Hydrogen (H_2) in Decarbonization and Economic Development

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Sustainable Cities Network Solar & Energy Efficiency (SEE) Workgroup Meeting – 15 June 2021

*ASU campus wide initiative on light inspired research for energy and sustainability

ASU LIGHTWORKS® BROAD CAMPUS WIDE INITIATIVE

LightWorks® pulls light-inspired research at ASU under one strategic framework.

Envisions a resilient and equitable energy future supported by innovations in technology, policy, law, governance, and markets.

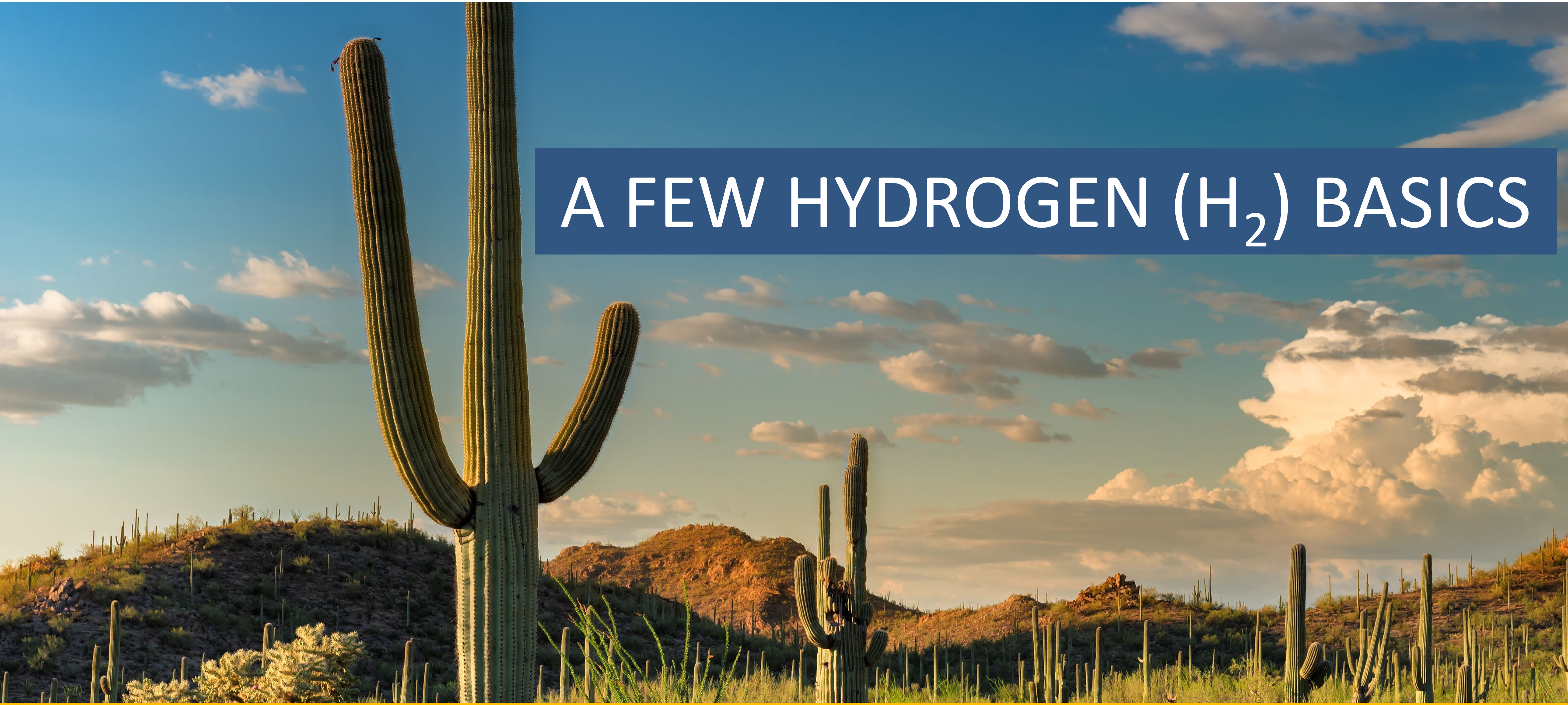
Pursues breakthroughs to achieve energy security; to secure energy justice, and to inspire future generations.

Focuses on the energy transition – how do we get from here to there?

Collaborates with like-spirited people and organizations to realize a shared vision

Why Solar: It is highly scalable and democratic
Distributed much more Equitably than Other Natural Resources, especially compared to Oil, Natural Gas, and some Critical Elements

A FEW HYDROGEN (H_2) BASICS



From Coal
Current project in Australia
500M AU$ project for export to Japan started production March 2021

Steam Reforming of Natural Gas
- **95% today**

~10 kg CO_2 per kg H_2

Produced from Natural Gas with carbon capture and sequestration

Produced from clean energy and no net carbon emissions

- Hydrogen is very abundant, lightest element on the periodic table, most versatile in its binding to other elements and is only bound to other elements.
- Molecular H_2 is a clean fuel that, when consumed in a fuel cell, produces only water.
- Hydrogen can be produced from a variety of domestic resources, such as natural gas, nuclear power, biomass, and renewables like solar and wind.
- H_2 can be used in cars, in houses, for portable power, and in many more applications.
- Hydrogen is an energy carrier that can be used to store, move, and deliver energy produced from other sources.
- Today, hydrogen fuel can be produced through several methods. The most common method today is steam reforming of natural gas reforming

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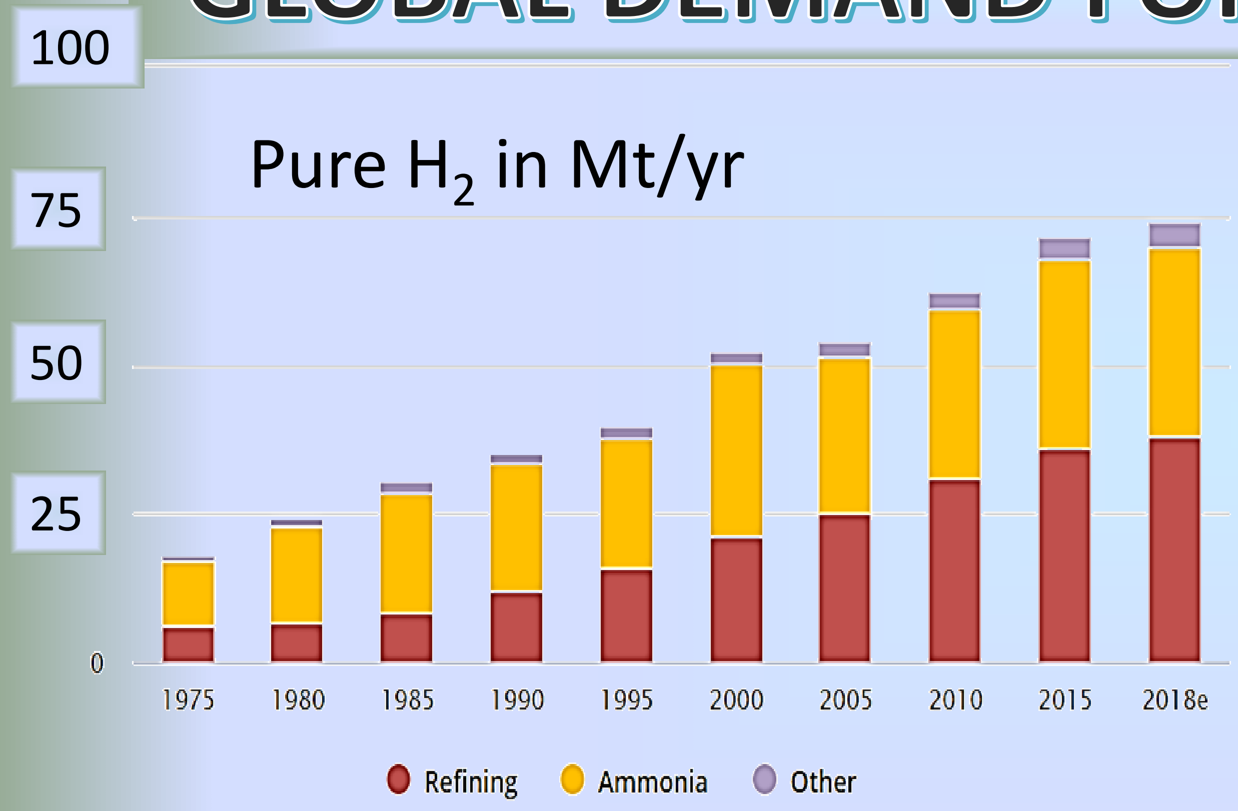
GLOBAL DEMAND FOR H_2 IS GROWING RAPIDLY

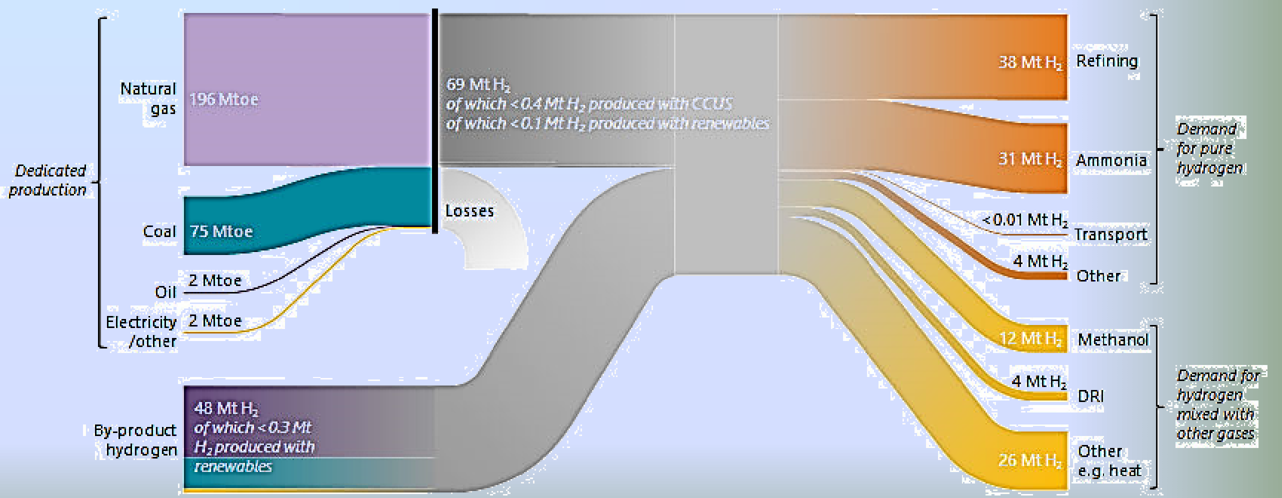


Today – refineries and ammonia production dominate

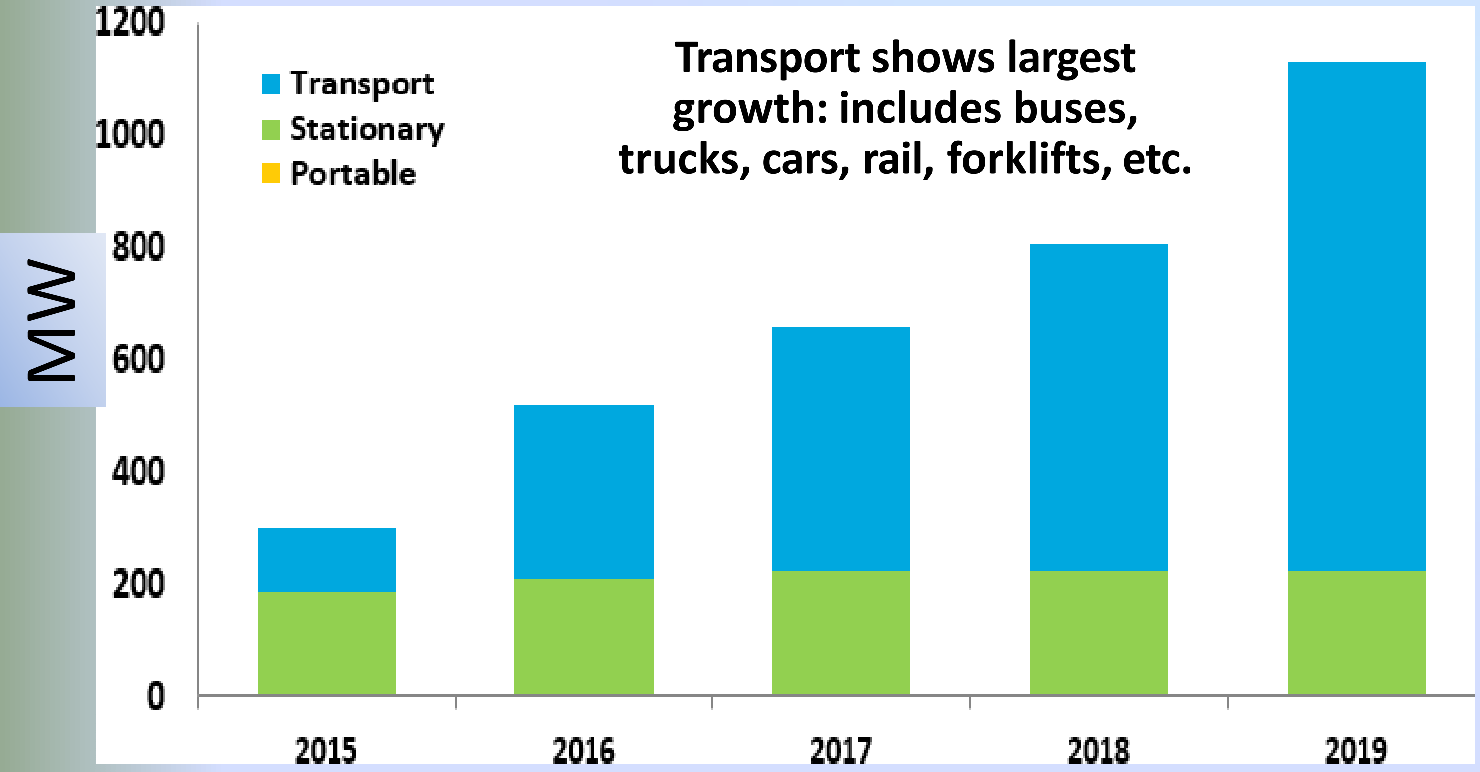
Grown more than threefold since 1975

Continues to rise – almost entirely supplied from fossil resourcs (grey and brown H_2)

6% of global natural gas and 2% of global coal for hydrogen production



GLOBAL FUEL CELL SHIPMENTS SURPASSED 1 GW



25-fold increase in electrolyzers deployed in the last decade

< 1 MW in 2010 to

>25 MW by the end of 2019

Global FCEVs doubled to >25,200

> 12.3K sold in 2019 vs. 5.8K in 2018

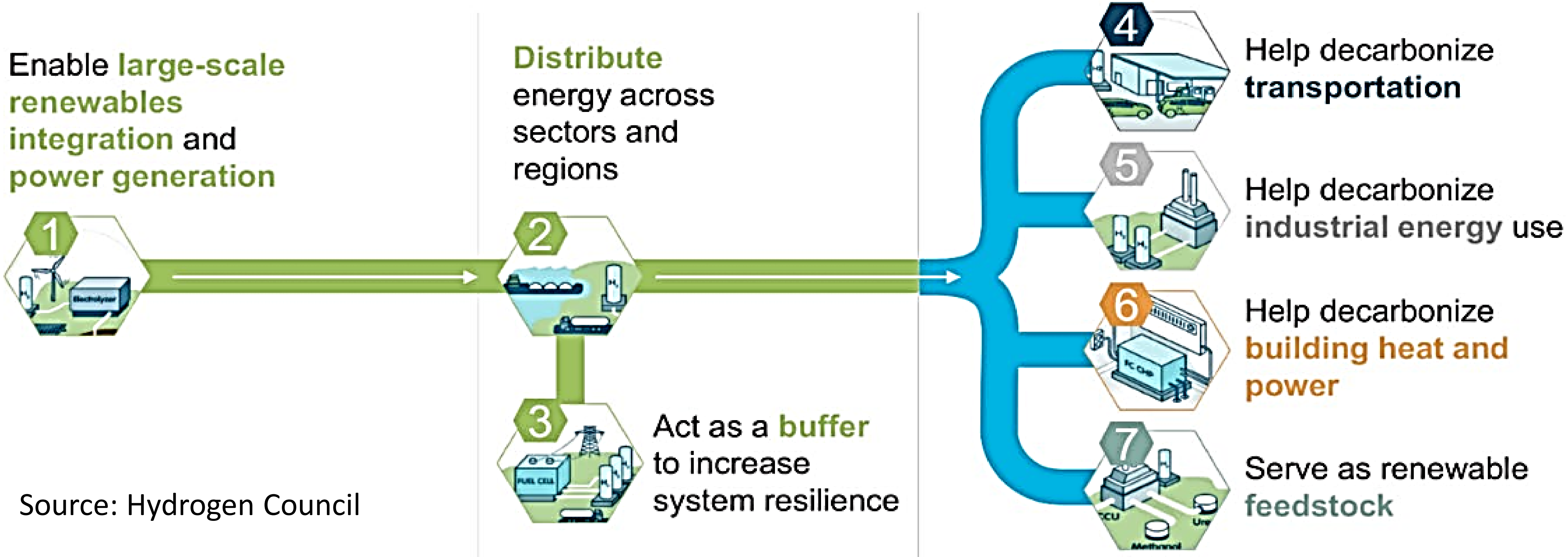
470 H_2 fueling stations worldwide

> 20% increase from 2018

Source: E4tech for DOE analysis project

Source: IEA (2020), *Hydrogen*, IEA, Paris, https://www.iea.org/reports/hydrogen

H_2 IS A CLEAN, VERSATILE ENERGY CARRIER



Source: Hydrogen Council

H_2 can contribute to a broad range of difficult to decarbonize applications

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HYDROGEN OPPORTUNITIES

EXAMPLE: CO-FUNDED BY U.S. DEPARTMENT OF ENERGY, CA STATE AGENCIES AND INDUSTRY

Project impact per year: savings of

- **285 metric tons of CO_{2e}**
- **280,000 grams of criterial pollutants**
- **56,000 gallons of diesel**

Could enable 8.8 million gallons savings per year if 1% of California's 253,000 Class 3-8 urban work trucks adopt

Goal:

Demonstrate hybrid electric delivery vans with fuel cell range extenders (up to 125-mile range)

- 5 trucks built, undergoing testing, 10 more in assembly
- Trucks to operate in disadvantaged community in CA

Examples of Applications

>500MW
Stationary Power

>35,000
Forklifts

>60
Fuel Cell Buses

>45
H_2 Retail Stations

>8,800
Fuel Cell Cars

Hydrogen Production Across the U.S.

- 10 million metric tons produced annually
- More than 1,600 miles of H_2 pipeline
- World's largest H_2 storage cavern

Hydrogen Stations: Examples of Plans Across States

California
200 Stations Planned
CAFCP Goal

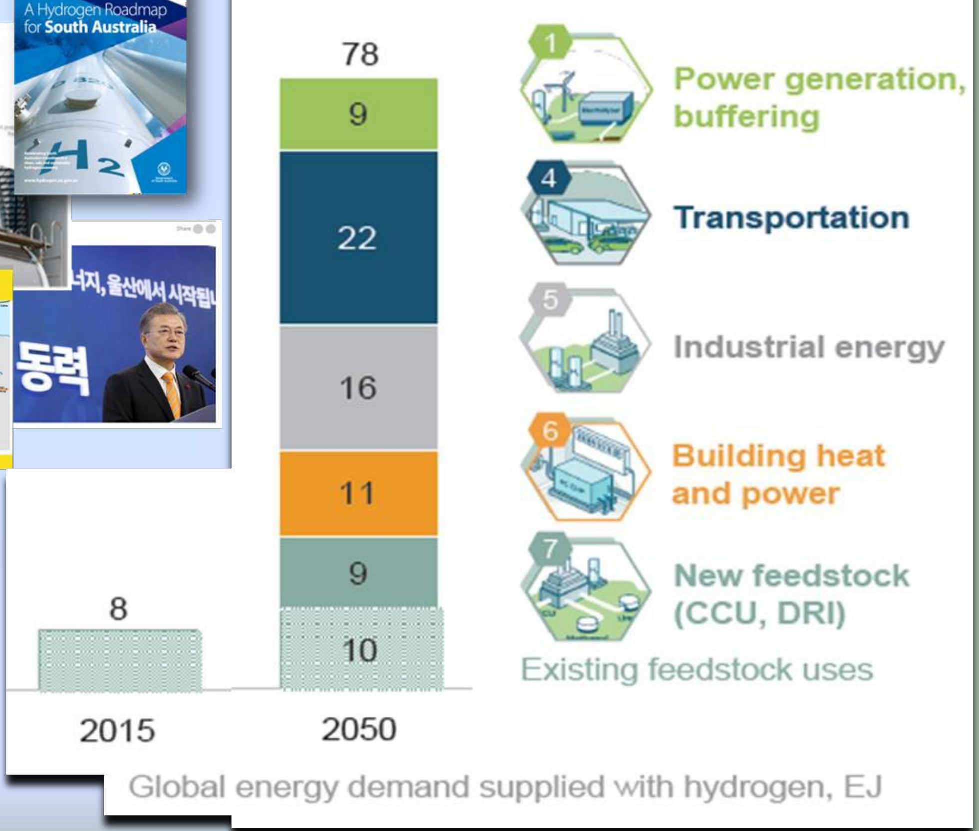
Northeast
12 – 20
Stations Planned

HI, OH, SC, NY, CT, MA, CO, UT, TX, MI
And Others

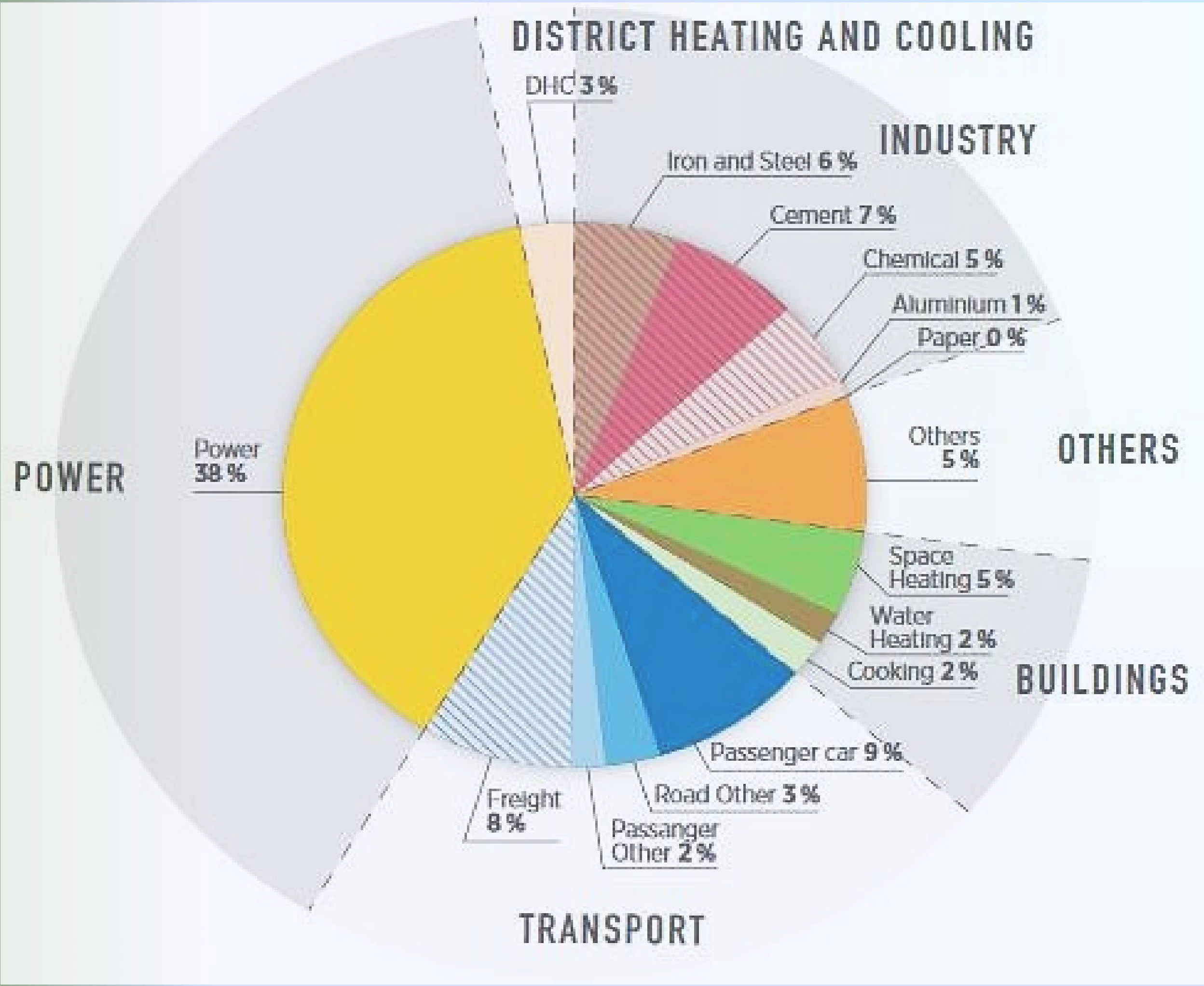
GLOBAL ACTION AGENDA GOALS: “10, 10, 10” 10M SYSTEMS, 10K STATIONS, 10 YEARS

Hydrogen Council: Global industry partnership projects up to 10 x increase in H_2 demand by 2050

78 EJ/yr = 2.5 TW



GLOBAL ENERGY RELATED CARBON EMISSIONS BY SECTOR



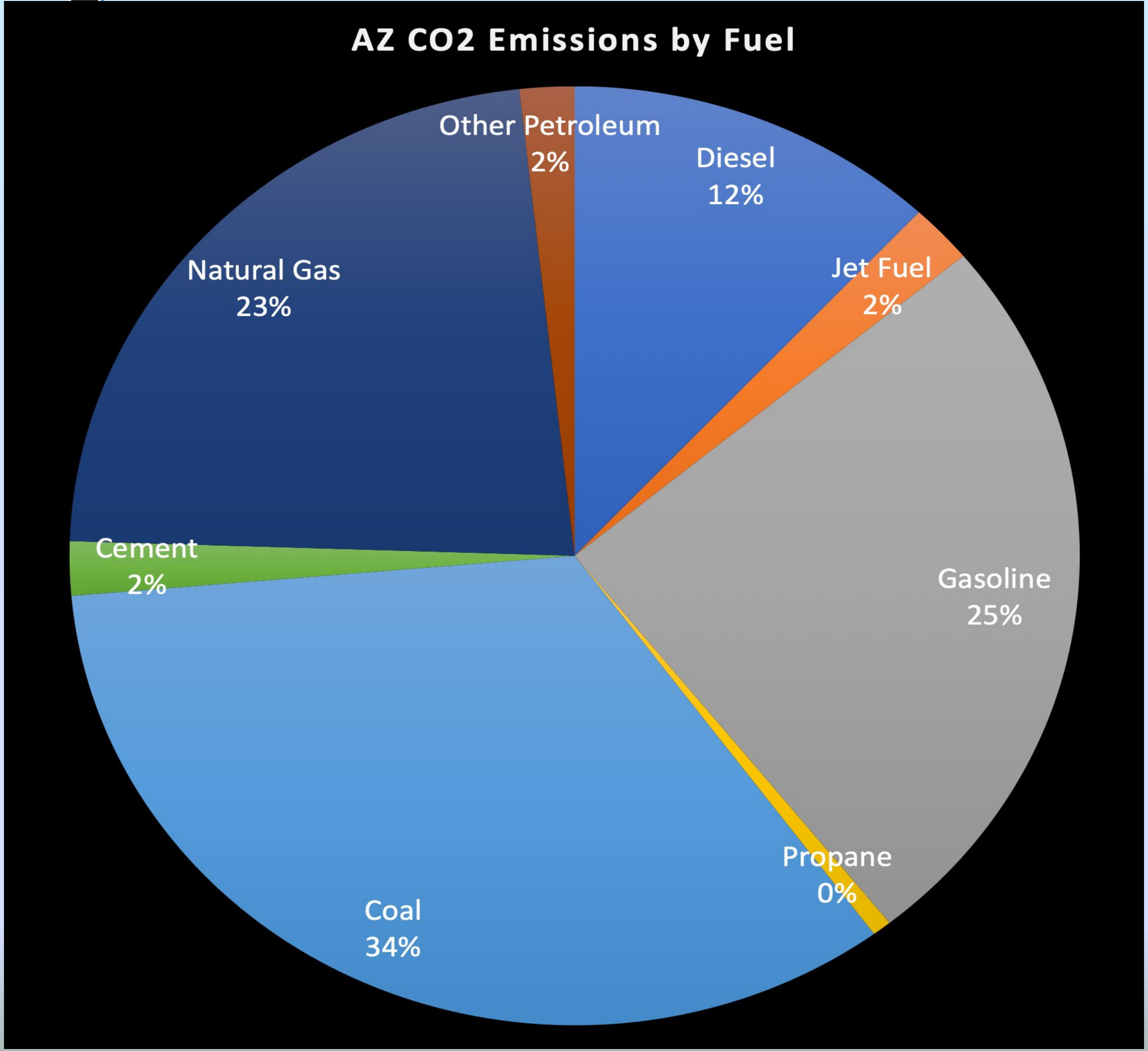
Sectors today with no economically scalable option for deep CO_2 emissions reductions

Role for H_2 in all sectors

Source: IRENA, 2017a from: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Sep/IRENA_Hydrogen_from_renewable_power_2018.pdf

ARIZONA CO_2 EMISSIONS INVENTORY

- **Coal: 31.5 mmt (34%)**
- **Natural Gas: 21.3 mmt (23%)**
  - NG (electricity): 15.7 mmt
  - NG (other): 5.6
- **Transport: 36.7 mmt (39%)**
  - Motor Gasoline: 23.7 mmt (25%)
  - Diesel: 11.1 mmt (12%)
  - Jet Fuel: 1.9 mmt (2%)
- **Other Petroleum: 2.2 mmt (2%)**
  - Propane: 0.6 mmt
  - Other: 1.6 mmt
- **Cement: 1.74 mmt (2%)**



2018 US Energy Information Administration

Annual CO_2 Emissions = 93.45 mmt

Prepared for ASU-SRP "last20%" workshop Nov 2020

CHALLENGES

WHAT ARE SOME H_2 BARRIERS OR CHALLENGES?

Main challenges for "clean" hydrogen (blue or green)

Affordable distribution and infrastructure

Affordable generation

Affordable storage

Safety

Global standards

Over 500 miles of hydrogen pipeline exists in the U.S. today

More than 300 miles in Europe

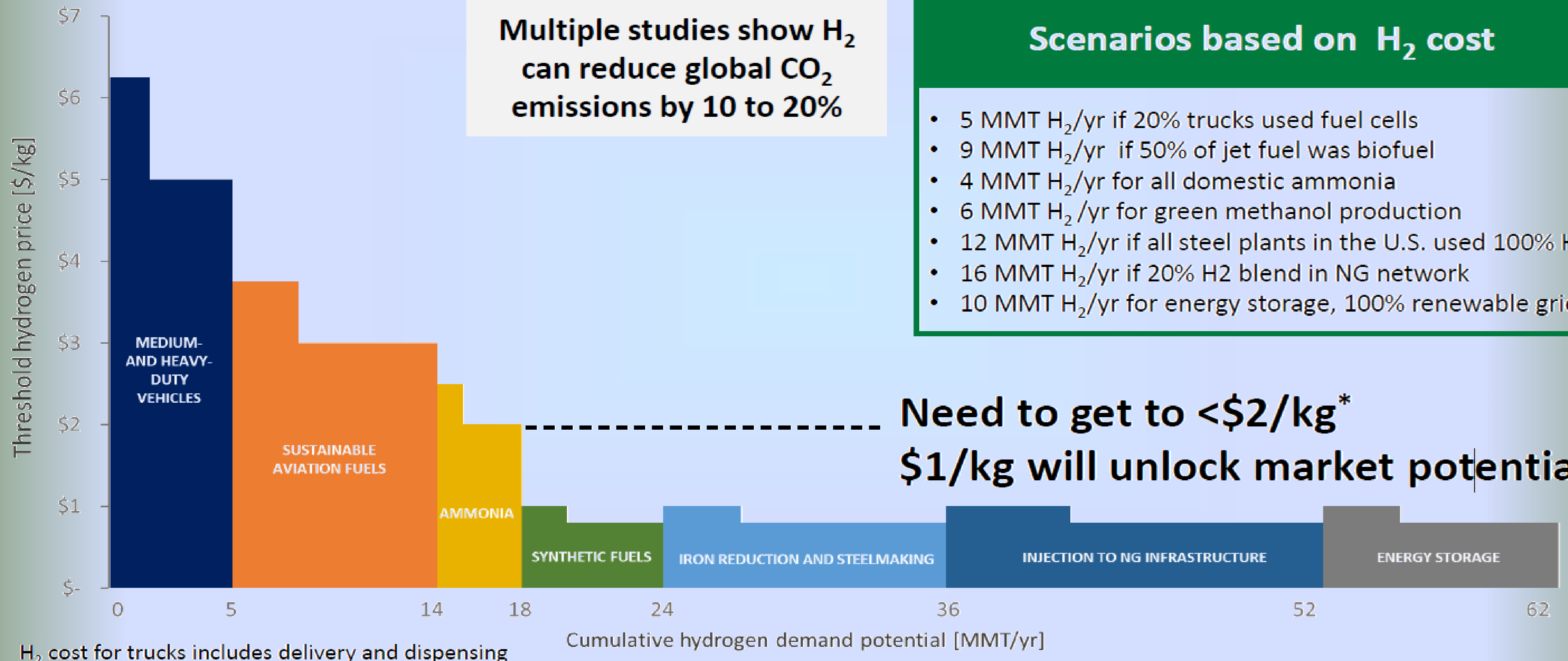
2 salt caverns in Texas

ADOPTION

Multiple studies show H_2 can reduce global CO_2 emissions by 10 to 20%

Scenarios based on H_2 cost

- 5 MMT H_2/yr if 20% trucks used fuel cells
- 9 MMT H_2/yr if 50% of jet fuel was biofuel
- 4 MMT H_2/yr for all domestic ammonia
- 6 MMT H_2 /yr for green methanol production
- 12 MMT H_2/yr if all steel plants in the U.S. used 100% H_2
- 16 MMT H_2/yr if 20% H2 blend in NG network
- 10 MMT H_2/yr for energy storage, 100% renewable grid



Need to get to <$2/kg*

$1/kg will unlock market potential

H_2 cost for trucks includes delivery and dispensing

* H_2 could compete at $1 to $2/kg higher cost with a carbon price

Results based on preliminary analysis

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Hydrogen Energy Earthshot

"Hydrogen Shot"

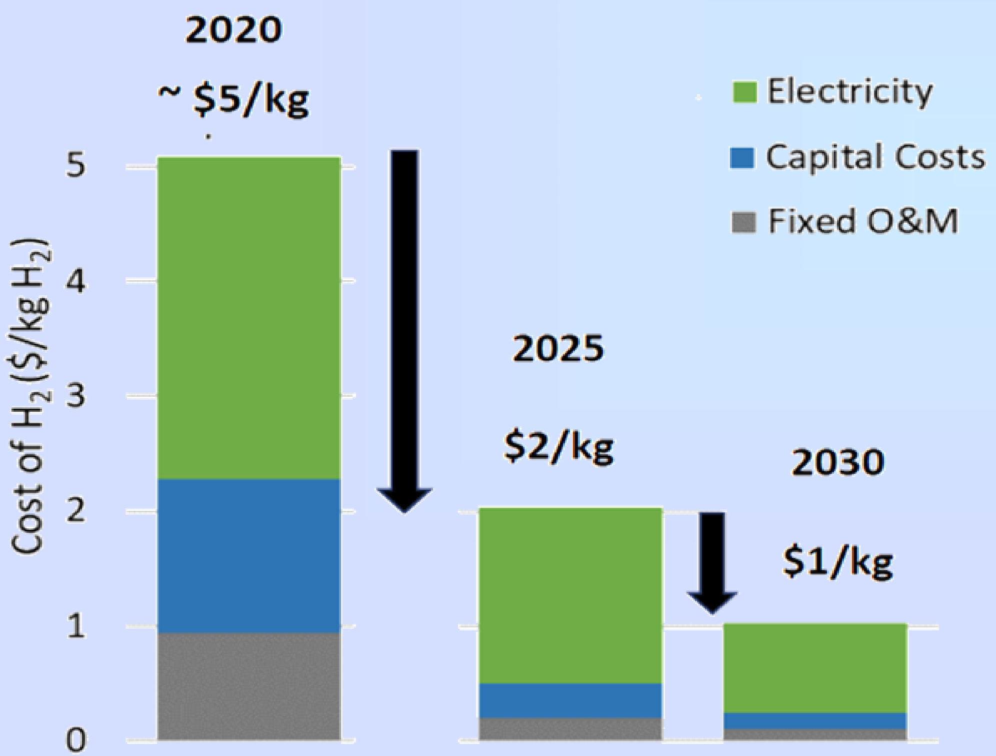
1	for	1	in	1
$1		1 kg H_2		1 decade

Launched June 7, 2021

Is Hydrogen Shot Achievable? How can we get there?

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Hydrogen

Cost of Clean H_2 from Electrolysis



- Reduce electricity cost from >$50/MWh to
  - $30/MWh (2025)
  - $20/MWh (2030)

SunShot Goal

- Reduce capital cost >80%
- Reduce operating & maintenance cost >90%

2020 Baseline: PEM low volume capital cost ~$1,500/kW, electricity at $50/MWh. Need less than $300/kW by 2025, less than $150/kW by 2030 (at scale)

BENEFITS

CLEAN, VERSATILE ENERGY CARRIER OR VECTOR: COUPLING THE SECTORS

Adds diversity (grid may only need 5-10%)

Can contribute to resilience; Disaster recovery

Can export or import (lessons from LNG)

Reductant (can pull oxygen out, e.g., steel – 65-75 kg H_2/t) or from biomass to make biofuels)

Can be a co-product from making O_2, Cu mining

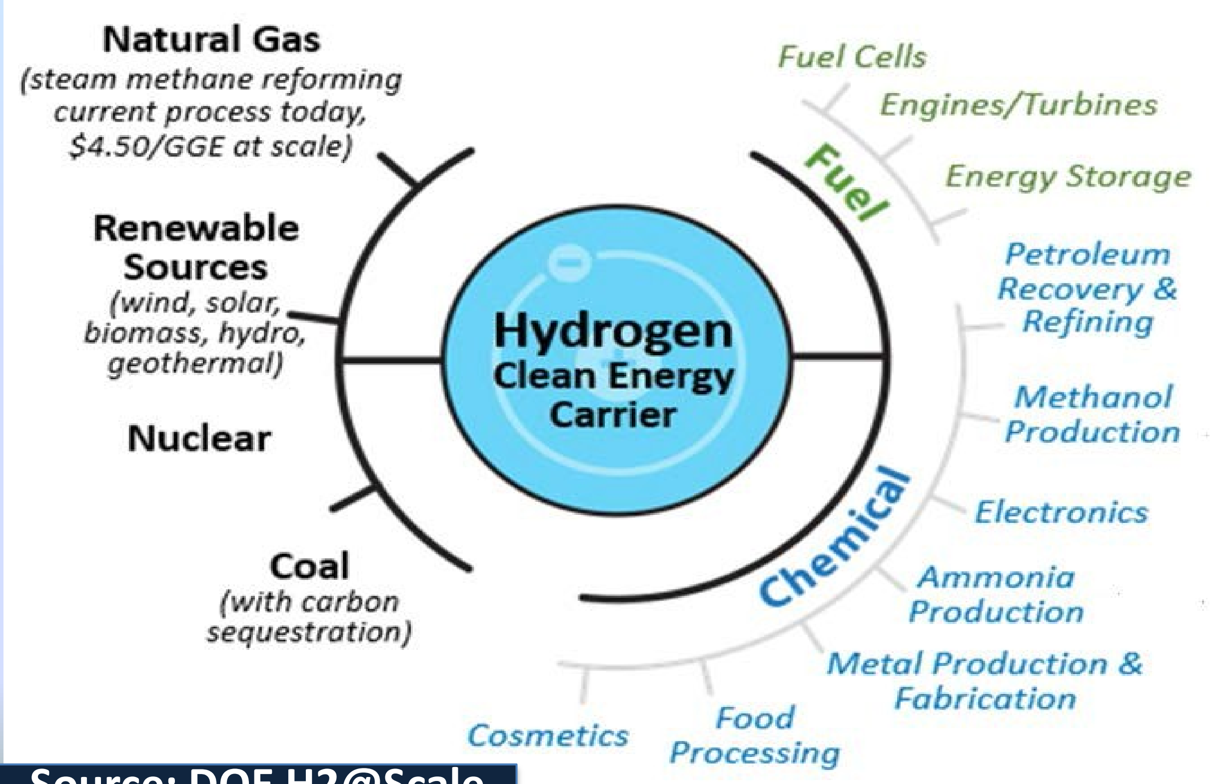
React with CO_2 and make synthetic hydrocarbons, e.g., liquid fuels, SNG, DME

2050 Hydrogen Council projections

- ~18% of energy system
- $2.5 T annual sales of H_2 + equipment

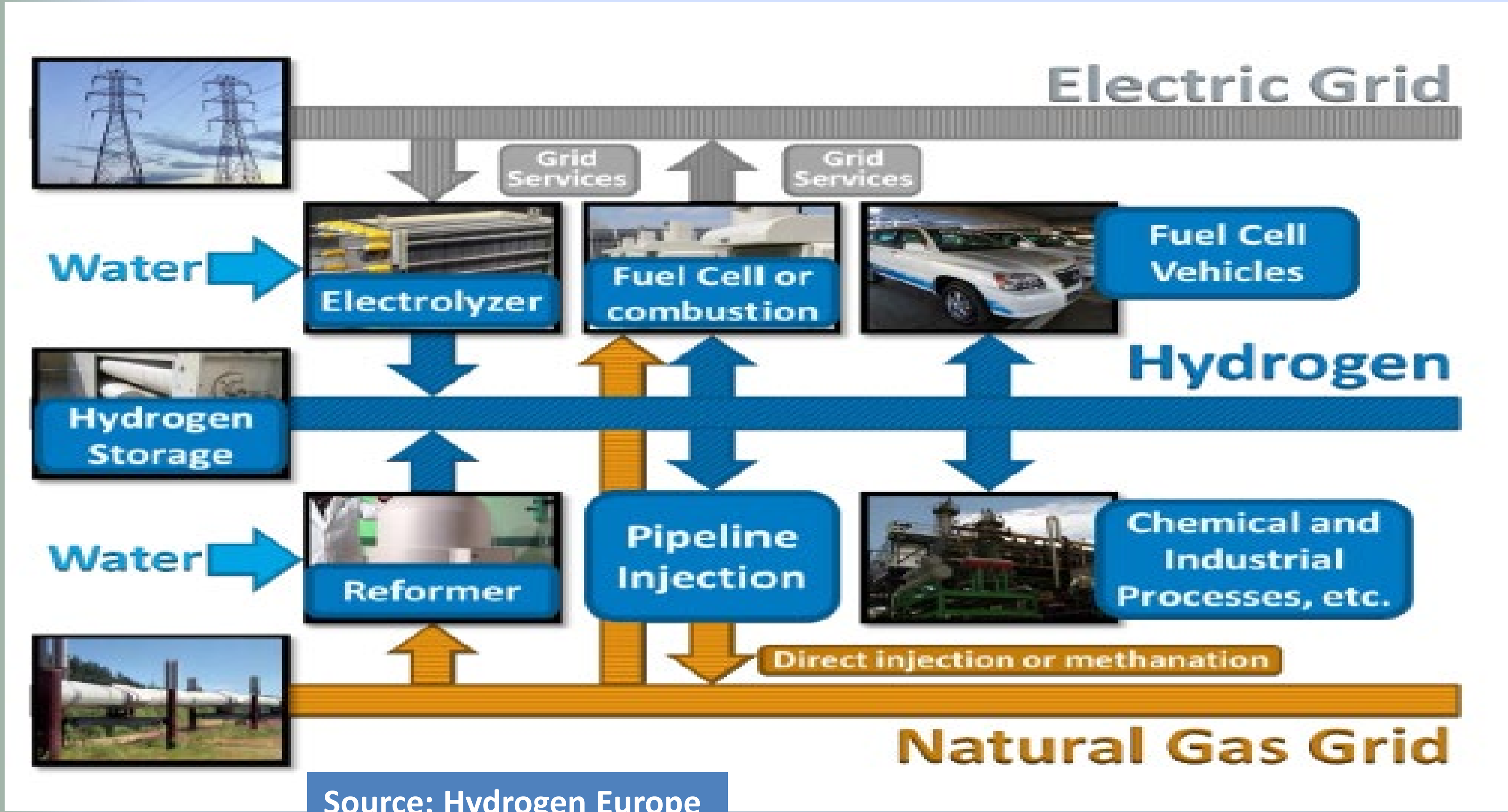
Diverse domestic sources can produce H_2

Many applications could benefit from H_2



Source: DOE H2@Scale

H_2 CAN INTEGRATE WITH THE ELECTRIC & NATURAL GAS GRIDS



Source: Hydrogen Europe

- 2.44 million miles of NG distribution pipelines in the U.S.
- 400 underground storage facilities, and 1,400 compressor stations
- ~977 GW of NG energy in US 2019 (4.5 TW global)
- 5% H_2 is significant

20% H_2 BLENDS COULD DOUBLE U.S. RENEWABLES CONSUMPTION

Cross-sectoral emissions reductions

Grid resiliency

Terawatt hours of energy storage

U.S. Projected Renewable Energy Consumption in Power Generation in 2019

702.7 TWh (Source: AEO 2020)

20% hydrogen blend in the U.S. by volume = 16 MMT/year,

~750 TWh of electricity if produced via electrolysis. (Source: Elgowainy, et al, 2020)

ELECTRICITY FROM H_2 IN TURBINES COULD SMOOTH THE TRANSITION

Big players are developing 100% hydrogen-fueled gas turbines

- Mitsubishi Hitachi Power Systems (MHPS)
- GE Power
- Siemens Energy, and
- Ansaldo Energiato)

Vattenfall's Magnum, Netherlands.

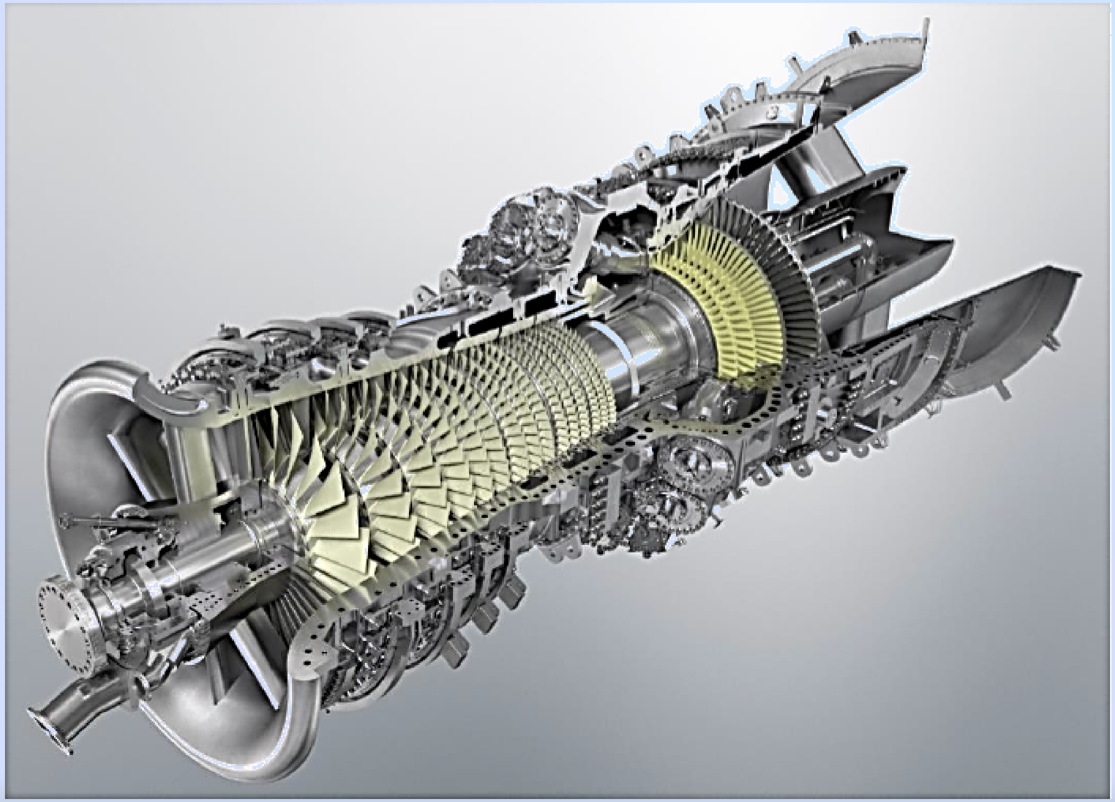
Mitsubishi Hitachi Power Systems (MHPS) has verified that conversion to H_2-fired power generation is possible on these units

High-Volume Hydrogen Gas Turbines Take Shape 05/01/2019, SonalPatel https://www.powermag.com/high-volume-hydrogen-gas-turbines-take-shape/

State of the Art: MHPS J-Series

Gas Turbines already operate on high levels of H_2

- Advanced Technology—M501 JAC

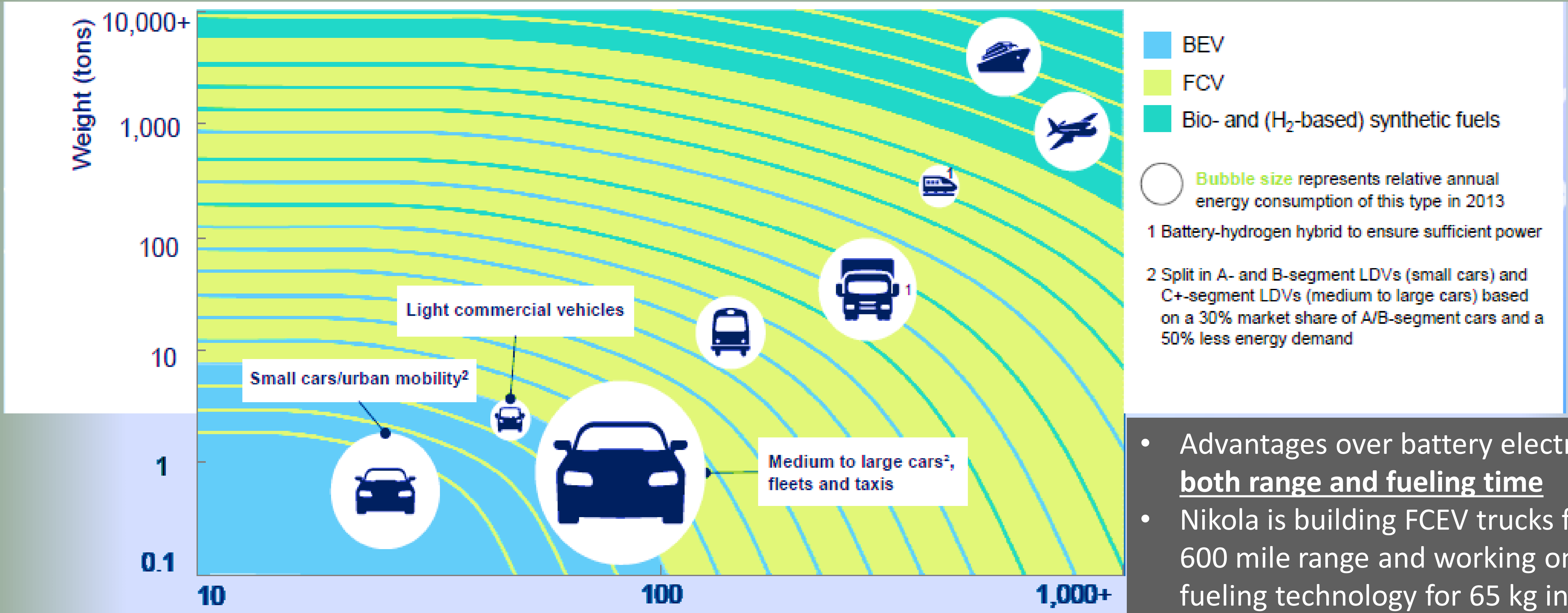


-- 425 MW
-- 44.0% Simple Cycle (SC) Efficiency
-- ~64% Combine Cycle (CC) Efficiency
-- 2 ppm NOx at the Stack
-- 50% turndown
-- 42 MW/min ramp rate
-- 30 min cold start
-- Air Cooled

---MHPS: (>1.0 million AOH* experience on the J Class equipment)
--MHPS: (>3.5 million AOH* of experience with hydrogen containing fuels)

* - AOH = Actual Operating Hours

MOBILITY: A LARGE MARKET FOR PRODUCED H_2



Source: Toyota, Hyundai, Daimler

- Advantages over battery electric in **both range and fueling time**
- Nikola is building FCEV trucks for 600 mile range and working on fueling technology for 65 kg in 15 minute. **~10MW**

UNMANNED AERIAL VEHICLES (UAV) RUNNING ON CLEAN H_2

Faster refueling for less down time

No battery or cable jumble

Better cold weather endurance

Better high altitude performance

Quiet operation

- e.g., Ballard is marketing their FCair™ UAV Power Systems
- 3x more run-time than the best batteries
- UAV market is projected to grow dramatically

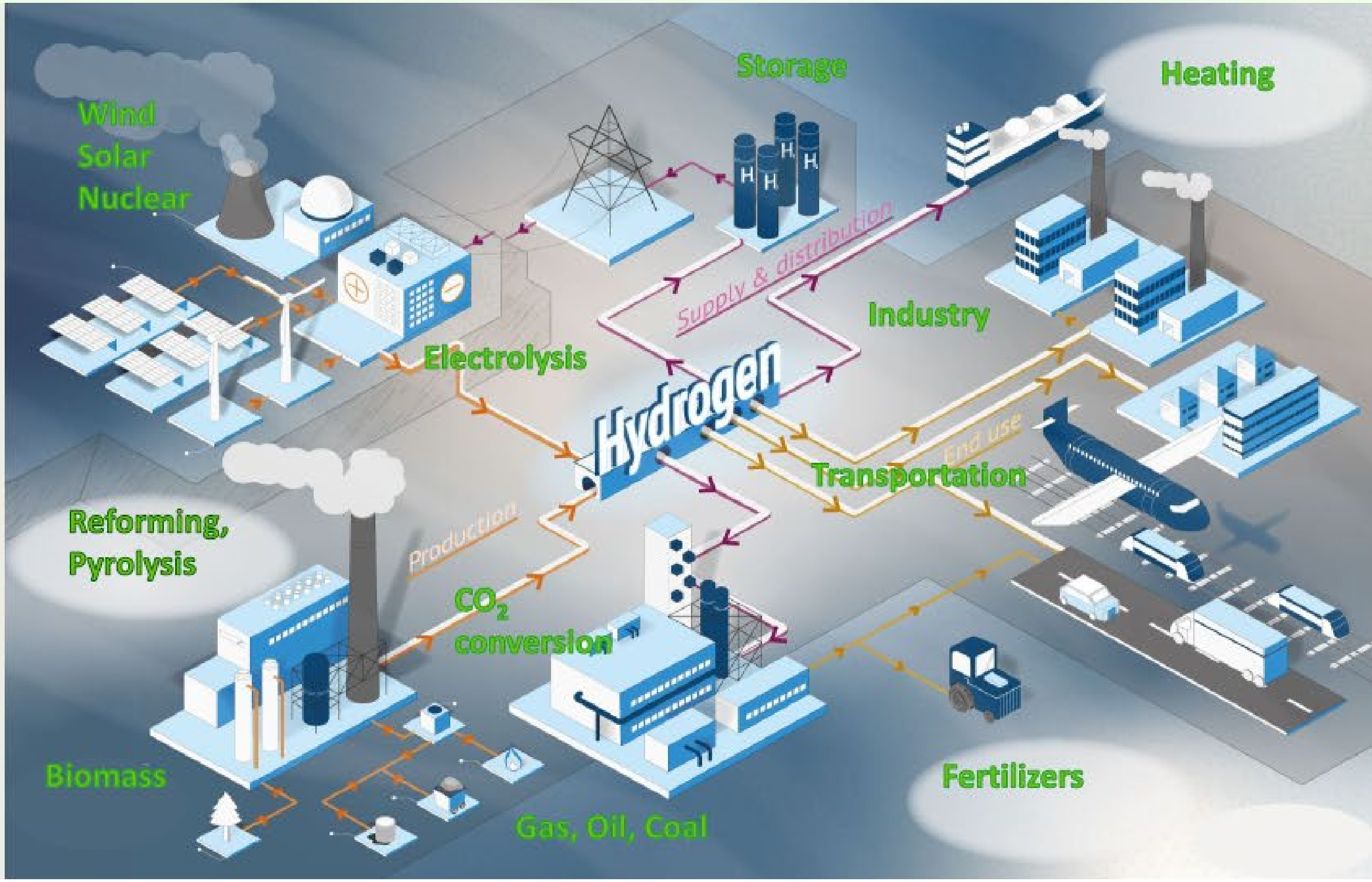
BENEFITS OF H_2 PRODUCTION AND REFUELING

- Fast refuel time – similar to diesel engines
- H_2 fuel can be produced without CO_2 emissions (blue and green H_2)
- H_2 production can serve to load balancing mechanism
- H_2 can provide an effective form of storage for intermittent energy sources

RESEARCH FRONTIER

RESEARCH AND DEVELOPMENT STRATEGY AT DOE

1) **Accelerate R&D to reduce cost**
2) **De-risk demonstration and enable deployments**
3) **Strategic scale up**
    - **Clusters**: co-locate supply and demand (e.g., at ports) and enable infrastructure
    - **RFI feedback** and regional analysis will guide activities



From DOE EERE HFTO 2021 Annual Merit Review

THERE ARE MULTIPLE PATHWAYS TO PRODUCE H_2

GREY → BLUE (CCS) → GREEN

FOSSIL RESOURCES

Coal Gasification with CCUS

Natural Gas Conversion with CCUS

BIOMASS/WASTE

Biomass Conversion

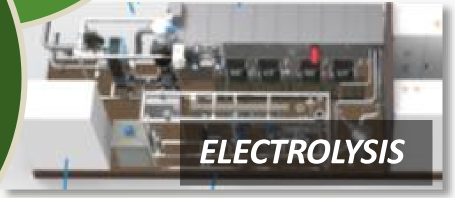
Waste to Energy

ADVANCED WATER SPLITTING

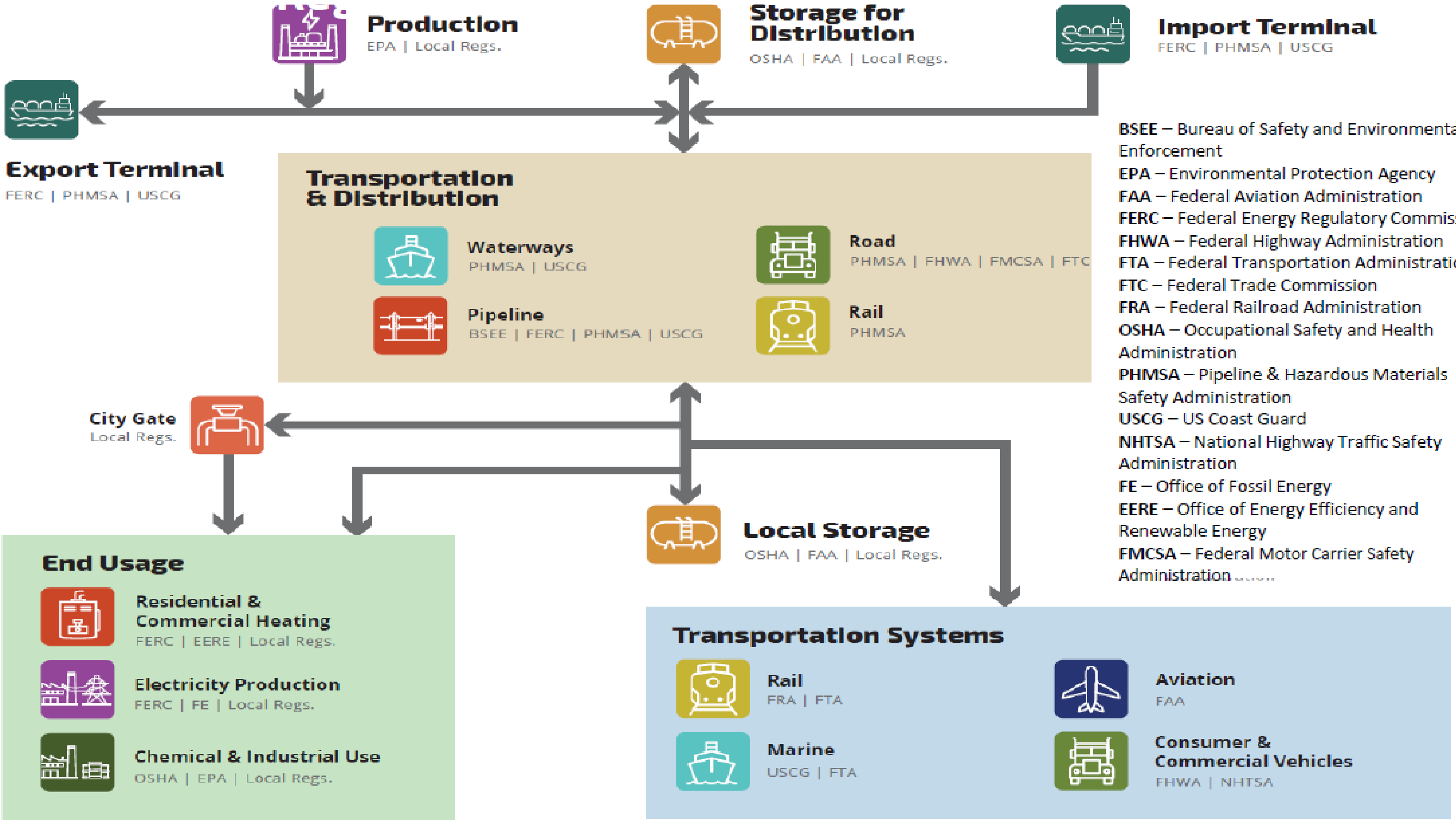
Low and High Temp Direct Solar

High Temp Electrolysis

Low Temp Electrolysis



THERE IS REGULATORY COMPLEXITY



BSEE – Bureau of Safety and Environmental Enforcement
EPA – Environmental Protection Agency
FAA – Federal Aviation Administration
FERC – Federal Energy Regulatory Commission
FHWA – Federal Highway Administration
FTA – Federal Transportation Administration
FTC – Federal Trade Commission
FRA – Federal Railroad Administration
OSHA – Occupational Safety and Health Administration
PHMSA – Pipeline & Hazardous Materials Safety Administration
USCG – US Coast Guard
NHTSA – National Highway Traffic Safety Administration
FE – Office of Fossil Energy
EERE – Office of Energy Efficiency and Renewable Energy
FMCSA – Federal Motor Carrier Safety Administration

Gaps Identified

- **FERC for pipeline transmission, electricity production, and heating**
- **FHWA for bridges and tunnels**
- **FRA, USCG, and FAA for rail, maritime, and aviation use**

Final Report Available:
energy.sandia.gov/wp-content/uploads/2021/03/H2-Regulatory-Map-Report_SAND2021-2955.pdf

I skate to where the puck is going to be and not where it has been.

Wayne Gretzky

Thank you for your kind attention

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