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Hydrogen Now to 2030: Opportunities & Limits in a Circular Carbon Economy

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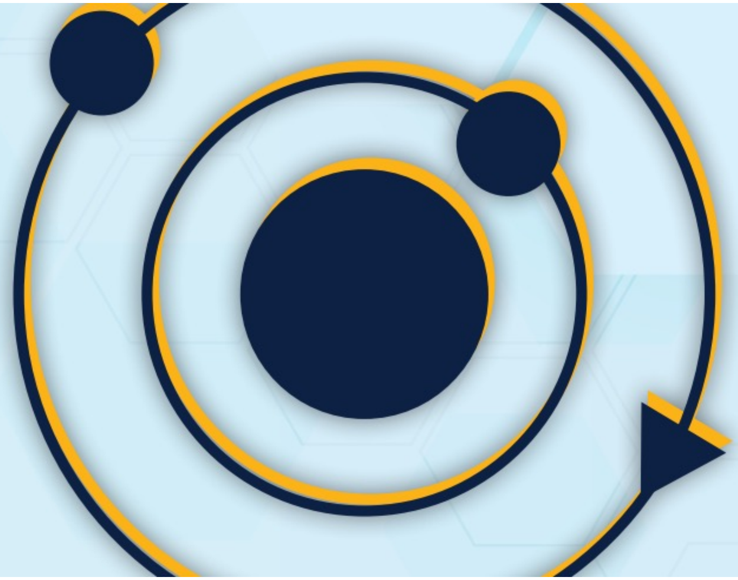
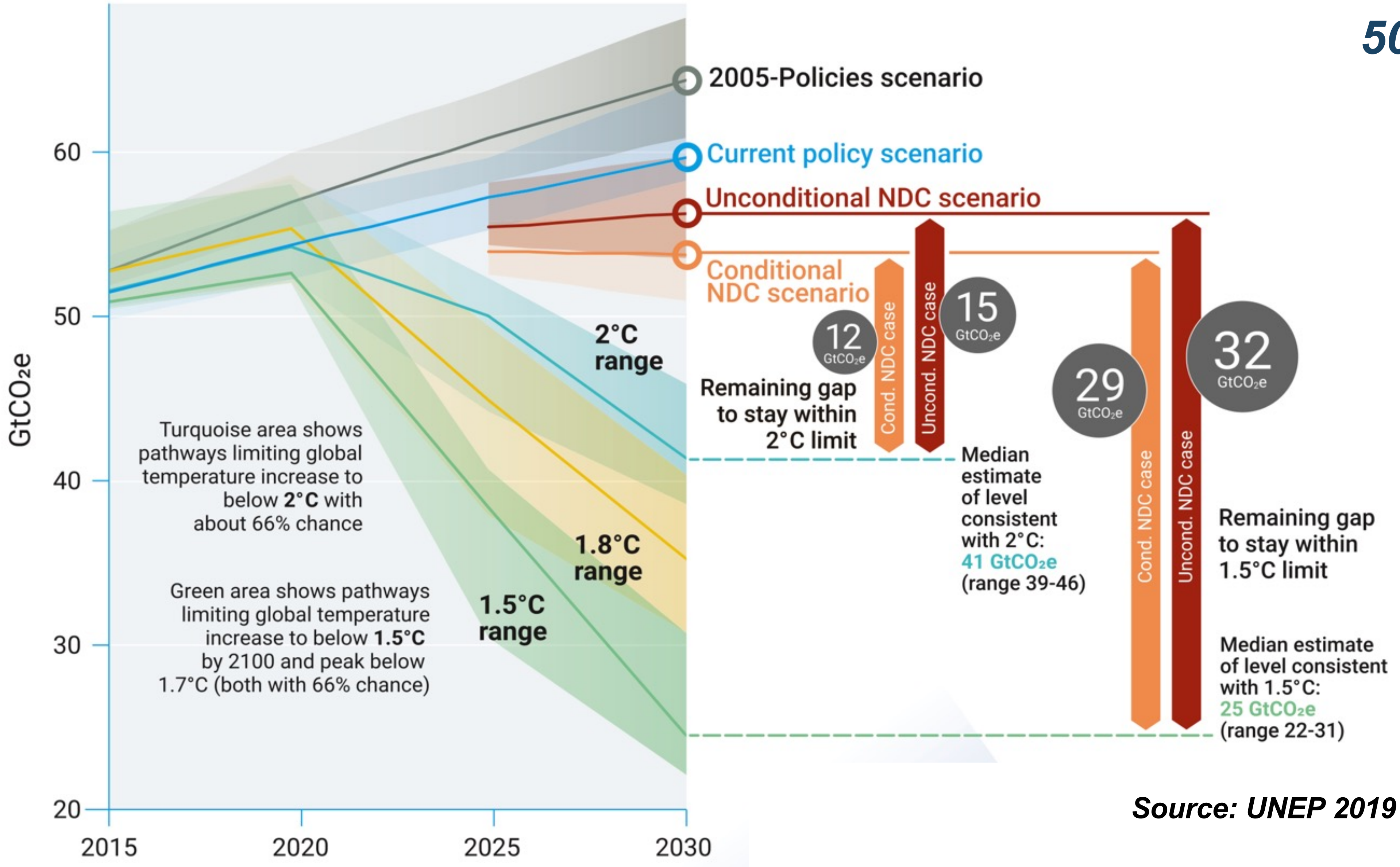


THE CIRCULAR CARBON ECONOMY: KEYSTONE TO GLOBAL SUSTAINABILITY SERIES assesses the opportunities and limits associated with transition toward more resilient, sustainable energy systems that address climate change, increase access to energy, and spark innovation for a thriving global economy.

https://circularcarboneconomy.co/resources/

These ten years: decisive on climate and energy transition



50% reduction in 10 years for 1.5°C

Source: UNEP 2019

Circular Carbon Economy: Faster & farther with hydrogen

Reduce

Reducing the production of CO_2 and other Greenhouse Gases as by-products (e.g. energy, efficiency, renewables etc.)

H_2

Reuse

Reusing CO_2 and other Greenhouse Gases **without chemically altering their composition** (e.g. EOR, CO_2 as working fluid)

Recycle

Recycling CO_2 and other Greenhouse Gases **by chemically altering their composition (e.g. urea, methanol, bioenergy).**

H_2

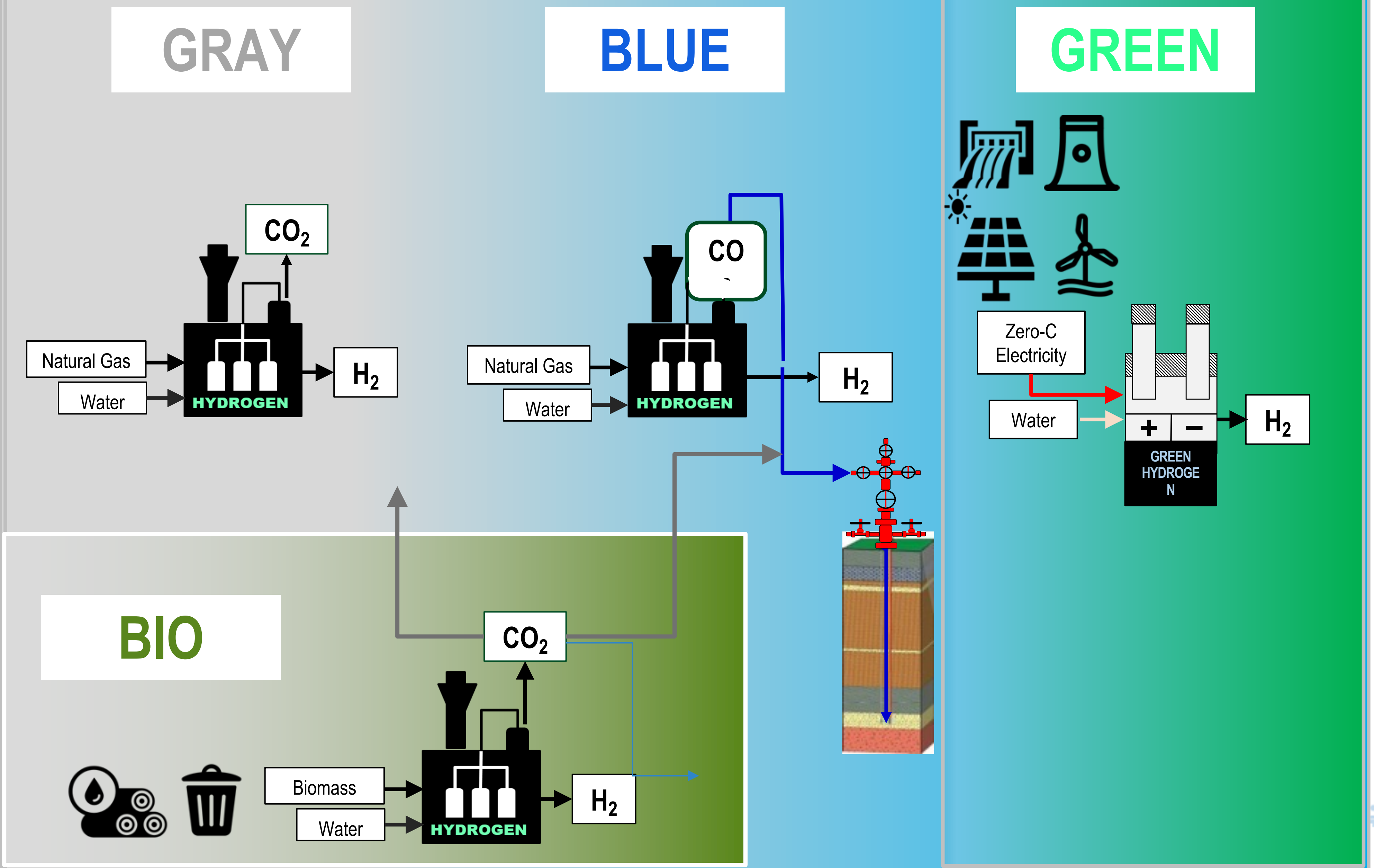
Remove

Recycling CO_2 and other Greenhouse Gases after they are already produced (e.g. carbon capture, nature based solutions).

H_2

Source: CCE Guide, 2020

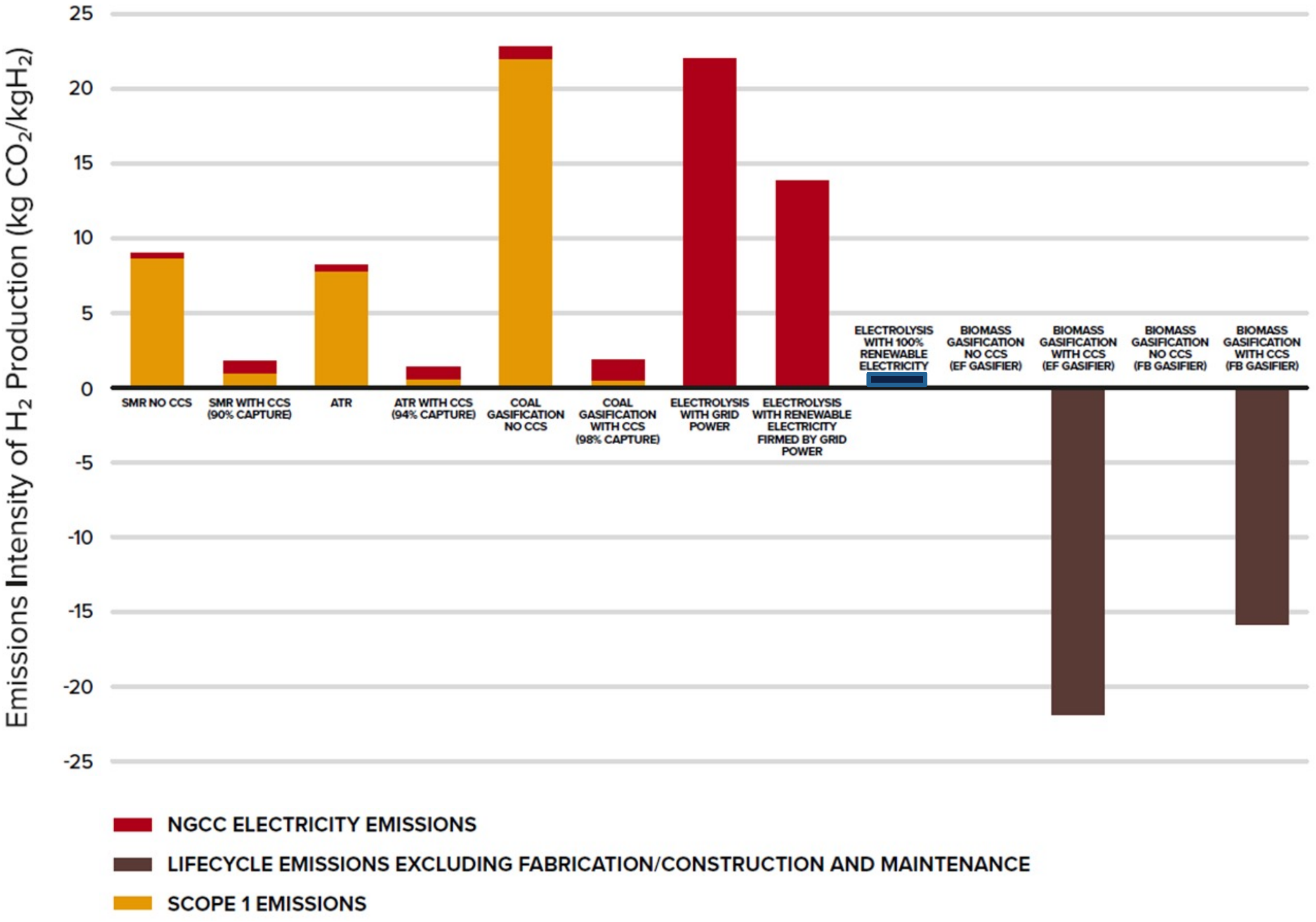
How hydrogen is made



Clean hydrogen is produced from

- *biomass or coal or gas + CCS; or*
- *electrolyzers powered by renewable or nuclear electricity*

Life cycle footprint depends on inputs (including upstream emissions) and CCS



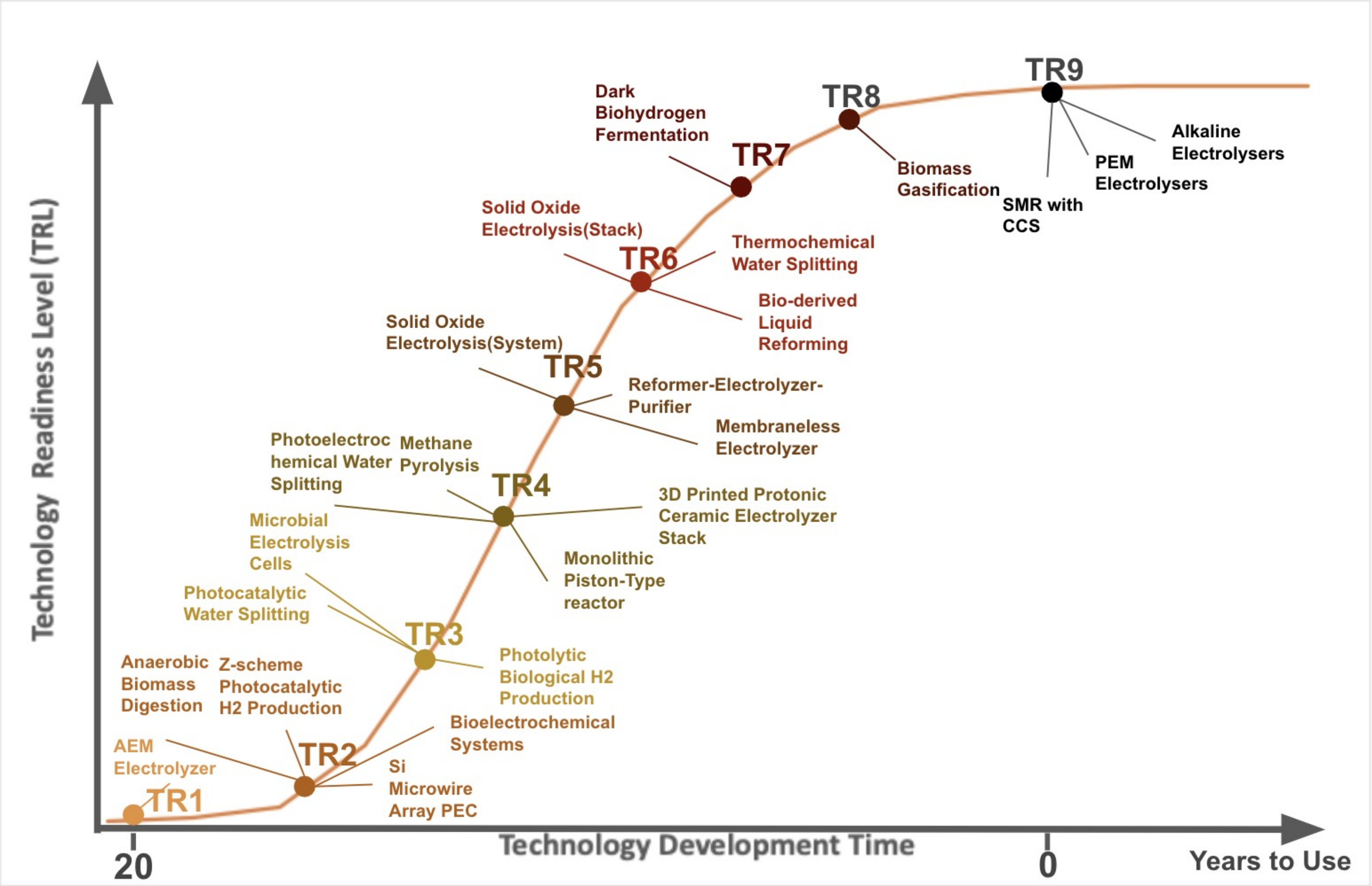
Source: Global CCS Institute, 2021

High level of technical readiness level

- **Blue:** TRL 9 (SMR)
- **Green:** TRL 9 (PEM & Alkalai); TRL 6 (solid oxide)
- **Bio:** TRL 8 (gasification)

Large set of potentially important tech & innovation opportunity

Blue, green, and bio-hydrogen can be produced today at commercial scale



Source: Fan et al., 2021

Zero-C fuels from H_2 are required for wide use

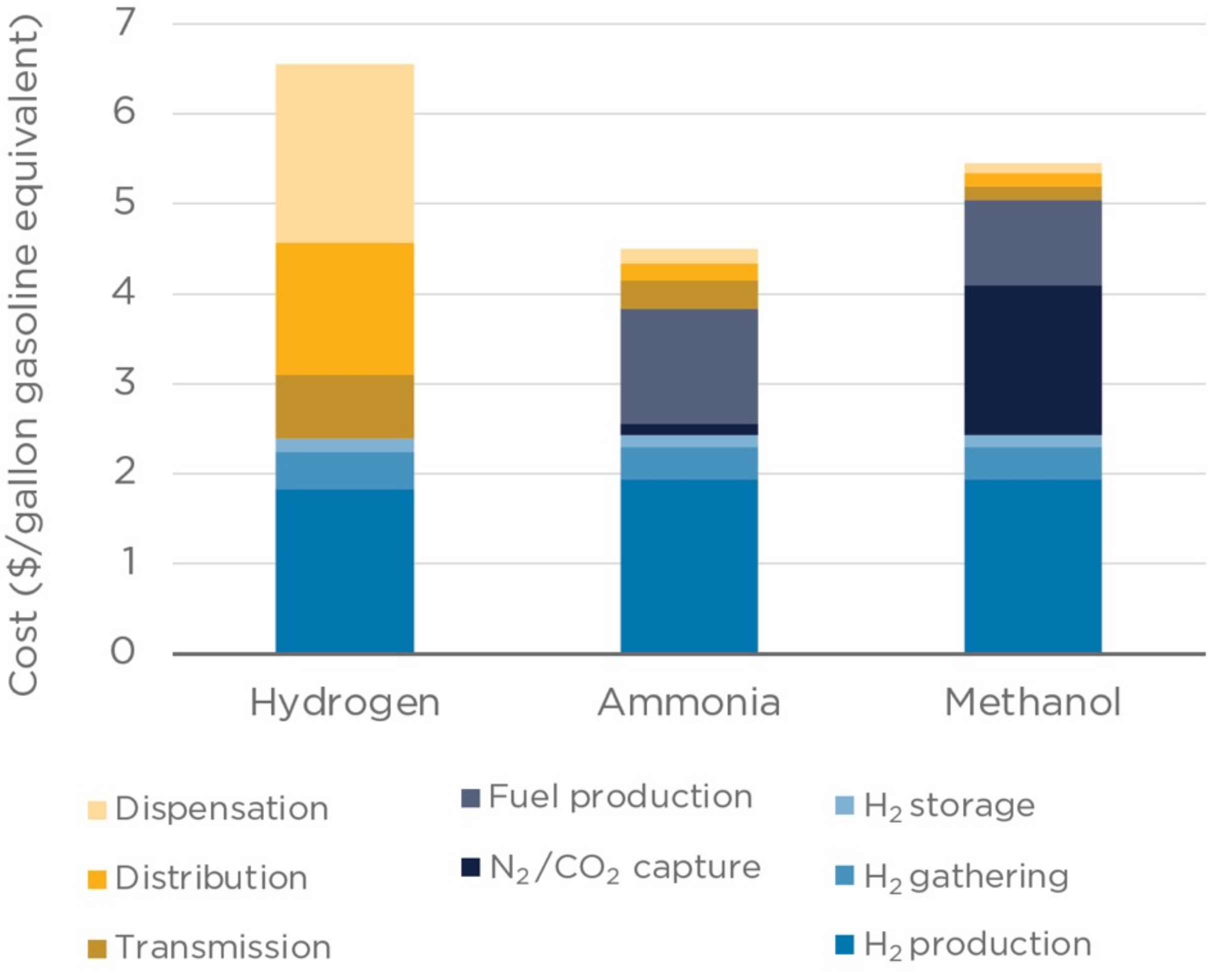
Liquid H_2, ammonia & zero-c methanol all available today

Ammonia looks good, esp. for ships

- Short-term: retrofit current fleet at 40% blend
- Long-term: carbon neutral solution
- Lowest cradle-to-gate cost
- Production & combustion on existing fleet has no technical barrier
- Largest barriers: cost and port infrastructure

Fuel cell upgrades provide much

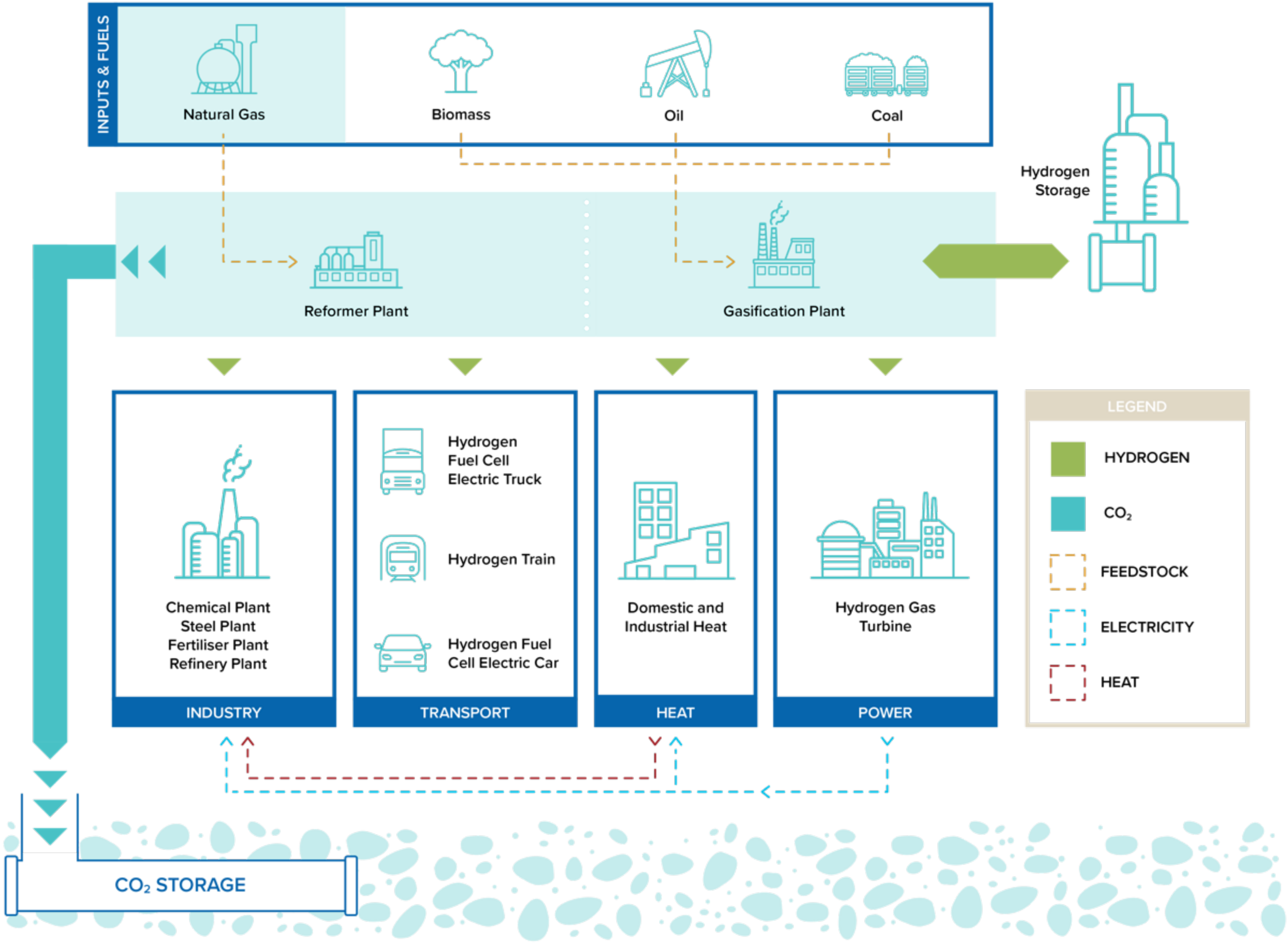
- ***higher efficiency (30% ➡ 60%)***
- ***health and environmental benefits (no SOx, NOx, PM)***



Source: Fan et al., 2021, after Zhou et al. 2018

Blue Hydrogen

Clean hydrogen (high % capture + low upstream emissions) can deliver multi-gigatonne abatement every year



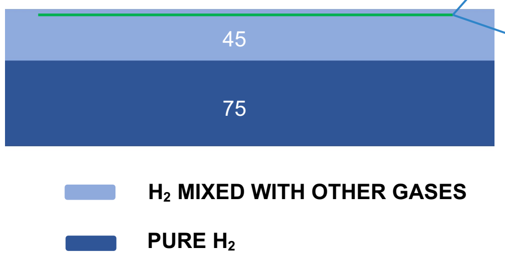
Source: Global CCS Institute, 2021

H_2 Production 2020

Total production:120Mtpa

Fossil origin H_2: 97.8%
- Without CCS: 97.5%
- With CCS: 0.4%

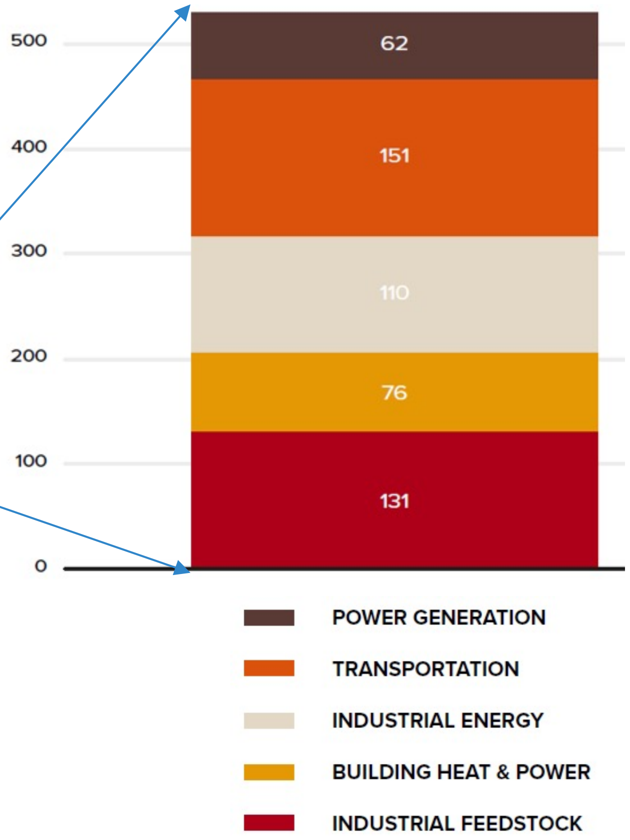
Electrolyzer H_2: 2.2%
- Chlor-Alkali: 1.9%
- Renewable: 0.3%

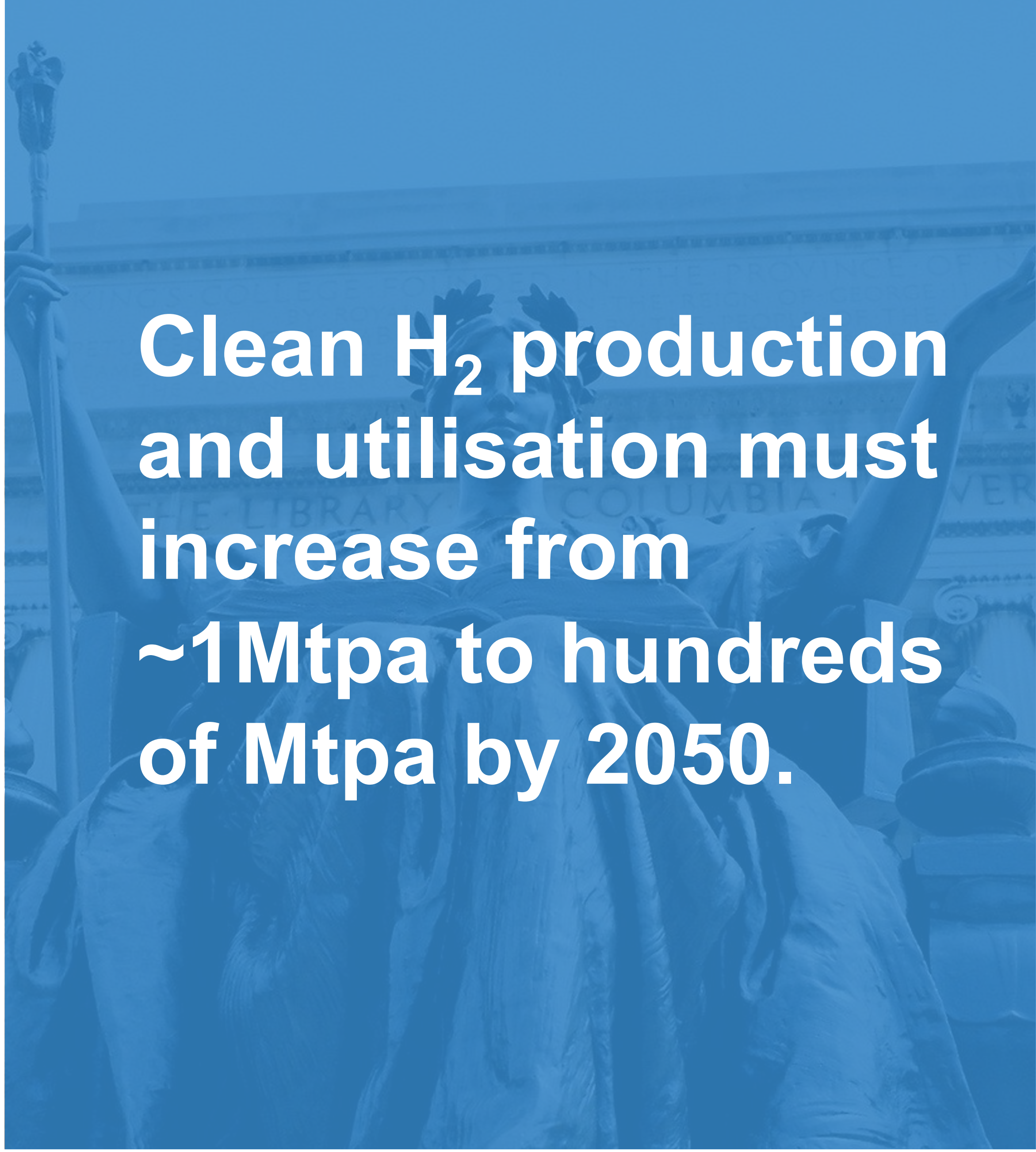


H_2 Production 2050

Total production:530Mtpa

Clean H_2: 100%





Clean H_2 production and utilisation must increase from ~1Mtpa to hundreds of Mtpa by 2050.

Blue H_2 production is mature & available at scale now

Facility	H_2 Production (tonnes/day)	H_2 Production Process	Operational Commencement
Blue hydrogen			
Enid Fertiliser	200 (in syngas)	Methane reformation	1982
Great Plains Synfuel	1,300 (in syngas)	Coal gasification	2000
Air Products	500	Methane reformation	2013
Coffeyville	200	Petroleum coke gasification	2013
Quest	900	Methane reformation	2015
Alberta Carbon Trunk Line - Sturgeon	240	Asphaltene residue gasification	2020
Alberta Carbon Trunk Line - Agrium	800	Methane reformation	2020
Sinopec Qilu	100 (estimated)	Coal/Coke gasification	2021 (planned)
Green hydrogen			
Trondheim	0.3	Electrolysis; Solar	2017
Fukushima (largest operating)	2.4	Electrolysis; Solar	2020
NEOM	650	Electrolysis; Wind + Solar	2025 (planned)
AREH	4800	Electrolysis; Wind + Solar	Possible after 2028

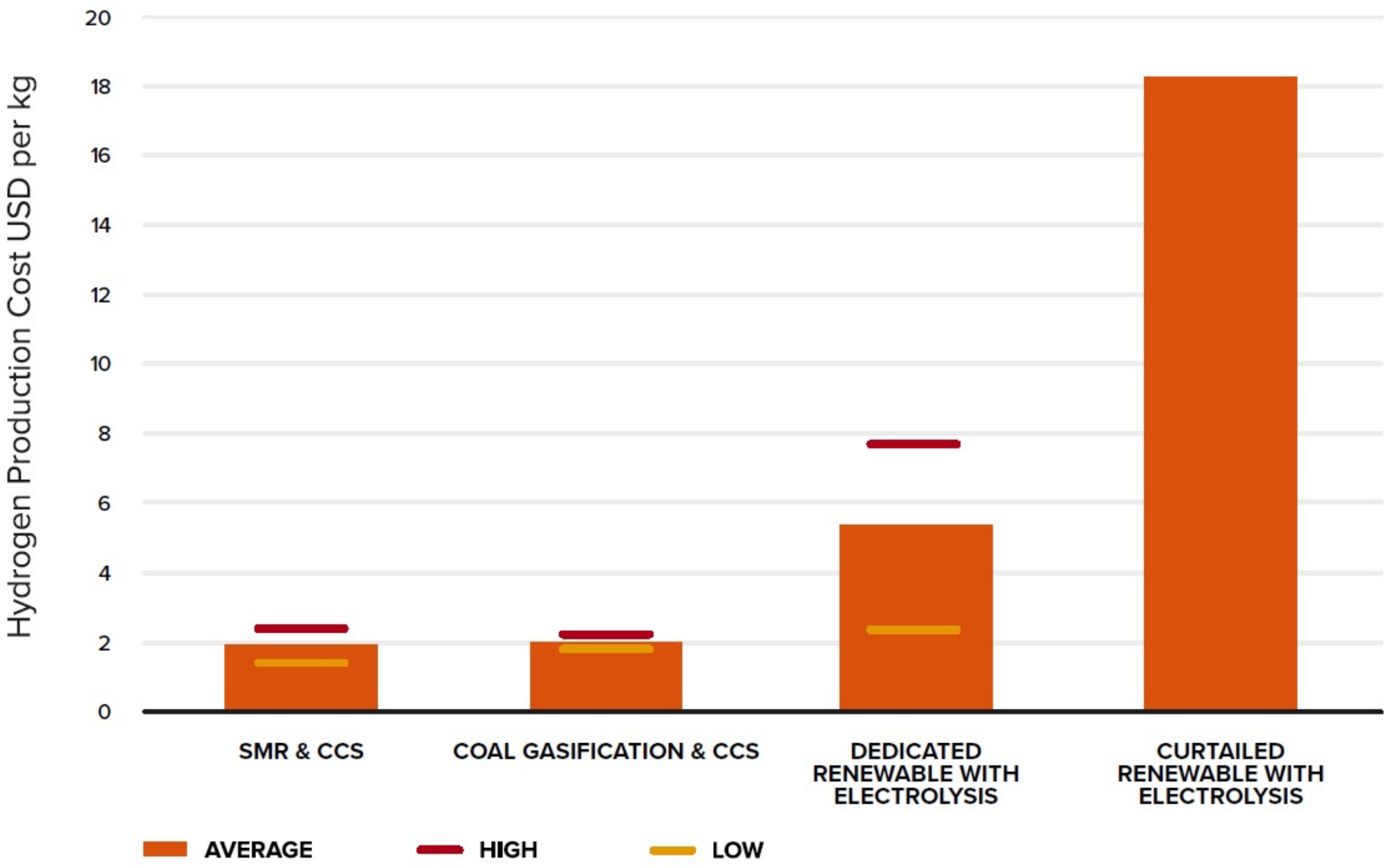
Source: Global CCS Institute 2021: Friedmann et al., 2020: Renew Economy 2020

Blue H_2 production is cost-competitive

Production costs from four recent publications:

- CSIRO 2018
- IRENA 2019
- IEA 2020
- Hydrogen Council 2020

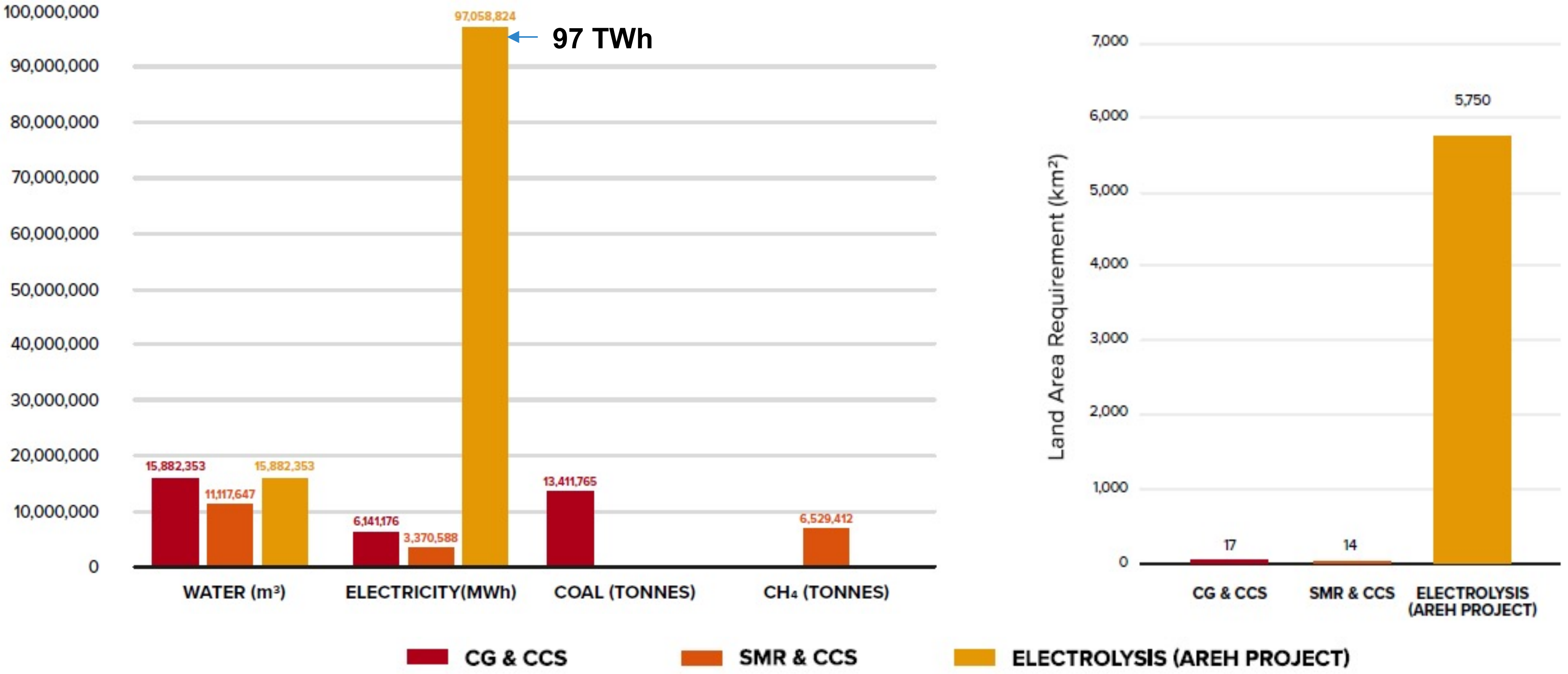
Caution: The basis for each cost estimate (e.g. assumed capacity factors, fuel & electricity costs) differs between studies. Actual costs will always be site-specific.



Source: Global CCS Institute, 2021

Blue H_2 production is not resource constrained

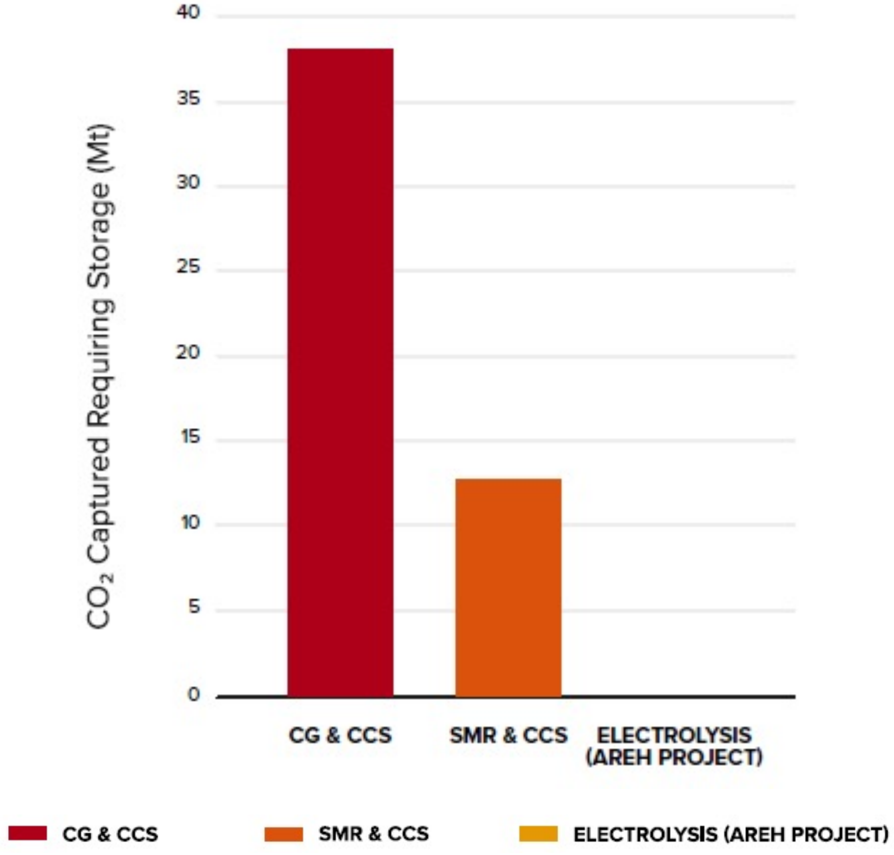
Resources required to produce 1.76Mt of clean H_2, equivalent to the annual production of the proposed Australian Renewable Energy Hub Project

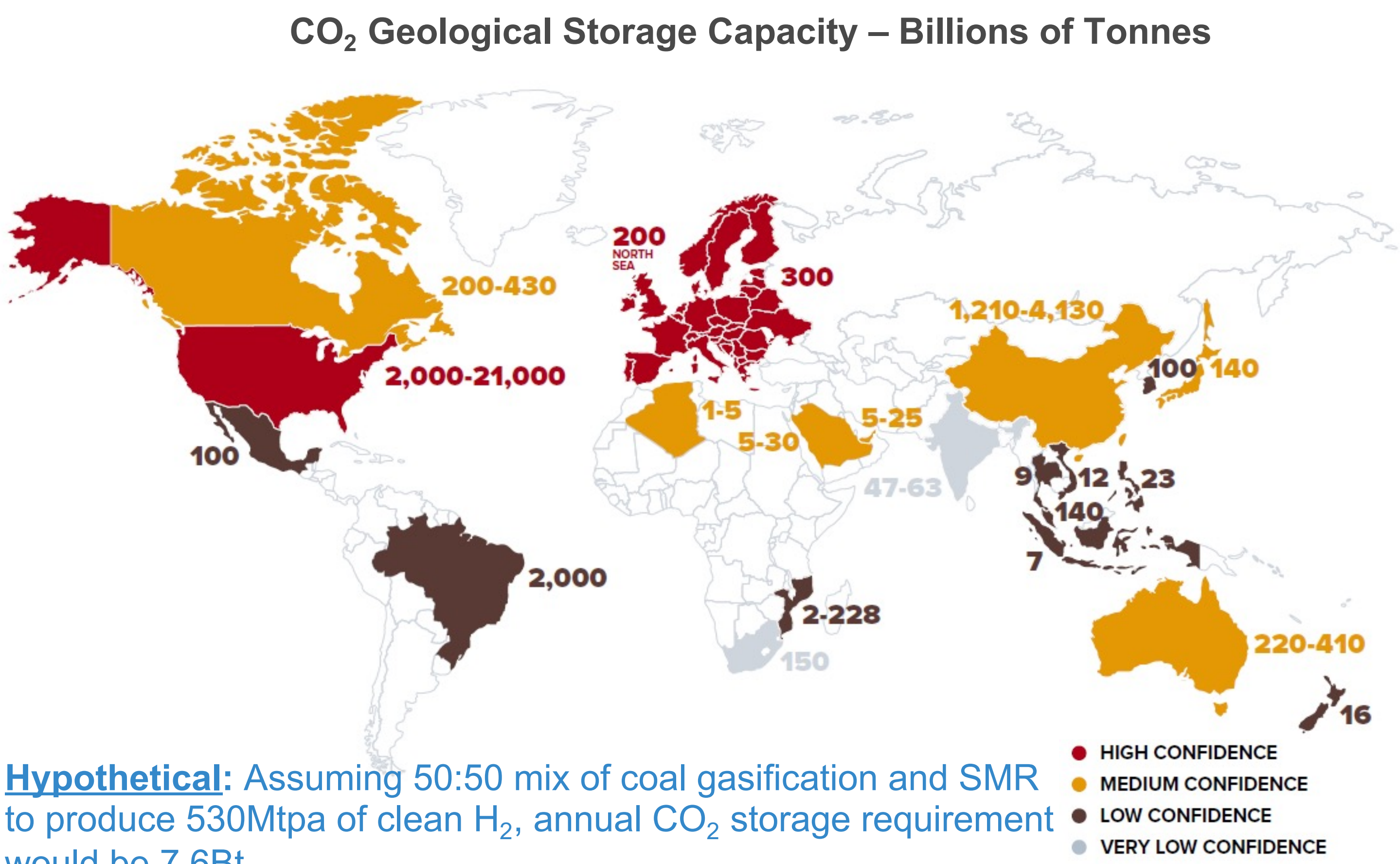


Source: Global CCS Institute, 2021

CO_2 geological storage capacity is more than adequate

CO_2 geological storage capacity required to produce 1.76Mt of clean H_2 (1 AREH Project)



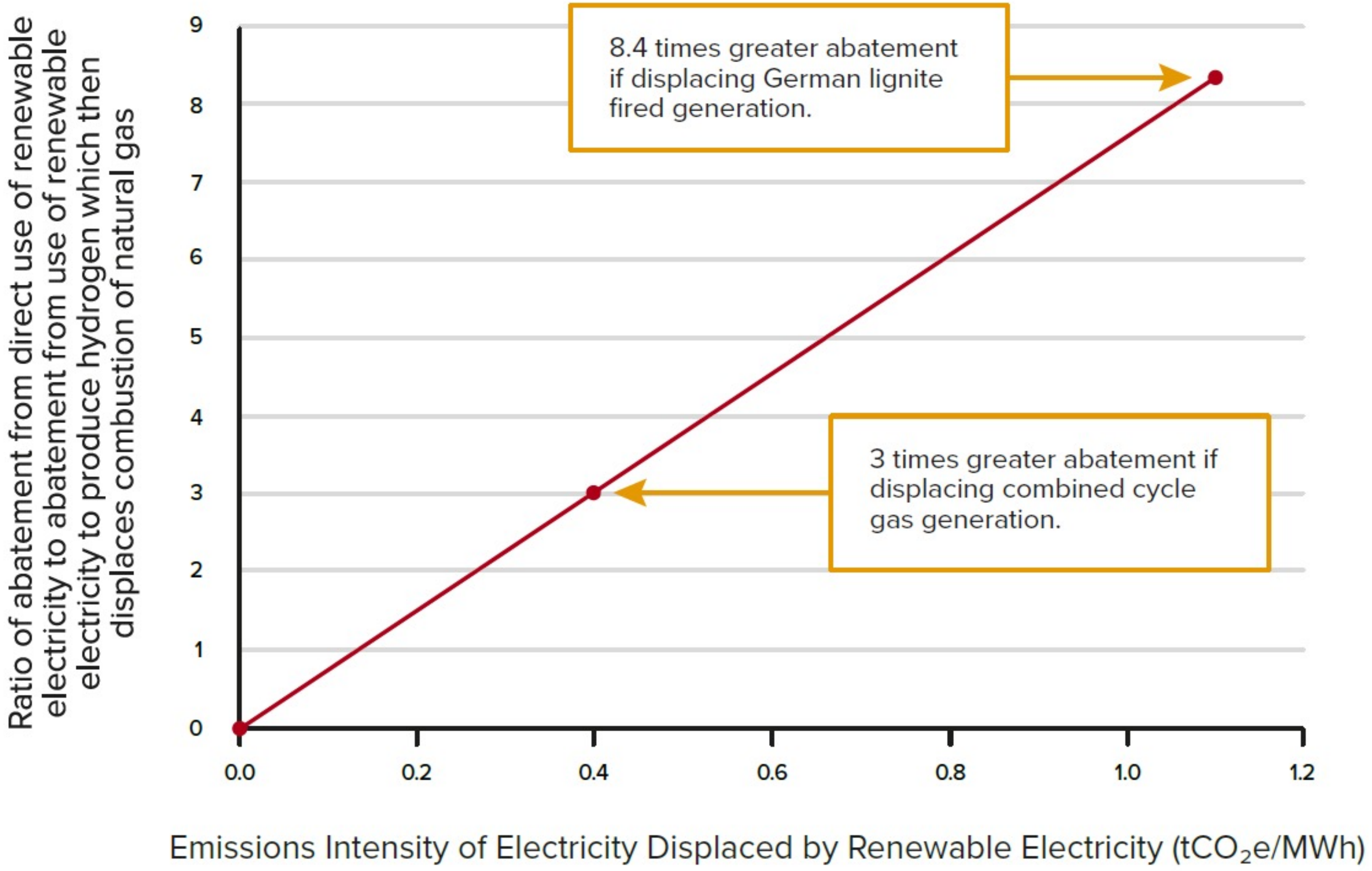


Hypothetical: Assuming 50:50 mix of coal gasification and SMR to produce 530Mtpa of clean H_2, annual CO_2 storage requirement would be 7.6Bt.

Source: Global CCS Institute, 2021

Renewable electricity **delivers more abatement displacing fossil electricity generation** than if used to produce H_2 which then displaces combustion of natural gas.

Renewable energy should be used to displace fossil electricity generation in preference to H_2 production

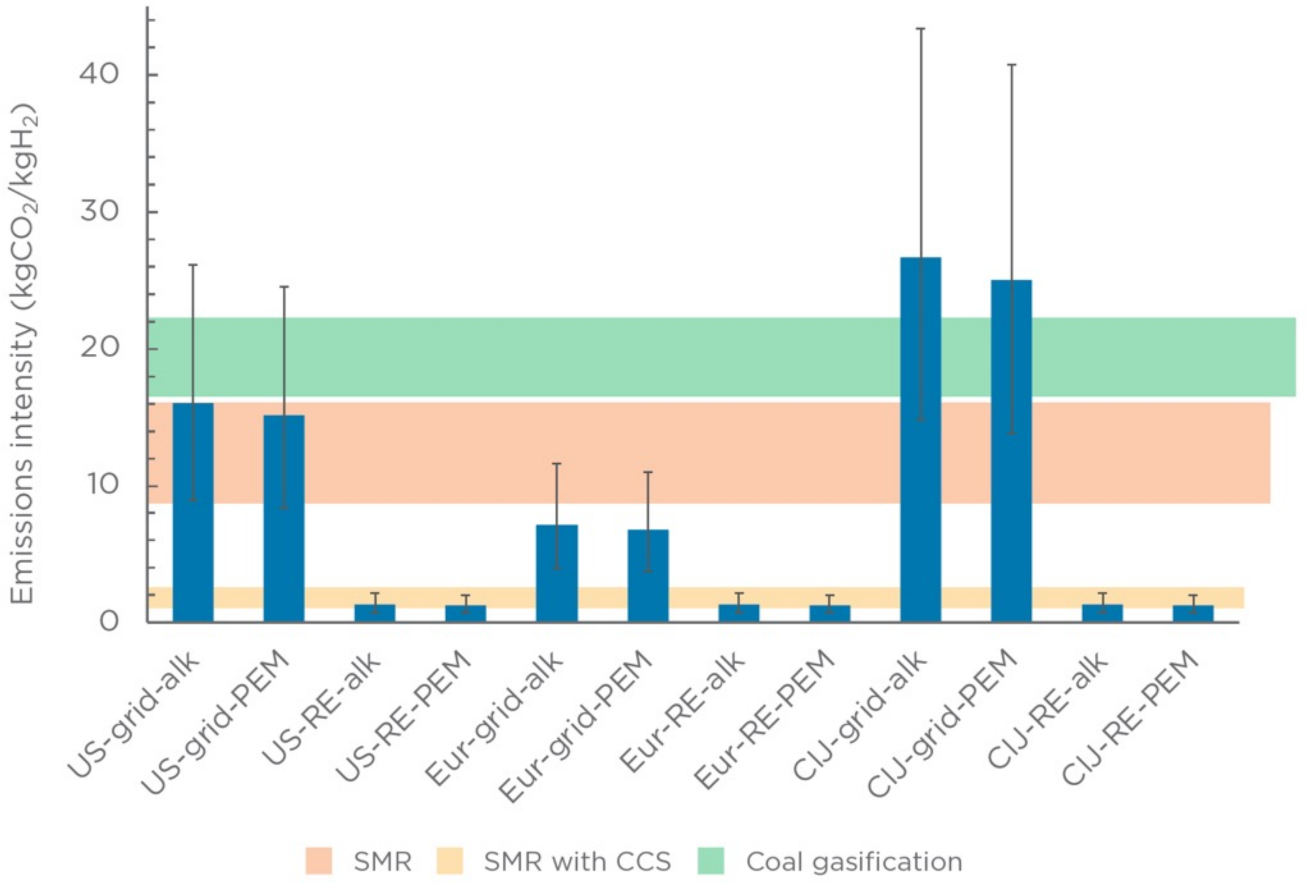


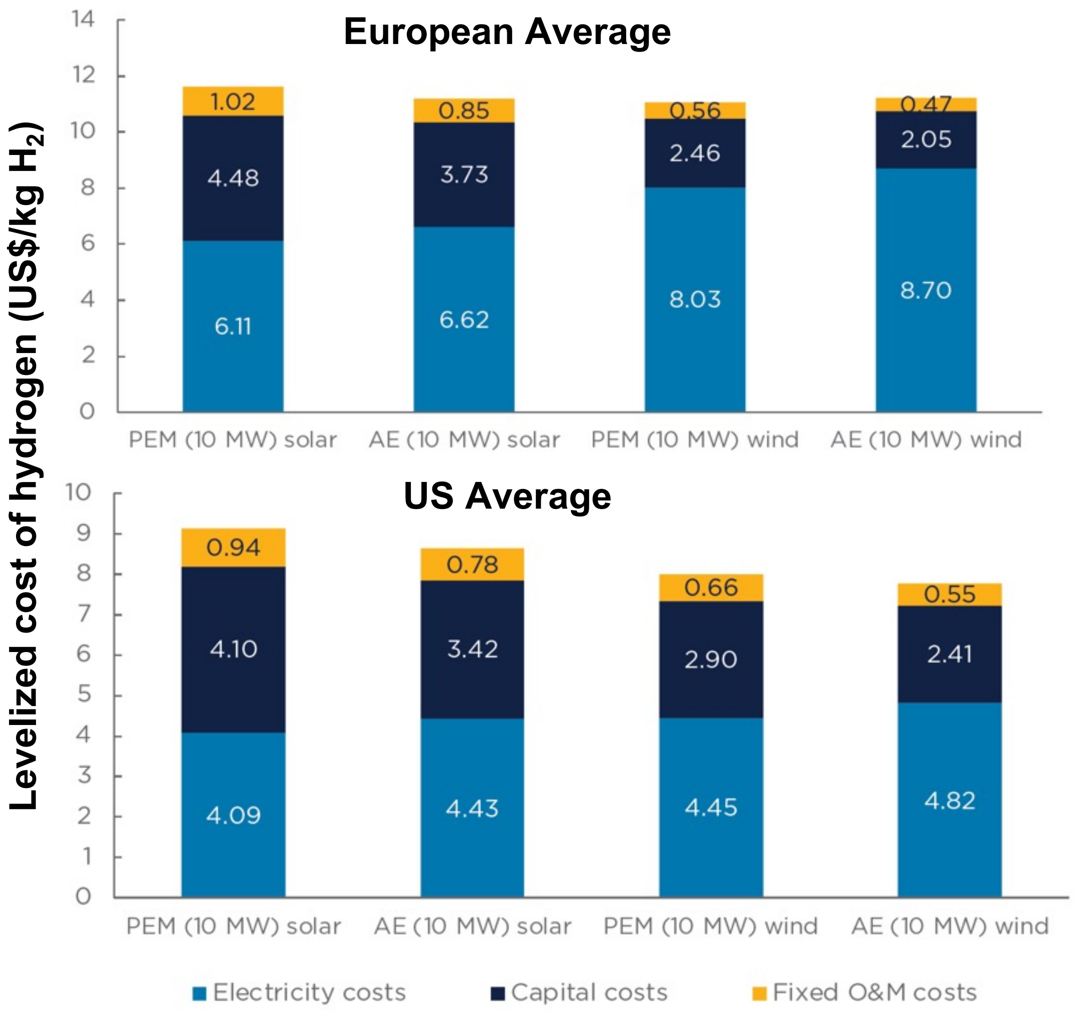
Source: Global CCS Institute, 2021

Green Hydrogen

Costs & footprint vary by technology, market and inputs

Alkali electrolyzers are lower efficiency, lower cost & more available today





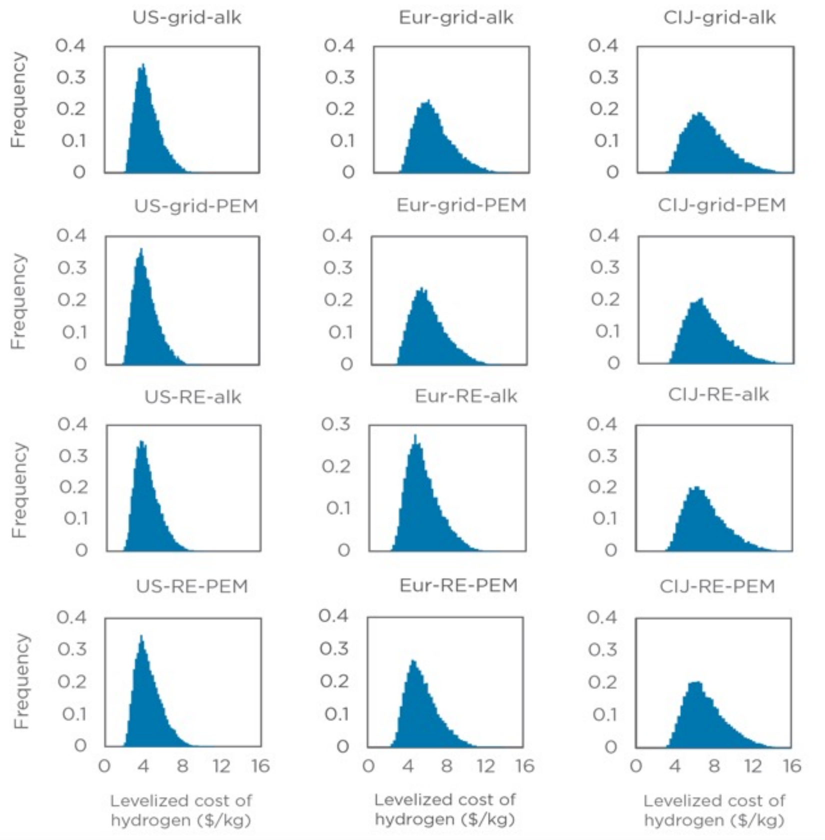
10 MW systems, 90% capacity factors, 78% PEM & 72% alk. efficiencies
market average prices today, 5% WACC

Source: Fan et al., 2021

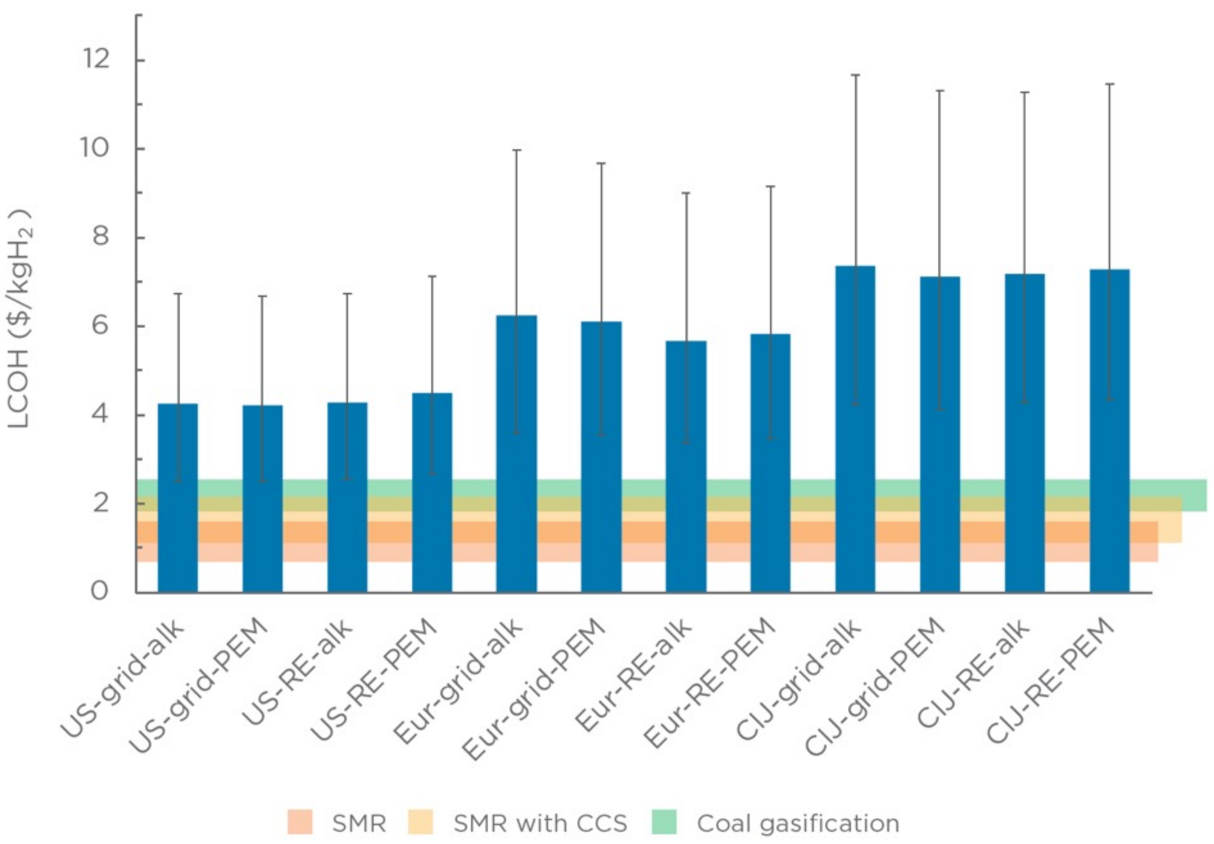
Costs falling quickly for renewable power & electrolyzers

Function of learning rate, deployment, local conditions & technology

Cost distribution by case



2030 estimated costs (US, EU, CIJ)



Monte Carlo analysis: 12,000 simulations per case
market average prices today, 5% WACC

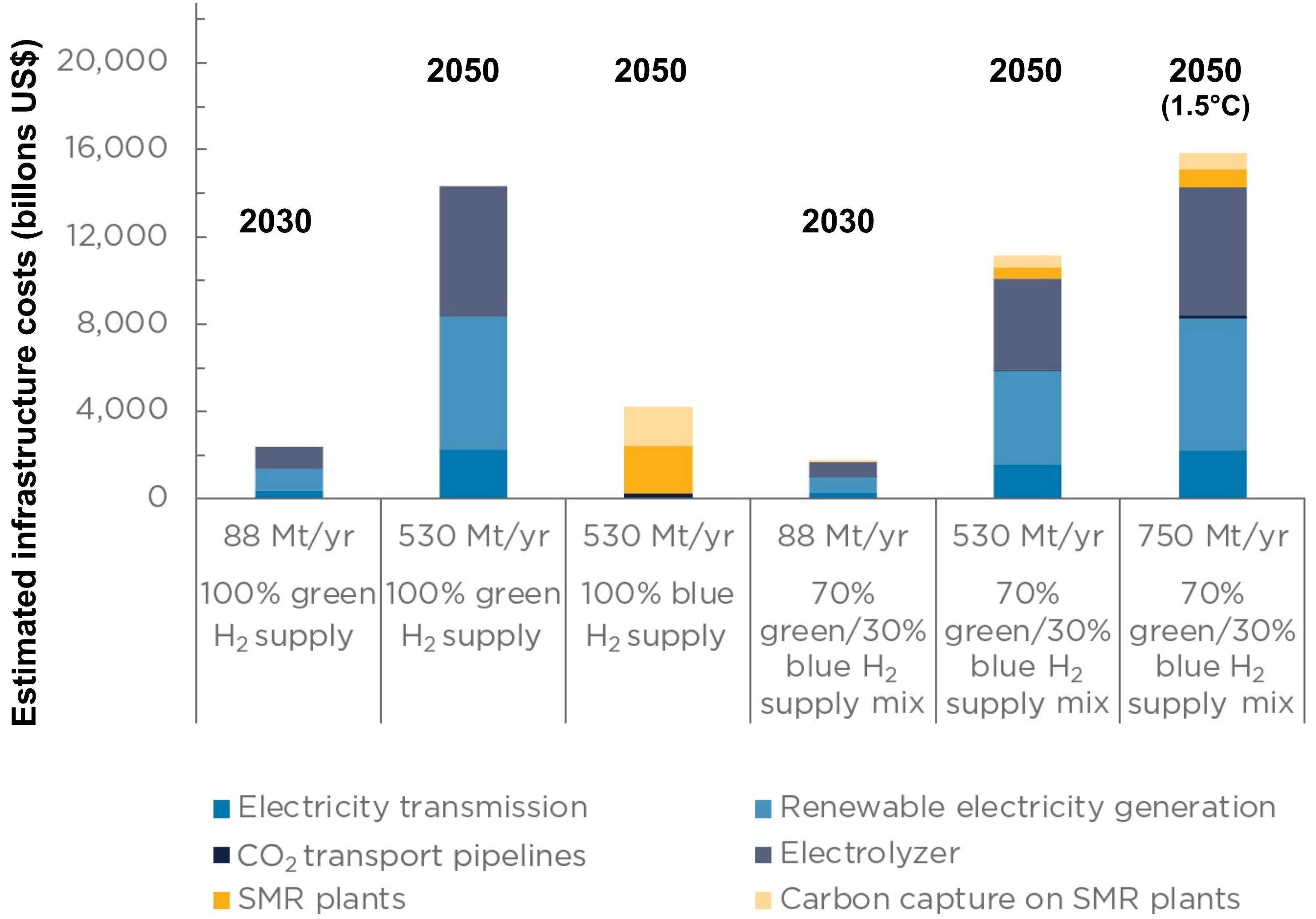
Source: Fan et al., 2021

Infrastructure limits will delay deployment & add to system costs

- Transmission lines
- Power build-out
- Electrolyzer costs

Mix of blue & green H_2 delivers lower cost + greater volumes

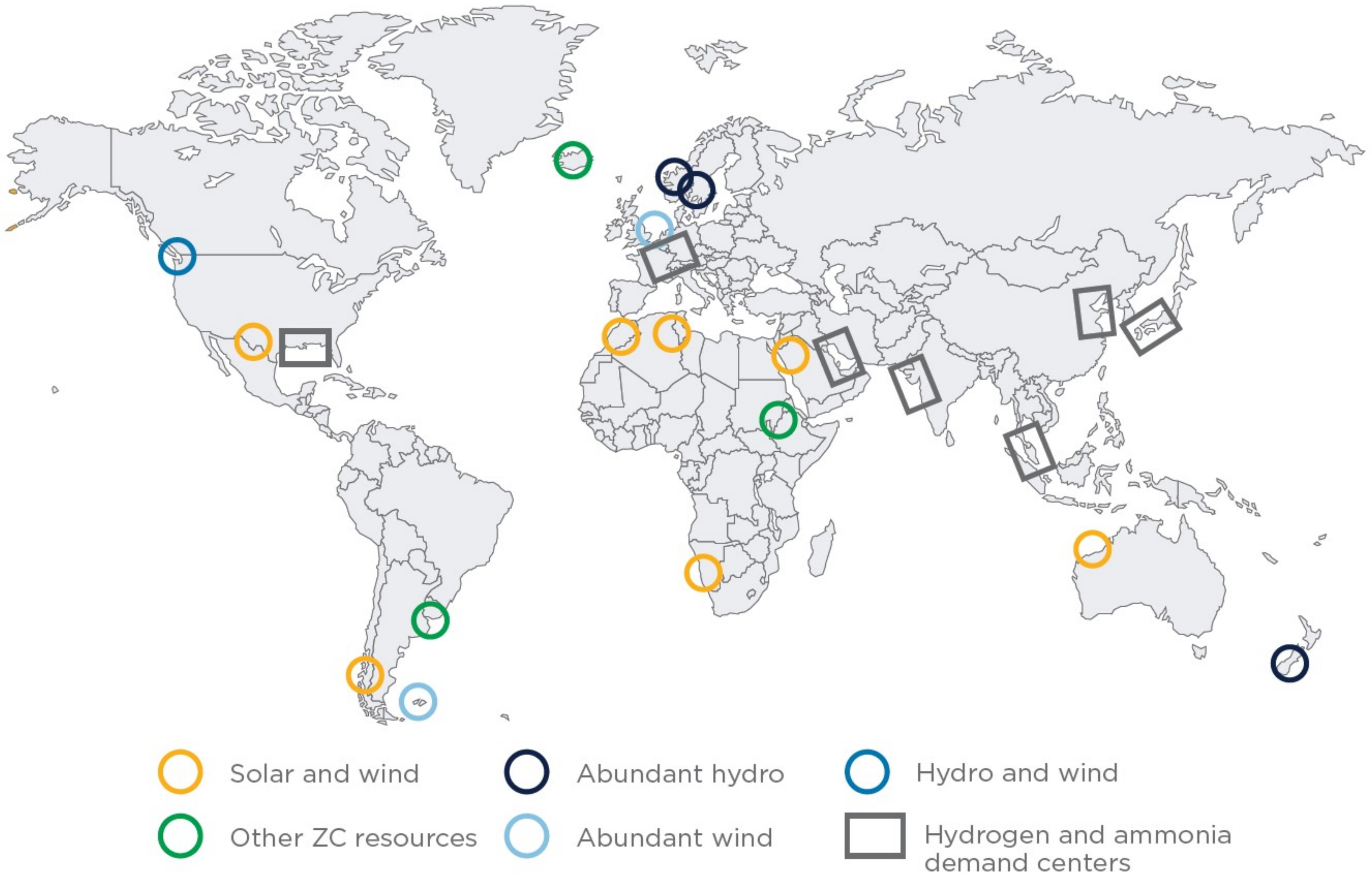
Global hydrogen demand (2030 & 2050; IEA scenarios)



Source: Fan et al., 2021

Geography of fuel production shifts green H_2

More production globally, but farther from demand centers today



Source: Fan et al., 2021

Policies and Recommendations

The policy landscape is changing very quickly

US

- Administration: net-zero goals (power by 2035; nation, by 2050); 10 industrial demos (incl. hydrogen & CCS)
- Congress: Innovation investment & authorization; 45Q & renewable tax extenders
- In progress: PTC/CfD for hydrogen; further 45Q expansion; transmission, port, pipelines

EU & UK

- Zero-C hydrogen infrastructure (blue & green) including power-to-X, CO_2 pipelines, ports, transmission
- UK - CfD; Germany - EEG relief; EU – electrolyzer incentives
- Norway, Sweden, Switzerland: $200/t carbon tax

Japan (Korea & SE Asia)

- Net-zero energy policy (2050) and zero-C fuel support (e.g., ammonia in coal a d gas power)
- Industrial policy for zero-C hydrogen (ships, manufacturing)
- Many bilateral agreements and strong innovation agenda (piloting, demos, early stage – full chain)

Others

- Australia: Hub investments; Tech investment roadmap (prioritizes low-C H_2 (blue and CCS)
- Canada: Hydrogen Roadmap; $170/t carbon tax; trunk infrastructure
- Chile: Hydrogen bigger than copper by 2030 (10% of GDP)
- Gulf states: Aggressive demo and infrastructure schedule, blue & green

Recommendations: Now to 2030 for Circular C Economy

Start with "color blind" planning and analysis

- Assess existing infrastructure in detail; estimate upgrade costs
- Engage local communities now
- Many bilateral agreements

Build infrastructure (”aqua” culture)

- Green (transmission & electrolyzers) and Blue (CO_2 pipelines & dedicated storage)
- Focus on ports (application production, shipping, transportation)

Provide incentives (carbon focus)

- Production side: tax credits, grants, revenue enhancements (CfD; feed-in tariffs)
- Use side: Engine swaps & subsidies; manufacturing support;

Multinational & bilateral politics

- International LCA standards; IMO; C accounting frameworks
- Move from bi-lateral to sectoral (2030) to commodity (2040)

Thank You

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