2022 DOE Hydrogen and Fuel Cells Program
Annual Merit Review

Argonne NATIONAL LABORATORY

Life Cycle Analysis of Hydrogen Pathways

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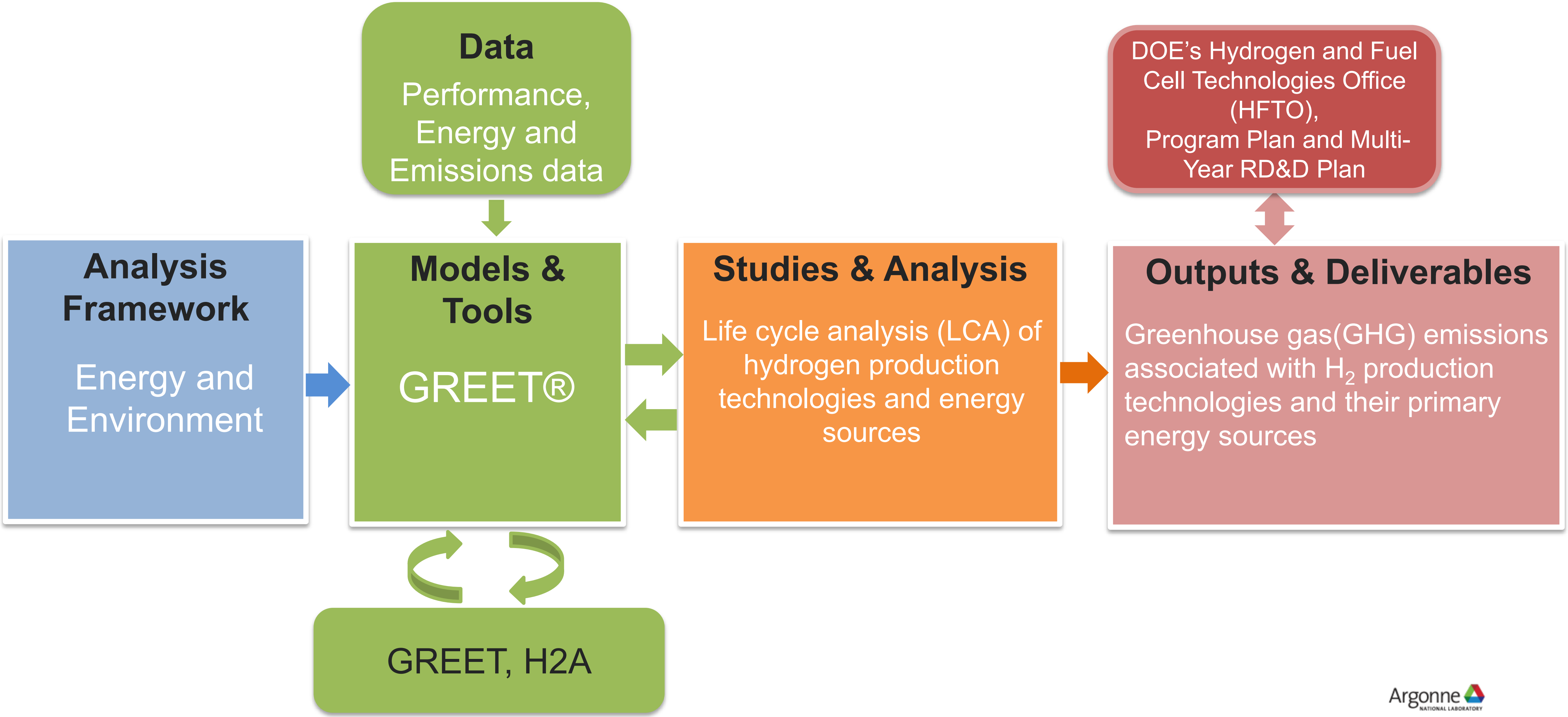
SA174

Project Overview

Timeline	Barriers Addressed
• Start: October 2019 • End: Determined by DOE • % complete (FY22): 80%	• Inconsistent data, assumptions and guidelines • Insufficient suite of models and tools • Stove-piped/Siloed analytical capability for evaluating sustainability

Budget	Partners
• Funding for FY22: $250K	• NETL • NREL • Industry experts

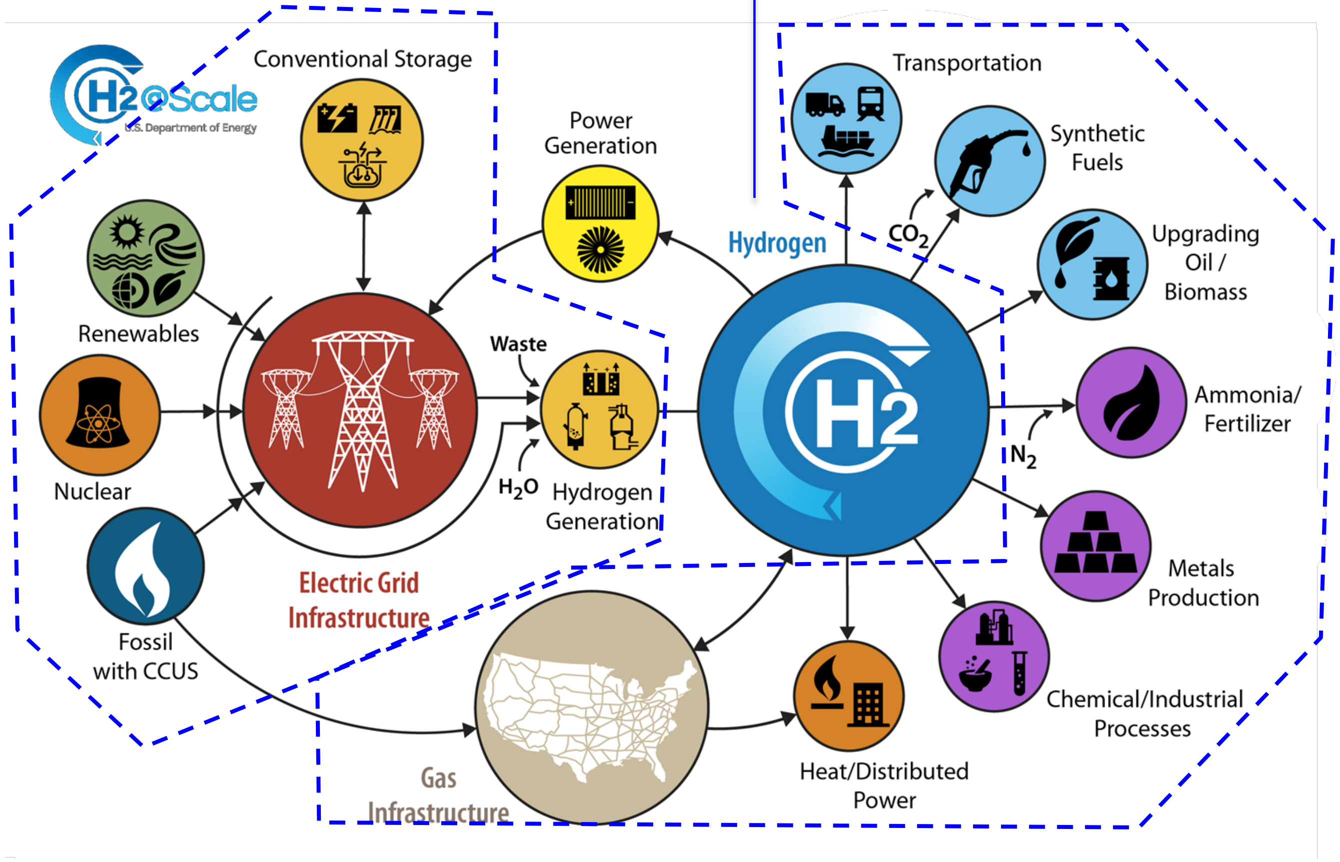
Project GOAL: *Evaluate environmental implications of H_2 production technologies*

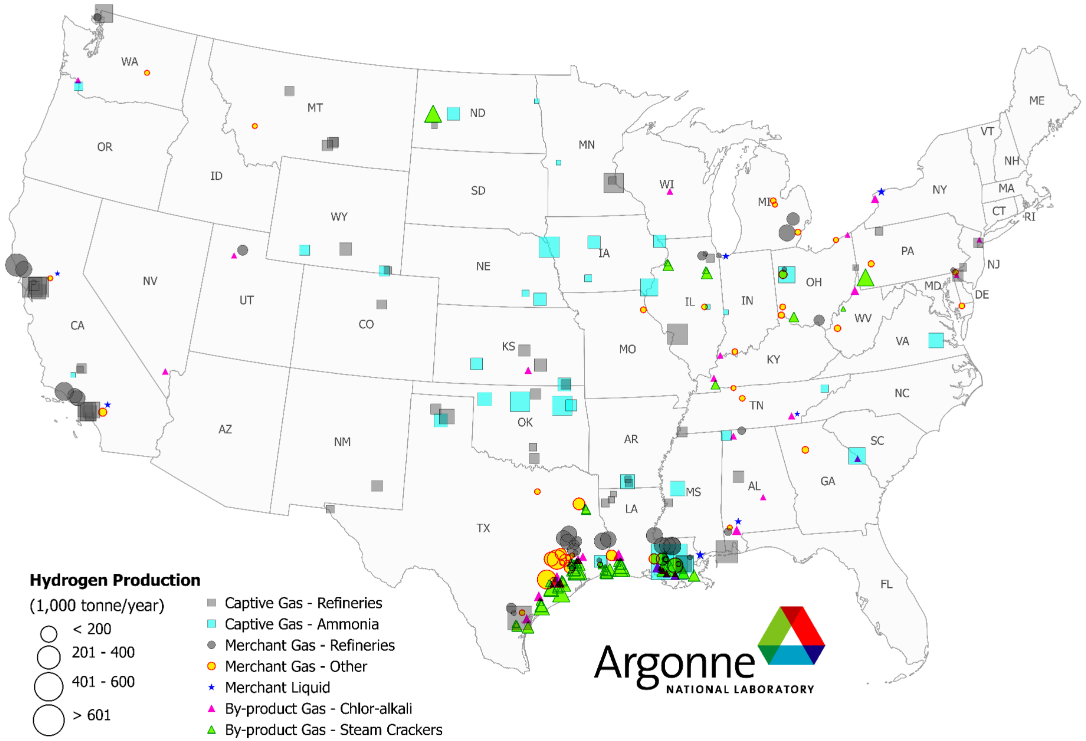


H2@Scale: a DOE initiative for a hydrogen economy

Well-to-H_2 production gate (WTG)

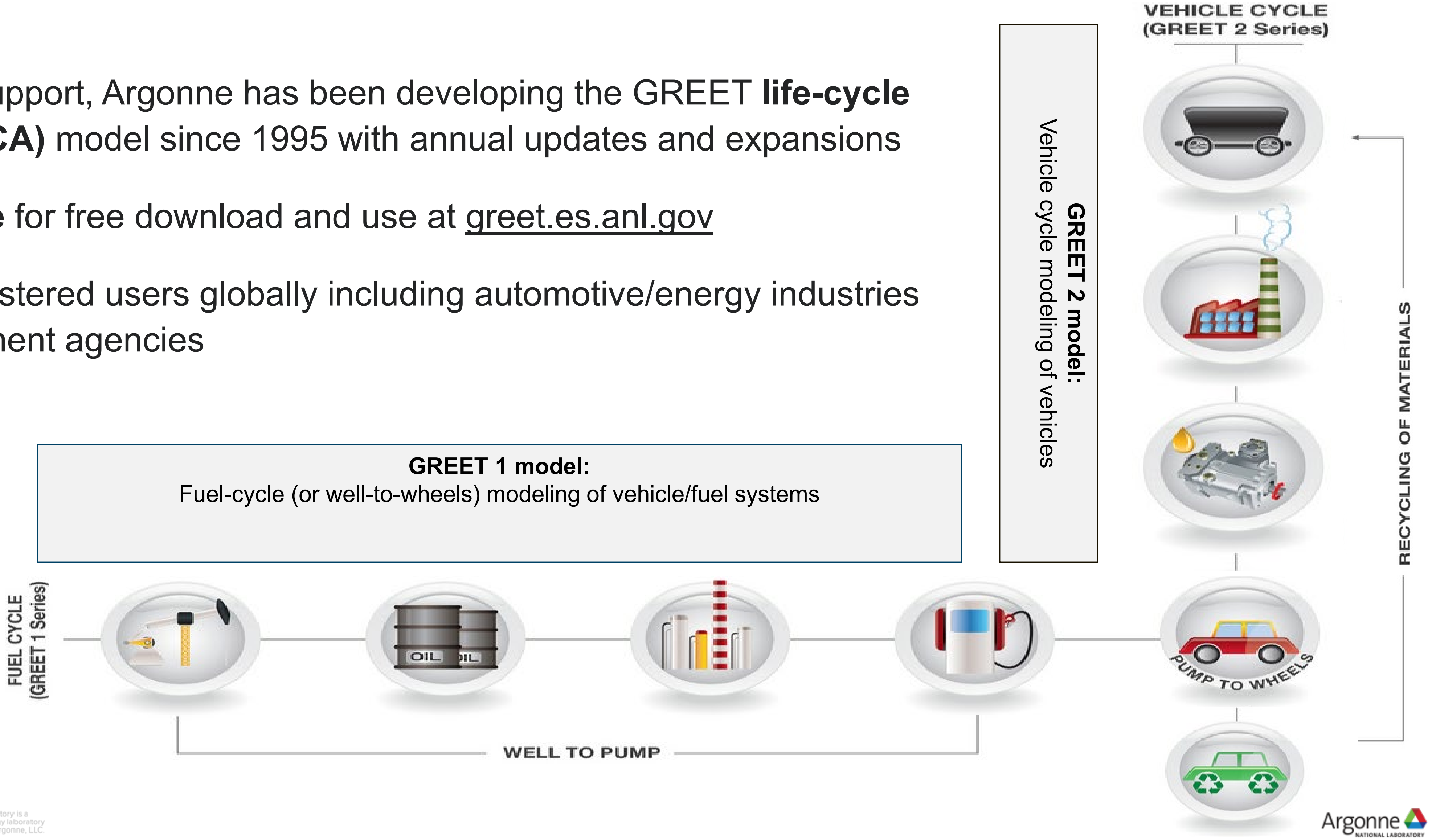
H_2 production gate-to-end user





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: 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

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

Focus of Presentation Today

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

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

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

Renewable Hydrogen via electrolysis:
- Wind
- Solar
- Nuclear

→

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

←

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

Global warming potentials (GWPs) of gases

- Allows comparisons of relative global warming impacts of different gases
- CO_2 is the reference gas with GWP=1
- GWP is mainly impacted by:
  - ✓ ability of gas to absorb energy
  - ✓ how long it stays in the atmosphere

GAS	GWP*	Timeframe	Life in the atmosphere
CO_2	1	All	~100s of years
CH_4	29.8	100 years	~10-20 years
	82.5	20 Years	
N_2O	273	100 Years	~100 years
H_2	?	100 Years	~ 2 years

* Based on latest IPCC AR6

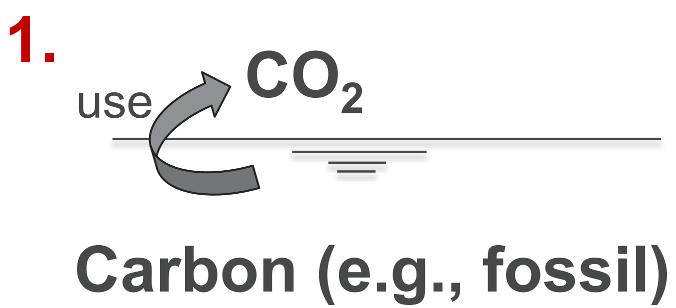
Greenhouse gases

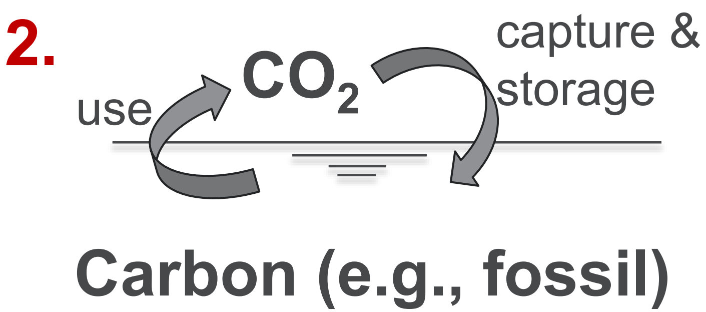
- CO_2, CH_4, N_2O, black carbon, others
- CO_{2e} with their global warming potentials

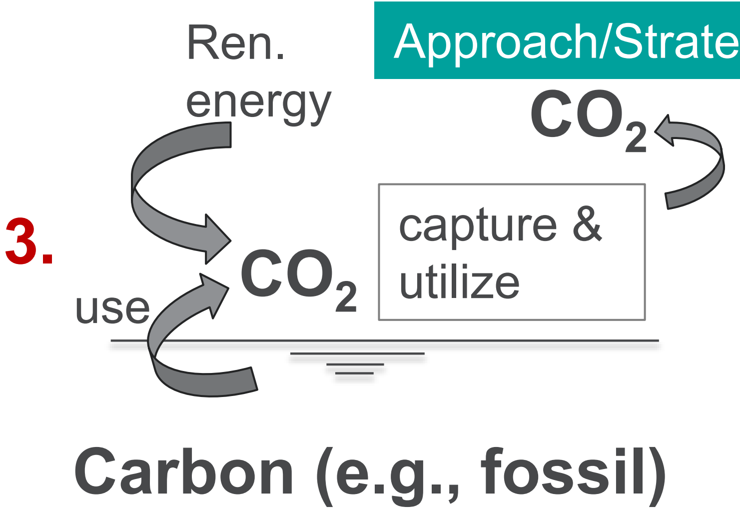
✓ H_2 GWP not yet in GREET

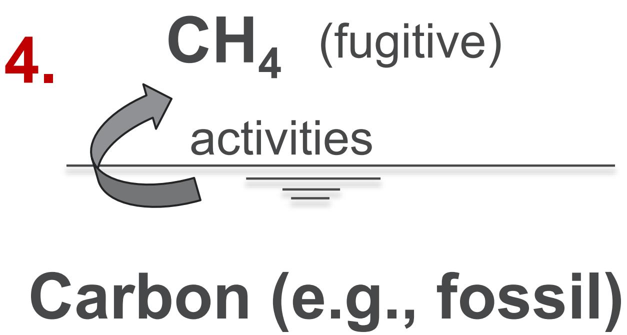
What really matters: carbon source and fate

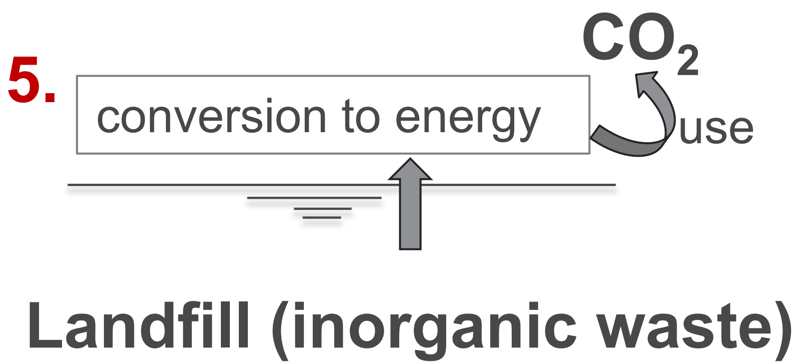
Approach/Strategy

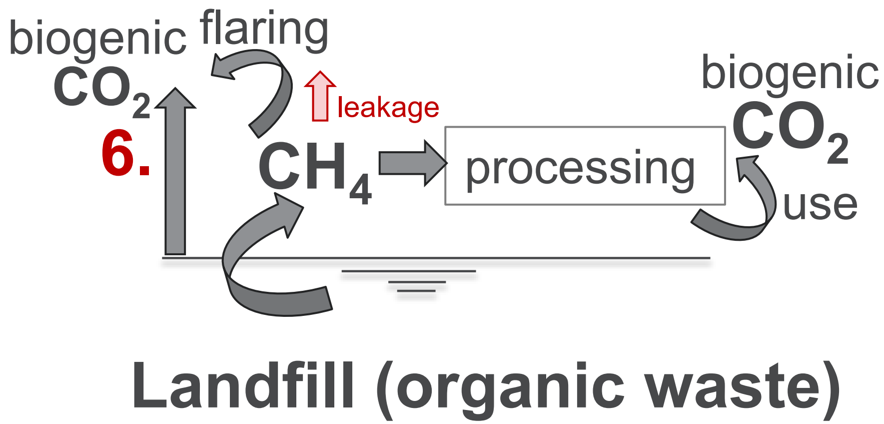


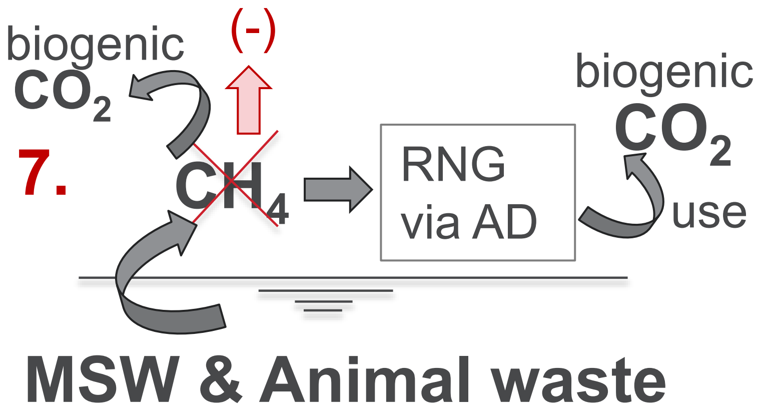


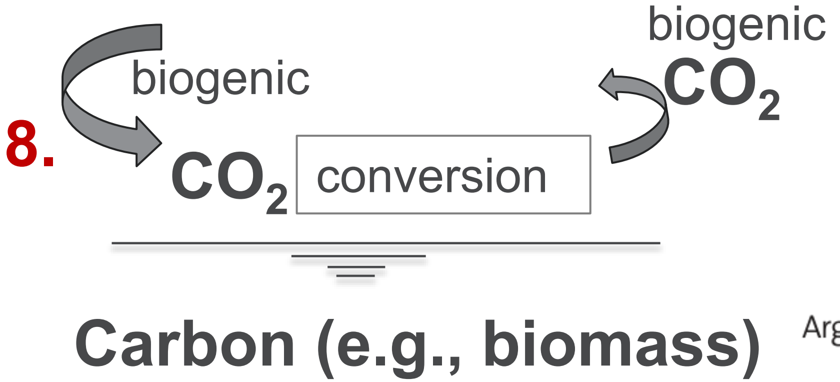




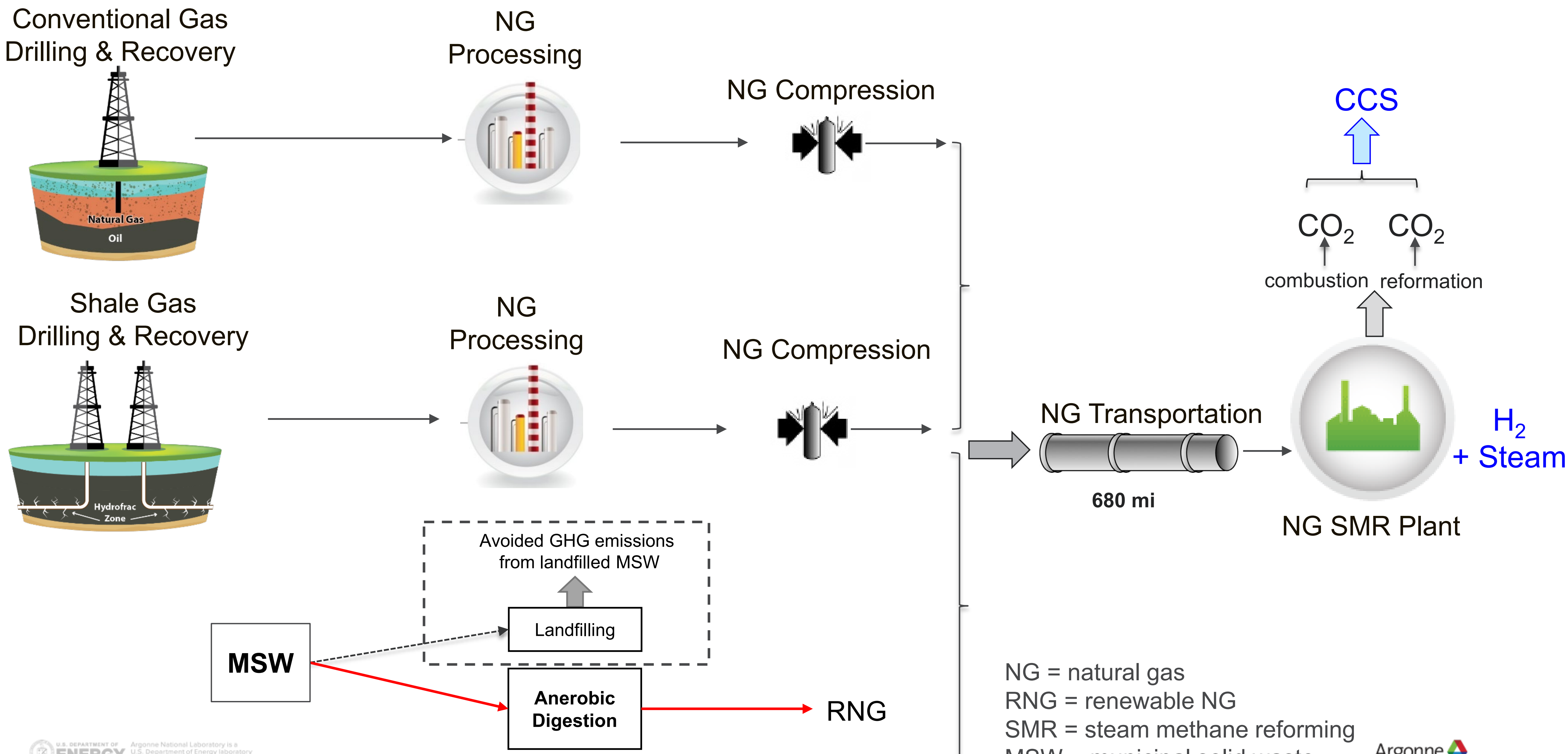






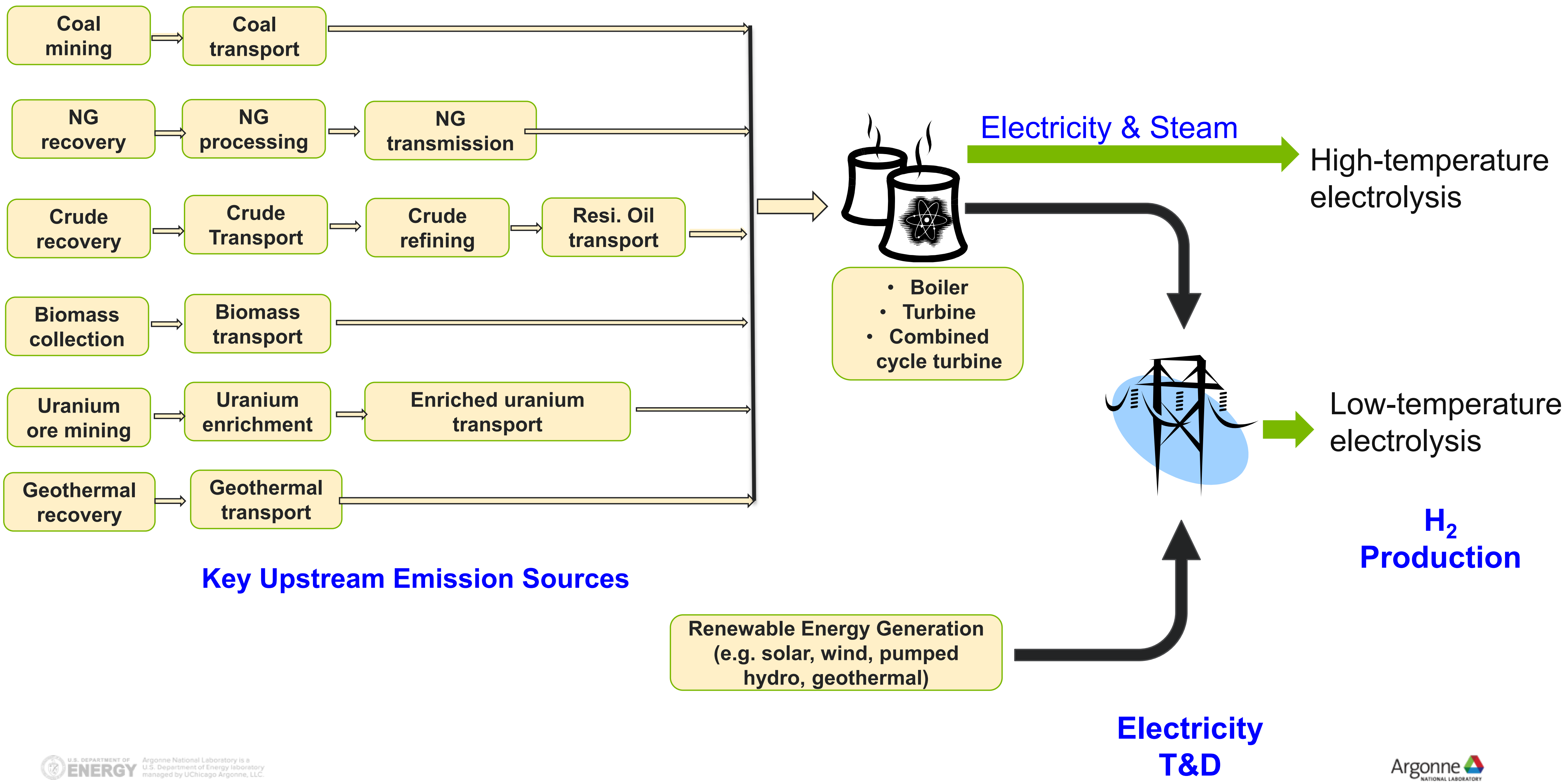


SMR hydrogen production pathway w/ and w/o CCS

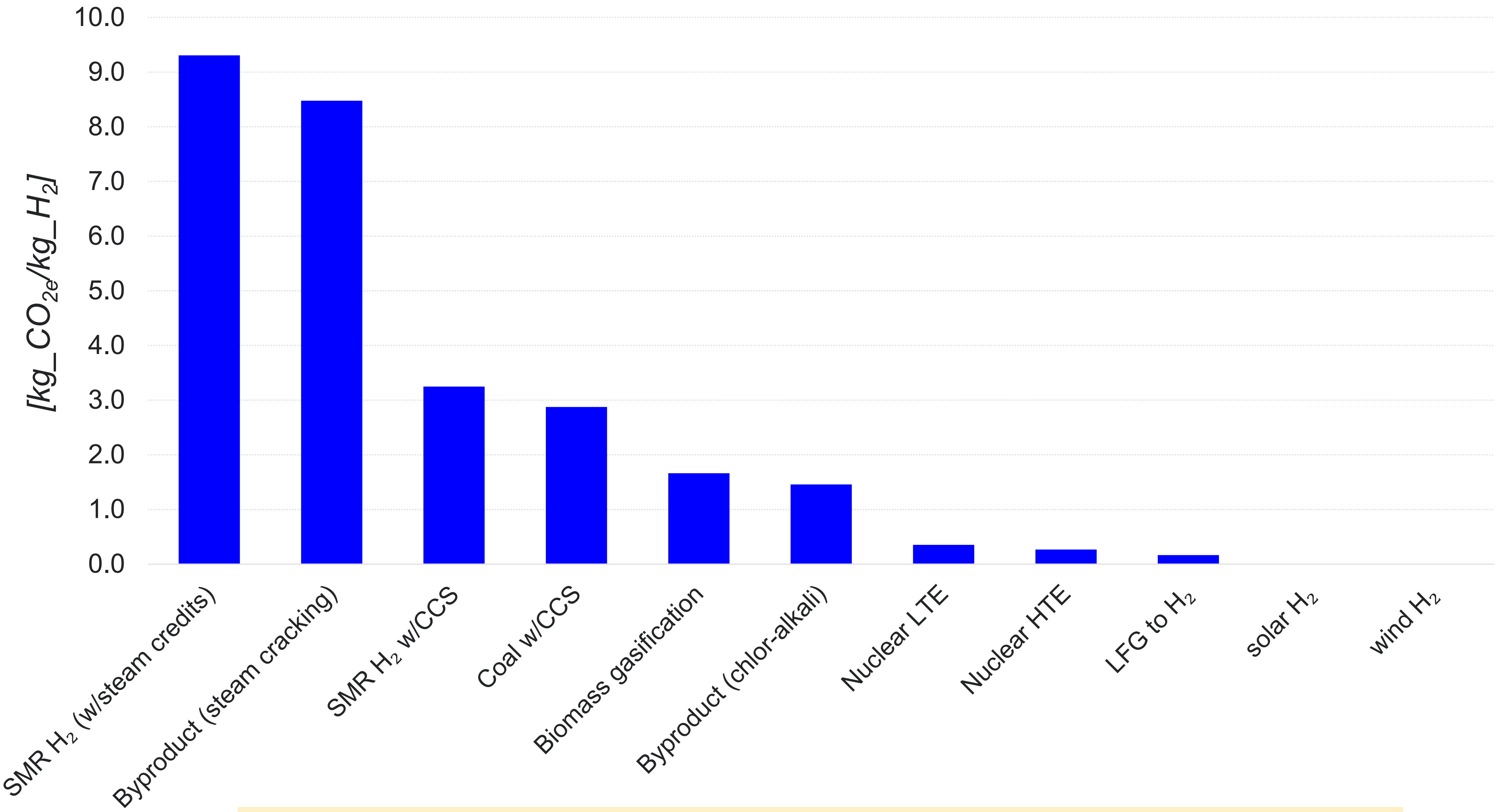


NG = natural gas
RNG = renewable NG
SMR = steam methane reforming
MSW = municipal solid waste

Example hydrogen production pathway: water electrolysis



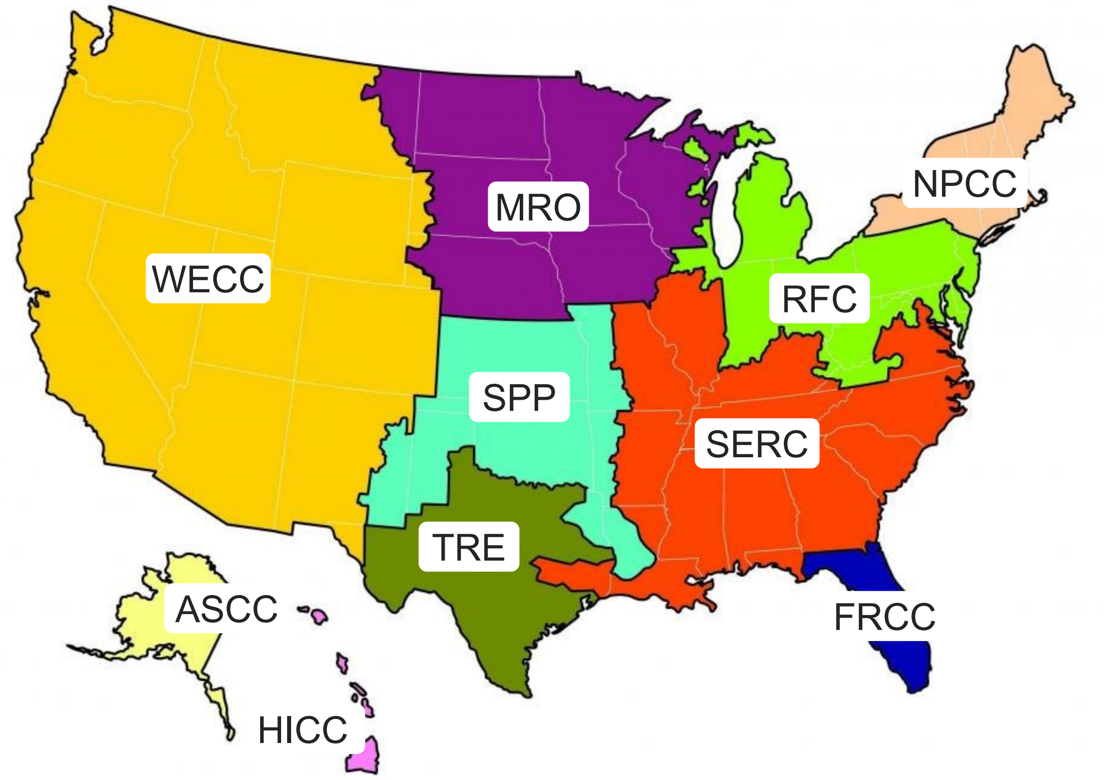
WTG GHG emissions of key hydrogen production pathways

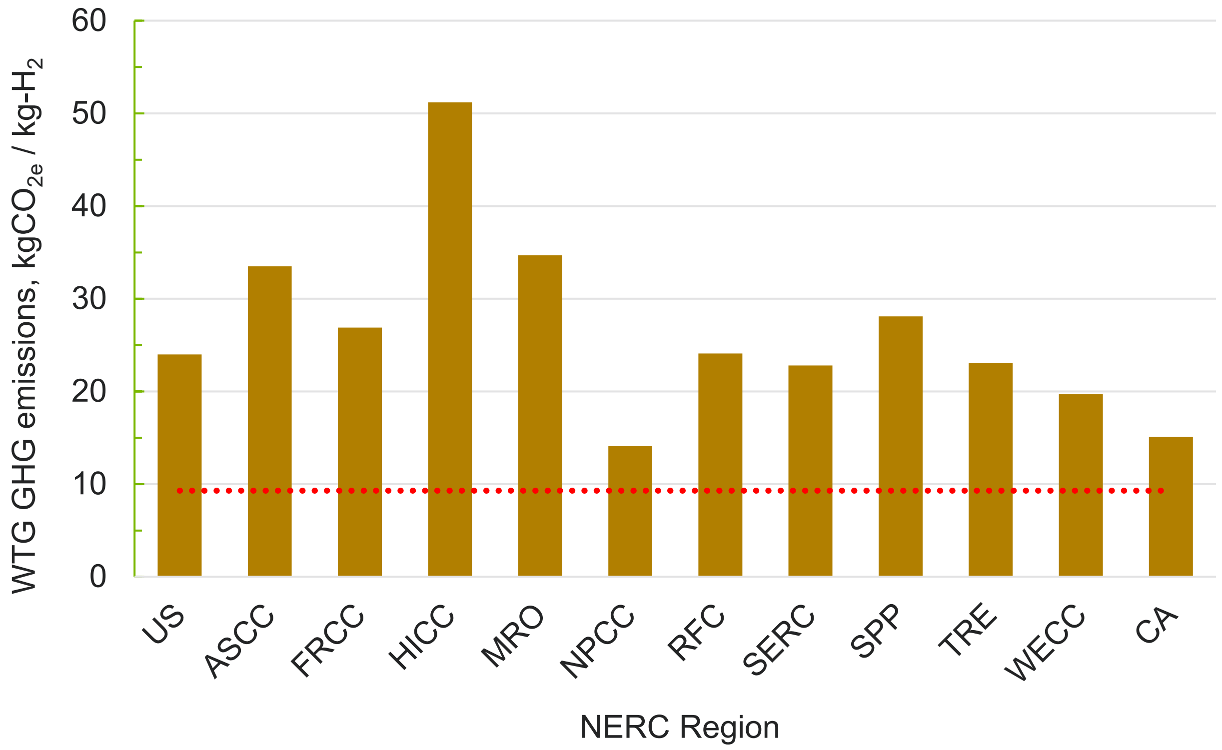


Results are driven by technology performance, such as plant energy efficiency and CO_2 capture rates, as well as other factor such as upstream methane leak rates for SMR

Electrolysis via regional grid electricity – including compression

- WTG emissions for electrolysis H_2





✓ The grid electricity CI decreases in the future, given the increasing share of renewable energy

Variability and uncertainty in LCA

- Technical variability of LCA results reflects
  - Variability of input data, which reflect variabilities in operations of a given facility, facility differences, regional differences, and temporal differences
    - Well defined scope of a LCA can help on data representation for targeted LCA for facilities, regions, or a given time period
    - Key inputs with variability that influence hydrogen production LCA include:
      - ✓ Plant level energy efficiency
      - ✓ Regional emissions intensity of energy supply for electricity
      - ✓ Type of biomass or waste feedstock
      - ✓ Transportation distance of NG
      - ✓ Treatment of co-products (e.g., SMR by-product steam)
  - Uncertainties
    - Sensitivity analysis can show importance of input parameters (e.g., upstream CH_4 leakage)
    - Scenario analysis to show LCA results of different future technologies
- Transparency is key to inform stakeholders

Summary

- Updated hydrogen production technology pathways in GREET
  - SMR w/ and w/o CCS, low-temperature and high-temperature electrolysis, coal and biomass gasification w/ and w/o CCS, by-product hydrogen from chlorine and steam cracking plants, etc.
- Updated hydrogen upstream energy supply chain in GREET
  - Natural gas, RNG, electricity, nuclear, biomass, etc.
- Conducted life cycle analysis with GREET® model for key hydrogen pathways of interest
- Documented data sources, methodology, results and sensitivity to key parameters in a journal article (currently under peer-review)

Collaborations and Acknowledgments

- NETL:
  - ✓ provided process-level mass and energy balance for SMR w/ and w/o CCS, and coal gasification w/ and w/o CCS
- NREL:
  - ✓ provided biomass gasification process level data through H2A models
- Industry stakeholders:
  - ✓ provided input on process level data and typical industry practices for various technologies

Future Work

- Develop user friendly interface for simple user input-output for hydrogen production technologies
  - Dissect GHG emissions by scope (Scope 1, 2, 3)
- Expand GREET model to include new/emerging technology pathways of interest (e.g., ATR,POX, methane pyrolysis, etc.)
- Include embodied emissions in H_2 production equipment and upstream CAPEX (e.g., solar PV, wind turbines, etc.)
- Include GWP of H_2 to assess impact of potential hydrogen leakage throughout value chain
- Model and analyze potential co-benefits of H_2 pathways such as impact on lowering air pollutant emissions as related to human health and environmental justice
- Publish GREET model with new and updated hydrogen technology pathways
- Document modeling and analysis in peer-reviewed publications

Any proposed future work is subject to change based on funding levels

Project Summary

- **Relevance**: Evaluate carbon intensity of hydrogen technology pathways from various energy sources along their value chain
- **Approach**: Expand and update GREET model for environmental life cycle analysis
- **Collaborations**: NETL, NREL and industry stakeholders
- **Technical accomplishments and progress**:
  - Updated hydrogen production technology pathways in GREET
  - SMR w/ and w/o CCS, low-temperature and high-temperature electrolysis, coal and biomass gasification w/ and w/o CCS, by-product hydrogen from chlorine and steam cracking plants, etc.
  - Updated hydrogen upstream energy supply chain in GREET:
  - Natural gas, RNG, electricity, nuclear, biomass, etc.
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  - Model and analyze potential co-benefits of H_2 pathways such as impact on lowering air pollutant emissions
  - Publish GREET model with new and updated hydrogen technology pathways
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TECHNICAL BACKUP AND ADDITIONAL INFORMATION

ACCOMPLISHMENTS AND PROGRESS: RESPONSES TO PREVIOUS YEAR REVIEWERS' COMMENTS

- Not Applicable: no reviewers comments from 2021 AMR on LCA of hydrogen pathways

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TECHNOLOGY TRANSFER ACTIVITIES

- Not applicable to this project

SPECIAL RECOGNITIONS AND AWARDS

- None for this project

PUBLICATIONS AND PRESENTATIONS

1. Young, B., Chiquelin, C., Hawkins, T.R., Sun, P. and A. Elgowainy (2022) "Environmental Life Cycle Assessment of Olefins and By-product Hydrogen from Steam Cracking of Natural Gas Liquids, Naphtha, and Gas Oil," Accepted for publication in Journal of Cleaner Production, in press.
2. Kelly, J., Elgowainy, A., Isaac, R., J., Ward, J., Islam, E., Rousseau, A., Sutherland, I., Wallington, T., Alexander, M., Muratori, M., Adam J., Rustagi, N. (2022) "Cradle-to-grave (C2G) lifecycle analysis of U.S. light-duty vehicle-fuel pathways: A GHG emissions and economic assessment of current (2020) and future (2030-2035) technologies," ANL-22/27.
3. Elgowainy, Amgad, Volume Editor, (2021) "Electric, Hybrid and Fuel Cell Vehicles", Encyclopedia of Sustainability Science and Technology Series, Springer (ISBN-13: 978-1071614914).
4. 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.

PROGRESS TOWARDS DOE TARGETS OR MILESTONES

Progress towards analysis targets / milestones can be assessed through our contributions to relevant barriers:

1. *Inconsistent data, assumptions and guidelines*
   - Updated hydrogen production technologies pathways in collaboration with other national laboratories and industry stakeholders to develop more representative technology performance data and produce more consistent LCA results

2. *Insufficient suite of models and tools*
   - Expanded and updated GREET model with more representative data of current industry practices

3. *Stove-piped/Siloed analytical capability for evaluating sustainability*
   - Developed common modeling platform using established LCA protocol to evaluate various hydrogen production technologies and value chains on a consistent basis
   - Vetted model inputs and analysis output with industry experts and national laboratories