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Introduction to GREET1.8 Excel Model

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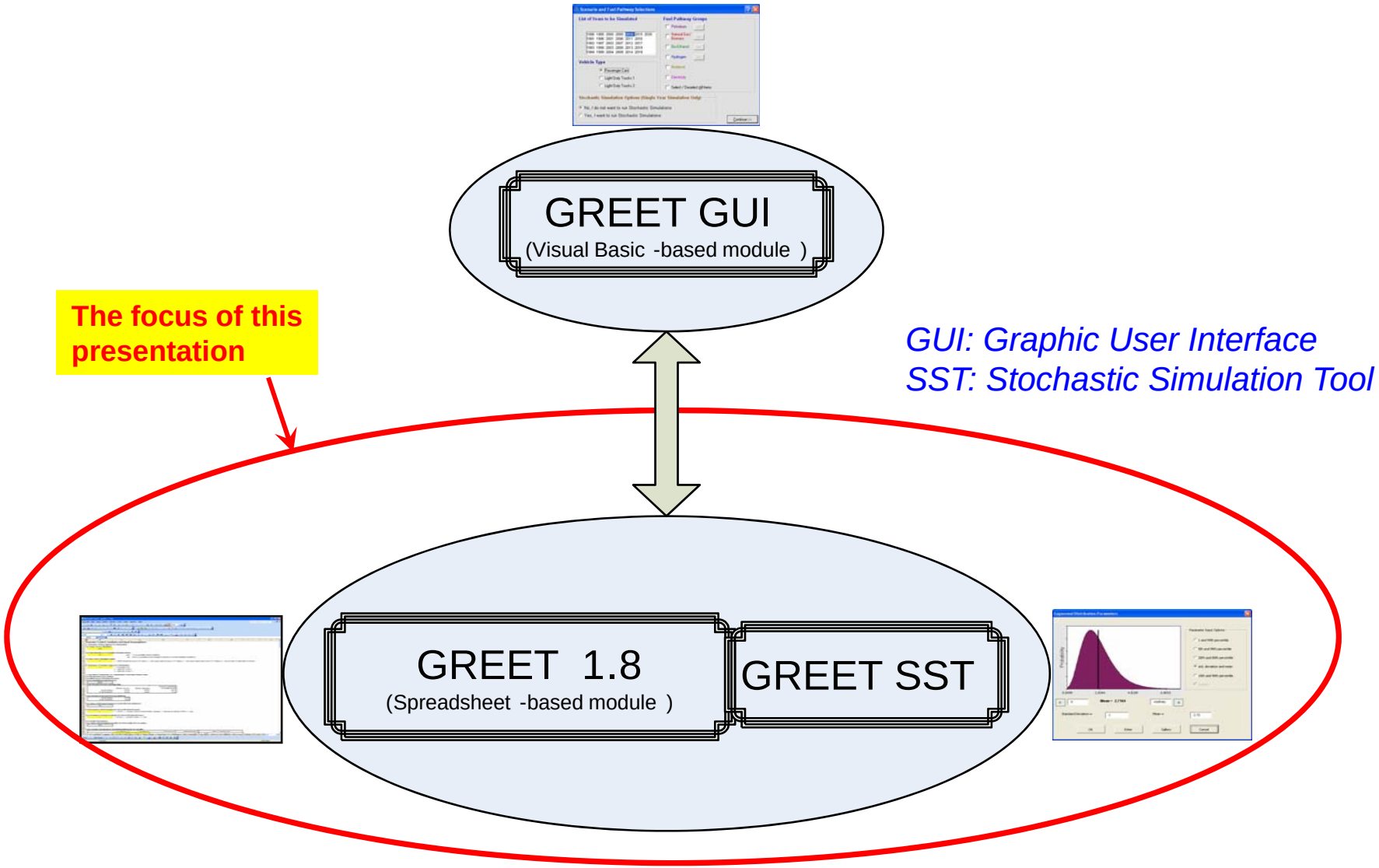
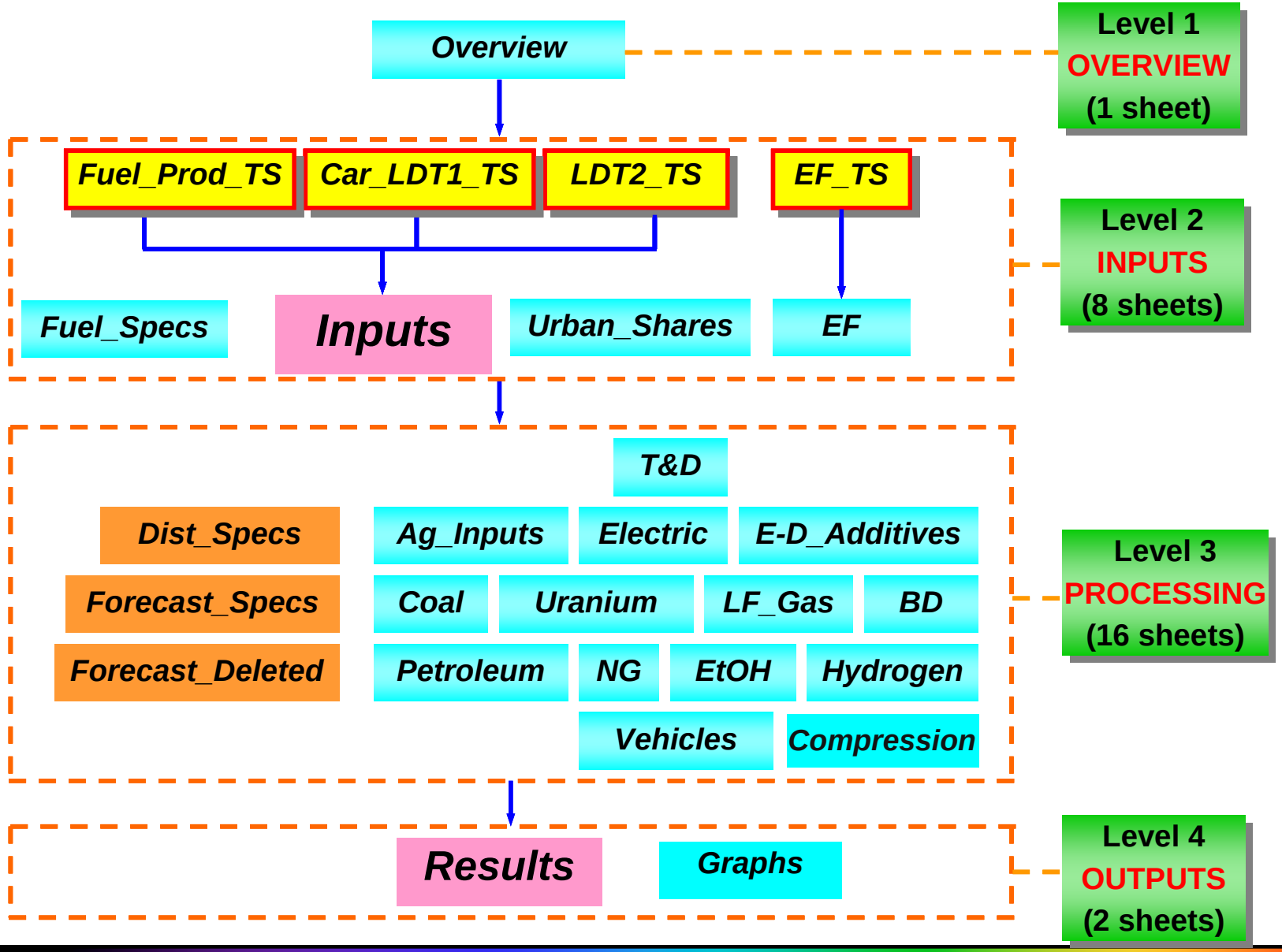
The Most Recent GREET 1.8 Model Includes 3 Modules



GREET1.8 Consists of 28 Microsoft® Excel Sheets



Brief Description of 28 Sheets in GREET1.8

- *Overview*: GREET copyright statement. It also presents a brief summary of each worksheet in GREET and is intended to provide brief introduction to the functions of each sheet.
- *Inputs*: Key input parameters that users can specify for GREET simulations. If users use the GREET GUI program, the GUI input values interact mostly with values in this sheet.
- *EF_TS*: Time-series tables for emission factors of combustion technologies applied to stationary sources.
- *EF*: Emission factors of combustion technologies by fuel type. This sheet interacts with EF_TS sheet.
- *Fuel_Specs*: Specifications (e.g., heating value, density, etc.) of individual fuels and global warming potentials of GHGs.
- *T&D*: Calculations of energy use and emissions for transportation and distribution of energy feedstocks and fuels.
- *Urban_Shares*: Share of urban emissions out of total emissions of criteria pollutants for major GREET simulated activities.
- *Fuel_Prod_TS*: Time-series tables for key parametric assumptions for well-to-pump fuel production processes. This sheet interacts with Inputs and other fuel production sheets.
- *Petroleum*: Calculations of well-to-pump energy use and emissions for petroleum-based fuels (including production of oxygenates).

Brief Description of 28 Sheets in GREET1.8 (Cont'd.)

- *NG*: Calculations of well-to-pump energy use and emissions for NG-based fuels (plus flared gas to liquid fuels; landfill gas to methanol; and biomass to methanol, DME, and FT fuels).
- *Hydrogen*: Calculations of well-to-pump energy use and emissions for hydrogen production pathways.
- *Ag_Inputs*: Calculations of energy use and emissions for manufacturing agricutural inputs including fertilizers, herbicides, and insecticides.
- *EtOH*: Calculations of well-to-pump energy use and emissions for producing ethanol from corn and cellulosic biomass.
- *E-D_Additives*: Calculations of well-to-pump energy use and emissions for additives to blend ethanol in diesel fuel.
- *BD*: Calculations of well-to-pump energy use and emissions for biodiesel from soybeans.
- *Coal*: Calculations of energy use and emissions for coal mining.
- *Uranium*: Calculations of energy use and emissions for uranium ore mining and uranium fuel production.
- *LF_Gas*: Calculations of energy use and emissions for landfill gas recovery.
- *Compression*: Calculations of energy and efficiency of compression processes.

Brief Description of 28 Sheets in GREET1.8 (Cont'd.)

- *Electric*: Calculations of energy use and emissions for electricity generation.
- *Car_LDT1_TS*: Time-series tables of fuel economy and emission rates/changes associated with vehicle operations for passenger cars and light duty truck 1.
- *LDT2_TS*: Time-series tables of fuel economy and emission rates/changes associated with vehicle operations for light duty truck 2.
- *Vehicles*: Calculations of energy use and emissions for vehicle operations.
- *Results*: Well-to-pump and well-to-wheels energy use and emissions results for vehicle/fuel technology combinations.
- *Graphs*: Graphic presentation of energy use and emissions for various vehicle/fuel technology combinations.
- *Dist_Specs*: Detailed specifications of the input parameters built with distribution functions. The user is cautioned against making any changes to this sheet.
- *Forecast_Specs*: Detailed information of defined forecast items for a particular stochastic simulation run. The user is cautioned against making any changes to this sheet.
- *Forecast_Deleted*: List of the forecast items that were deleted, if any, as specified by the user. The user is cautioned against making any changes to this sheet.

The Inputs Sheet Contains Key Variables and Options for Each WTW Stage

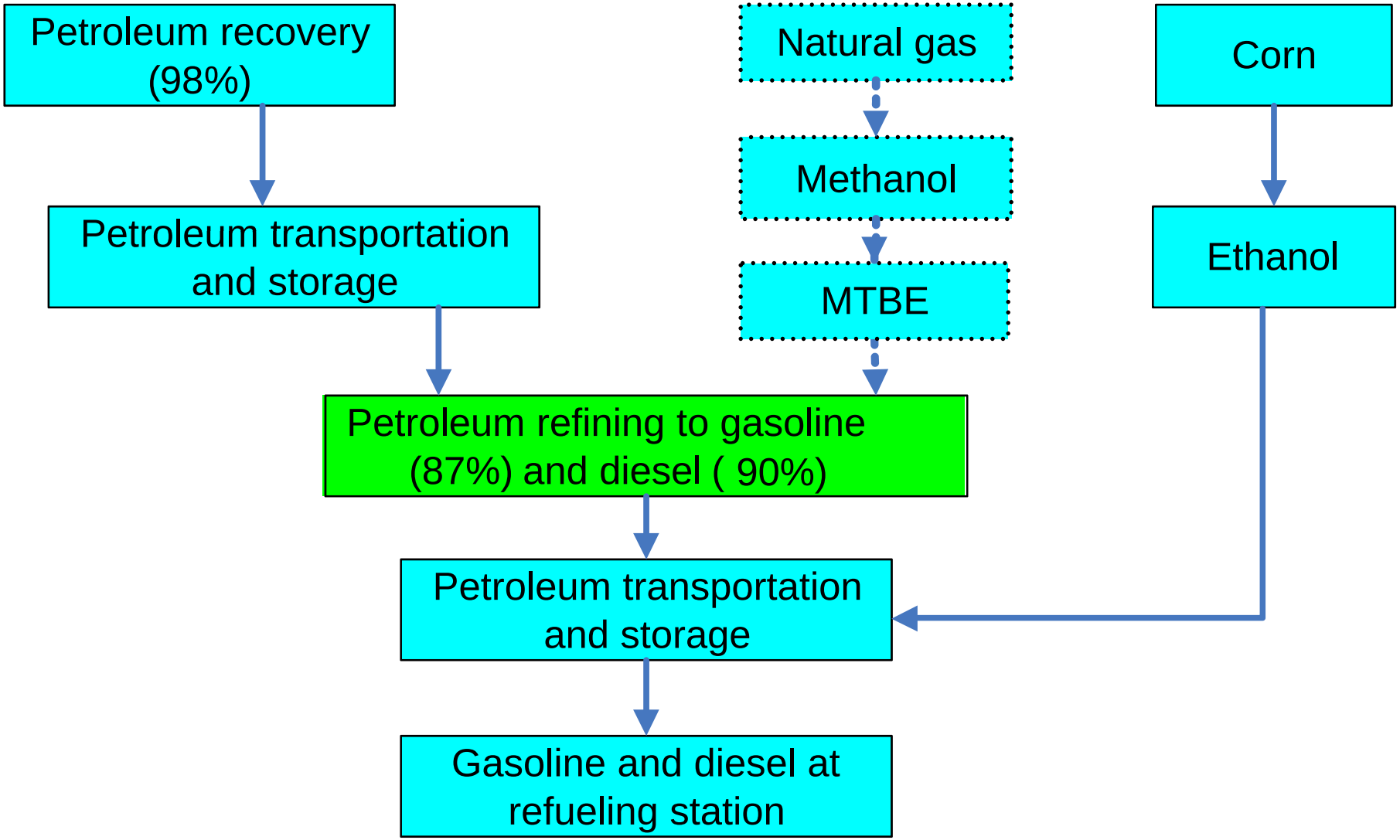
- This sheet presents key variables for various WTP and PTW scenarios, and specifies key parametric assumptions for GREET simulations
- **This sheet is separated into 13 sections:**

1. Selection of key options for simulation
2. Selection of vehicle types for simulation
3. Key input parameters for simulating petroleum-based fuels
4. Key input parameters for simulating natural gas-based fuels (Input parameters for feedstocks [e.g., biomass] other than NG for simulating FTD, DME, and MeOH are also included in this section.)
5. Key input parameters for simulating hydrogen
6. Assumptions regarding boil-off effects of liquefied natural gas and liquid H2
7. Key input parameters for simulating fuel ethanol
8. Key input parameters for simulating soybean-based biodiesel
9. Key input parameters for simulating electricity generation
10. Key input parameters for setting fuel blending options
11. Key GREET default assumptions for WTP activities
12. Fuel economy and emission rates of baseline vehicles
13. Fuel economy and emission changes by alternative-fueled vehicles and advanced vehicle technologies

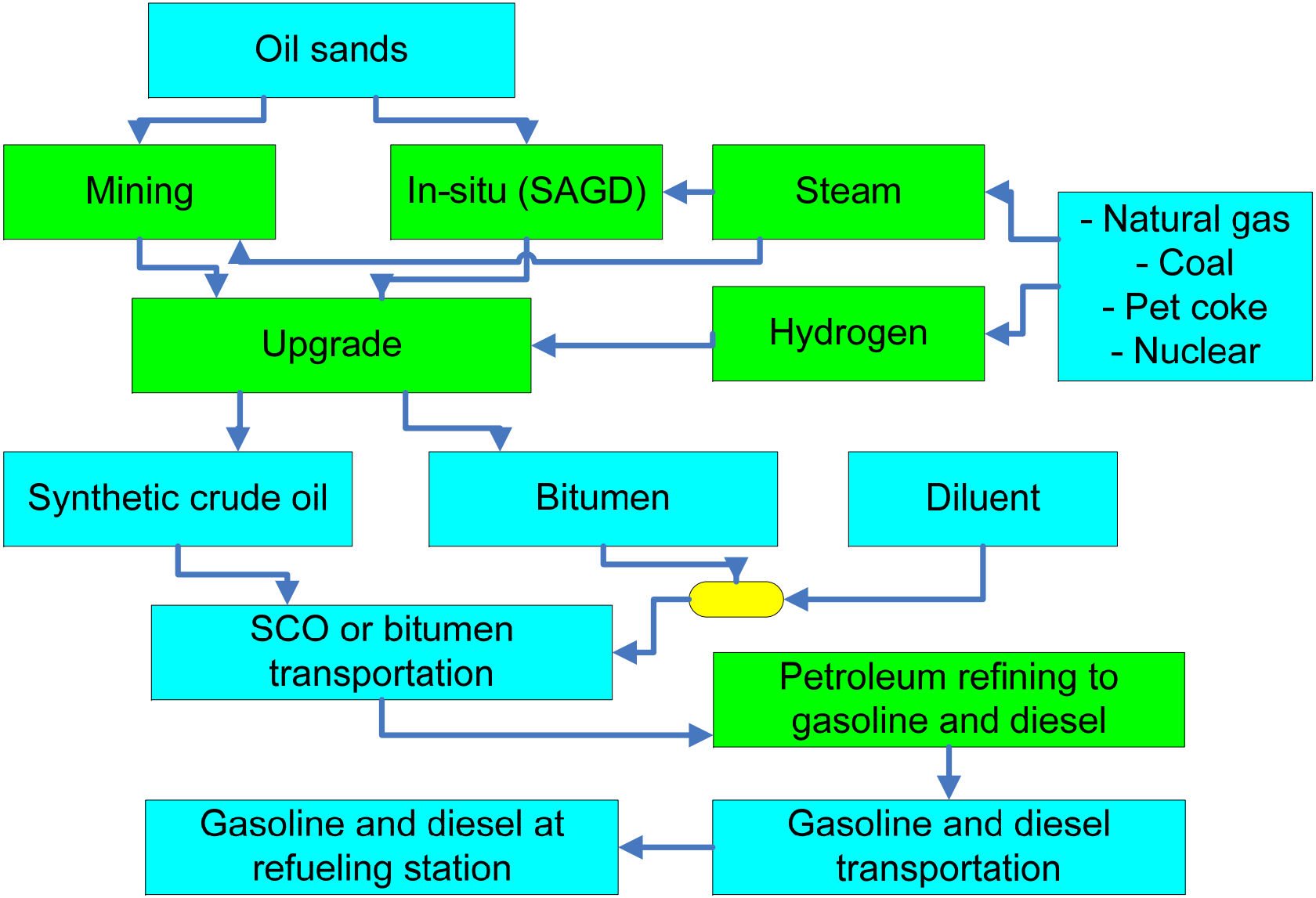
The Petroleum Sheet Serves as the Key Sheet to Calculate WTP Energy Use and Emissions Related to Petroleum-based Fuels

- This sheet calculates WTP energy use and emission rates for the following eight petroleum-based fuels:
  - Conventional gasoline (CG)
  - Reformulated gasoline (RFG)
  - California reformulated gasoline (CARFG)
  - Conventional diesel (CD)
  - Low-sulfur diesel (LSD)
  - Liquefied petroleum gas (LPG)
  - Crude naphtha
  - Residual oil
- The feedstock sources for petroleum fuels in GREET include conventional crude oil and oil sands from Canada.
- This sheet also presents calculations for MTBE, ETBE, and TAME, which can be used as oxygenates for the Federal RFG and CARFG fuels.
- This worksheet consists of the following five sections:
  - ***Scenario control and key input parameters*.** The values in this section derive primarily from the *Inputs* sheet.
  - ***Shares of combustion processes for each stage*,** which are used for emission calculations.
  - ***Calculation of energy use and emissions for individual stages*.** In this section, GREET calculates energy use and emissions for each individual stage.
  - ***Calculation of energy use and emissions of oxygenate production***.
  - ***Summary of energy use and emissions*.** Other sheets use the summary results from this sheet for individual vehicle/fuel WTW calculations.

Petroleum Refining is the Key Energy Conversion Step for Gasoline and Diesel From Conventional Crude



The Pathway of Oil Sands to Gasoline and Diesel Requires a Large Amount of Steam and H_2



The Key Logic and Formula in Calculations of Energy Consumption and Emissions for each Process Stage

- The ***energy efficiency*** is defined as [energy output]/[energy input].
- The ***energy use by each process fuel type i*** is calculated by:

$$EnergyUse_i = 1{,}000{,}000 \times \left(\frac{1}{EnergyEfficiency} - 1\right) \times Shares_i$$

- The ***total energy use*** calculates all the energy consumption (fossil energy plus renewable energy) for a given stage.
- The ***fossil energy use*** calculates fossil energy consumption (coal, NG and petroleum) for a given stage, which is a subset of ***total energy use***.
- The ***coal energy use*** calculates coal consumption for a given stage, which is a subset of ***fossil energy use***.
- The ***natural gas energy use*** calculates NG consumption for a given stage, which is a subset of ***fossil energy use***.
- The ***petroleum energy use*** calculates petroleum consumption for a given stage, which is a subset of ***fossil energy use***.

31	3) Calculations of Energy Consumption and Emissions for Petroleu				
32		Crude Oil			
33		Recovery	Transportation to U.S. Refineries	Transportation to CA Refineries	Storage
34	**Energy efficiency**	98.0%			
35	**Urban emission share**	2.0%	32.5%	47.5%	80.0%
36	**Loss factor**	1.000	1.000	1.000	1.000
37	**Shares of process fuels**				
38	Crude oil	1.0%			
39	Residual oil	1.0%			
40	Diesel fuel	15.0%			
41	Gasoline	2.0%			
42	Natural gas	61.9%			
43	Coal	0.0%			
44	Electricity	19.0%			
45	Refinery still gas	0.0%			
46	Feed loss	0.1%			
47	**Energy use: Btu/mmBtu of fuel throughput**				
48	Crude oil	204			
49	Residual oil	204			
50	Diesel fuel	3,057			
51	Gasoline	408			
52	Natural gas	12,635			
53	Coal				
54	Electricity	3,872			
55	Feed loss	28	62	62	0
56	Refinery still gas				
57	Natural gas flared	[illegible]			
58	Total energy	28,311	9,950	3,387	0
59	Fossil fuels	27,002	9,830	3,372	0
60	Coal	6,464	641	92	0
61	Natural gas	15,826	1,760	227	0
62	Petroleum	4,712	7,429	3,053	0
63	**Total emissions: grams/mmBtu of fuel throughput**				
64	VOC	0.654	0.546	0.273	
65	CO	3.957	2.543	1.217	
66	NOx	11.428	13.000	6.827	

Overview / Inputs / EF_TS / EF / Fuel_Specs / T&D / Urban_Shares / Fuel_Prod

The Key Logic and Formula in Calculations of Energy Consumption and Emissions for Each Process Stage (Cont'd)

- The ***total emissions*** for a given stage is calculated by:

$$EM_i = \left(\sum_j (EM_{cm,i,j} + EF_{up,i,j}) \times EC_j\right) \div 1{,}000{,}000$$

where

EM_i= Emissions of pollutant i in g/10^6 Btu of fuel throughput from a given stage;

$EM_{cm,i,j}$=Combustion emissions of pollutant i in g/10^6 Btu of process fuel j burned;

$EF_{up,i,j}$=Upstream emissions of pollutant i in g/10^6 Btu of process fuel j to produce and distribute the process fuel to the stage (considered within GREET through circular calculation programming); and

EC_j=Energy consumption of fuel j during the stage

- ***Shares of combustion processes*** for a given stage plays a key role in emissions calculations because different combustion processes may result in significantly different emission profiles.
- The calculation of ***urban emissions*** for a given stage involves one more factor: ***urban emission share***.

		Crude Oil			
33		Recovery	Transportation to U.S. Refineries	Transportation to CA Refineries	Storage
34	**Energy efficiency**	98.9%			
35	**Urban emission share**	2.0%	32.5%	47.5%	80.0%
36	**Loss factor**	1.000	1.000	1.000	1.000
37	**Shares of process fuels**				
38	Crude oil	1.0%			
39	Residual oil	1.0%			
40	Diesel fuel	15.0%			
47	**Energy use: Btu/mmBtu of fuel throughput**				
48	Crude oil	204			
49	Residual oil	204			
50	Diesel fuel	3,057			
63	**Total emissions: grams/mmBtu of fuel throughput**				
64	VOC	0.654			
65	CO	3.957			
66	NOx	11.428			
67	PM10	1.449			
68	PM2.5	0.576			
69	SOx	2.387	5.927	3.950	
70	CH4: combustion	7.178	1.231	0.332	
71	N2O	0.055	0.019	0.006	
72	CO2	[illegible]	793	277	
73	VOC from bulk terminal	0.702	1.534	1.534	
74	VOC from ref. Station				
75	CH4: non-combustion	13.152	69.536	69.536	
76	**Urban emissions: grams/mmBtu of fuel throughput**				
77	VOC	0.046	0.539	0.752	0.000
78	CO	0.132	0.141	0.089	0.000
79	NOx	0.404	0.686	0.485	0.000
80	PM10	0.022	0.023	0.016	0.000
81	PM2.5	0.015	0.016	0.012	0.000
82	SOx	0.392	0.346	0.288	0.000

2) Shares of Combustion Processes fo

		Crude Recovery	Oil Sands
17			
18	Residual oil industrial or co	100.0%	100.0
19	Diesel commercial boiler	25.0%	0.0
20	Diesel stationary engine	50.0%	0.0
21	Diesel turbine	25.0%	0.0
22	Diesel locomotive		
23	Diesel HDE truck		100.0
24	NG engine	50.0%	0.0
25	NG large turbine	0.0%	0.0
26	NG large industrial boiler	0.0%	100.0
27	NG small industrial boiler	50.0%	0.0
28	NG pipeline turbine		
29	Coal industrial boiler		100.0
30			

- The ***non-combustion emission*** items (e.g., evaporative VOC/CH4) are direct inputs in GREET.

Iterative Calculations of Energy Consumption and Emissions for Each Process Stage (Cont'd)

Consideration of energy use and emissions of upstream stages for a fuel cycle involves circular calculation (e.g., Diesel fuel)

$$EM_i = \left(\sum_j \left(EM_{cm\,i,j} + EF_{up\,i,j}\right) \times EC_j\right) \div 1{,}000{,}000$$

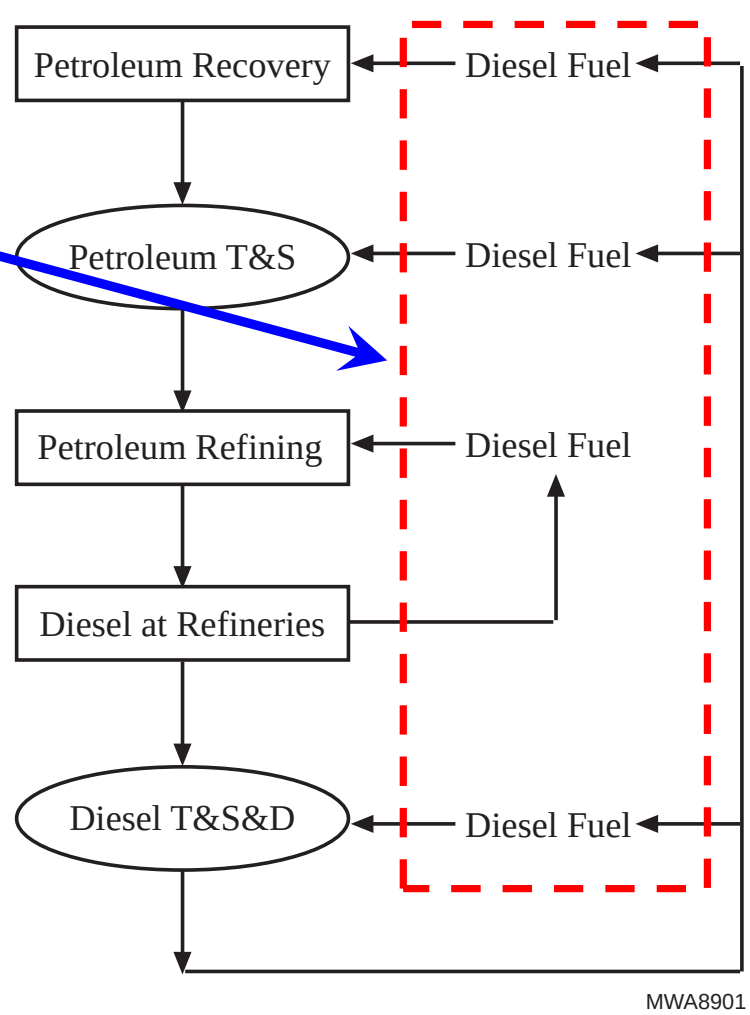
where

EM_i= Emissions of pollutant i in g/10^6 Btu of fuel throughput from a given stage;

$EM_{cm,i,j}$=Combustion emissions of pollutant i in g/10^6 Btu of process fuel j burned;

$EF_{up,i,j}$=Upstream emissions of pollutant i in g/10^6 Btu of process fuel j to produce and distribute the process fuel to the stage (considered within GREET through circular calculation programming); and

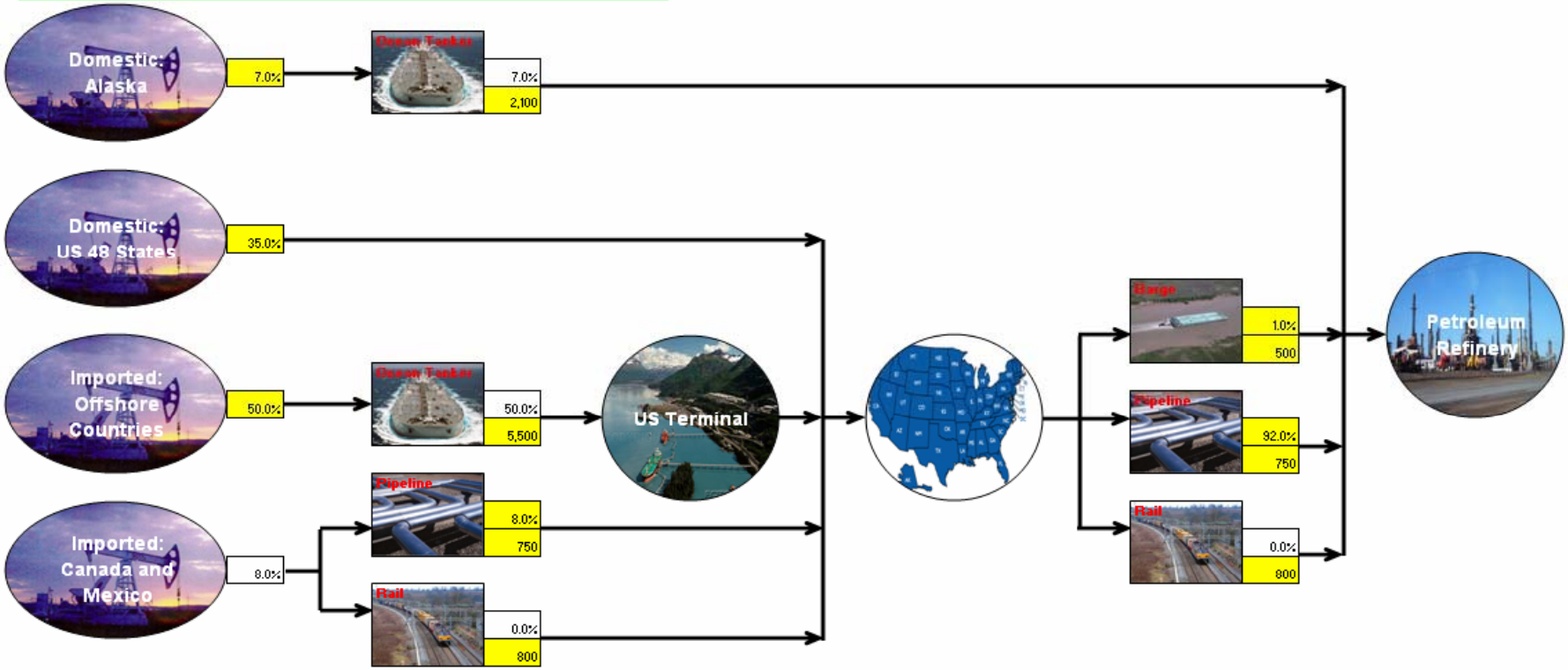
EC_j=Energy consumption of fuel j during the stage



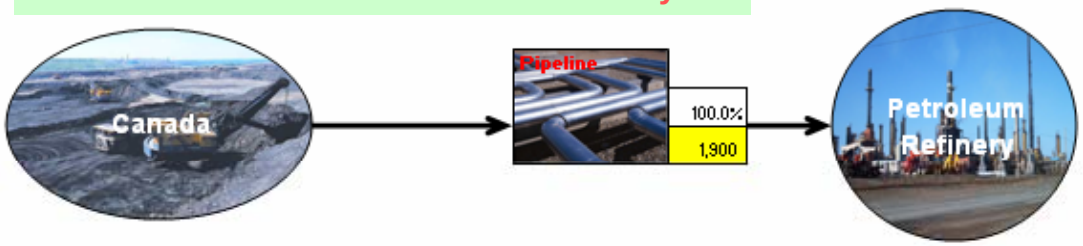
The GREET model applies Excel iteration calculation feature to perform circular calculations.

Transportation Modes and Distance are Two Key Parameters for any Given WTP Transportation Activity

Conventional Crude to Petroleum Refinery

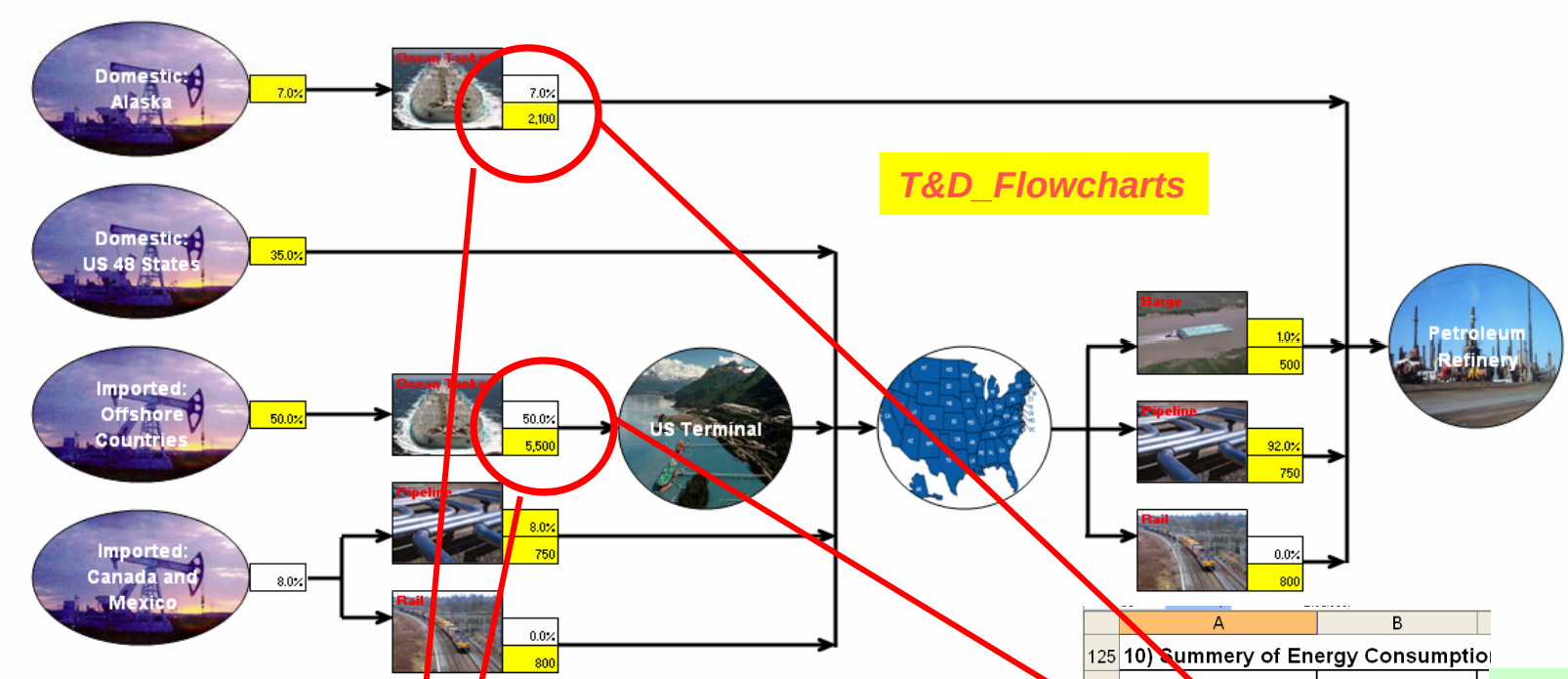


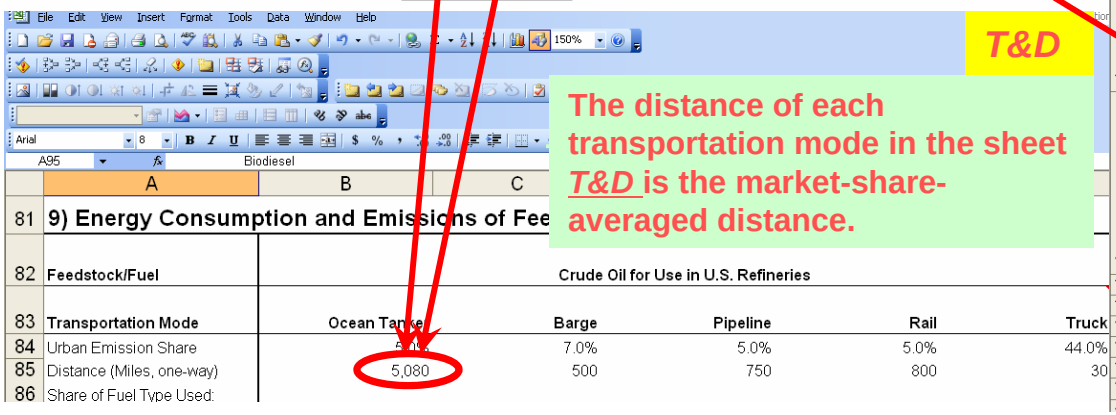
Canadian Oil Sands to Petroleum Refinery



T&D Flowchart Sheet:

Example :Conventional Crude to Petroleum Refinery

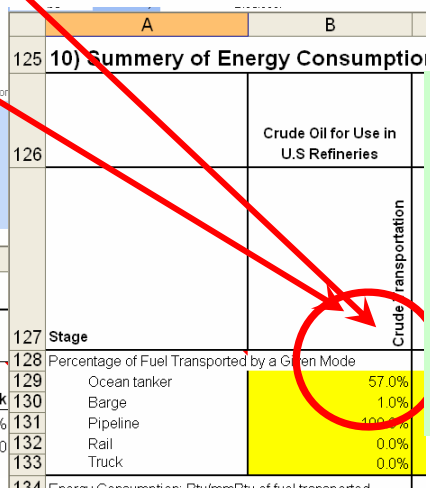




	A	B	C			
81	9) Energy Consumption and Emissions of Fee					
82	Feedstock/Fuel	Crude Oil for Use in U.S. Refineries				
83	Transportation Mode	Ocean Tanker	Barge	Pipeline	Rail	Truck
84	Urban Emission Share	[illegible]	7.0%	5.0%	5.0%	44.0%
85	Distance (Miles, one-way)	5,080	500	750	800	30
86	Share of Fuel Type Used:					

T&D

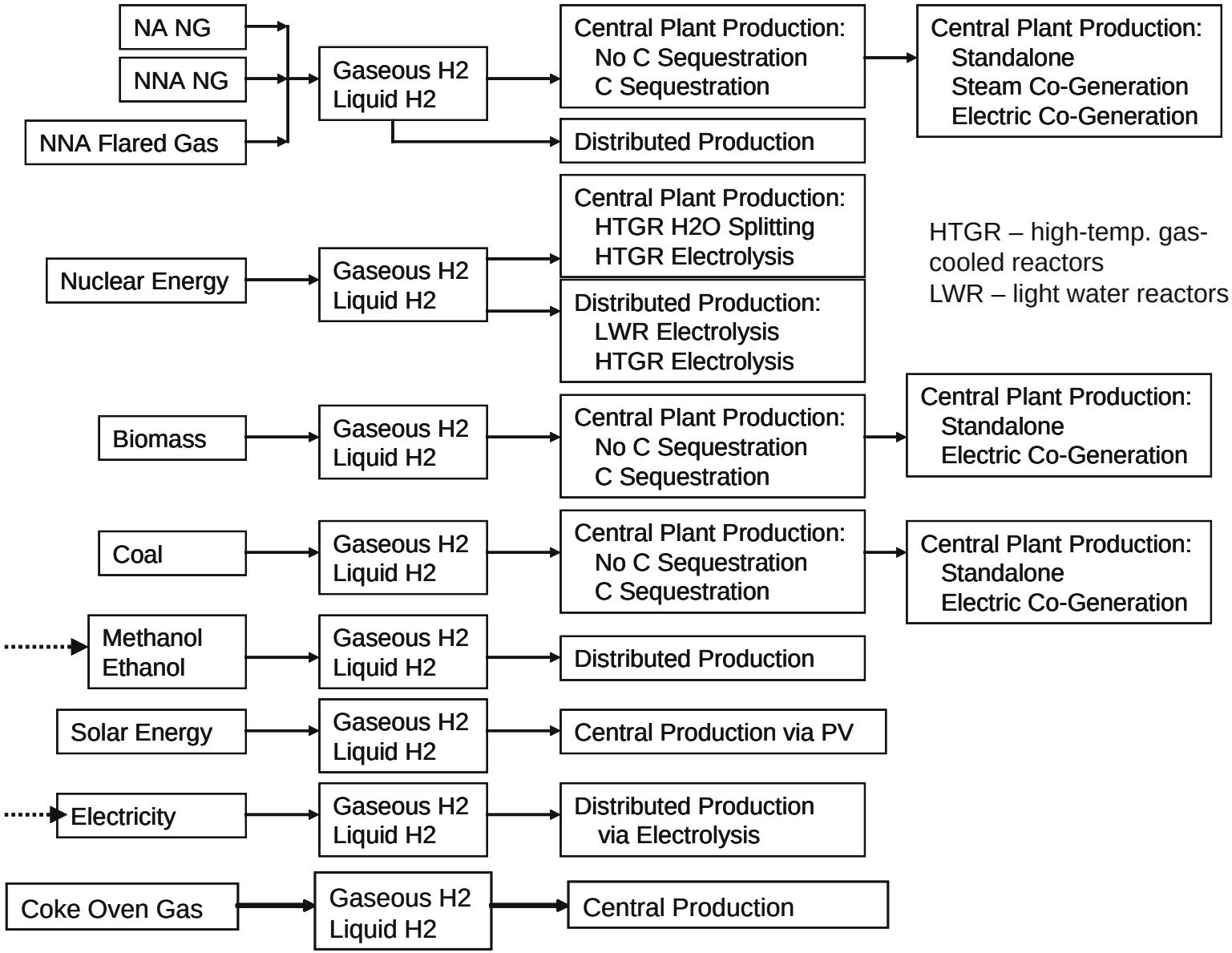
The distance of each transportation mode in the sheet *T&D* is the market-share-averaged distance.



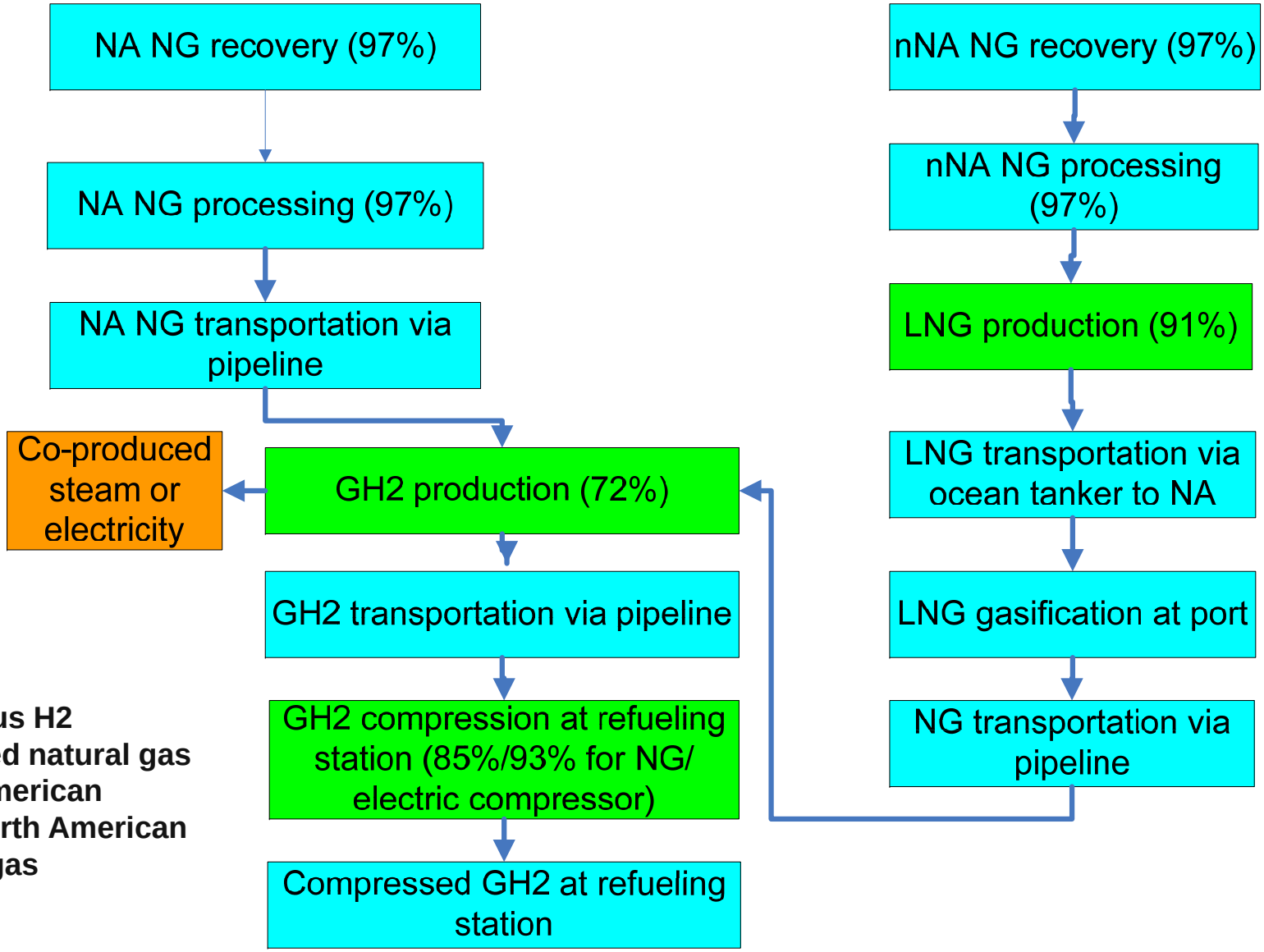
	A	B
125	10) Summery of Energy Consumptio	
126		Crude Oil for Use in U.S Refineries
127	Stage	Crude transportation
128	Percentage of Fuel Transported by a Given Mode	
129	Ocean tanker	57.0%
130	Barge	1.0%
131	Pipeline	[illegible]
132	Rail	0.0%
133	Truck	0.0%

The share of each transportation mode in the sheet *T&D* may not add up to 100% since feedstock sources may not be transported by a single mode.

GREET Includes a Varity of Hydrogen Production Pathways



Production and Compression Are Key Steps for Central Gaseous H_2 Production



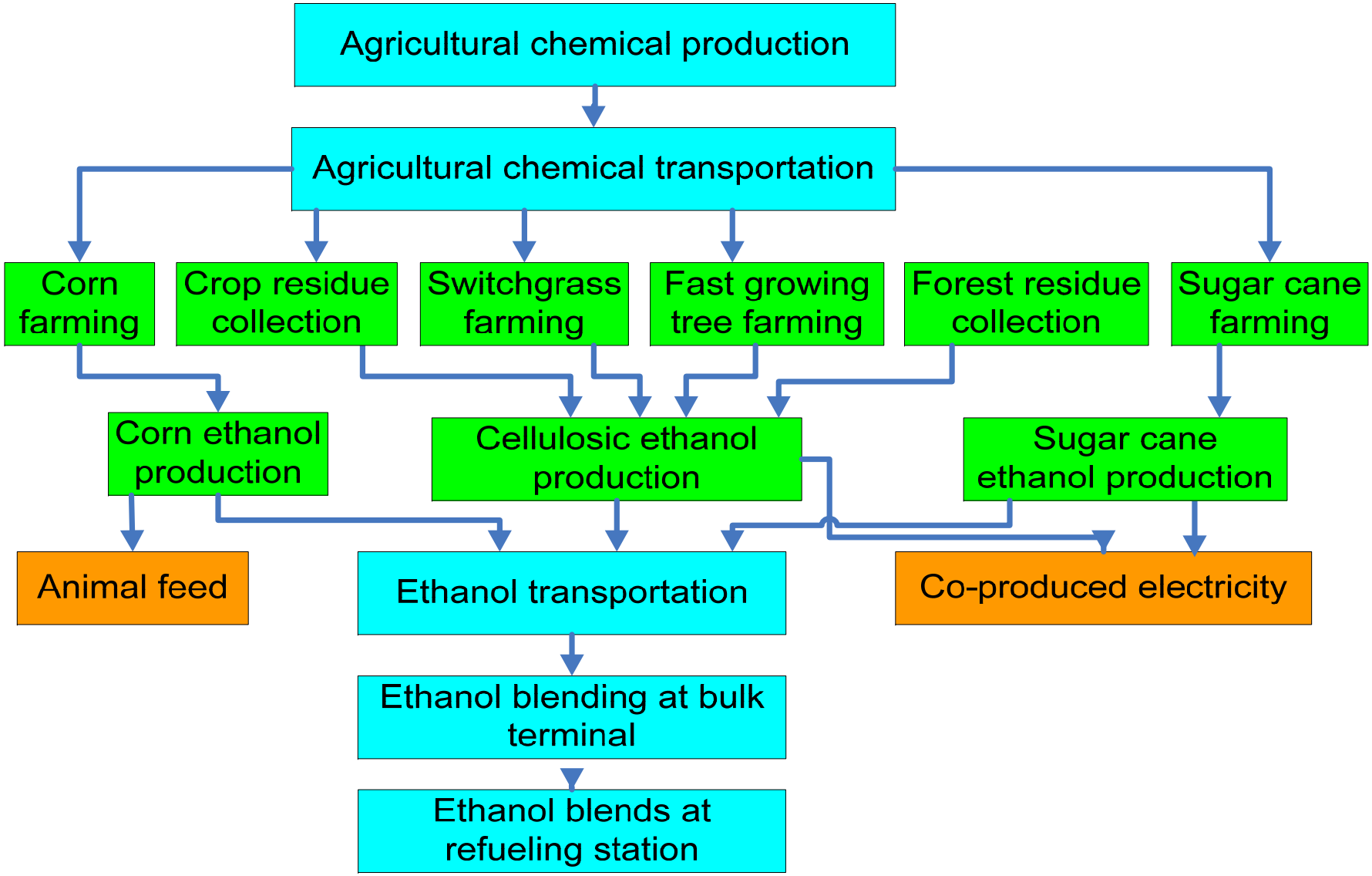
G.H2: gaseous H2
LNG: liquefied natural gas
NA: North American
nNA: non-North American
NG: natural gas

The EtOH Sheet Serves as the Key Sheet to Calculate Energy Use and Emission Rates for Ethanol Produced from Various Biomass Feedstocks

- **This worksheet consists of the following four sections:**
  - ***Scenario control and key input parameters*.** The values in this section derive primarily from the *Inputs* sheet.
  - ***Shares of combustion processes for each stage*,** which are used for emission calculations.
  - ***Calculation of energy use and emissions for individual stages*.** In this section, GREET calculates energy use and emissions for each individual stage
  - ***Summary of energy use and emissions*.** Other sheets use the summary results from this sheet for individual vehicle/fuel WTW calculations.

- **Production of agricultural chemicals (fertilizers and pesticides) are simulated in the *Ag_Inputs* sheet, and the results are linked to the *EtOH* sheet.**
- **CO2 emissions need to be carefully examined in the biofuel pathways: e.g., CO2 credit/emissions during land use change, CO2 sequestration via photosynthesis during biomass growth, etc.**
- **Dealing with the co-products is a key for biofuel pathways: displacement method vs. Allocation method vs. other methods.**

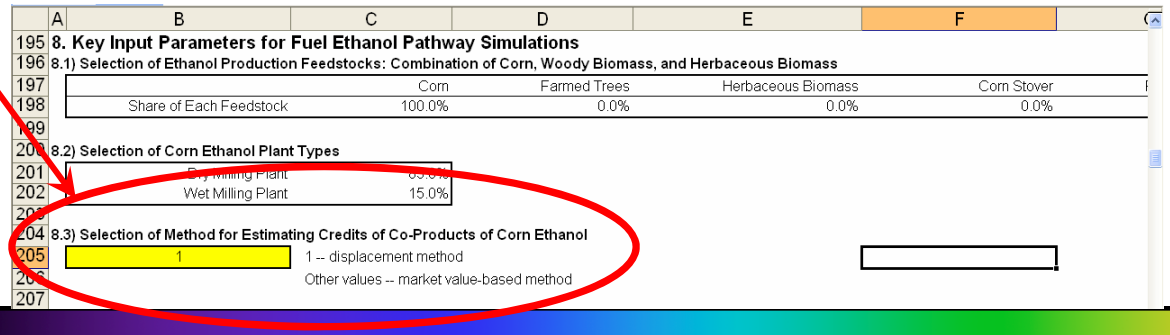
Ethanol WTP Pathways Include Activities from Fertilizer to Ethanol at Stations



Accounting for Animal Feed is a Critical Factor in Ethanol's Lifecycle Analysis

Allocation Method	Wet milling	Dry milling
Weight	52%	51%
Energy content	43%	39%
Process energy	36%	41%
Market value	30%	24%
Displacement	~16%	~20%

GREET default is the displacement method (most conservative)



	A	B	C	D	E	F
195	8. Key Input Parameters for Fuel Ethanol Pathway Simulations					
196	8.1) Selection of Ethanol Production Feedstocks: Combination of Corn, Woody Biomass, and Herbaceous Biomass					
197			Corn	Farmed Trees	Herbaceous Biomass	Corn Stover
198		Share of Each Feedstock	100.0%	0.0%	0.0%	0.0%
199						
200	8.2) Selection of Corn Ethanol Plant Types					
201		Dry Milling Plant	85.0%			
202		Wet Milling Plant	15.0%			
203						
204	8.3) Selection of Method for Estimating Credits of Co-Products of Corn Ethanol					
205		1	1 -- displacement method			
206			Other values -- market value-based method			
207						

Vehicle Technologies Simulated in the Current Version of GREET

- **Only light-duty vehicles are simulated in GREET** (75+ vehicle/fuel systems)**:**
  - Passenger cars (PC): GREET sets mid-size car as default.
  - Light-duty trucks 1 (LDT1) with a gross vehicle weight (GVW) less than 6000 lbs: GREET sets mid-size SUV as default.
  - Light-duty trucks 2 (LDT2) with a GVW between 6000 and 8500 lbs: GREET sets mid-size pick-up truck as default.
- **Spark-ignition vehicle fueled with gasoline, and the compression-ignition direct-injection vehicle fueled with diesel are considered <u>baseline</u> vehicles.**
- **All other vehicles are considered <u>alternative-fueled</u> vehicles or advanced vehicle technologies. The users specifies the change rates of:**
  - fuel economy (relative to the baseline SI gasoline vehicle).
  - emission factors (SI technologies relative to the baseline SI gasoline vehicle and CIDI technologies relative to the baseline CIDI diesel vehicle).
- **Many vehicle technologies are for use in the future, not yet available in the historical U.S. market. In GREET, these vehicle technology options including (1) H2 SI ICE vehicles, (2) SIDI vehicles, (3) GI SI HEVs, (4) GC SI HEVs, (5) GI CIDI HEVs, (6) GC CIDI HEVs, and (7) Fuel-cell vehicles, can be only simulated for model-year 2005 and after.**

Fuel Economy and Emissions Rates Are Key Input Parameters for the Vehicle Operation Stage

Pump-to-Wheels Data Sources

- **Fuel economy**
  - Open literature
  - Vehicle simulations with models such as Argonne's PSAT model
  - Lab-tested fuel economy data are adjusted to reflect the on-road deterioration
- **Vehicle operation emissions**
  - Open literature
  - Emission testing results
  - EPA MOBILE6.2 model
  - CARB EMFAC2002 model

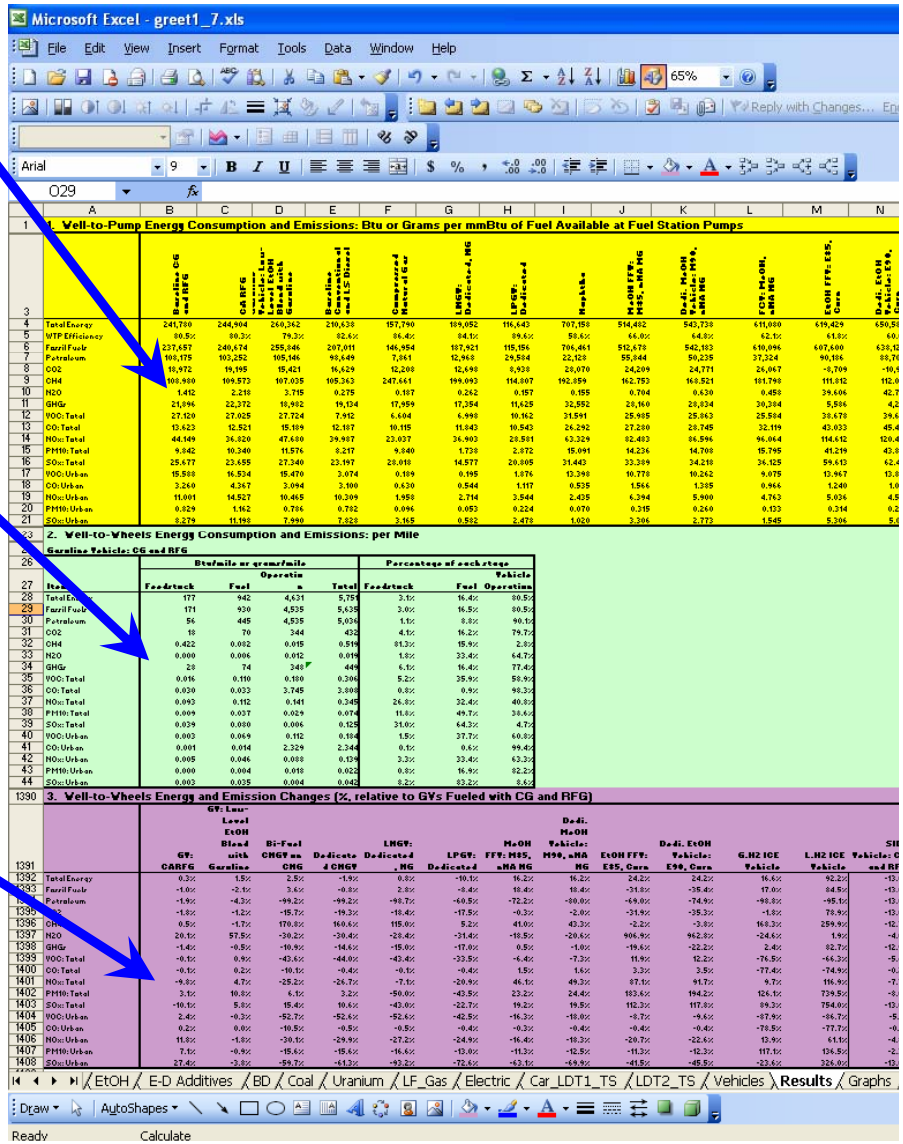
The fuel economy and emission factor values in the TS tables of the two sheets Car_LDT1_TS and LDT2_TS are based on each five-model-year instead of calendar-year (i.e., target year). Because emission rates of vehicle operations will deteriorate over time, the data of the lifetime mileage midpoint for a typical model-year vehicle should be applied for simulation. The GREET model was designed to do so. On average, half lifetime of a light-duty vehicle is about five years in the U.S. That means in GREET, for example, simulation for calendar year 2010 uses the values for model-year 2005 vehicles.

WTW Results Are Summarized in the Results Sheet

- 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)

- 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.

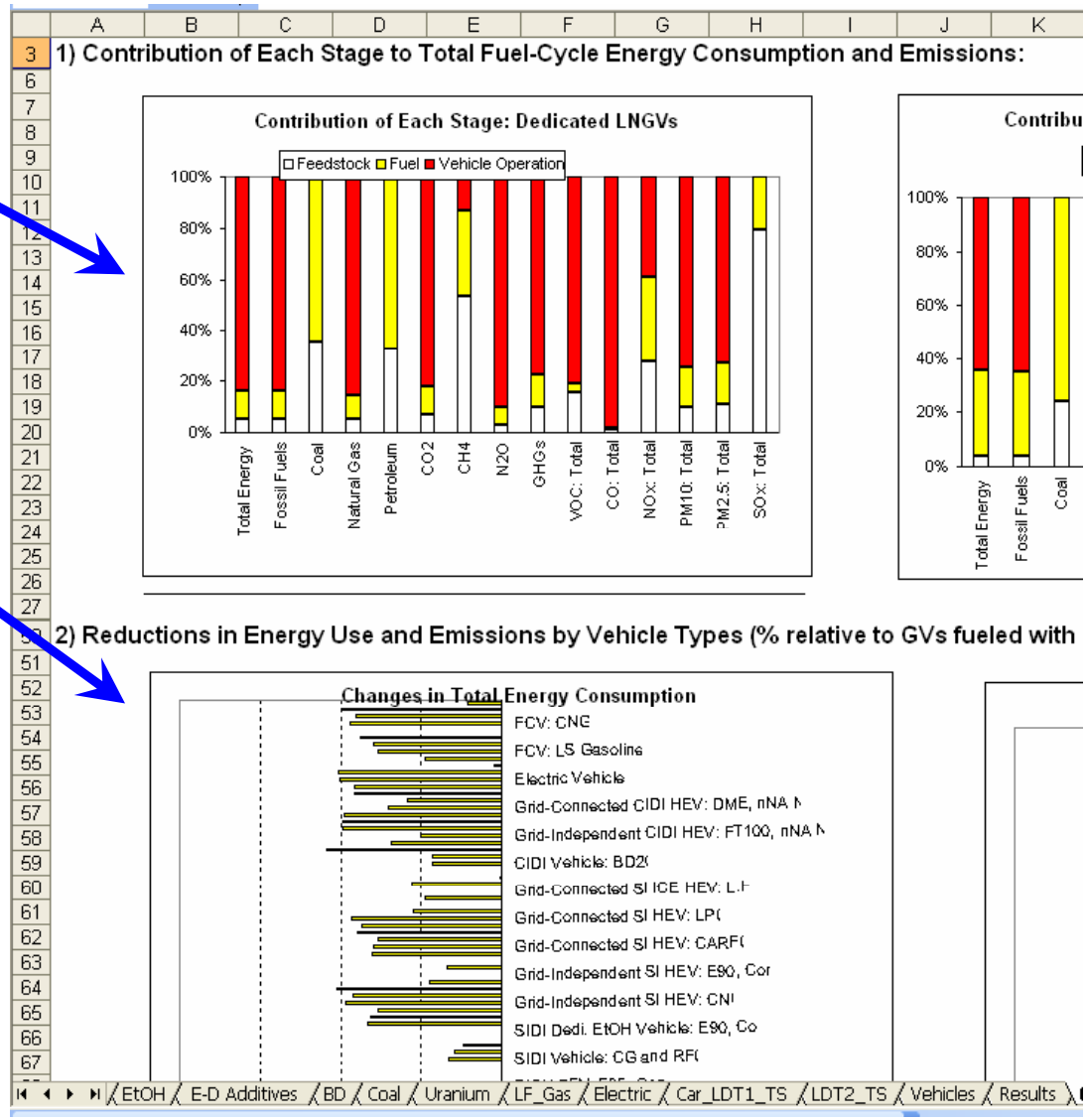
- The ***Well-to-Wheels Energy and Emission Changes*** section calculates changes in fuel-cycle energy use and emission rates for each alternative-fueled vehicle or advanced vehicle technology relative to baseline gasoline vehicle.



WTW Results Are Presented as Charts in the Graphs Sheet

- The ***first*** section presents the charts in terms of contribution of each stage to total fuel-cycle energy consumptions and emissions.

- The ***second*** section presents the charts in terms of reductions in energy use and emissions by vehicle types (% relative to GVs fueled with gasoline).



Time-Series Tables are Designed in the GREET1.8 to Reflect the Technology Advancement over Time

- GREET1.8 can simulate a target year or multiple years (through GUI) between 1990 and 2020
  - Previous versions were based on two snap-shot simulations: near term vs. long term
  - Technology advancement over time is established with time-series look-up tables

0.069	
0.069	
5-year period	**LDGV: NOx**
1990	1.285
1995	0.656
2000	0.300
2005	0.141
2010	**0.069**
2015	0.069
2020	0.069

71.50%	
71.50%	
5-year period	**G.H2 Production Efficiency (Central, NA-NG, no export)**
1990	68.0%
1995	69.0%
2000	71.0%
2005	71.5%
2010	**71.5%**
2015	72.0%
2020	73.0%

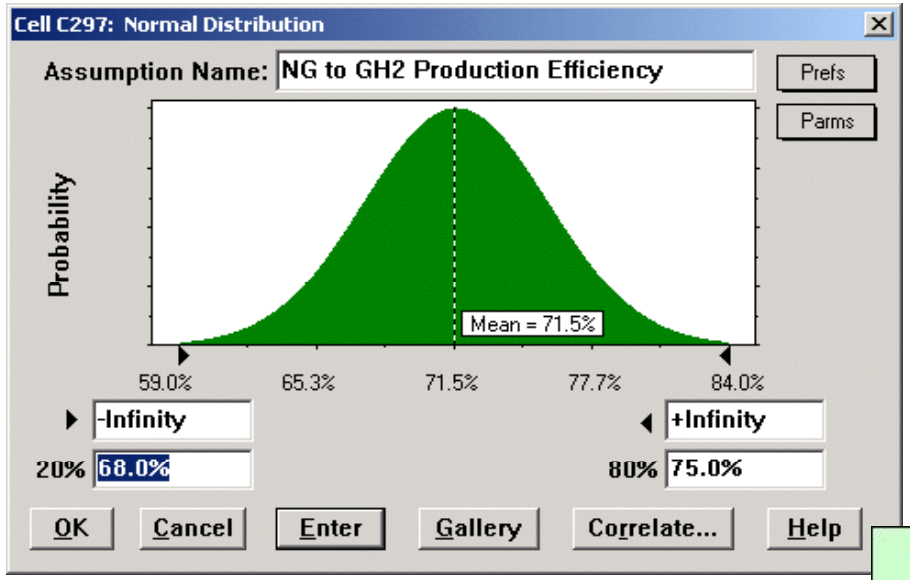
U.S. mix: Average

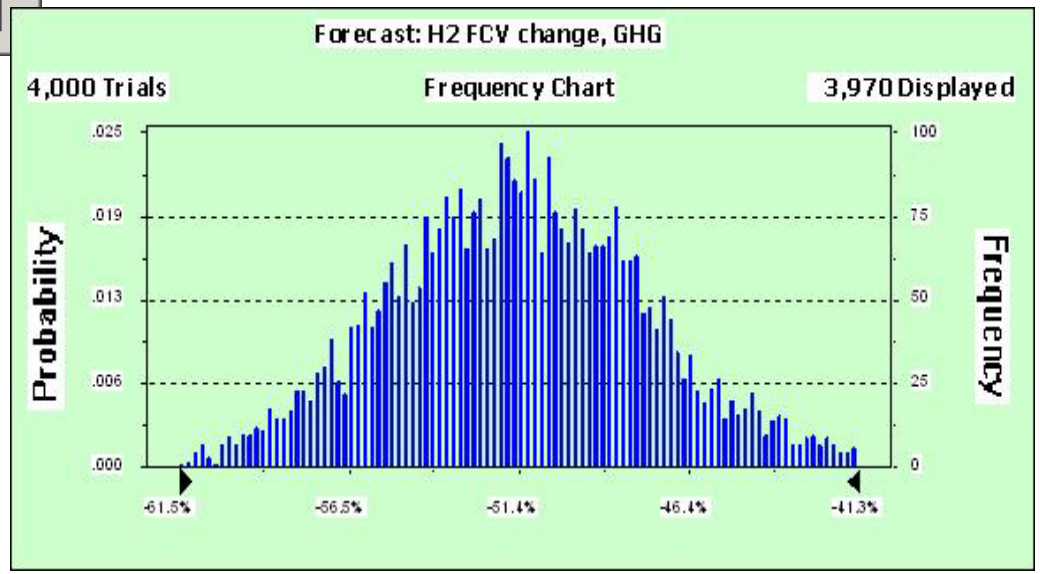
	1.7%	20.6%	50.2%	17.7%	9.8%
5-year period	**Residual Oil**	**Natural Gas**	**Coal**	**Nuclear**	**Others**
1990	4.2%	12.3%	52.5%	19.0%	12.0%
1995	2.2%	14.8%	51.0%	20.1%	11.9%
2000	2.9%	15.8%	51.7%	19.8%	9.8%
2005	1.7%	18.4%	50.3%	19.4%	10.2%
2010	**1.7%**	**20.6%**	**50.2%**	**17.7%**	**9.8%**
2015	2.5%	22.7%	48.6%	16.6%	9.6%
2020	1.9%	24.2%	49.2%	15.4%	9.3%

- For any simulation year between within a five-year interval listed in the TS tables, GREET uses a linear interpolation algorithm to calculate the estimate for that particular year
- Time-series look-up tables are located primarily in four sheets in GREET: 1) ***Fuel_Prod_TS***; 2) ***EF_TS***; 3) ***Car_LDT1_TS***; and 4) ***LDT2_TS***.

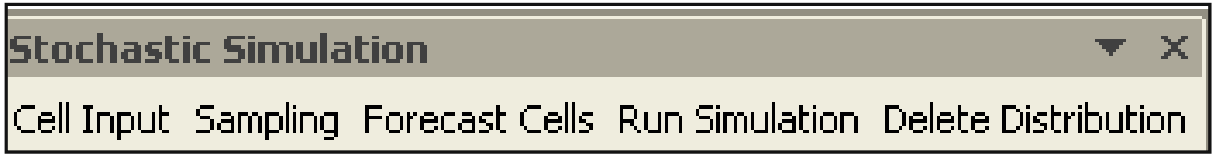
GREET Is Designed With Stochastic Simulations to Address Uncertainties

Distribution-Based Inputs Generate Distribution-Based Outputs





The Structure of the Stochastic Simulation Tool



- **Assign probability distribution functions to the input variables**
  - **GREET 1.8 includes ~1,000 key parameters with distribution functions**
  - **The tool includes as many as 11 probability distribution function types**
- **Specify the number of samples required and the sampling technique**
  - **Four sampling techniques are included in the tool**
- **Define the forecast variables**
  - **GREET 1.8 includes ~3,000 forecast variables**
- **Propagate the uncertainties**
- **Statistically analyze the outputs**

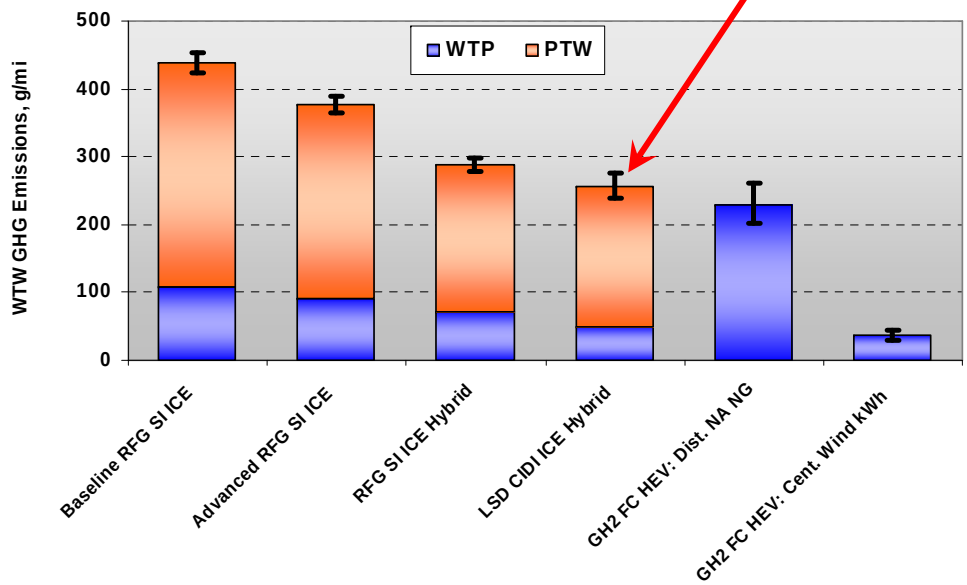
Statistically Analyzing the Outputs after Each Stochastic Simulation Run Is Required

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

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).**

	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	2
3		3163.628235	2765.352496	99.08984517	2
4		3079.852945	2692.116244	96.43835883	2
5		3238.052196	2830.417478	101.4902298	
6		3140.147283	2744.825733	98.35458792	2
7		3043.772242	2660.582457	95.3074409	2
8		3200.222875	2797.343163	100.2726682	2
9		3116.192323	2723.887281	97.57959977	2
10		2986.787116	2610.767386	93.50614537	2
11		3171.191209	2771.966214	99.33162812	2
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	[illegible]	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.**



It may take several minutes to more than an hour to complete a particular stochastic simulation run depending on many factors, such as the number of selected forecast cells, the number of selected samples, and the hardware configuration of the computer system.