gas.

Accelerated Actions: Global Primary Energy by Regional Group



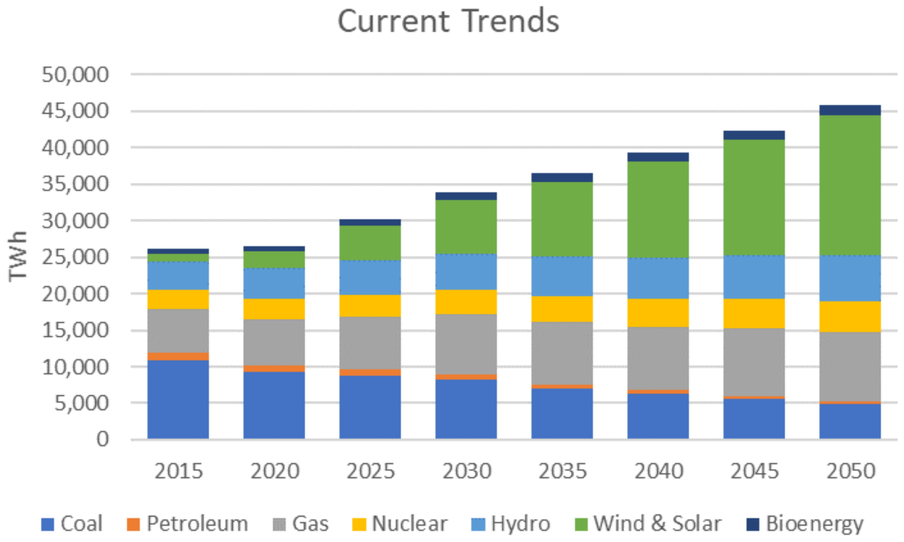


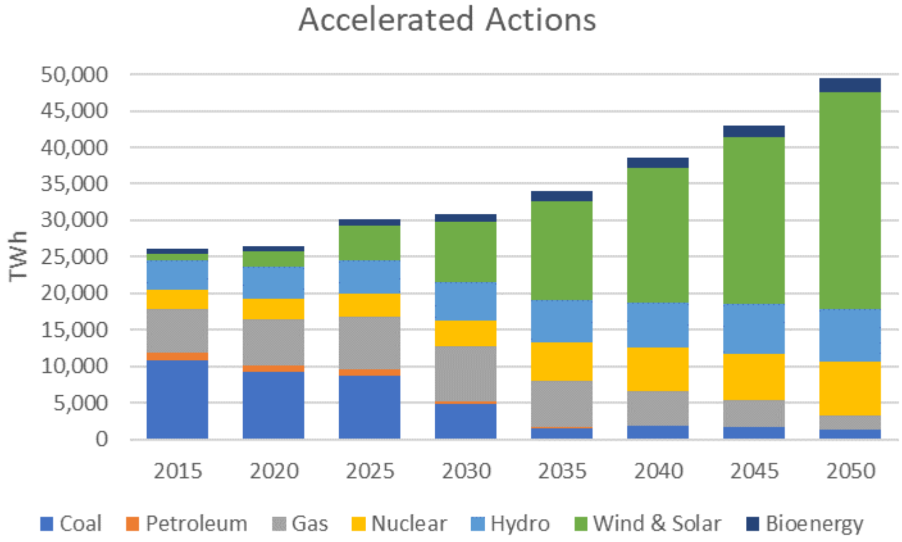


Energy consumption declines in all regions by mid-century

Developed: liquid and gaseous fuels are reduced (but not eliminated), coal eliminated, renewables grow 10-fold.
India&China: coal is substantially reduced, renewables grow 10-fold.
Rest of the World: very different (reduced) role for natural gas, renewables grow 45-fold, much bigger role for energy efficiency.

Global Electricity Production





In the *Current Trends* scenario, global electricity production (and use) grows by **73%** from 2020 to 2050. In comparison to primary energy growth of 15% over the same period, electricity grows much faster, resulting in a continuing **electrification** of the global economy.

In the Accelerated Actions scenario, electricity production grows even faster (**87%** between 2020 and 2050).

Electricity generation from **renewable (and low-carbon)** sources becomes a dominant source of power by 2050 in both scenarios, providing 60-80% (70-90%) of global power generation by midcentury.

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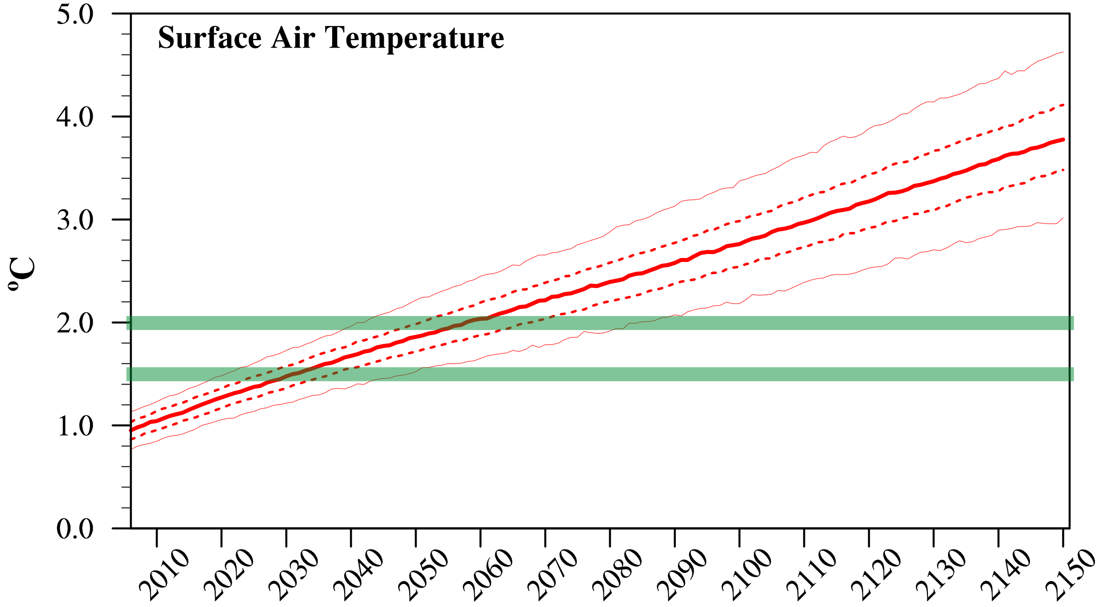
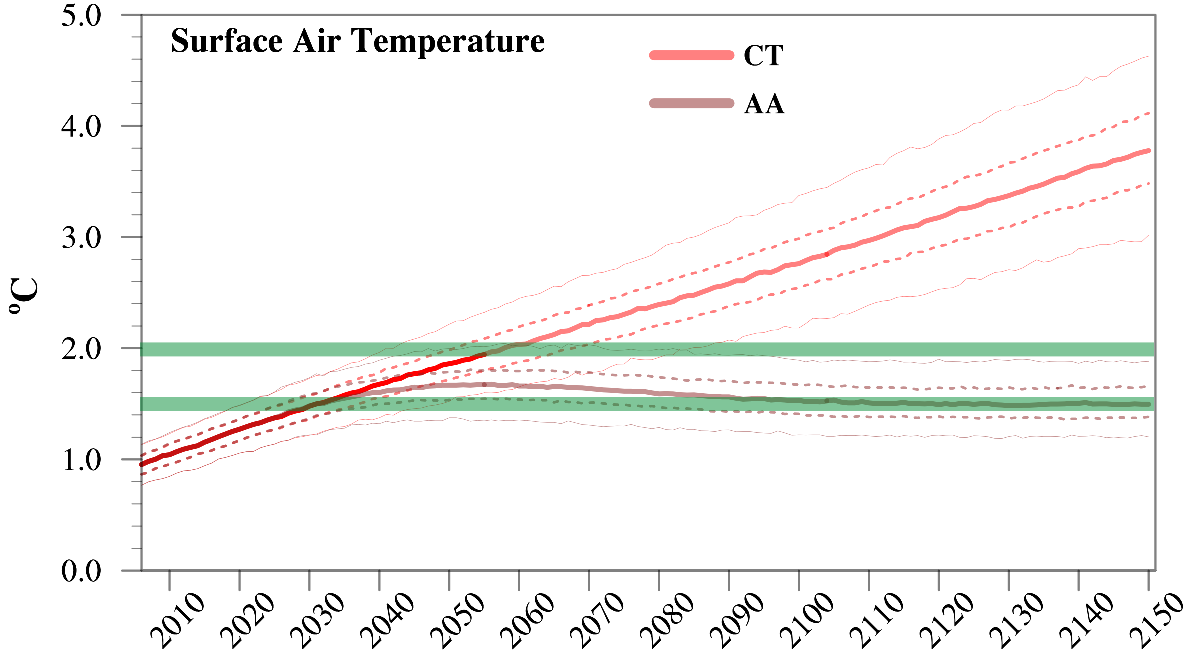
Global Average Surface-Air Temperature Changes

Current Trends (CT) Scenario



By 2060, more than half of the IGSM ensemble's Paris Forever projections exceed 2°C global climate warming, a figure that rises to more than 75% by early 2070s and more than 95% by 2085.

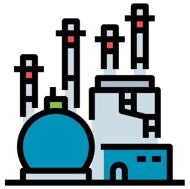
Accelerated Actions (AA) Scenario



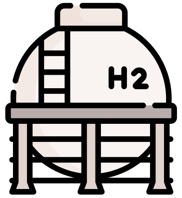
Under *Accelerated Actions*, by midcentury global temperature rise will cease and decline slightly before stabilizing through the latter half of the century and into the 22nd century (to just below 1.5°C median warming).

H_2 *production* costs by source (NREL estimates)

Source	H_2 price	Additional Info

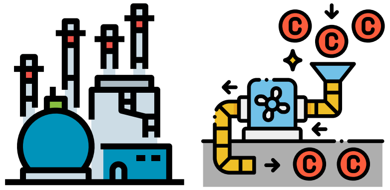


SMR only (not clean!)

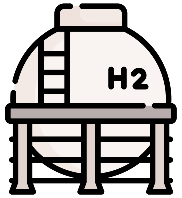


$1.15/kg$H_2$

- $10/GJ LHV (production cost only; **delivery cost is often much more than production cost!**)

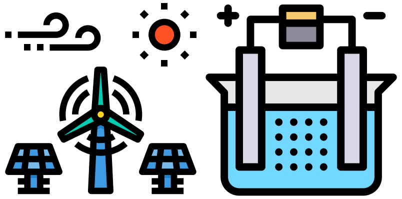


SMR + CCS

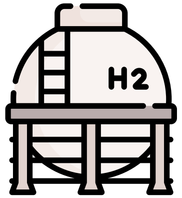


$1.56/kg$H_2$

- **$13/GJ LHV** (production cost only)
- CO_2 captured: 13.6 kgCO_2/kgH_2
- Possible to capture >99% of CO2 but more expensive.
- Must be in location with cheap gas where CCS is possible.



Electrolysis



$4.66/kg$H_2$

- **$39/GJ LHV** (production cost only)
- Electrolyzer Efficiency: 181 t H_2/y/MW per NREL projection, assumes $0.07/kWh
- **Sensitive to price of low-carbon electricity.**
- **Plausible price could drop to ~$2/kg in *good* locations**

Source: https://www.nrel.gov/hydrogen/h2a-production-models.html

Typical Assumptions about Hydrogen Production Costs

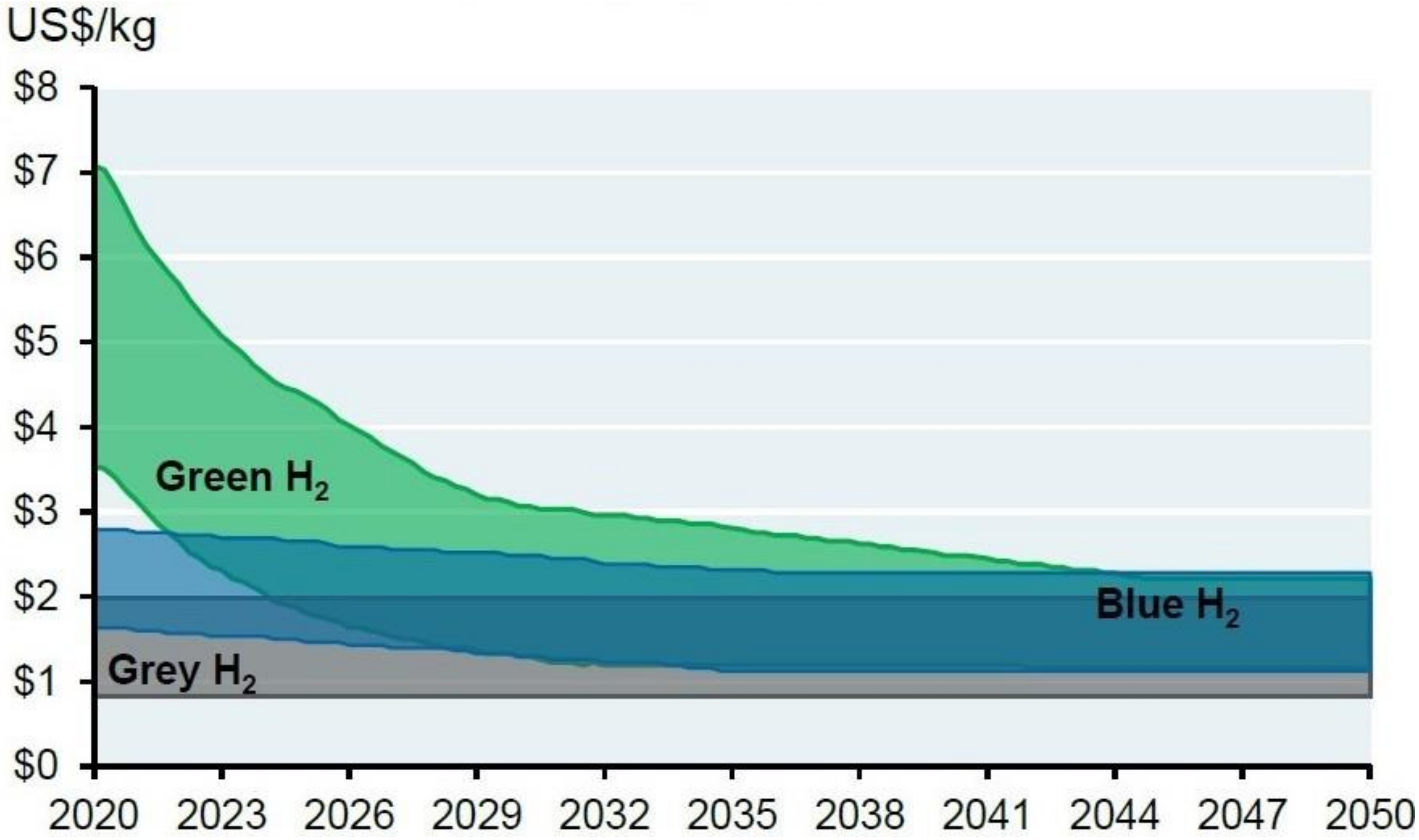
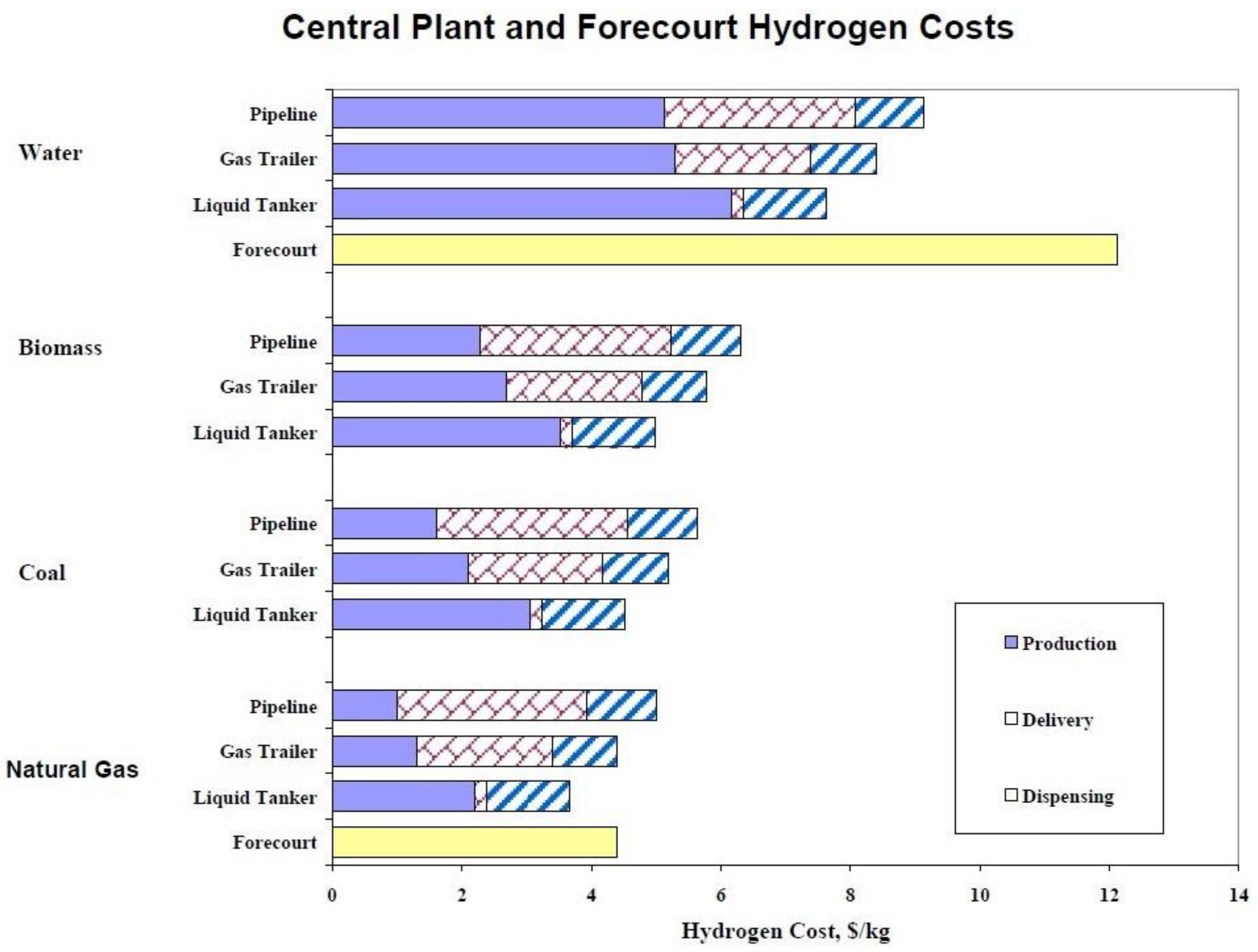


Figure Source: GS (2022)

Transportation is a major cost item for Hydrogen



IEA (2018):

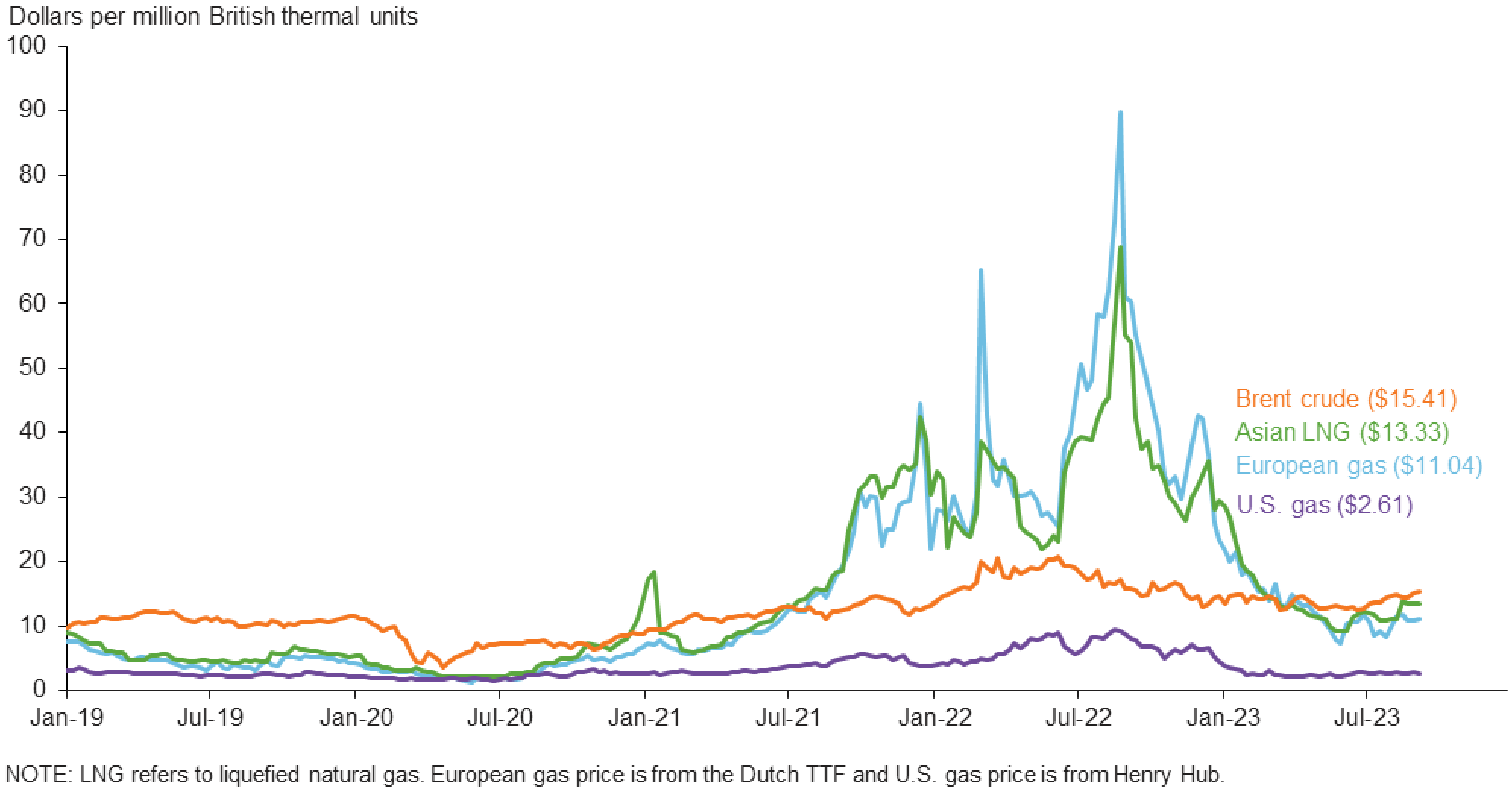
Long-distance shipping in 2040 as

Ammonia 2.50 $/kg
Liquid H_2 3 $/kg

Reported prices at California hydrogen car stations: 10-15 $/kg

Source: Simbeck and Chang (2002)

To convert cost of H_2 in $/kg to an equivalent natural gas price, multiply by 8.78

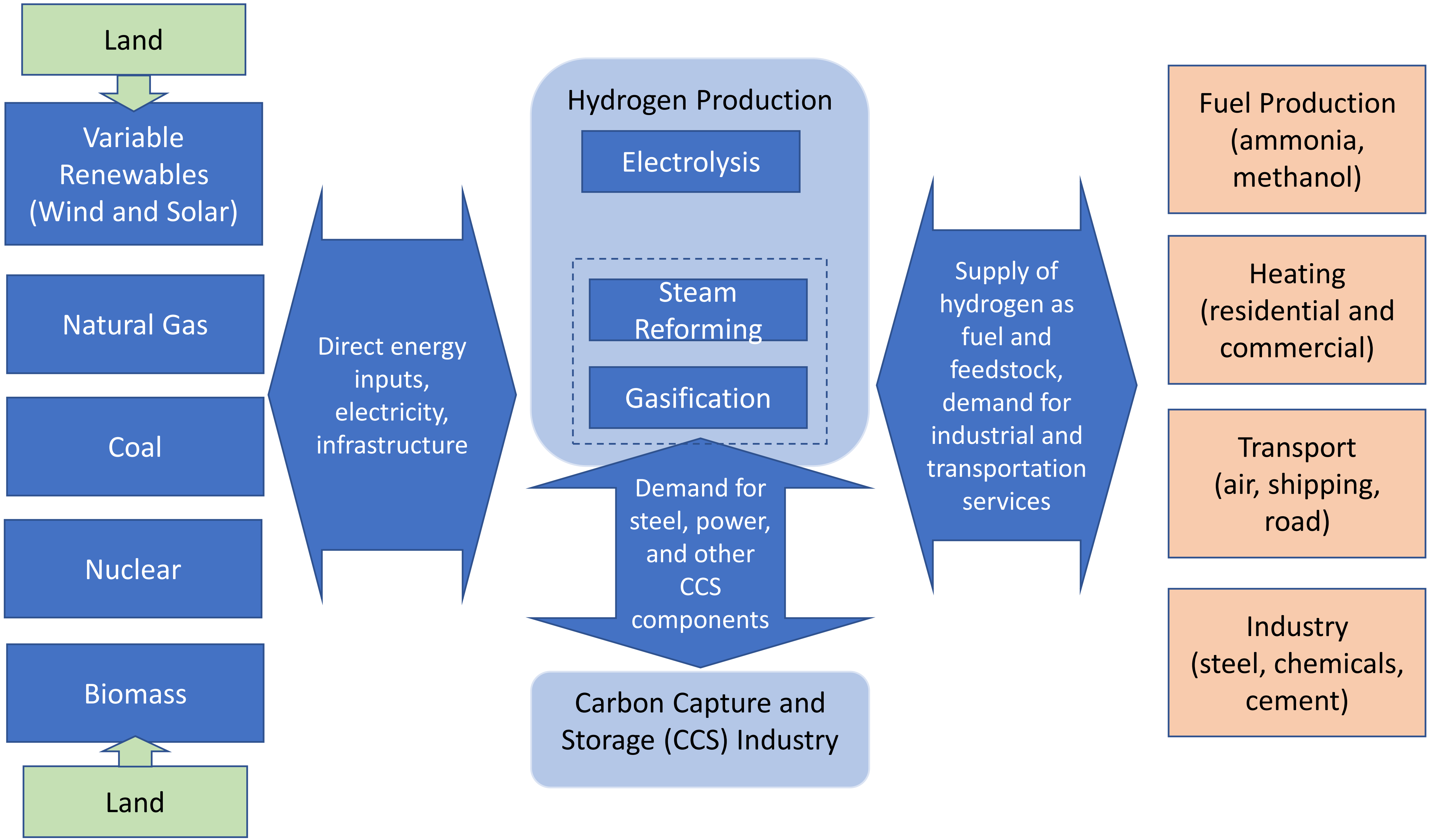


2 $/kg H_2 = 17.60 $/MMBTU

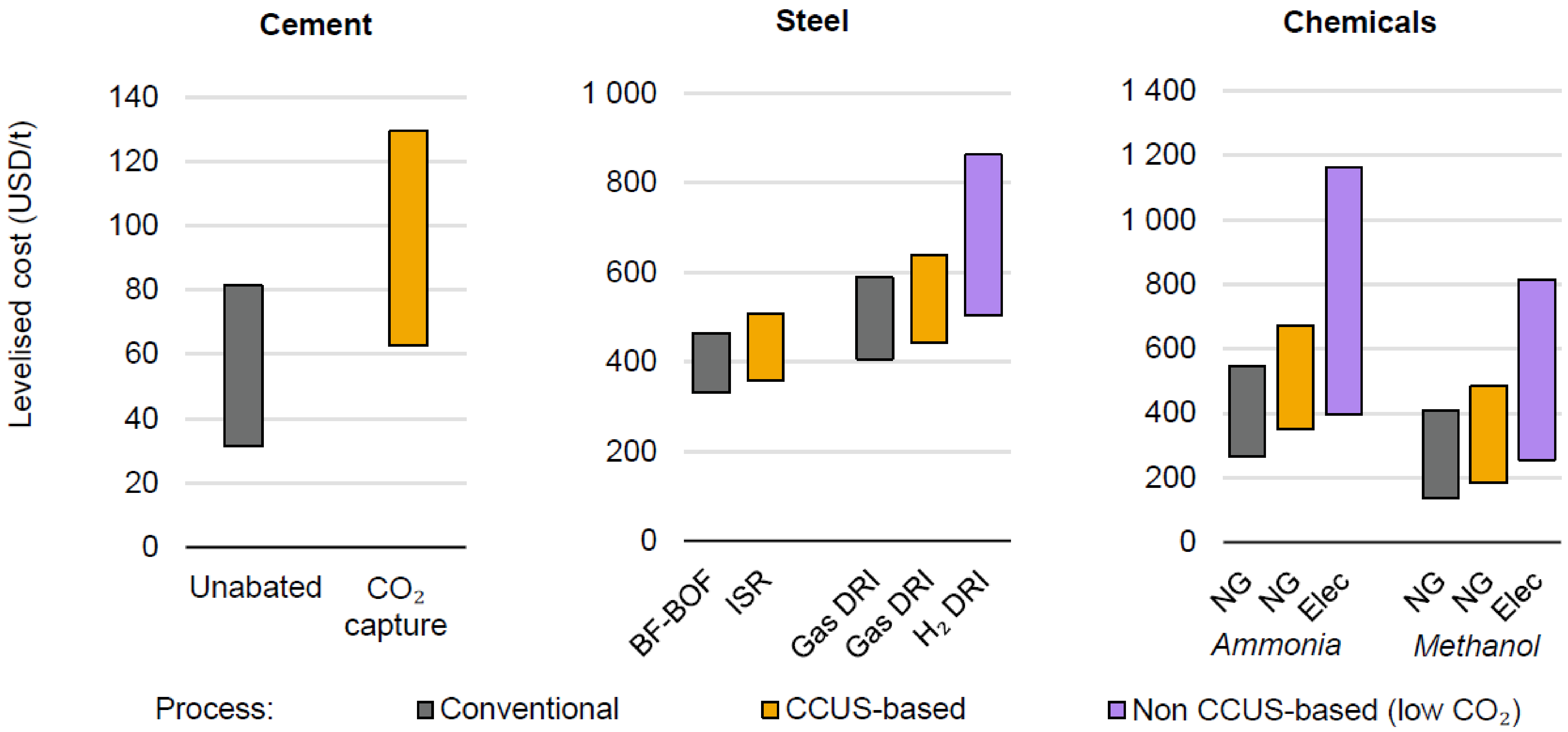
4 $/kg$H_2$ = 35.10 $/MMBTU

6 $/kg H_2 = 52.70 $/MMBTU

Figure Source: Federal Reserve Bank of Dallas (2023)


Land
Variable Renewables (Wind and Solar)
Natural Gas
Coal
Nuclear
Biomass
Land
Direct energy inputs, electricity, infrastructure
Hydrogen Production
Electrolysis
Steam Reforming
Gasification
Demand for steel, power, and other CCS components
Carbon Capture and Storage (CCS) Industry
Supply of hydrogen as fuel and feedstock, demand for industrial and transportation services
Fuel Production (ammonia, methanol)
Heating (residential and commercial)
Transport (air, shipping, road)
Industry (steel, chemicals, cement)

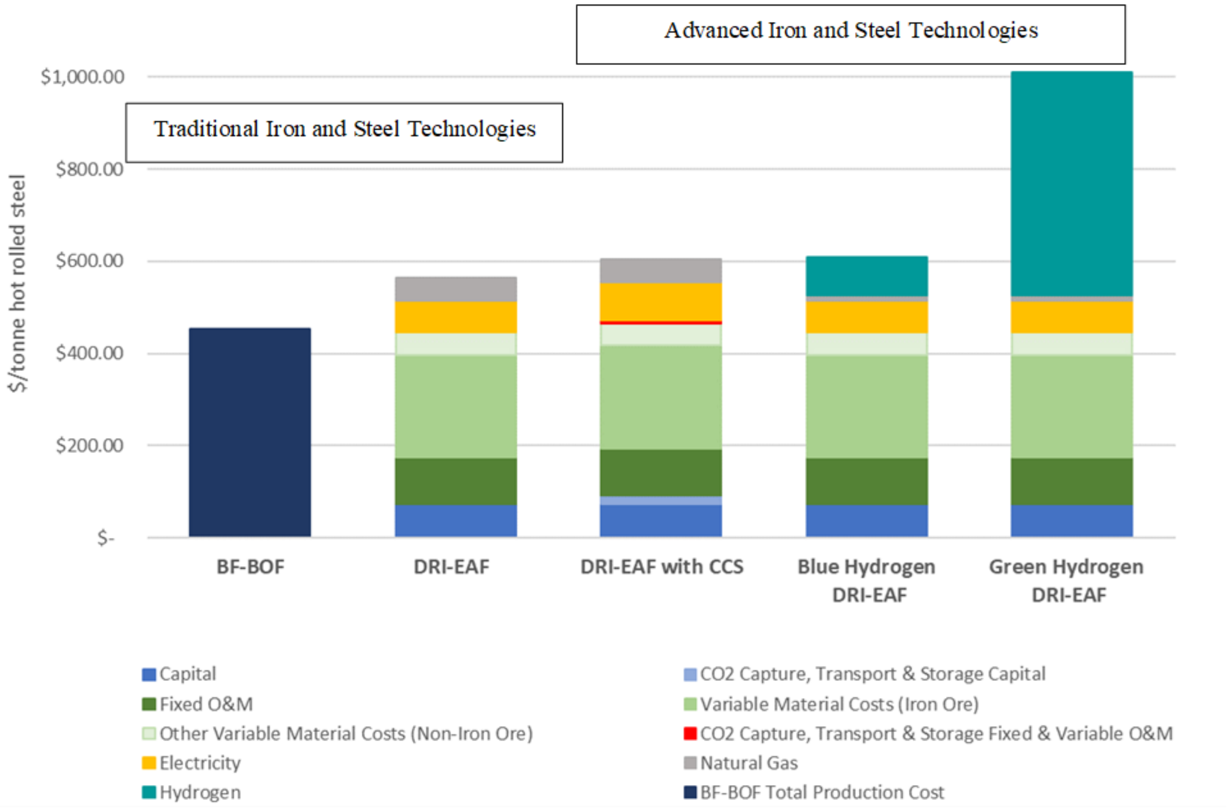
CCS vs Hydrogen Costs

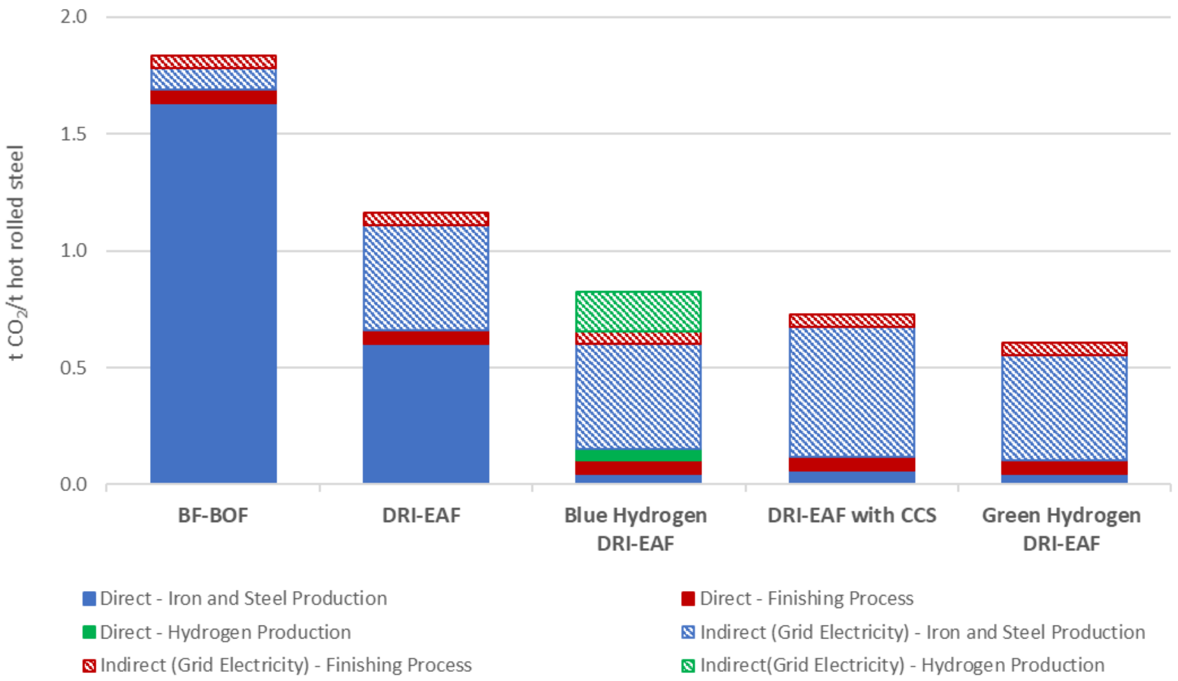


Source: IEA (2020)

ISR – innovative smelting reduction
NG – natural gas
Elec – electrolytic hydrogen

CCS and Hydrogen Cost in Steelmaking





Source: Benavides, K., A. Gurgel, J. Morris, B. Mignone, B. Chapman, H. Kheshgi, H. Herzog, S. Paltsev, 2024, “Mitigating emissions in the global steel industry: Representing CCS and hydrogen technologies in integrated assessment modeling,” *International Journal of Greenhouse Gas Control*, 131, 103963.

1 icon represents limited long-term opportunity 🔋
2 icons represents large long-term opportunity 🔋🔋
3 icons represents greatest long-term opportunity 🔋🔋🔋

	BATTERY/ELECTRIC	HYDROGEN	SUSTAINABLE LIQUID FUELS
Light Duty Vehicles (49%)*	🔋🔋🔋	—	TBD
Medium, Short-Haul Heavy Trucks & Buses (~14%)	🔋🔋	Ⓗ	⛽
Long-Haul Heavy Trucks (~7%)	🔋	ⒽⒽⒽ	⛽⛽
Off-road (10%)	🔋🔋	Ⓗ	⛽
Rail (2%)	🔋🔋	ⒽⒽ	⛽⛽
Maritime (3%)	🔋	ⒽⒽ†	⛽⛽⛽
Aviation (11%)	🔋	Ⓗ	⛽⛽⛽
Pipelines (4%)	🔋🔋	TBD	TBD
Additional Opportunities	• Stationary battery use • Grid support (managed EV charging)	• Heavy industries • Grid support • Feedstock for chemicals and fuels	• Decarbonize plastics/chemicals • Bio-products
RD&D Priorities	• National battery strategy • Charging infrastructure • Grid integration • Battery recycling	• Electrolyzer costs • Fuel cell durability and cost • Clean hydrogen infrastructure	• Multiple cost-effective drop-in sustainable fuels • Reduce ethanol carbon intensity • Bioenergy scale-up

* All emissions shares are for 2019

† Includes hydrogen for ammonia and methanol

Source: U.S. National Blueprint for Transportation Decarbonization (2023)

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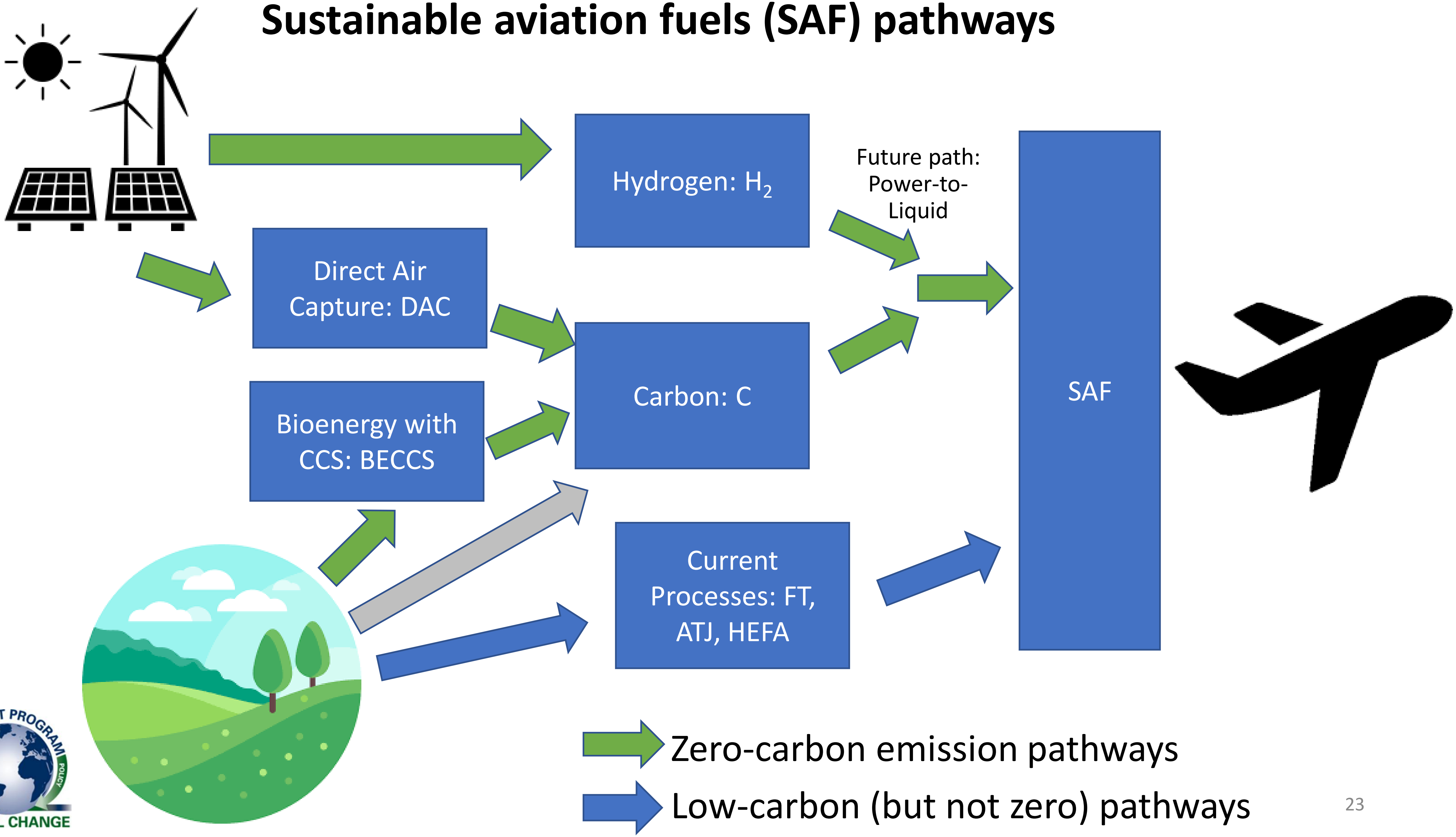
Sustainable aviation fuels (SAF) pathways



Zero-carbon emission pathways

Low-carbon (but not zero) pathways

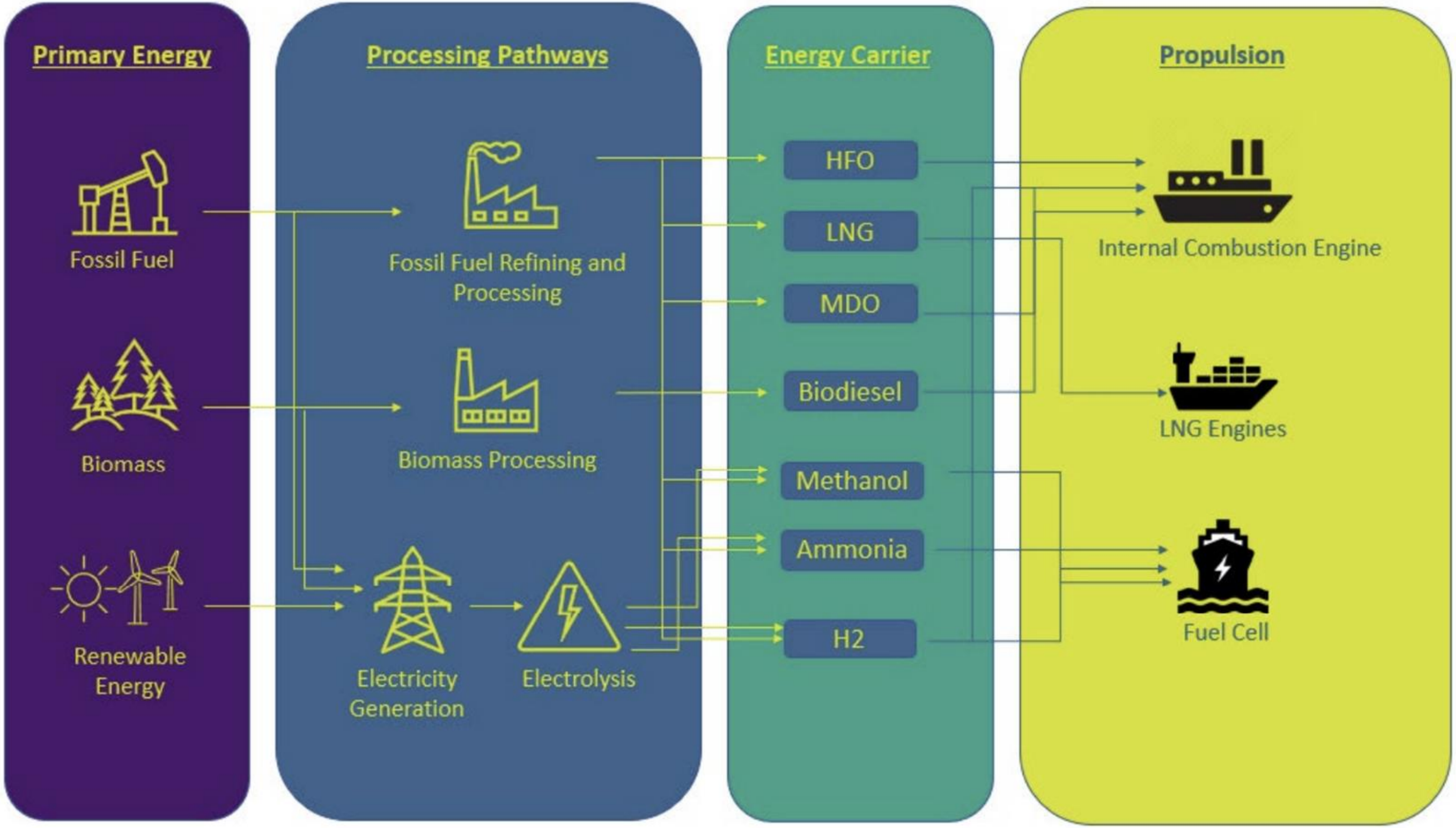


Figure 12 Current and potential pathways to marine fuels

S H I P P I N G

Source: Hong (2022) https://globalchange.mit.edu/publication/17867

Example: Increased Germany Hydrogen Demand (geopolitics + new climate target)

Earlier study (pre-Feb 2022):

2020 Germany use of natural gas:
90 bcm (2022: 80 bcm; industry is 1/3)

Replace all with H_2: 30 Mt H_2
Need to produce green H_2: 1600 TWh

2020 imports from Norway: 30 bcm
2050 imports from Norway: 15 bcm

10 bcm for H_2 production (from Norway) = 2 Mt H_2

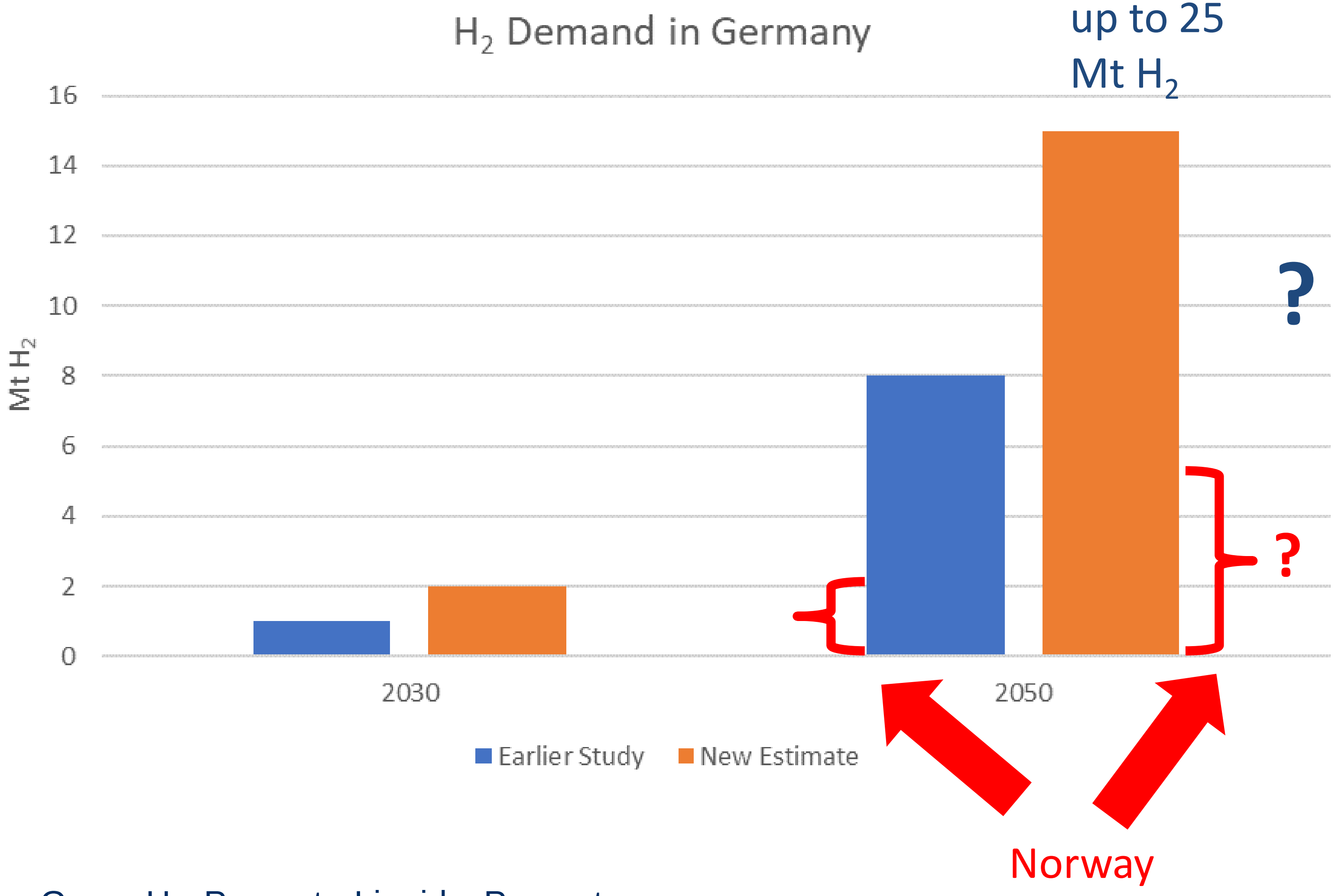
4 Mt Green H_2 = 200 TWh
2 Mt H_2 – other gas imports

Wind Potential: 300-400 TWh
Solar Potential: 200-300 TWh

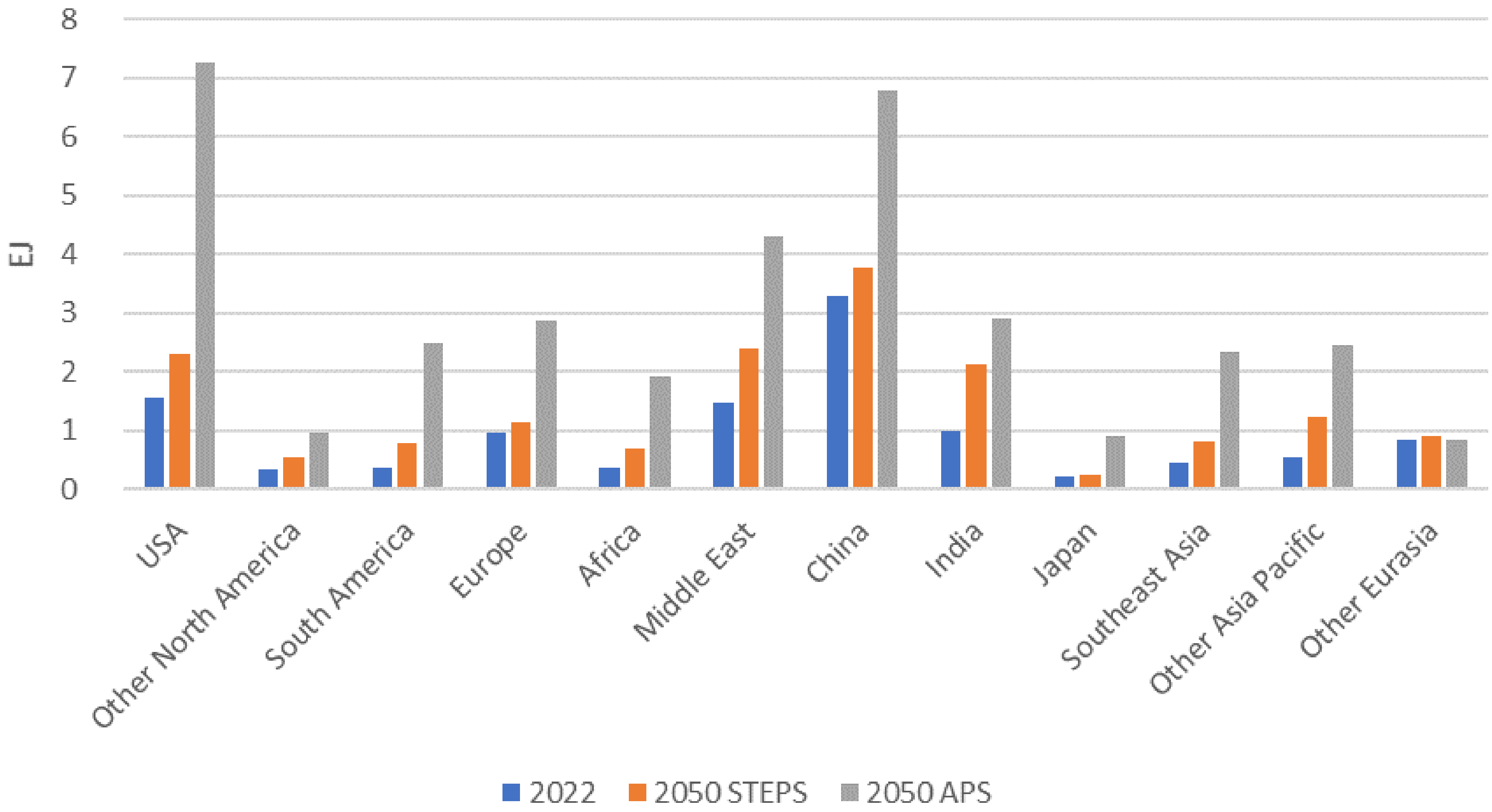
Conventional Use of Electricity: 550-600 TWh

Additional Use of Electricity: Electricity needs for Green H_2, Power-to-Liquids, Power-to-Gas could be doubled or tripled depending on technology and demand assumptions

German studies: up to 25 Mt H_2



Hydrogen Demand (for all uses)



Global H_2 Demand

2022 = 11.5 EJ

2050 STEPS = 17 EJ

2050 APS = 35 EJ

2050 NZE = 50 EJ

Data Source: IEA (2023)

2050 IEA Global Projections (STEPS-APS-NZE)

Total LCI Hydrogen Output in 2050:
3 EJ (STEPS), 23 EJ (APS), 39 EJ (NZE)

Hydrogen in Electricity Production:
0.4 EJ (STEPS), 3 EJ (APS), 6 EJ (NZE)

Total Final Energy Consumption (i.e., industry, transport, buildings):
536 EJ (STEPS), 429 EJ (APS), 343 EJ (NZE)

Hydrogen in Final Consumption (including as ammonia and synthetic fuels):
1.5 EJ (STEPS), 15 EJ (APS), 26 EJ (NZE)

If all 39 EJ in NZE are "Green H2", then 17,500 TWh are needed to prduce it

Global Electricity Generation in 2022 was 29,000 TWh

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Power sector

- Nuclear fusion
- Next-generation energy storage
- Carbon Capture and Storage (CCS)

Industry

- Hydrogen in steelmaking
- Iron ore electrolysis
- Carbon Capture and Storage (CCS)

Transport

- Hydrogen aviation/shipping
- Hyperloops
- Advanced biofuel supply
- Next-generation energy storage

Buildings

- Alternative building materials for steel and cement

Carbon removal

- Bio-char
- Ocean liming
- Direct Air Carbon Capture (DACC)
- Biomass Carbon Capture and Storage (BECCS)

Graphics: EPFL

Also important: Demand Side Management

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zero Emission

Thank you

Questions or comments?
Please contact Sergey Paltsev at paltsev@mit.edu