GREET® MODEL FOR HYDROGEN LIFE CYCLE GHG EMISSIONS

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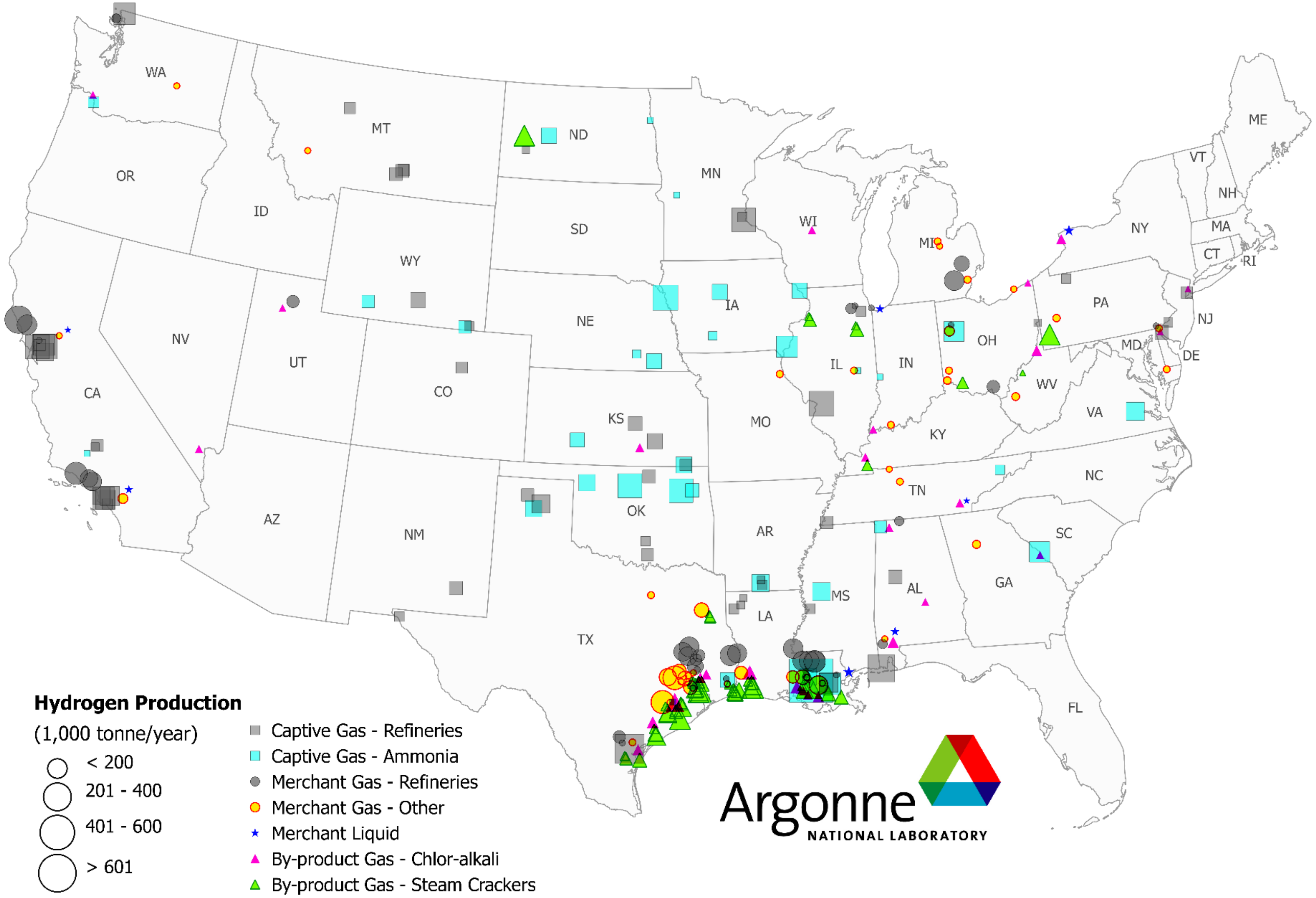
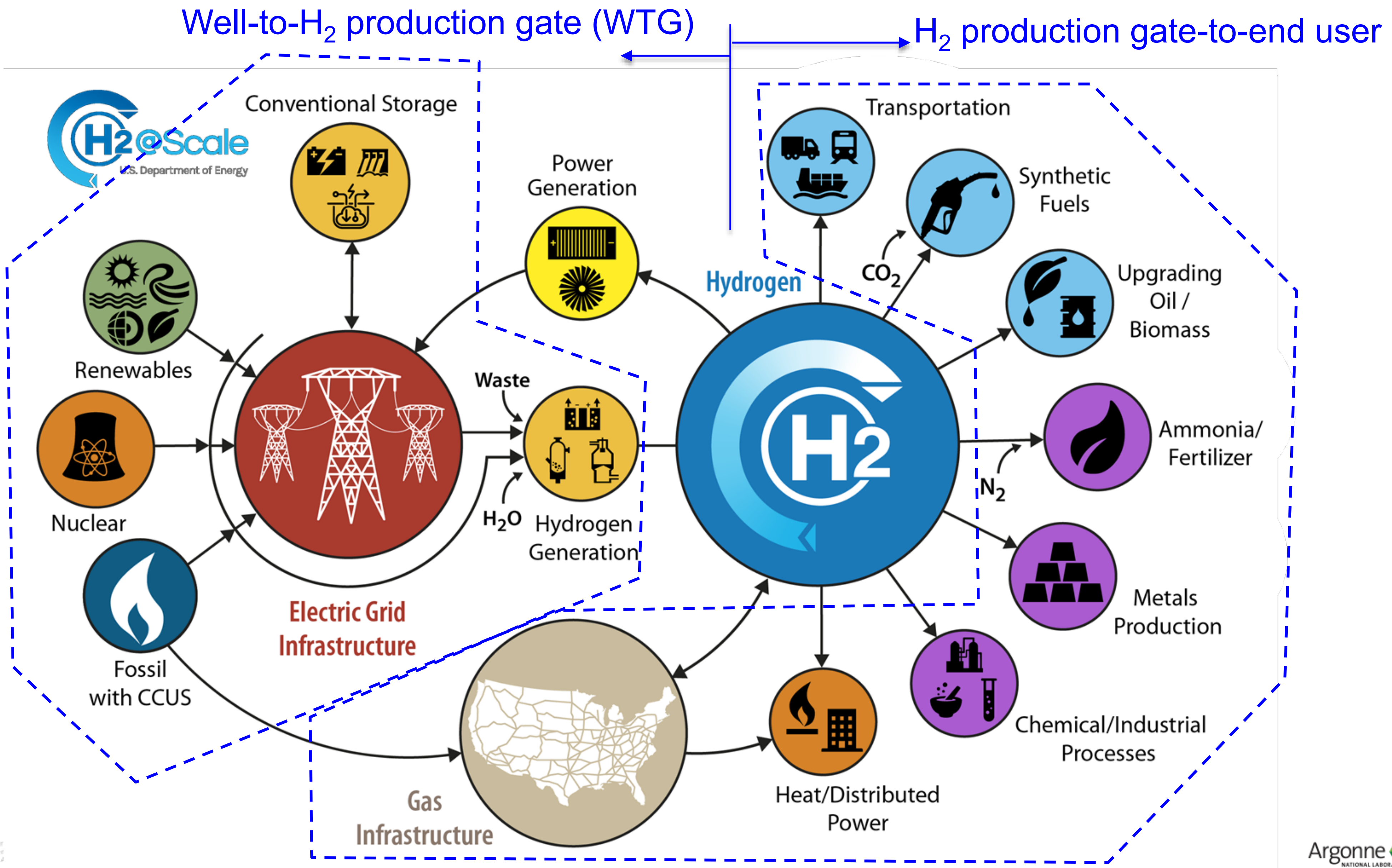
Today, more than 10M metric tons of hydrogen are produced in the U.S. annually, mainly from SMR of natural gas

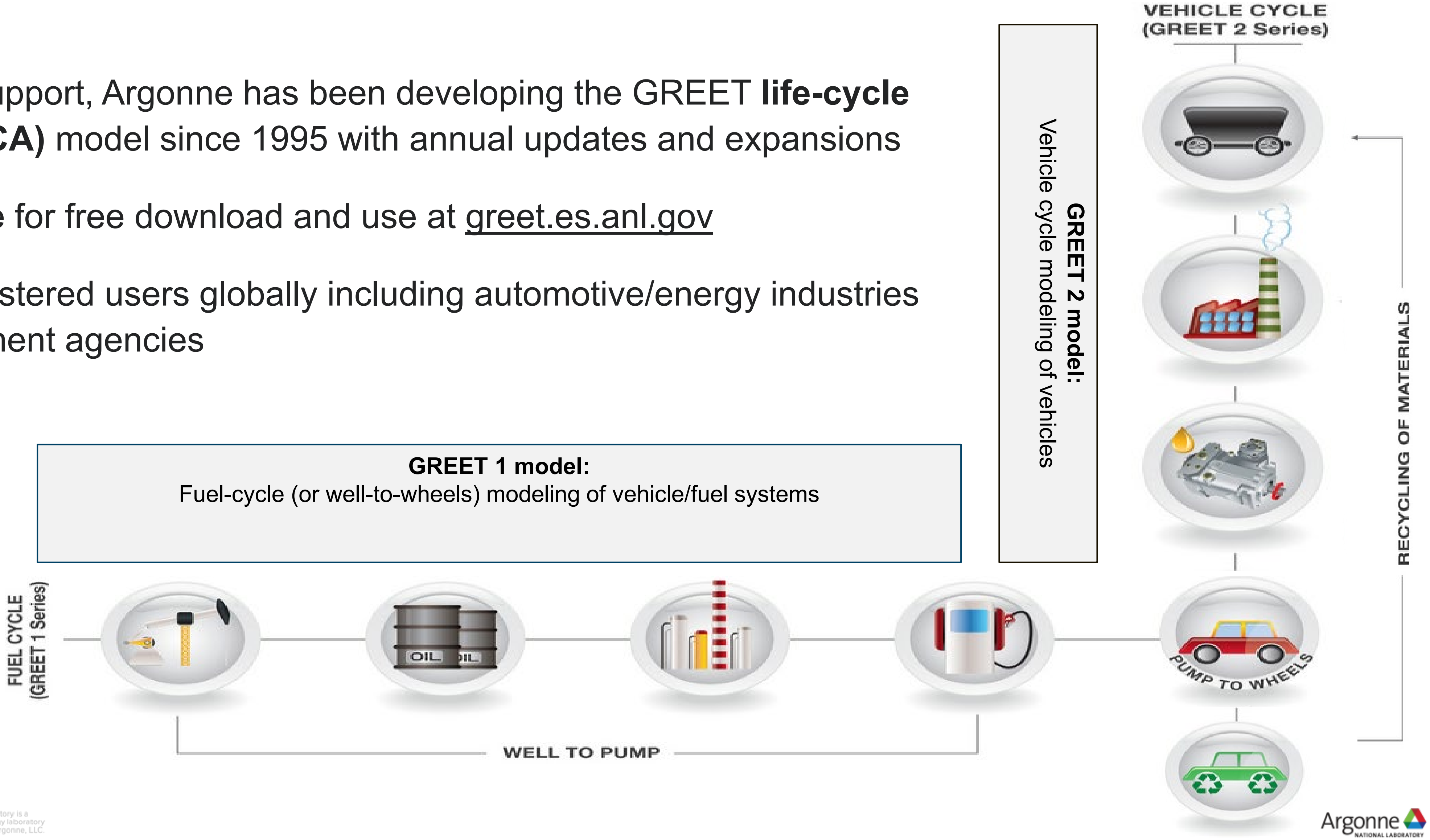


H2@Scale: a DOE initiative for a hydrogen economy



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

- With DOE support, Argonne has been developing the 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
- >50,000 registered users globally including automotive/energy industries and government agencies



GREET includes a suite of models and tools

- GREET coverage
  - ✓ GREET1: fuel cycle (or WTW) model of vehicle technologies and transportation fuels
  - ✓ GREET2: vehicle manufacturing cycle model of vehicle technologies
- Modeling platform
  - ✓ Excel
  - ✓ .net
- GREET derivatives
  - ✓ ICAO-GREET by ANL, based on GREET1
  - ✓ China-GREET by ANL, with support of Aramco
  - ✓ CA-GREET by CARB, based on GREET1
  - ✓ AFLEET by ANL: alternative-fuel vehicles energy, emissions, and cost estimation
  - ✓ EverBatt by ANL: energy, emissions, and cost modeling of remanufacturing and recycling of EV batteries

GREET applications by agencies

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 RFS2 used GREET and other tools for LCA of fuel pathways; GHG regulations

NHTSA National Highway Traffic Safety Administration (NHTSA) fuel economy regulation

FAA and ICAO AFTF using GREET to evaluate aviation fuel pathways

USDRIVE Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability 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

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

Energy use	Air pollutants	Greenhouse gases	Water consumption
• Total energy: fossil energy and renewable energy • Fossil energy: petroleum, natural gas, and coal • Renewable energy: biomass, nuclear energy, hydro-power, wind power, and solar energy	• VOC, CO, NOx, PM_{10}, $PM_{2.5}$, and SOx • Estimated separately for total and urban (a subset of the total) emissions	• CO_2, CH_4, N_2O, black carbon, and albedo • CO_{2e} of the five (with their global warming potentials)	• Addressing water supply and demand (energy-water nexus)

- GREET LCA functional units
  - Per service unit (e.g., mile driven, ton-mile, passenger-mile)
  - Per unit of output (e.g., million Btu, MJ, gasoline gallon equivalent)
  - Per units of resource (e.g., per ton of biomass)

GREET covers 100s of pathways, including H_2 production

Petroleum Sector:
- Conventional oil
- Shale oil
- Oil Sands

→

Gasoline
Diesel
Jet fuel
Liquefied petroleum gas
Naphtha
Residual oil

Electric Systems:
- Electricity generation at US plant level
- Aggregate to national, NERC, and state level
- With CCS, if applicable

←

Natural gas
Coal
Residual oil
Biomass
Nuclear
Hydro
Wind
Solar

Natural Gas Sector:
- Conventional NG
- Shale gas

→

- NG end use in electric, industrial, and residential sectors
- Transportation sector: CNG, LNG
- Alternative fuels: LPG, methanol, DME, FT diesel, FT jet

Renewable Energy/Fuels:
- Ethanol
- Biodiesel
- Renewable diesel
- Renewable gasoline
- Renewable jet fuel
- Renewable natural gas

←

1st Gen Feedstocks:
- Corn
- Sorghum
- Soybeans
- Rapeseeds
- Sugarcane
- Palm

2nd Gen Feedstocks:
- Dedi. energy crops
- Crop residues
- Forest residues
- MSW
- Animal wastes

Algae

Hydrogen Applications:
- Gaseous hydrogen
- Liquid hydrogen

←

Conventional and Ren. Natural gas with and without CCS
Electrolysis with electricity
Electrolysis with Nuclear energy
Biomass
Byproduct of chlorine and crackers
Coal
Petroleum coke
Coke oven gas

Renewable Hydrogen via electrolysis:
- Wind
- Solar
- Nuclear

→

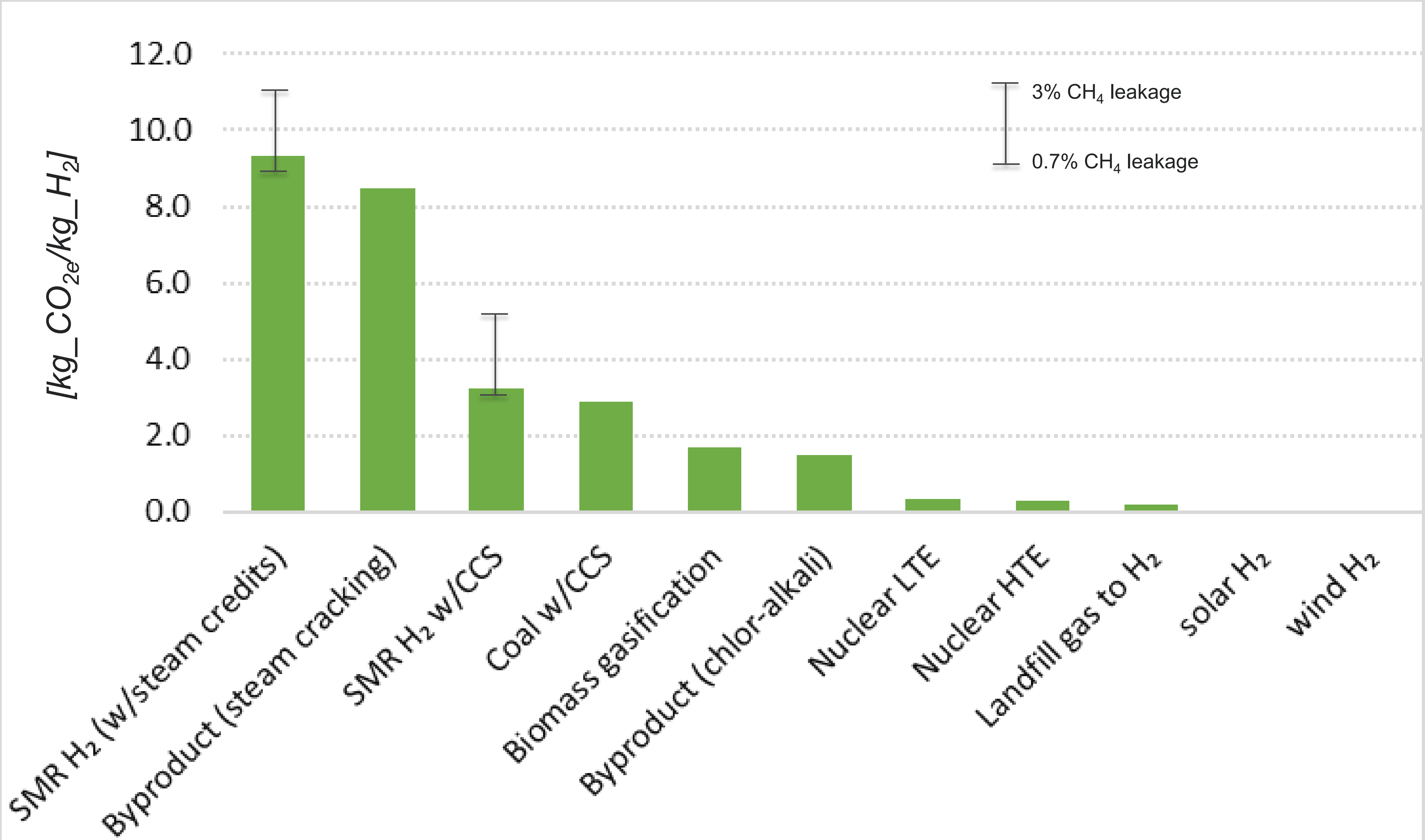
Electro-Fuels
- Gasoline
- Diesel
- Jet fuel
- Methanol
- Ammonia

←

CO_2 Sources
- Ethanol plants
- NG SMR plants
- Cement plants
- Etc.

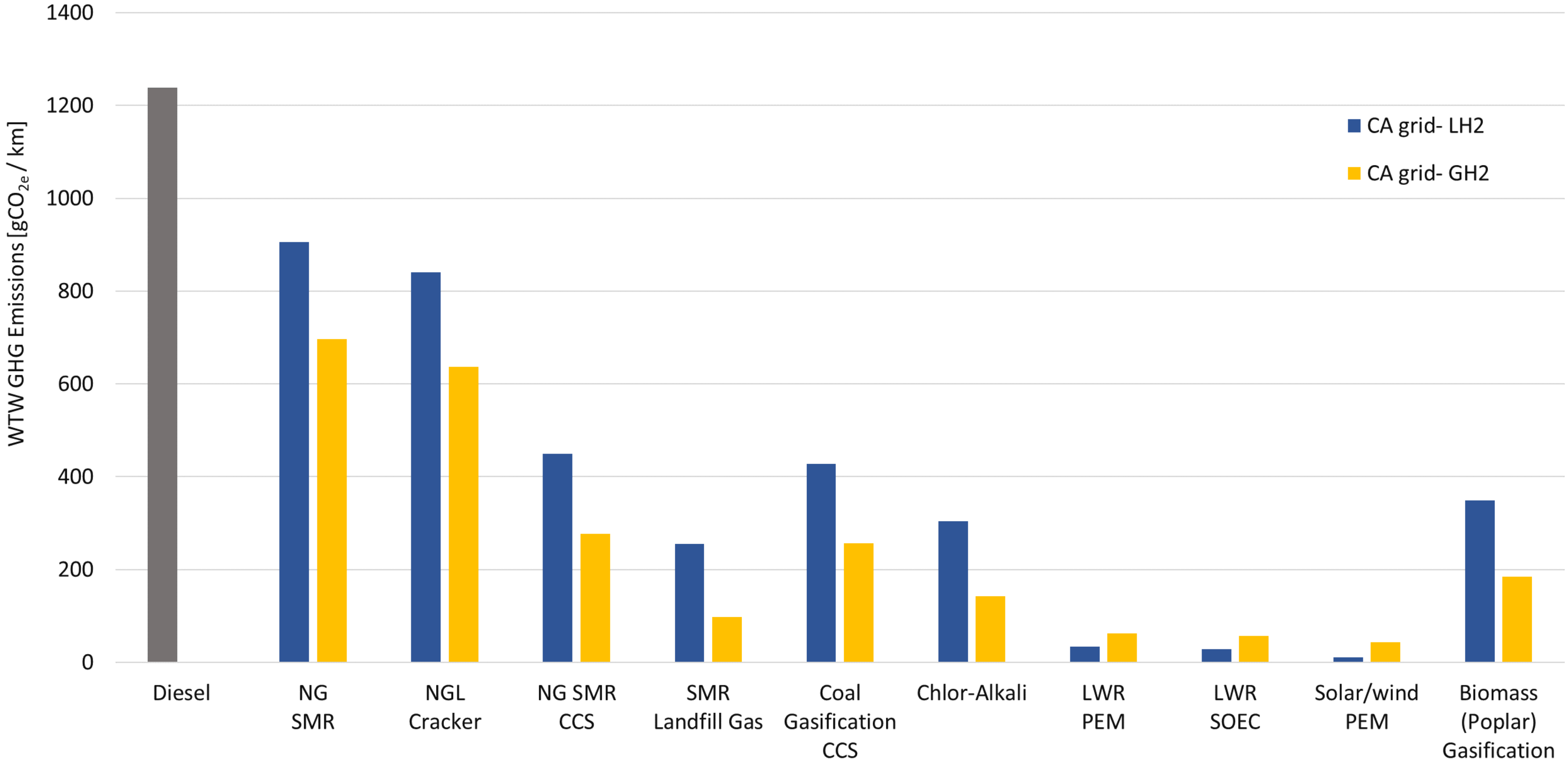
The users are also capable of creating their own pathway with existing feedstocks and technologies in the GREET database

Well-to-gate (WTG) GHG emissions of hydrogen production pathways



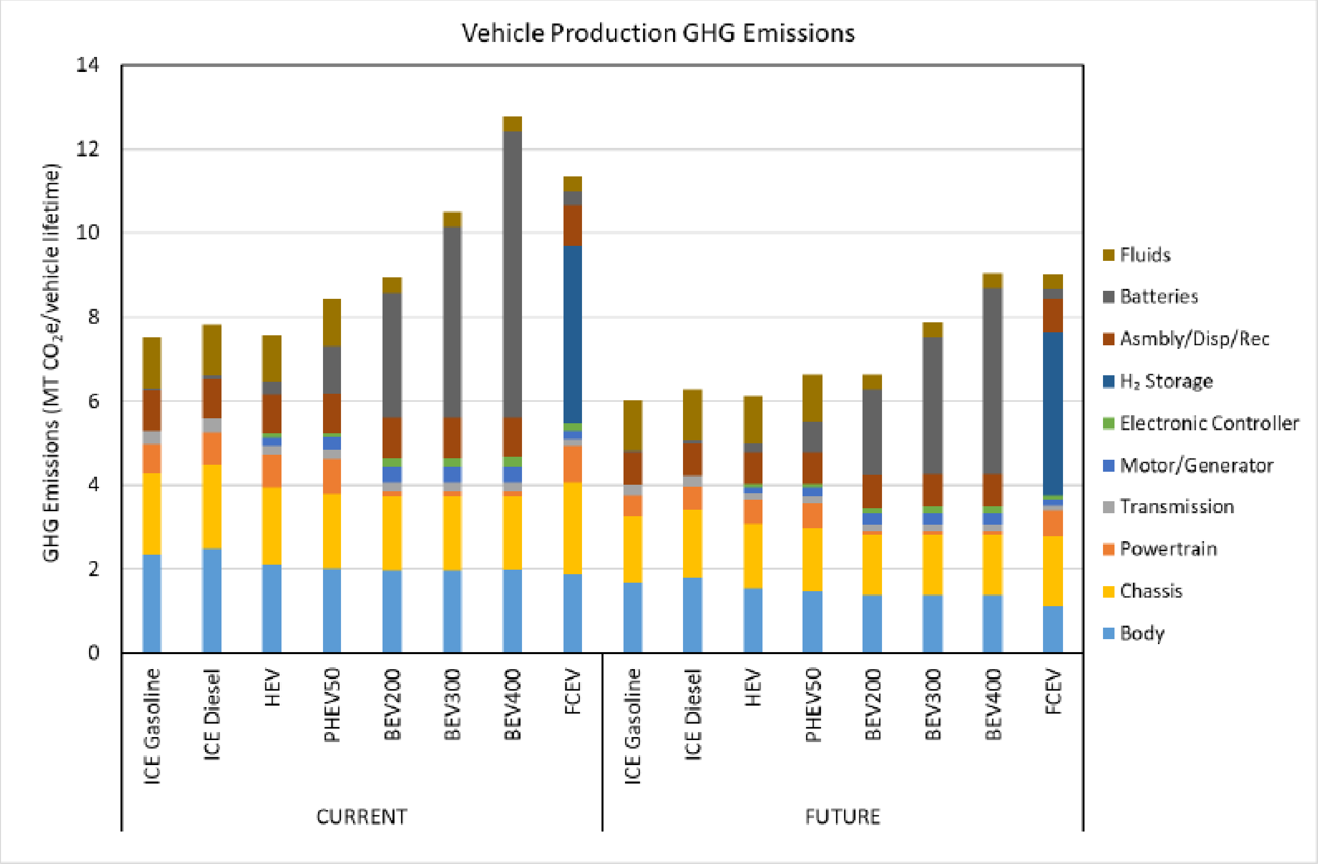
Publication forthcoming

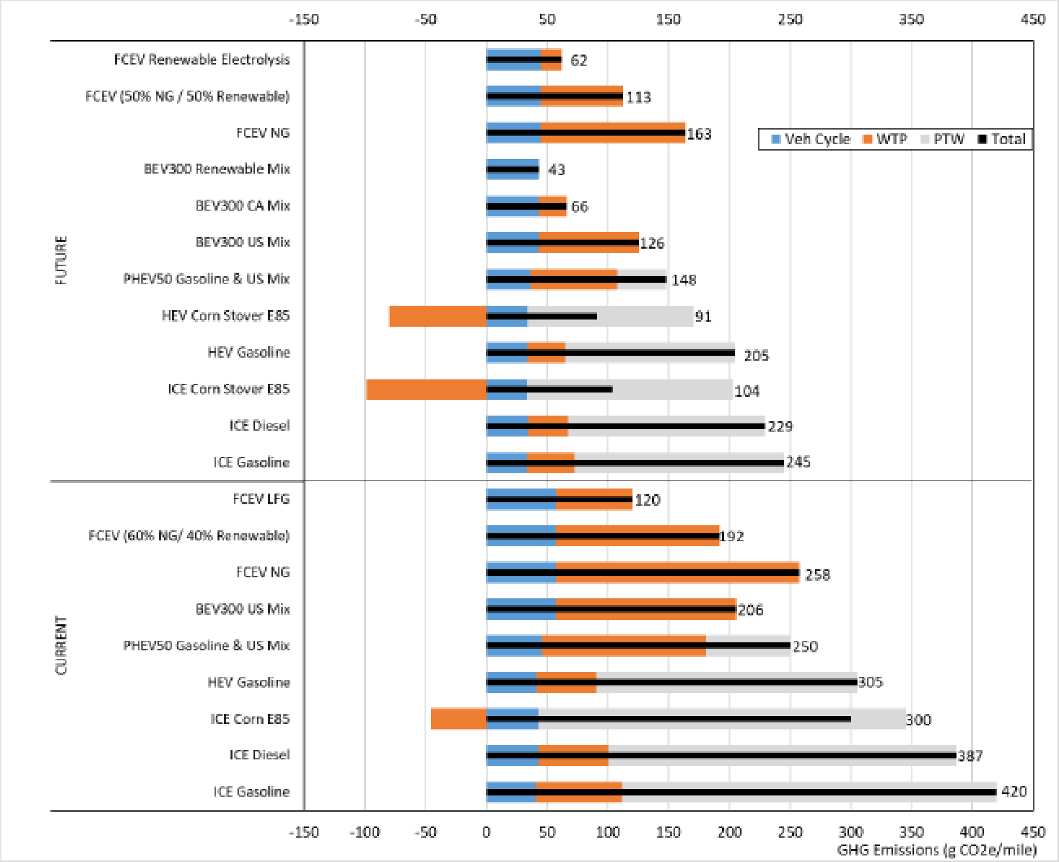
Well-to-Wheels (WTW) GHG emissions of H_2 pathways for fuel cell buses vs. diesel buses



Publication forthcoming

Cradle-to-grave (C2G) analysis of fuel/vehicle systems, including H_2 FCEVs

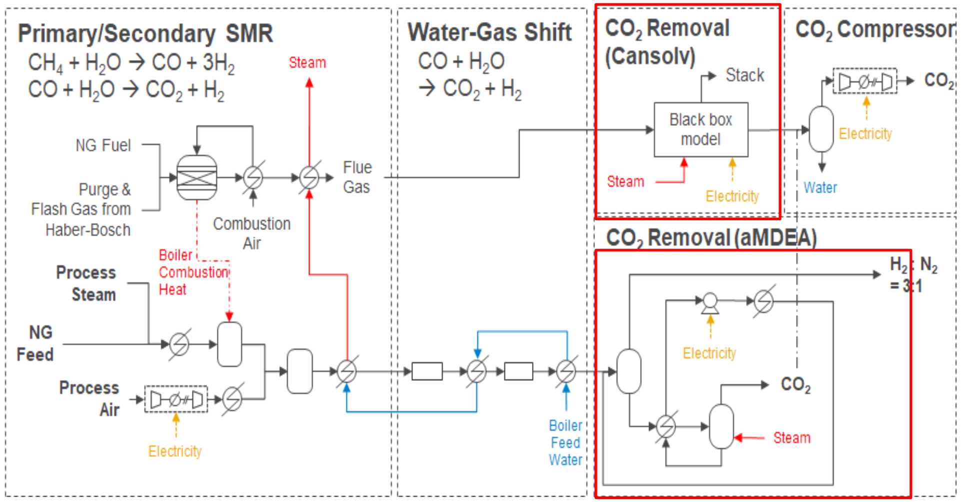




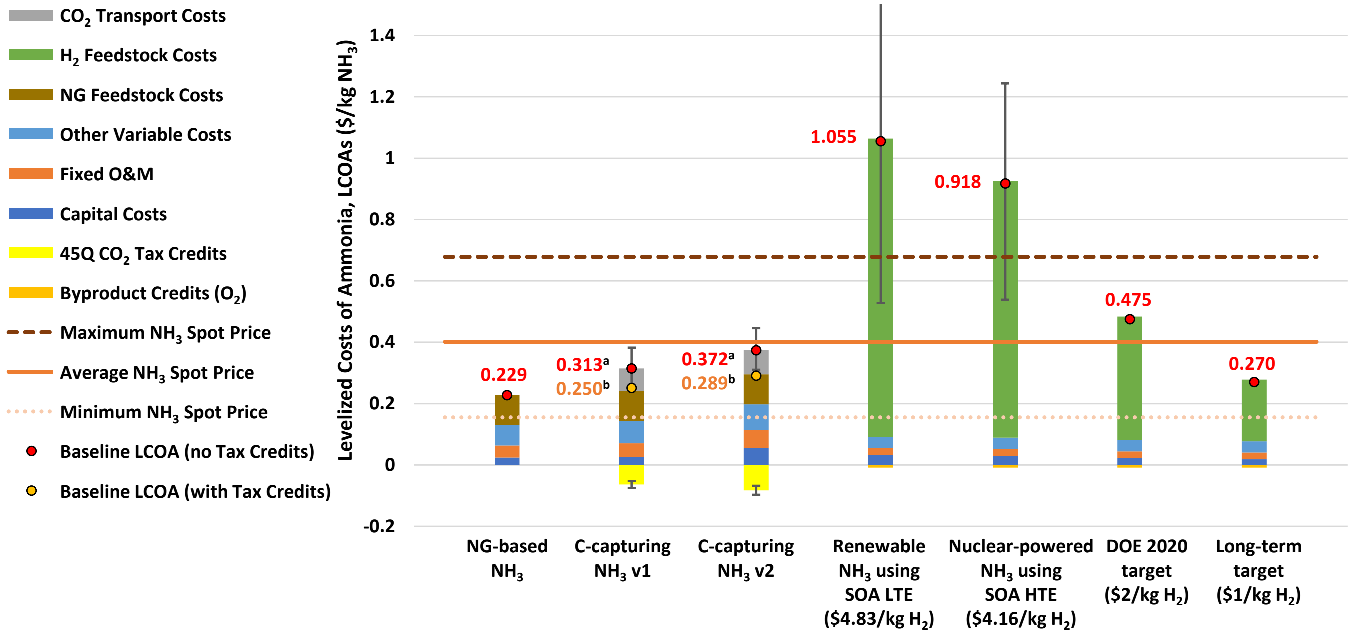
(DOE EERE Record 21003, Sept. 2021)
https://www.hydrogen.energy.gov/pdfs/21003-life-cycle-ghg-emissions-small-suvs.pdf

Ammonia as H_2 carrier

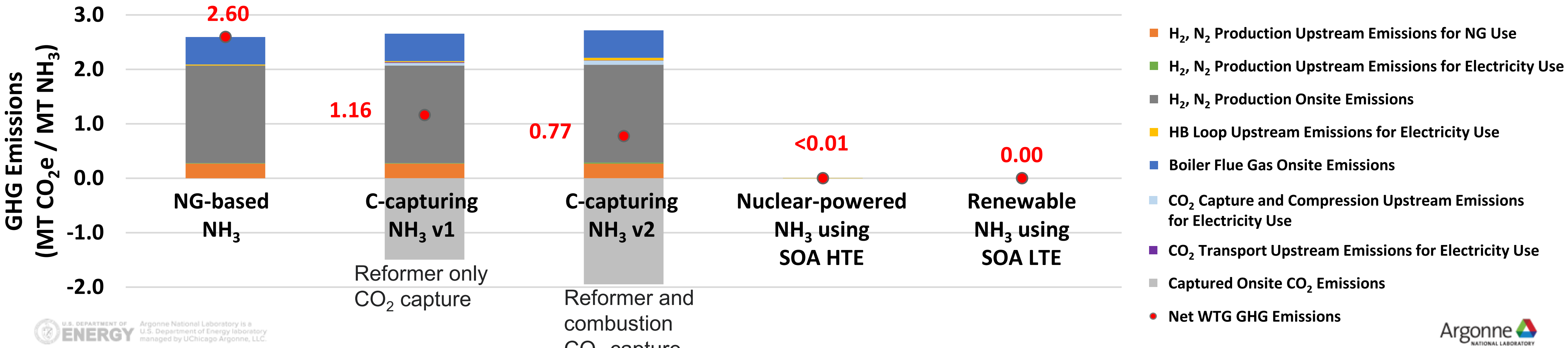
- Ammonia production process modeling



- Techno-economic analysis



- Well-to-gate emissions

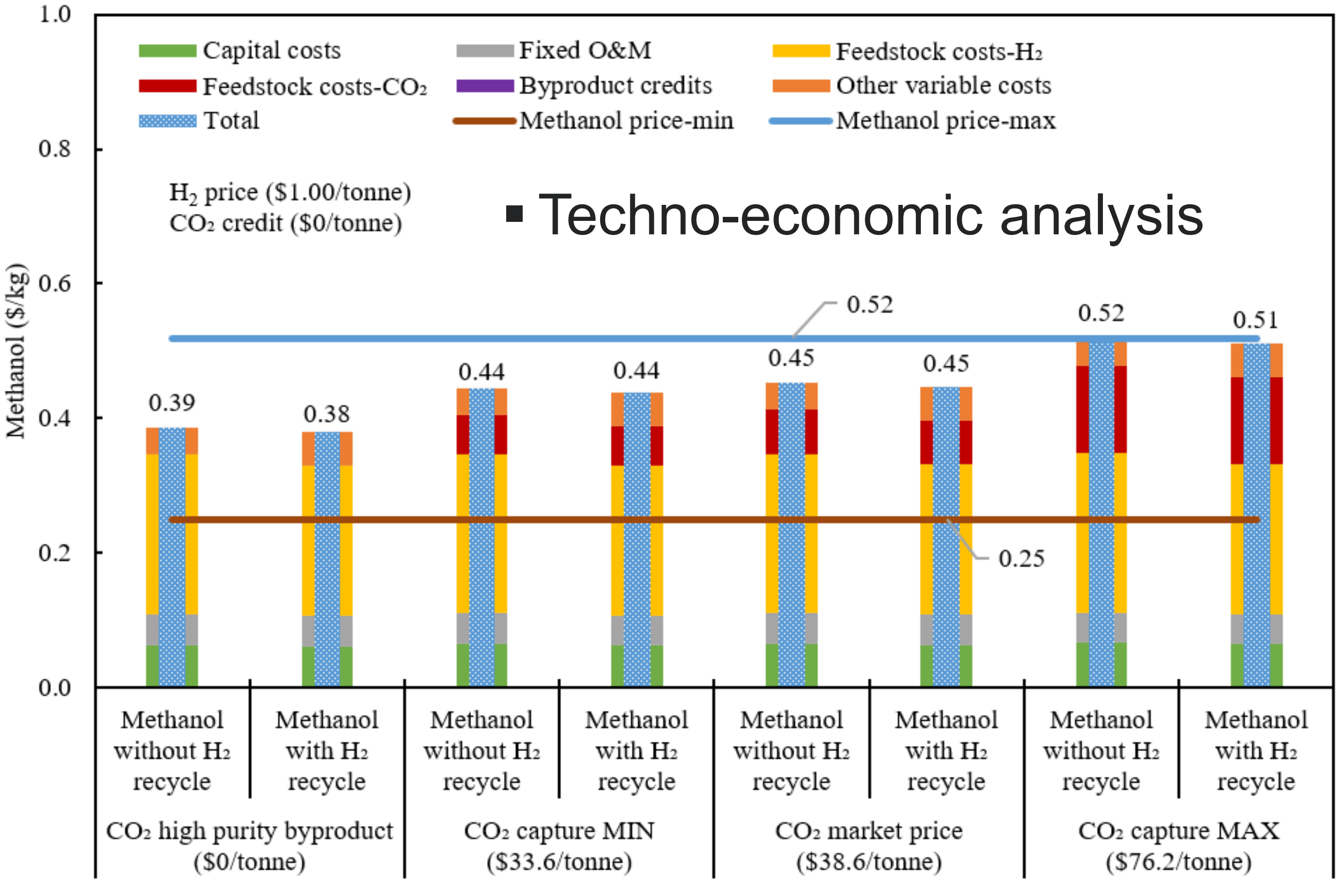


https://pubs.rsc.org/en/content/articlelanding/2022/gc/d2gc00843b/unauth

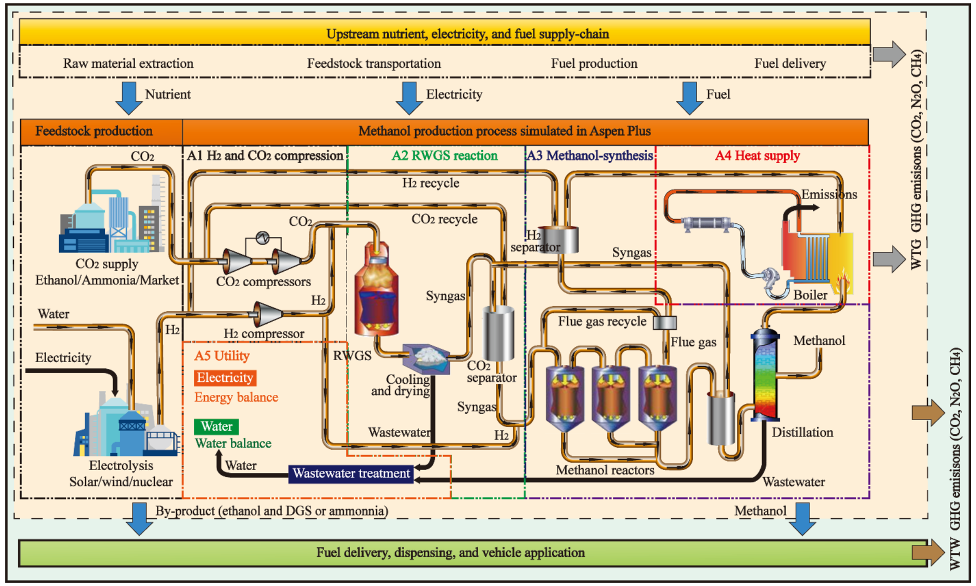
Methanol as H_2 carrier

- Methanol can be synthesized by using CO_2 and H_2 via RWGS and methanol reaction
- $CO_2 + H_2 \rightarrow$ syngas $\rightarrow$ methanol

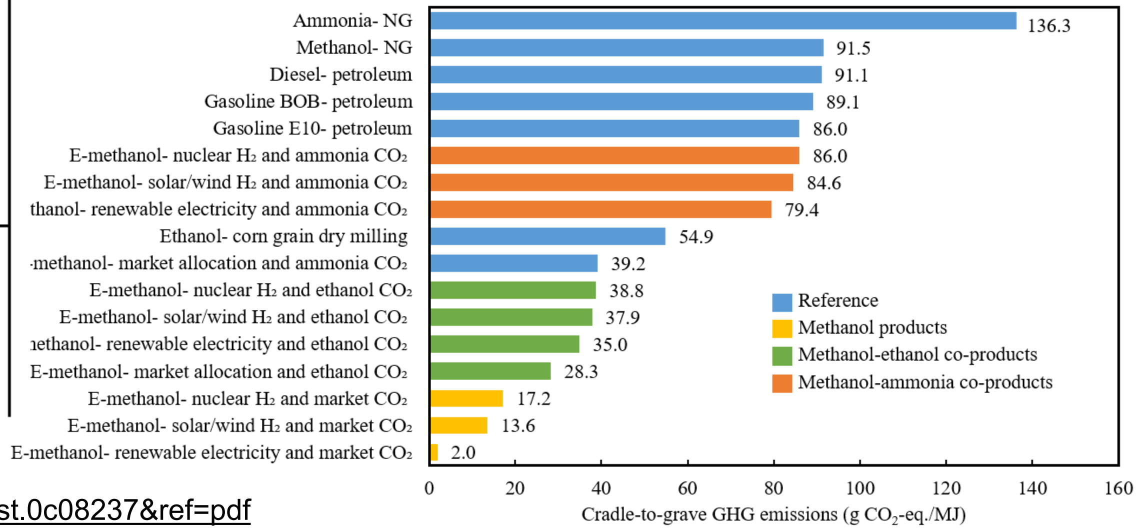
▪ Techno-economic analysis



▪ Conversion process modeling



▪ Well-to-gate GHG emissions

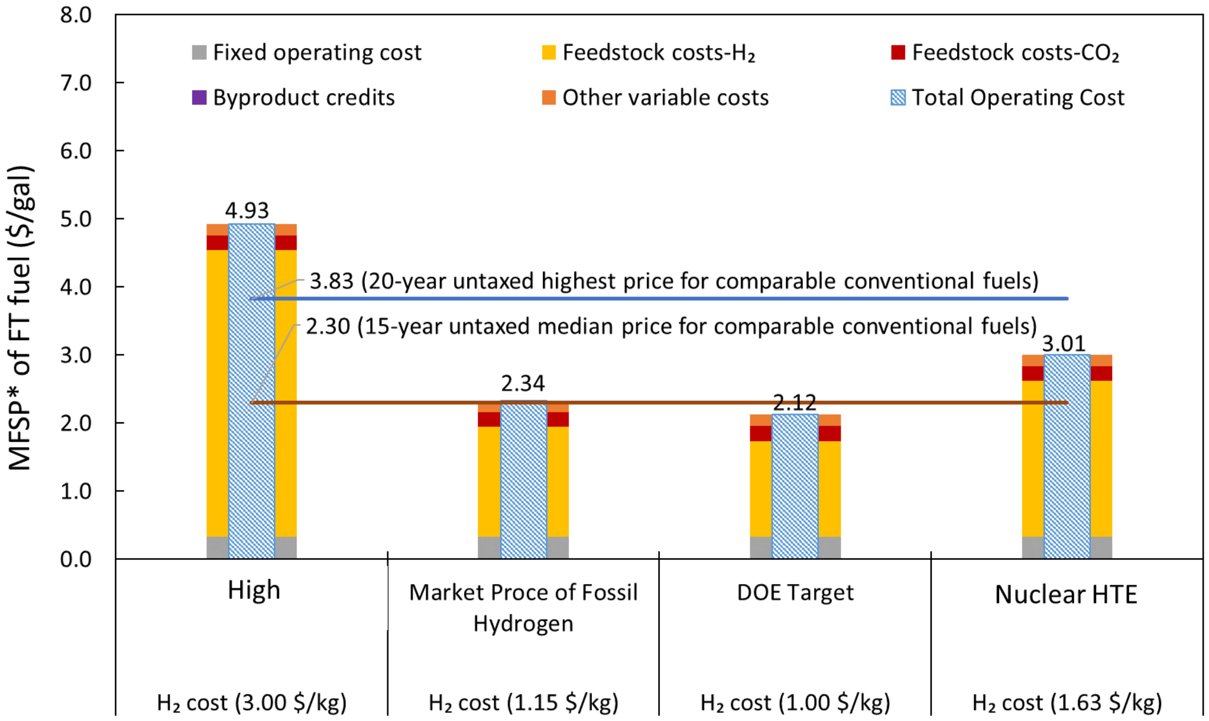


https://pubs.acs.org/action/showCitFormats?doi=10.1021/acs.est.0c08237&ref=pdf

Fischer-Tropsch (FT) Fuels

- FT fuels can be synthesized by using CO_2 and H_2 via RWGS and FT reaction
- $CO_2 + H_2 \rightarrow$ syngas $\rightarrow$ FT fuels

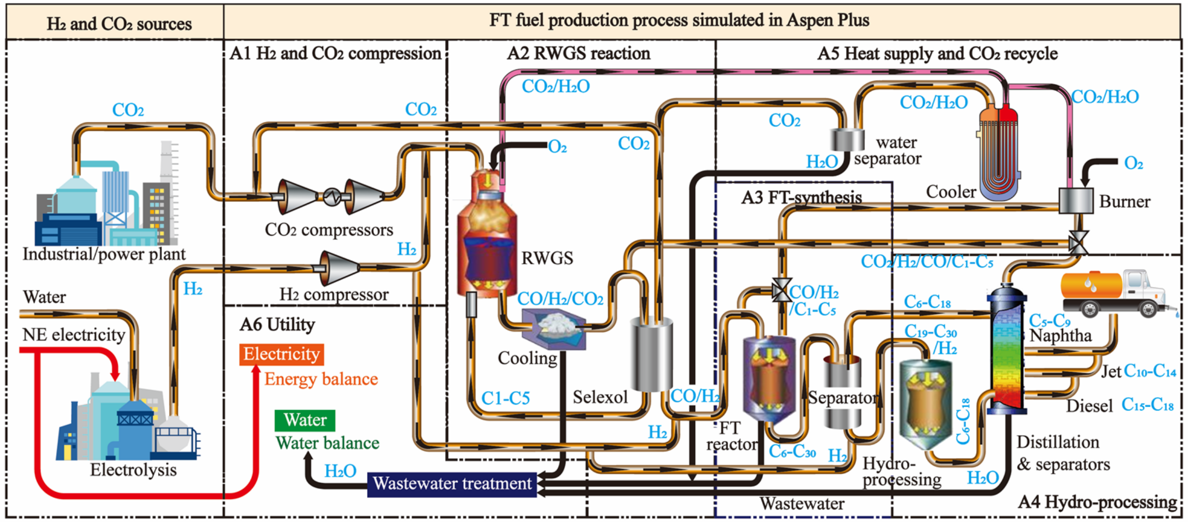
▪ Techno-economic analysis



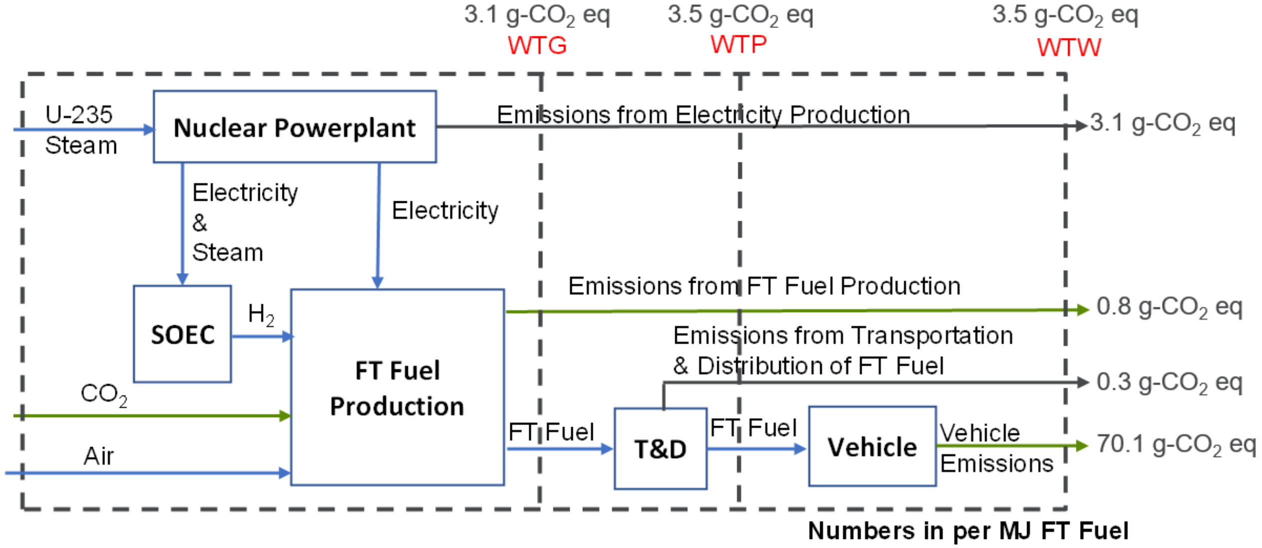
*MSFP=minimum fuel selling price

https://www.osti.gov/biblio/1868524

▪ Conversion process modeling



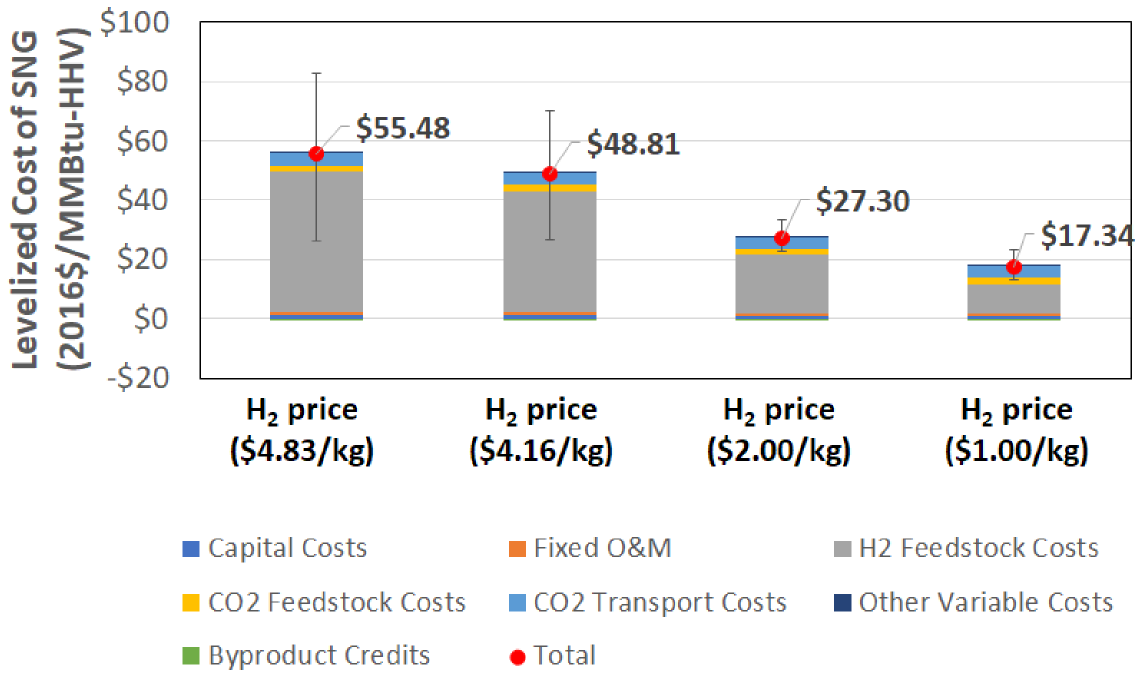
▪ Well-to-gate emissions



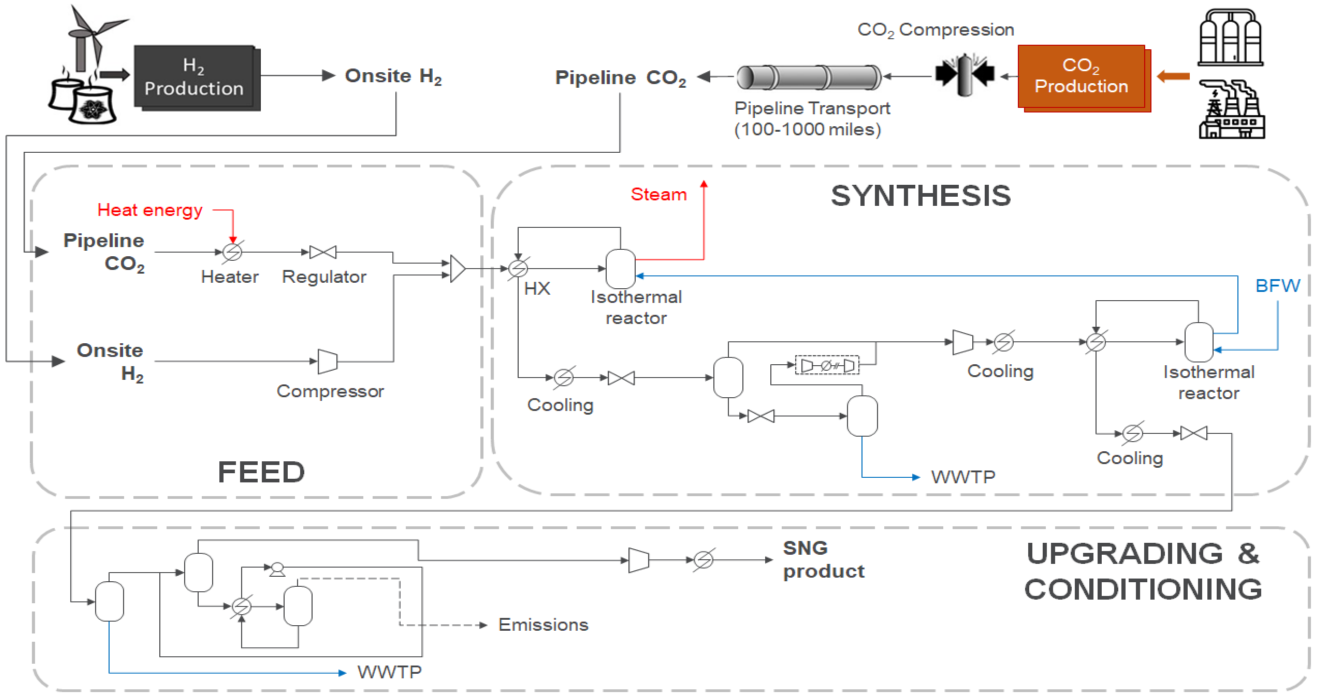
Synthetic natural gas (SNG)

- Synthetic NG can be synthesized by using CO_2 and H_2 via Sabatier reaction.
- $CO_2 + H_2 \rightarrow NG$

▪ Techno-economic analysis

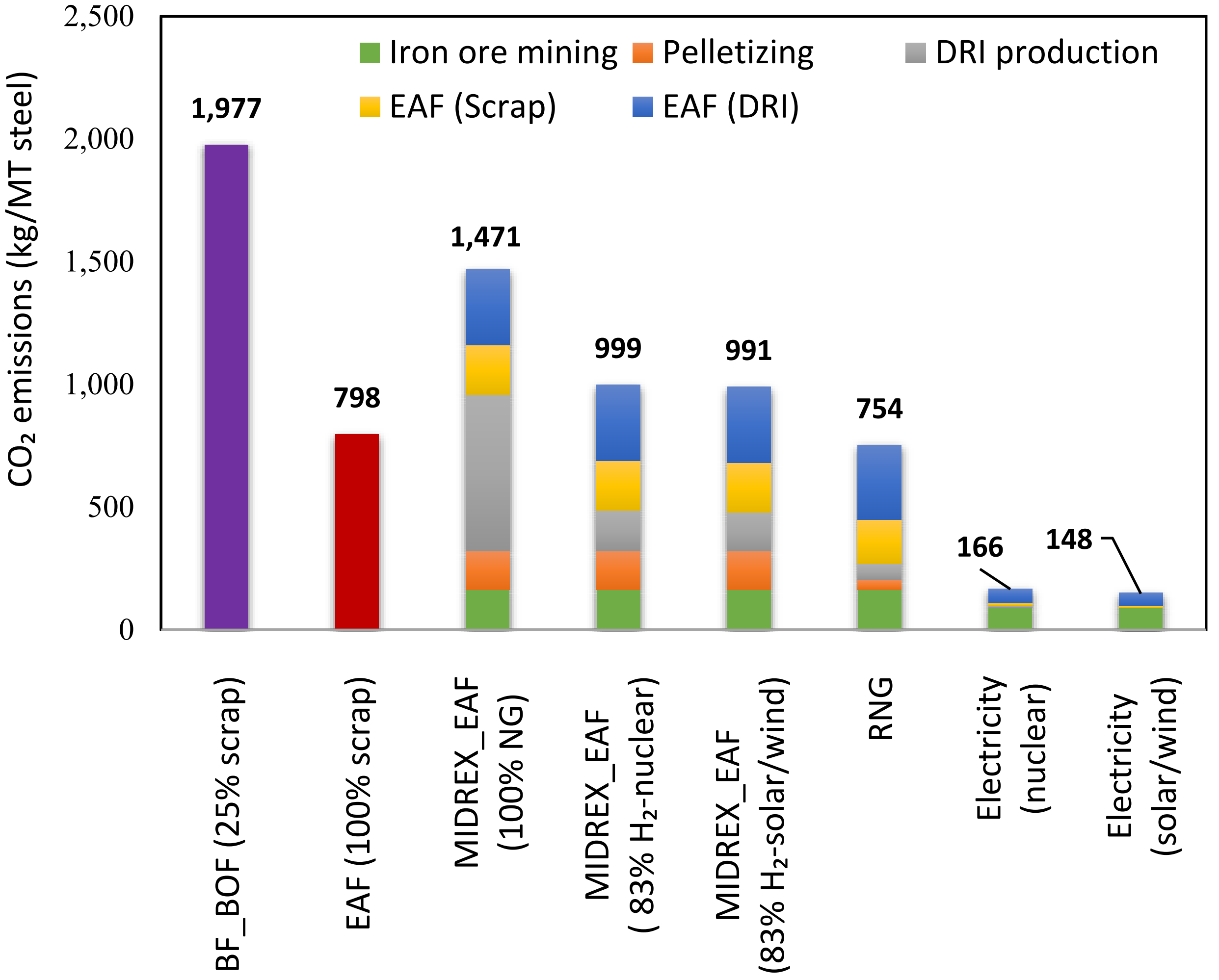


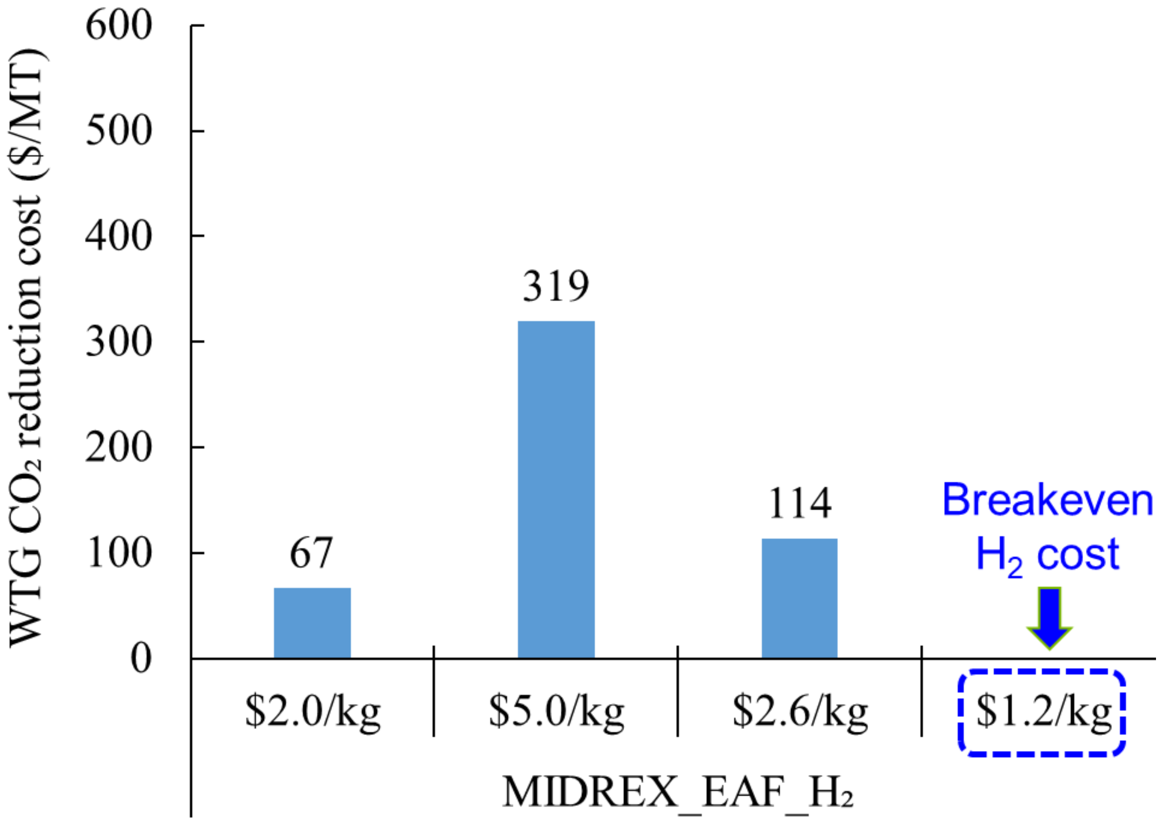
▪ Conversion process modeling



Publication forthcoming

Low-carbon H_2 cost is key for cost-effective steel decarbonization

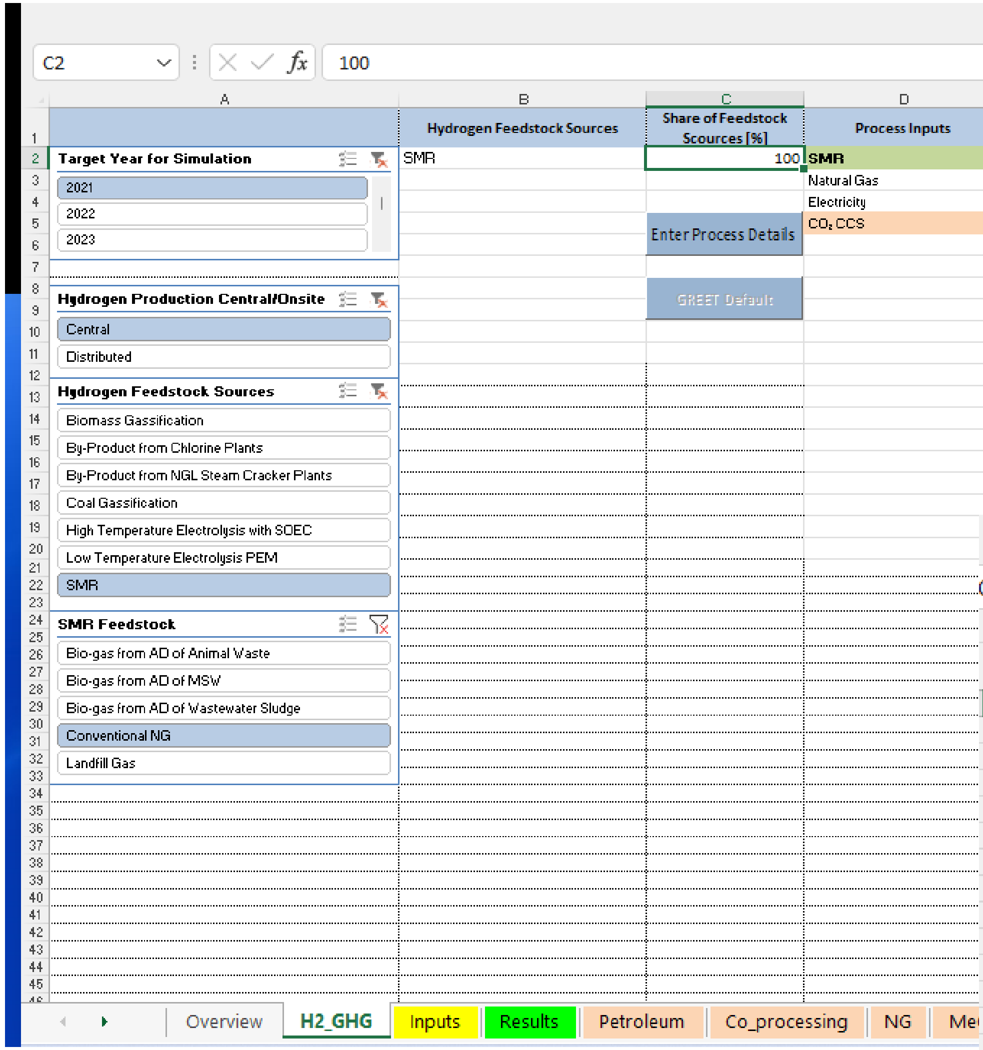


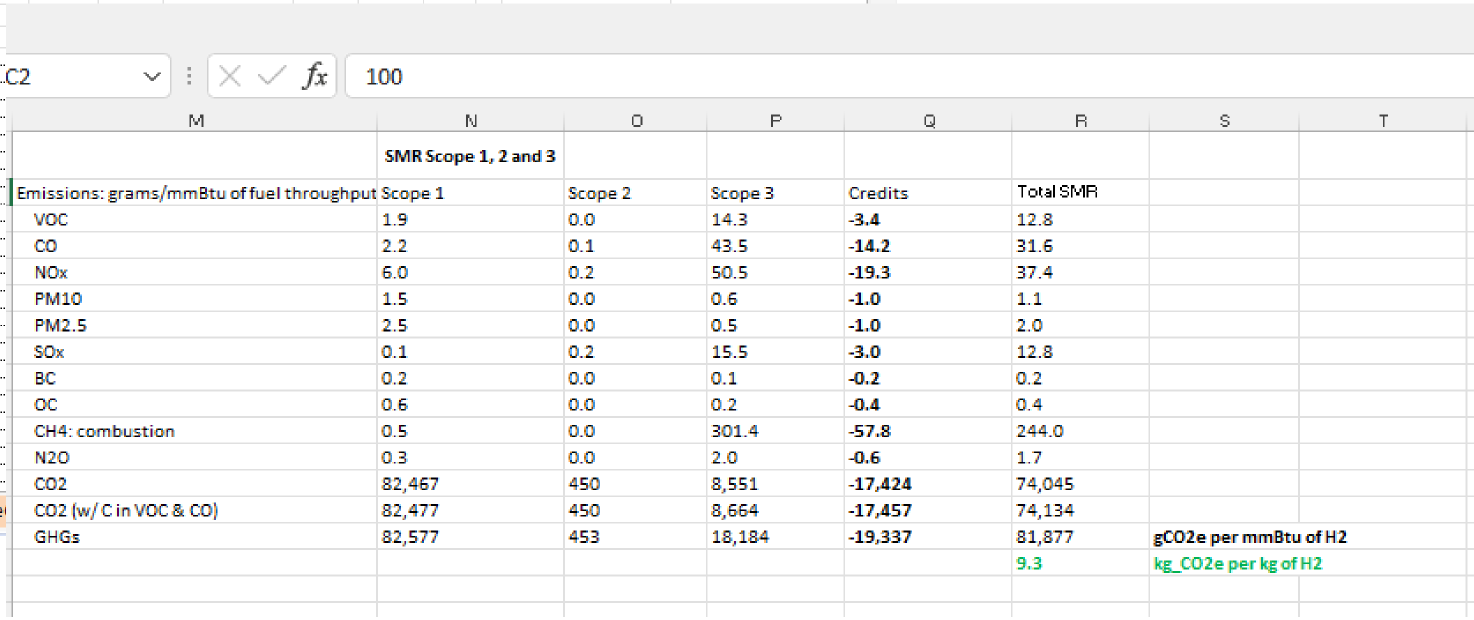


BF-BOF=blast furnace-basic oxygen furnace
EAF=electric arc furnace
DRI=direct reduction of iron
RNG=renewable natural gas
WTG=well-to-gate

Publication forthcoming

GREET demonstration for selected H_2 pathways





	SMR Scope 1, 2 and 3					
Emissions: grams/mmBtu of fuel throughput	Scope 1	Scope 2	Scope 3	Credits	Total SMR	
VOC	1.9	0.0	14.3	-3.4	12.8	
CO	2.2	0.1	43.5	-14.2	31.6	
NOx	6.0	0.2	50.5	-19.3	37.4	
PM10	1.5	0.0	0.6	-1.0	1.1	
PM2.5	2.5	0.0	0.5	-1.0	2.0	
SOx	0.1	0.2	15.5	-3.0	12.8	
BC	0.2	0.0	0.1	-0.2	0.2	
OC	0.6	0.0	0.2	-0.4	0.4	
CH4: combustion	0.5	0.0	301.4	-57.8	244.0	
N2O	0.3	0.0	2.0	-0.6	1.7	
CO2	82,467	450	8,551	-17,424	74,045	
CO2 (w/ C in VOC & CO)	82,477	450	8,664	-17,457	74,134	
GHGs	82,577	453	18,184	-19,337	81,877	gCO2e per mmBtu of H2
					9.3	kg_CO2e per kg of H2

- ✓ User friendly interface
- ✓ Results include scope 1, 2 and 3 emissions
- ✓ Process inputs and outputs by user in various units

Argonne NATIONAL LABORATORY

Acknowledgment

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ANL Team

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Thank You!

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GREET tutorials:

https://youtu.be/BrqRhJ3qRml

Our models and publications are available at:

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

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