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

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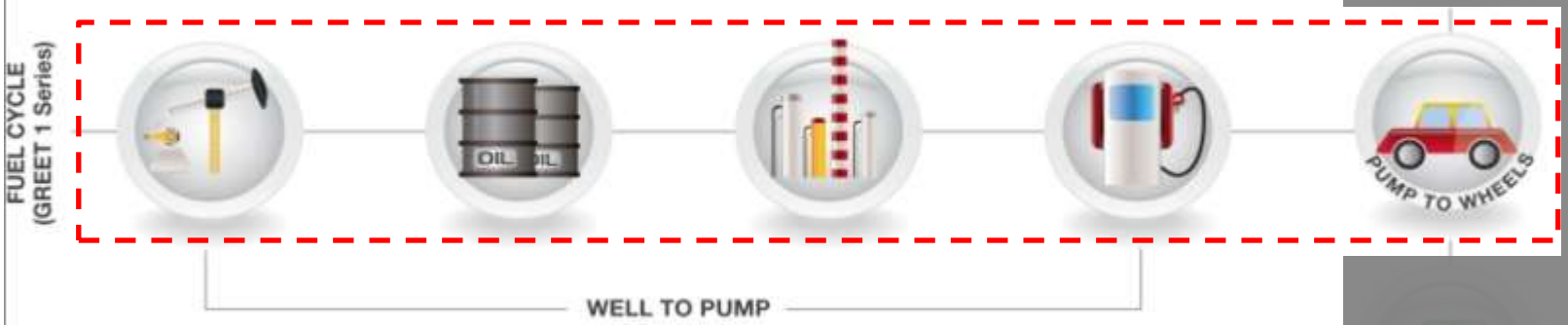
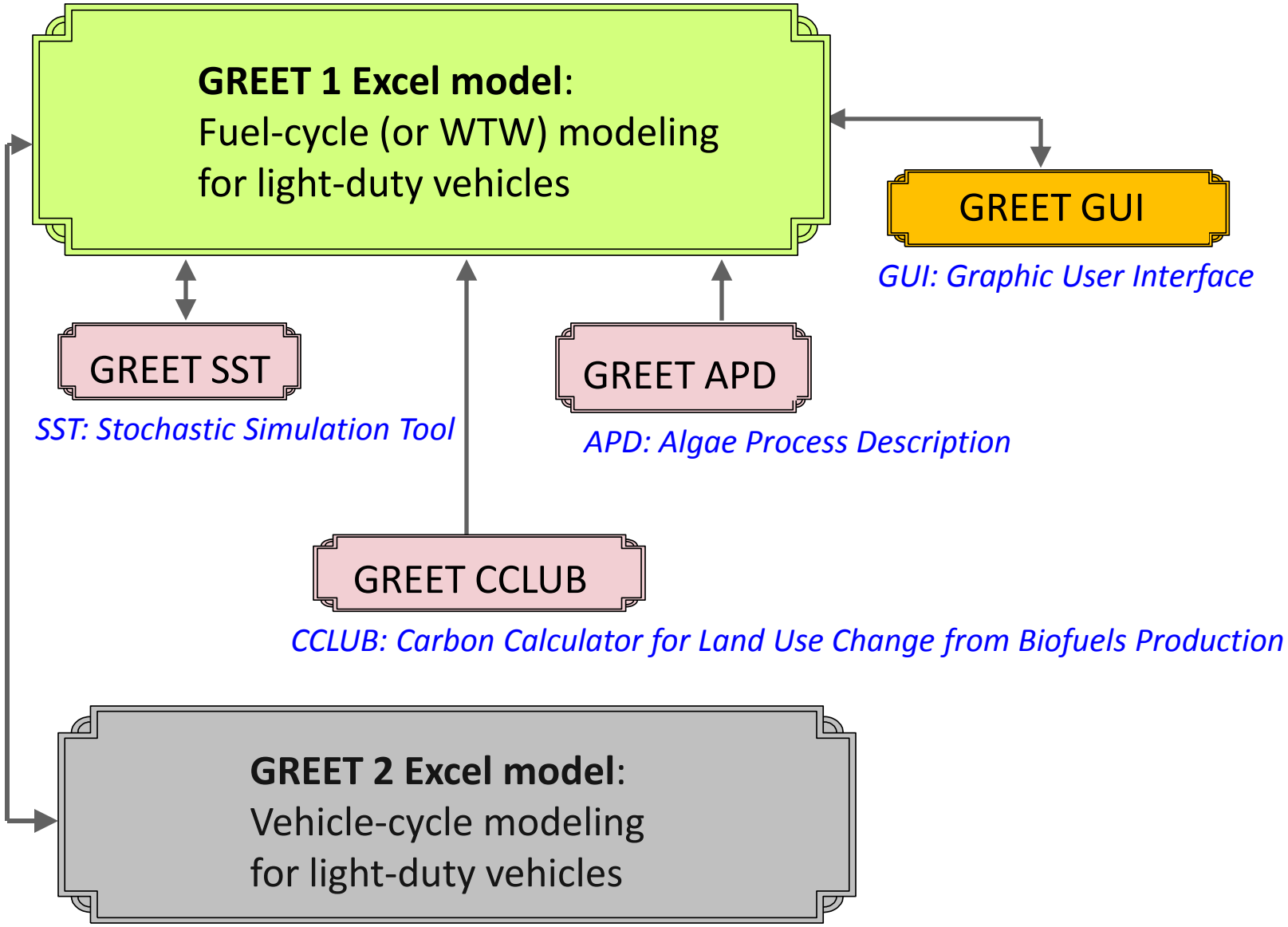
The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) Model



The Suite of GREET Models



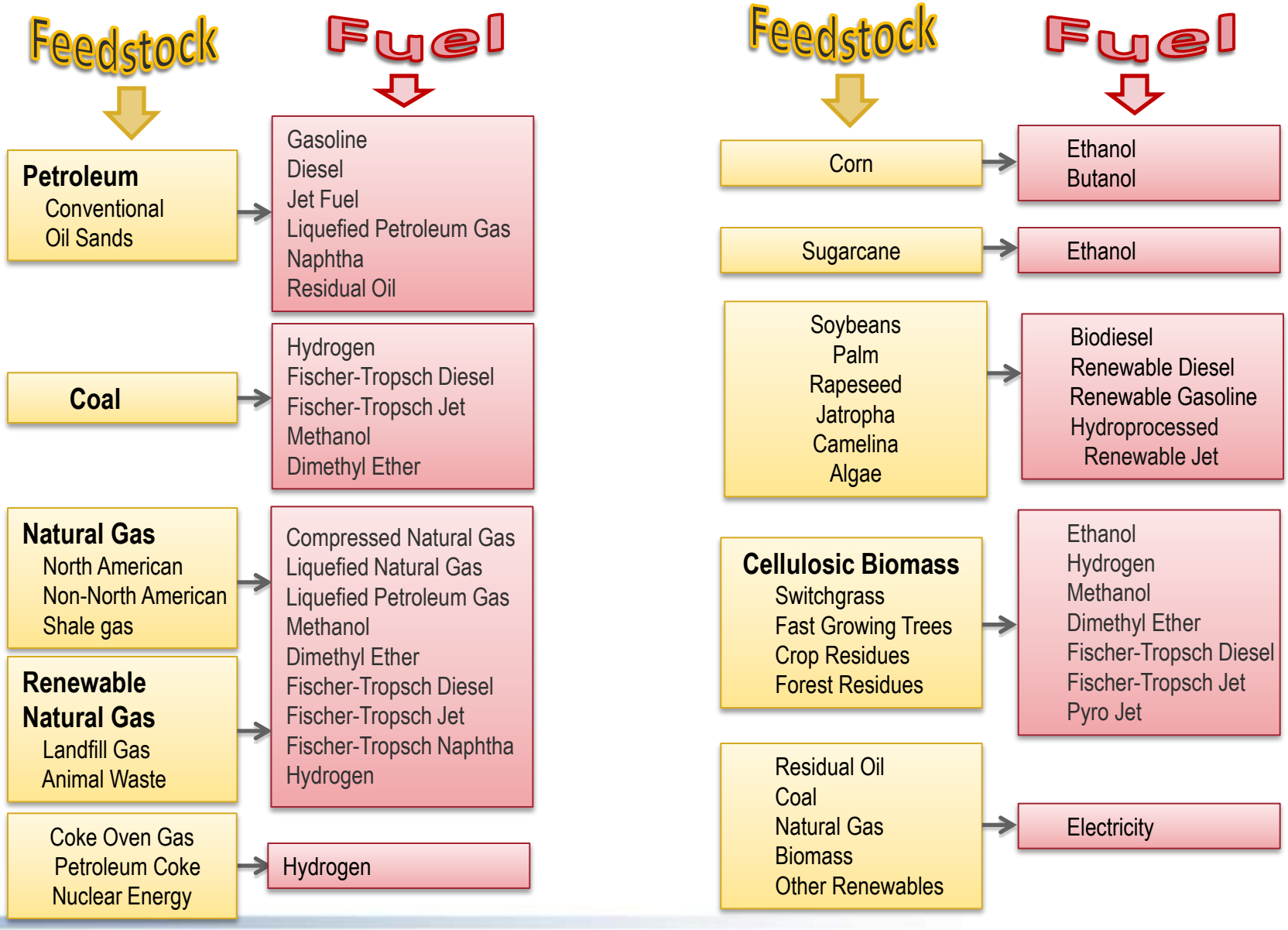
GREET Covers Emissions and Energy Use

- GREET includes emissions of **greenhouse** gases (GHGs)
  - **CO2**, **CH4** (GWP=25), and **N2O** (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

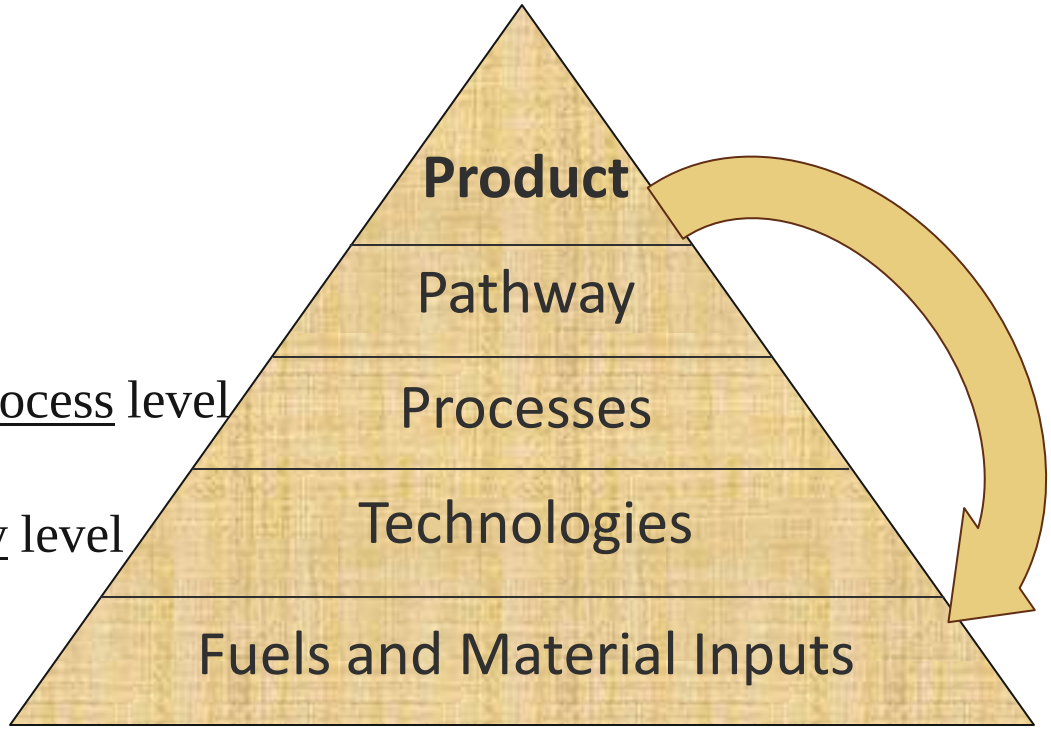


A Process is The Building Block of a Pathway in GREET

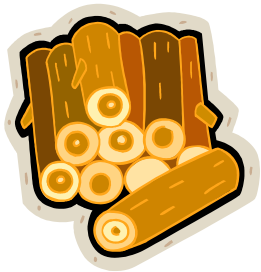
- A process employs technologies
- Technologies employ fuels and may produce emissions

Energy is defined at process level

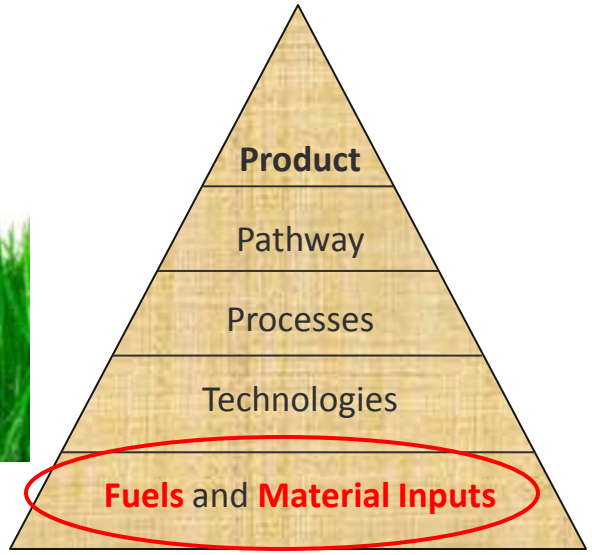
Emissions are defined at technology level



I. Fuels and Material Inputs:



Biomass



Fuels

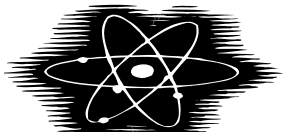
EF / Fuel_Specs / T&D_Fl

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

Electricity

um / Electric / C

Nuclear



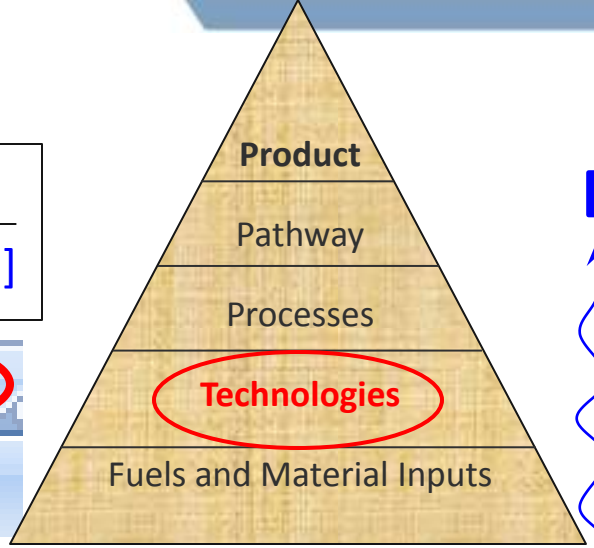
Uranium

Fertilizers

Ag_Inputs

II. Technologies (Combustion)

Emissions Factor (EF_i) = Emissions of species i [g] / Unit of Fuel used [mmBtu]

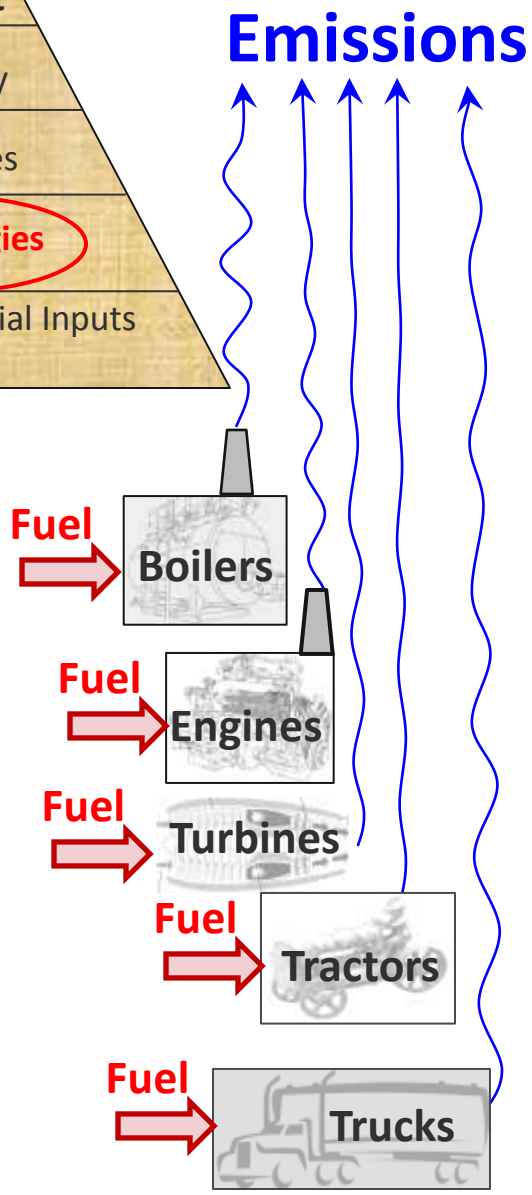


Species vector include:

- **CH4** and **N2O**
- VOC, CO, NOx, PM10, and PM2.5
- EF may include SOx (if emissions control on sulfur)

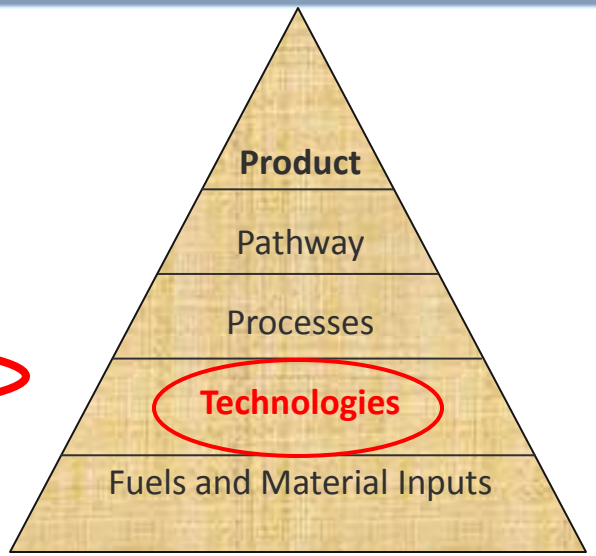
Important Notes:

- **CO2** 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)

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

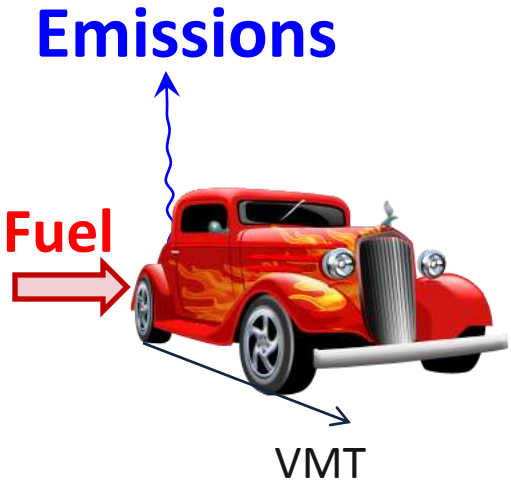


Species vector include:

- **CH4** and **N2O**
- VOC, CO, NOx, PM10, and PM2.5

Important Notes:

- **CO2** 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)



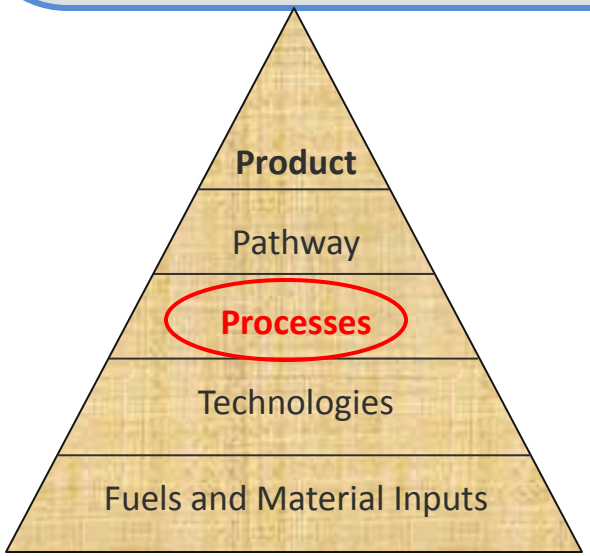
III. Processes (The Building Blocks of Pathways)

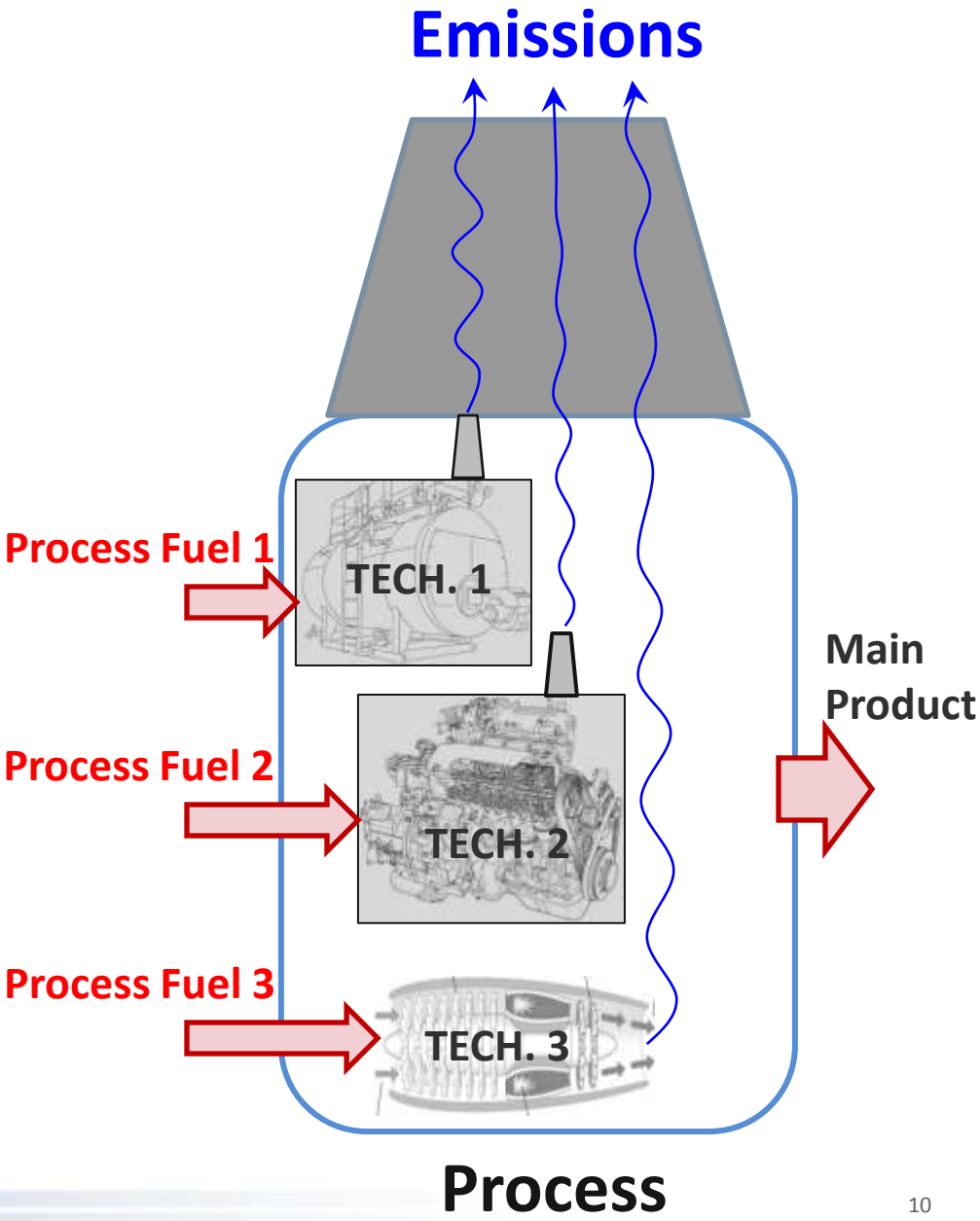
For Energy:

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

For Emissions:

- Define Technology share for each process fuel





Example of Process Definition and Calculations in GREET

(a) Energy Accounting:

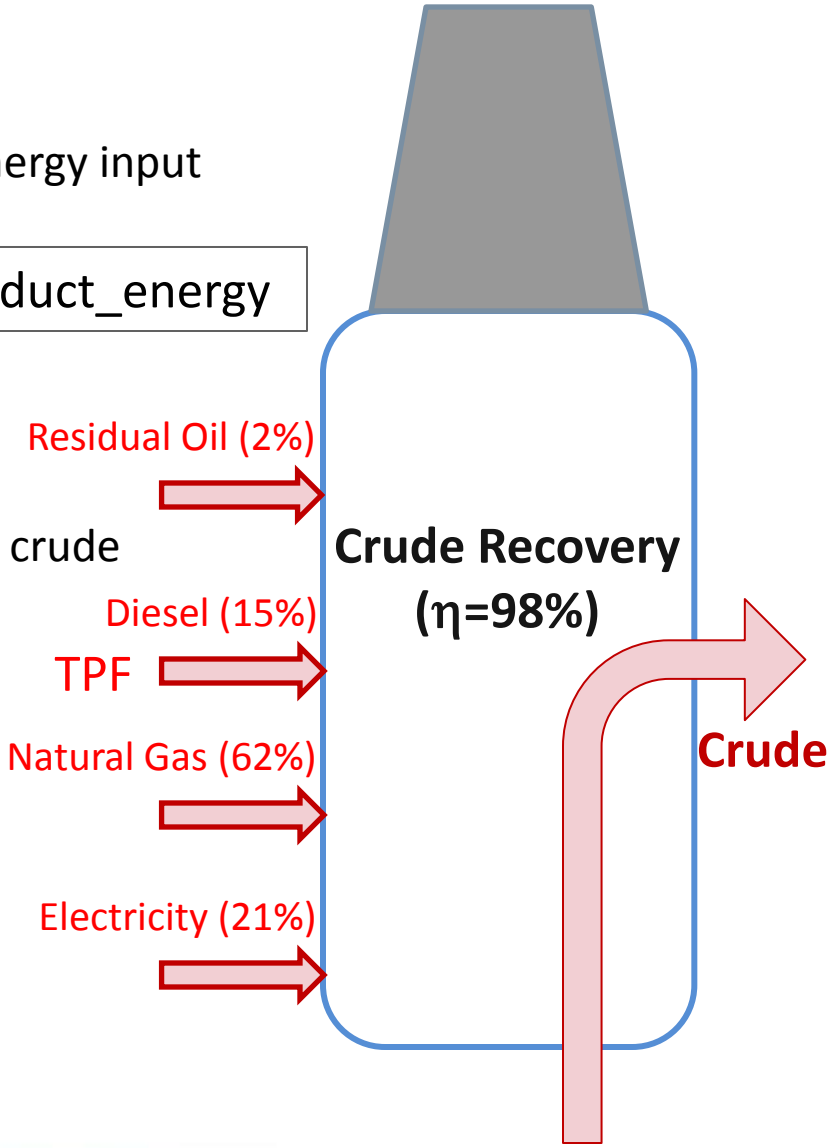
- Define output-input relation
  - ➢ Efficiency (η) = 98% = energy in product/ all energy input

Total Process Fuel used (TPF) = [(1/η) – 1] x product_energy

- ➢ TPF = [(1/0.98) – 1] x 1 mmBtu
  - = 20,408 Btu
  - = total process fuel to recover 1 mmBtu of crude

- Define Process Fuel Share
  - ➢ 2% Residual Oil
  - ➢ 15% Diesel
  - ➢ 62% NG
  - ➢ 21% Electricity

→ Residual oil = 0.02 x 20,408 = 408 Btu
→ Diesel = 0.15 x 20,408 = 3,061 Btu
etc.



Example of Process Definition and Calculations in GREET

(b) Emissions Accounting:

- Define Technology share for each process fuel
  - Residual Oil → 100% Boiler
  - Diesel → 75% Engine, 25% Turbine
  - NG → 50% Boiler, 50% Engine
  - Electricity → Emissions free (at point of use)

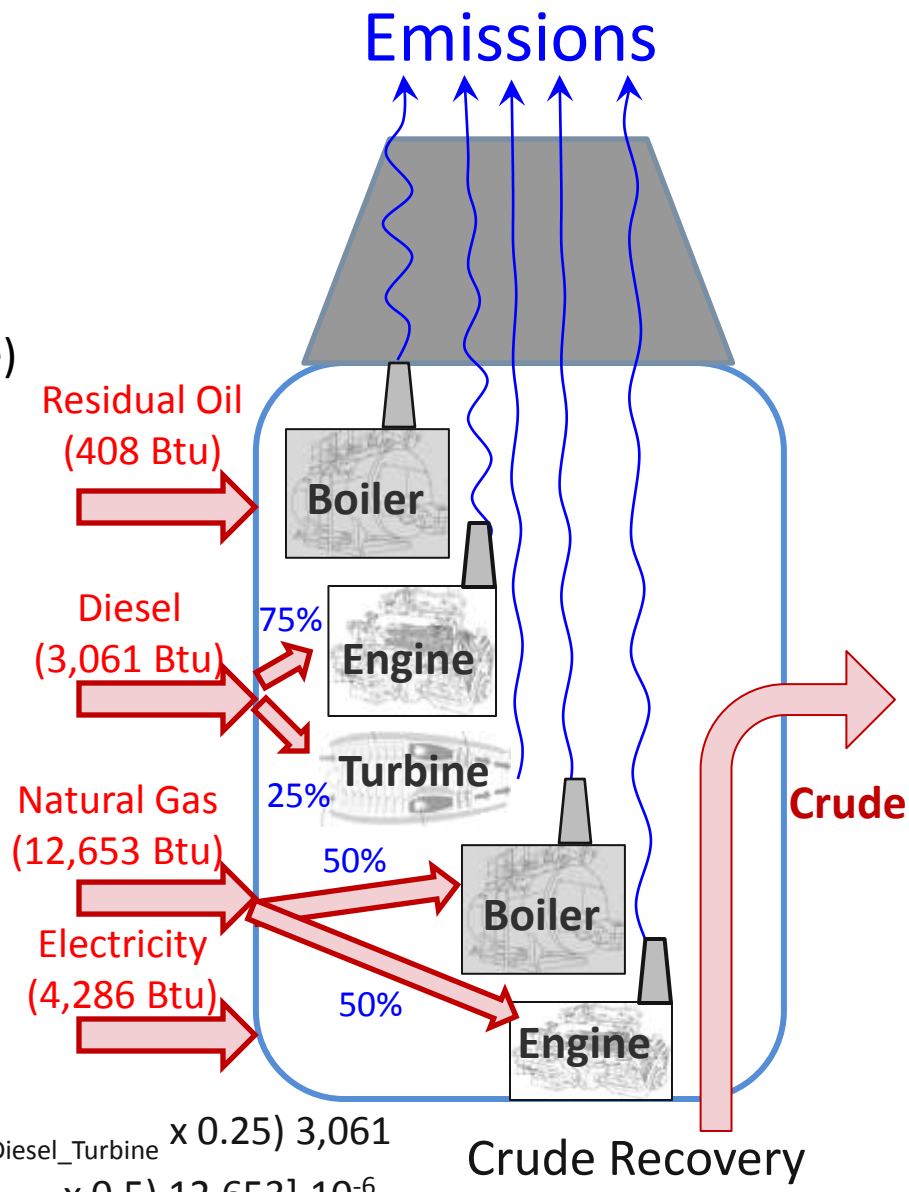
$$E_i = \Sigma_j [\Sigma_k EF_i(j, k) \cdot PF(j) \cdot Share(j,k)]$$

Where:

E_i = Total process emissions of pollutant i

$EF_i(j, k)$ = Emissions Factor of pollutant i when fuel j is used in technology k

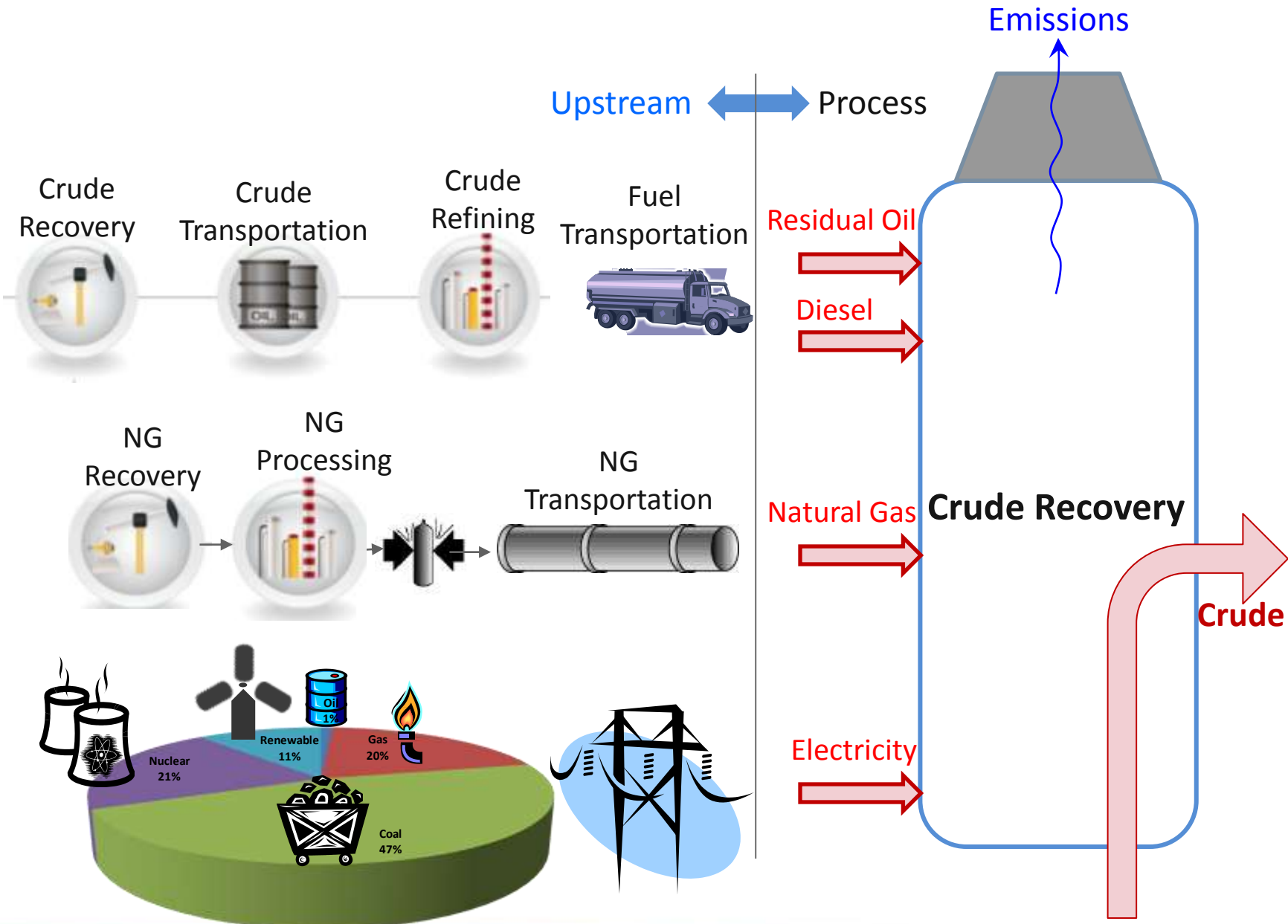
Share (j,k) = Share of fuel j used in technology k



Example:

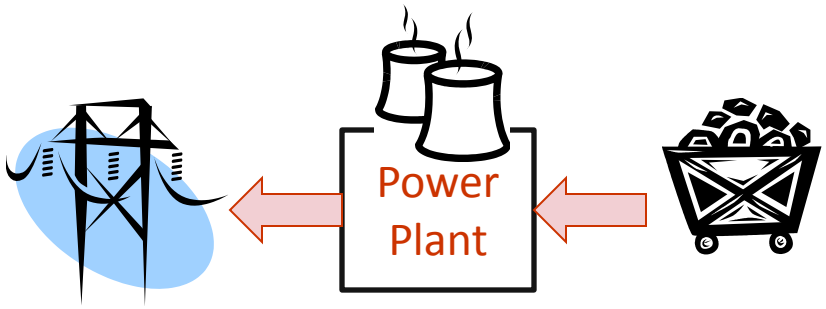
$$E_{co} = [EF_{CO,RO\_Boiler} \times 1 \times 408 + (EF_{CO,Diesel\_Engine} \times 0.75 + EF_{CO,Diesel\_Turbine} \times 0.25)\ 3{,}061 + (EF_{CO,NG\_Boiler} \times 0.5 + EF_{CO,NG\_Engine} \times 0.5)\ 12{,}653]\ 10^{-6}$$

Example of Process + Upstream



Process Energy I/O Definition in GREET

1. **Efficiency**

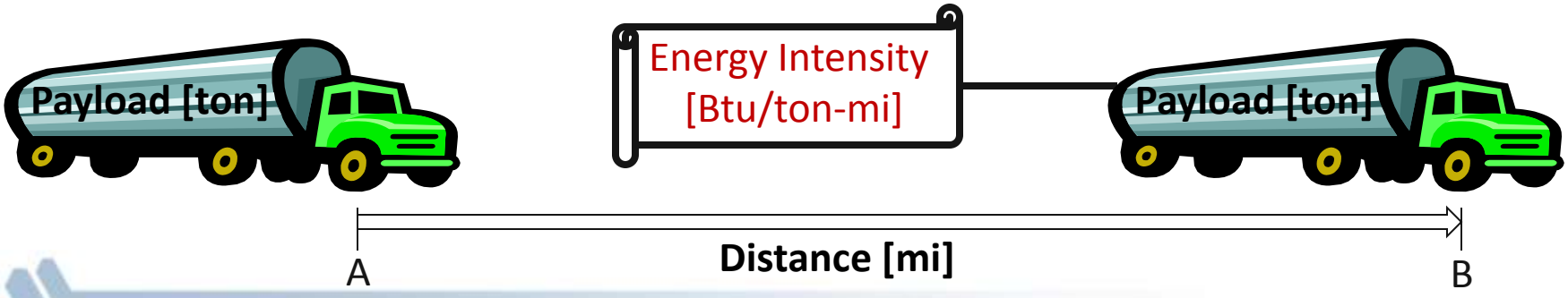


Example: Electric energy (output) per fuel energy (input)

2. **Yield**

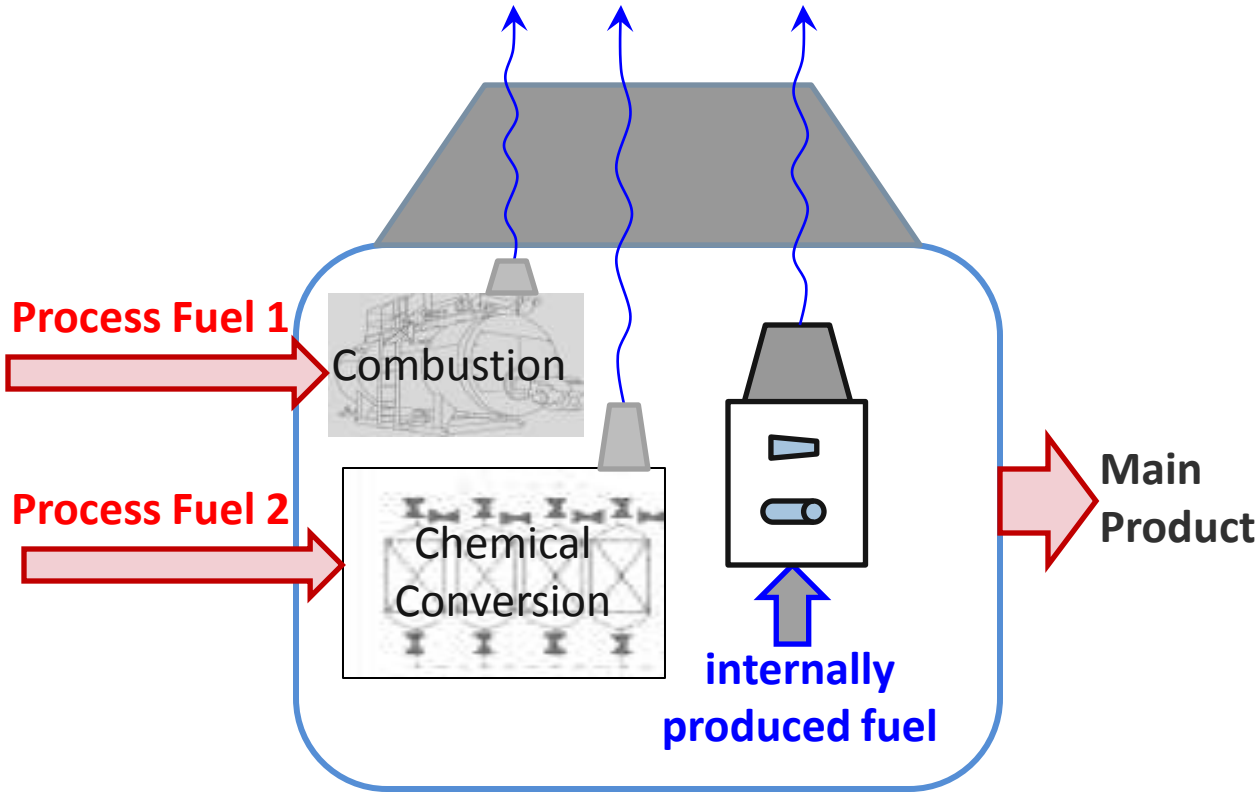
Example: Gallons of Ethanol (output) per Bushel of Corn (input)

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



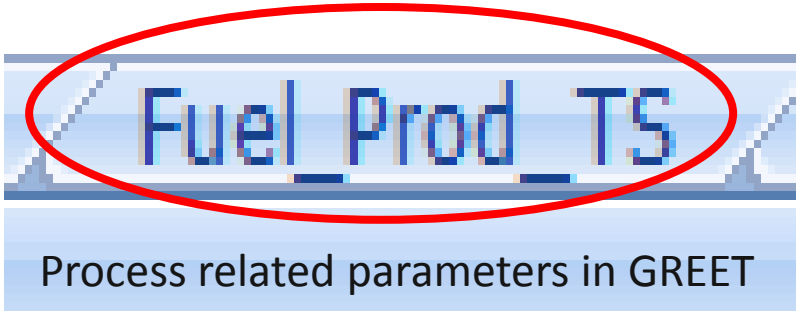
Three Categories of Process Emissions in GREET

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)



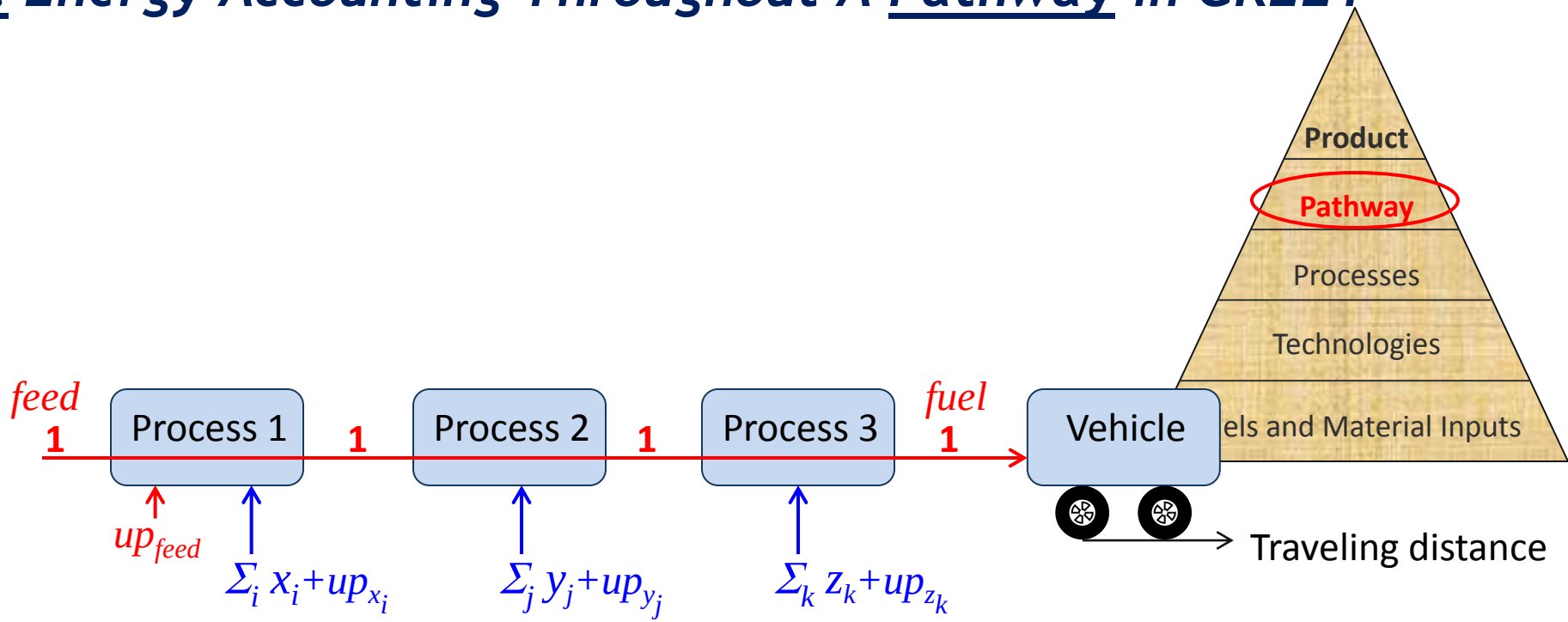
Process Related Parameters in GREET

- 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:

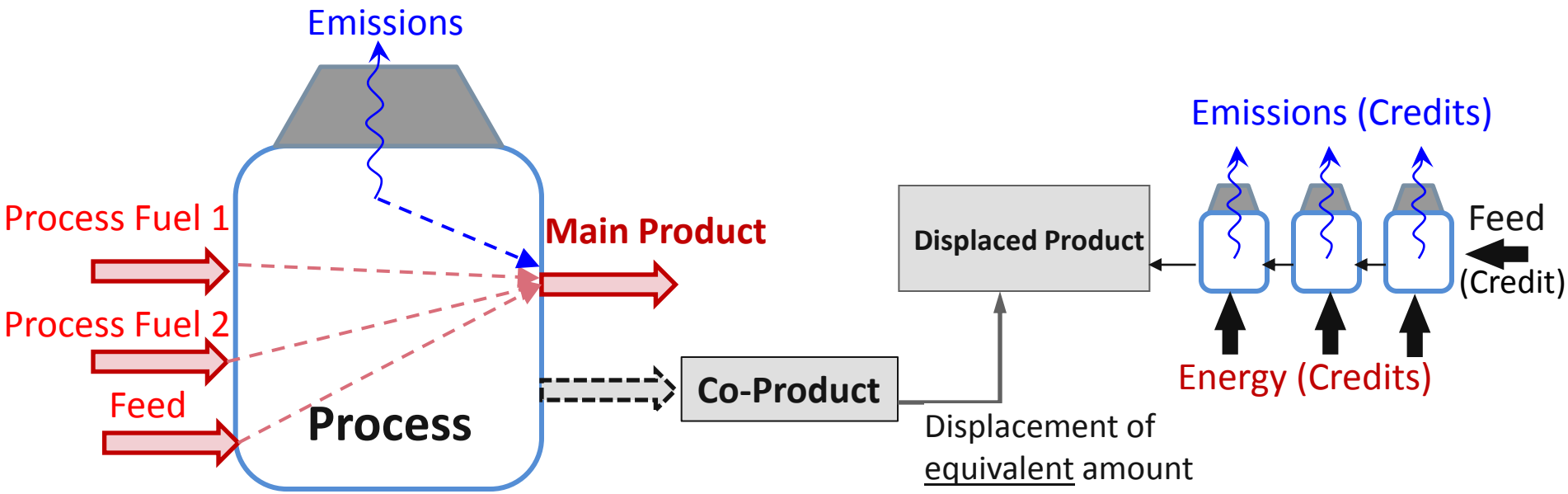
- ✓ up_{feed} is upstream energy needed to produce **1** unit of feed
- ✓ x, y, and z are energy in process fuels or input materials
- ✓ up_{x_i} is upstream energy needed to produce x_i amount of fuel or material i

Process Co-Products Handling Methodology in GREET

Several methods are implemented in GREET:

- Displacement (of equivalent product)
- Allocation
  - ✓ Energy-based
  - ✓ Mass-based
  - ✓ Market value-based
- Hybrid

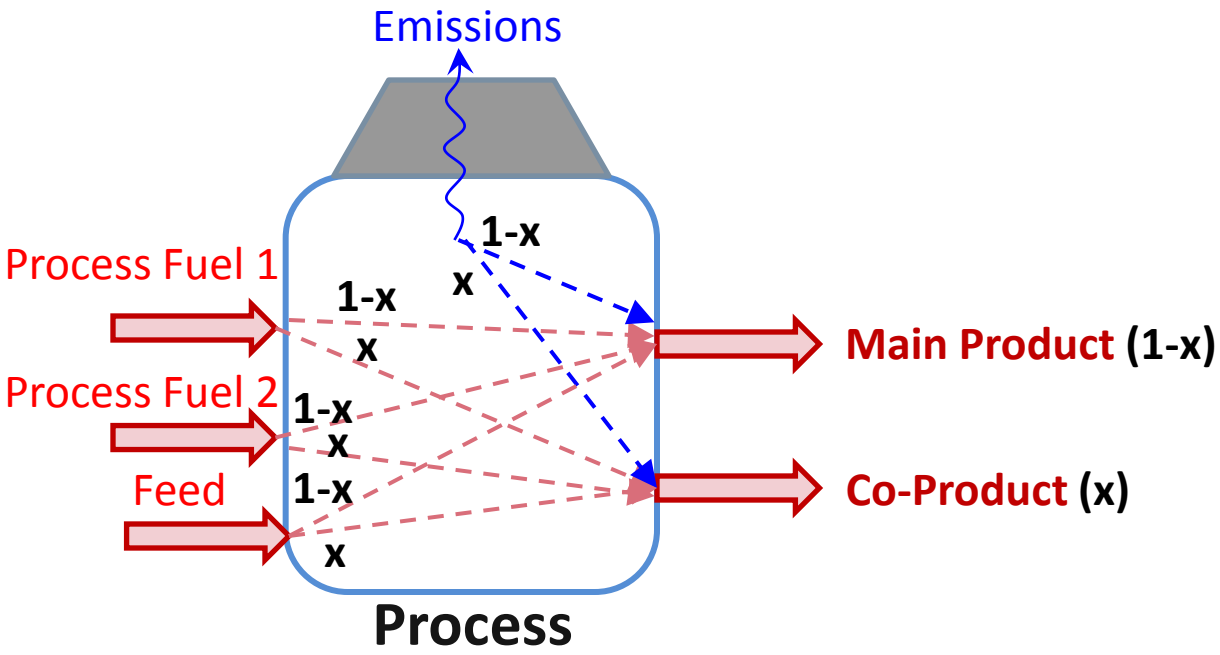
Co-Product Displacement of Equivalent Product



Important Notes:

- Main product carry the burden of all process energy and emissions
- Co-product does not carry any burden
- Displaced product is identical or equivalent to co-product
  - ✓ If not identical, a displacement ratio may apply
- All life-cycle energy and emissions of the displaced product are credited to main product
- For large co-product/main product ratio, credits may overwhelm main process emissions

Allocation of Process Energy and Emissions to Co-Products



Important Notes:

- **x** is the ratio of co-product in all products by mass, energy, or market value
- Main product and co-product carry energy and emissions burden based on their ratios in the total products
- The main product and co-product are equivalent (function at end use, quality, etc.)
- Same process efficiency applies to all products for energy allocation (implied)

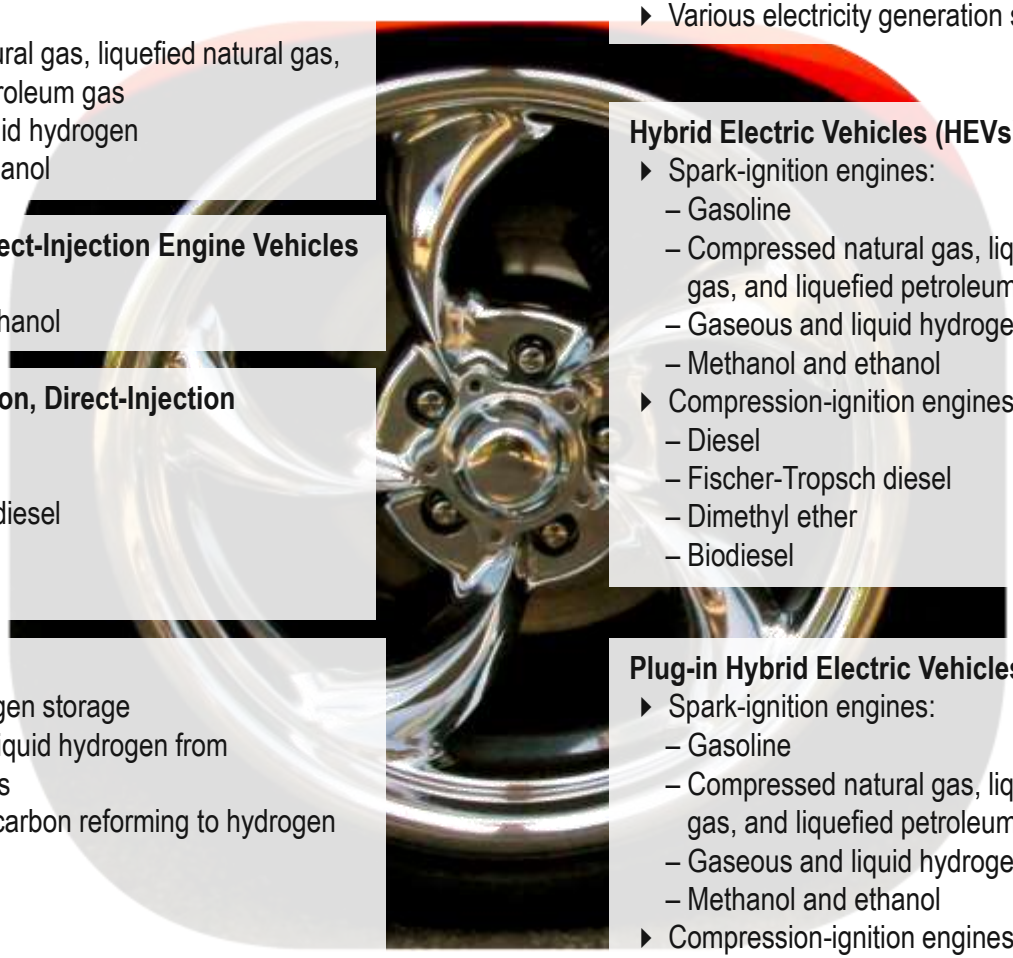
GREET Examines More Than 80 Vehicle/Fuel Systems

Conventional Spark-Ignition Engine Vehicles
- Gasoline
- Compressed natural gas, liquefied natural gas, and liquefied petroleum gas
- Gaseous and liquid hydrogen
- Methanol and ethanol

Spark-Ignition, Direct-Injection Engine Vehicles
- Gasoline
- Methanol and ethanol

Compression-Ignition, Direct-Injection Engine Vehicles
- Diesel
- Fischer-Tropsch diesel
- Dimethyl ether
- Biodiesel

Fuel Cell Vehicles
- On-board hydrogen storage
  - Gaseous and liquid hydrogen from various sources
- On-board hydrocarbon reforming to hydrogen
  - Methanol
  - Ethanol
  - Gasoline
  - Naphtha
  - Compressed natural gas, liquefied natural gas, and liquefied petroleum gas
  - Diesel



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

Light-Duty Vehicle Technologies

Vehicle Operation (PTW)

- 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

Questions?