CLEAN AIR TASK FORCE

Zero-Carbon Fuels for Decarbonization

Background Information

April 2021

Clean Air Task Force Zero-Carbon Fuels Program

Content and Quick Links

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About CATF

Founded in 1996, Clean Air Task Force (CATF) is a non-profit research and advocacy organization that pushes for the change in technologies and policies needed to get to a *zero-emissions, high-energy planet at an affordable cost*, so that we can meet the world's rising energy demand in a way that is financially, socially and environmentally sustainable.

Our headquarters are in Boston and we have offices around the United States and in Europe.

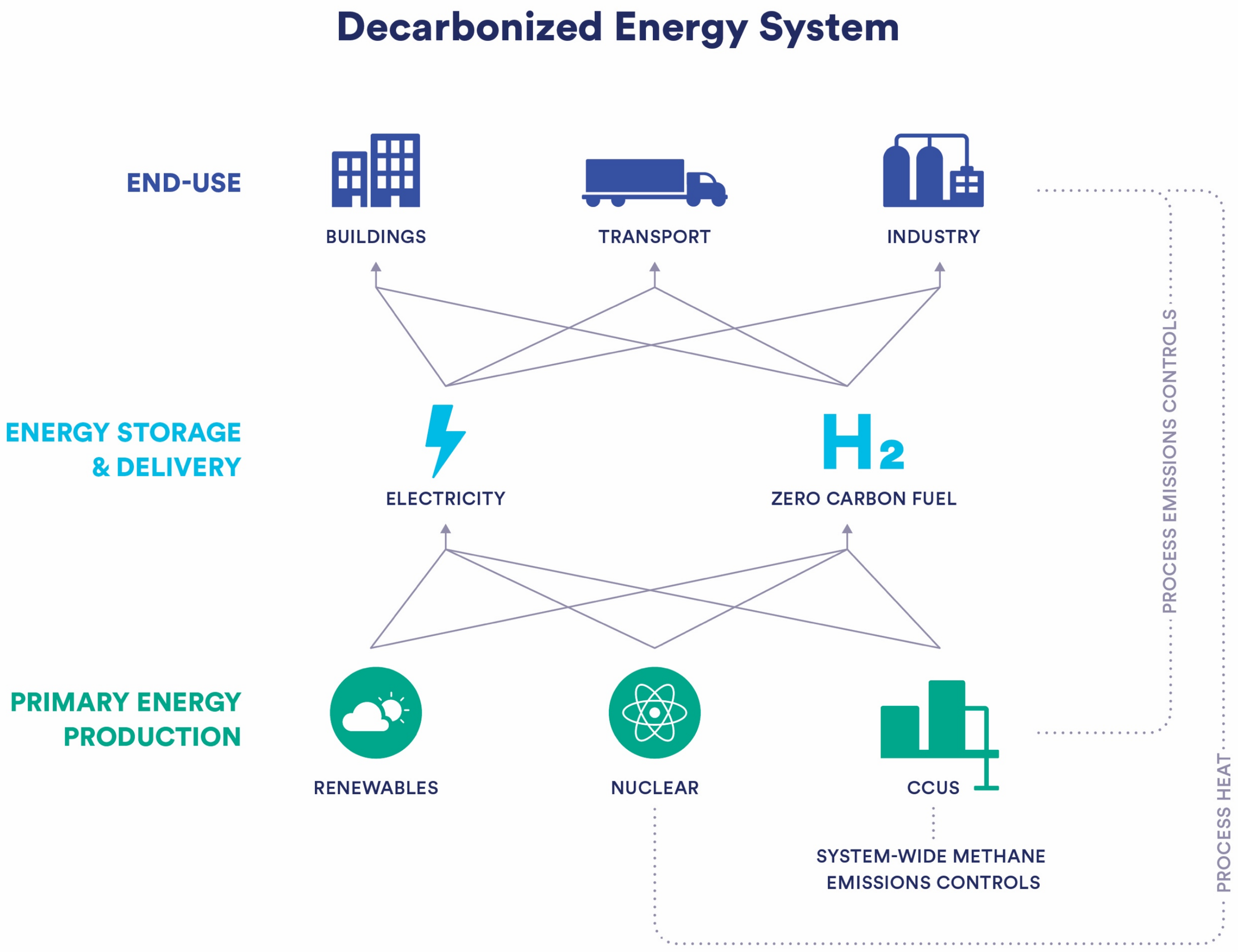
More about CATF is available on the web at www.catf.us

CATF has received the highest possible 4-star rating from Charity Navigator, a 2020 Gold Seal of Transparency from Guidestar, and has been endorsed as a highly effective organization by Founders Pledge.

Where Can Zero -Carbon Fuels Play A Role?

To achieve the scale needed for decarbonization, all low-emitting energy (renewables, nuclear, fossil CCS) likely will be needed and should be developed as options.

Although ultimate role of zero-carbon fuels (ZCF) is subject to uncertainty and debate, there appear to be some sectors where ZCF could be key to achieving net-zero GHG targets.



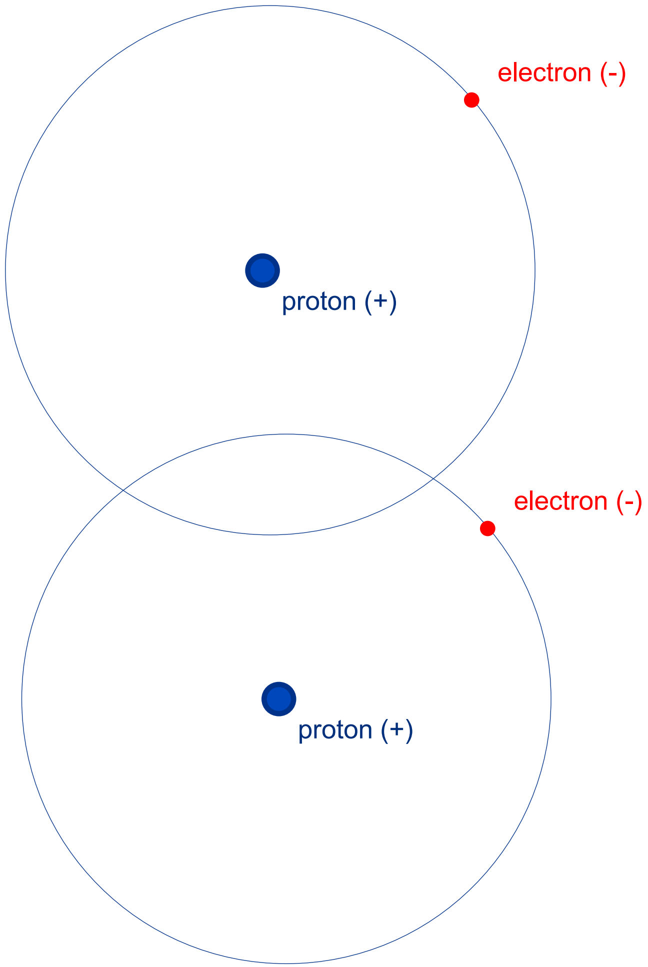
► *CATF's efforts focus on developing ZCF options for those sectors where electrification appears to be most challenging.*

What is Hydrogen?

Hydrogen is...

- The simplest, most abundant element in the universe, just one proton and one electron orbiting around it – with chemical symbol "H"
- Reactive, and on Earth almost always found bonded to some other element like oxygen, carbon or nitrogen (e.g., as in water, methane, or ammonia)
- When isolated, hydrogen is usually a diatomic molecule – called "H_2"
  - An odorless, colorless gas (except at *extremely* low temperatures; boils at -253°C)
- Other common diatomic molecules on Earth are oxygen ("O_2") and nitrogen ("N_2") which make up more than 99% of dry air
- Hydrogen could be useful because it releases a tremendous amount of energy when it reacts with oxygen from air, and does not create CO_2:
  - $2 \cdot H_2 + O_2 \Longleftrightarrow 2 \cdot H_2O$ + 120 million Joules of energy per kg of H_2
  - The energy released is called the heating value. One kg of hydrogen has about the same heating value as one gallon of gasoline.
- Compare this to methane, which makes up 90% or more of natural gas:
  - $CH_4 + 2 \cdot O_2 \Longleftrightarrow 2 \cdot H_2O + CO_2$ + 50 million Joules of energy per kg of CH_4
  - Methane carries less than half the heating value of hydrogen, and creates CO_2 when burned.

Diatomic Hydrogen (H_2)



► *H_2 could be very useful as a carbon-free fuel. Unfortunately, natural sources of H_2 are quite limited on Earth. We need to manufacture it from some other energy sources first. For this reason some analysts call hydrogen an "energy carrier".*

Hydrogen Production Basics

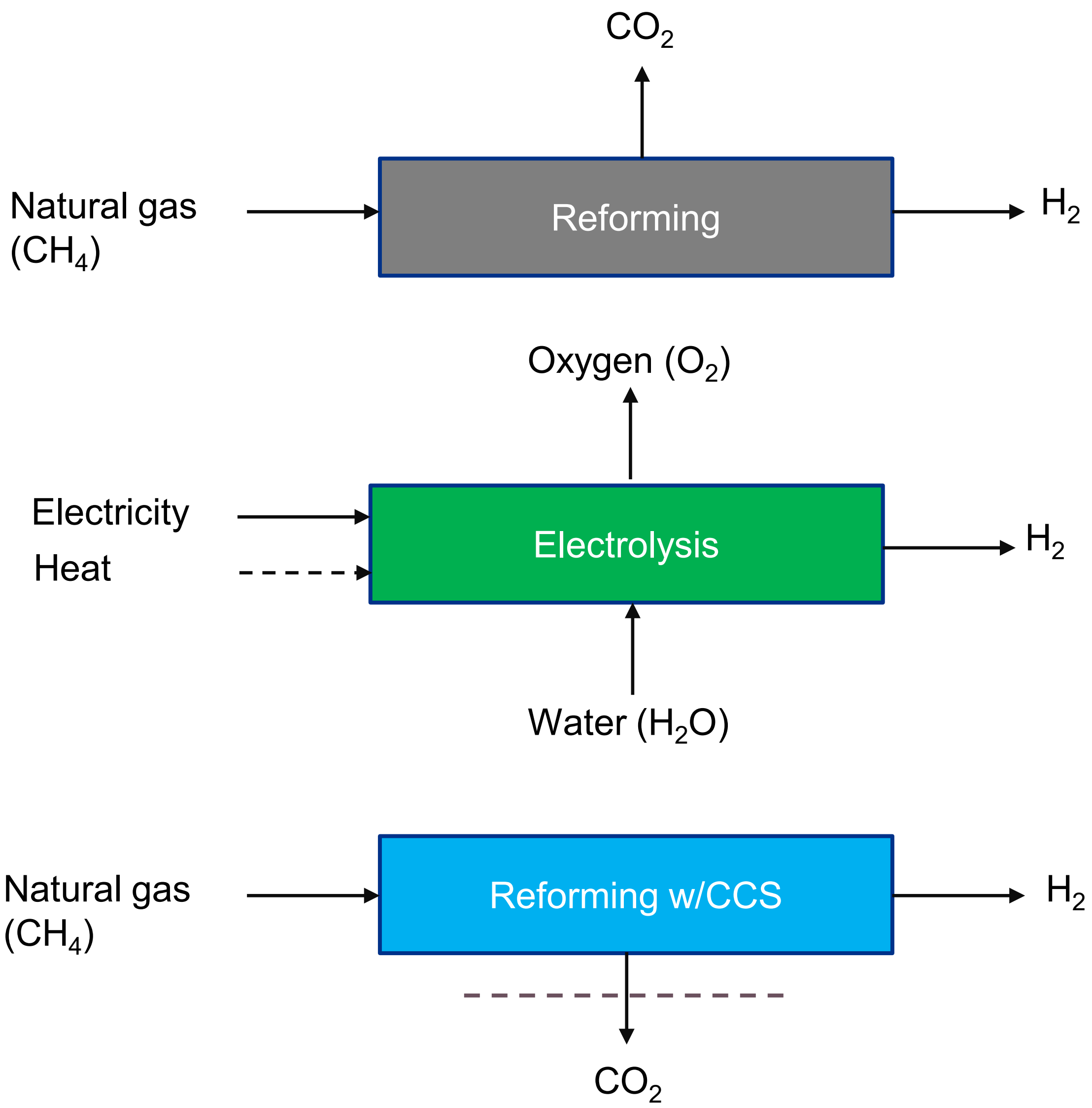
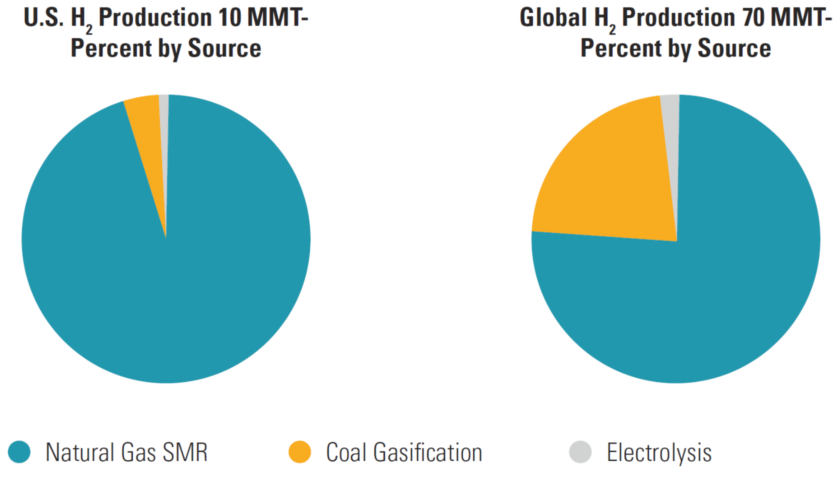


Figure 3. U.S. and Global Production of Hydrogen



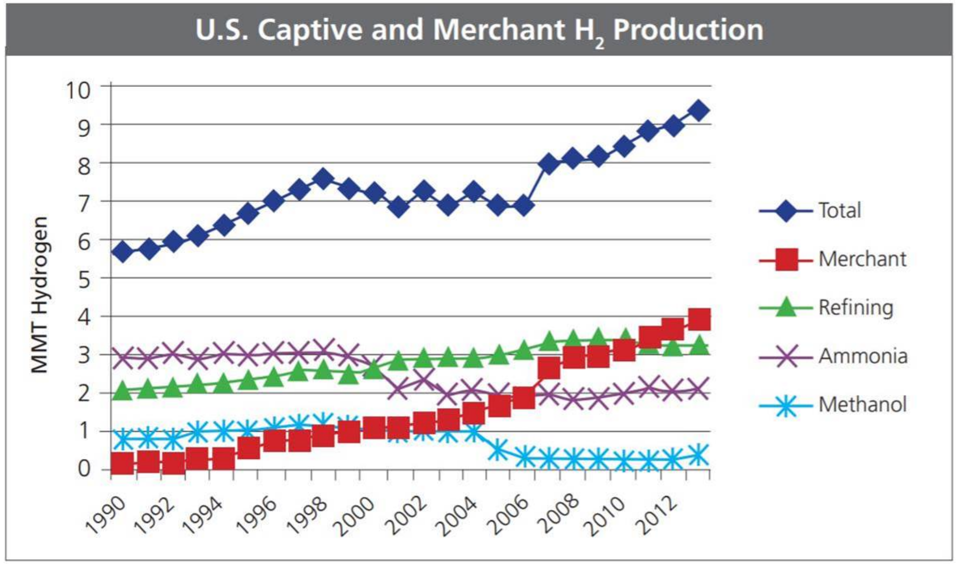


Figure 1

Source: The Outsourcing of Refinery Hydrogen Production

► *Gas reforming without CCS is the dominant hydrogen production pathway today, but CO_2 emissions are high.*

Alternative Energy Carrier: Ammonia

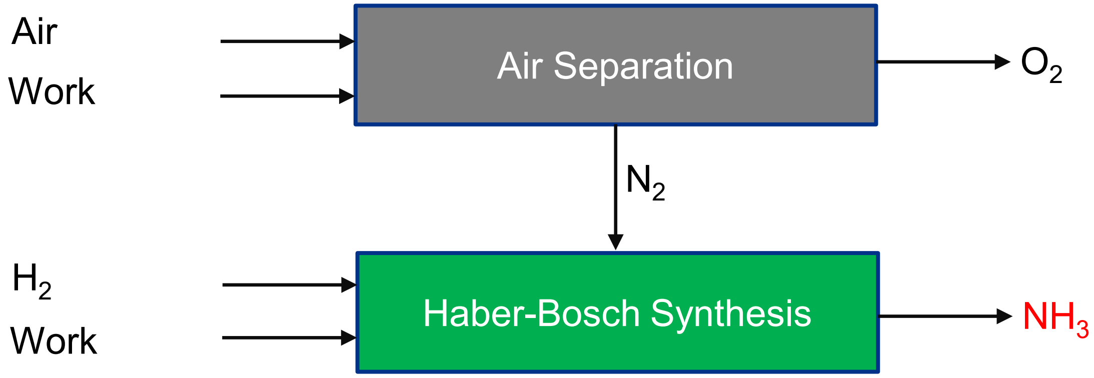
Ammonia is an energy carrier made from hydrogen and nitrogen, which also produces no CO_2 when consumed:

- $4 \cdot NH_3 + 3 \cdot O_2 \Longleftrightarrow 2 \cdot N_2 + 6 \cdot H_2O$ + 18.6 MJ per kg of NH_3

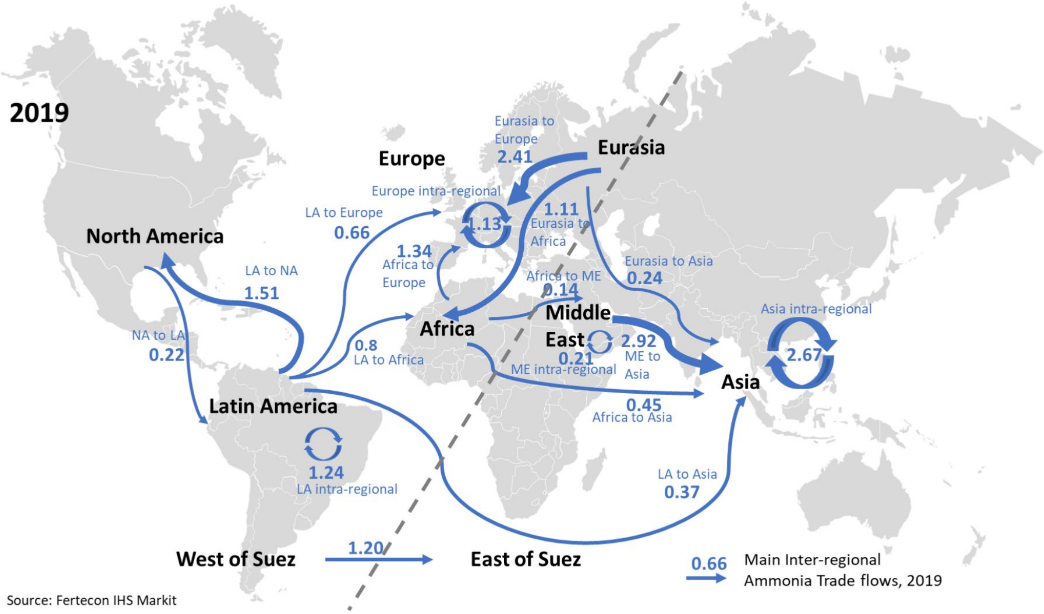
Considerably lower heating value than hydrogen, but a dense liquid at much milder conditions than hydrogen

- boils at -33°C (similar to propane)

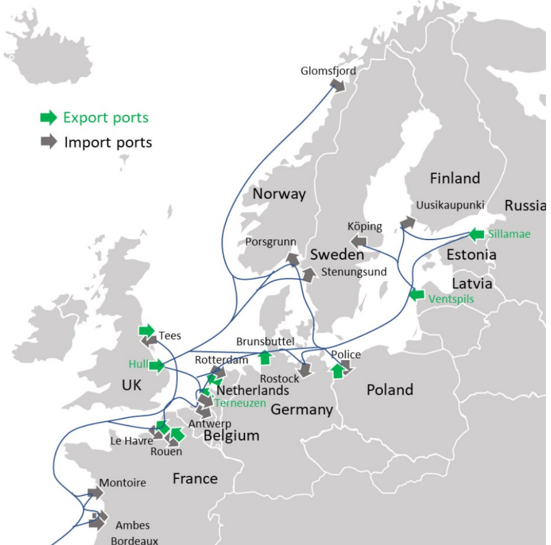
Large existing infrastructure in fertilizer industry



Region	2018/19
(1000 metric tons Ammonia)	
North America	19.477
Latin America	13.644
Western Europe	12.214
Central Europe	8.341
Eurasia	31.033
Africa	12.828
West Asia	22.247
South Asia	22.426
East Asia	98.819
Oceania	2.259
World Total	**243.288**



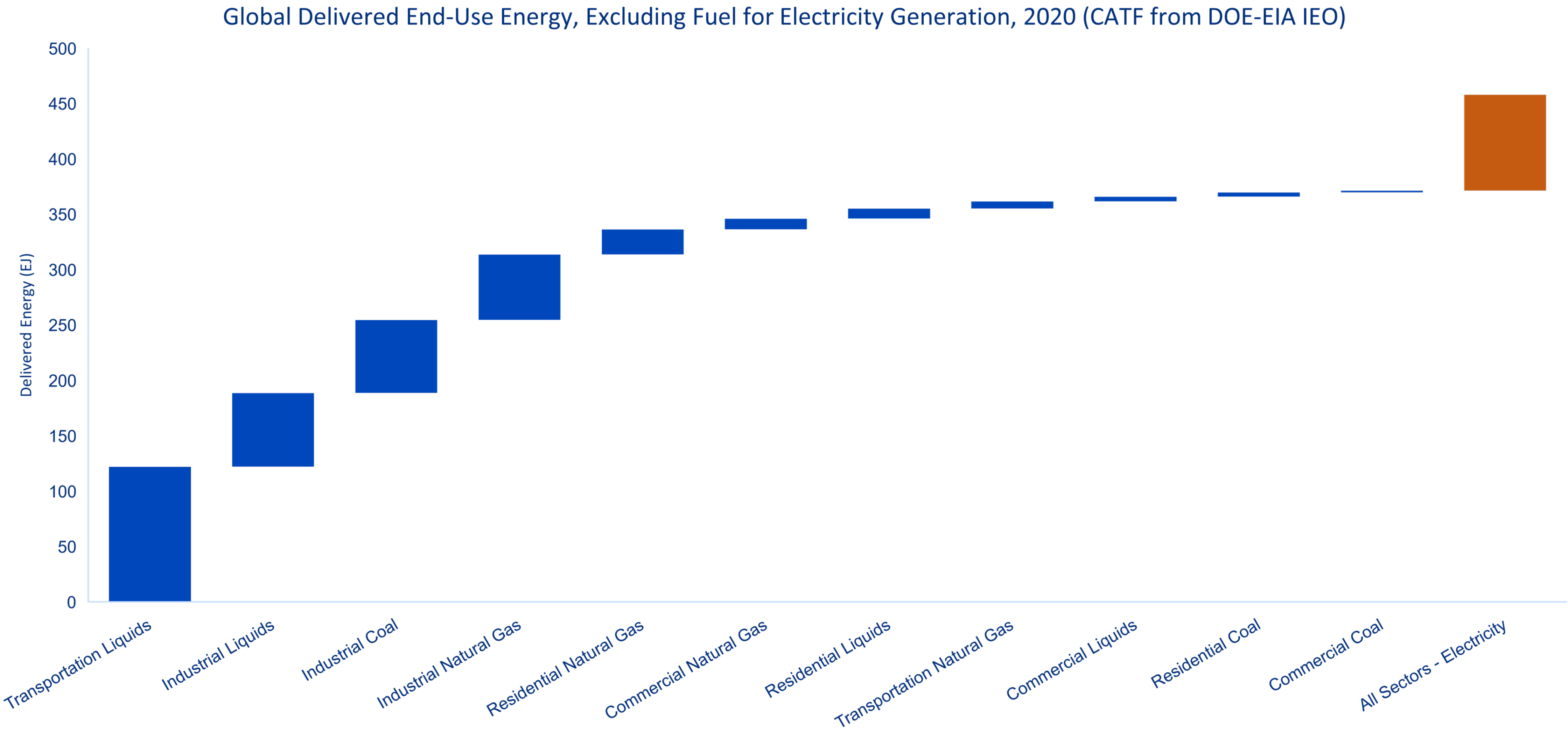
Source: Fertecon IHS Markit



Source: Fertecon IHS Markit

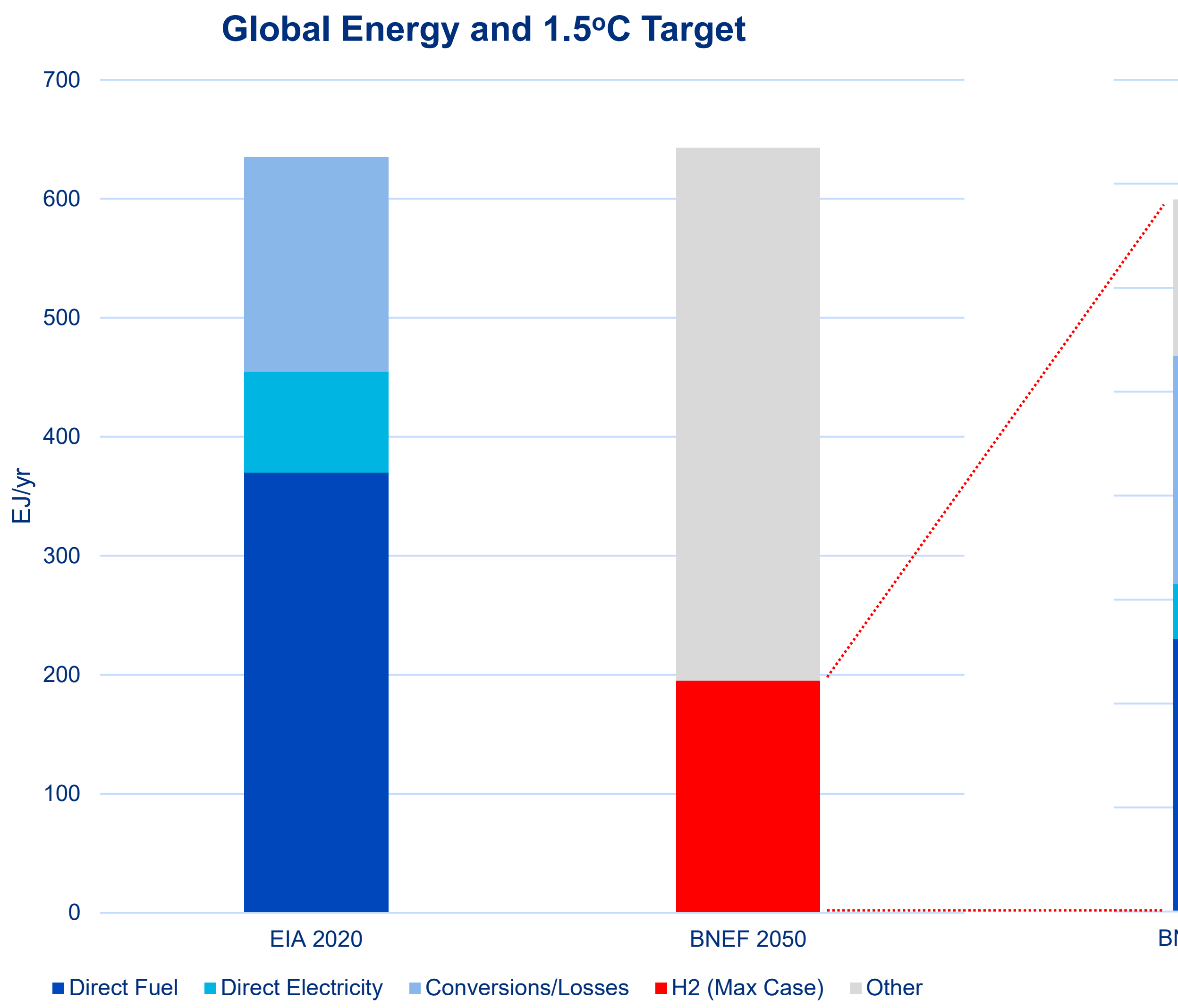
► *Ammonia could be an attractive hydrogen carrier for certain end uses where fuel logistics are especially challenging*

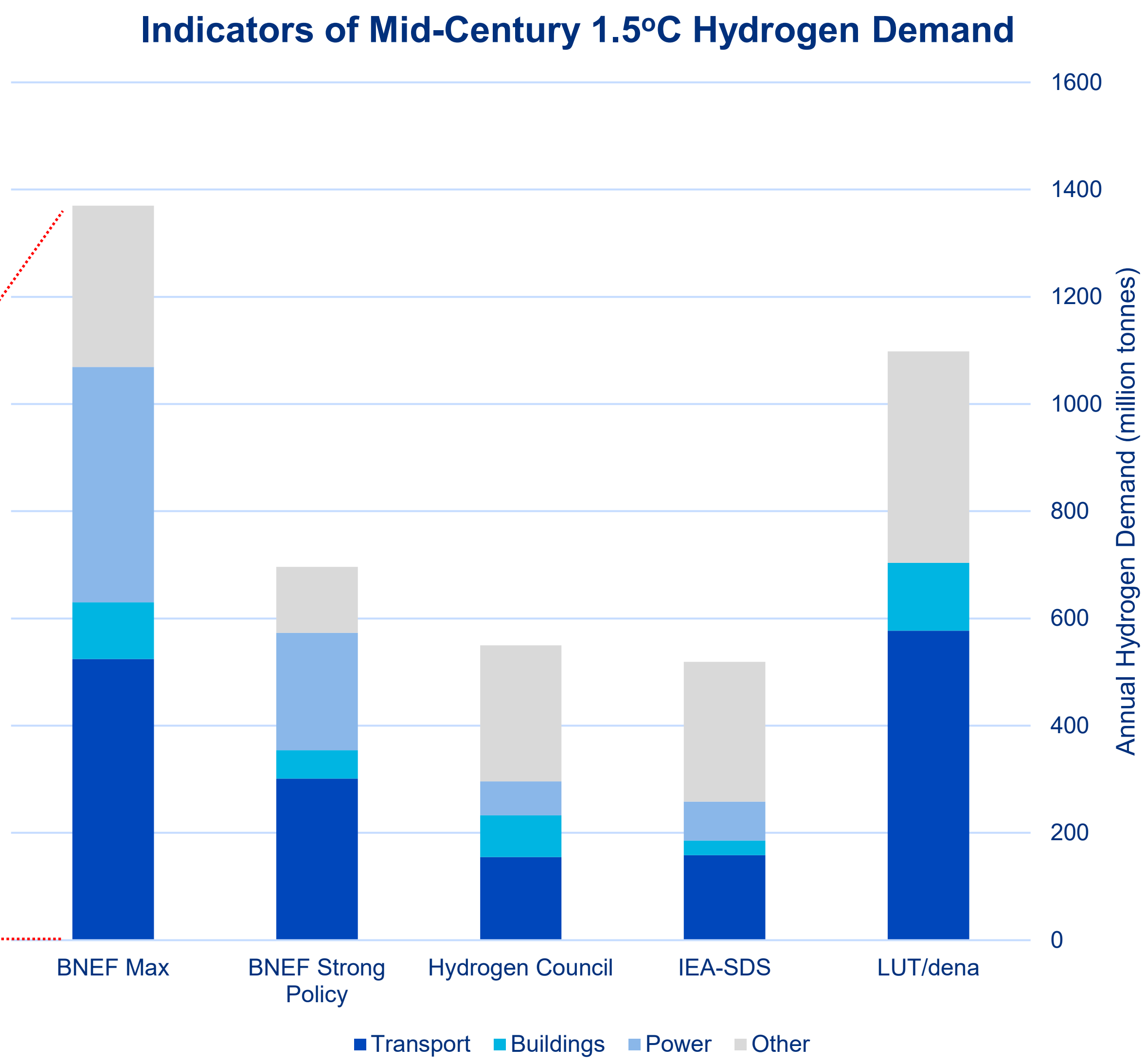
Why is Hydrogen Needed?



► *Electricity provides only 20% of energy at point of use, fuels provide 80%; due to performance characteristics replacing fuels with electricity will be very difficult in some sectors*

Hydrogen's Role in Decarbonization





► *As much as 200 EJ of hydrogen might be required by 2050*

► *Transportation and industry are key drivers of demand*

Key Potential Applications for ZCF

Marine Shipping

Heavy Trucking

Industrial Process Heating

Ironmaking

Cold-Climate Building and Water Heating

Power Balancing

CATF

Existing Hydrogen Infrastructure

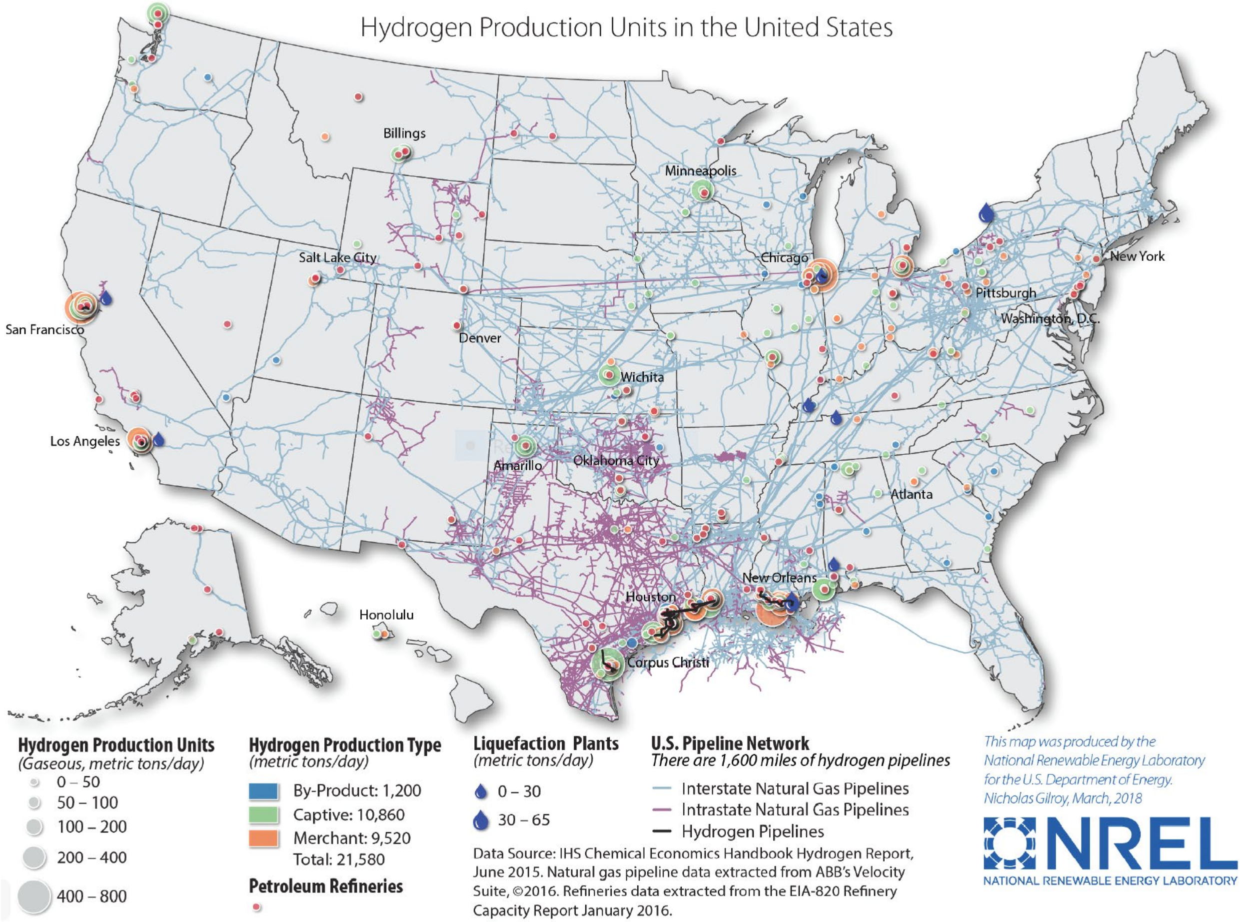
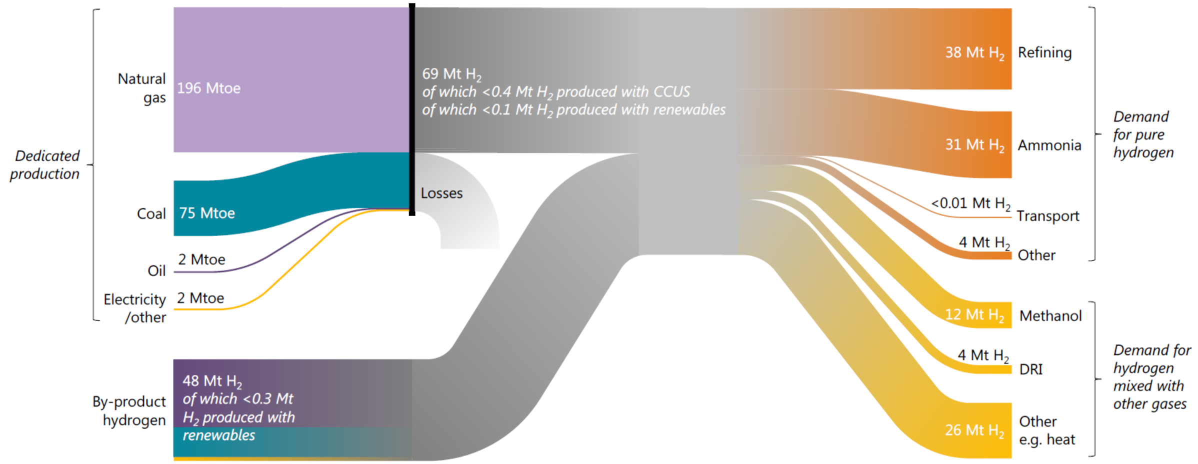


Figure 6. Today's hydrogen value chains



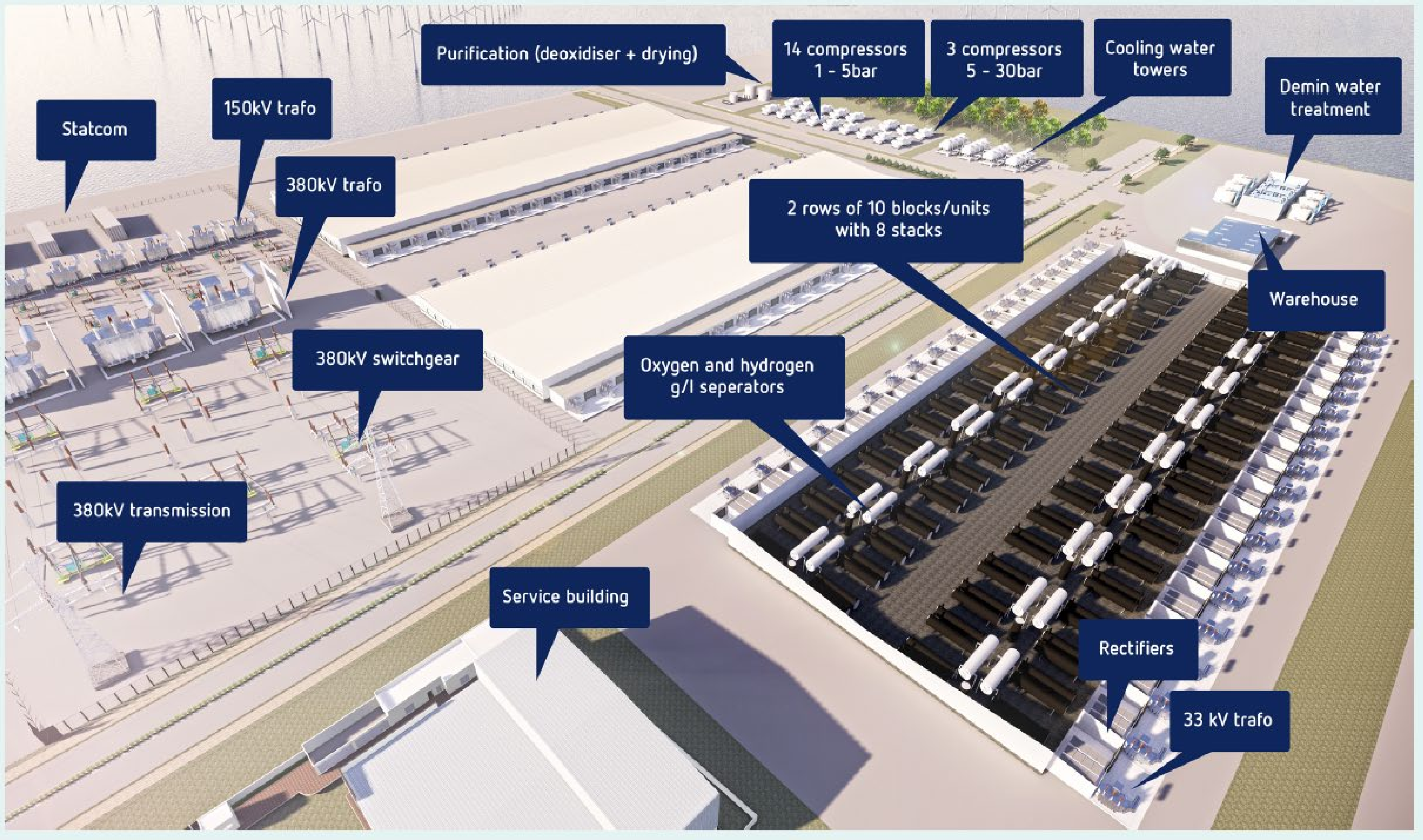
Notes: Other forms of pure hydrogen demand include the chemicals, metals, electronics and glass-making industries. Other forms of demand for hydrogen mixed with other gases (e.g. carbon monoxide) include the generation of heat from steel works arising gases and by-product gases from steam crackers. The shares of hydrogen production based on renewables are calculated using the share of renewable electricity in global electricity generation. The share of dedicated hydrogen produced with CCUS is estimated based on existing installations with permanent geological storage, assuming an 85% utilisation rate. Several estimates are made as to the shares of by-products and dedicated generation in various end uses, while input energy for by-product production is assumed equal to energy content of hydrogen produced without further allocation. All figures shown are estimates for 2018. The thickness of the lines in the Sankey diagram are sized according to energy contents of the flows depicted.

Source: IEA 2019.

Today's hydrogen industry is large, with many sources and uses. Most hydrogen is produced from gas in dedicated facilities, and the current share from renewables is small.

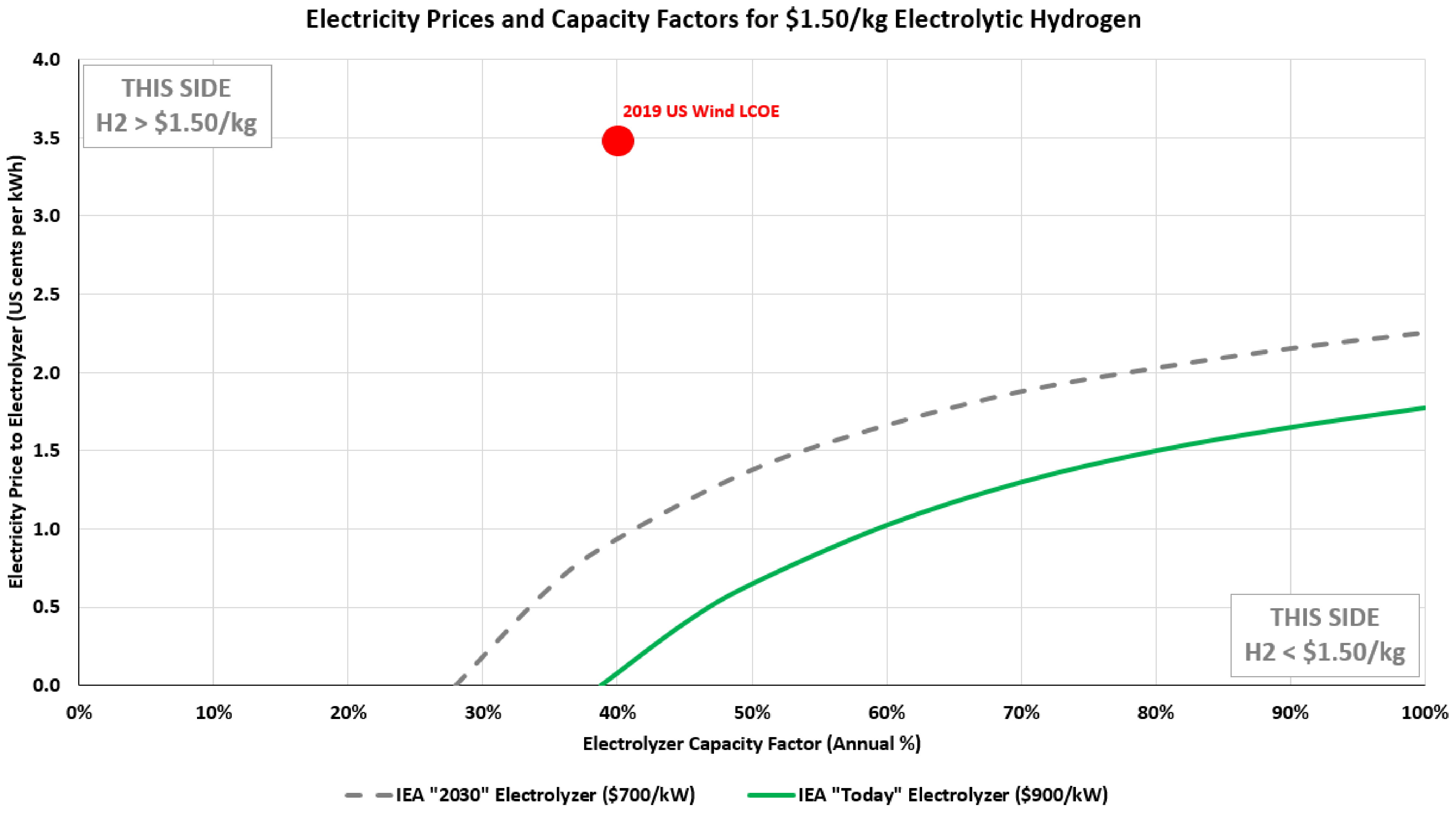
► *There is already substantial infrastructure in place to produce and use hydrogen, although mostly in the refining and chemicals sectors.*

Artist's Rendering of 1 GWe Electrolysis Plant



► *Electrolysis is technically feasible and commercially available today at large scale from multiple vendors*

Electrolytic Hydrogen Cost Frontier



► *Clean electrolytic hydrogen for less than $1.50/kg requires very low cost clean electricity at high capacity factors*

Fossil CCS Hydrogen Production Examples (1/2)

Three operating "blue" hydrogen project examples

Air Products, Port Arthur, TX

Air Products Port Arthur, TX, hydrogen production with carbon capture, successful operation since 2013. Per IEA, 1.0 million tpy CO2, 125k Nm3/hr zero-carbon estimated normalized capacity.

Shell Quest, Alberta, Canada

Shell Quest Alberta, Canada hydrogen production with carbon capture, successful operation since 2015. Per IEA, 1.2 million tpy CO2, 150k Nm3/hr zero-carbon estimated normalized capacity.

Nutrien, Alberta, Canada

Nutrien Alberta, Canada hydrogen (ammonia) production with carbon capture, feeding Alberta Carbon Trunk Line from June 2020. Per IEA, 0.3 million tpy CO2, 38k Nm3/hr zero-carbon estimated normalized capacity.

► *"Blue" hydrogen will be an important part of the hydrogen supply picture. Combined these projects produce around 250,000 tonnes of zero-carbon (normalized) hydrogen per year and send 2.5 million tonnes of CO2 to pipeline. Producing this much hydrogen from electrolysis would require around 1.5 GWe of installed capacity operating 24/7/365.*

Source: IEA Hydrogen Database (2019); CATF calculation for electrolysis equivalent.

Fossil CCS Hydrogen Production Examples (2/2)

Examples from US and UK projects in development targeting > 90% CCS

Linde (Praxair), Convent, LA

(4) *Engineering Design of a Linde-BASF Advanced Post-Combustion CO_2 Capture Technology at a Linde Steam Methane Reforming H_2 Plant* – **Praxair** (Danbury, CT) will complete an initial engineering design study for a Linde-BASF CO_2 capture system at a commercial steam methane reforming (SMR) hydrogen plant in Convent, LA. The plant will be one of the largest of its kind in the world. Its CO_2 capture and compression operations will be designed to recover at least 90 percent of the CO_2 from a flue gas stream produced by the SMR process.

HyNet, Greater Manchester, UK

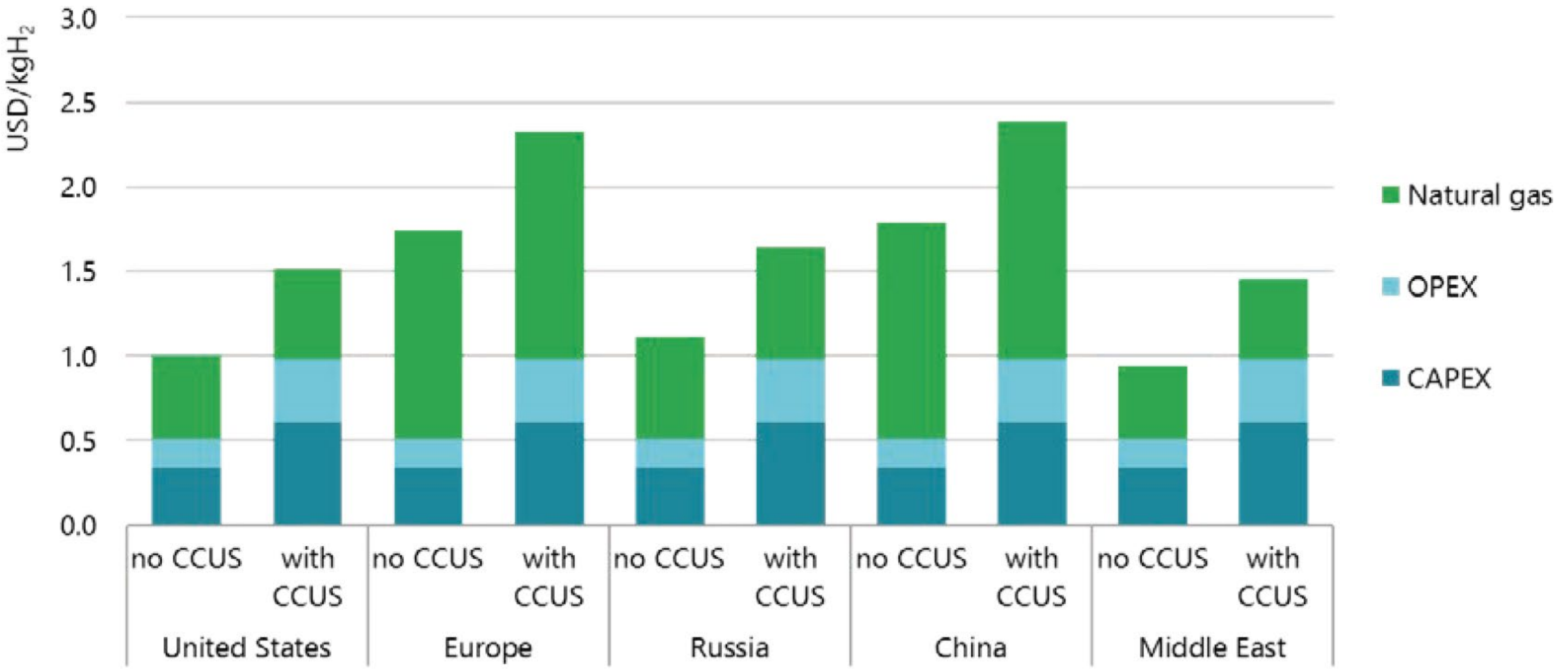
Capture Rate: The plant shall capture as carbon dioxide a minimum of 95% of the total carbon entering the plant with a target of 97%. The lower figure is set as this is regarded as the current level expected within the industry. A higher target has been set given the value, both economically and in terms of net-zero, of achieving higher capture rates. In FEED further value engineering work will be done to see if the achieved rate can exceed the above target.

► *Combined the two projects shown here would produce around 240,000 tonnes of clean hydrogen per year (equivalent to ~1.4 GWe of installed capacity operating 24/7/365).*

Sources:
Linde Convent - https://www.energy.gov/fe/articles/foa-2187-and-foa-2188-project-selections
HyNet - https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/866401/HS384_-_Progressive_Energy_-_HyNet_hydrogen.pdf

Fossil CCS Hydrogen Production Costs

Figure 9. Hydrogen production costs using natural gas in different regions, 2018

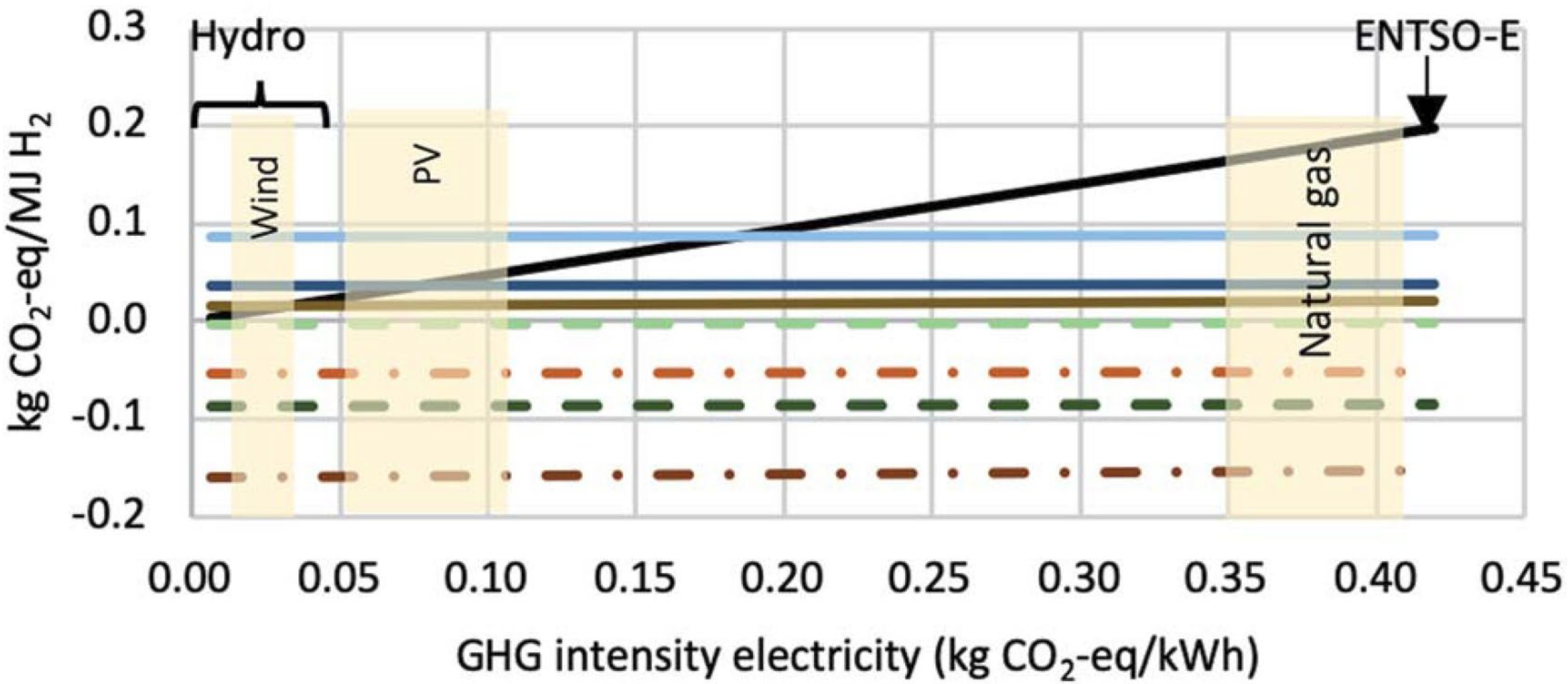


Notes: kgH_2 = kilogram of hydrogen; OPEX = operational expenditure. CAPEX in 2018: SMR without CCUS = USD 500–900 per kilowatt hydrogen (kW_{H2}), SMR with CCUS = USD 900–1 600/kW_{H2}, with ranges due to regional differences. Gas price = USD 3–11 per million British thermal units (MBtu) depending on the region. More information on the underlying assumptions is available at www.iea.org/hydrogen2019.

Source: IEA 2019.

► *In key geographies including the US and Middle East fossil hydrogen with 90% CCS could be $1.50/kg or less.*

Hydrogen Production GHG Emissions



Source: Treyer et al, 2020

► *The electricity for electrolysis must be clean for the hydrogen to be "clean". Fossil CCS routes and electrolytic routes can both have low associated emissions.*

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114 State Street, 6th Floor
Boston, MA 02109

Phone: 617-624-0234
Email: info@catf.us

CATF.US