GREET 1: A Fuel-Cycle Model for Alternative Fuels and Light-Duty Vehicles

Amgad Elgowainy

Systems Assessment Group

Center for Transportation Research

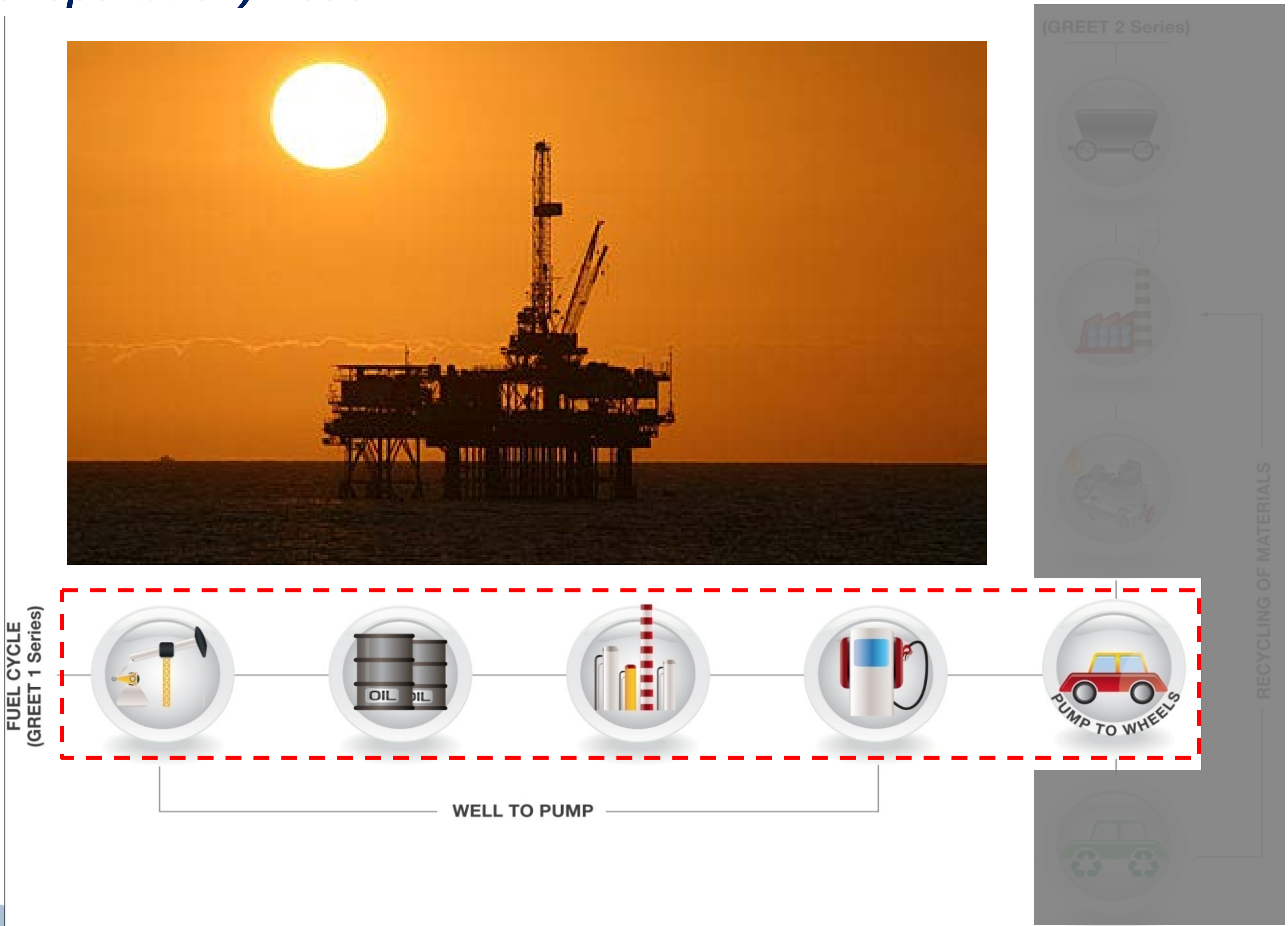
Argonne National Laboratory

GREET Training Workshop

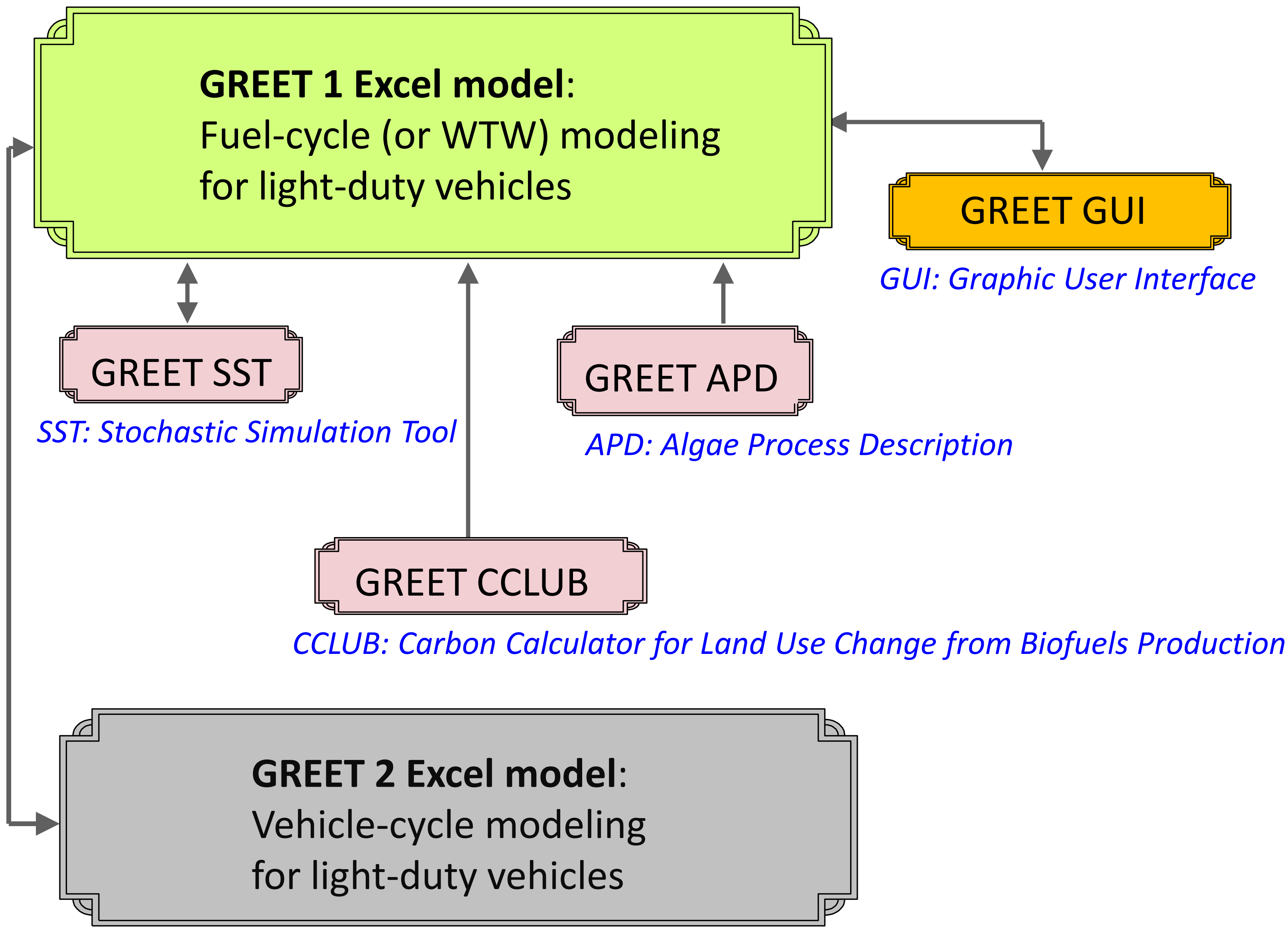
USDA, Washington D.C.

January 31, 2012

The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) Model



The Suite of GREET Models



GREET Covers Emissions and Energy Use

- GREET includes emissions of **greenhouse** gases (GHGs)
  - **CO_2**, **CH_4** (GWP=25), and **N_2O** (GWP=298)
  - VOC, CO, and NOx as optional GHGs

- GREET estimate emissions of six **criteria pollutants** (total and urban separately)
  - VOC, CO, NOx, PM10, PM2.5, and SOx

- GREET separates **energy** use into
  - All energy sources
    - ✓ Fossil fuels
      - Petroleum
      - Natural Gas
      - Coal

GREET Includes More Than 100 Fuel Production Pathways from Various Energy Feedstock Sources

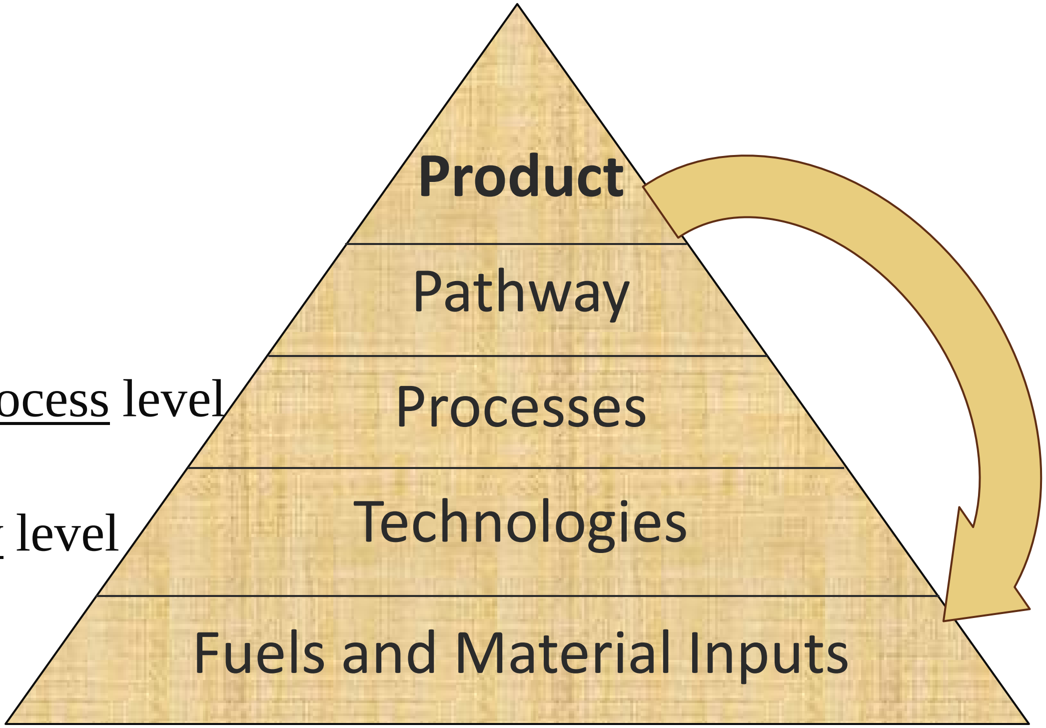
Feedstock	Fuel
Petroleum: Conventional, Oil Sands	Gasoline, Diesel, Jet Fuel, Liquefied Petroleum Gas, Naphtha, Residual Oil
Coal	Hydrogen, Fischer-Tropsch Diesel, Fischer-Tropsch Jet, Methanol, Dimethyl Ether
Natural Gas: North American, Non-North American, Shale gas; **Renewable Natural Gas**: Landfill Gas, Animal Waste	Compressed Natural Gas, Liquefied Natural Gas, Liquefied Petroleum Gas, Methanol, Dimethyl Ether, Fischer-Tropsch Diesel, Fischer-Tropsch Jet, Fischer-Tropsch Naphtha, Hydrogen
Coke Oven Gas, Petroleum Coke, Nuclear Energy	Hydrogen
Corn	Ethanol, Butanol
Sugarcane	Ethanol
Soybeans, Palm, Rapeseed, Jatropha, Camelina, Algae	Biodiesel, Renewable Diesel, Renewable Gasoline, Hydroprocessed Renewable Jet
Cellulosic Biomass: Switchgrass, Fast Growing Trees, Crop Residues, Forest Residues	Ethanol, Hydrogen, Methanol, Dimethyl Ether, Fischer-Tropsch Diesel, Fischer-Tropsch Jet, Pyro Jet
Residual Oil, Coal, Natural Gas, Biomass, Other Renewables	Electricity

A Process is The Building Block of a Pathway in GREET

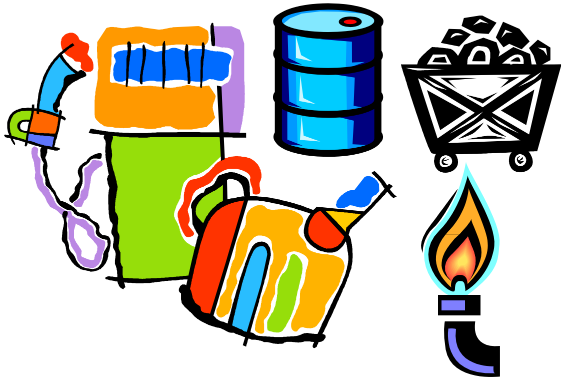
- A process employs technologies
- Technologies employ fuels and may produce emissions

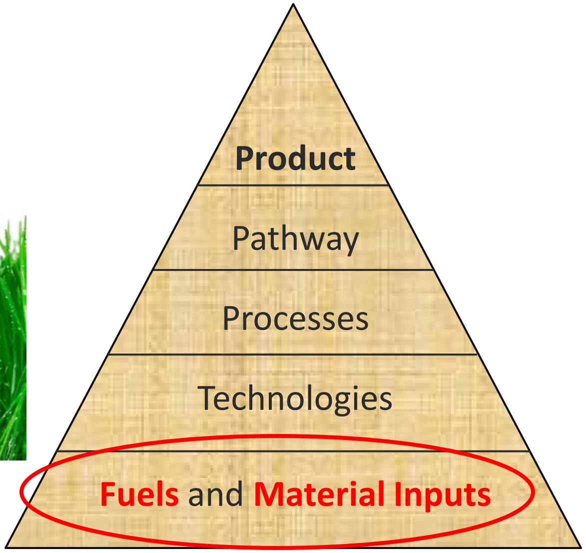
Energy is defined at process level

Emissions are defined at technology level



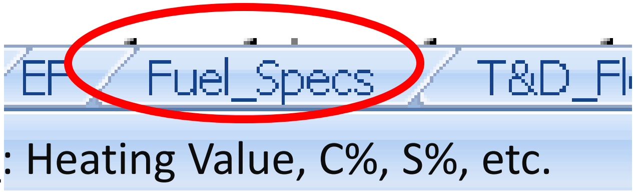
I. Fuels and Material Inputs:





Biomass

Fuels

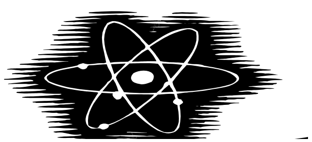


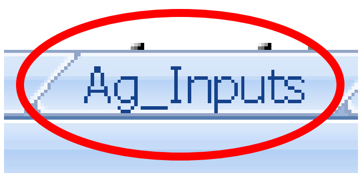
Properties: Heating Value, C%, S%, etc.

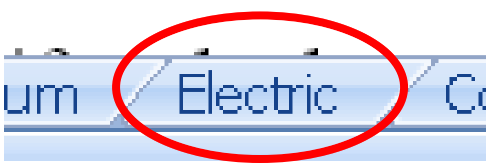
Fertilizers

Nuclear

Electricity



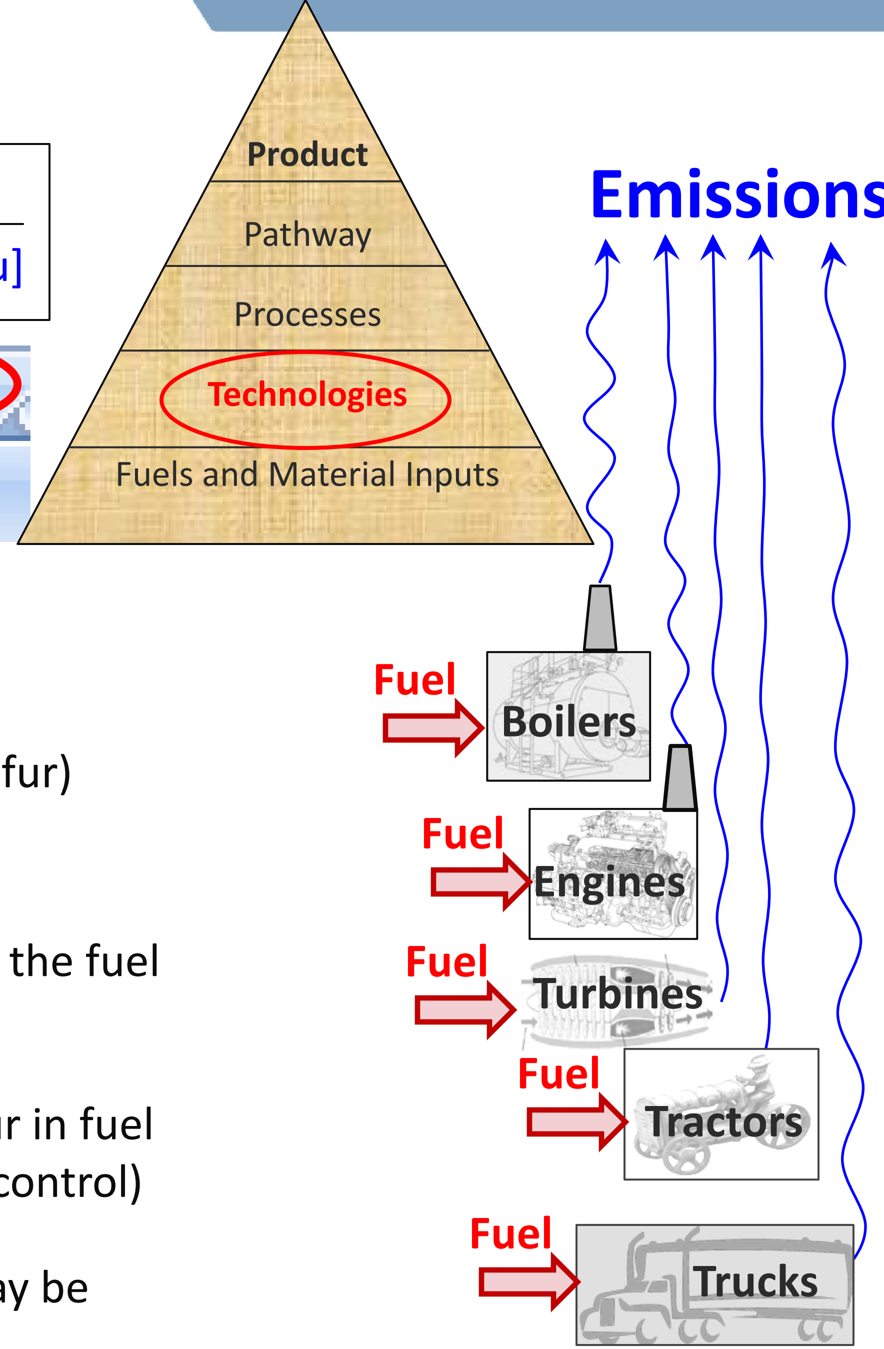




II. Technologies (Combustion)

$$\textbf{Emissions Factor } (EF_i) = \frac{\text{Emissions of species i [g]}}{\text{Unit of Fuel used [mmBtu]}}$$

Sheets for Emission Factors in GREET



Species vector include:

- CH_4 and N_2O
- VOC, CO, NOx, PM10, and PM2.5
- EF may include SOx (if emissions control on sulfur)

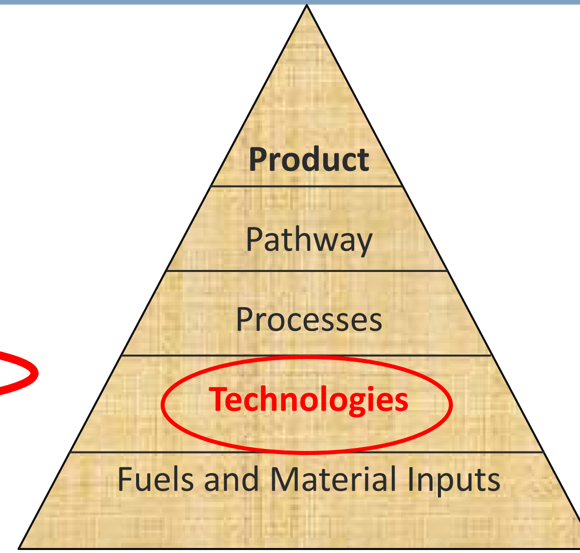
Important Notes:

- CO_2 is calculated by balancing carbon in the fuel with carbon in emissions
- SOx may be calculated by balancing sulfur in fuel with sulfur in emissions (if no emissions control)
- EF for power generation technologies may be specified in [g/kWhe]

II. Technologies (Light-Duty Vehicles)

$$\textbf{Emissions Factor } (EF_i) = \frac{\text{Emissions of species i [g]}}{\text{Vehicle Miles Travelled [mi]}}$$

Sheets for Vehicle
Emission Factors in GREET

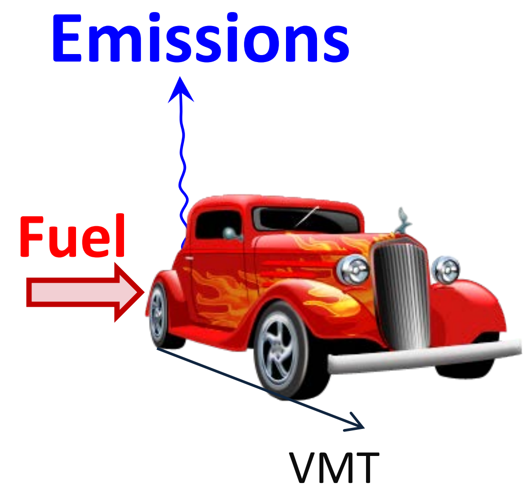


Species vector include:

- **CH_4** and **N_2O**
- VOC, CO, NOx, PM10, and PM2.5

Important Notes:

- **CO_2** is calculated by balancing carbon in the fuel with carbon in emissions
- SOx is calculated by balancing sulfur in fuel with sulfur in emissions
- Emission factors are independent of fuel economy
- The vehicle technology is a process by itself (PTW)



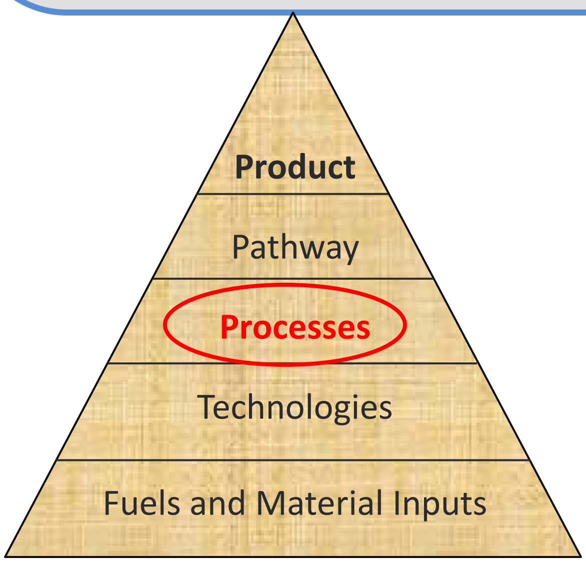
III. Processes (The Building Blocks of Pathways)

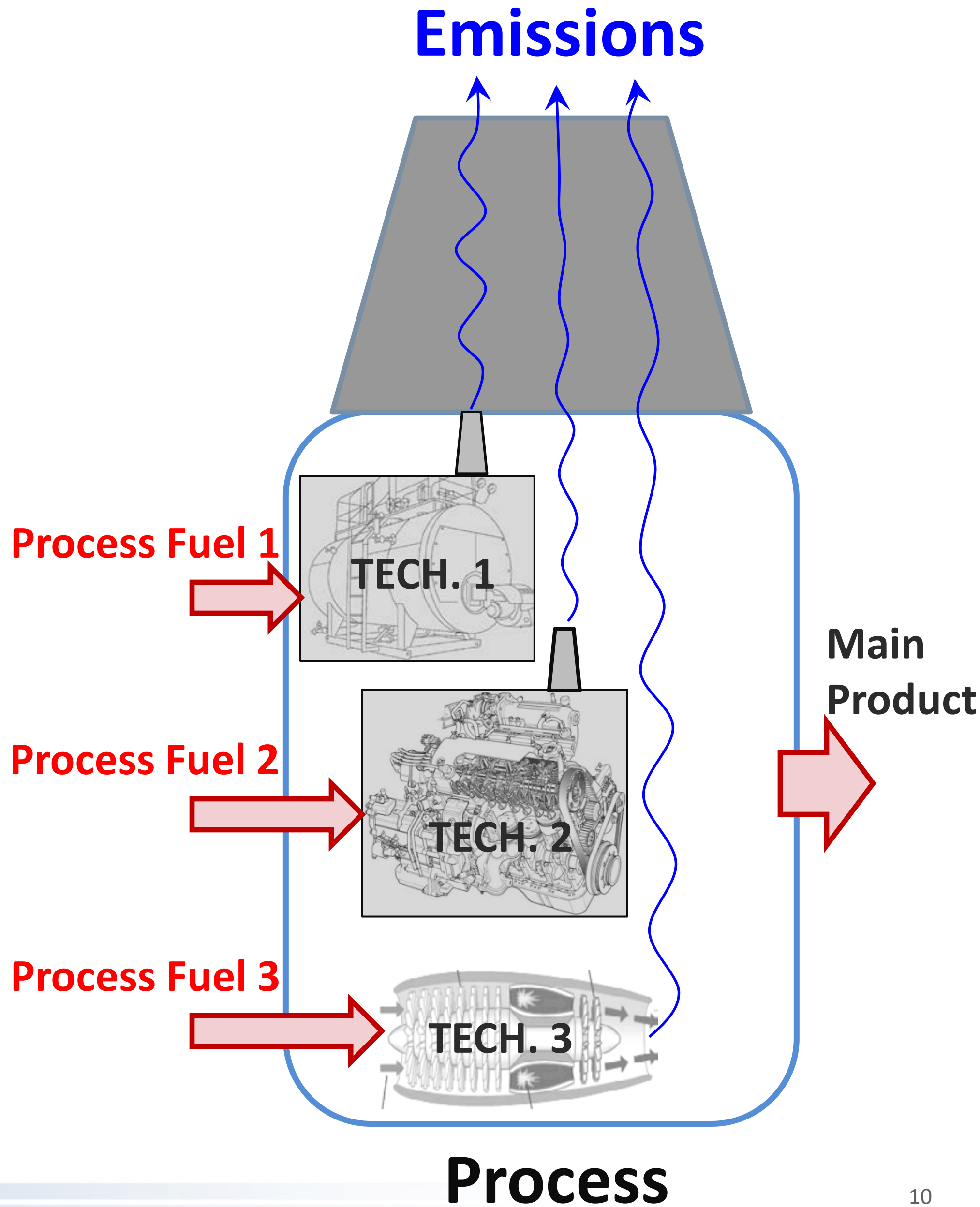
For Energy:

- Define output-input relation (e.g., efficiency)
- Define Process Fuel Share

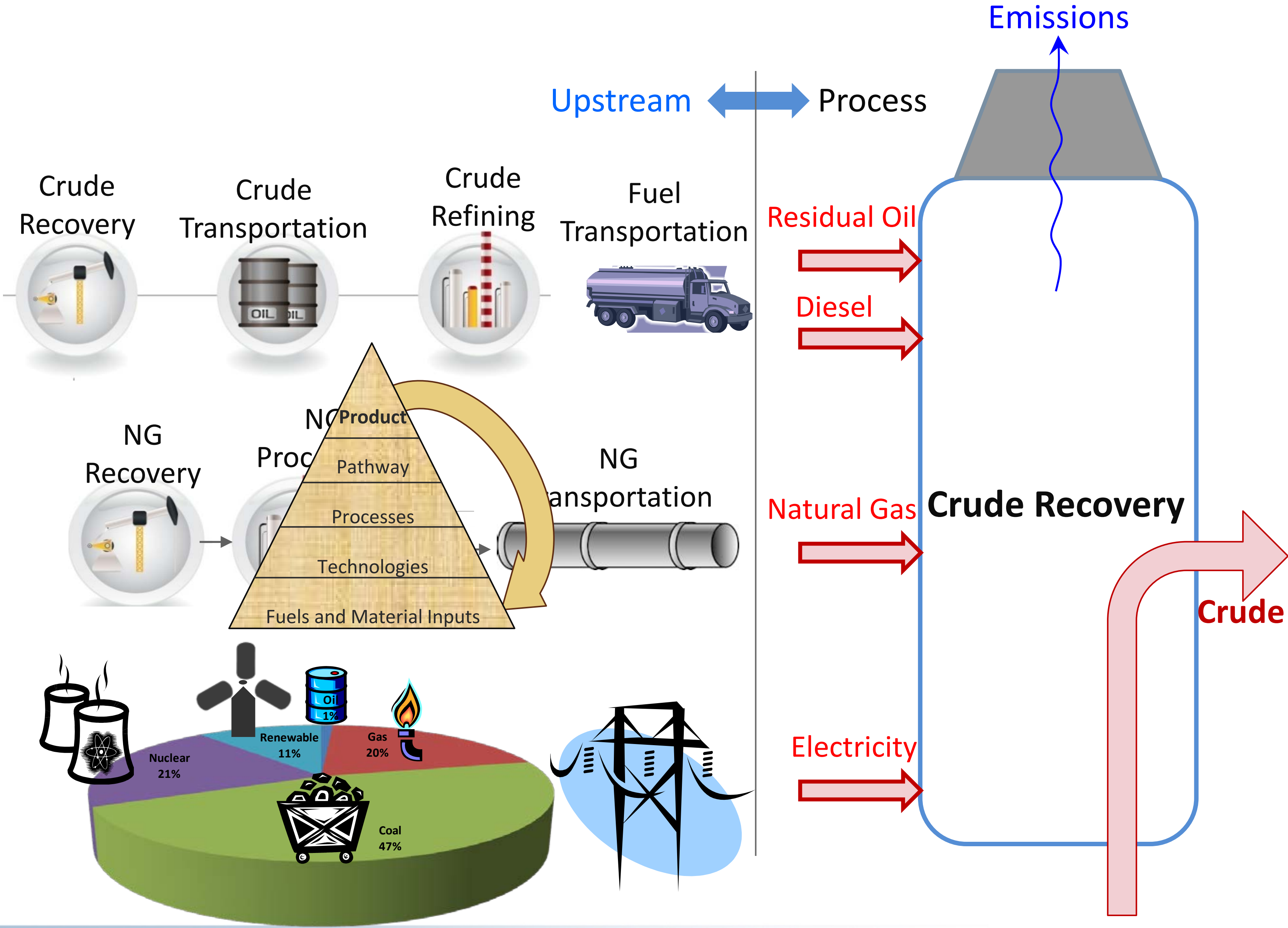
For Emissions:

- Define Technology share for each process fuel



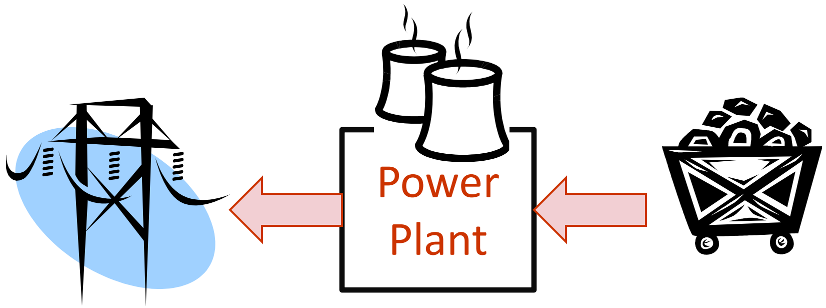


Example of Process + Upstream



Process Energy I/O Definition in GREET

1. **Efficiency**

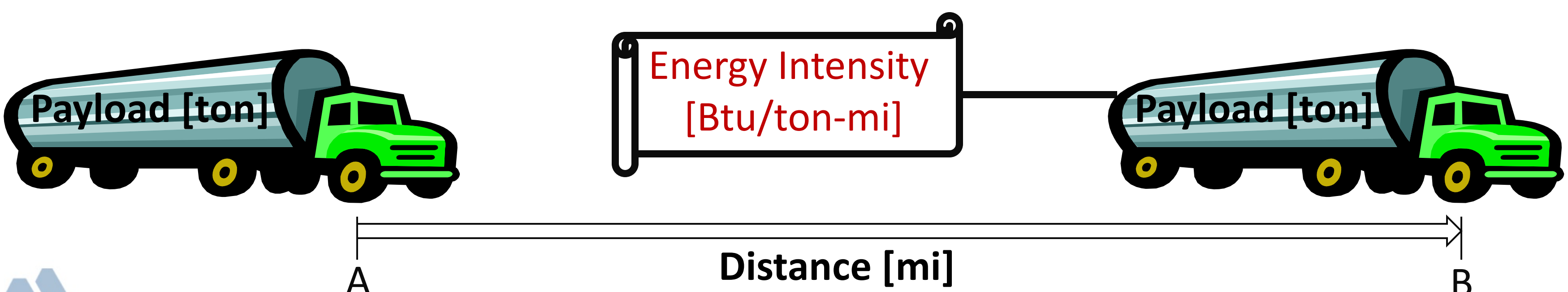


Example: Electric energy (output) per fuel energy (input)

2. **Yield**

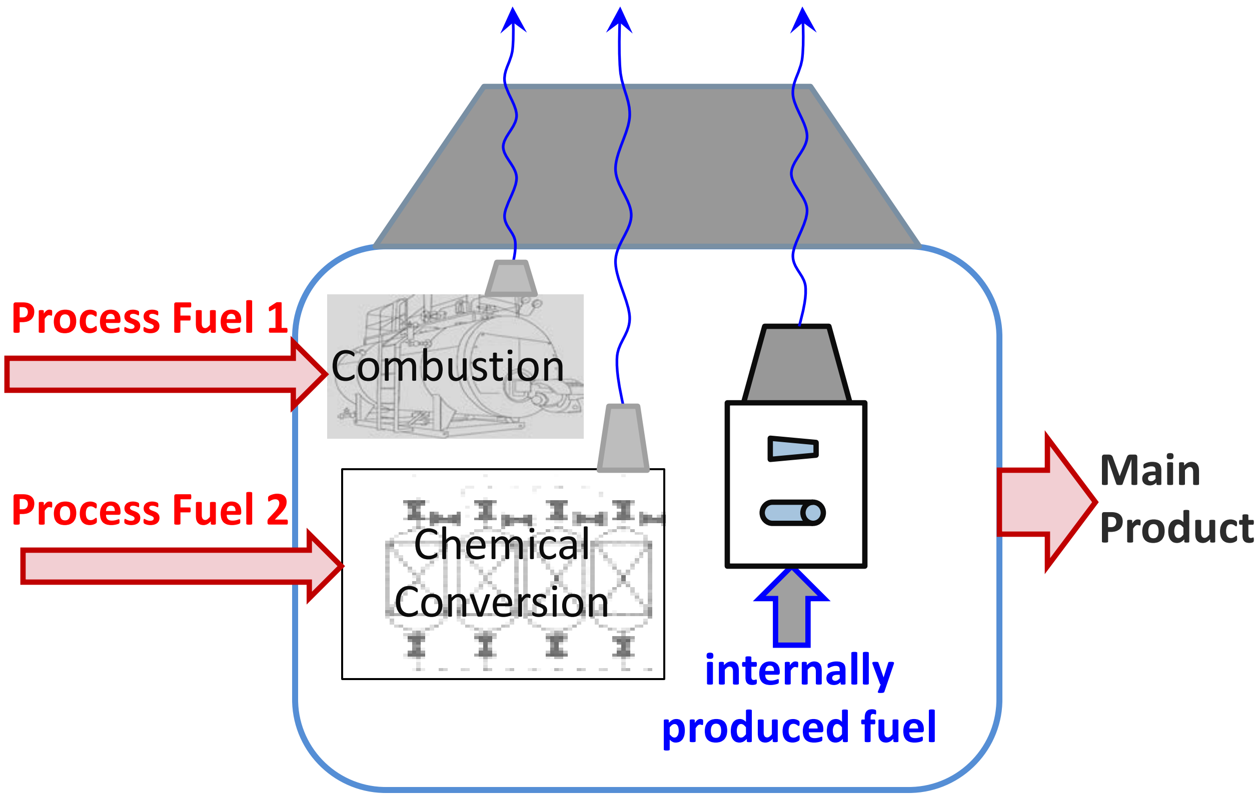
Example: Gallons of Ethanol (output) per Bushel of Corn (input)

3. **Energy intensity . Payload . Transportation distance**



Three Categories of Process Emissions in GREET

1. Combustion emissions (e.g., engines, boilers, turbines, etc.)
2. Non-combustion emissions (e.g., SMR, GTL, etc.)
3. Other emissions (from internally produced fuels)

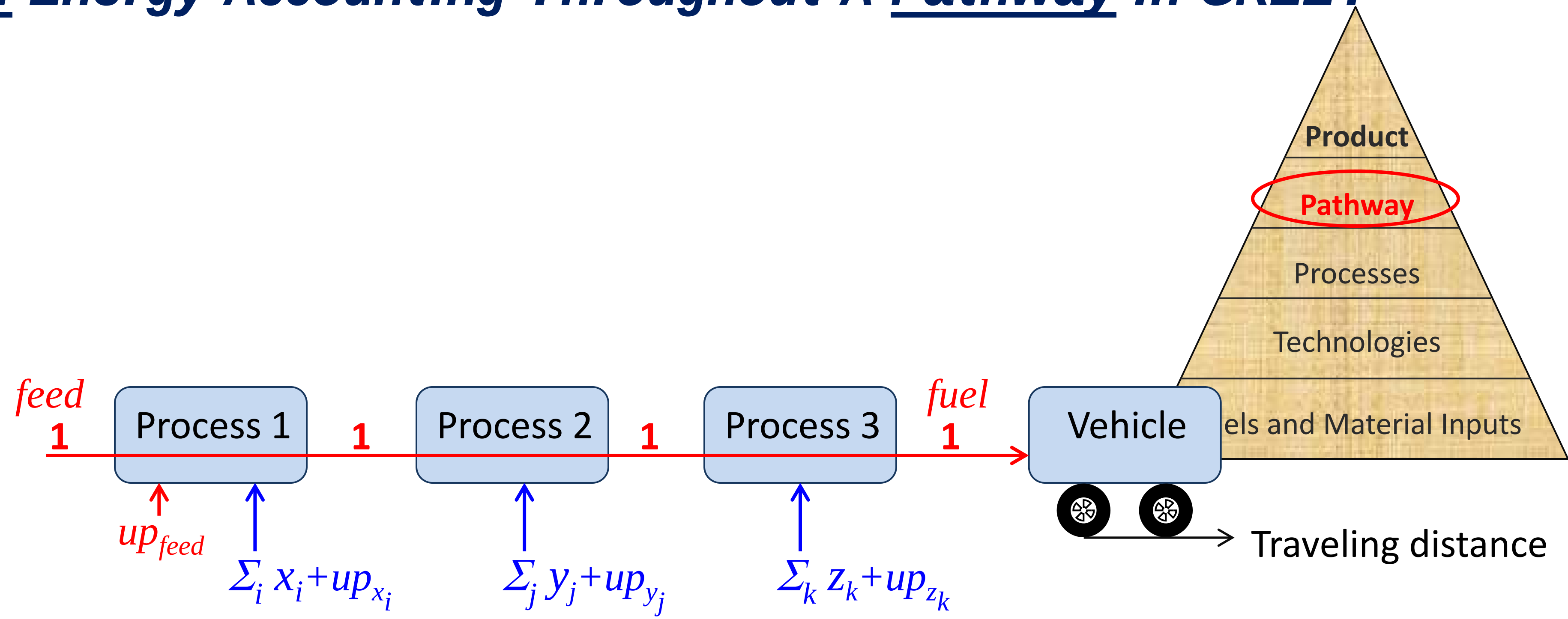


Process Related Parameters in GREET

- Input / output relation (e.g., efficiency, yield, energy intensity, etc.)
- Co-product amount (e.g., steam, electricity, etc.)
- Energy for carbon capture and sequestration (CCS)
- Market shares of feedstock or product (Petroleum/oil sands, CG/RFG, electricity generation mix, etc.)
- Technology shares (e.g., NG simple cycle / NG steam cycle / NG combined cycle, Dry mill / wet mill, etc.)

Process related parameters in GREET

IV. Energy Accounting Throughout A Pathway in GREET



Where:

- ✓ up_{feed} is upstream energy needed to produce **1** unit of feed
- ✓ x, y, and z are energy in process fuels or input materials
- ✓ up_{x_i} is upstream energy needed to produce x_i amount of fuel or material i

GREET Examines
More Than 80 Vehicle/Fuel Systems

Conventional Spark-Ignition Engine Vehicles

- Gasoline
- Compressed natural gas, liquefied natural gas, and liquefied petroleum gas
- Gaseous and liquid hydrogen
- Methanol and ethanol
- Renewable gasoline
- Pyrolysis-based gasoline

Spark-Ignition, Direct-Injection Engine Vehicles

- Gasoline
- Methanol and ethanol

Compression-Ignition, Direct-Injection Engine Vehicles

- Diesel
- Fischer-Tropsch diesel
- Dimethyl ether
- Biodiesel
- Renewable diesel
- Pyrolysis-based diesel

Fuel Cell Vehicles

- On-board hydrogen storage
  - Gaseous and liquid hydrogen from various sources
- On-board hydrocarbon reforming to hydrogen

Battery-Powered Electric Vehicles

- Various electricity generation sources

Hybrid Electric Vehicles (HEVs)

- Spark-ignition engines:
  - Gasoline
  - Compressed natural gas, liquefied natural gas, and liquefied petroleum gas
  - Gaseous and liquid hydrogen
  - Methanol and ethanol
- Compression-ignition engines
  - Diesel
  - Fischer-Tropsch diesel
  - Dimethyl ether
  - Biodiesel

Plug-in Hybrid Electric Vehicles (PHEVs)

- Spark-ignition engines:
  - Gasoline
  - Compressed natural gas, liquefied natural gas, and liquefied petroleum gas
  - Gaseous and liquid hydrogen
  - Methanol and ethanol
- Compression-ignition engines
  - Diesel
  - Fischer-Tropsch diesel
  - Dimethyl ether
  - Biodiesel
- Fuel cell
  - Gaseous and liquid hydrogen from various sources

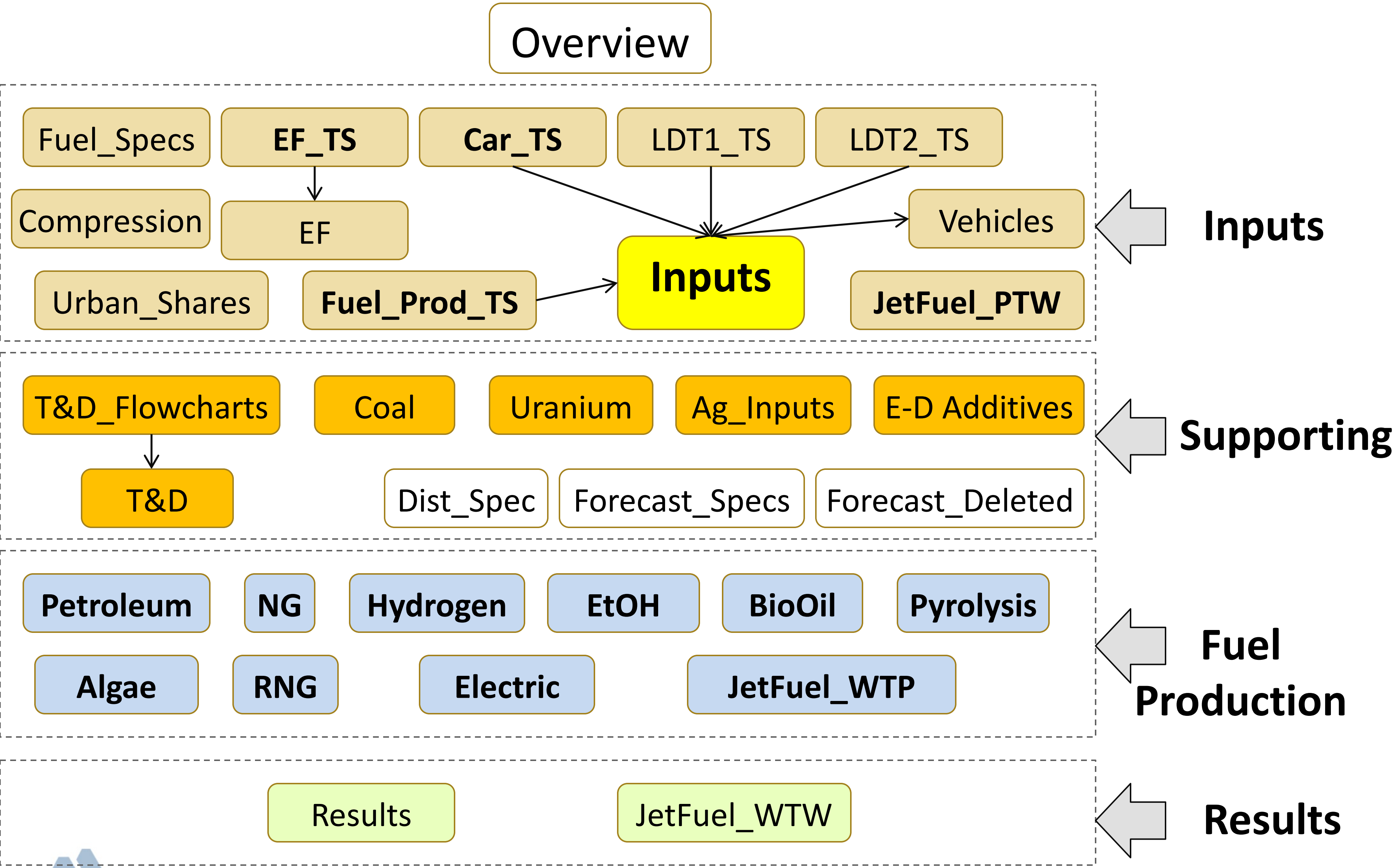
Light-Duty Vehicle Technologies

Vehicle Operation (PTW)

Sheets for Vehicle Fuel Economy in GREET

- Three Vehicle classes
  - Passenger cars
  - LDT1 (GVW < 6000 lb)
  - LDT2 (6000 lb < GVW <= 8500 lb)
- Fuel economy of various vehicle technologies
  - Adjusted for on-road performance
    - ✓ EPA (post 2008) mpg-based formulae
    - ✓ 43/57 City/HWY split
    - ✓ Special treatment for PHEVs
- Alternative vehicle’s fuel economy is relative to baseline gasoline ICEV
- Representative vehicle model year is five years older than simulation year

GREET1_2011 Consists of 34 Microsoft® Excel Sheets



Time-Series Tables are Designed in GREET1 to Reflect the Technology Advancement over Time

- GREET1 can simulate a target year or multiple years (through GUI) between 1990 and 2020

U.S. Mix: Stationary Use

5-year period	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Others
	1.0%	22.9%	46.4%	20.3%	0.2%	9.2%
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	**1.0%**	**22.9%**	**46.4%**	**20.3%**	**0.2%**	**9.2%**
2015	0.9%	21.5%	44.2%	21.0%	0.5%	11.8%
2020	0.9%	20.2%	45.1%	21.1%	0.9%	11.7%

- For any simulation year within the 5-year time interval, GREET uses a linear interpolation algorithm to calculate the estimate for that particular year

Results Sheet Show WTP and WTW

- The ***Well-to-Pump Energy Use and Emissions*** section presents energy and emission results from wells to refueling station pumps (in Btu or grams per mmBtu of fuel available at fuel pumps)

	1. Well-to-Pump Energy Consu	
2		
3		Baseline CG and RFG
4	Total Energy	231,640
5	WTP Efficiency	81.2%
6	Fossil Fuels	210,832
7	Coal	16,720
8	Natural Gas	121,405
9	Petroleum	72,707
10	CO2 (w/ C in VOC & CO)	16,249
11	CH4	132.599
12	N2O	1.124
13	GHGs	19,899
14	VOC: Total	27.488
15	CO: Total	12.550

- The ***Well-to-Wheels Energy Use and Emissions*** section calculates fuel-cycle energy use and emission rates for all vehicle/fuel system. Results are separated into three stages: feedstock, fuel, and vehicle operation.

29	Gasoline Vehicle: CG and RFG				
30		Btu/mile or grams/mile			
31	Item	Feedstock	Fuel	Vehicle Operation	Total
32	Total Energy	320	816	4,908	6,045
33	Fossil Fuels	313	722	4,806	5,841
34	Coal	35	47	0	82
35	Natural Gas	209	387	0	596
36	Petroleum	69	288	4,806	5,163
37	CO2 (w/ C in VOC & CO)	20	60	377	457
38	CH4	0.444	0.207	0.015	0.665
39	N2O	0.000	0.005	0.012	0.018
40	GHGs	31	67	381	478
41	VOC: Total	0.018	0.117	0.180	0.315
42	CO: Total	0.029	0.033	3.745	3.807
43	NOx: Total	0.135	0.099	0.141	0.375
44	PM10: Total	0.013	0.024	0.029	0.065
45	PM2.5: Total	0.008	0.011	0.015	0.034
46	SOx: Total	0.056	0.068	0.006	0.131

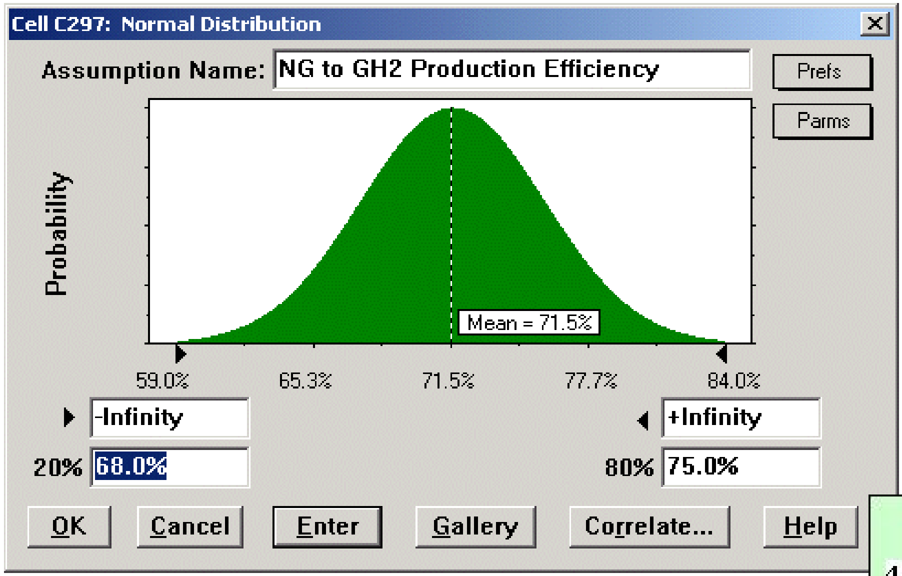
Results (Cont'd)

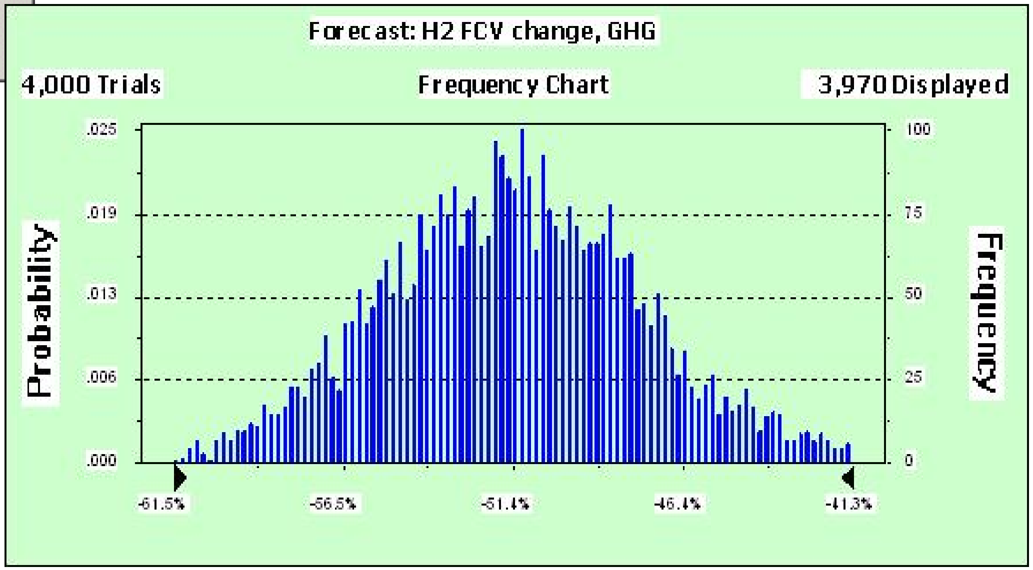
- The ***Well-to-Wheels Energy and Emission Changes*** section calculates changes in fuel-cycle energy use and emission rates for alternative-fueled vehicles relative to baseline gasoline vehicle.

	A	B	C	D
1828				
1829	**3. Well-to-Wheels Energy and Emission Changes (**			
1830		**GV: CARFG**	**GV: Low-Level EtOH Blend with Gasoline**	**Bi-Fuel CNGV on CNG, NA NG**
1831	Total Energy	-0.9%	4.2%	5.0%
1832	Fossil Fuels	-3.3%	-2.4%	7.8%
1833	Coal	0.9%	21.1%	191.8%
1834	Natural Gas	-14.0%	10.4%	910.9%
1835	Petroleum	-2.1%	-4.2%	-99.4%
1836	CO2 (w/ C in VOC & CO)	-3.3%	-1.9%	-16.4%
1837	CH4	-5.3%	2.0%	435.0%
1838	N2O	17.6%	52.2%	-26.1%
1839	GHGs	-3.1%	-1.1%	-0.8%
1840	VOC: Total	-0.1%	1.8%	-44.6%
1841	CO: Total	-0.2%	0.1%	-10.0%
1842	NOx: Total	-11.8%	2.5%	-18.5%
1843	PM10: Total	-1.6%	9.4%	14.4%
1844	PM2.5: Total	-5.1%	4.8%	-15.8%
1845	SOx: Total	-13.7%	5.4%	2.2%
1846	VOC: Urban	2.3%	-0.2%	-53.6%
1847	CO: Urban	0.2%	0.0%	-10.4%
1848	NOx: Urban	7.4%	-0.8%	-23.8%
1849	PM10: Urban	10.4%	-1.1%	-28.3%
1850	PM2.5: Urban	10.3%	-1.2%	-31.1%
1851	SOx: Urban	21.4%	-2.7%	-61.6%

GREET Incorporates Stochastic Simulations to Address Uncertainties

Distribution-Based Inputs Generate Distribution-Based Outputs





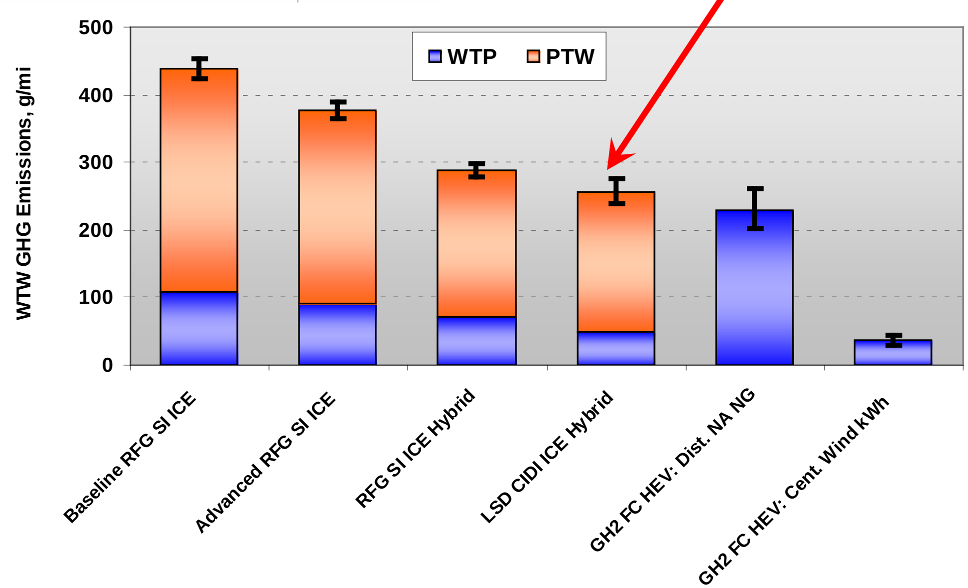
Statistically Analyzing the Outputs after Each Stochastic Simulation Run Is Required

Step 1: the stochastic simulate tool will automatically generate the results for each sample after the run is completed .

	A	B	C	D	E
1		EV-Electricity-WTW-Total Energy	EV-Electricity-WTW-Fossil Fuels	EV-Electricity-WTW-Petroleum	EV-Electricity-
2		3321.399464	2903.273558	104.0725773	
3		3163.628235	2765.352496	99.08984517	
4		3079.852945	2692.116244	96.43835883	
5		3238.052196	2830.417478	101.4902298	
6		3140.147283	2744.825733	98.35458792	
7		3043.772242	2660.582457	95.3074409	
8		3200.222875	2797.343163	100.2726682	
9		3116.192323	2723.887281	97.57959977	
10		2986.787116	2610.767386	93.50614537	
11		3171.191209	2771.966214	99.33162812	
12					
13	Mean	3146.124589	2750.053201		
14	S.D.	96.73637538	84.56405135		
15	P0	2986.787116	2610.767386		
16	P10	3038.07373	2655.60095		
17	P20	3072.636804	2685.809487		
18	P30	3105.290509	2714.35597		
19	P40	3130.565299	2736.450352		
20	P50	3151.887759	2755.089115		
21	P60	3166.653425	2767.997983		
22	P70		2779.579299		
23	P80		2803.958026		
24	P90		2837.703086		
25	P100		2903.273558		
26					
27					
28					

Step 2: the stochastic simulate tool will automatically generate the statistical results, e.g., mean value, standard deviation, P50, etc., to summarize the observation of all samples.

Step 3: with the statistical results, the user may manually draw graphs (e.g., the uncertainty range between the P10 and P90 values in the demo chart below).



Questions?

Loading the Stochastic Simulation Tool into GREET