SEPT. 16, 2024

PRESENTATION AT HYDROGEN EMISSIONS AND ENVIRONMENTAL IMPACTS WORKSHOP

IRVINE, CA

Modeling and analysis of hydrogen value chain: environmental and economic assessment

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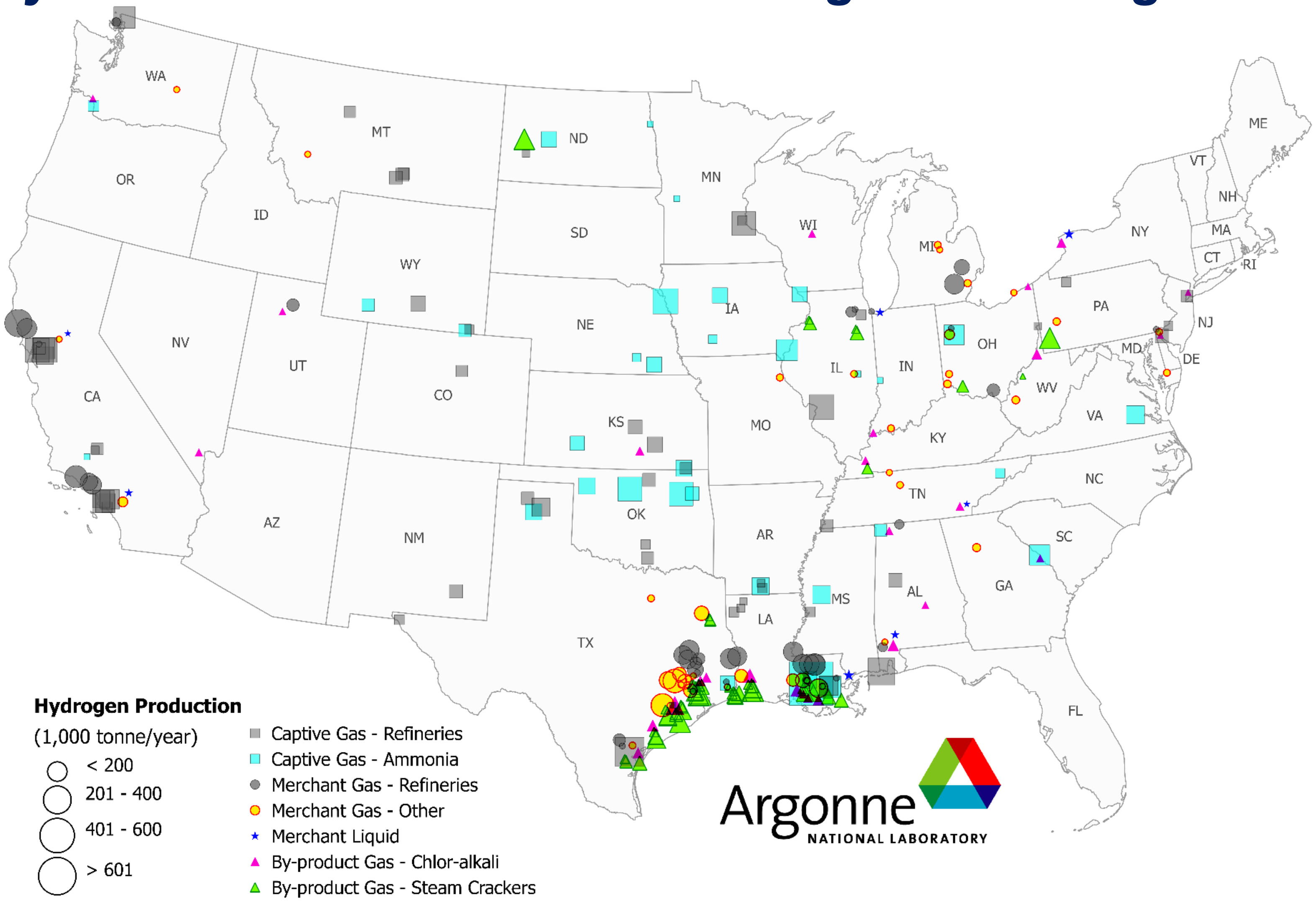
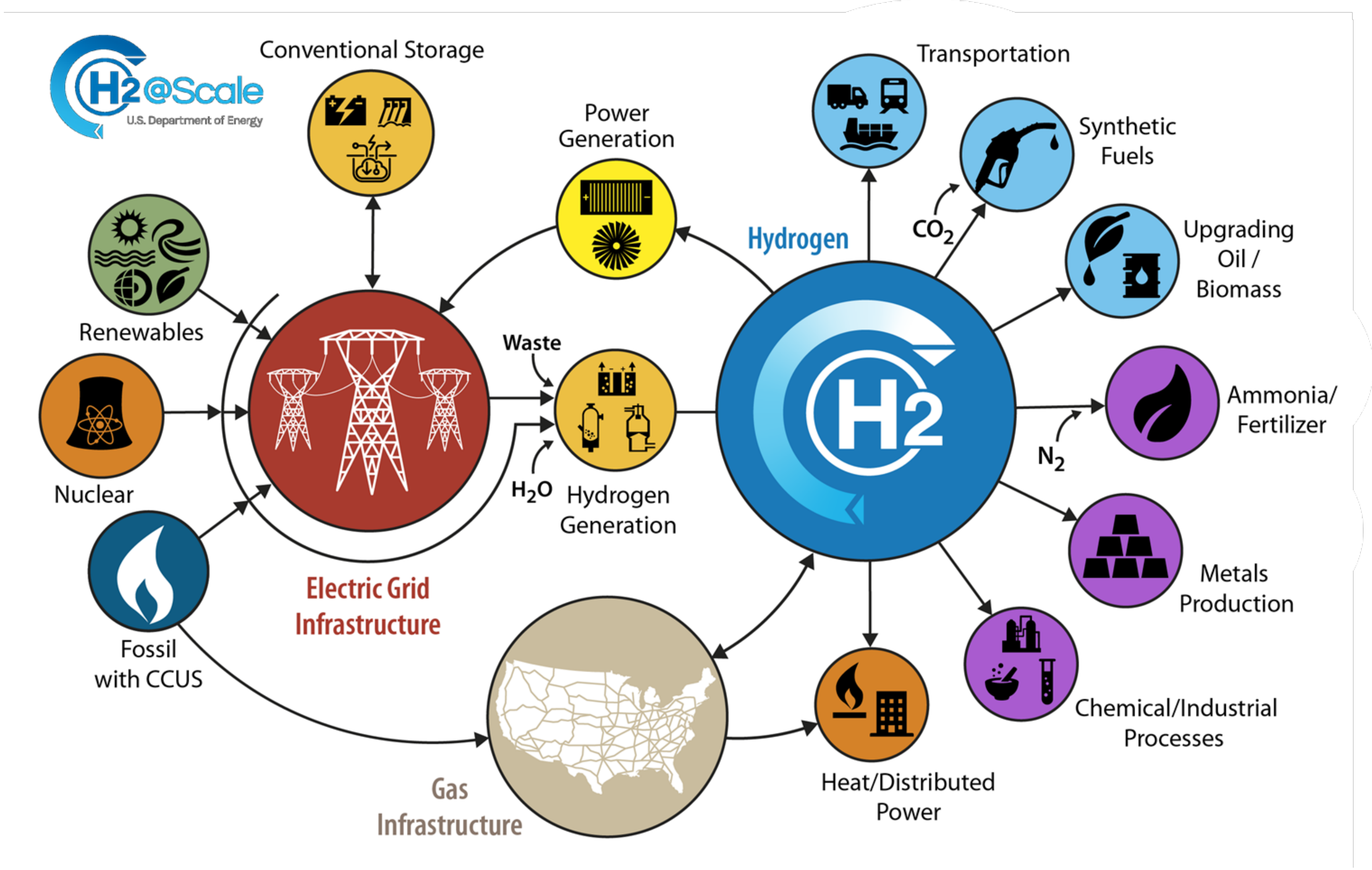
Today, ~ 10M metric tons (1.5 Quad Btu) of hydrogen are produced in the U.S. annually, mainly from steam methane reforming of natural gas

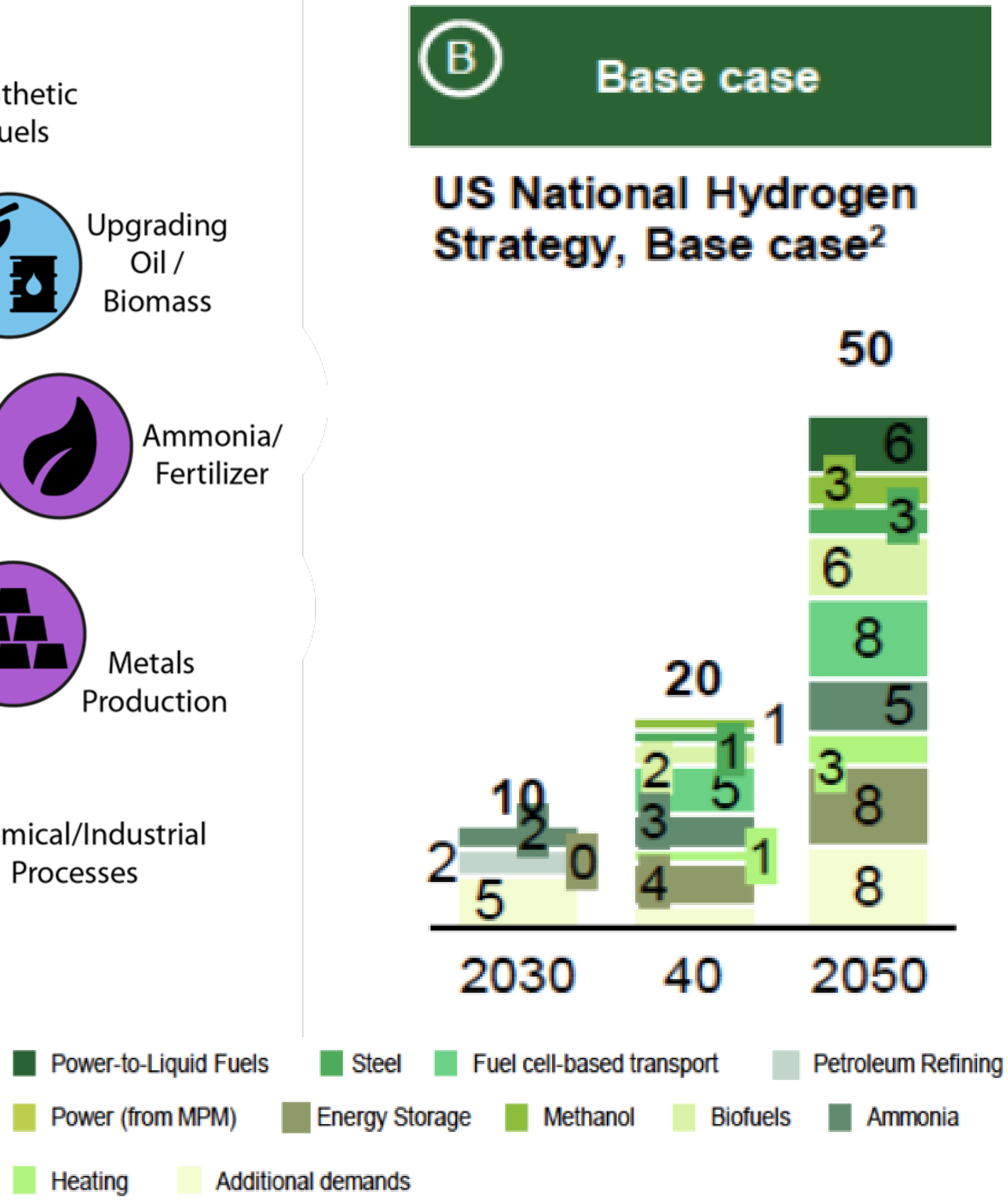


- Currently, >90% of hydrogen production is for industrial use
- Hydrogen is mainly produced next to industrial use
- 1600 mi of transmission pipelines, mainly in the gulf

H2@Scale: current and potential future value chain



https://liftoff.energy.gov/clean-hydrogen/



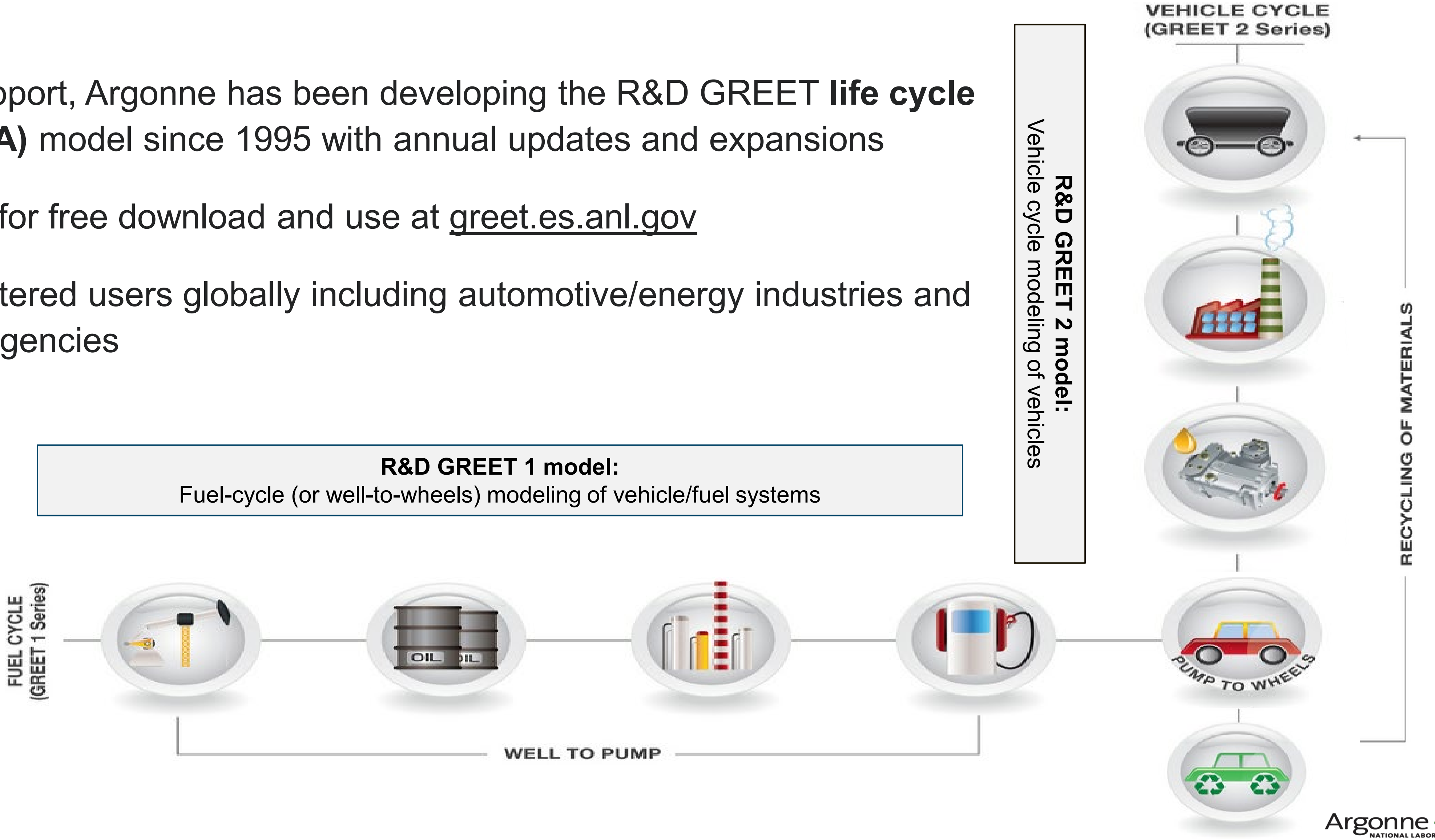
➢ Most of the projected increase in hydrogen liftoff is in industrial use

The R&D GREET® (Greenhouse gases, Regulated Emissions, and Energy use in Technologies) model

- With DOE support, Argonne has been developing the R&D GREET **life cycle analysis (LCA)** model since 1995 with annual updates and expansions
- It is available for free download and use at greet.es.anl.gov
- >60,000 registered users globally including automotive/energy industries and government agencies

R&D GREET 1 model:
Fuel-cycle (or well-to-wheels) modeling of vehicle/fuel systems

R&D GREET 2 model:
Vehicle cycle modeling of vehicles



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R&D GREET includes a suite of models and tools

- R&D GREET coverage
  - ✓ R&D GREET1: fuel cycle (or WTW) model of energy systems
  - ✓ R&D GREET2: vehicle manufacturing cycle and material embodied emissions
- Modeling platform
  - ✓ Excel
  - ✓ .net
- Other GREET derivatives
  - ✓ 45VH2-GREET for IRA based on GREET1
  - ✓ 40BSAF-GREET for IRA based on GREET1
  - ✓ ICAO-GREET by ANL, based on GREET1
  - ✓ CA-GREET by CARB, based on GREET1
  - ✓ China-GREET and MENA-GREET by ANL, with support of Aramco
  - ✓ AFLEET by ANL: alternative-fuel vehicles energy, emissions, and cost estimation
  - ✓ EverBatt by ANL: cost modeling of remanufacturing and recycling of EV batteries

GREET use by agency

United States Government	Production tax credits under IRA
California Environmental Protection Agency Air Resources Board	CA-GREET3.0 built based on and uses data from ANL GREET
State of Oregon Department of Environmental Quality (DEQ)	Oregon Dept of Environ. Quality Clean Fuel Program
EPA	EPA RFS2 used GREET and other sources for LCA of fuel pathways; GHG regulations
NHTSA	National Highway Traffic Safety Administration (NHTSA) fuel economy regulation
ICAO / Federal Aviation Administration	FAA and ICAO AFTF using GREET to evaluate aviation fuel pathways
USDRIVE	GREET was used for the US DRIVE Fuels Working Group Well-to-Wheels Report
MARAD Maritime Administration	LCA of renewable marine fuel options to meet IMO 2020 sulfur regulations for the DOT MARAD
USDA	US Dept of Agriculture: ARS for carbon intensity of farming practices and management; ERS for food environmental footprints; Office of Chief Economist for bioenergy LCA
Government of Canada	Environment and Climate Change Canada for its Clean Fuel Standard

R&D GREET sustainability metrics include energy use, criteria air pollutants, GHG, and water consumption

Energy use

- Total energy: fossil energy and renewable energy
- Fossil energy: petroleum, natural gas, and coal
- Non-fossil energy: biomass, nuclear energy, hydro-power, wind power, and solar energy

Resource availability and energy security

Air pollutants

- VOC, CO, NOx, PM_{10}, $PM_{2.5}$, and SOx
- Estimated separately for total and urban (a subset of the total) emissions

Air quality, human health and environmental justice

Greenhouse gases

- CO_2, CH_4, N_2O, others
- CO_{2e} of the five (with their global warming potentials)

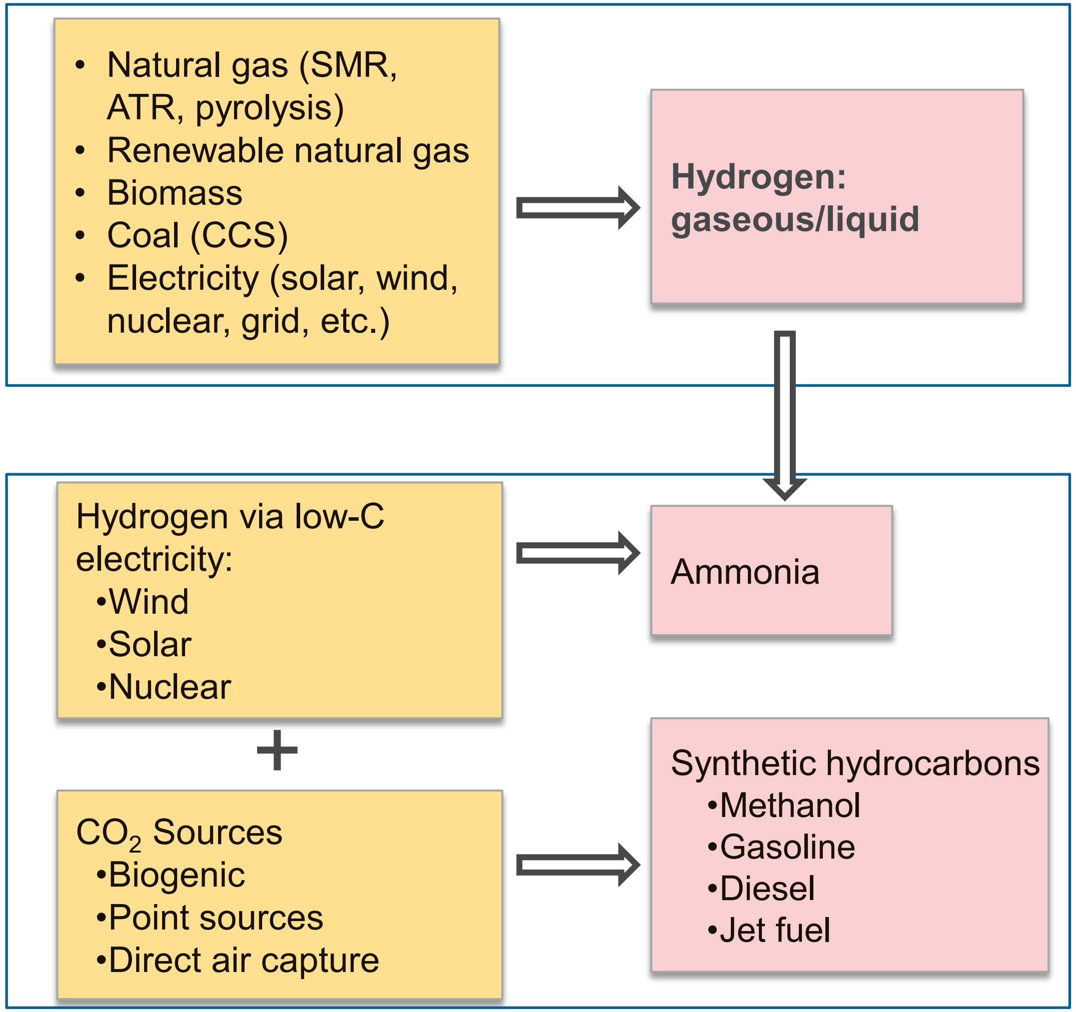
Global warming impacts

Water consumption

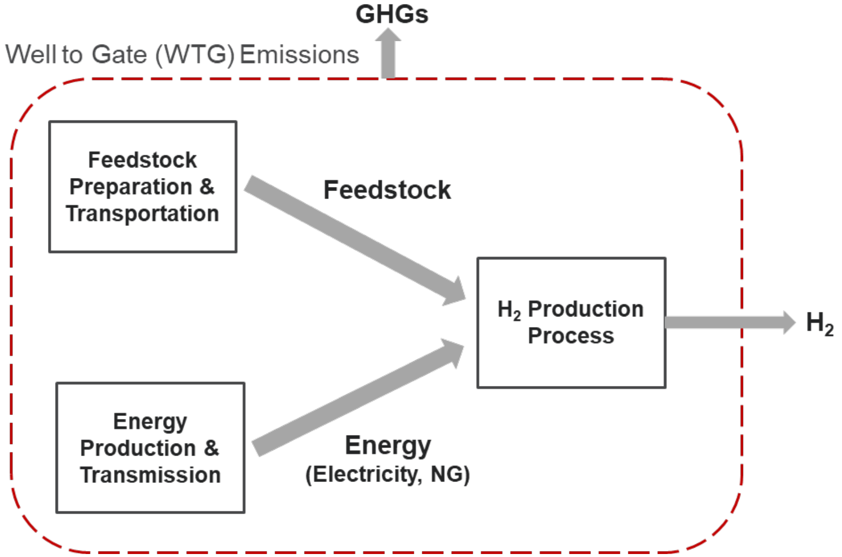
- Addressing water supply and demand (energy-water nexus)

Regional/seasonal water stress impacts

R&D GREET covers current and emerging H_2 technologies and applications



R&D GREET 2023 was released Dec. 2023



Hydrocarbon based

1) Steam Methane Reforming (NG SMR): **w CCS & w/o CCS**
2) SMR using renewable natural gas (RNG)
3) Autothermal Reforming (NG ATR): **using NG & RNG**
4) Methane Pyrolysis: **using NG & RNG**
5) Coal Gasification: **w CCS & w/o CCS**
6) Biomass Gasification
7) Pet coke gasification
8) Dark Fermentation and MEC
9) Coke Oven Gas
10) Methanol and ethanol reforming

Electrolysis based

1) Low Temperature Electrolysis using PEM and alkaline
2) High Temperature Electrolysis using SOEC
3) Electrolysis HTGR
4) Thermochemical Cracking of Water

Byproduct H_2

- From NGL Steam Crackers
- From Chlorine plants

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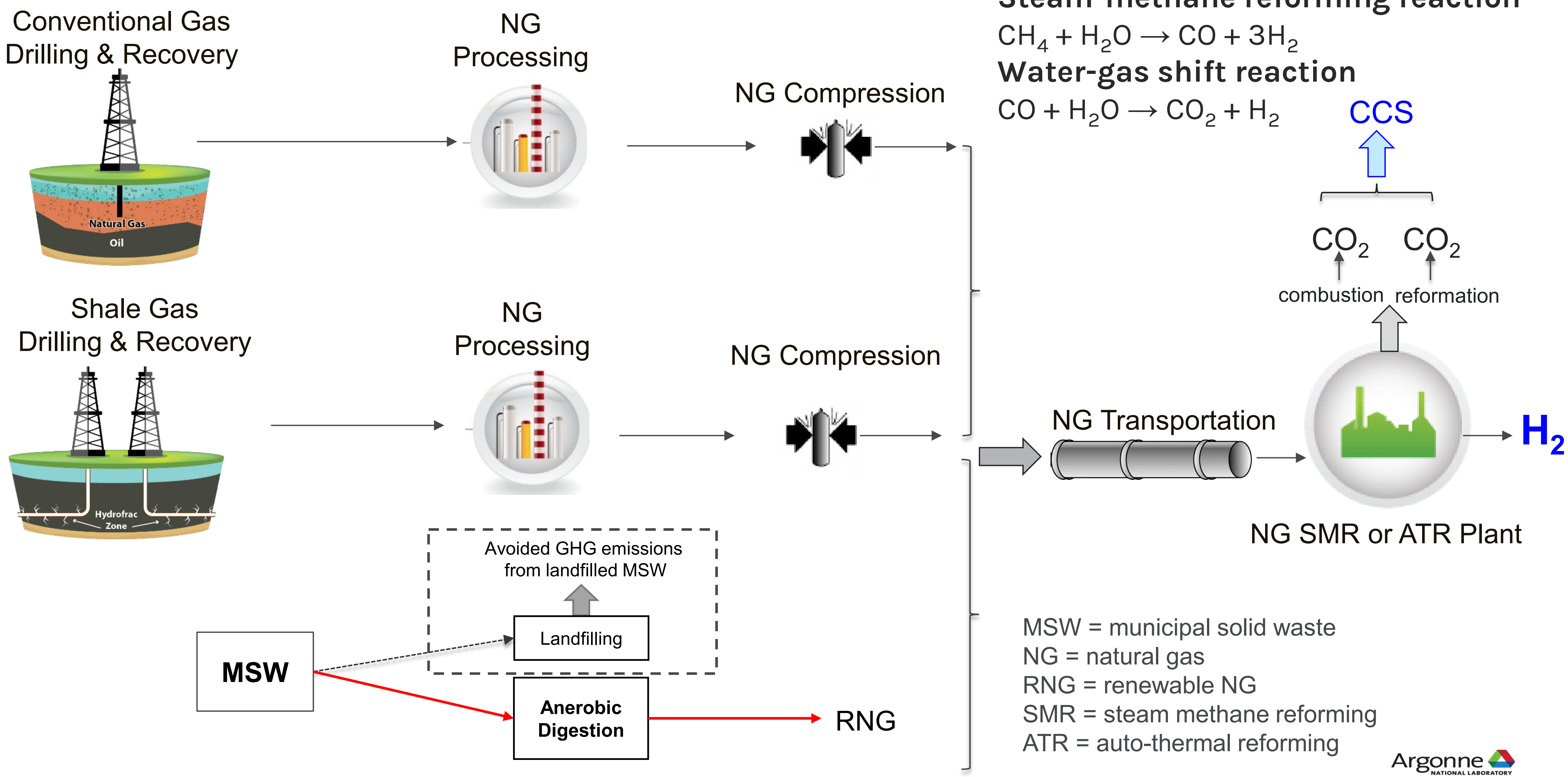
LCA of H_2 production via methane (CH_4) reforming

Steam-methane reforming reaction

$CH_4 + H_2O \rightarrow CO + 3H_2$

Water-gas shift reaction

$CO + H_2O \rightarrow CO_2 + H_2$



MSW = municipal solid waste
NG = natural gas
RNG = renewable NG
SMR = steam methane reforming
ATR = auto-thermal reforming

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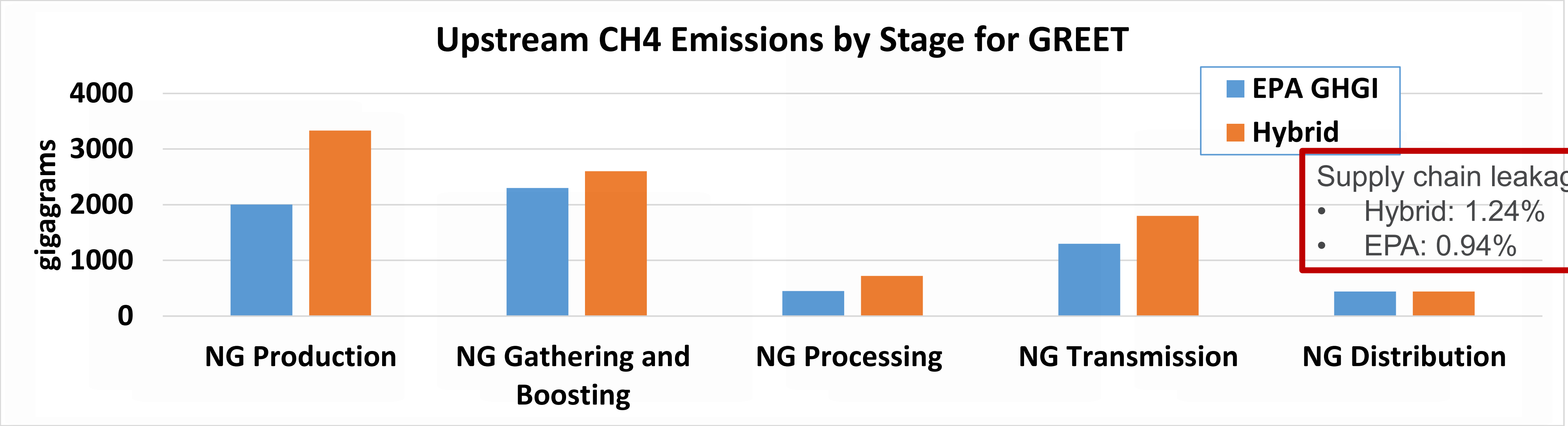
ANL evaluates studies of methane leakage of NG supply chains for GREET

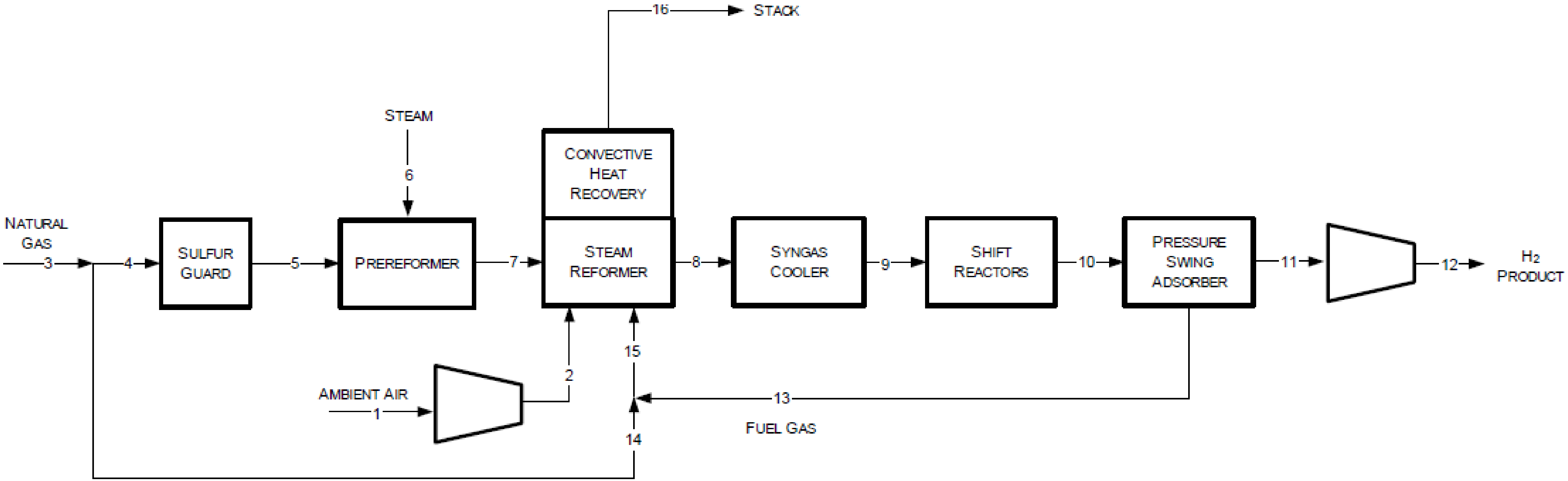
Sector	CH4 Emissions: Gross Volumetric Leakage (Percent)											
	EPA-GHGI 5 yr avg (2011)	NOAA-DJ Basin (2012)	EPA-GHGI 2011 data (2013)	Stanford-US (2014)	CSU/ WSU studies (2015)	NETL-2012 data (2017)	Alvarez EDF-US 2015 data (2018)	Barkley-Marcellus (2019)	Howarth-US Shale Gas (2019)	EPA GHGI 2017 (2019)	Barkley-South/East US 2012 data (2021)	EPA GHGI 2021 (2023)
Gas Field	1.16	2.3-7.7	0.44		0.58		1.5-2.2	0.2-0.8		0.65	0.9-1.1	0.42
Processing	0.15		0.16		0.09		0.13			0.07		0.06
Transmission	0.39		0.34		0.25		0.32			0.19		0.20
Distribution	0.28		0.23		0.07		0.08			0.07		0.07
Total	1.97		1.17	3.6-7.1	0.99	1.3-2.2	2.0-2.7		2.9-4.0	0.98		0.74



Supply chain leakage rate:
- Hybrid: 1.24%
- EPA: 0.94%

➢The bulk of methane emissions is in the field and over 300,000 miles of transmission, moving >30 Quads Btu

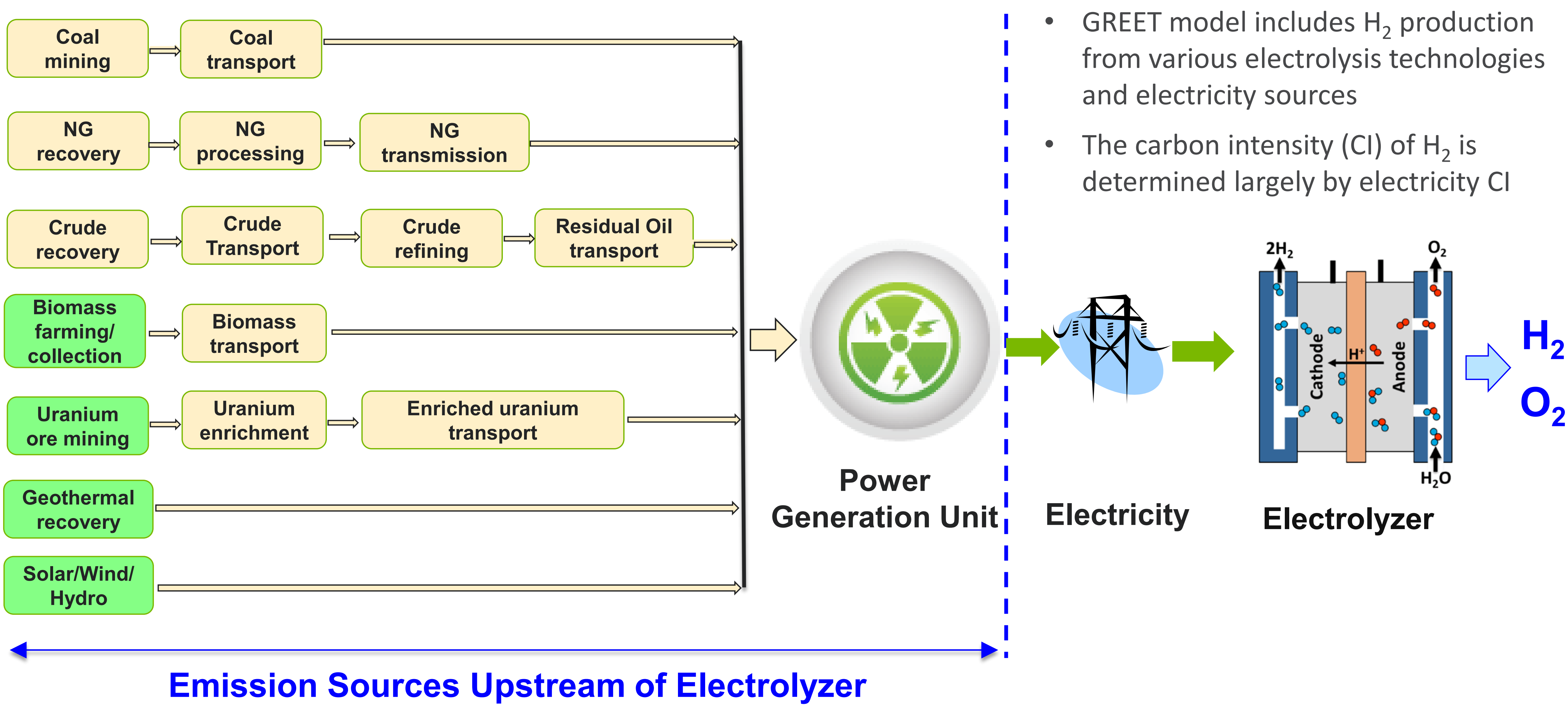
Hydrogen production process via methane reforming



Reference: Lewis et al, "COMPARISON OF COMMERCIAL, STATE OF THE ART, FOSSIL BASED HYDROGEN PRODUCTION TECHNOLOGIES," DOE/NETL-2022/3241

➢ Hydrogen appears near the end of the production processes after separation unit

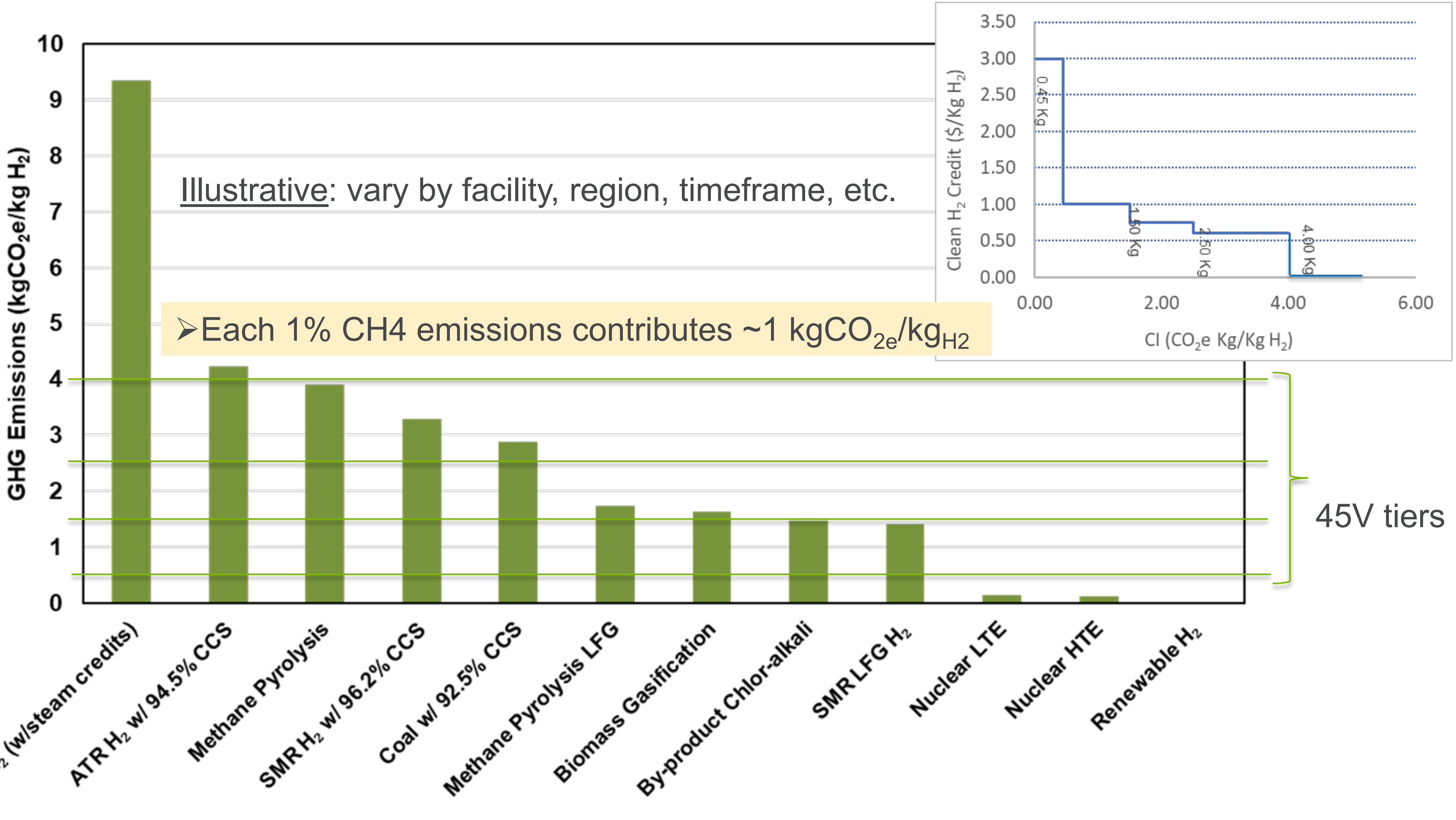
LCA of H_2 production via water electrolysis



- GREET model includes H_2 production from various electrolysis technologies and electricity sources
- The carbon intensity (CI) of H_2 is determined largely by electricity CI

➢Hydrogen is produced in a separate channel from oxygen with high purity >99.9%

Sample WTG H_2 production GHG emissions in R&D GREET



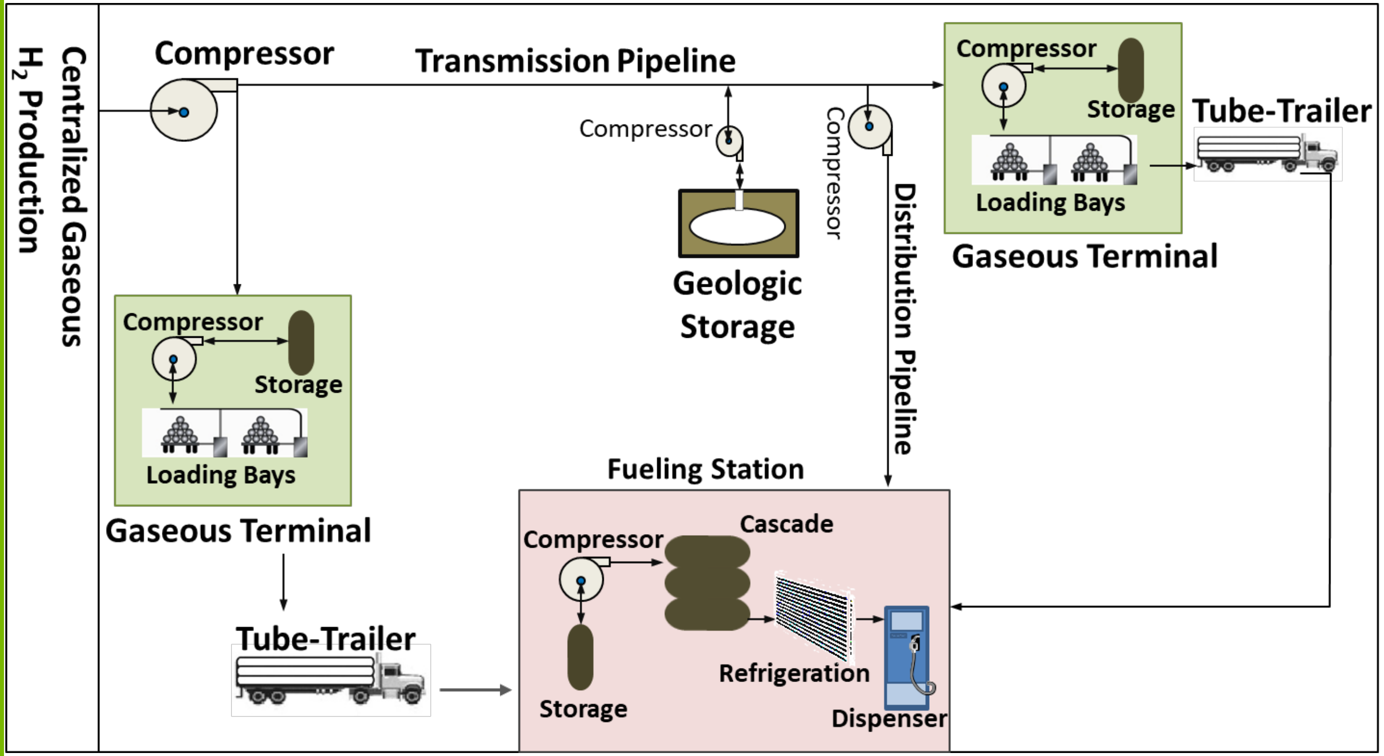
Illustrative: vary by facility, region, timeframe, etc.

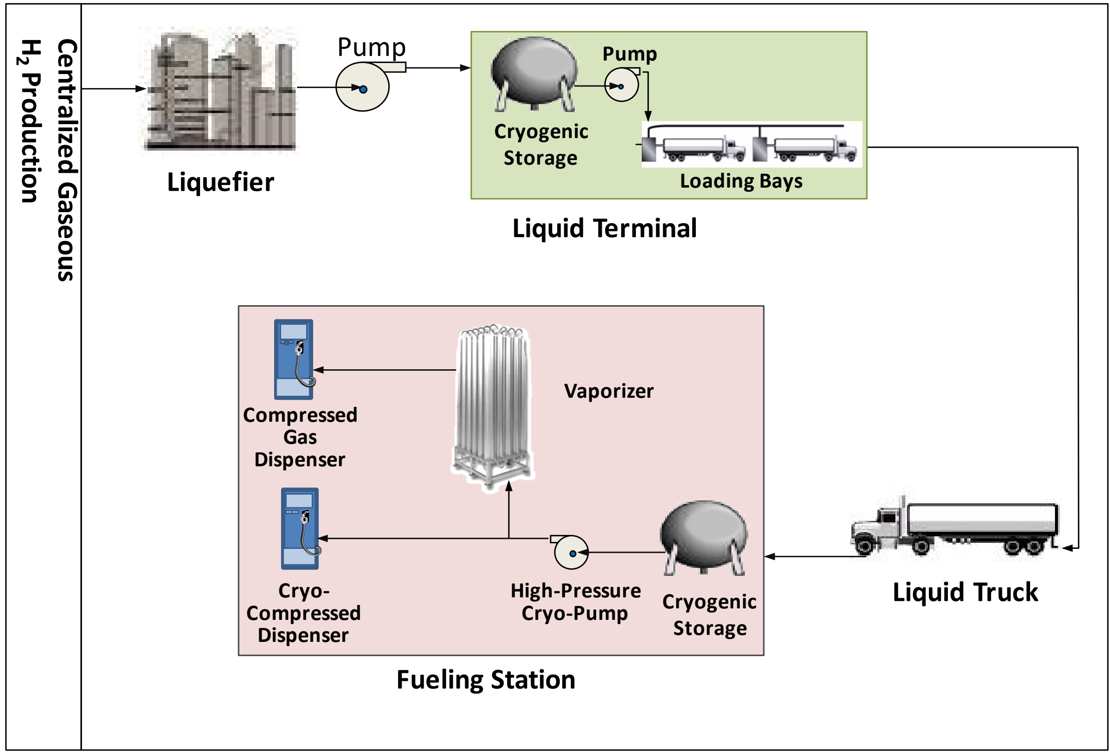
- Each 1% CH4 emissions contributes ~1 $kgCO_{2e}/kg_{H2}$

45V tiers

Elgowainy, Amgad, Pradeep Vyawahare, Clarence Ng, Adarsh Bafana, Andrew Burnham, Pingping Sun, Hao Cai, et al. (2022) "Hydrogen Life Cycle Analysis in Support of Clean Hydrogen Production." Argonne National Laboratory, ANL/ESIA-22/2. https://www.osti.gov/biblio/1892005.

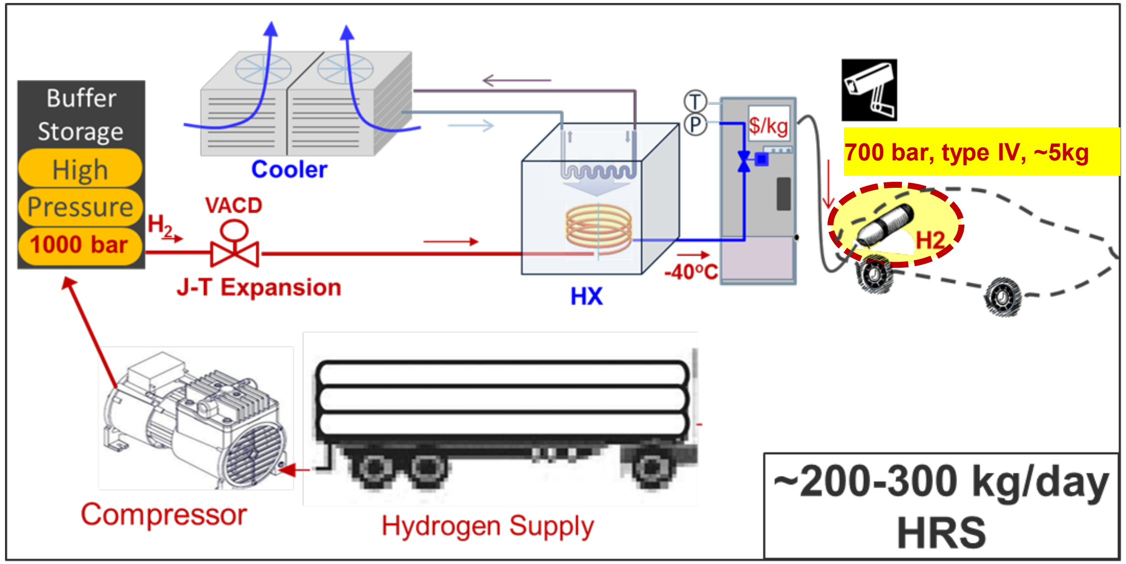
Hydrogen delivery involves energy intensive processes such as compression, liquefaction, storage and trucking



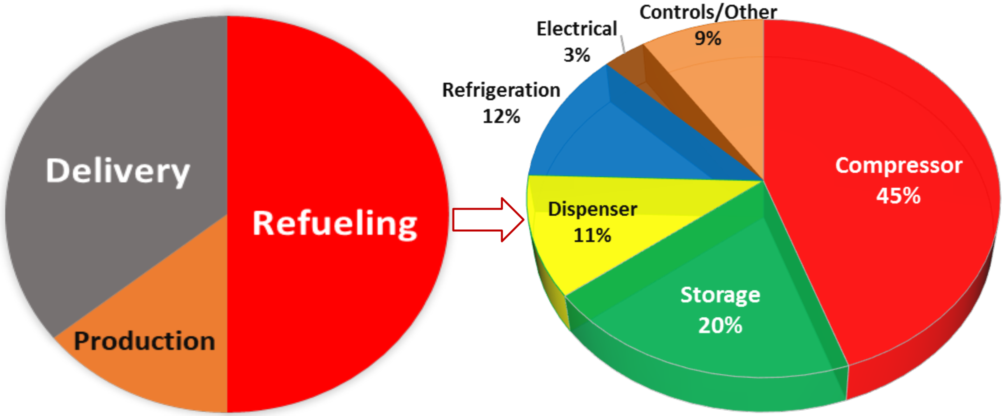


- ➢ Fugitive emissions in gaseous hydrogen delivery pathways are unknown but believed to be small
- ➢ Currently, emissions in liquid hydrogen delivery pathways are significant
  - ✓ These are controlled releases that can be easily mitigated
  - ✓ ~1% of produced hydrogen is liquefied

Cost of hydrogen delivery and refueling for FCEVs is strongly driven by onboard storage requirement and H_2 supply chain



✓ HX: Heat Exchange	✓ VACD: Variable Area Control Device
✓ J-T: Joule-Thomson	✓ CA: California



Bulk of H_2 cost is in delivery and refueling

HRS

https://www.sciencedirect.com/science/article/pii/S0360319917320311

➢ The main drivers for reducing hydrogen losses are safety and economics

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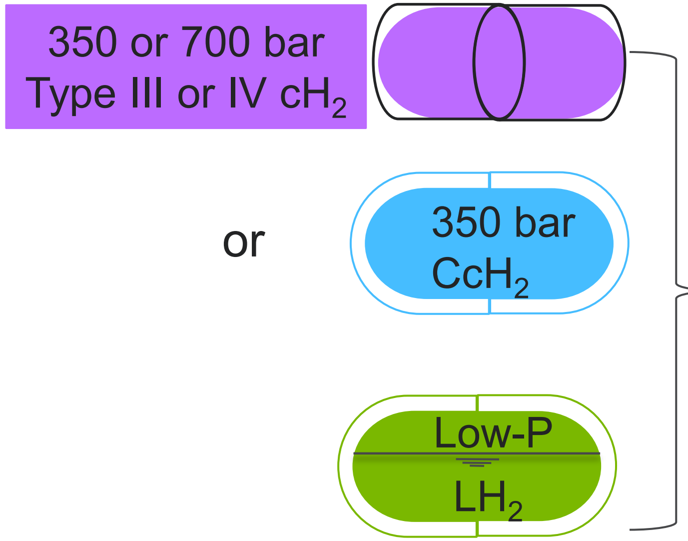
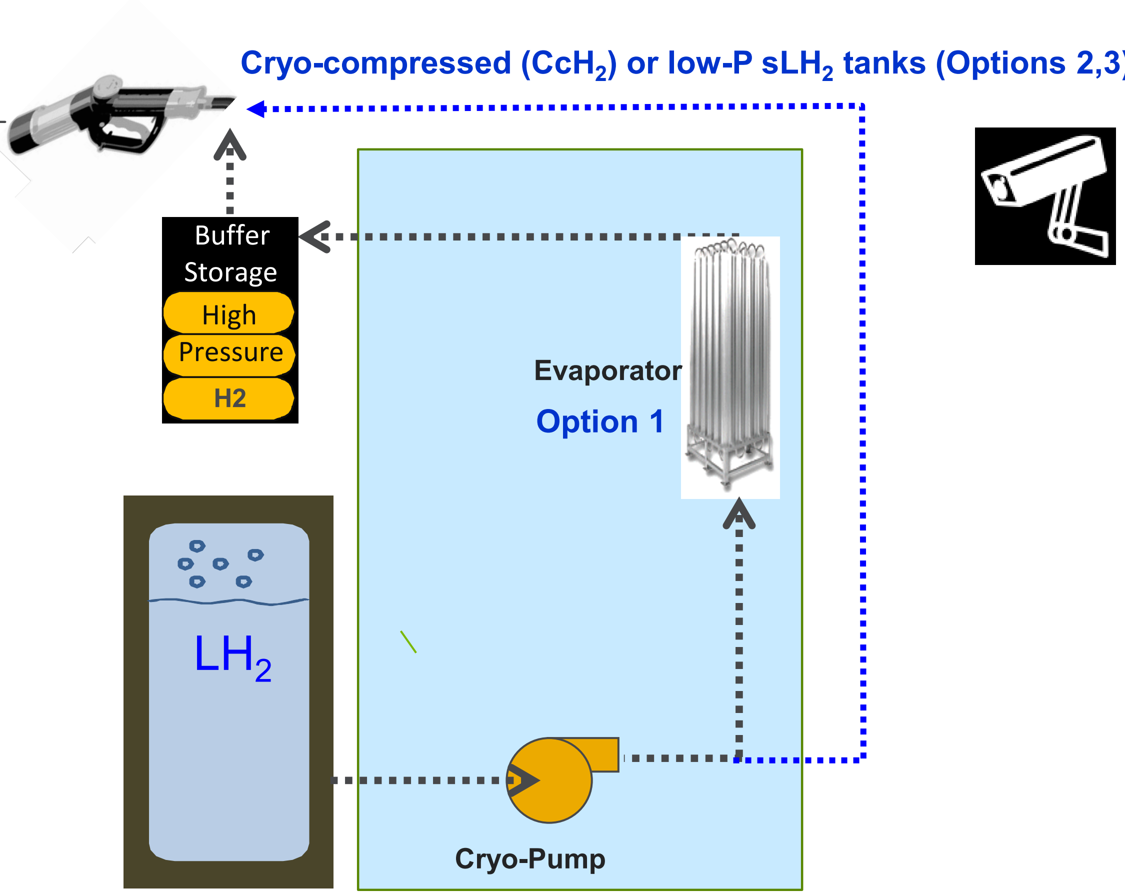
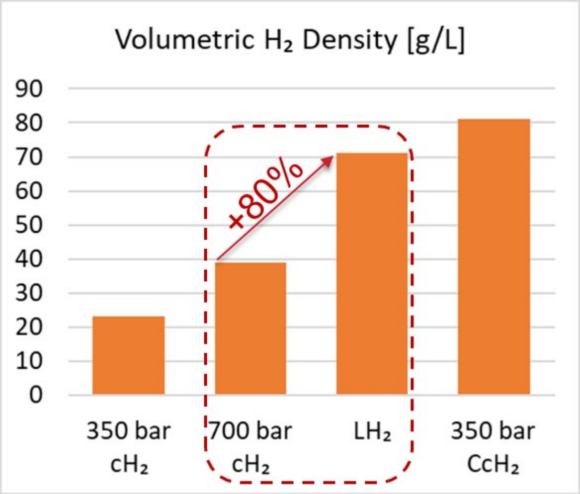
Versatile refueling configurations with LH_2 delivery: simplifies HRS configuration

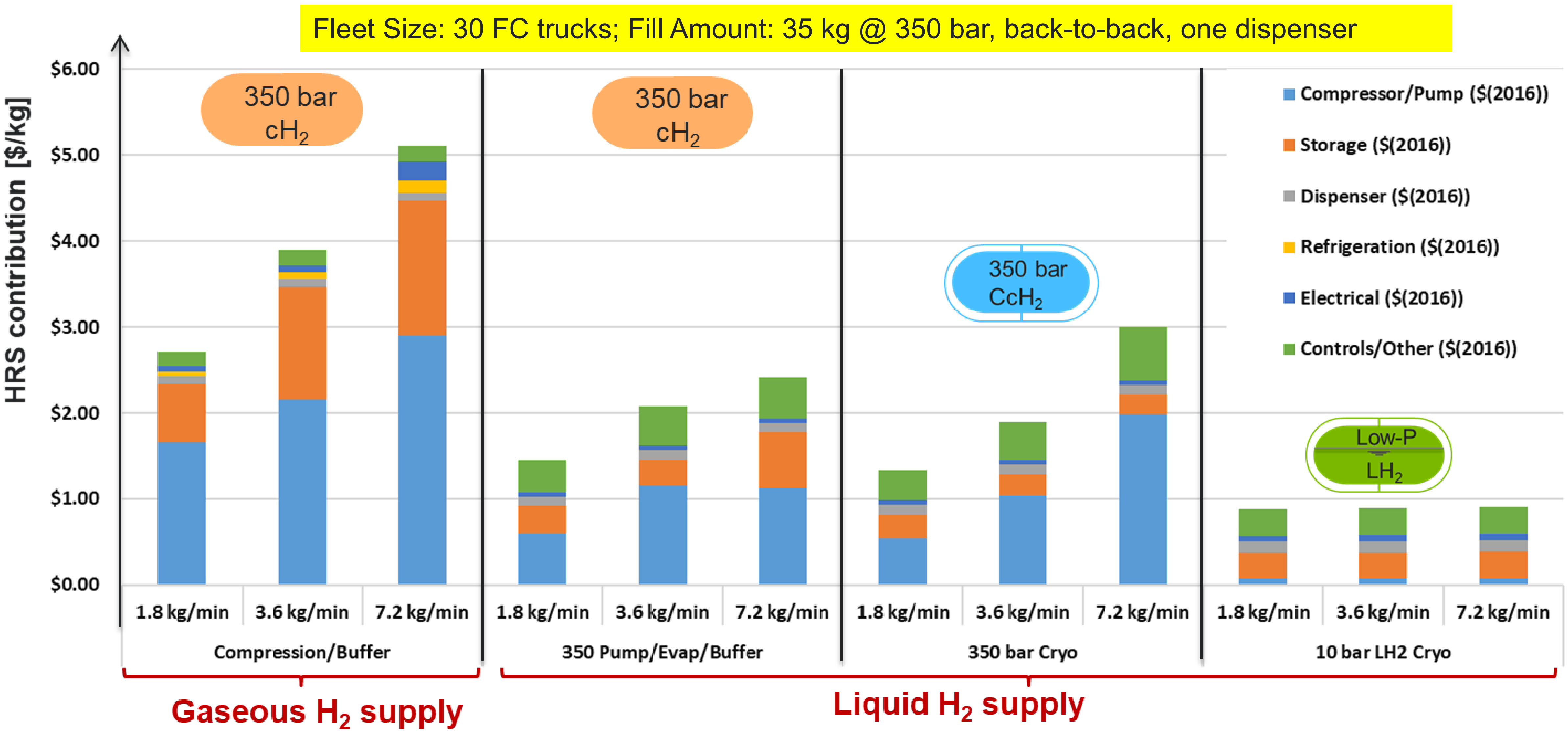






- ✓ LH_2: Liquid Hydrogen
- ✓ CcH_2: Cryo-compressed hydrogen
- ✓ cH_2: compressed hydrogen
- ✓ Low-P: Low Pressure (<10 bar)

Liquid H_2 supplied stations can handle faster fills with lower cost compared to gaseous H_2 supply



➢ Delivered hydrogen cost is additional

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Energy use and CO_2 emissions are critical for environmental sustainability of H_2 liquefaction*

Region	Liquefaction Capacity (MT/day)
California	30
Louisiana	70 (2x35)
Indiana	30
New York	40
Alabama	30
Ontario	30
Nevada	30
Quebec	27
Tennessee	6
Total	~300 (~1% of total H_2 production)

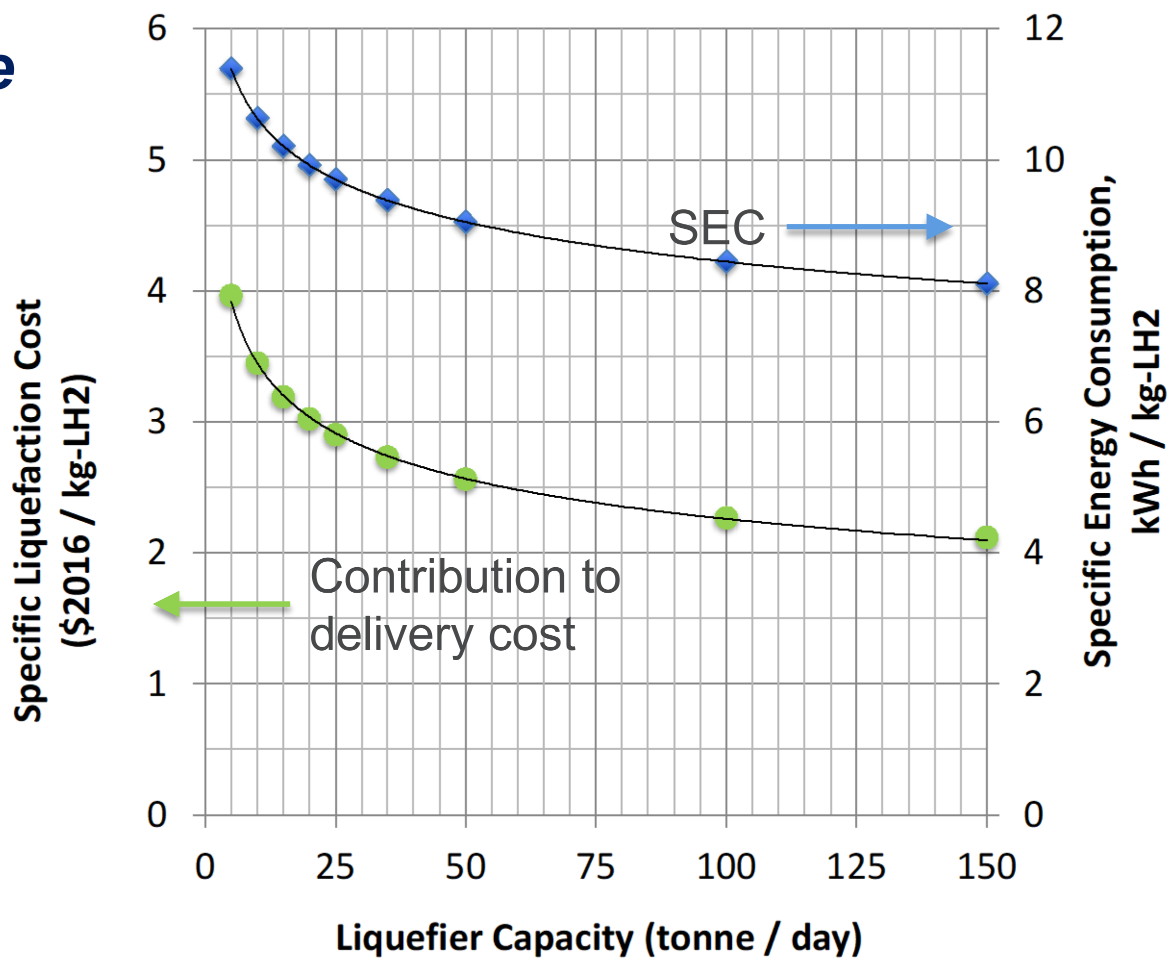
→ Liquefaction CO_2 emissions*= 0-10 $kg_{CO_{2e}}/kg_{H_2}$ (~5 with US mix in 2022)

- Additional H_2 liquefaction plants have been recently announced to serve the growing H_2 market
- Low-carbon electricity is critical for sustainability of LH_2 supply

* At 11 $kWhe/kg_{H2}$

H_2 liquefaction is energy and cost intensive

- Scaling laws based on aggregation of industry input
  - Liquefier CAPEX
  - Specific energy consumption (SEC)
- Modeling and analysis in the literature suggest SEC can potentially be as low as 6 kWh/kg
- SLC – Specific liquefaction cost



➢ The main drivers for reducing hydrogen losses are safety and economics

Delivered	Liquefier	SLC	SEC	GHG Emissions 2021 (US mix)
	5 tpd	\$4.0 / kg-LH2	11 kWh / kg	4.8 $kgCO_{2e}$ / kgH_2
30 tpd	33 tpd	**\$2.8 / kg-LH2**	**9.4 kWh / kg**	**4.1 $kgCO_{2e}$ / kgH_2**
120 tpd	130 tpd	**\$2.1 / kg-LH2**	**8.2 kWh / kg**	**3.6 $kgCO_{2e}$ / kgH_2**

Frank, E.D., Elgowainy, A., Reddi, K. and A. Bafana (2021) "Life-Cycle Analysis of Greenhouse Gas Emissions from Hydrogen Delivery: A Cost-Guided Analysis," *International Journal of Hydrogen Energy*, ISSN 0360-3199. https://doi.org/10.1016/j.ijhydene.2021.04.078.

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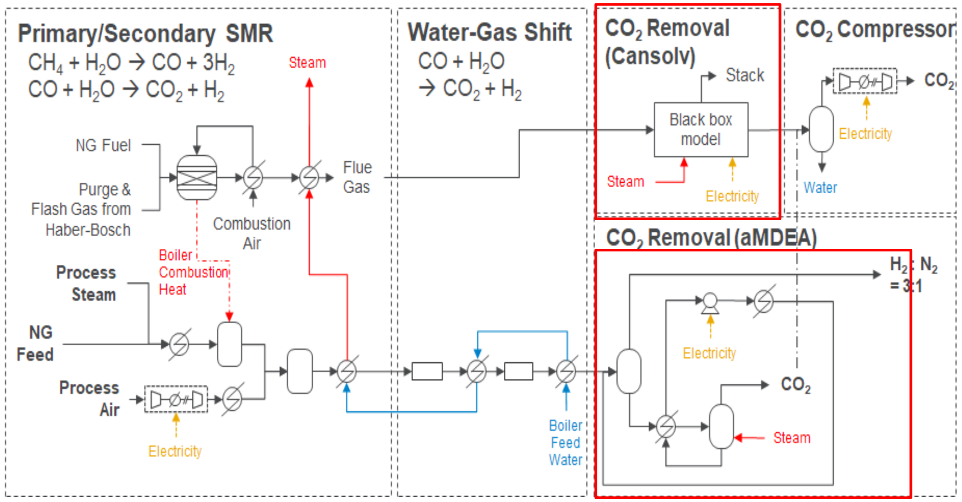
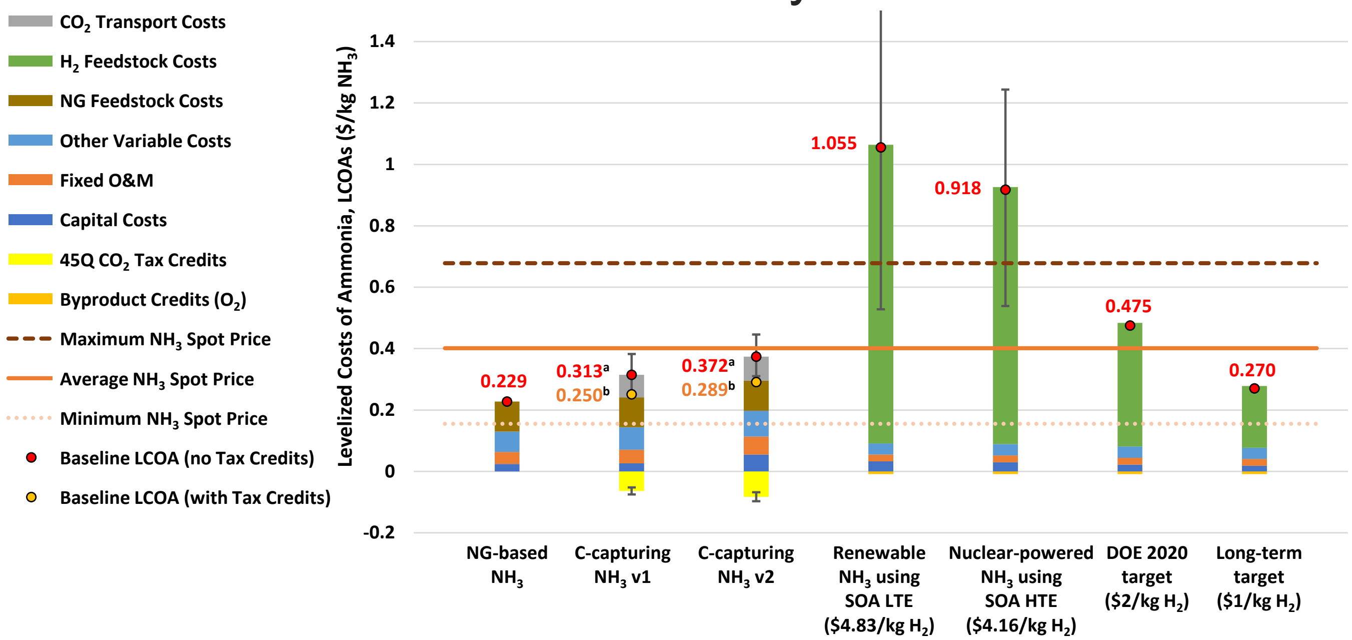
Ammonia as fertilizer, fuel and H_2 carrier

- Ammonia production process modeling

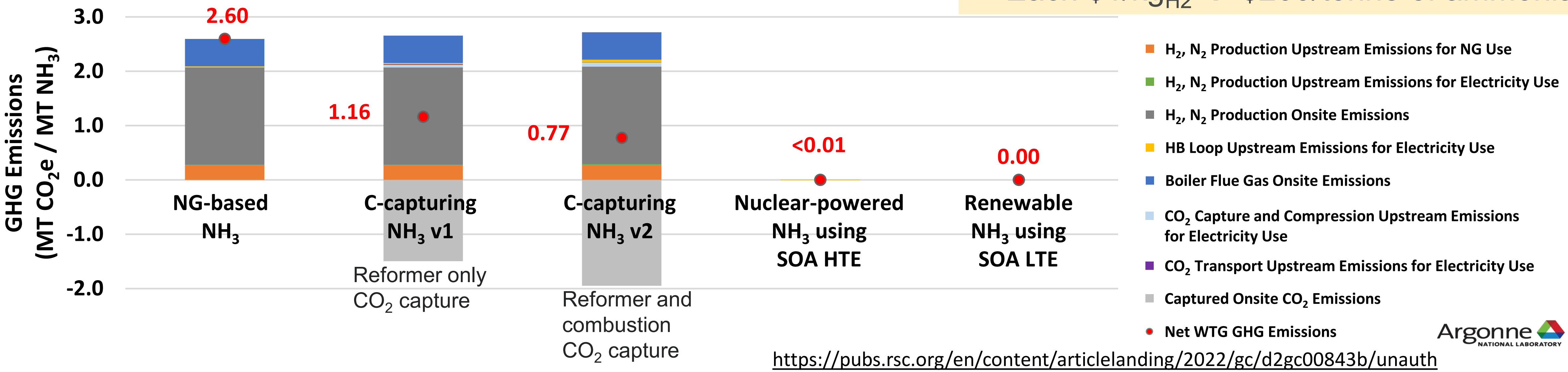


- Techno-economic analysis



➢ Each $1/kg$_{H2}$ → $200/tonne of ammonia

- Well-to-gate emissions



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https://pubs.rsc.org/en/content/articlelanding/2022/gc/d2gc00843b/unauth

Concluding Remarks

- Hydrogen is very different from natural gas with respect to:
  - ✓ Production volume (1.5 vs > 30 Quad Btu)
  - ✓ Most of the natural gas emissions occur in the field during recovery
    - There is no field or recovery of hydrogen
  - ✓ Much shorter transmission pipeline (1,600 vs 300,000 mi)
  - ✓ Natural gas is much lower cost than clean hydrogen production
    - $2-4/mmBtu vs $20-50/mmBtu (an order of magnitude difference)
    - The main drivers to reduce hydrogen losses are safety and economics
  - ✓ Gaseous hydrogen delivery losses are unknown but believed to be small
    - Need to be measured and reported
  - ✓ Liquid hydrogen delivery has significant losses
    - < 1% of produced hydrogen is currently liquefied
    - Losses are controlled rather than fugitive
    - Controlled emissions (venting) can be easily mitigated (e.g., via flaring or oxidation)

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Thank you!

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Our models, tutorials and publications are available at:

https://greet.es.anl.gov/

https://hdsam.es.anl.gov/