U.S. DEPARTMENT OF ENERGY
Fossil Energy and Carbon Management

LCA/Carbon Footprint of Hydrogen Production

U.S.-Norway Bilateral CCS/CCUS Meeting

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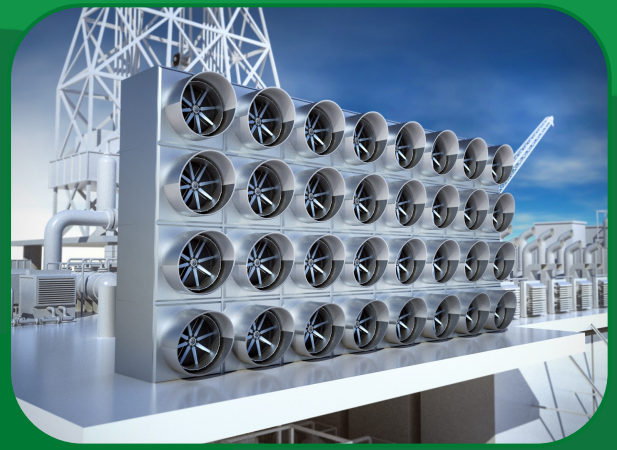
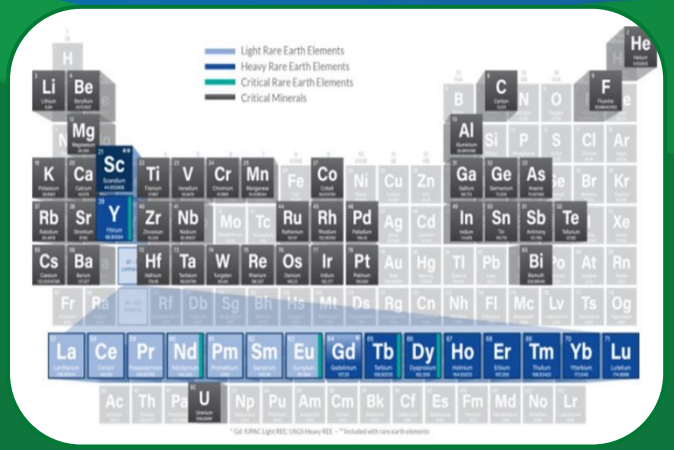
November 1, 2023

Agenda

- Inflation Reduction Act Provisions for H2
- Recent H2 production study from NETL
- International guidance efforts on GHG accounting for H2 production and transportation
- Overview of ANL GREET model and H2 pathways

Inflation Reduction Act (IRA) – Examples of H_2 and Fuel Cell Incentives

Clean Hydrogen Production Tax Credit (45V) up to $3/kg

Carbon Intensity (kg CO_2 per kg H_2)*	Max Tax Credit ($/kg H_2)
4–2.5	$0.60
2.5–1.5	$0.75
1.5–0.45	$1.00
0.45–0	$3.00

* Well-to-gate, using GREET

Qualified Commercial Clean Vehicles Credit (45W)

Creates a **new 30% credit** for commercial fuel cell electric vehicles through 2032, capped at **$40,000**:

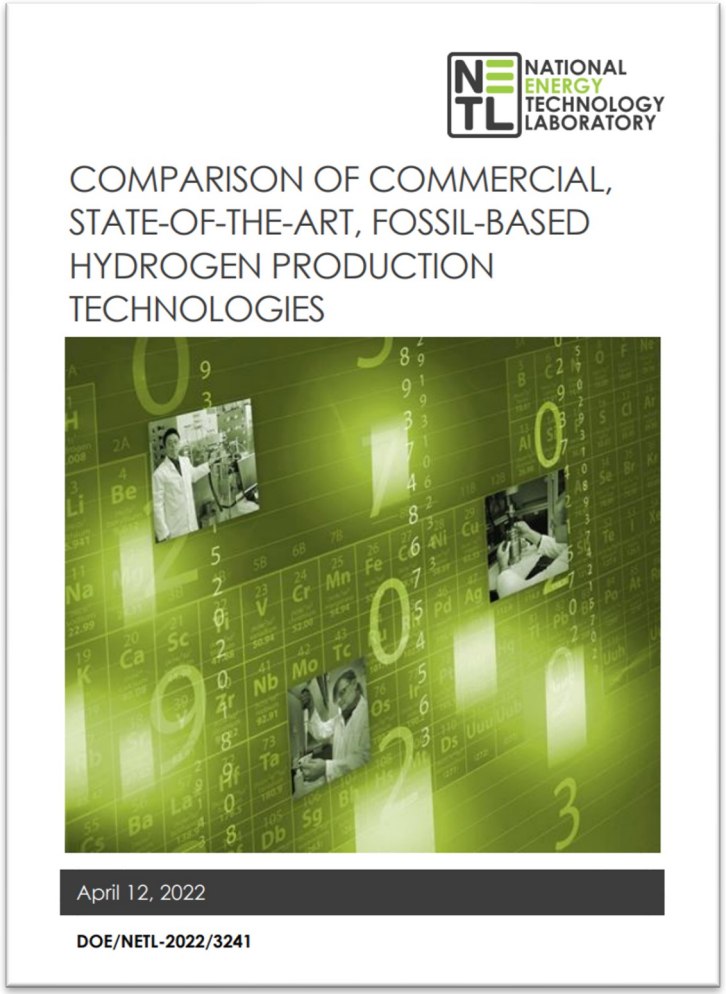
- Class 1–3 vehicles: **$7,500 tax credit** for purchase of qualified clean vehicles
- Class 4 and above: **$40,000 tax credit**

Alternative Fuel Refueling Property Credit (30C)

Tax credit up to 30% of the cost of alternative fuel refueling property up to **$100,000**

DOE/NETL fossil-based H2 study

- TEA/LCA of fossil-to-H_2 production routes using current, commercial technologies provides a basis for DOE FECM R&D program planning to reduce the levelized cost of hydrogen (LCOH) and greenhouse gas (GHG) footprint of future fossil-to-H_2 plants
  - Develop a reference study of H_2 production technologies using current, commercial technologies with emphasis on coal gasification, co-gasification of coal with an alternative feedstock, and natural gas (NG) technologies using the LCOH (2018 $/kg) as the figure of merit
  - Identify areas of R&D to further improve the performance and cost of fossil fuel-based H_2 production, including follow-on analyses



https://www.osti.gov/biblio/1862910

DOE/NETL fossil-based H2 study: Cases

Case[A]	Plant Type	Feedstock(s)	Reformer Type	Gasifier Type	CO_2 Capture (%)	H_2 Purification	H_2 Production Capacity
1	Reforming	NG	SMR	-	0	PSA	200 MMSCFD 483 tonne/day
2					96.2		
3			ATR		94.5		274 MMSCFD 660 tonne/day
4	Gasification	Illinois No. 6 Coal	-	Shell[B]	0		
5					92.5		
6		Illinois No. 6 Coal/Torrefied Woody Biomass			92.6		55 MMSCFD 133 tonne/day

[A] Reforming and gasification plants are assumed to operate at 90 and 80 percent capacity factor, respectively, and are located at a generic plant site in the midwestern United States.

[B] The Shell gasifier has been used in multiple prior NETL studies. As of May 2018, Air Products has acquired the coal gasification technology licensing business from Shell. To be consistent with prior NETL studies and avoid confusion, the gasifier is labeled the "Shell" gasifier.

DOE/NETL fossil-based H2 study: Overview

- **Plant performance, cost, and environmental results reflect only the process configurations studied**
  - Alternative process configurations (i.e., internal power generation, CO_2 capture approach) will produce different results
  - Capital cost estimates carry uncertainty ranges of -15%/+25% (reforming) and -25%/+50% (gasification)
- **Life cycle green house gas emissions**
  - NG –variability throughout the life cycle and across the regional sources of NG
  - Coal – mostly from variability in reported coal mine methane emissions
  - Southern yellow pine – variability in yield and fertilization rates
  - Electricity – variability in reported emissions
- **LCA Impact Assessment method**
  - Default values use Intergovernmental Panel on Climate Change (IPCC) AR5 GWPs with climate carbon feedback.
  - 100-year time horizon
  - Key here is the value of 36 kg CO_2-equivalents per kg of fossil methane.
  - Results based on other vintages of GWPs are provided in the report

DOE/NETL fossil-based H2 study: Results

Life cycle green house gas emissions

- NG – variability throughout the life cycle and across the regional sources of NG
- Coal – mostly from variability in reported coal mine methane emissions
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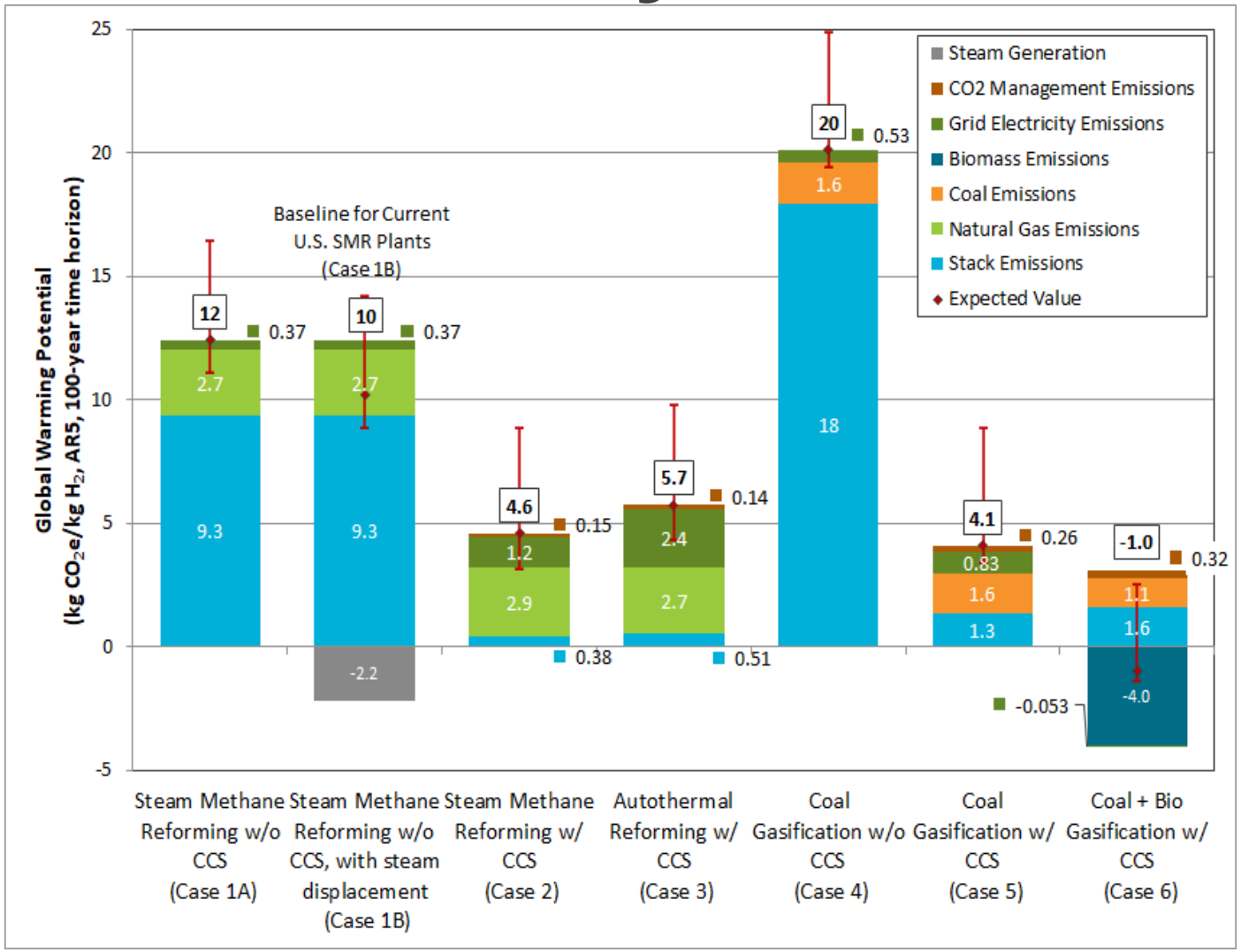
LCA Impact Assessment method

- Default values use Intergovernmental Panel on Climate Change (IPCC) AR5 GWPs with climate carbon feedback.
- 100-year time horizon

When assumptions and boundaries are aligned to GREET model, cases 2 and 5 result in expected values of < 4 kg CO_2e/kg H_2



IPHE H2 Production GHG Methodology

Mutually Agreed Upon Methods of Life Cycle Analysis:
International Partnership for Hydrogen in the Economy (IPHE)
Hydrogen Production Analysis (H2PA) Task Force

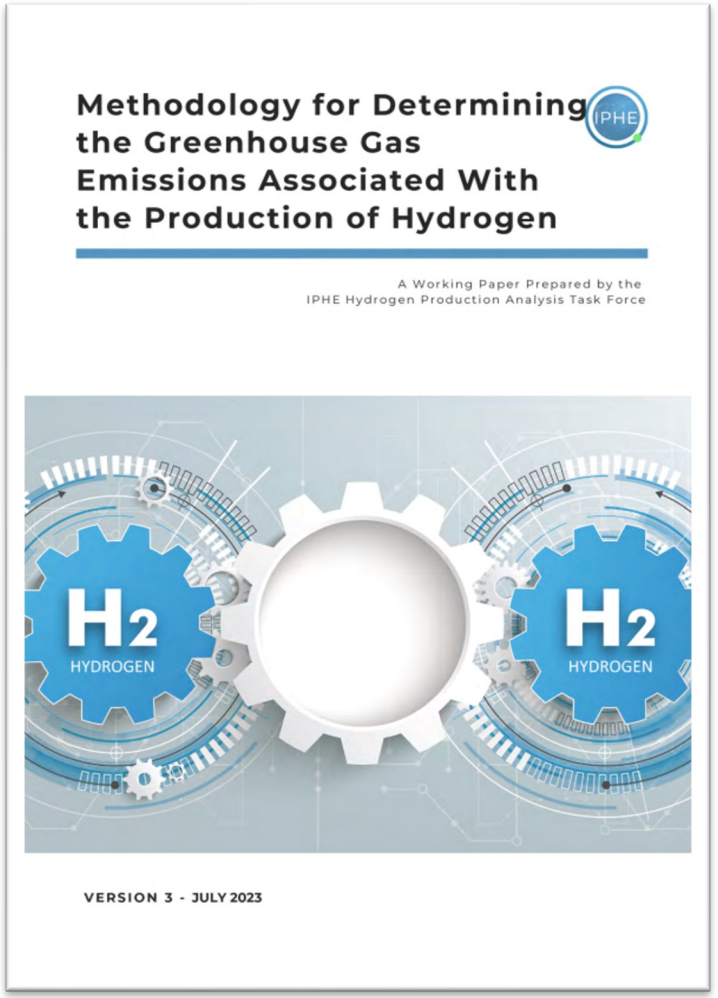
Production pathways:

- Electrolysis
- SMR/CCS, ATR/CCS
- Coal Gasification w/CCS
- Biomass Gasification w/ CCS
- Industrial Bi-Product

Also included in Version 3 are the following Conditioning & Carriers:

- Ammonia as a Hydrogen Carrier
- Liquid Hydrogen
- Liquid Organic Hydrogen Carriers (LOHCs)

This Version 3 includes the GHG evaluation for transportation from production to consumption gate.



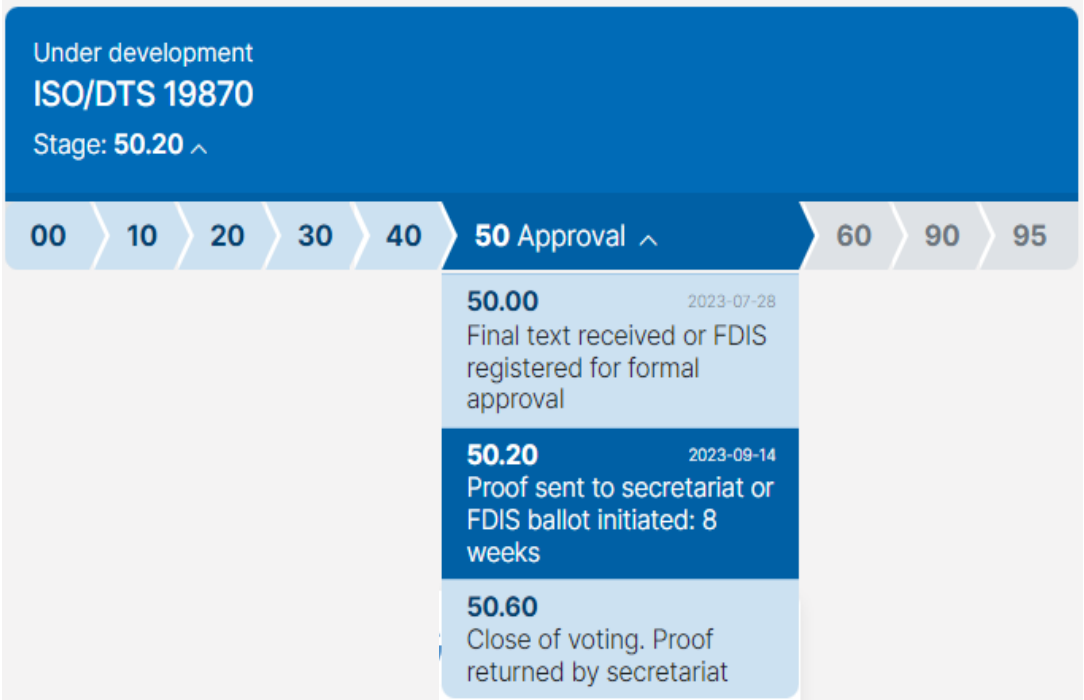
ISO/Draft Technical Specification (DTS) 19870 – Hydrogen technologies

The scope of this proposal is to establish a methodology and analytical framework to determine the GHG emissions related to a unit of produced hydrogen up to the consumption gate.

This NP proposes a Technical Specification consisting of the following 3 Parts:

- Part 1: Hydrogen production
- Part 2: Hydrogen conditioning
- Part 3: Hydrogen transportation

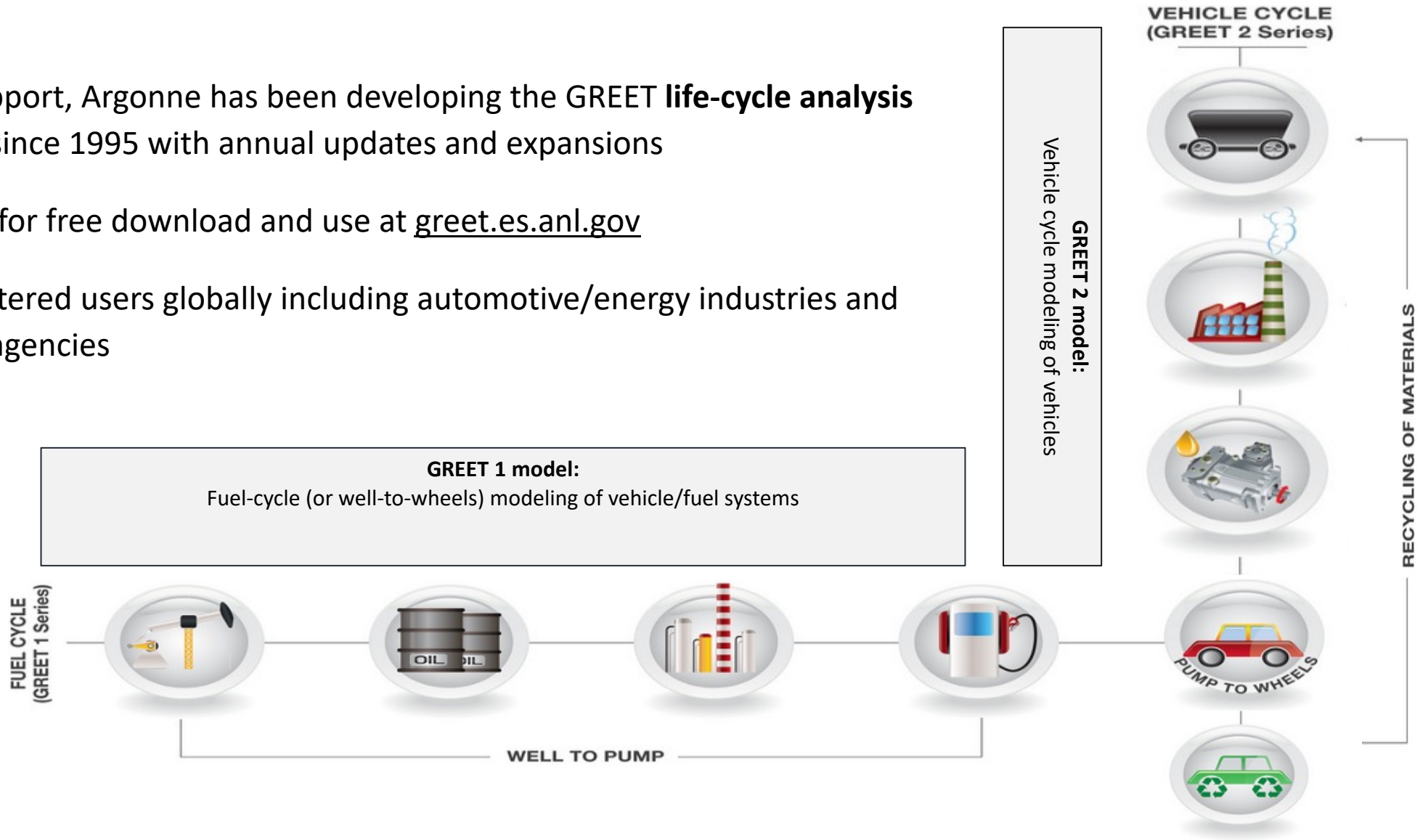
NOTE: Once a draft of this comprehensive TS is developed (estimated December 2023), the intent is to use it as a seed document for the development of 3 individual standards – one per each part noted above – belonging to the same family of standards. This will require 3 individual NPs.



https://www.iso.org/standard/65628.html

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

United States Government	Production tax credits and clean hydrogen standard under IRA and BIL
California Environmental Protection Agency Air Resources Board	CA-GREET3.0 built based on and uses data from ANL GREET
DEQ State of Oregon Department of Environmental Quality	Oregon Dept of Environ. Quality Clean Fuel Program
	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 · OACI · ИКАО; Federal Aviation Administration	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

- 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

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

Human health and environmental justice

Greenhouse gases

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

Global warming impacts

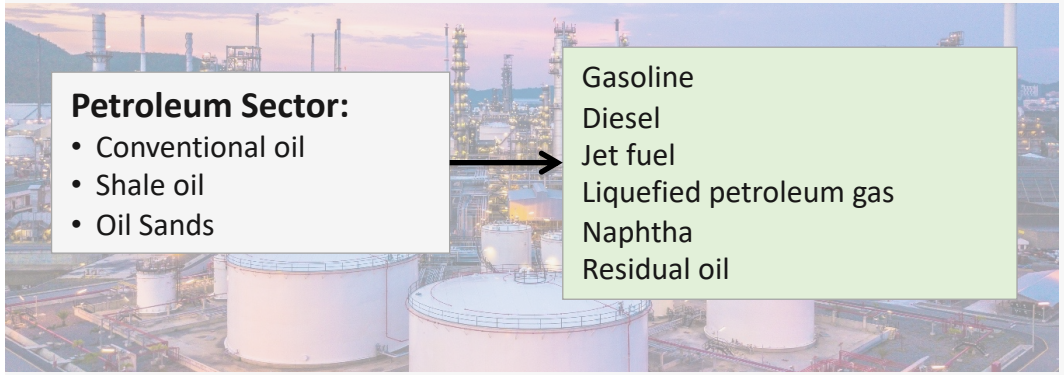
Water consumption

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

Regional/seasonal water stress impacts

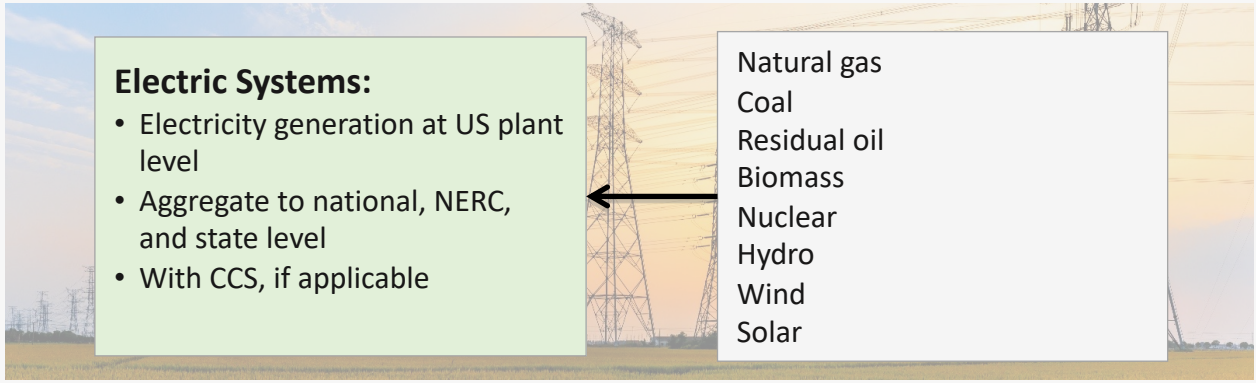
GREET covers many groups of energy systems

Photo credit: Shutterstock.com



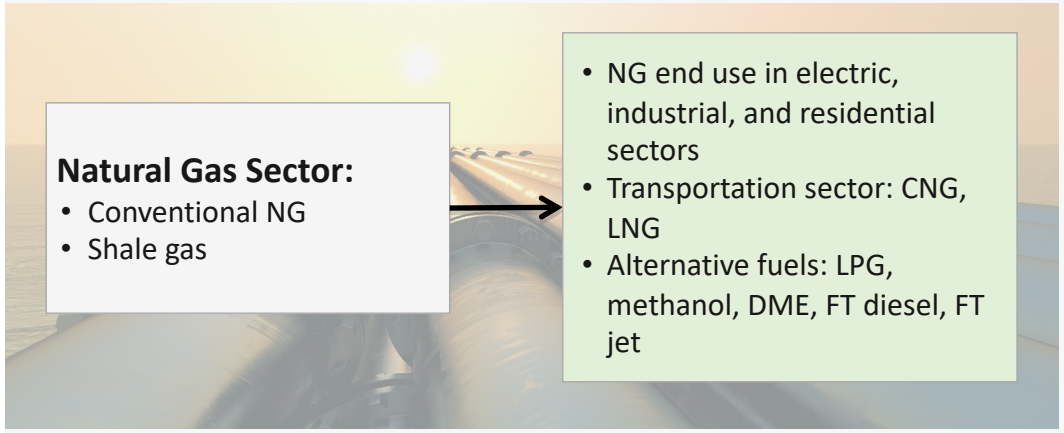
Petroleum Sector:
- Conventional oil
- Shale oil
- Oil Sands

→ Gasoline, Diesel, Jet fuel, Liquefied petroleum gas, Naphtha, Residual oil



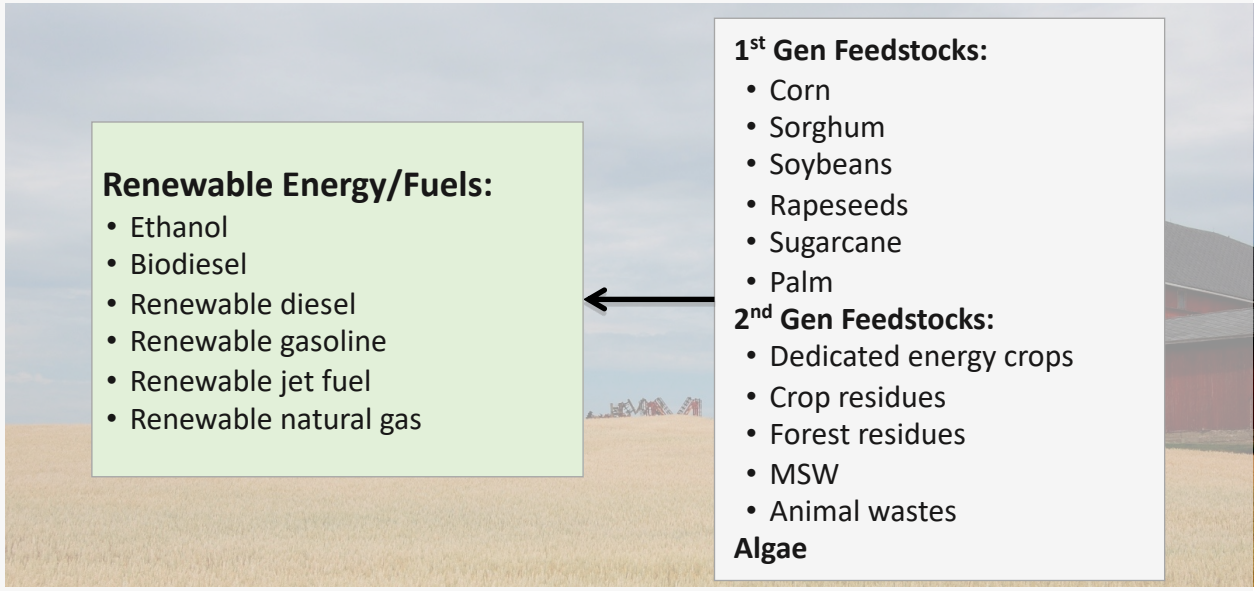
Electric Systems:
- Electricity generation at US plant level
- Aggregate to national, NERC, and state level
- With CCS, if applicable

← 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

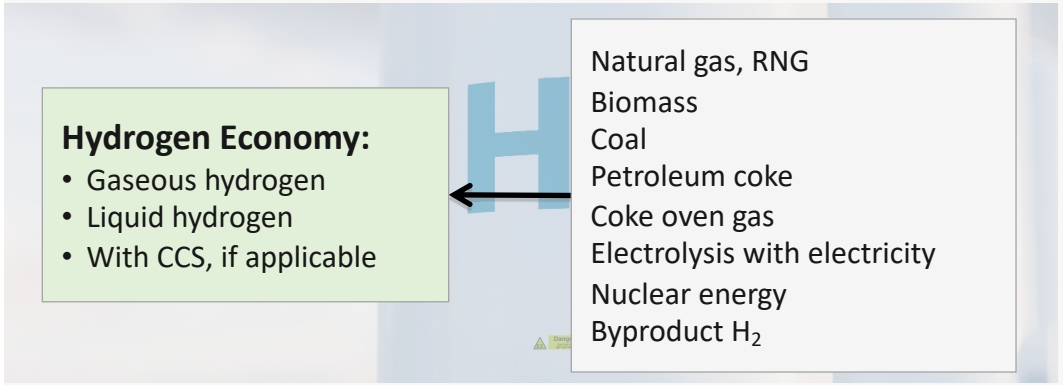


Renewable Energy/Fuels:
- Ethanol
- Biodiesel
- Renewable diesel
- Renewable gasoline
- Renewable jet fuel
- Renewable natural gas

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

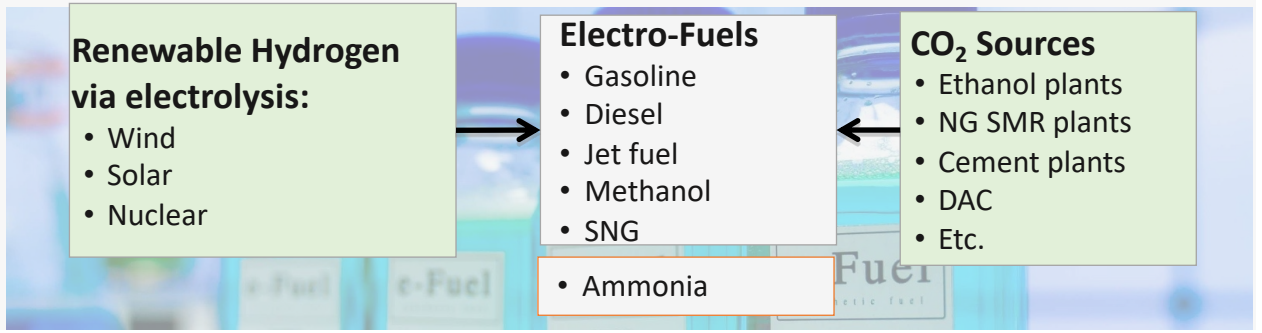
2nd Gen Feedstocks:
- Dedicated energy crops
- Crop residues
- Forest residues
- MSW
- Animal wastes

Algae



Hydrogen Economy:
- Gaseous hydrogen
- Liquid hydrogen
- With CCS, if applicable

← Natural gas, RNG, Biomass, Coal, Petroleum coke, Coke oven gas, Electrolysis with electricity, Nuclear energy, Byproduct H_2



Renewable Hydrogen via electrolysis:
- Wind
- Solar
- Nuclear

→ **Electro-Fuels**
- Gasoline
- Diesel
- Jet fuel
- Methanol
- SNG
- Ammonia

← **CO_2 Sources**
- Ethanol plants
- NG SMR plants
- Cement plants
- DAC
- Etc.

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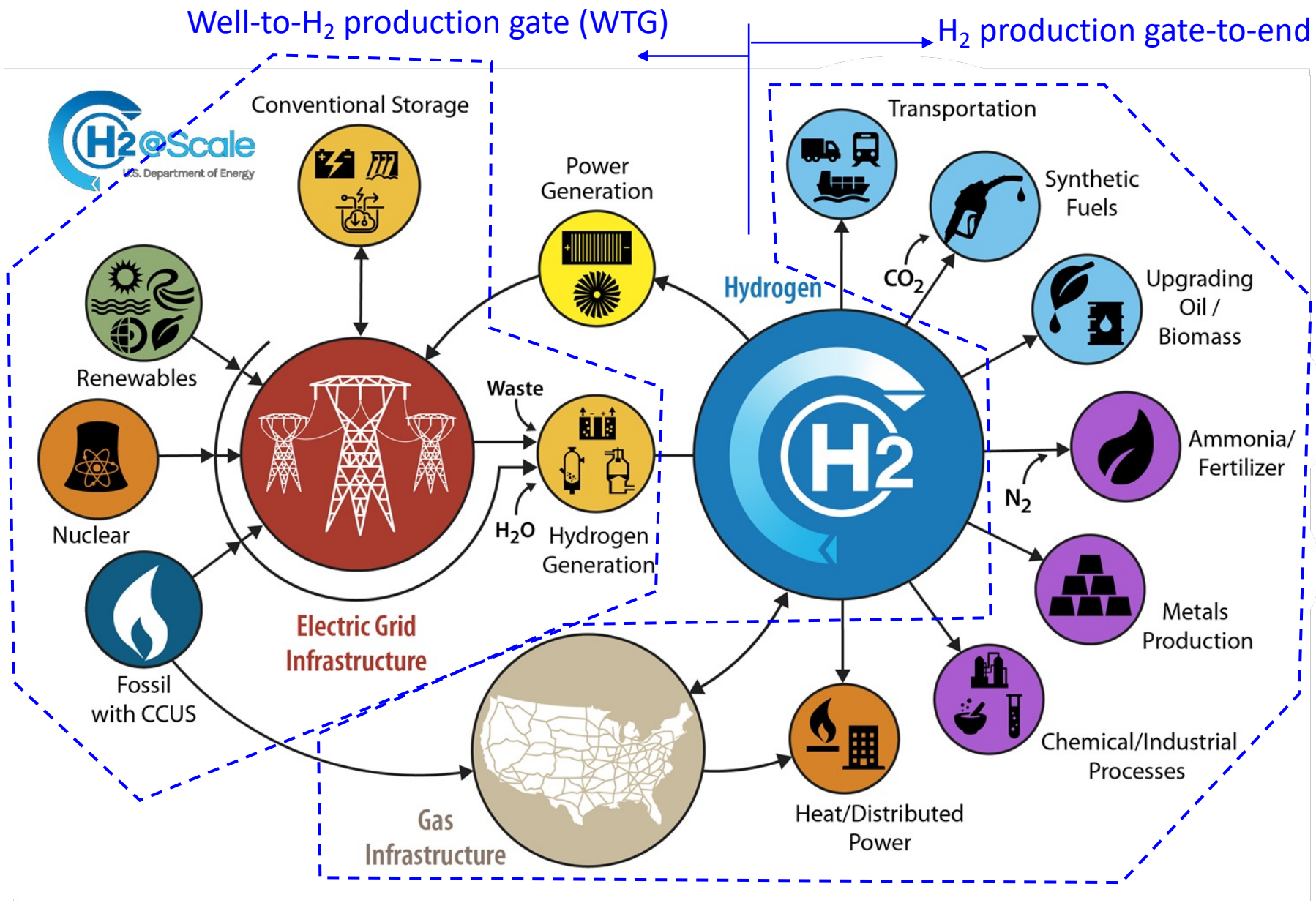
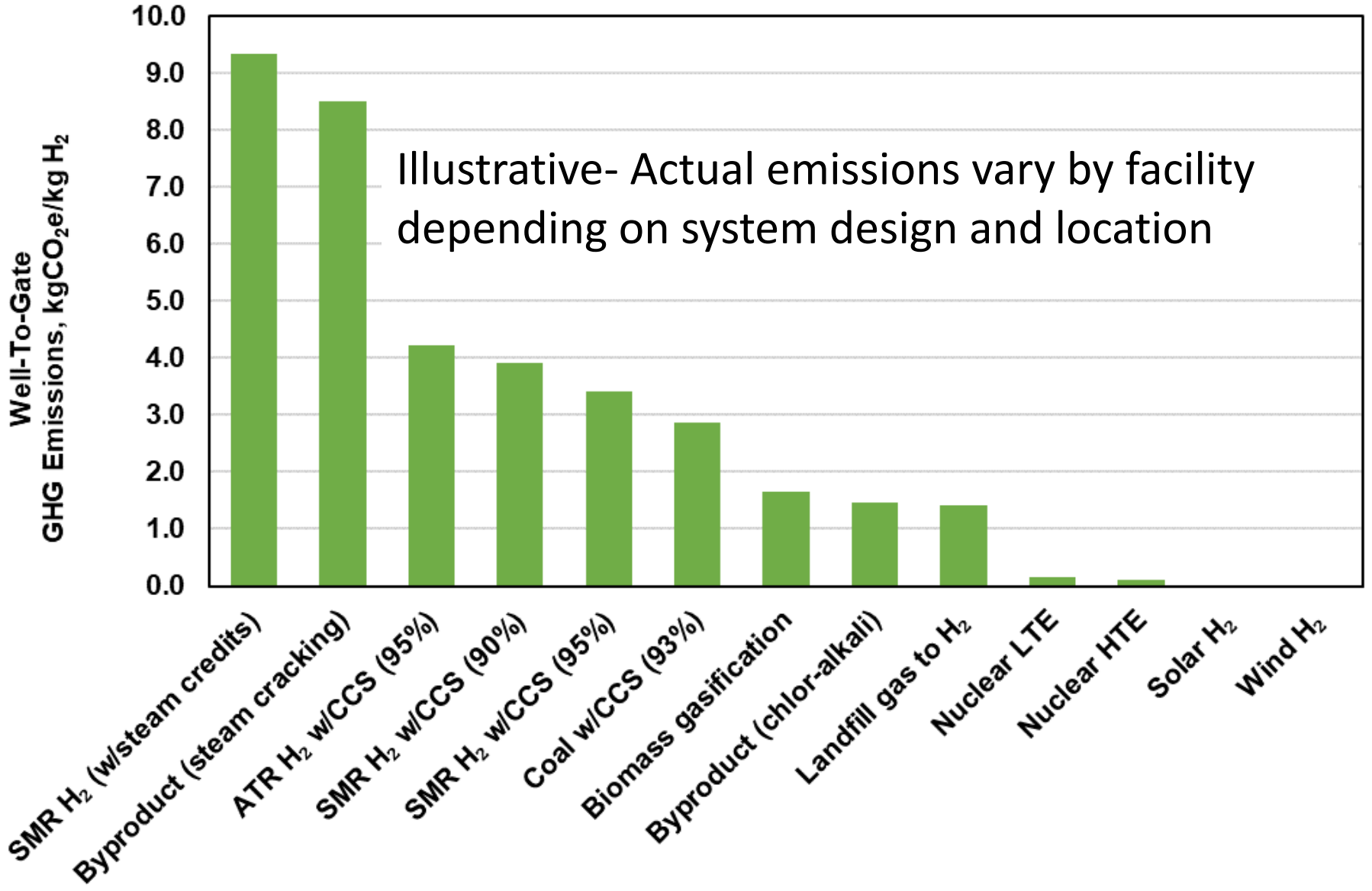
H2@Scale: a DOE initiative for a hydrogen economy



- Bipartisan Infrastructure Law (BIL)
  - ✓ November 2021
  - ✓ $9.5B for clean H_2 production and deployment
  - ✓ Clean Hydrogen Production Standard (<4 $kgCO_{2e}/kg_{H2}$)
- Inflation Reduction Act (IRA)
  - ✓ August 2022
  - ✓ Up to $3/kg credit based on H_2 well-to-gate carbon intensity (CI)
  - ✓ Argonne GREET model for CI calculations

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



SMR= Steam Methane Reforming;
ATR=Autothermal Reforming
CCS=Carbon Capture and Sequestration;
LTE=Low-Temp Electrolysis;
HTE=High-Temp Electrolysis;
LFG=Landfill Gas

https://greet.es.anl.gov/files/hydrogenreport2022