Seminar to the Network on
Sustainability through Life Cycle Approaches

January 30, 2025

Life Cycle Analysis of Technologies with R&D GREET Model

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Argonne National Laboratory

The R&D GREET effort at Argonne National Laboratory is supported by the Office of Energy Efficiency and Renewable Energy, the Office of Fossil Energy and Carbon Management, the Office of Clean Energy Demonstration, the Office of Technology Transitions, the Office of Nuclear Energy, and ARPA-E of the US Department of Energy (DOE) under contract DE-AC02-06CH11357.

Argonne's R&D GREET is to inform the life cycle analysis of technical community. Not all pathways and data in R&D GREET are appropriate for use in circumstances where a high level of quantitative certainty or precision is required. GREET is referenced in numerous independent state and federal compliance and incentive programs (including solicitations, rulemakings, and tax incentives), but it is important to note that R&D GREET is not the version used by any of these specific programs. Argonne does not warrant that use of R&D GREET is consistent with the requirements of any particular regulatory or incentive program.

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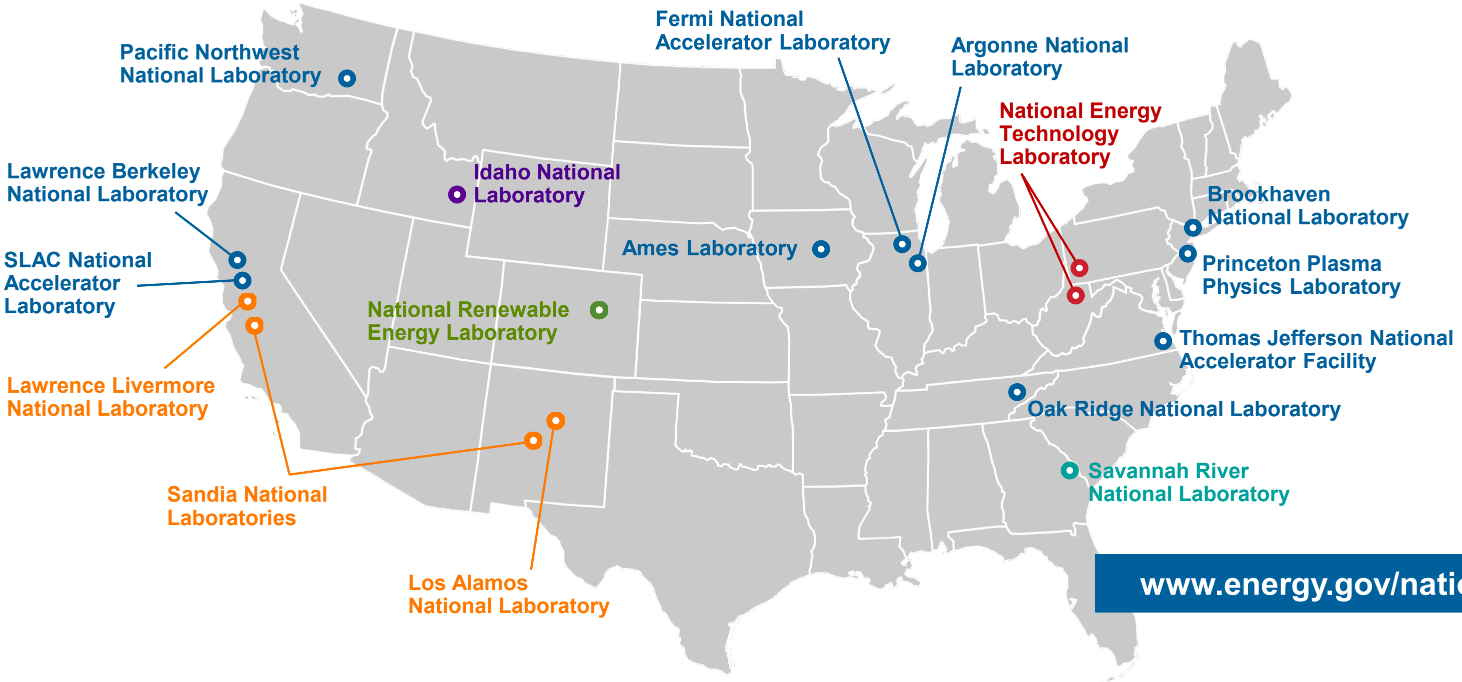

LABORATORIES BY OFFICE OR ADMINISTRATION

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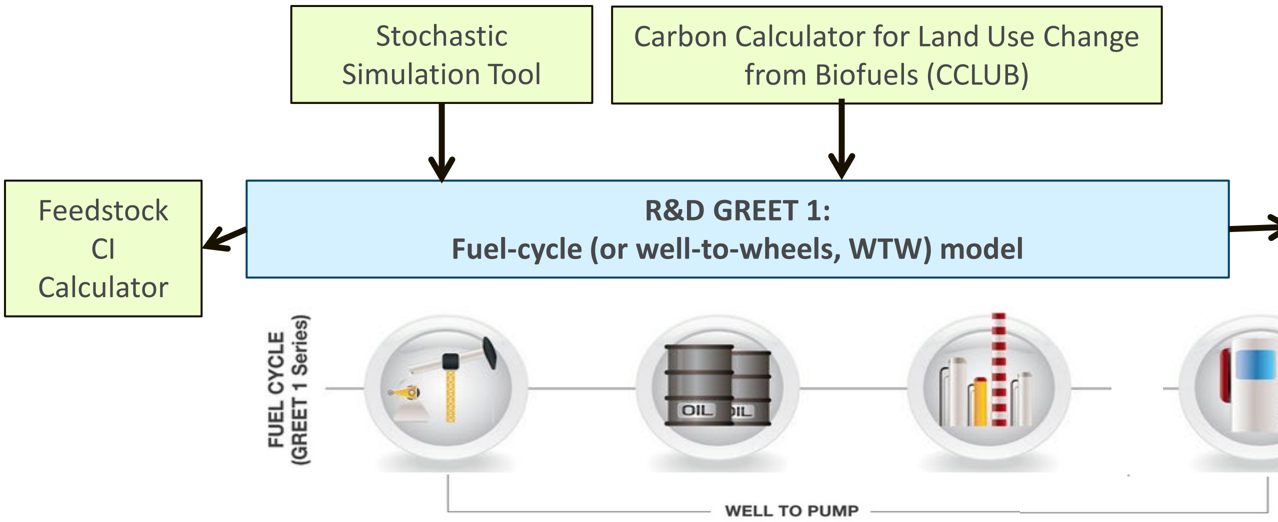
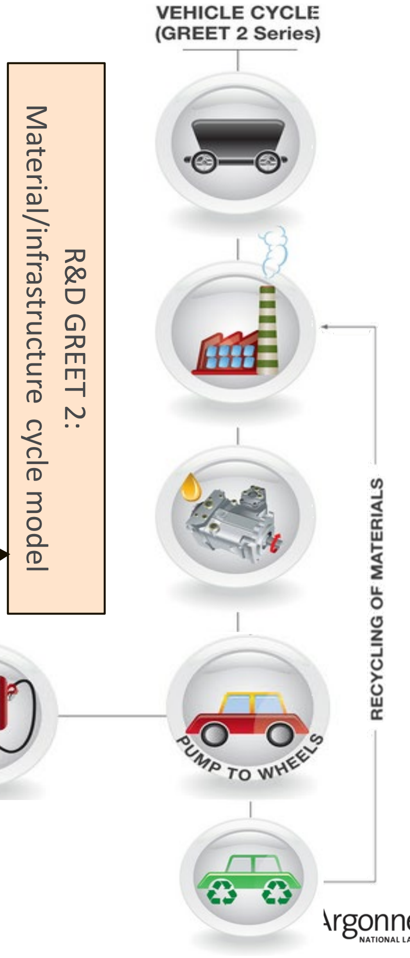
The R&D GREET (Greenhouse gases, Regulated Emissions, and Energy use in Technologies) model framework

- Argonne has been developing the R&D GREET **life-cycle analysis (LCA)** model since 1995 with annual updates and expansions
- R&D GREET is available at greet.anl.gov
- R&D GREET Outputs: GHG emissions, Criteria Air Pollutant emissions, Energy Use, and Water Consumption

(Vehicle manufacturing cycle as the example)





R&D GREET LCA objectives

- Tracks life cycle performance of technologies to present their value propulsition and inform R&D and business decisions by agencies and corporations
- Build LCA modeling capacity for DOE, other agencies, and R&D community
- Build a consistent LCA platform with reliable, widely accepted methods/protocols
- Address emerging LCA issues
- Conduct detailed LCA and to document data sources, modeling and analysis approaches, and results/conclusions
- Maintain openness and transparency of LCAs by making GREET, its data, and publications publicly available

LCA is data intensive; data, as well as methodology, drive LCA results

- Background vs. foreground data: in relation to specific technology under LCA
  - Background data: reflect background systems
    - ✓ Improvements of the rest of economy on specific technology under LCA
    - ✓ Consistency and up-to-date are key
  - Foreground data: reflect the state of the technology under LCA
    - ✓ Spatial representation: regional differences where technologies will be deployed
    - ✓ Temporal representation: past, present, and future performance of technologies
    - ✓ Data verification is key

- Primary vs. secondary data: related mainly to foreground data
  - Primary data: data from facility operations (surveys, etc.)
  - Secondary/proxy:
    - ✓ Simulations with process engineering modeling (techno-economic analysis)
    - ✓ Literature data
    - ✓ Approximation

- Data quality: affecting LCA reliability
  - Quality rating is usually subjective
  - Technologies at different TRLs affect data availability, thus data quality

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

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

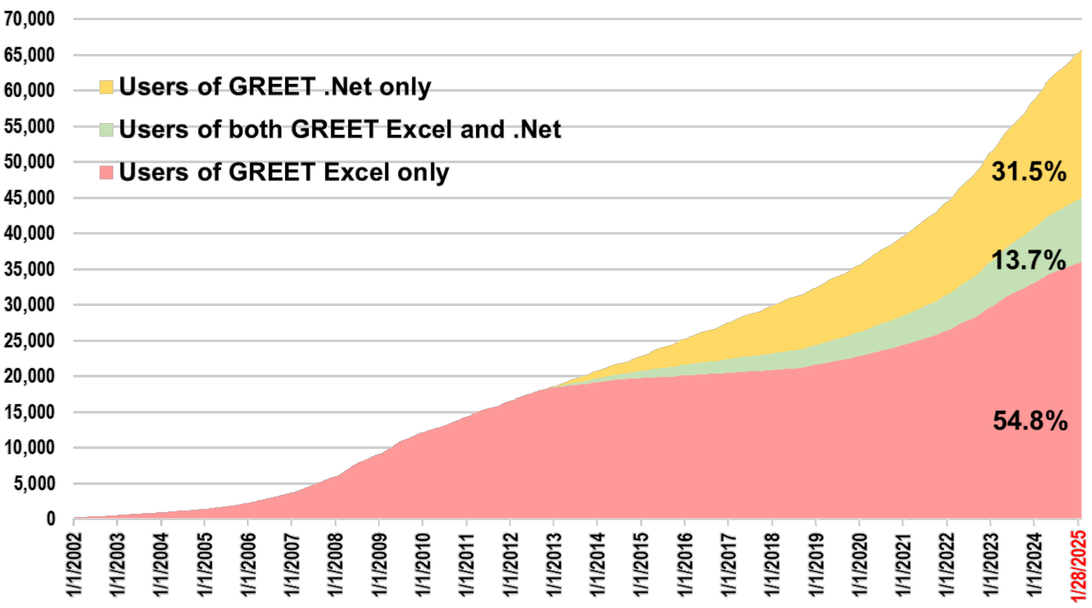
Global warming impacts

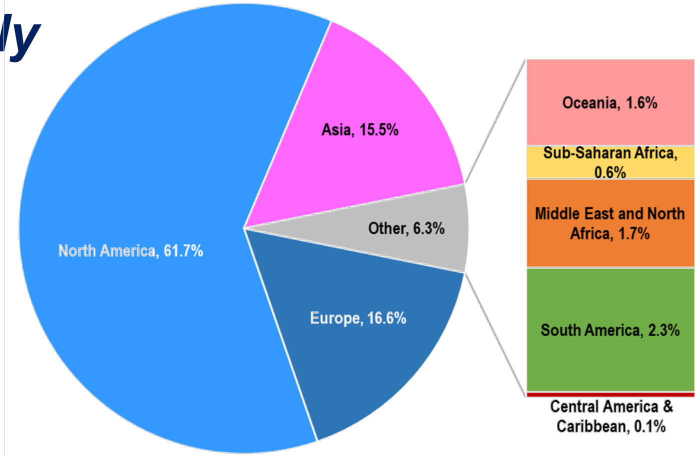
Water consumption

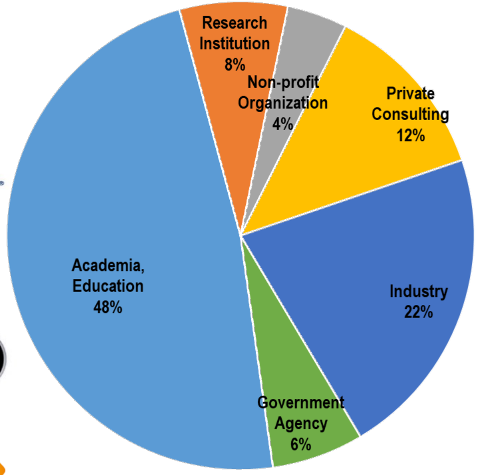
- Addressing water supply and demand (energy-water nexus)

Regional/seasonal water stress impacts

>65,000 Registered R&D GREET Users Globally







Argonne GREET website has R&D GREET, technical reports, journal articles, and technical memos.

ANL/ESIA-24/20

Summary of Expansions and Updates in R&D GREET® 2024

Prepared by
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Systems Assessment Center
Energy Systems and Infrastructure Analysis Division
Argonne National Laboratory

January 2025

Argonne's R&GREET Model
https://greet.anl.gov

Energy Systems and Infrastructure Analysis

Argonne NATIONAL LABORATORY

RESEARCH CAPABILITIES PUBLICATIONS NEWS

R&D GREET®

- Publications
- Databases
- R&D GREET Model Platforms
  - R&D GREET .Net
  - R&D GREET Excel
    - Fuel-Cycle Model
    - Vehicle-Cycle Model
- GREET Tools
  - R&D GREET Building Module
  - R&D GREET Marine Module
  - R&D GREET Rail Module
  - R&D GREET Battery Module
  - ICAO-GREET Model
  - GREET+ Model
  - FD-CIC Tool
  - WTW Calculator
  - AFLEET Tool

This is Argonne National Laboratory's R&D version of GREET.
For GREET versions used for determining tax credits, please click here.
A brief introduction to R&D GREET can be found here.

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

GREET News

R&D GREET 2024 Release January 10, 2025

The Argonne National Laboratory's Systems Assessment Center is pleased to announce the 2024 release of the suite of R&D GREET Models. Please read Summary of Expansions and Updates in R&D GREET® 2024 (451KB pdf) for more details on updates in this version.

DISCLAIMER

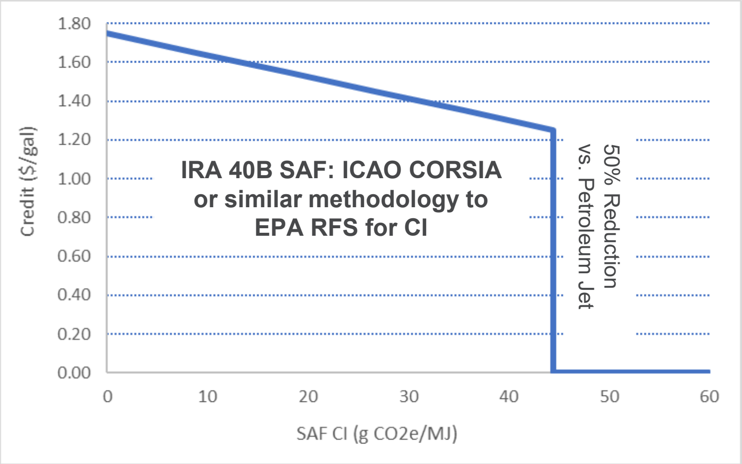
R&D GREET 2024 is being released, consistent with Argonne National Laboratory's routine annual R&D GREET update process. Consistent with annual updates since 1995, R&D GREET (also historically called "ANL GREET") includes representation of new fuel pathways and updates to underlying assumptions. Pathways represented in the tool include two major categories: A) those that have been rigorously evaluated and have high certainty; and B) those that are preliminary, which could include pathways that have not recently been evaluated; those where there is still a gap in the science or data, and/or those that are currently under internal or external peer review. Argonne's annual releases of R&D GREET are comprehensive in order to inform the life cycle analysis technical community and elicit stakeholder feedback. These annual releases are meant to share the early-stage perspectives in life-cycle analysis, particularly in preliminary form, so as to gather feedback from the academic and technical expert community and determine where additional research, analysis and data are needed. Not all pathways and data in R&D GREET are appropriate for use in circumstances where a high level of quantitative certainty or precision is required. Inclusion of a pathway or module in R&D GREET does not necessarily represent U.S. Government concurrence for any specific use, but instead is intended to gather technical feedback and advance the science of life-cycle analysis.

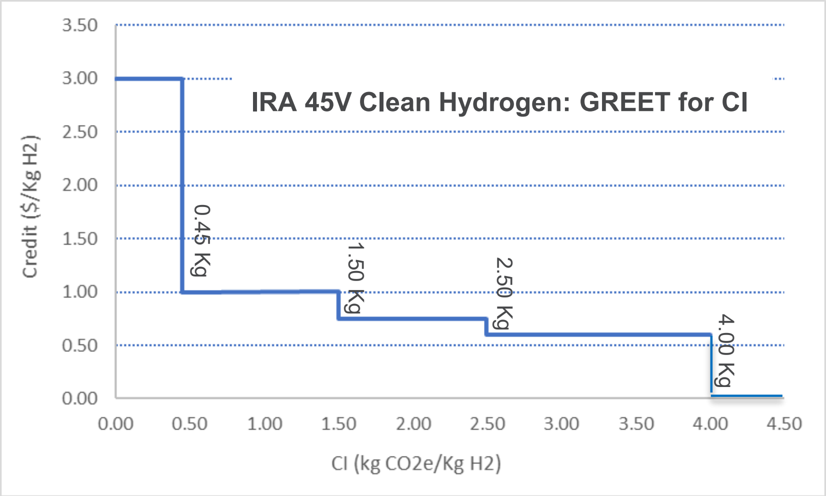
R&D GREET informs policies and regulations

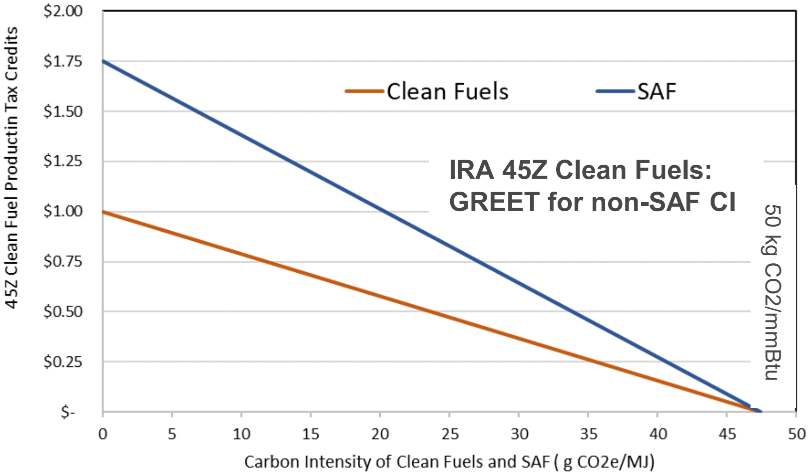
- **CA-GREET** is an adaptation of Argonne's GREET model
- **Oregon Clean Fuels Program** also uses an adaptation of Argonne's GREET model
- **State of Washington Clean Fuel Regulation** relies on CA-GREET
- **U.S. EPA** uses GREET with other sources for **Renewable Fuels Standard** pathway evaluations
- **National Highway Traffic Safety Administration** for fuel economy regulation
- **Federal Aviation Administration** and **International Civil Aviation Organization** using GREET to evaluate aviation fuel pathways
- **Canadian Clean Fuel Regulation** for Environment and Climate Change Canada fuel pathways

- LCA results for use in different provisions of the 2021 **Bipartisan Infrastructure Law** and the 2022 **Inflation Reduction Act**

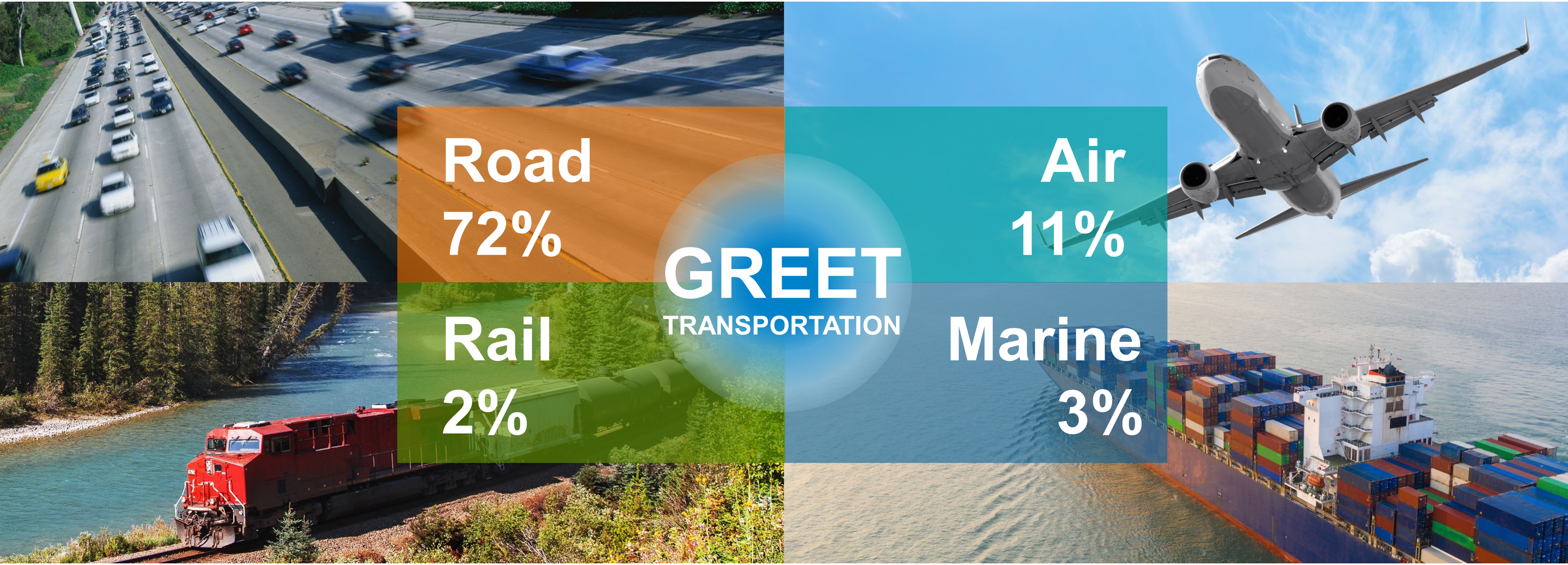
SAF, clean fuel, and clean hydrogen incentives under the Inflation Reduction Act (IRA)







R&D GREET covers all transportation subsectors



Share of US transportation GHG emissions; remaining 12% for US is from pipelines and offroad.

R&D GREET also includes materials, chemicals, bioproducts and plastics (and other bulk materials)

- Platform chemicals from refinery operations
- Bio-based chemicals

- Materials for vehicles
- Building and construction materials

- Major building blocks to promote and expand the U.S bioeconomy
- Integration of biorefinery process with biofuels

- Major fossil-based plastics
- Bioplastics,
- Plastic re-/upcycling, and plastic-to-fuels

R&D GREET covers an extensive list energy systems

Petroleum ⟹

- Gasoline
- Diesel
- Jet fuel
- Etc.

- Natural gas
- Renewable natural gas
- Coal mine methane
- Coal
- Electricity (solar, wind, nuclear, grid, etc.)

⟹ Hydrogen: gaseous/liquid

Renewable Hydrogen via low-C electricity:
- Wind
- Solar
- Nuclear

\+

CO_2 Sources
- Biogenic
- Point sources
- Direct air capture

⟹ Electro-fuels
- Gasoline
- Diesel
- Jet fuel
- Methanol

- Natural gas
- Shale gas
- Renewable natural gas
- Coal mine methane

⟹

- Electricity/Heat
- Hydrogen
- Methanol
- Ammonia
- Diesel/jet fuel

- Natural gas
- Coal
- Nuclear
- Hydro
- Wind
- Solar
- etc.

⟹ Electricity: national, NERC, and state level

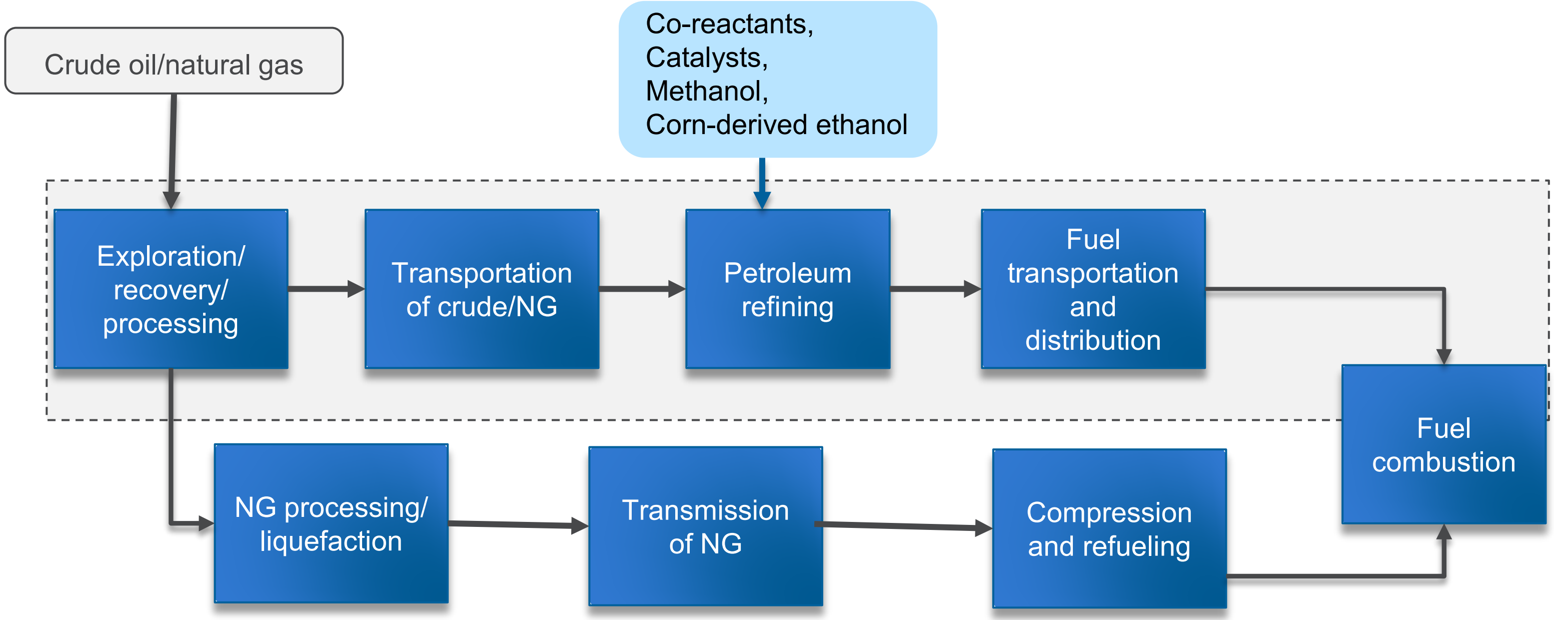
1st Gen Feedstocks:
- Corn
- Soybeans
- Sugarcane
- Etc.

2nd Gen Feedstocks:
- Energy crops
- Crop/forest residues
- Wastes (MSW, animals)

⟹

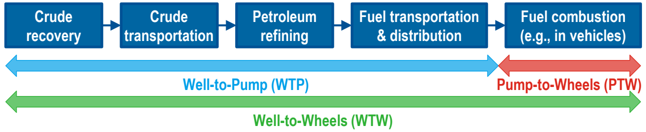
- Ethanol
- Biodiesel
- Renewable diesel
- Sustainable aviation fuels (SAF)

Life cycle of fuels from petroleum and natural gas

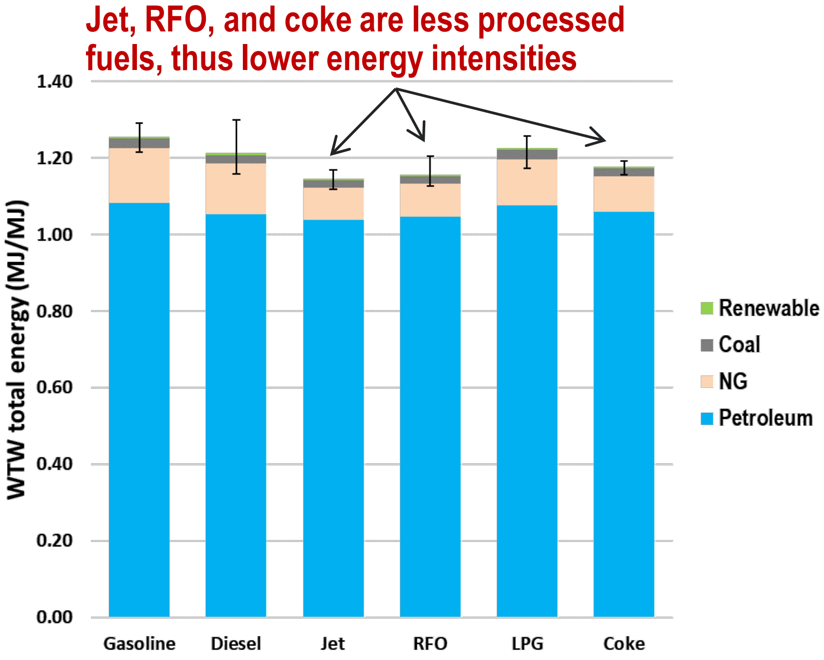


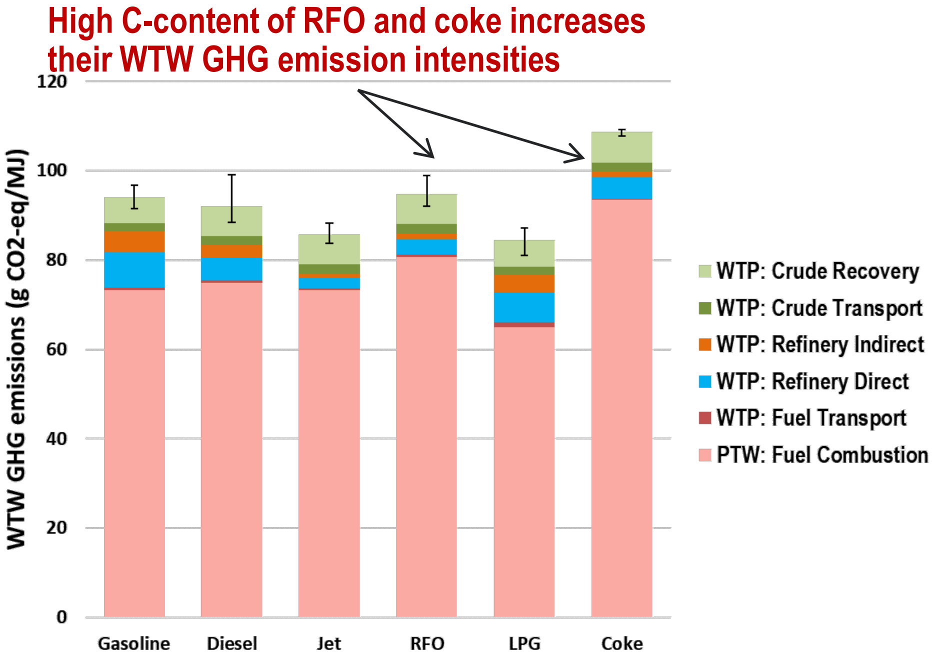
- All direct activities and emissions in the above flowcharts are included
- **Land disturbance** of oil/NG recovery was assessed and included in R&D GREET (up to 2 g/MJ)
- Methane leakage of the NG supply chain is based on combined bottom-up (EPA GHG Inventory) and top-down (individual studies) approach

Petroleum product well-to-wheels results



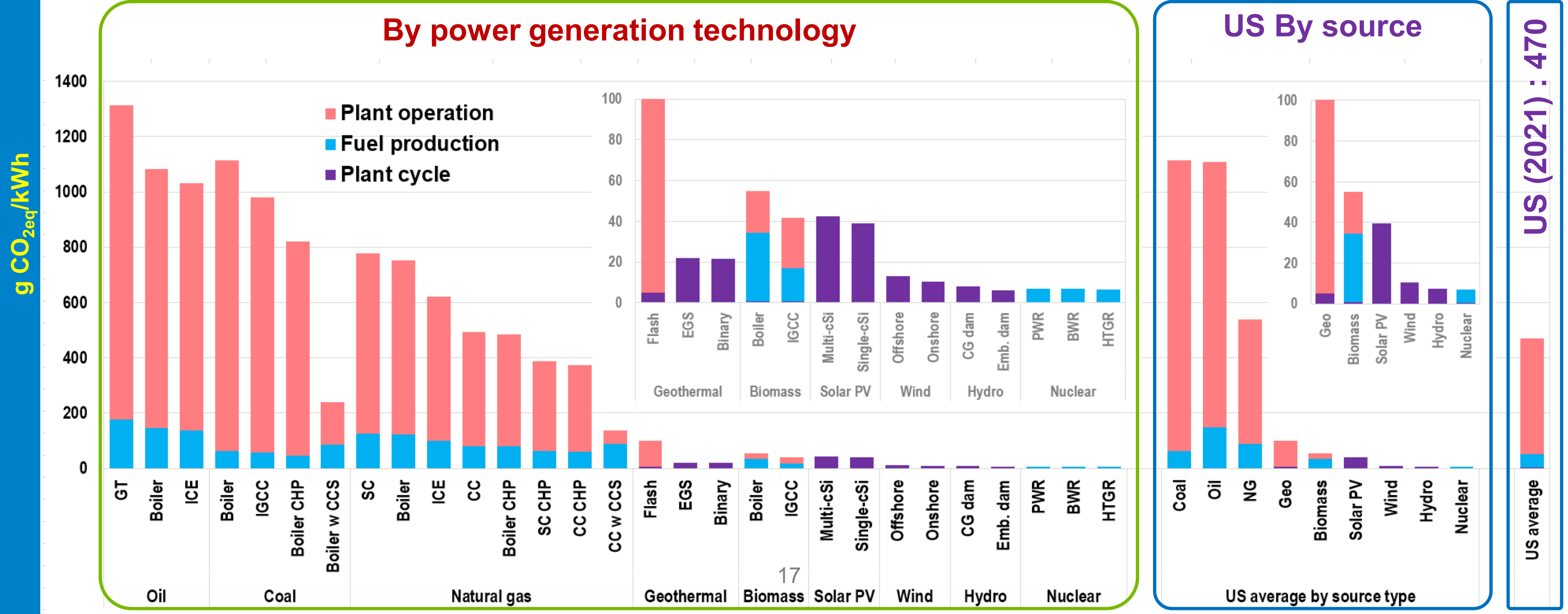
- WTW GHG emissions of petroleum fuels are dominated by end use release of CO_2; refinery direct/indirect emissions a distant second



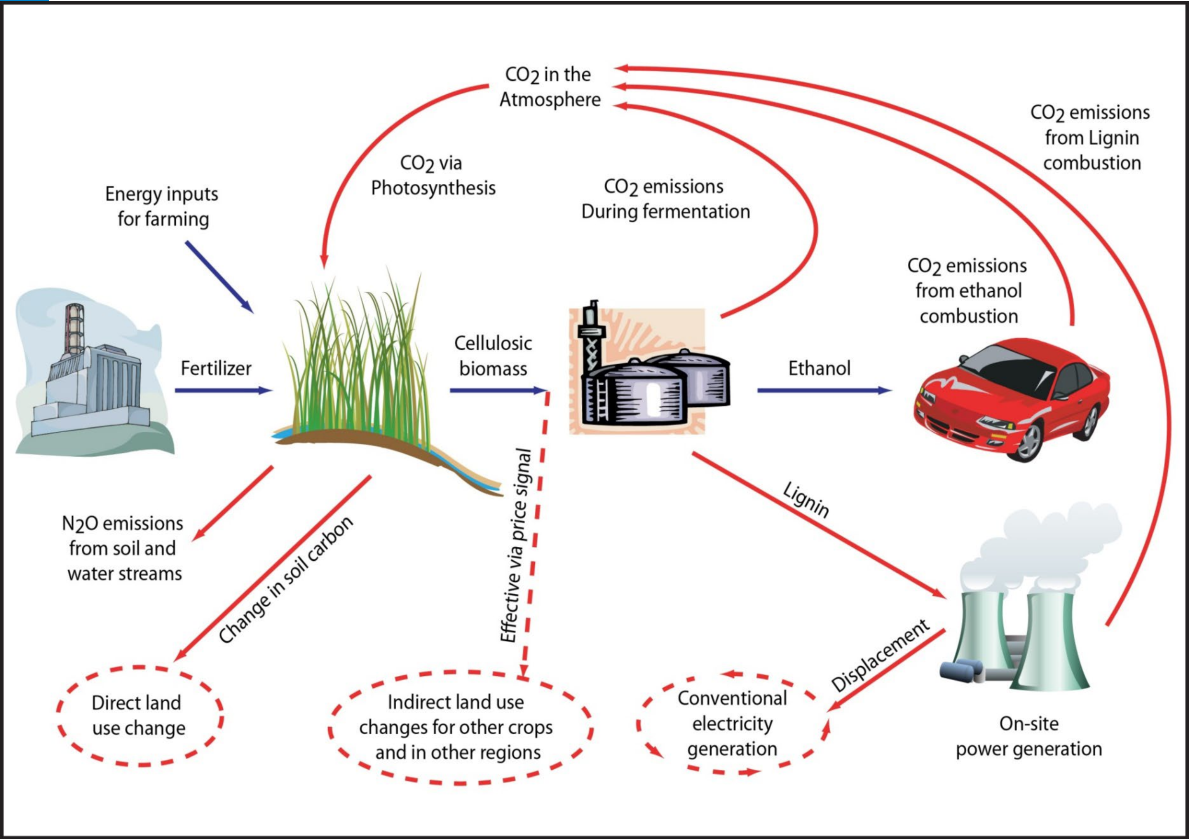


Life-cycle GHG emissions of electricity vary among technologies

- Thermal power plants (coal, gas, oil, biomass) results are dominated by GHG emissions from plant operation and plant fuel production stages
- Plant cycle GHG emissions of renewable power infrastructure are higher than those of fossil-fired and nuclear plants



R&D GREET system boundary for biofuel LCA: direct activities and indirect effects are included



Key stages of biofuel LCA

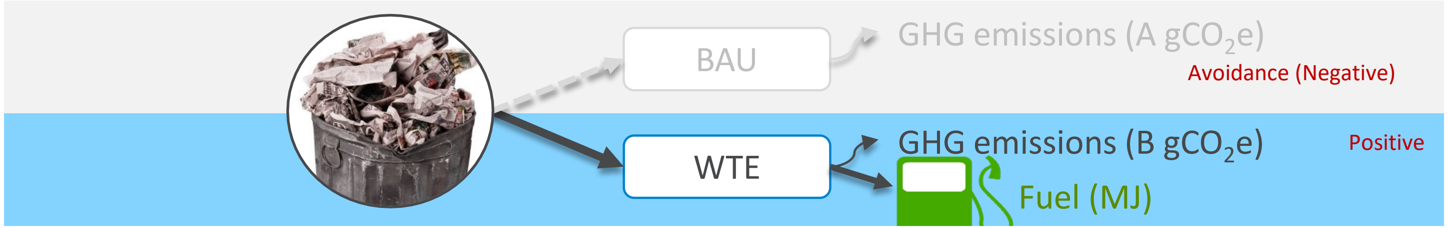
- ❑ Fertilizer production
- ❑ Farming activities
- ❑ Biofuel conversion

Key biofuel LCA issues addressed:

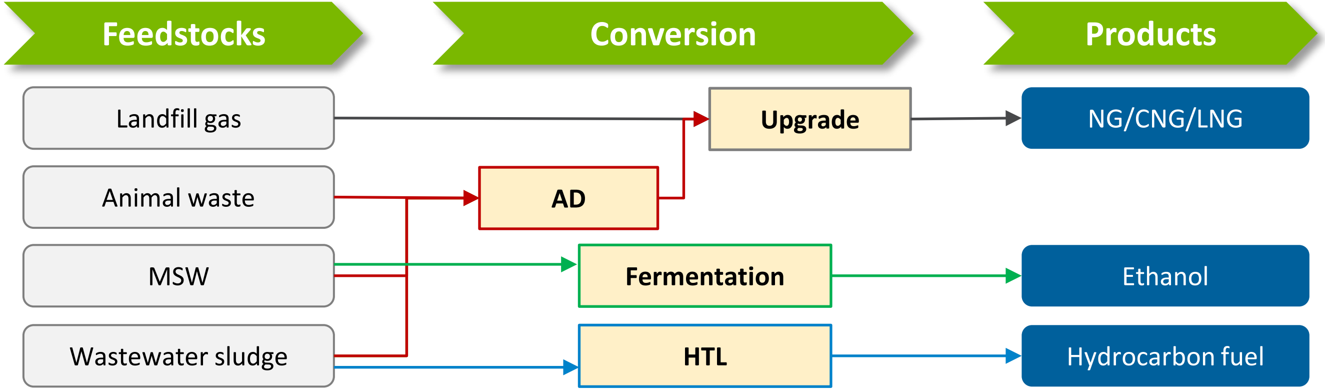
- ❑ Expand LCA system boundary considerably
- ❑ LCA co-product methods have advanced
- ❑ Technology improvement over time is key factor
- ❑ Direct and indirect land use changes

R&D GREET considers avoided counterfactual scenario emissions for waste-based energy systems

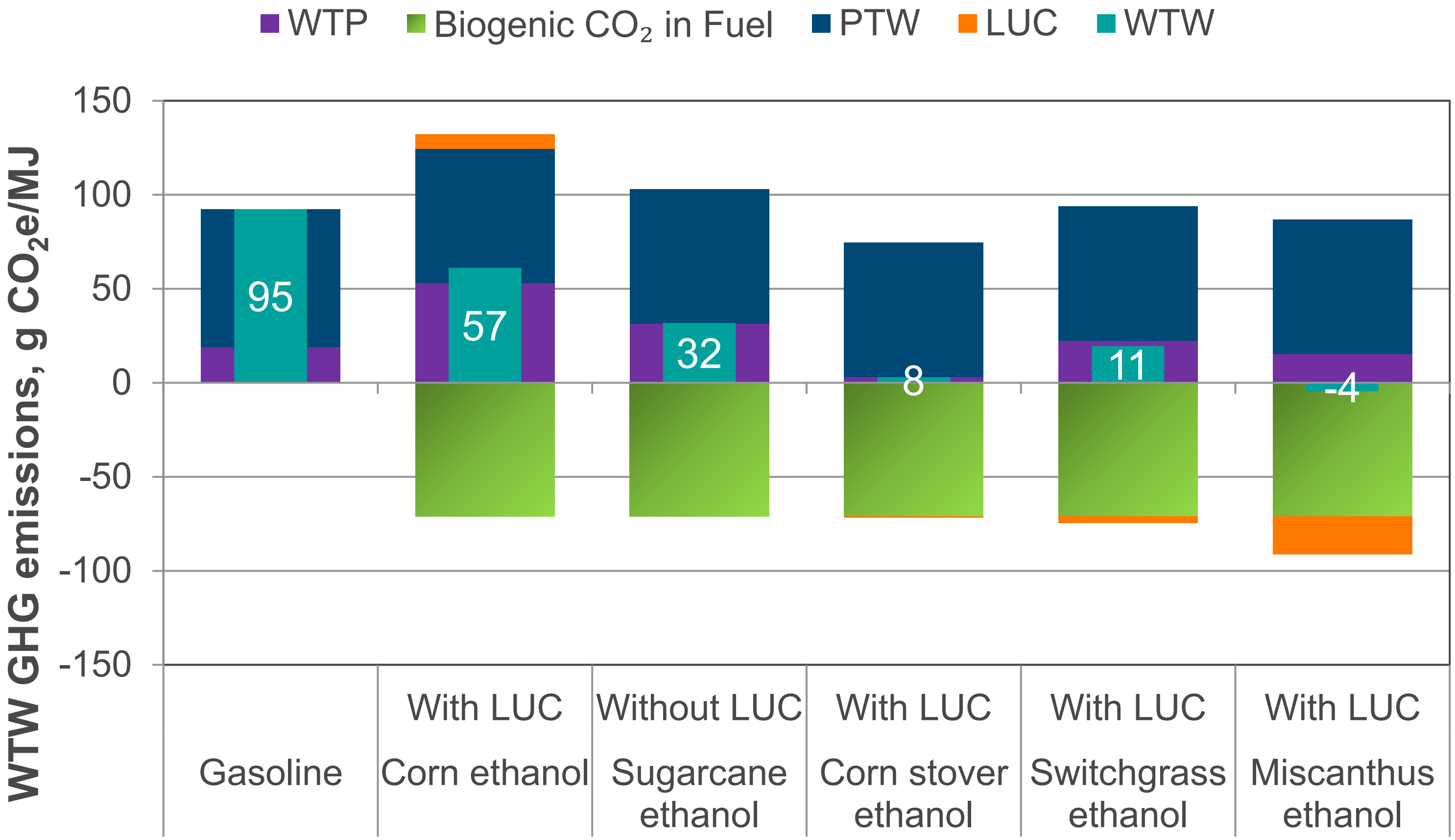
LCA of waste-to-energy (WTE) pathways are evaluate emissions associated with business-as-usual (BAU) case of waste management to account for avoided emissions



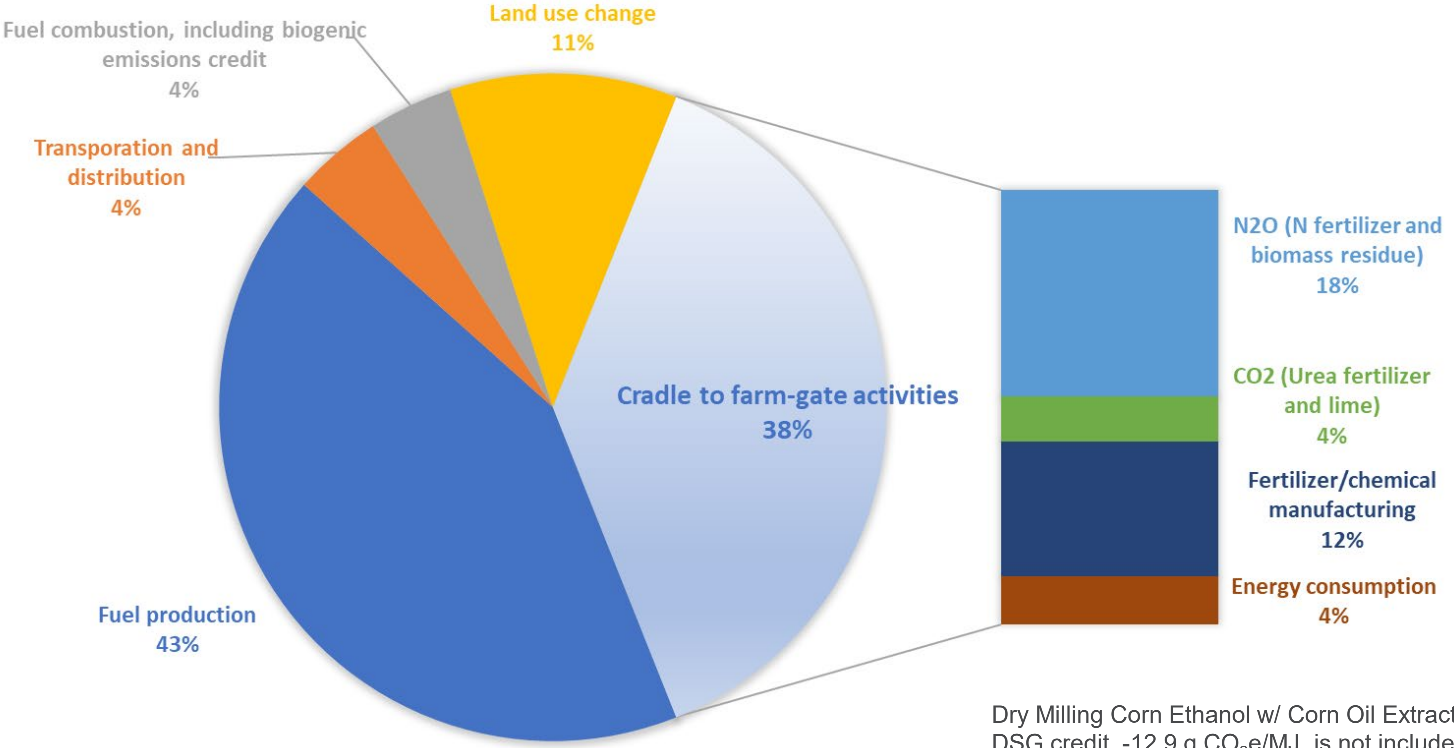
Pathways in GREET



R&D GREET life-cycle GHG emissions of ethanol: feedstock is the main driver



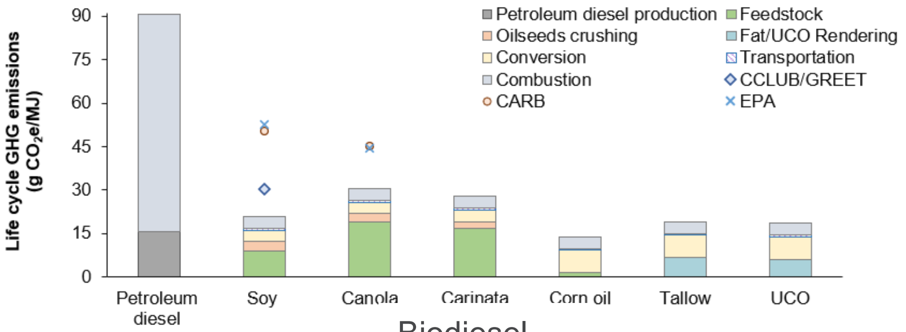
Feedstock and ethanol production are two significant contributors to corn ethanol LCA GHGs



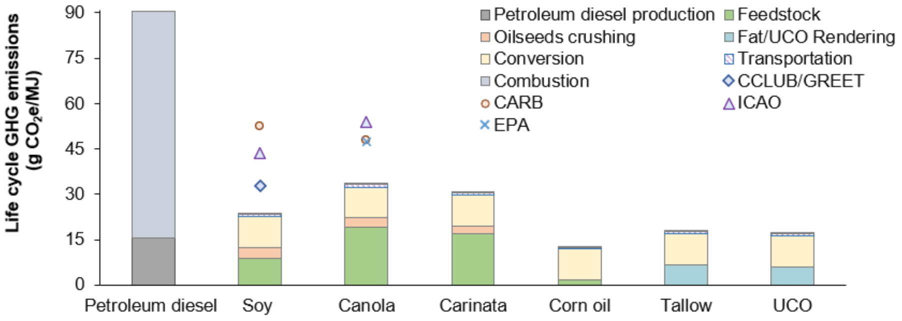
Dry Milling Corn Ethanol w/ Corn Oil Extraction.
DSG credit, -12.9 g CO_2e/MJ, is not included

LCA results of biodiesel and renewable diesel

- CI of soy BD and RD are 30.2 and 32.6 g CO_2e/MJ, respectively. Soy oil has lower GHG emissions than canola and carinata (higher yield, no N input requirement)
- With LUC emissions accounted for, GHG of soy oil BD and RD could still be 64% to 67% (using GREET LUC value) or 42% to 52% (using LUC values from EPA, CARB, and ICAO) lower than petroleum diesel
- Converting tallow, UCO, and corn oil to BD and RD could achieve higher GHG reductions of 79% to 86%, mainly because they are residue feedstock



Biodiesel



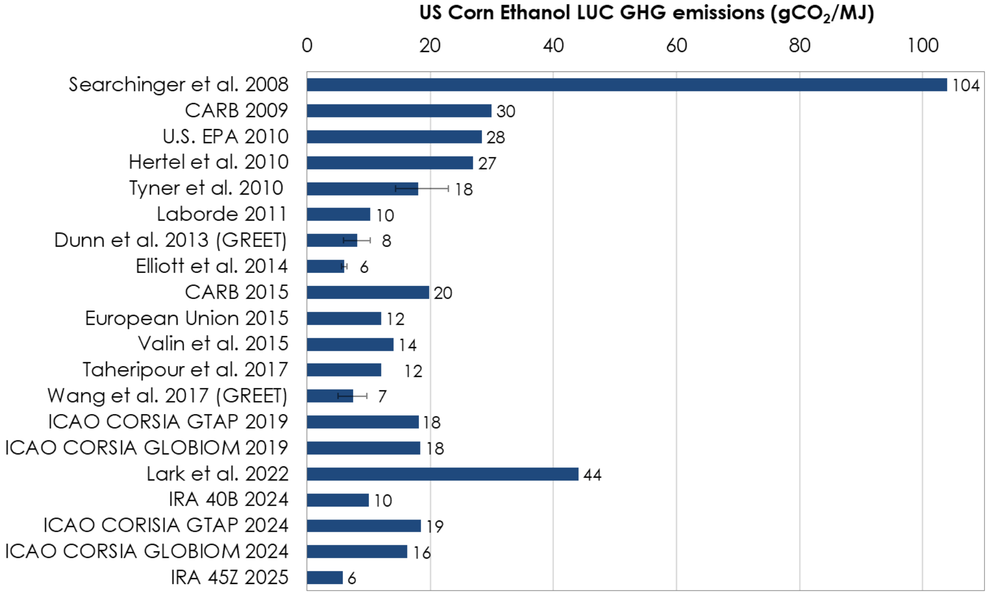
Renewable diesel

Two approaches are used in regulations/programs to address Induced Land-Use Change (iLUC) GHG emissions

- Quantify potential iLUC GHGs to include in regulations:
  - ✓ CA LCFS (and several other states)
  - ✓ EPA RFS
  - ✓ The Inflation Reduction Act incentives for clean hydrogen, sustainable aviation fuels, and clean fuels
  - ✓ ICAO CORSIA
- Risk-based approach to prevent high-risk LUC with sustainability criteria:
  - ✓ EU Renewable Energy Directive
  - ✓ Canadian Clean Fuel Regulation
  - ✓ Brazilian RenovaBio Program
  - ✓ Potential IMO GHG program

The LUC GHG emissions from large-scale ethanol production have been simulated since 2008

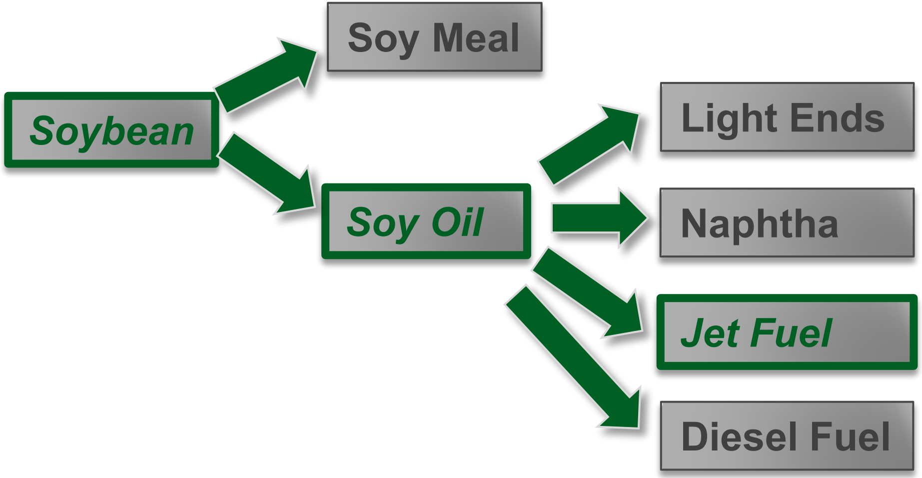
- Induced LUC is defined as the shift in land use and land cover (e.g., forest and grassland) that could accompany large-scale feedstock production in cropland to produce biofuels
  - Economic models simulate the scenarios of biofuel production volume shocks to estimate LUC
  - The estimated LUC area is multiplied by "emission factors" (EF, CO2e emitted per unit area)
  - EFs can be modeled using simple and/or sophisticated modeling frameworks
- The down trends in estimated LUC emissions are a result of better developed, calibrated economic models to incorporate up-to-date data



GREET LCA Co-Product Handling Methods

- Displacement (system boundary expansion)
- Process level allocation based on purposes of processes within a facility
- Mass allocation
- Energy allocation
- Market revenue allocation

Co-product usage and allocation in biofuel LCA: soybean to biofuels via hydrotreating esters and fatty acids (HEFA)



Argonne documented different co-product methods in a 2011 journal article

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Methods of dealing with co-products of biofuels in life-cycle analysis and consequent results within the U.S. context

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the choice of co-product method can significantly influence the WTW results of biofuels. Of the five methods examined in this study, ISO 14040 advocates use of the displacement method. As we discussed in principle and simulated in practice, the displacement method can generate distorted LCA results if the co-products are actually main products (for the cases of biodiesel and renewable diesel from soybeans). It is far from settled whether use of a given method should be uniformly and automatically recommended for LCA studies. We suggest that a generally agreed-upon method should be applied for a given fuel production pathway. Consistency in choice of co-product method may not serve the purpose of providing reliable LCA results. On this note, the transparency of LCA method(s) selected is important in given LCA studies and sensitive cases with multiple co-product methods may be warranted in LCA studies where co-products can significantly impact study outcomes.

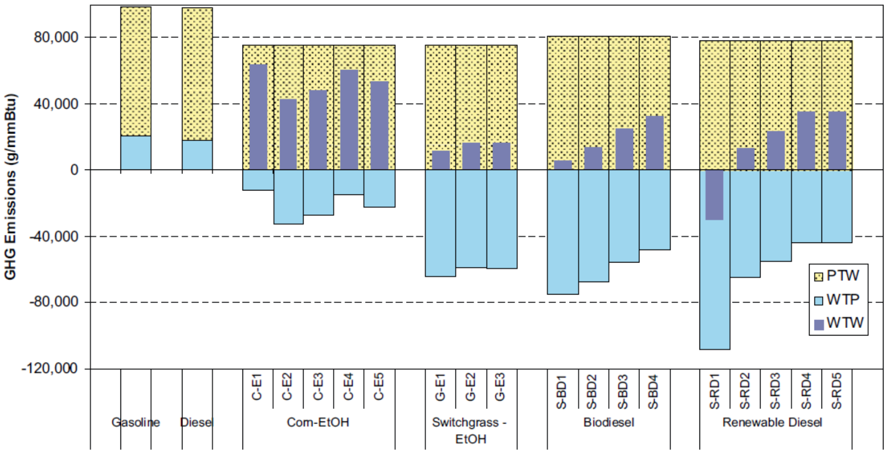
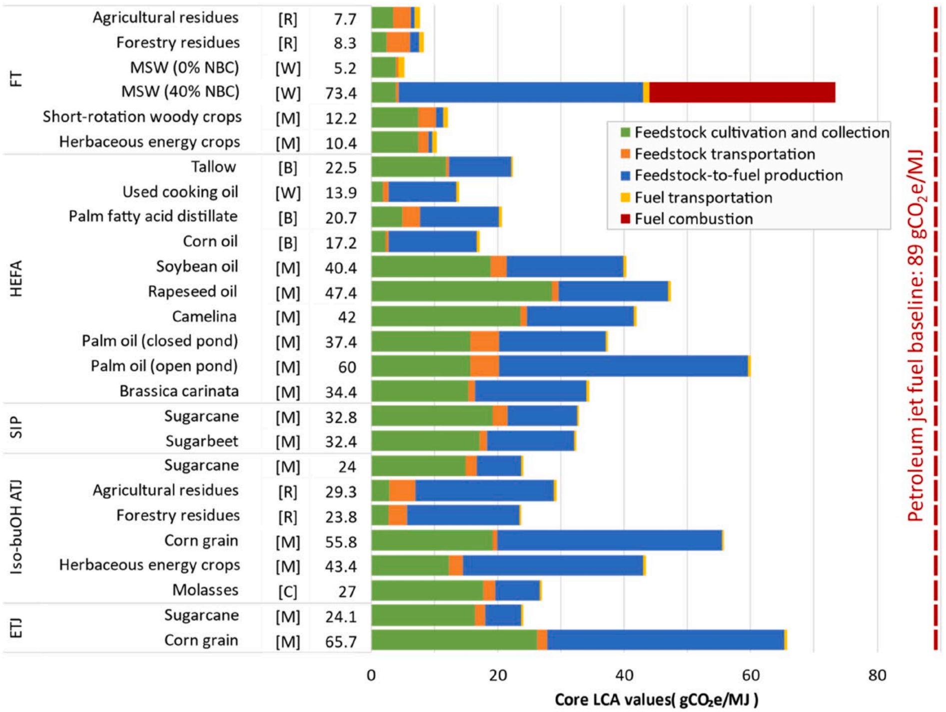


Fig. 9. WTW Greenhouse Gas Emissions of Petroleum Fuels and Biofuels (grams of CO_2e/ million Btu).

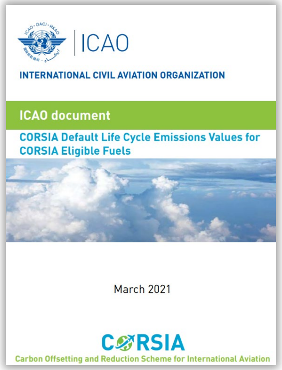
Biofuel Pathway	Method of Dealing with Multiple Products	Case Number
Corn to ethanol	Displacement	C-E1
	Mass	C-E2
	Energy content	C-E3
	Market value	C-E4
	Process purpose	C-E5
Switchgrass to ethanol	Displacement	G-E1
	Energy content	G-E2
	Market value	G-E3
Soybeans to biodiesel	Displacement	S-BD1
	Mass	S-BD2
	Energy content	S-BD3
	Market value	S-BD4
Soybeans to renewable diesel	Displacement	S-RD1
	Mass	S-RD2
	Energy content	S-RD3
	Market value	S-RD4
	Hybrid allocation	S-RD5

Argonne generated LCA values of SAF pathways using a R&D GREET version



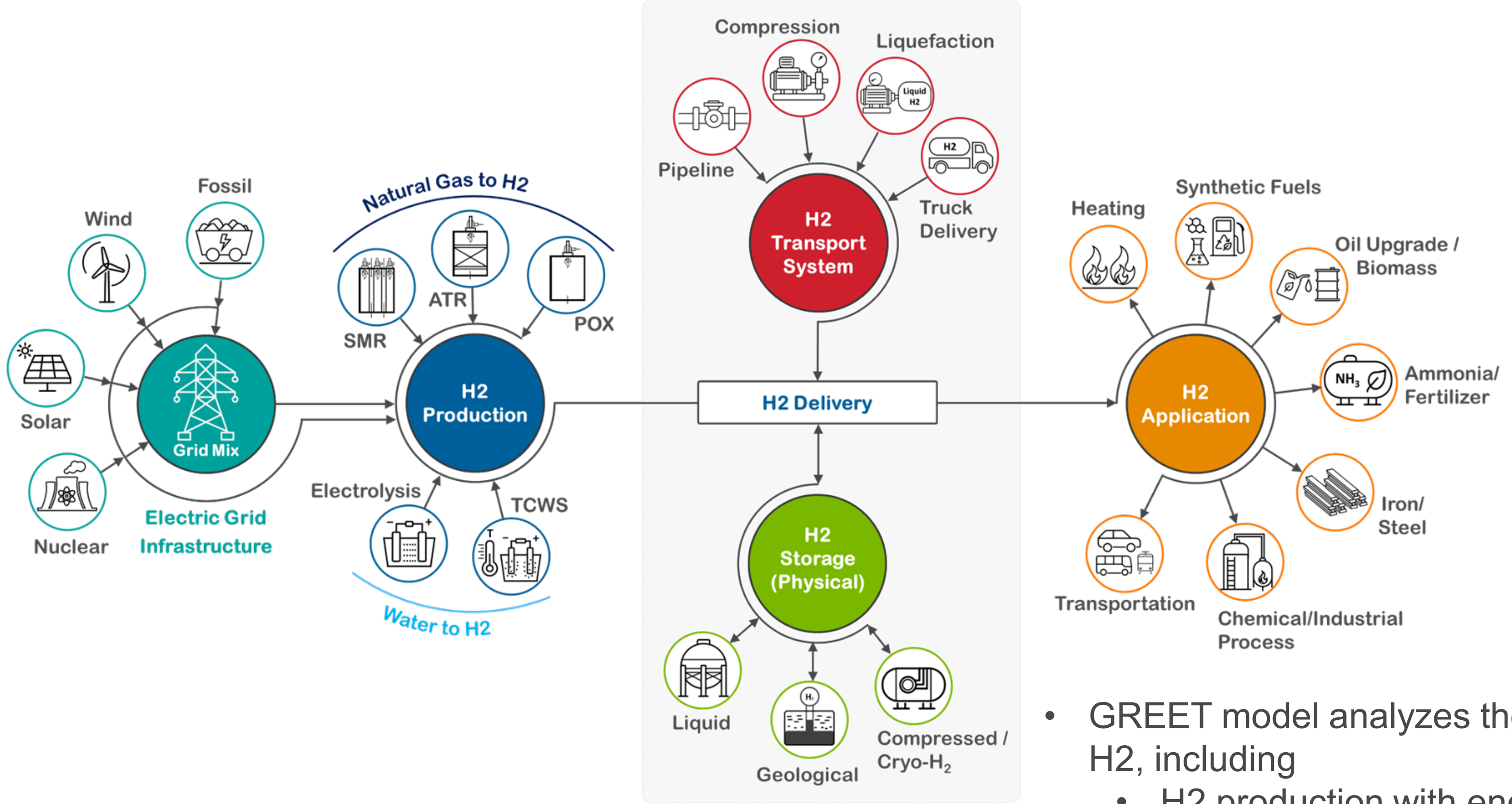
(Prussi et al. 2021)

- Argonne has been a member of ICAO's Fuels Task Group (FTG) since inception
- Argonne's GREET was used to calculate the core LCA values of SAFs for CORSIA
- Default LCA values available in CORSIA documents



FT: Fischer-Tropsch | HEFA: hydroprocessed esters and fatty acids
SIP: Synthesized iso-paraffins | Iso-BuOH: Iso-butanol
ATJ: Alcohol-to-jet | ETJ: Ethanol-to-jet | NBC: non-biomass carbon

R&D GREET model H_2 analysis scope

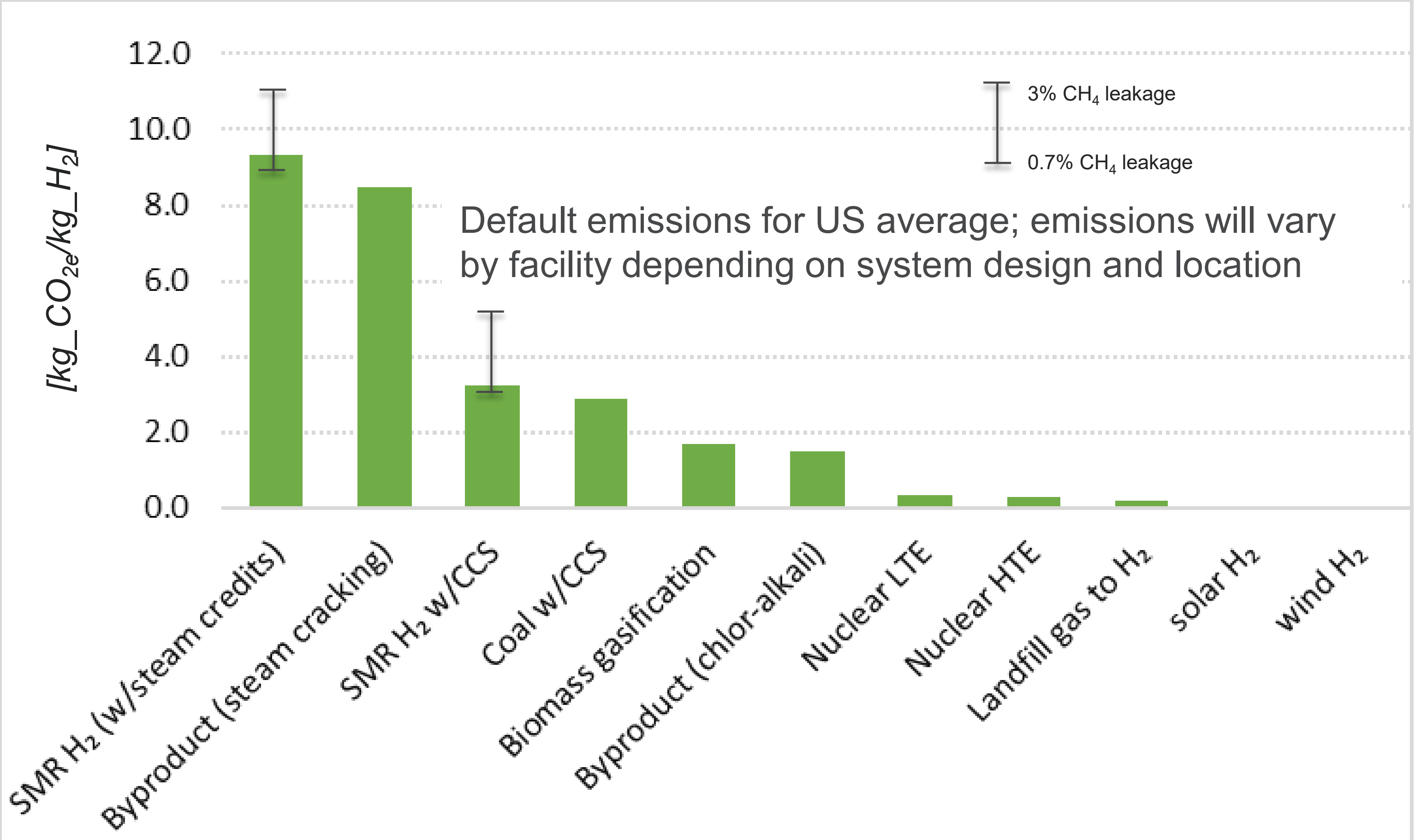


Hydrogen Infrastructure
(Hydrogen Delivery Scenario Analysis Model, HDSAM)

- GREET model analyzes the ecosystem of H2, including
  - H2 production with energy sources
  - H2 infrastructure (gaseous/liq, delivery)
  - Various end applications

Well-to-Gate (WtG) GHG emissions of H_2 production pathways

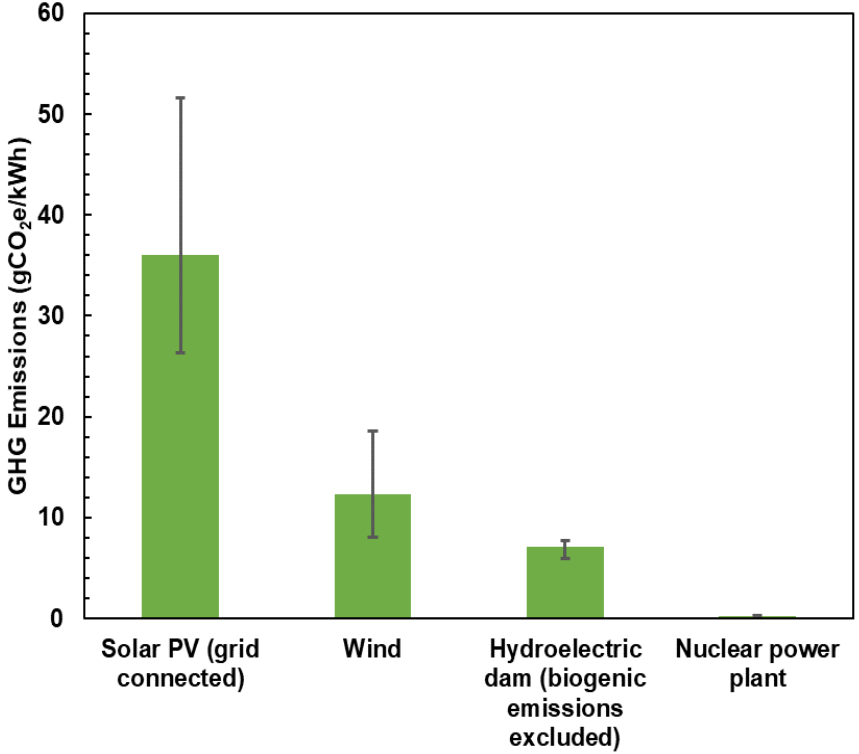
SMR= Steam Methane Reforming; CCS=Carbon Capture and Sequestration; LTE=Low-Temp Electrolysis; HTE=High-Temp Electrolysis; LFG=Landfill Gas



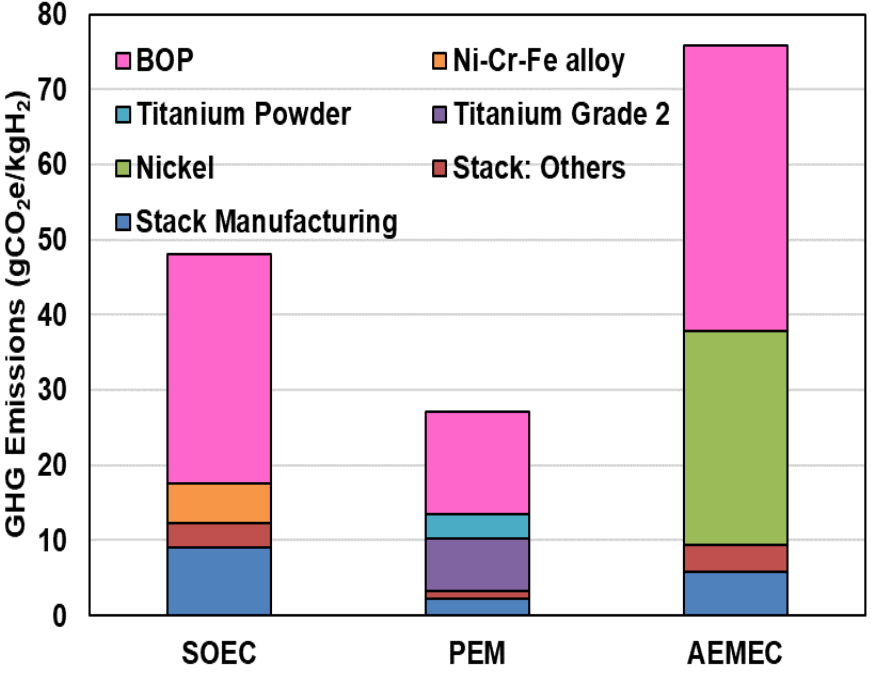
https://greet.es.anl.gov/files/hydrogenreport2022

Infrastructure-embodied GHG emissions for hydrogen and electricity from R&D GREET

Embodied GHG emissions of different electricity infrastructure
(per kWh of electricity)

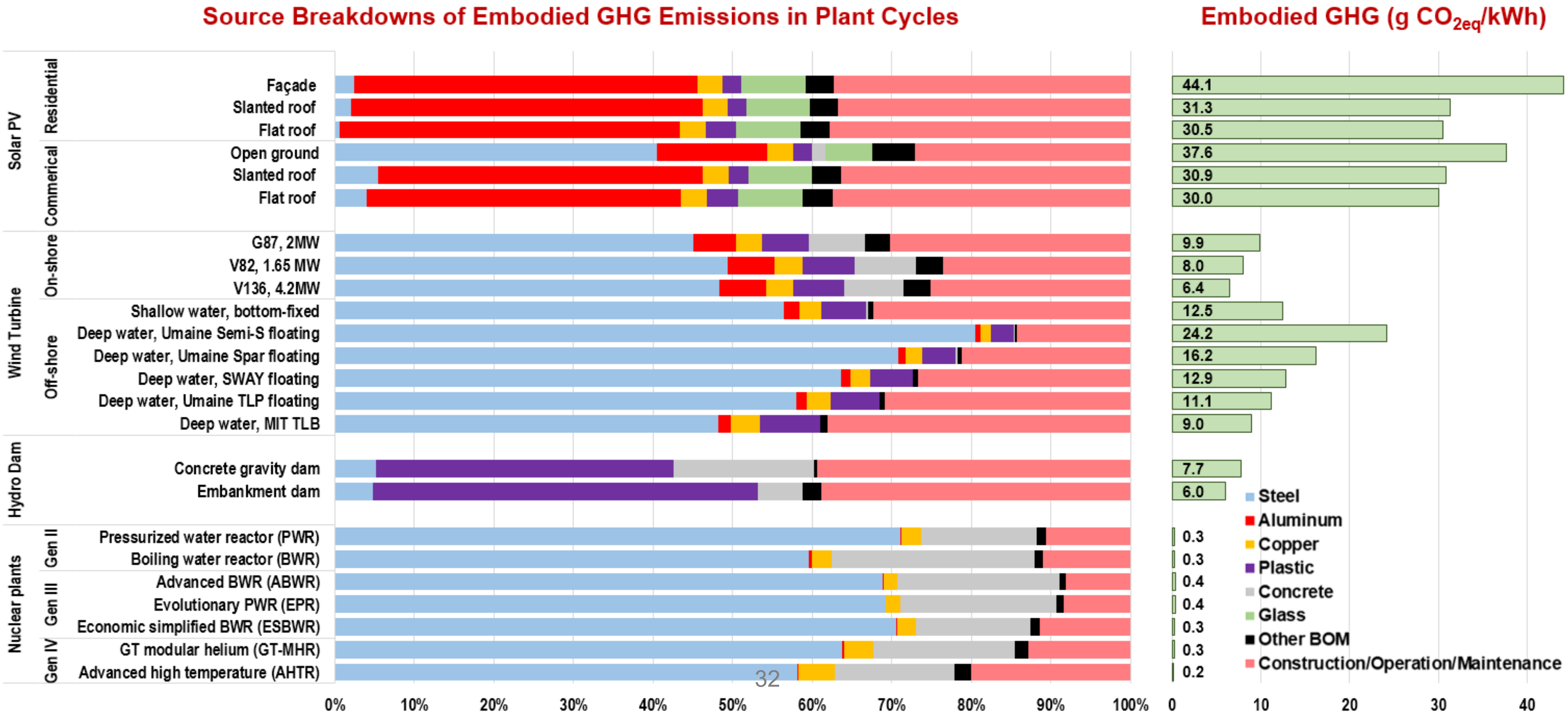


Electrolyzer Stack + BOP: GHG Emissions
(per kg H_2)



Embodied GHG emissions in solar PV systems, wind turbines, hydro dams, and nuclear plants depend on facility types/designs/models

Per kWh GHG emissions: solar PV > wind turbine > hydro dam > nuclear plants



R&D GREET includes extensive lists of critical materials/minerals: examples for EVs and batteries

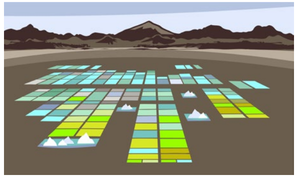
EVs

- Copper
- Aluminum
- Steel
- Magnesium
- Carbon Fiber
- Glass Fiber
- Plastics
- Titanium
- PGM for fuel cells

Battery

- Nickel
- Lithium
- Manganese
- Cobalt
- $LiPF_6$
- Ethylene carbonate
- Dimethyl carbonate
- Phosphorous
- PVDF
- NMP
- Graphite
- Silicon
- Li metal

Detailed supply chain for lithium LCA



Brine-based Li Production

Brine recovery

Brine concentration

Truck transport

Li_2CO_3 / LiOH production

Truck transport

Ocean transport

Land transport

Ore-based Li Production

Ore mining

Spodumene concentration

Truck transport

Ocean transport

Land transport

Li_2CO_3 / LiOH production

Land Transport

Cathode production

Transport

Cell production

Transport

Module production

Transport

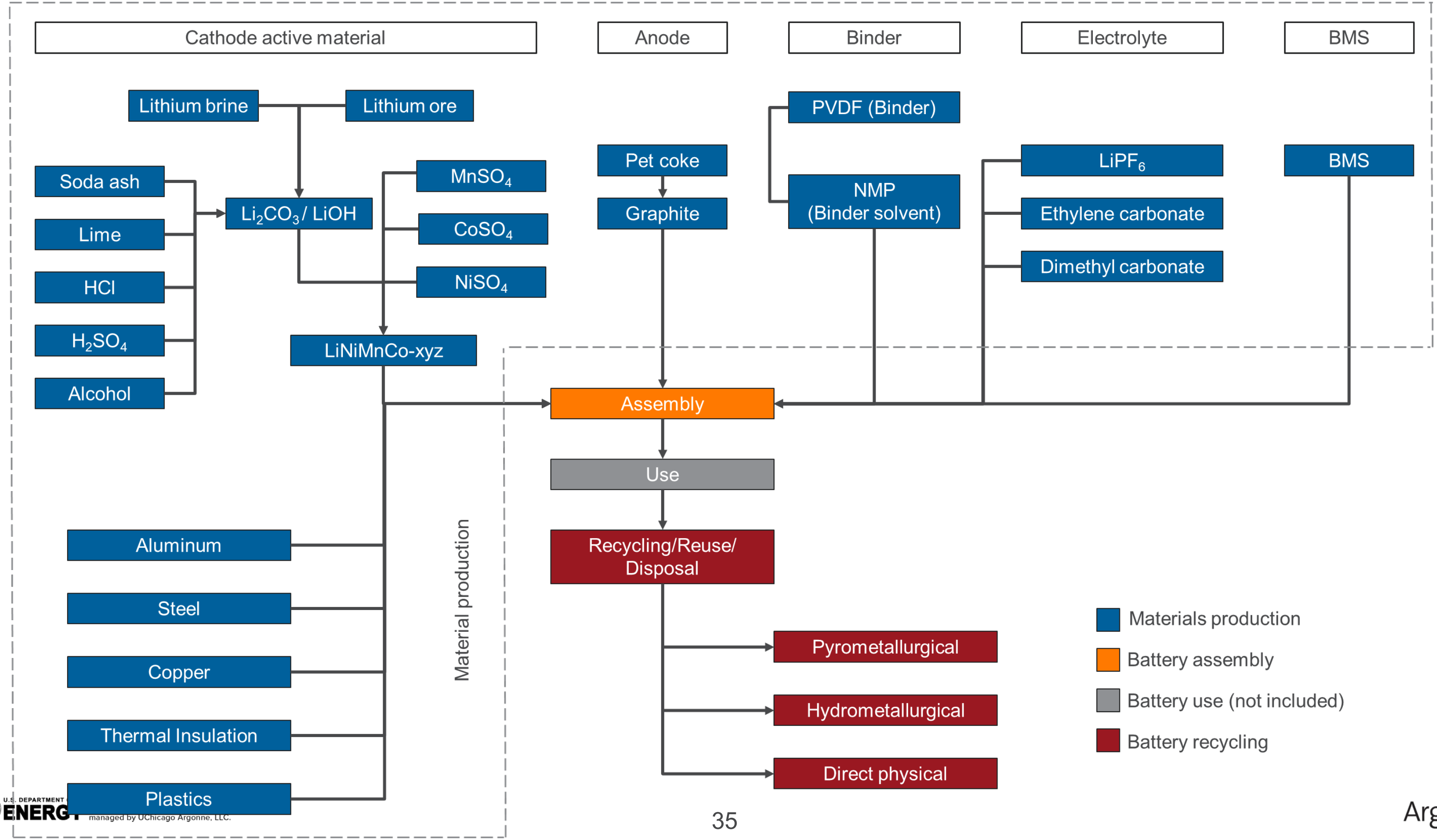
Pack production

Transport

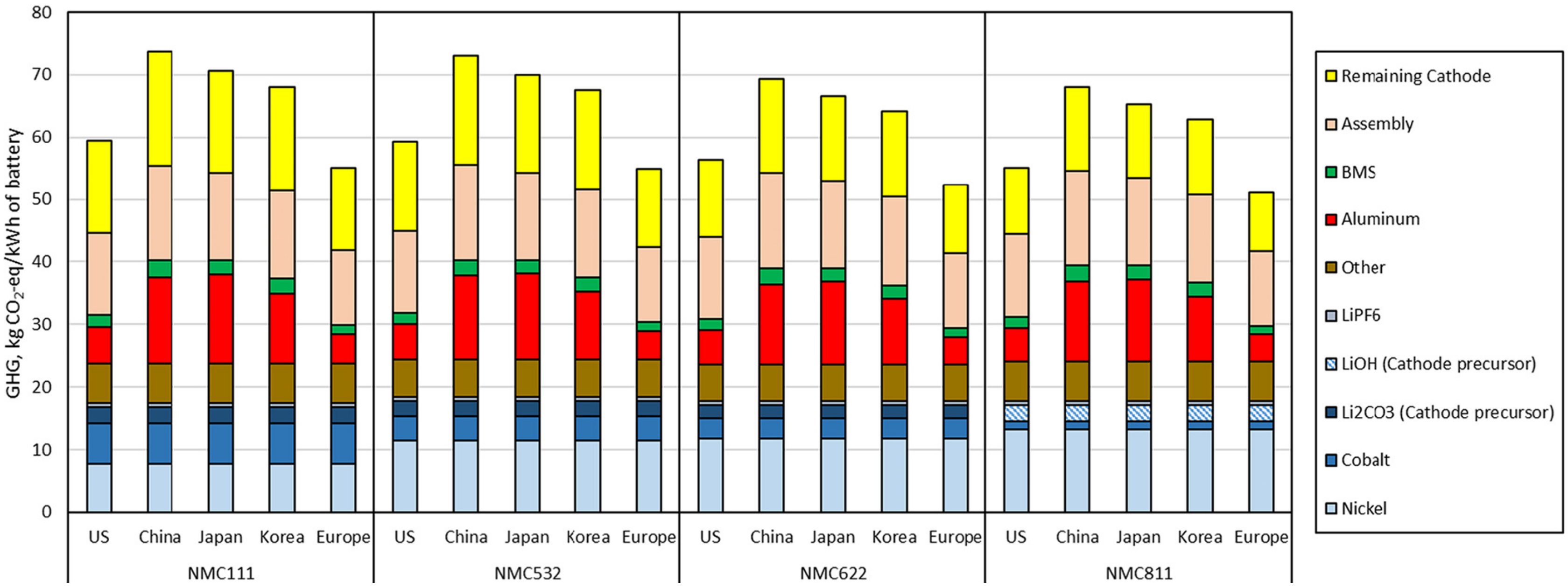
EV production

Battery Production

Battery LCA coverage in R&D GREET



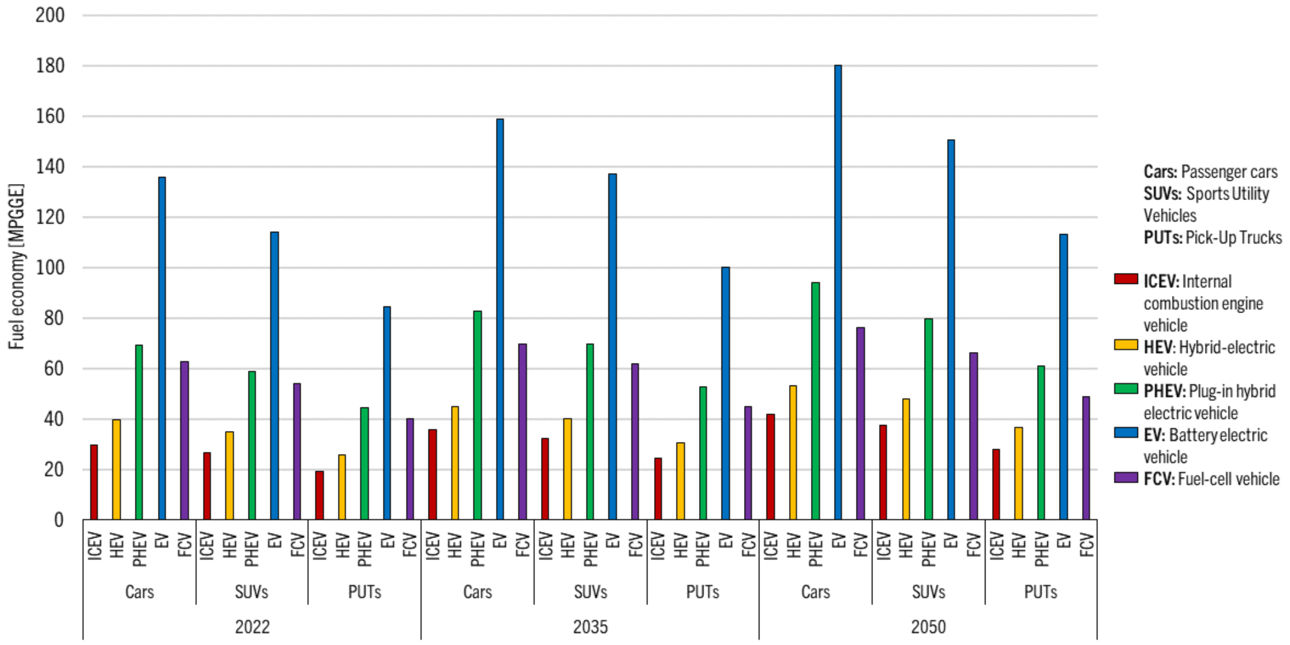
Global supply chains of current battery production impact LCA results



LIB life-cycle GHG emissions by chemistries and production regions

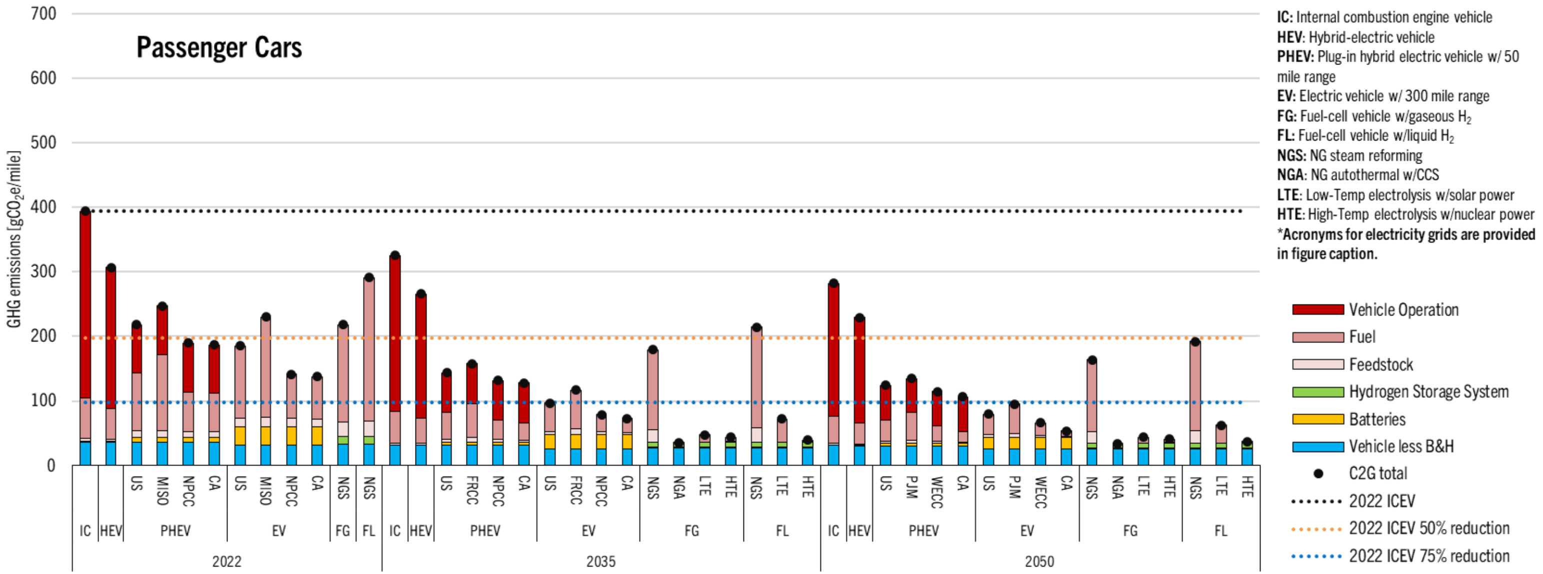
Winjobi, Kelly, and Dai (2022) (https://doi.org/10.1016/j.susmat.2022.e00415)

SAE PAPER 2024-01-2830:
LIGHT DUTY VEHICLE FUEL ECONOMY



- All five powertrain options are projected to have improved future fuel economies
- However, EV could achieve significantly higher fuel economy than any other powertrain options in all LDV options (Cars, SUVs, PUTs)

LCA: RESULTS – PASSENGER CARS



- Black dotted line notes the baseline: GHG emissions of passenger cars ICEV in 2022
- Yellow dotted line is 50% reduction from the baseline
- Blue dotted line is a 75% reduction from the baseline

Summary

- LCA is a major step to holistically evaluate sustainability of technologies and policies
  - From singular stages to the complete supply chain; shift in environmental burdens from one stage to another is not missed
  - LCA thinking has helped changes in corporation and consumer behaviors
- Recent trends of LCA applications
  - US domestic regulations and programs
    - ✓ Regulations such as the CA LCFS (and several other states) and EPA RFS
    - ✓ New proposed rule by Security Exchange Commission to require reporting of emissions of three scopes by public companies for company climate risk assessment
  - International activities
    - ✓ International Civil Aviation Organization's CORSIA program for SAFs
    - ✓ International Marine Organization's discussion of potential low-GHG fuel standard
    - ✓ EU Renewable Fuel Directive
    - ✓ Canadian Clean Fuel Standard
- LCA methodologies and results need further improvements
  - Methodologies need to be consistent; models need to be open and transparent
  - Data reliability and representation
    - ✓ Temporal and geographic/spatial variations
    - ✓ Measurement, Reporting, and Verification (MRV) and new data gathering technologies will help

Questions?

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