NOVEMBER 7, 2022

GREET TRAINING WORKSHOP

GREET 1 Model: Fuel Cycle Analysis

Uisung Lee, PhD

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

greet.es.anl.gov

GREET®

- Publications
- Databases
- GREET Model Platforms
  - GREET .Net
  - GREET Excel
    - Fuel-Cycle Model
    - Vehicle-Cycle Model
- GREET Tools
  - WTW Calculator
  - AFLEET Tool
  - AWARE-US Model
  - FD-CIC Tool
  - Refinery Products VOC
  - GREET Building Module
  - GREET Aviation Module
  - GREET w/ H_2 User Interface
- Other Related Models
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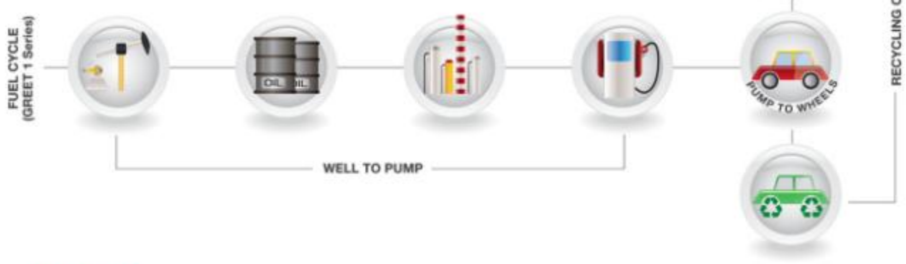
GREET® Model

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.

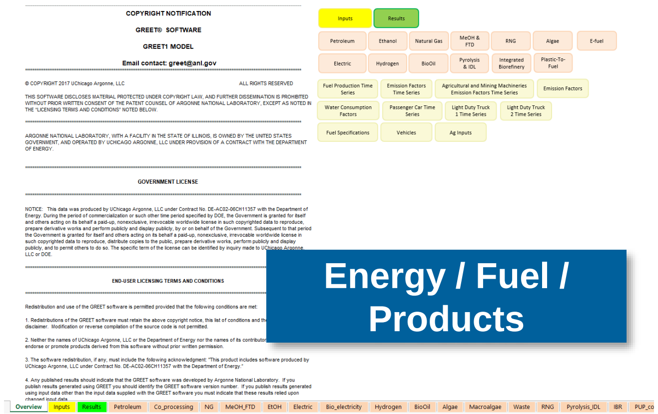


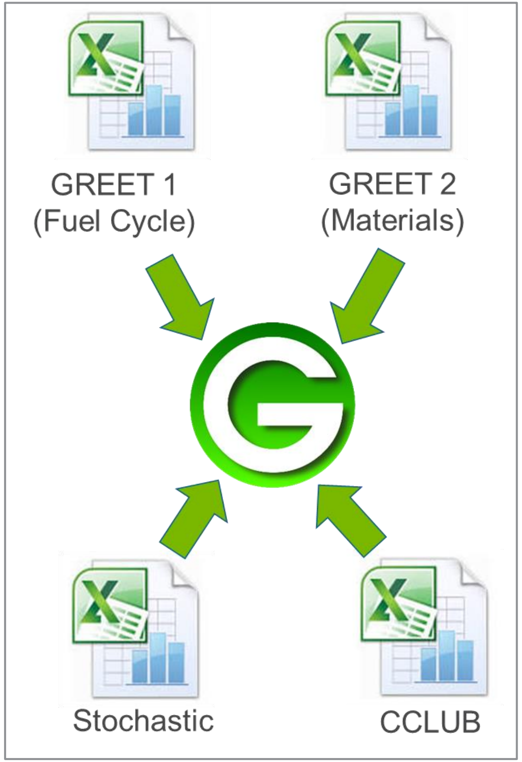
GREET News

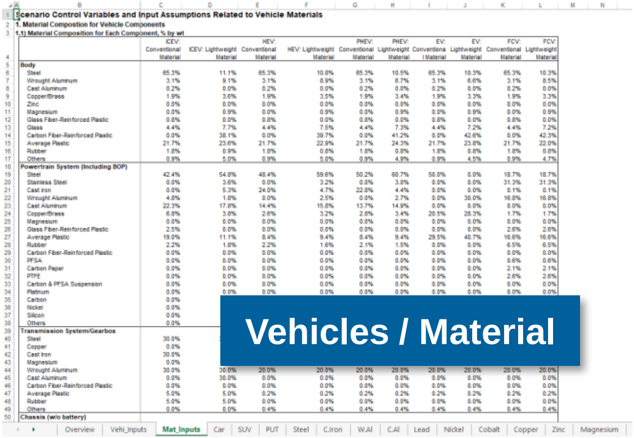
GREET User Training Workshop at Argonne — Nov 7, 2022 - Nov 8, 2022

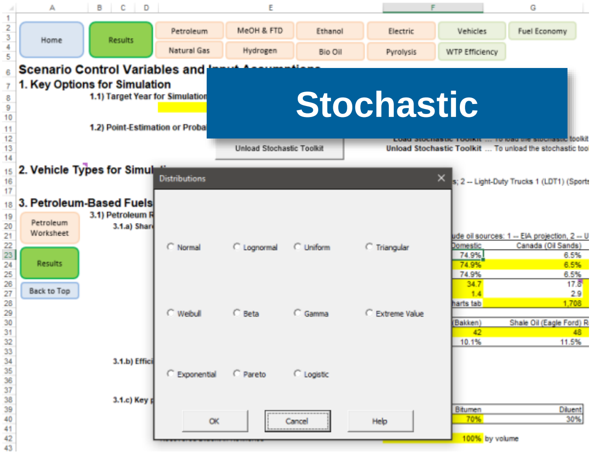
Argonne National Laboratory is pleased to announce an in-person GREET user workshop to be held at Argonne, November 7-8, 2022. For event details, please visit: https://www.anl.gov/event/greet-training-workshop.

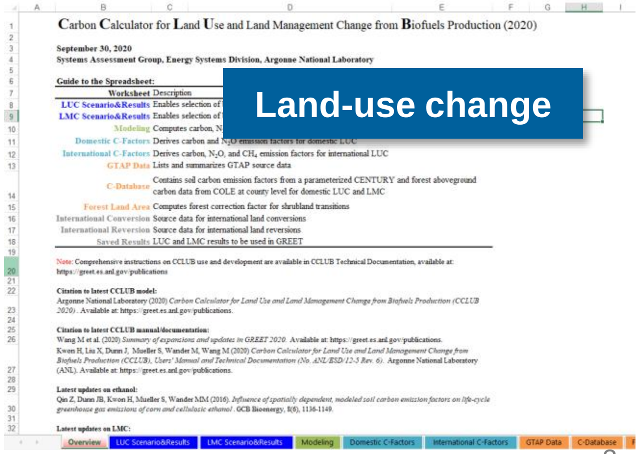
GREET Excel version is completely transparent with multiple modules









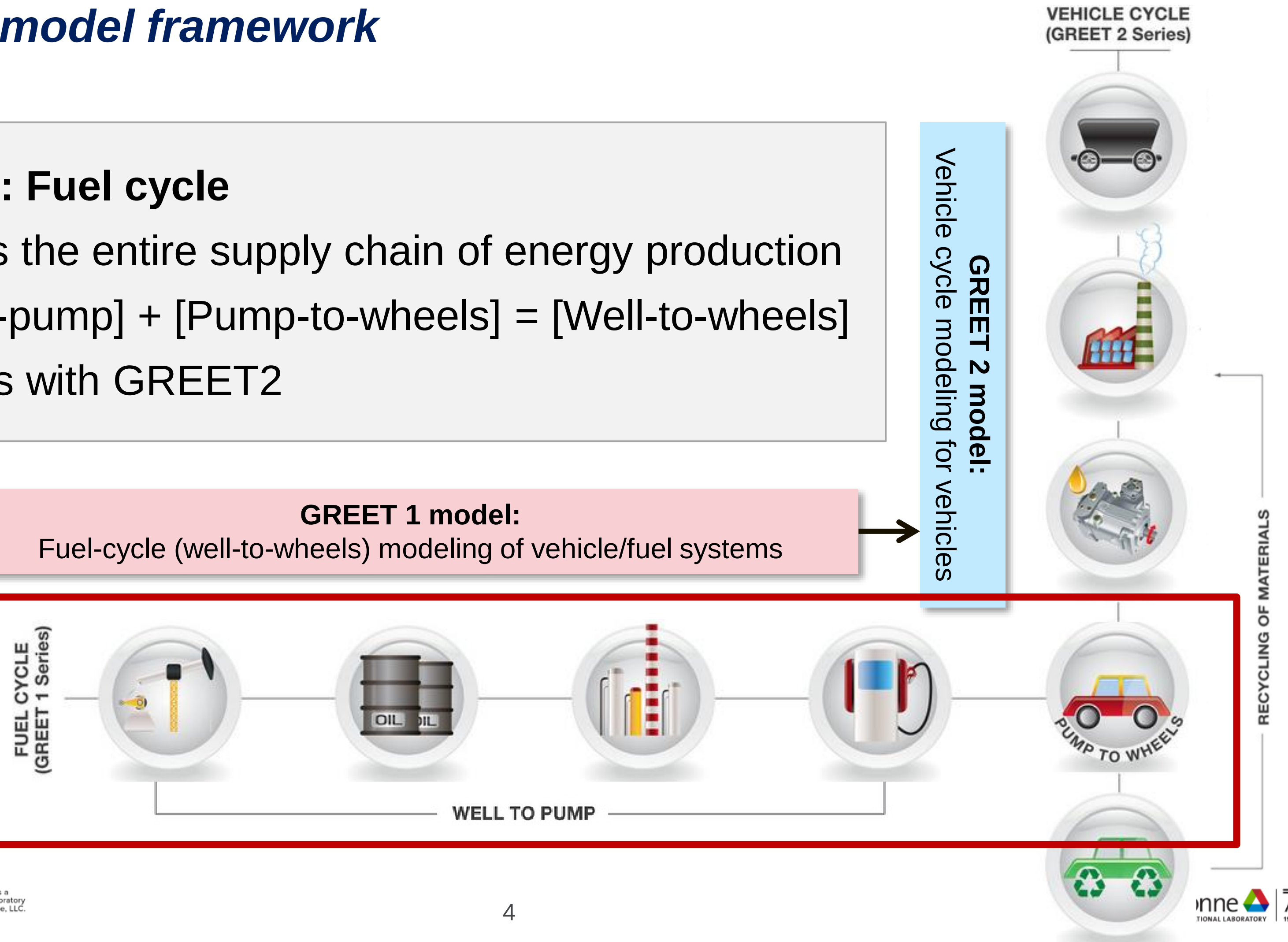


The GREET model framework

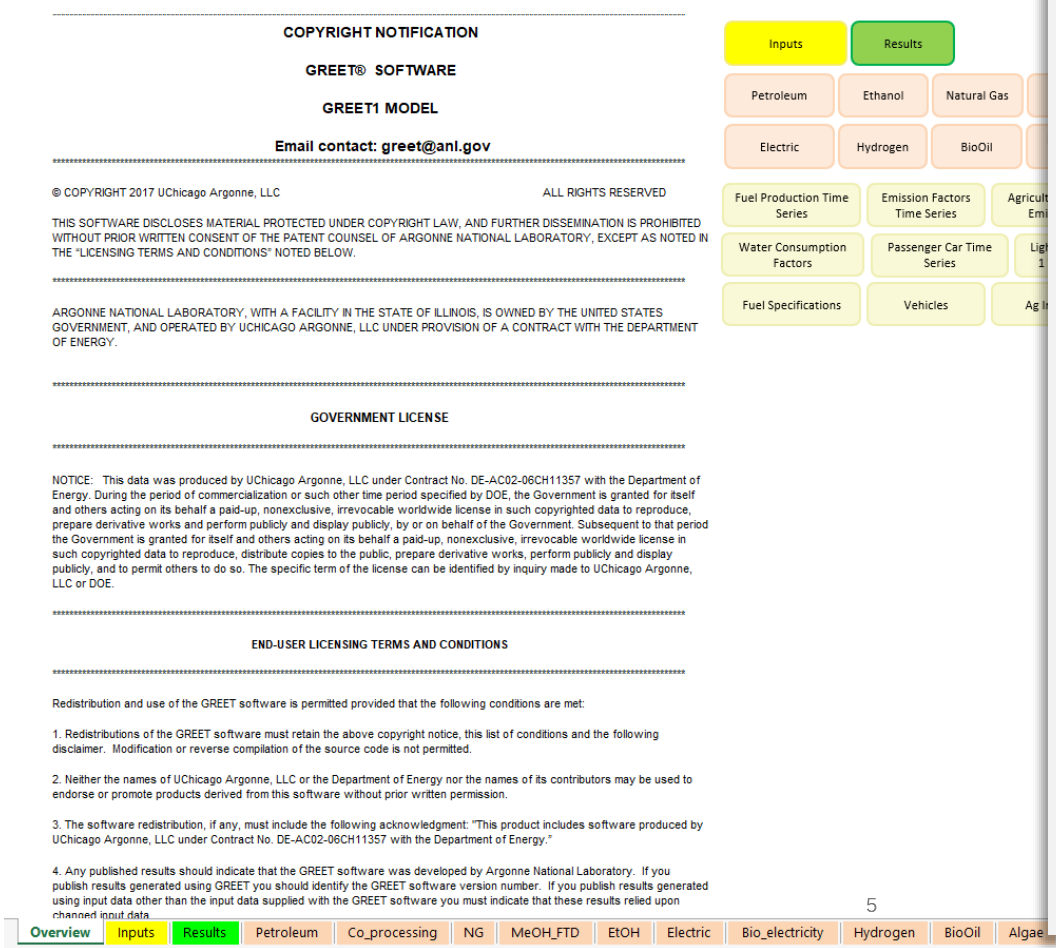
- **GREET1: Fuel cycle**
  - Includes the entire supply chain of energy production
  - [Well-to-pump] + [Pump-to-wheels] = [Well-to-wheels]
  - Interacts with GREET2

GREET 1 model:
Fuel-cycle (well-to-wheels) modeling of vehicle/fuel systems

GREET 2 model:
Vehicle cycle modeling for vehicles



GREET1: Microsoft Excel-based LCA tool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GREET® SOFTWARE

GREET1 MODEL

Email contact: greet@anl.gov

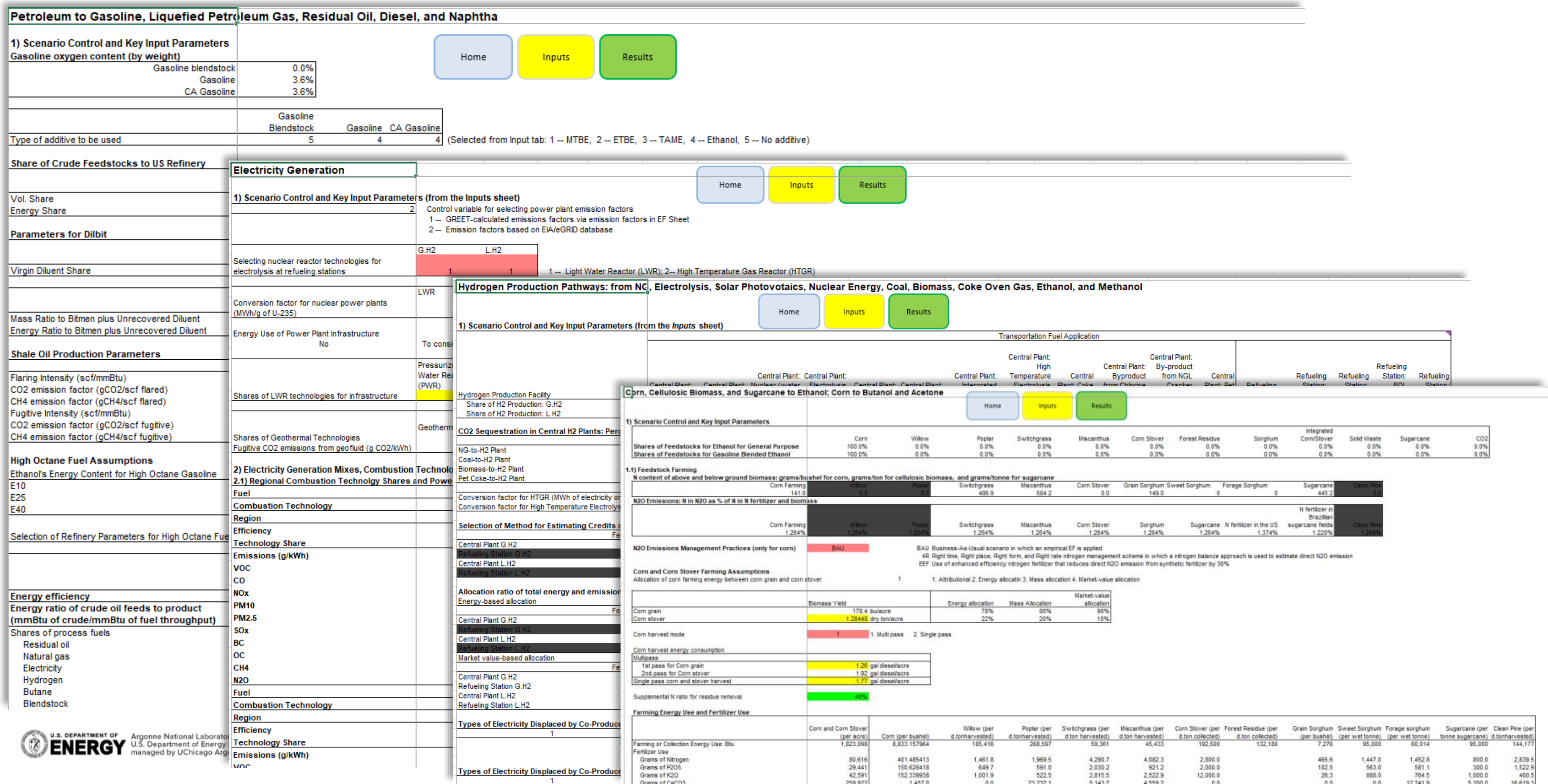
59 tabs in GREET1

- Inputs
- Results
- Petroleum
- Co_processing
- NG
- MeOH&FTD
- EtOH
- Electric
- Bio_electricity
- Hydrogen
- BioOil
- Algae
- Macroalgae
- Waste
- RNG
- Pyrolysis_IDL
- IBR
- PUP_conversion
- E_fuel
- Fuel_Prod_TS
- EF_TS
- AgMining_EF_TS
- EF
- WCF
- Fuel_Specs
- Car_TS
- LDT1_TS
- LDT2_TS
- Vehicles
- Urban_Shares
- Compression
- Coal
- T&D_Flowcharts
- T&D
- Uranium
- ASU
- Ag_Inputs
- Enzymes_Yeast
- Pretreatment
- Catalyst
- Steam_Cracking
- Chemicals
- Plastics
- Animal_Feed
- EtOH-Diesel_Additives
- OilGasCoalInfra
- ElecInfra
- Woody
- HDV_TS
- HDV_WTW
- JetFuel_WTP
- JetFuel_PTWa
- JetFuel_WTWa
- Rail_PTW
- Rail_WTW
- MarineFuel_WTH
- Dist_Specs
- Forecast_Specs
- Forecast_Deleted

GREET1 major components

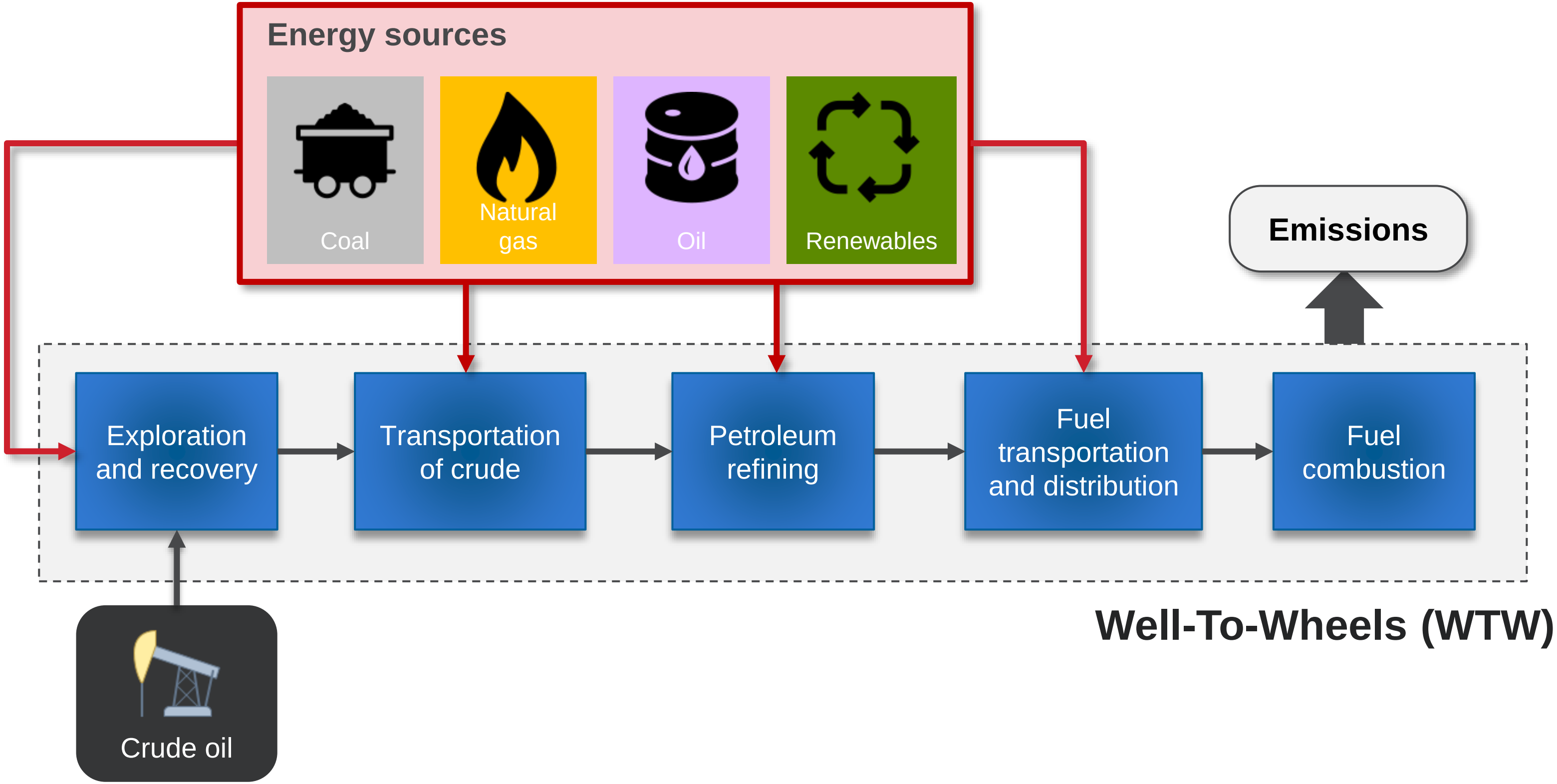
Energy/Fuels	Intermediates/ Products	Applications	Supporting information
• Petroleum • Natural gas • Electricity • Hydrogen • Biofuels • E-fuels • Waste-to-Energy • Coal • Nuclear	• Chemicals • Catalysts • Enzymes • Ag. inputs • Plastics • Animal feed	• LDVs • HDVs • Rail • Marine • Aviation	• Emission factors • Fuel specs • Time-series values • Water consumption factors • Stochastic simulation

Each tab includes detailed modeling parameters enabling comprehensive LCA

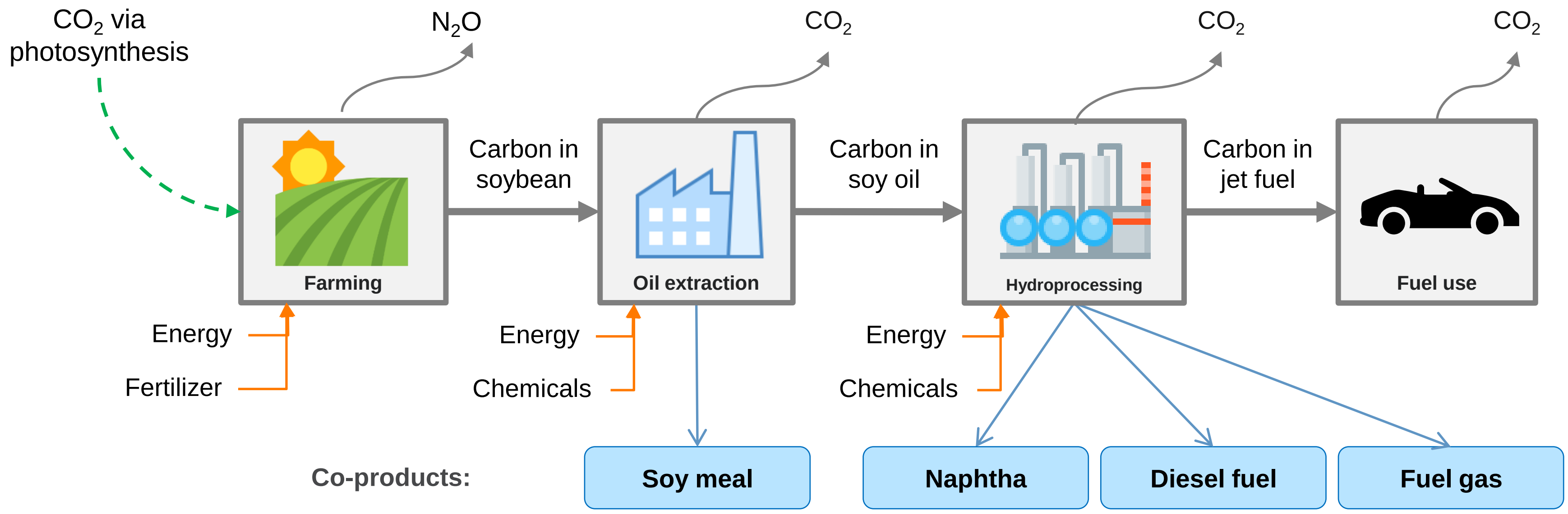


GREET LCA Methodology: Well-to-Pump

Fuel Pathways: Petroleum Fuels

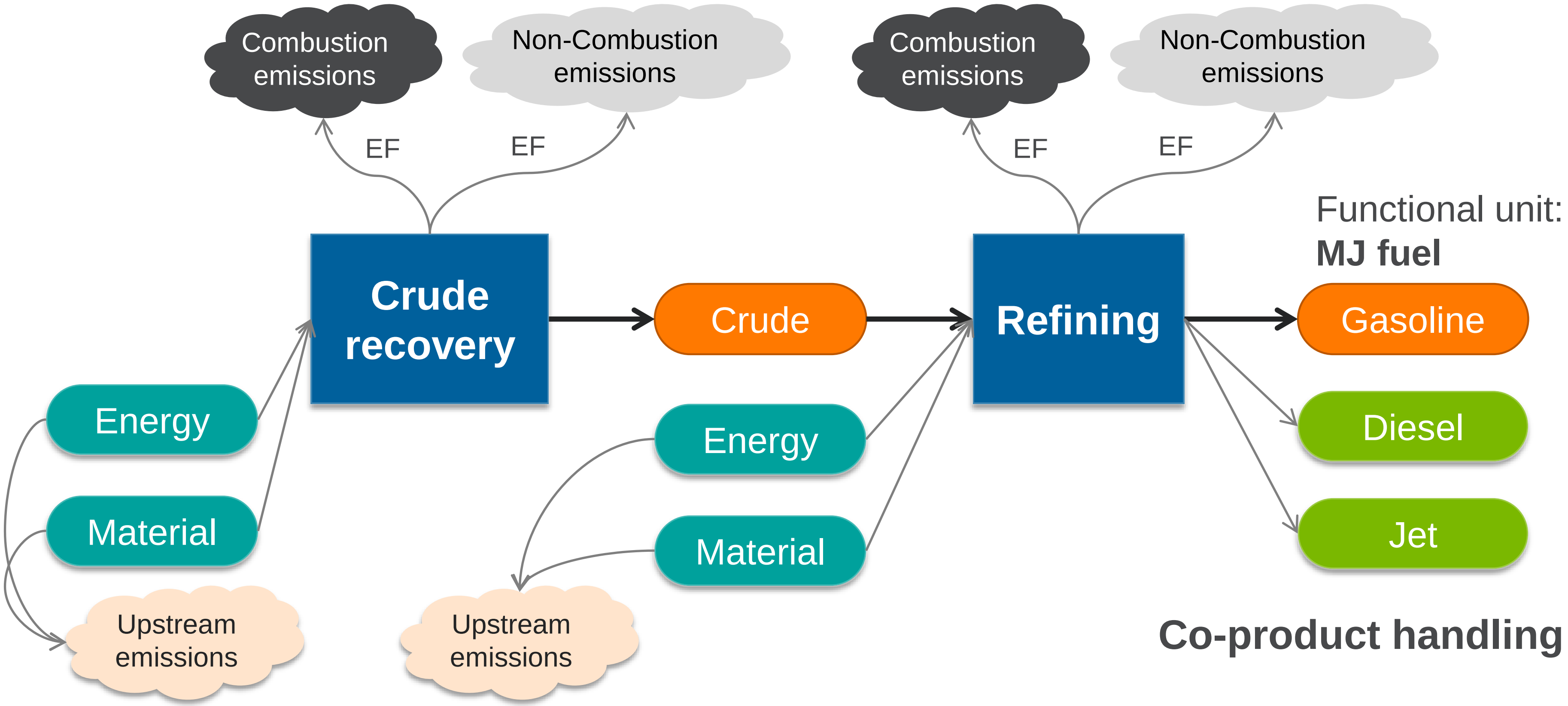


Fuel Pathways: Biofuels



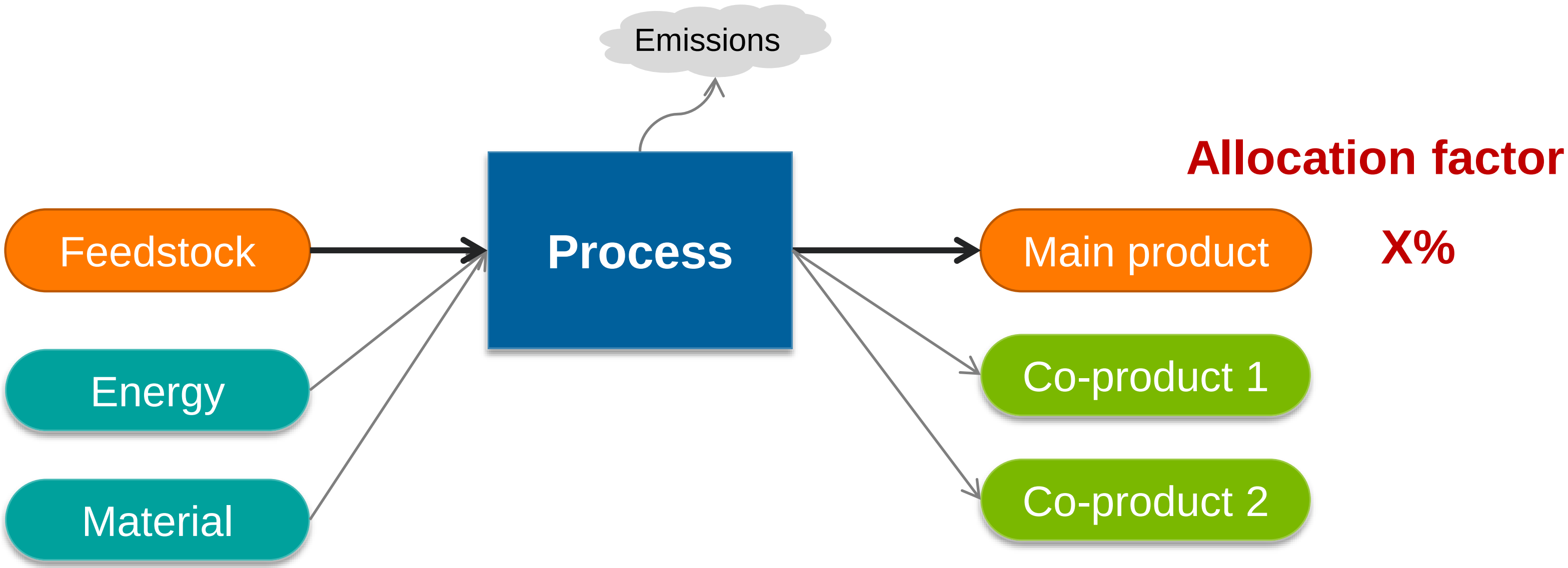
- Carbon cycle via photosynthesis provides key CO_2 benefits with biofuel pathways.

GREET1 example fuel production pathway (simplified)



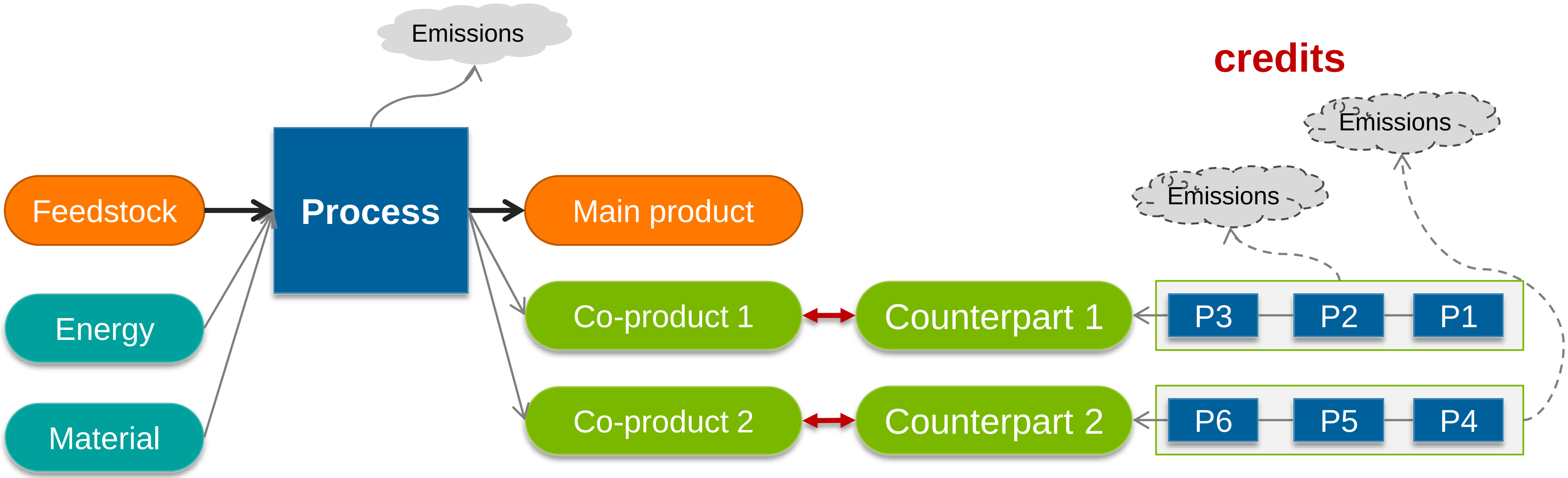
Co-product handling: allocation

- Main product and co-product carry energy and emissions burdens and can be allocated based on their relative ratios in the total product slate;
- Allocation can be done based on mass, energy, or market-value.



Co-product handling: displacement (substitution)

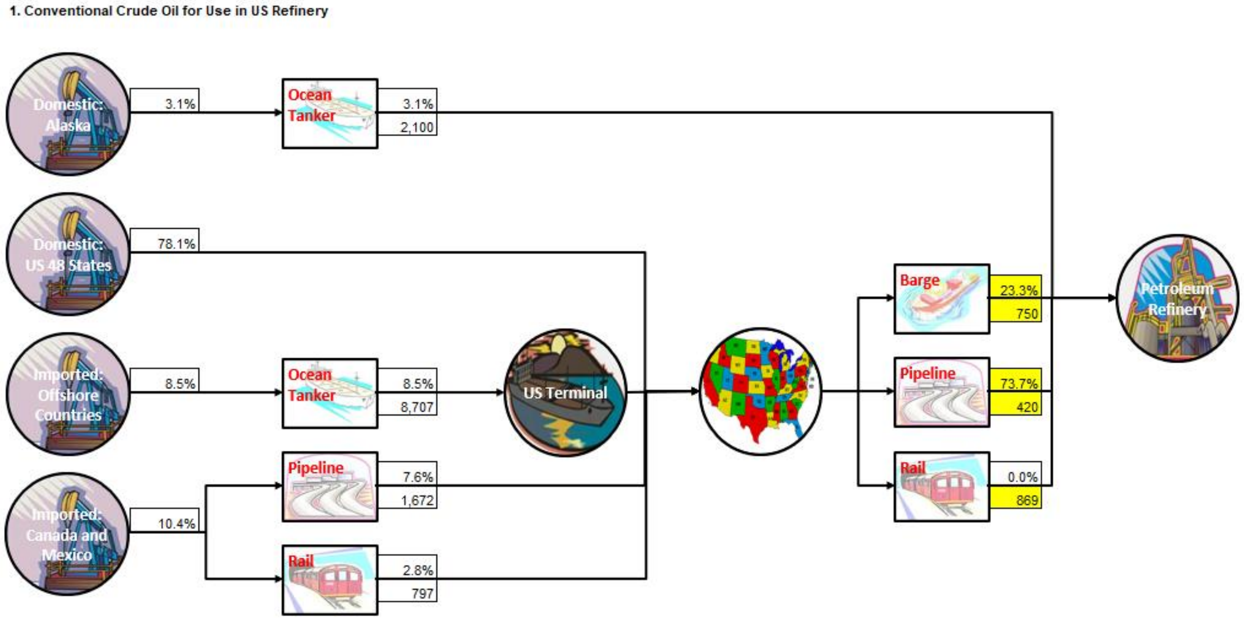
- Main product carries the burden of all process energy and emissions, and all life-cycle energy and emissions of the displaced product are credited to the main product.



Users can select the co-product handling method in GREET

Transportation process

- Transportation modes: ocean tanker, barge, truck, rail, and pipeline
- Parameters: payload (ton), energy consumption (Btu/ton-mi), distance (mi), mode share (%), fuel type (diesel, residual oil, natural gas, and electricity, back-haul



GREET outputs 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, NO_x, PM_{10}, $PM_{2.5}$, and SO_x
- Estimated separately for total and urban (a subset of the total) emissions

Greenhouse gases (GHG)

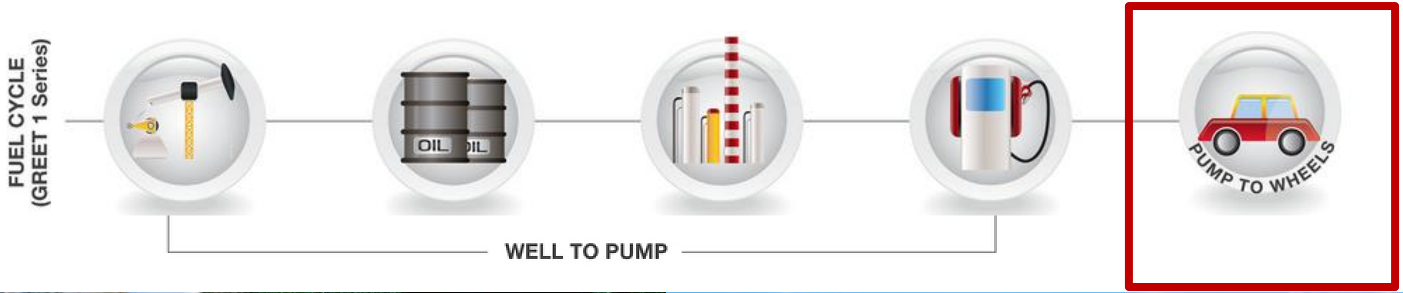
- CO_2, CH_4, N_2O, black carbon, and surface albedo
- CO_{2e} of the five (combined with their global warming potentials)

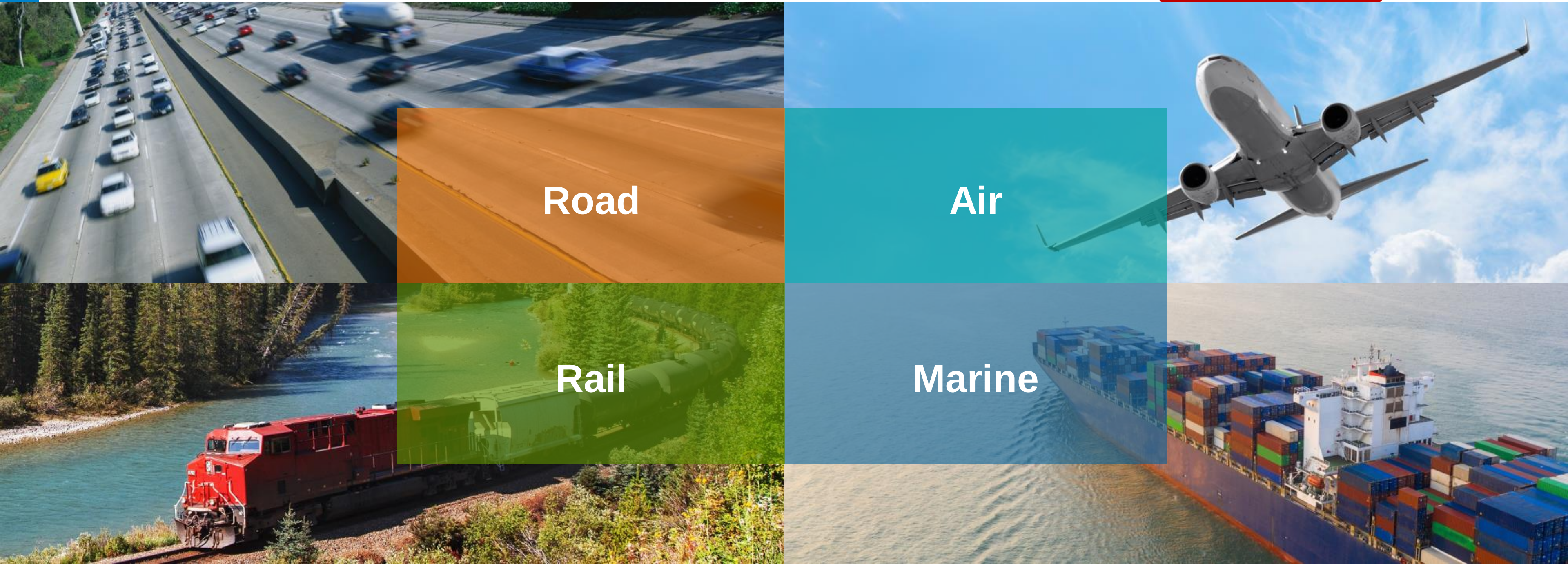
Water consumption

- Freshwater consumption
- Water stress, considering water supply and demand (energy-water nexus)

GREET LCA Methodology: Pump-to-Wheels (Vehicle Operation)

Pump-to-Wheels





GREET includes key vehicle technologies

Types of LDVs in GREET

- Conventional Spark-Ignition Engine Vehicles
- Spark-Ignition, Direct-Injection Engine Vehicles
- Compression-Ignition, Direct-Injection Engine Vehicles
- Hybrid Electric Vehicles (HEVs)
- Plug-in Hybrid Electric Vehicles (PHEVs)
- Battery-Powered Electric Vehicles
- Fuel Cell Vehicles

Types of fuels for LDVs

- Gasoline/Ethanol
- Electricity
- Hydrogen
- CNG
- Diesel
- Biodiesel
- Renewable diesel
- DME/F-T diesel/Methanol

3) Per-Mil

														LH2 ICE Vehicle												CIDI Vehicle: Conventional and LS Diesel
Urban Emis														70.0%												70.0%
MPGGE (pe														31.4												31.6
Total fuel us														3,574												3,553
Fossil fuel u														3,574												3,553
Coal use (E														0												0
Natural gas														3,574												0
Petroleum u														0												3,553
Emissions: grams/mile																										
VOC: exhaust	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.014	0.014	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.143
VOC: evaporation	0.161	0.161	0.161	0.081	0.000	0.000	0.000	0.137	0.137	0.137	0.137	0.137	0.000	0.000	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.161	0.137	0.137	0.005
CO	2.741	2.741	2.741	2.741	2.741	2.741	2.741	2.741	2.741	2.741	2.741	2.741	0.548	0.548	2.741	2.741	2.741	2.741	2.741	2.741	2.741	2.741	2.741	2.741	2.741	3.531
NOx	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.097
PM10: exhaust	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.000	0.000	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.003
PM10: brake and tire wear	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031
PM2.5: exhaust	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.000	0.000	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
PM2.5: brake and tire wear	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004
SOx	0.002	0.002	0.002	0.001	0.001	0.000	0.000	0.001	0.000	0.001	0.000	0.001	0.000	0.000	0.000	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.000	0.001	0.002
BC	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.000	0.000	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
OC	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.000	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.000
CH4	0.015	0.015	0.015	0.146	0.146	0.146	0.015	0.015	0.015	0.015	0.015	0.015	0.001	0.001	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.092
N2O	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.001
CO2	324	324	324	270	263	264	287	310	288	318	308	297	0	0	317	308	337	308	307	306	281	281	281	267	276	275
CO2 (w/ C in VOC & CO)	329	329	329	275	268	269	292	315	293	323	313	302	1	1	322	313	342	313	312	312	286	286	286	272	281	281
GHGs	330	330	330	281	273	274	293	316	294	325	315	304	2	2	324	314	343	315	314	313	288	288	288	274	283	284
Misc. item	-21	-21	-21	0	0	0	0	0	0	-246	-313	-230			-322	-313	-342	-20	-54	-91	-19	-19	-19	0	-214	

Light-duty vehicles: Fuel economy and emission factors

- Fuel economy values are based on Argonne's Autonomie, which is a detailed vehicle simulation model.
- Emission factors are based on EPA's MOVES model (the latest MOVES3)
- Light-duty vehicles include three types: passenger cars, sports utility vehicles (LDV1), and pickup truck (LDV2)

1) Fuel Economy and Emission Rates of Passenger Cars Baseline Vehicles: gasoline-equivalent MPG and grams/mile emissions

(fuel economy is adjusted for on-road performance using the EPA mpg-based method, and using 43%city/57%highway VMT split)

Model Year **2016**

Lag year 5

Gasoline Car: Values from non-stochastic simulations and for adjustments to distribution functions

Model year is 5 years earlier than simulated technology year

	Model Year	MPGGE	VOC (Exhaust)	VOC (Evap.)	CO	NOx	PM10 (Exhaust)	PM10 (TBW)	PM2.5 (Exhaust)	PM2.5 (TBW)	BC	OC	CH4	N2O
		26.16	0.069	0.161	2.741	0.082	0.004	0.031	0.003	0.004	0.002	0.001	0.015	0.004
		26.16	0.069	0.161	2.741	0.082	0.004	0.031	0.003	0.004	0.002	0.001	0.015	0.004
MY	1990	22.10	1.071	2.641	13.152	2.908	0.021	0.031	0.018	0.004	0.004	0.010	0.179	0.040
MY	1995	21.70	0.658	2.626	9.472	1.860	0.014	0.031	0.012	0.004	0.003	0.006	0.110	0.027
MY	2000	22.00	0.244	2.611	5.791	0.812	0.006	0.031	0.006	0.004	0.001	0.003	0.041	0.014
MY	2005	23.40	0.115	0.166	3.871	0.203	0.002	0.031	0.002	0.004	0.000	0.001	0.022	0.006
MY	**2010**	**26.08**	**0.074**	**0.164**	**2.986**	**0.090**	**0.002**	**0.031**	**0.002**	**0.004**	**0.001**	**0.001**	**0.016**	**0.006**
MY	2015	26.16	0.069	0.161	2.741	0.082	0.004	0.031	0.003	0.004	0.002	0.001	0.015	0.004
MY	2020	30.70	0.040	0.114	1.466	0.039	0.004	0.031	0.004	0.004	0.003	0.001	0.008	0.004
MY	2025	31.49	0.029	0.101	1.016	0.021	0.004	0.031	0.004	0.004	0.003	0.001	0.005	0.004
MY	2030	35.43	0.029	0.099	1.011	0.021	0.004	0.031	0.003	0.004	0.003	0.001	0.005	0.004
MY	2035	38.28	0.028	0.098	1.006	0.021	0.004	0.031	0.003	0.004	0.003	0.001	0.005	0.004
MY	2050	44.48	0.027	0.096	0.993	0.020	0.004	0.031	0.003	0.004	0.002	0.001	0.005	0.004

Heavy-duty vehicles: Fuel economy and emission factors

- HDV_TS and HDV_TWT tabs

Types of HDVs in GREET

- Combination Long-Haul Trucks
- Combination Short-Haul Trucks
- Heavy Heavy-Duty Vocational Vehicles
- Medium Heavy-Duty Vocational Vehicles
- Light Heavy-Duty Vocational Vehicles
- Heavy-Duty Pick-Up Trucks and Vans
- Refuse Trucks
- School Buses
- Transit Buses
- Intercity Buses

Types of fuels for HDVs

- Diesel
- Biodiesel
- Renewable diesel
- DME/F-T diesel/Methanol
- CNG/LNG
- Electricity
- Hydrogen

Rail, marine, and aviation modules can generate results for different service functional units

- Rail (per ton-mi or per passenger-mi results)
  - Rail types: freight rails, intercity rails, commuter rails, and transit rails
  - Fuel types: diesel, LNG, LPG, DME, FTD, RD, RG, H_2, and electricity

- Marine (per million tonne-km or per defined trip)
  - Vessel types: bulk, container-large, and tanker VLCC
  - Trip types: domestic-domestic, domestic-CA, CA-CA, domestic-international, and CA-international
  - Regions: Pacific, Atlantic, Gulf of Mexico, and Great Lakes
  - Fuel types: HFO, MDO, MGO, LNG, FTD, Pyrolysis oil, methanol, ammonia, etc.

- Aviation (per passenger-km or per kg-km)
  - Aircraft types (passenger and freight): single aisle, small twin aisle, large twin aisle, large quad, and regional jet
  - Fuel types: petroleum jet and sustainable aviation fuels (SAF)

Time-series tables characterize technology advancement over time and enable simulating temporal effects

Fuel_Prod_TS	EF_TS	AgMining_EF_TS	EF	WCF	Fuel_Specs	Car_TS	LDT1_TS	LDT2_TS

- Many major parameters have time-series (TS) values.

5-year period	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Others
1990	4.2%	12.3%	52.5%	19.0%	1.1%	10.9%
1995	2.2%	14.8%	51.0%	20.1%	1.2%	10.7%
2000	2.9%	15.8%	51.7%	19.8%	1.1%	8.7%
2005	2.9%	15.7%	51.7%	20.3%	1.2%	8.2%
2010	0.9%	22.7%	46.0%	20.3%	0.3%	9.8%
2013	**0.6%**	**26.2%**	**40.3%**	**20.2%**	**0.3%**	**12.3%**
2014	**0.7%**	**26.2%**	**39.8%**	**20.2%**	**0.4%**	**12.6%**
2015	**0.7%**	**31.6%**	**34.2%**	**20.3%**	**0.4%**	**12.8%**
2016	**0.6%**	**32.7%**	**31.4%**	**20.5%**	**0.3%**	**14.5%**
2017	**0.5%**	**30.6%**	**31.0%**	**20.9%**	**0.4%**	**16.6%**
2018	**0.4%**	**33.4%**	**29.0%**	**20.3%**	**0.3%**	**16.5%**
2019	**0.4%**	**36.7%**	**24.6%**	**20.4%**	**0.3%**	**17.5%**
2020	**0.4%**	**39.6%**	**20.0%**	**20.4%**	**0.3%**	**19.4%**
2021	**0.3%**	**36.5%**	**23.8%**	**19.6%**	**0.3%**	**19.5%**
2025	0.2%	34.7%	17.7%	18.9%	0.3%	28.3%
2030	0.2%	33.5%	16.1%	16.7%	0.3%	33.3%
2035	0.2%	32.6%	14.0%	15.4%	0.3%	37.5%
2040	0.1%	33.0%	12.3%	14.7%	0.2%	39.5%
2045	0.1%	34.0%	11.1%	14.2%	0.2%	40.3%
2050	0.1%	34.2%	10.5%	13.4%	0.2%	41.6%

1. Key Options for Simulation

1.1) Target Year for Simulation

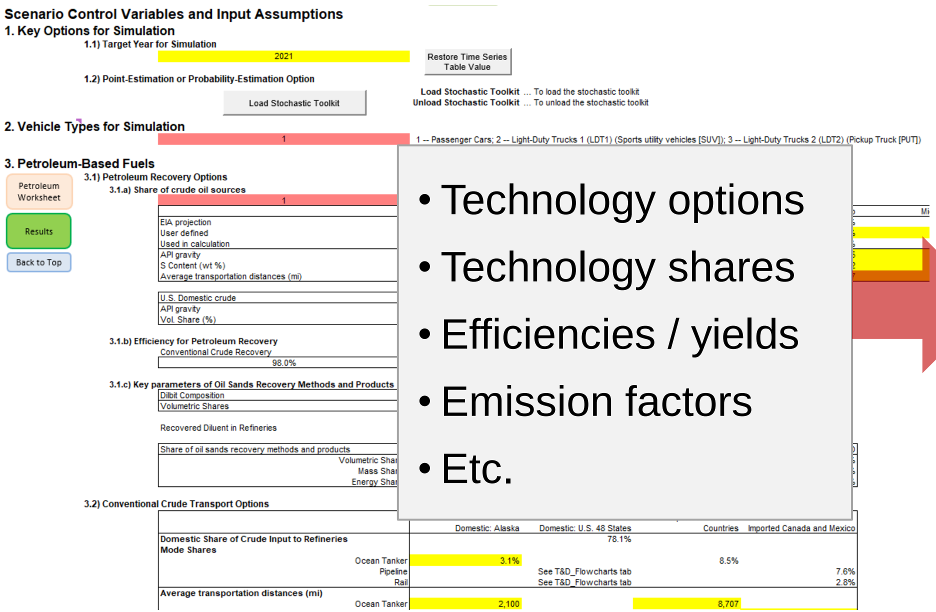
2021

- Depending on the selected simulation year, GREET reads the parameters in the TS tables of relevant parameters for the simulation year.

What can we do with GREET?

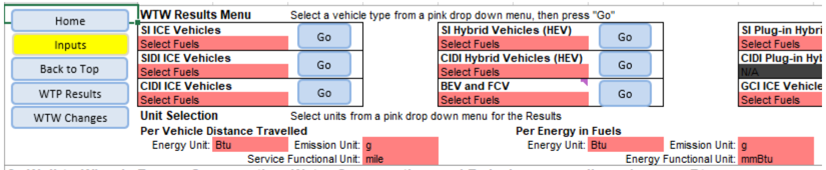
GREET 1 can simulate various fuel production pathways in specific scenarios

Inputs



- Technology options
- Technology shares
- Efficiencies / yields
- Emission factors
- Etc.

Results



2. Well-to-Wheels Energy Consumption, Water Consumption, and Emissions: per mile and per mmBtu

Gasoline Vehicle: Gasoline

	Btu/mile or Gallon/mile or g/mile				Btu/mmBtu or Gallon/mmBtu or g/mmBtu			
Item	Feedstock	Fuel	Vehicle Operation	Total	Feedstock	Fuel	Vehicle Operation	Total
Total Energy	233	953	4,289	5,476	54,414	222,307	1,000,000	1,276,720
Fossil Fuels	219	846	4,003	5,069	51,118	197,360	933,326	1,181,804
Coal	23	34	0	57	5,361	7,863	0	13,224
Natural Gas	158	541	0	698	36,792	126,052	0	162,844
Petroleum	38	272	4,003	4,314	8,965	63,445	933,326	1,005,736
Water Consumption	0.1	0.2	0	0	15	38	0	53
CO2 (w/ C in VOC & CO)	-2	63	329	390	-527	14,689	76,702	90,864
CH4	0.320	0.187	0.015	0.522	74.590	43.607	3.414	121.611
N2O	0.000	0.012	0.004	0.016	0.073	2.827	0.911	3.811
GHGs	7	72	330	410	1,716	16,760	77,053	95,529
VOC: Total	0.013	0.114	0.230	0.357	3.008	26.513	53.597	83.119
CO: Total	0.027	0.043	2.741	2.811	6.187	10.113	639.104	655.404
NOx: Total	0.042	0.072	0.082	0.196	9.729	16.848	19.209	45.786
PM10: Total	0.002	0.010	0.035	0.047	0.502	2.407	8.044	10.953
PM2.5: Total	0.002	0.007	0.007	0.016	0.420	1.532	1.729	3.680
SOx: Total	0.011	0.022	0.002	0.035	2.470	5.172	0.456	8.098
BC Total	0.000	0.001	0.003	0.004	0.074	0.183	0.609	0.866
OC Total	0.001	0.001	0.002	0.004	0.152	0.272	0.415	0.838
VOC: Urban	0.002	0.066	0.161	0.229	0.534	15.298	37.518	53.351
CO: Urban	0.001	0.011	1.919	1.931	0.256	2.580	447.373	450.210
NOx: Urban	0.002	0.017	0.058	0.076	0.514	3.853	13.446	17.813
PM10: Urban	0.000	0.004	0.024	0.028	0.039	0.830	5.631	6.500
PM2.5: Urban	0.000	0.003	0.005	0.008	0.034	0.723	1.210	1.966
SOx: Urban	0.001	0.006	0.001	0.009	0.278	1.393	0.319	1.991
BC: Urban	0.000	0.000	0.002	0.002	0.003	0.082	0.426	0.512
OC: Urban	0.000	0.000	0.001	0.002	0.010	0.106	0.290	0.407

Users can change the value (yellow)

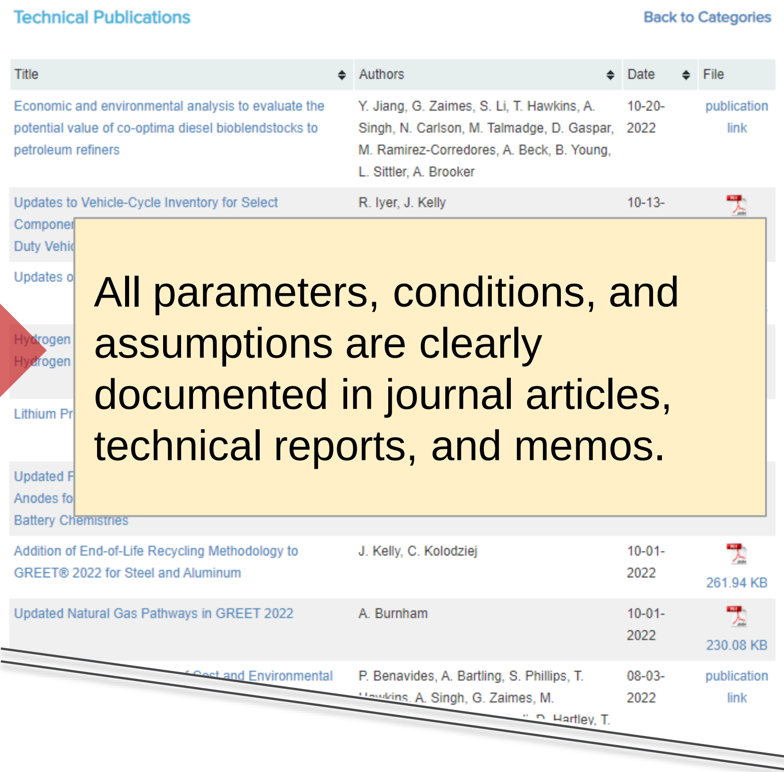
Users can select an option (pink)

GREET generates substantial and reliable datasets for energy/transportation technologies

GREET includes

- Feedstock specifications
- Fuel specifications
- Major parameters (e.g., fuel yield, energy and material inputs, etc.) of various fuel production technologies
- Major parameters of various material production technologies
- Vehicle fuel economy and emission factors

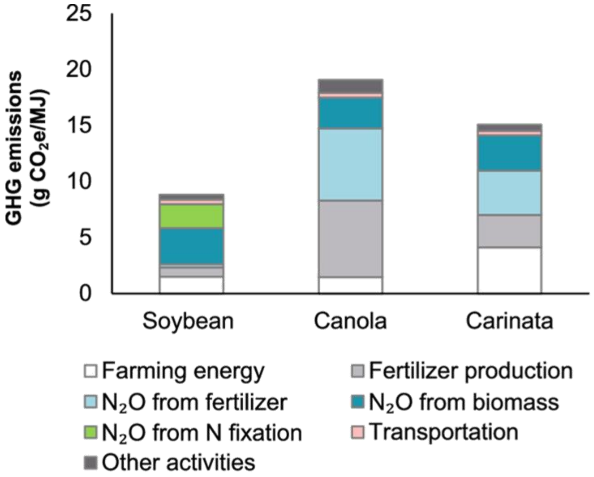
https://greet.es.anl.gov/publications



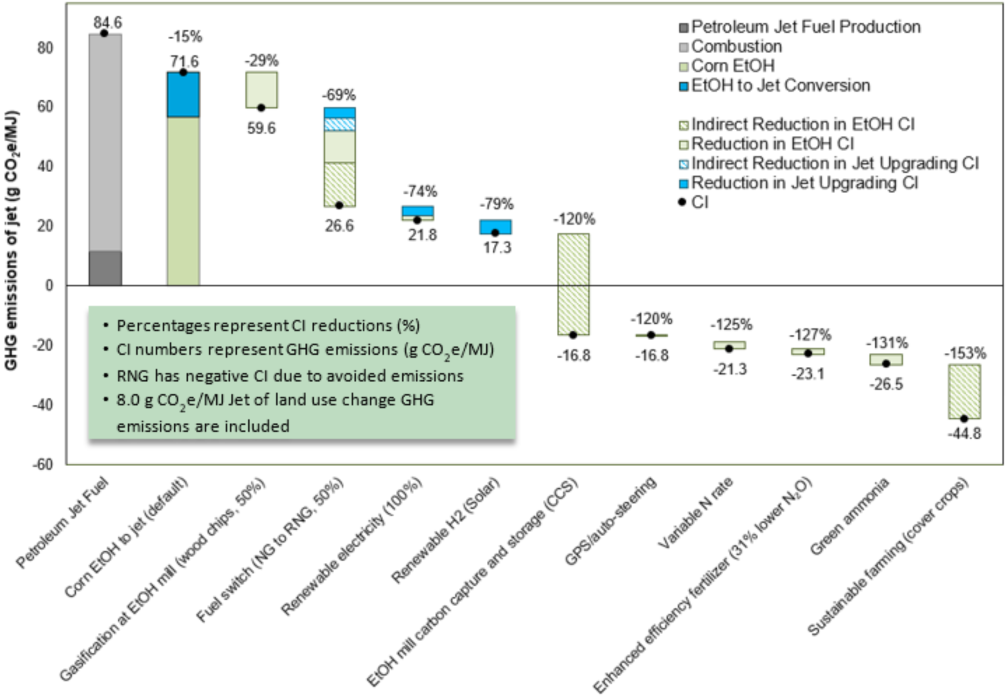
All parameters, conditions, and assumptions are clearly documented in journal articles, technical reports, and memos.

GREET 1 identifies hotspots and opportunities for technology improvement

- Results can be presented at the process level showing the contribution of major parameters.
- Can help reduce environmental impacts through multiple options available in GREET.



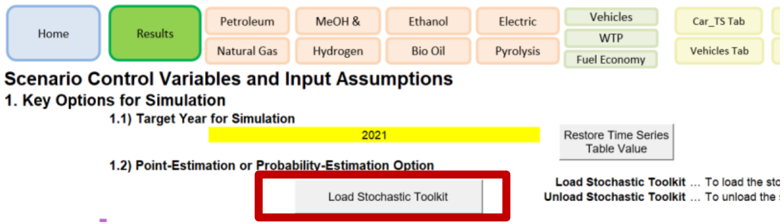
https://pubs.acs.org/doi/10.1021/acs.est.2c00289

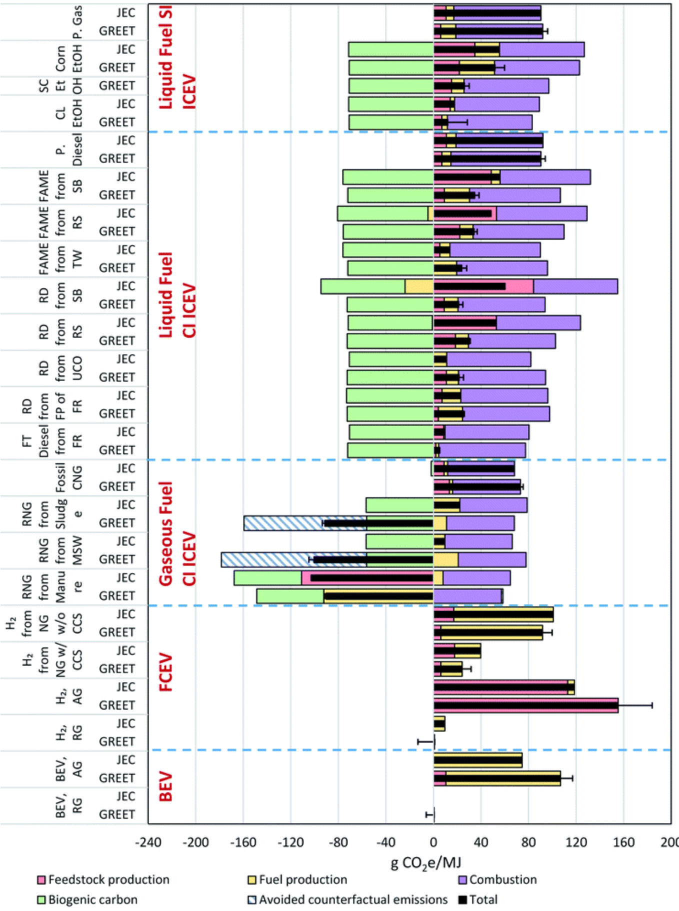


Source: Jim Spaeth(2021) (https://www.energy.gov/eere/bioenergy/articles/sustainable-aviation-fuels-low-carbon-ethanol-production)

Stochastic simulation in GREET1 quantifies uncertainties

- Stochastic simulation feature is incorporated in GREET
  - Assign probability distribution functions to the input variables
  - Specify the number of samples required and the sampling technique
  - Define the forecast variables
  - Propagate the uncertainties
  - Statistically analyze the outputs

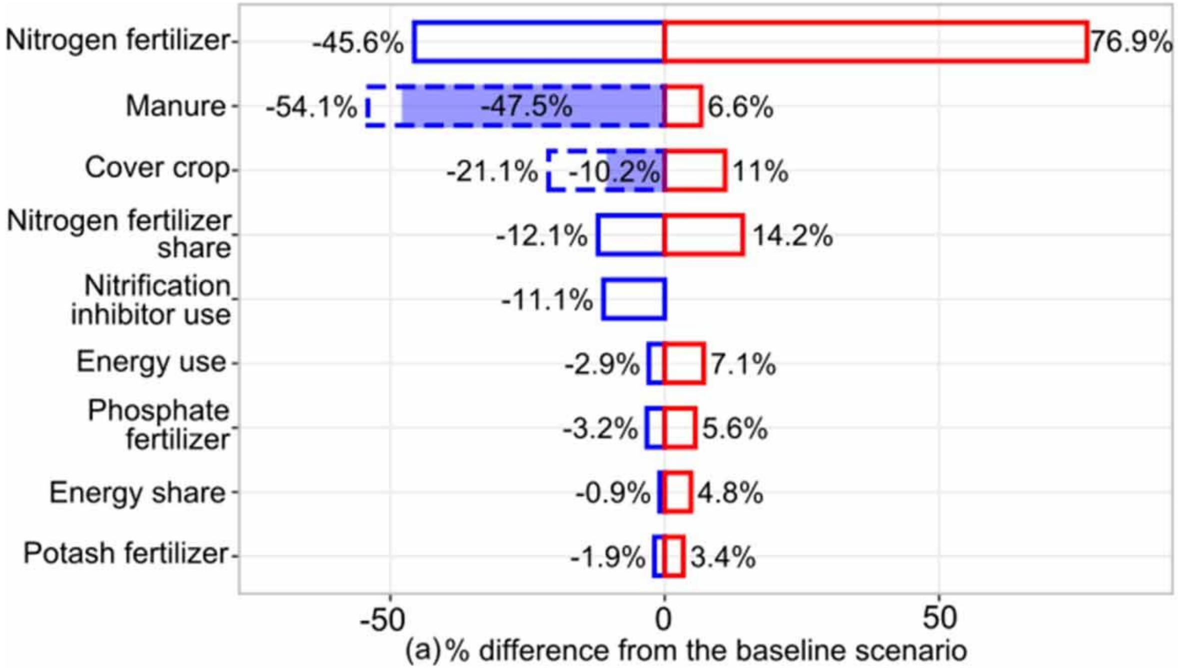




https://pubs.rsc.org/en/content/articlehtml/2022/se/d2se00411a

Sensitivity analysis with transparent access and modifications to key inputs

- Sensitivity analysis help reveal the impact of each parameter



https://iopscience.iop.org/article/10.1088/1748-9326/ac018f/pdf

GREET1 2022 Contributors:

Michael Wang, Amgad Elgowainy, Uisung Lee, Kwang Hoon Baek, Adarsh Bafana, Pahola Thathiana Benavides, Andrew Burnham, Hao Cai, Vincenzo Cappello, Peter Chen, Yu Gan, Ulises R Gracida-Alvarez, Troy R. Hawkins, Rakesh Krishnamoorthy Iyer, Taemin Kim, Shishir Kumar, Hoyoung Kwon, Kyuha Lee, Xinyu Liu, Zifeng Lu, Farhad H. Masum, Clarence Ng, Longwen Ou, Krishna Reddi, Nazib Siddique, Pingping Sun, Pradeep Vyawahare, Hui Xu, George G. Zaimes

Day 2 8:30am – GREET1 Demonstration

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

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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