NOVEMBER 7 2022

GREET TRAINING WORKSHOP

Overview of the GREET Life-Cycle Analysis Model

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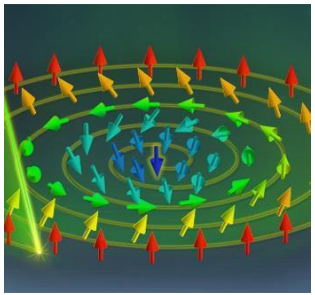

Energy manufacturing science and engineering

The universe as our laboratory

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Applications of Life Cycle Analysis

- 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
    - ✓ The Inflation Reduction Act incentives for clean hydrogen, sustainable aviation fuels, and clean fuels are based on LCA GHG results
    - ✓ The Bipartisan Infrastructure Bill requires LCA-based GHGs for projects under different hubs
  - 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
    - ✓ Brazilian RenovoBio program

LCA methodologies

- LCA approach and related system boundary
  1. Process-based LCA (sometimes the so-called attributional LCA): the entire supply chain of products/technologies: cycle based approach; mass and energy balances are key
  2. Emissions of the three scopes of enterprise operations along the supply chains of their products/operations
  3. Economic input-output (EIO) approach: complementary and complementary to process-based LCA: economic linkages among activities
  4. Consequential analysis (sometimes the so-called consequential LCA): global, economy-wide effects of regulations/programs – web based approach
- Co-product methods in LCA (related to Approach 1 and 2 above)
  - Displacement (system boundary expansion)
  - Mass allocation
  - Energy allocation
  - Market revenue allocation
  - Process level allocation based on purposes of processes within a facility
- Functional units: for comparative purposes
  - Per unit of output: MJ, kg, mile, ton-mile, etc.: comparisons of products providing identical/similar services to consumers and society
  - Per unit of inputs: per bbl of oil, per-ton of biomass: best of use of limited resources

LCA is data intensive

- Background vs. foreground data: in relation to specific technology under LCA
  - Background data:
    - ✓ Improvements of the rest of economy on specific technology under LCA
    - ✓ Consistency is key
  - Foreground data
    - ✓ Representation of specific technology under LCA
    - ✓ Geographic and temporal differences
    - ✓ 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
    - ✓ Mass and energy balance can help verification
- Confusing terminologies: LCI data vs. LCA results
  - Life-cycle inventory data: data for LCA?
    - ✓ Energy/mass balance of individual process/facility
    - ✓ Embodied energy/emissions of input energy and materials (LCA results of them): LCA models help
- Data quality:
  - Quality rating is usually subjective
  - Technologies at different TRLs affect data availability, thus data quality

LCA execution and LCA result reliability

- Point estimation modeling
  - Perceived precision is the major problem
  - Users of LCA results usually want point estimates
- Stochastic methods in LCA (Approach 1 and 2)
  - Probability distribution function-based parameters result in PDF-based results
  - Objective vs. subjective PDFs
- Scenario analysis of alternative technology performances
- Sensitivity analysis to test importance of input parameters: tornado charts

GREET life cycle analysis model covers fuels, materials, and technologies

Fuel cycle + vehicle cycle = cradle-to-grave (C2G) (GREET1 + GREET2 models)

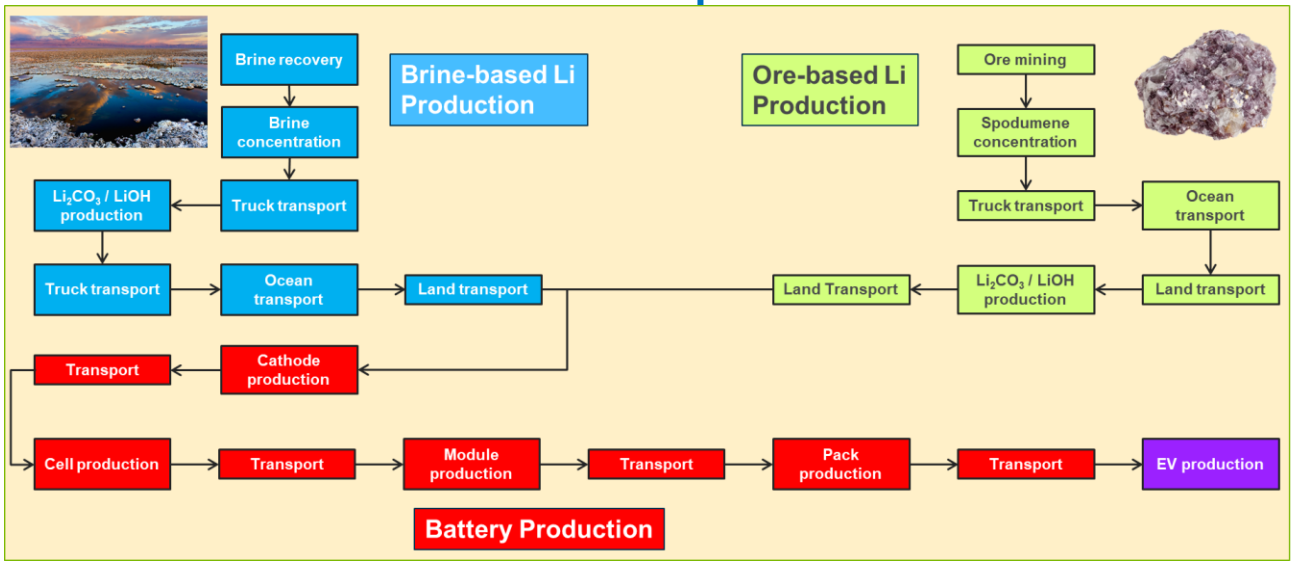
Fuel production cycle (WTP) + vehicle operation (PTW) = well to wheels fuel cycle (WTW) (GREET1)

Fuel Production Cycle (Well-to-Pump, WTP) → **Vehicle Operation: Pump-to-Wheels (PTW)**

Vehicle manufacturing cycle + vehicle end of life = vehicle cycle (GREET2)

Vehicle Manufacturing Cycle (VMC) (Battery Manufacturing Cycle) → **Vehicle End of Life (EOL)**

- ***GREET (Greenhouse gases, Regulated Emissions, and Energy use in Technologies)*** examines life-cycle impacts, simulating the energy use and emissions output for vehicle and fuel combinations, covering road, air, rail and maritime transportation
- It is available at greet.es.anl.gov



DOE has been main sponsors of GREET development and applications

- DOE EERE
  - Vehicle Technology Office
  - Hydrogen and Fuel Cell Technology Office
  - Bioenergy Technology Office
  - Building Technology Office
  - The Strategic Analysis Office
- DOE ARPA-E
- DOE Fossil Energy and Carbon Management Office
- DOE Nuclear Energy Office
- Other federal agencies
  - Federal Aviation Administration of DOT
  - Federal Maritime Administration of DOT
  - Federal Rail Administration of DOT
  - USDA
  - The National Institute of Standards and Materials of Department of Commerce
  - Bureau of Offshore Energy Management of Department of Interior
- Numerous trade associations and corporate sponsors in energy, automotive, materials, and agriculture sector

GREET LCA modeling framework and objectives

- Build LCA modeling capacity
- Build a consistent LCA platform with reliable, widely accepted methods/protocols
- Address emerging LCA issues
- Access to data sources and conduct detailed analysis
- Document sources of data, modeling and analysis approach, and results/conclusions
- Maintain openness and transparency of LCAs by making GREET and its documentation publicly available
- Primarily process-based LCA approach (the so-called attributional LCA); some consequential effects are incorporated

GREET relies on a variety of data sources

Baseline technologies and systems: background data

- Energy Information Administration's data and its Annual Energy Outlook projections
- EPA eGrid for electric systems
- US Geology Services for water data

Field operation data: foreground data

- Oil sands and shale oil operations
- Ethanol plants energy use
- Farming data from USDA

Simulations with models: foreground data

- ASPEN Plus for fuel production
- ANL Autonomie for fuel economy
- EPA MOVES for vehicle emissions, EPA AMPD for stationary emissions
- LP models for petroleum refinery operations
- Electric utility dispatch models for marginal electricity analysis

Collaborations with other organizations and Industries

- National labs
- Universities
- Fuel producers and technology developers on fuels
- Automakers and system components producers on vehicles

GREET sustainability metrics include energy use, criteria pollutants, greenhouse gases, 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

Air pollutants

- VOC, CO, NOx, PM_{10}, $PM_{2.5}$, and SOx
- Estimated separately for total and urban (a subset of the total) emissions
- Results can help address environ. justice impact

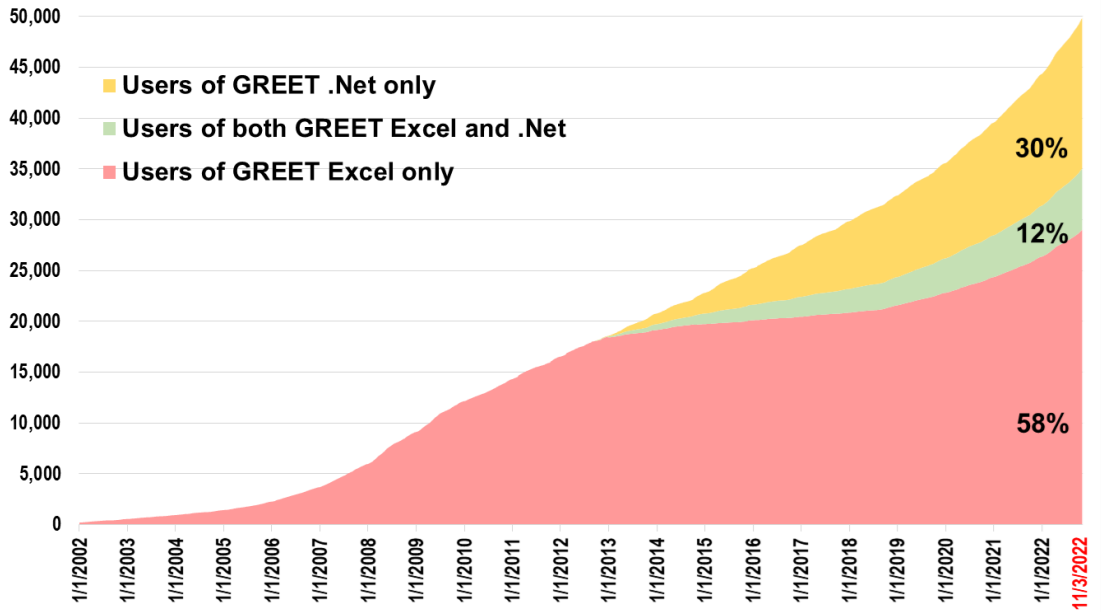
Greenhouse gases

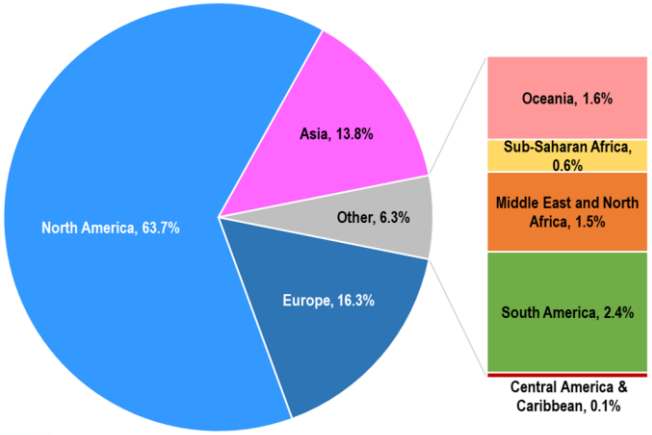
- CO_2, CH_4, N_2O, black carbon, and albedo
- CO_{2e} of the five (combined with their global warming potentials)

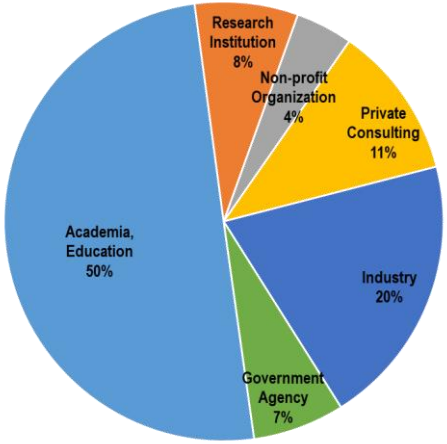
Water consumption

- Addressing water supply and demand (energy-water nexus)
- Results used in AWARE-US for water stress impact

There are ~50,000 registered GREET users globally







GREET covers all transportation subsectors

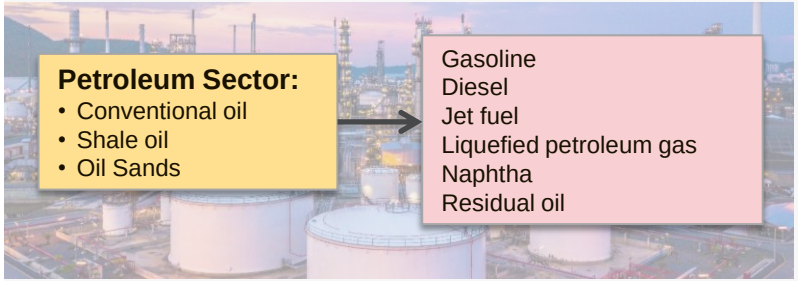
Share of US transportation GHG emissions; remaining 12% for US is from pipelines and offroad.

GREET covers many groups of energy systems

Photo credit: Shutterstock.com

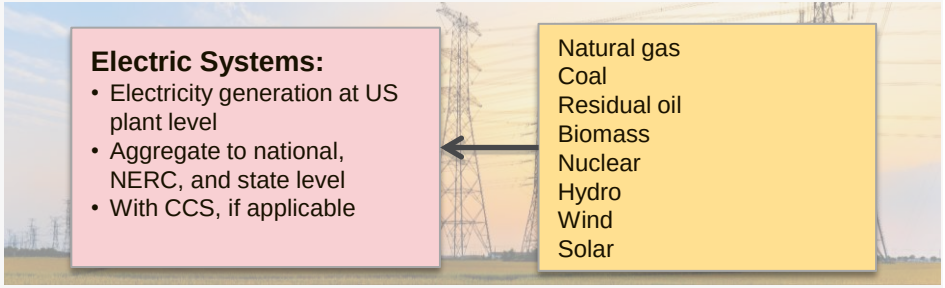
GREET covers many groups of energy systems

Photo credit: Shutterstock.com



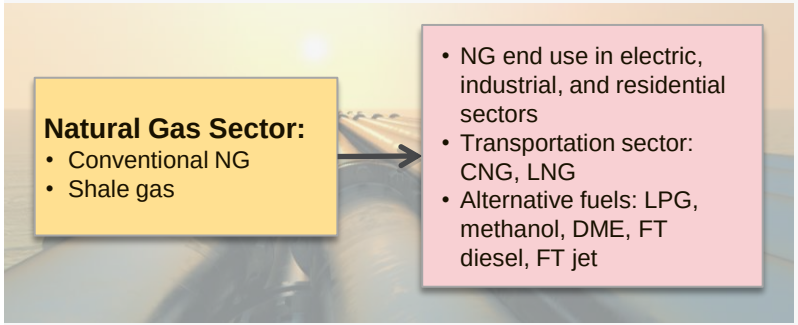
Petroleum Sector:
- Conventional oil
- Shale oil
- Oil Sands

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



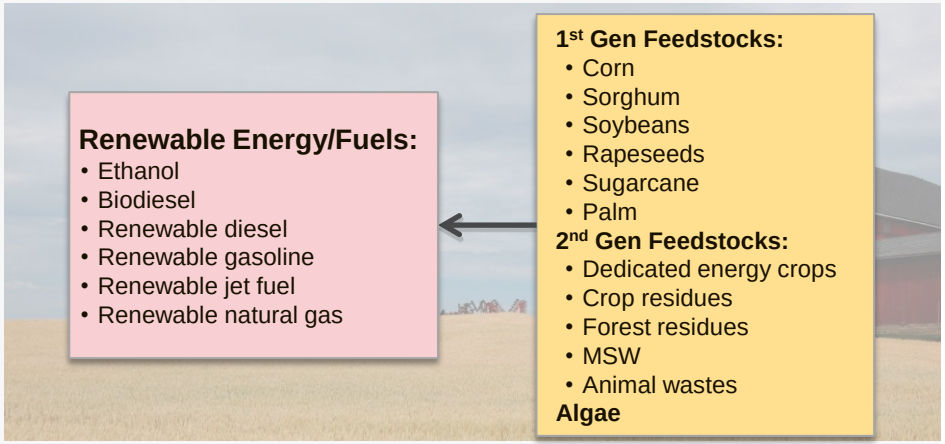
Electric Systems:
- Electricity generation at US plant level
- Aggregate to national, NERC, and state level
- With CCS, if applicable

← 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

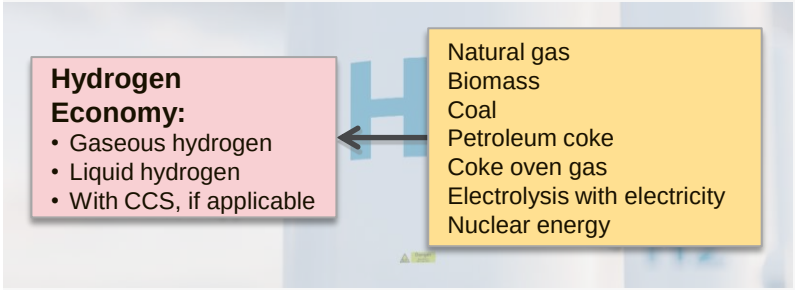


Renewable Energy/Fuels:
- Ethanol
- Biodiesel
- Renewable diesel
- Renewable gasoline
- Renewable jet fuel
- Renewable natural gas

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

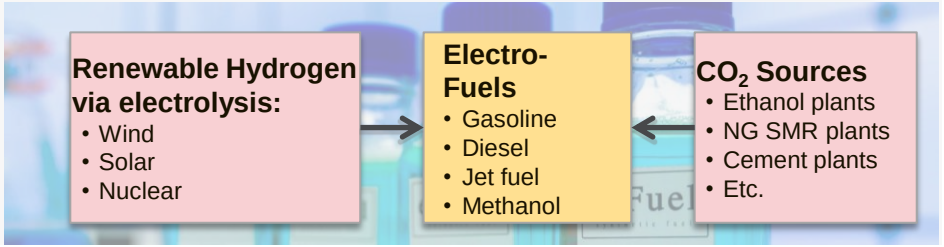
2nd Gen Feedstocks:
- Dedicated energy crops
- Crop residues
- Forest residues
- MSW
- Animal wastes

Algae



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

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



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.

GREET also includes material production pathways

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GREET includes key propulsion technologies for light-duty and heavy-duty vehicles

Conventional Spark-Ignition Engine Vehicles
- Liquid and gaseous fuels

Spark-Ignition, Direct-Injection Engine Vehicles
- Liquid and gaseous fuels

Compression-Ignition, Direct-Injection Engine Vehicles
- Liquid fuels

Hybrid Electric Vehicles (HEVs)
- Spark-ignition engines:
- Compression-ignition engines

Plug-in Hybrid Electric Vehicles (PHEVs)
- Spark-ignition engines:
- Compression-ignition engines

Battery-Powered Electric Vehicles
- Various electricity generation sources

Fuel Cell Vehicles
- Hydrogen and on-board hydrocarbon reforming to hydrogen

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
  - ✓ The aviation module
  - ✓ The marine module
  - ✓ The rail module
  - ✓ The building LCA Module
  - ✓ CCLUB
  - ✓ FD-CIC
  - ✓ WTW Calculator
  - ✓ China-GREET by ANL, with support of Aramco
  - ✓ MENA-GREET
  - ✓ CA-GREET by CARB, based on GREET1
  - ✓ Global GREET (with IEA under the IEA GREET+ project) (under development)
  - ✓ AFLEET by ANL: alternative-fuel vehicles energy, emissions, and cost estimation

In-depth applications
- LCA of batteries and EVs
- LCA of hydrogen production pathways

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- Publications
- Databases
- GREET Model Platforms
  - GREET .Net
  - GREET Excel
    - Fuel-Cycle Model
    - Vehicle-Cycle Model
- GREET Tools
  - WTW Calculator
  - AFLEET Tool
  - AWARE-US Model
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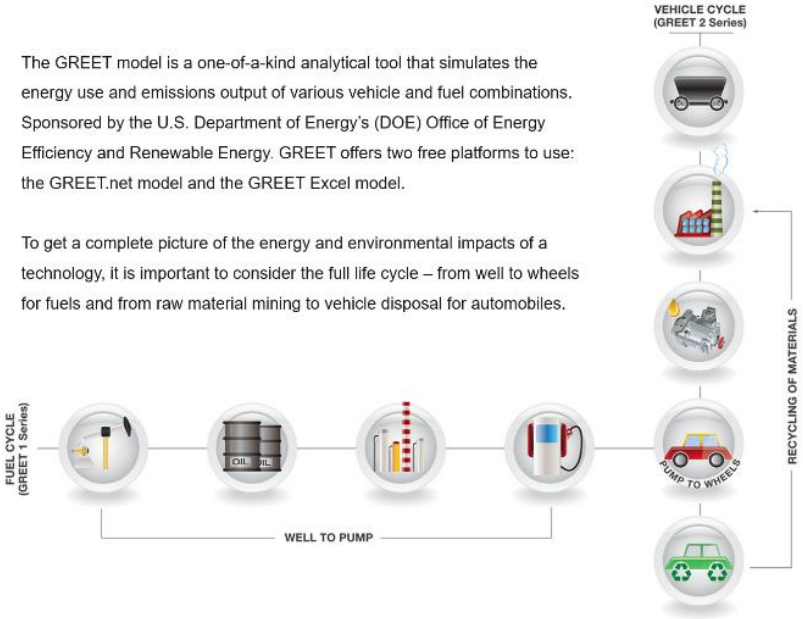
GREET® Model

The Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model

The GREET model is a one-of-a-kind analytical tool that simulates the energy use and emissions output of various vehicle and fuel combinations. Sponsored by the U.S. Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy. GREET offers two free platforms to use: the GREET.net model and the GREET Excel model.

To get a complete picture of the energy and environmental impacts of a technology, it is important to consider the full life cycle – from well to wheels for fuels and from raw material mining to vehicle disposal for automobiles.



GREET News

GREET User Training Workshop at Argonne — Nov 7, 2022 - Nov 8, 2022

Argonne National Laboratory is pleased to announce an in-person GREET user workshop to be held at Argonne, November 7-8, 2022. For event details, please visit: https://www.anl.gov/event/greet-training-workshop.

GREET 2022 Release — Oct 11, 2022

The Argonne National Laboratory's Systems Assessment Center is pleased to announce the 2022 release of the suite of GREET Models. Please read Summary of Expansions and Updates in GREET® 2022 (793KB pdf) for more details on updates in this version.

Informing Policies and Regulations

- **California-GREET** is an adaptation of Argonne's GREET model
- **Oregon Clean Fuels Program** also uses an adaptation of Argonne's GREET model
- **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
- **USDRIVE** Well-to-Wheels Report
- **U.S. Maritime Administration -** renewable marine energy options for IMO GHG intensity and sulfur limits
- **U.S. Dept. of Agriculture bioenergy LCA** and carbon intensity of farming practices
- **Canadian Clean Fuel Standard** for Environment and Climate Change Canada fuel pathways
- LCA results for use in different provisions of the 2021 Bipartisan Infrastructure Bill and the 2022 Inflation Reduction Act

GREET 1 updates in 2022 release

- Updated and expanded hydrogen production pathways with GUI in GREET Excel version
- Updated CO2 utilization simulations: carbon accounting, detailed modeling of CO2 capture, compression, and transportation, direct air capture
- Included offshore macroalgae production technologies
- Updated and expanded marine fuel production pathways, with a GREET marine module
- Updated and expansion of biodiesel and renewable diesel: used cooking oil is added.
- Updated post-use plastic pyrolysis conversion
- Updated and expanded waste to polylactic acid (PLA) and plastic modeling
- Updated and expanded of ammonia production pathways (conventional, blue, and green ammonia)
- Added post-use plastic to lubricant product pathways (including synthetic lubricants poly-alpha olefins)
- Added an air separation unit to O2 and N2 production

GREET 2 updates in 2022 release

- Updated infrastructure LCA for nuclear power plants, hydropower, wind turbines, solar PVs
- Updated and expanded LCA of electrolyzers (solid oxide, alkaline, and proton exchange membrane)
- Updated LDV and MHDV vehicle components
- Updated and expanded the battery LCA module with new materials (graphite, lithium, and silicon) and domestic lithium production
- Updated inventory data for aluminum production
- Updated LCA of critical materials (nickel, copper, titanium, and rare earth elements)
- Added the end-of-life credit approach of vehicle recycling (steel and aluminum)

Background data updates in 2022 release

- Global warming potentials of AR6
- US electricity generation mix and crude oil mix
- Methane leakage of natural gas supply chain
- Fuel use for natural gas recovery
- Expansion of plastic inventory
- Energy intensity of rail movement of passengers
- Aviation payload energy intensities and fuel combustion emissions
- HD hybrid electric vehicle fuel economy
- U.S. feedstock slate for steam crackers

Observations: LCA results are subject to variations and uncertainties

- LCA system boundary depends on scope of LCA
- Attributional and consequential LCA address different questions and have completely different boundaries
- Co-product methods in LCA can be subjective and affect LCA results significantly
- Data availability and representation
  - ✓ Temporal variation
  - ✓ Geographic/spatial variation
  - ✓ Data uncertainty (e.g., sources of process energy/chemicals, methane emissions, land use changes from biofuels)
- Limitations of comparative results from LCA
  - ✓ Current vs. uncertain future
  - ✓ Different technology readiness levels (TRLs) across processes and pathways
  - ✓ Resource and infrastructure availability
  - ✓ Economics, production scalability, and market acceptance/competitiveness

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Summary of Expansions and Updates in GREET® 2022

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Argonne National Laboratory

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GREET Questions: best way via emails

- Greet@anl.gov
- Subject: area of your questions (such as biofuels, electric vehicles, hydrogen, etc.)
- Questions in email text