NATIONAL ENERGY TECHNOLOGY LABORATORY

Modeling the Uncertainty of Fischer-Tropsch Jet Fuel Life Cycle Inventories with Monte Carlo Simulation

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Study Background and Purpose:

- **Defense Logistics Agency (DLA) provided funding to CCAT**
- **Demonstrate liquid fuel production from coal that meets the Energy Independence and Security Act (EISA) of 2007, Section 526 requirements**

EISA Section 526: *Life Cycle GHG emissions for alternative fuels contracted by a Federal agency other than for research and testing must be less than or equal to life cycle emissions from conventional fuel from conventional sources*

- **Study Purposes**
  - Process level evaluation of six alternative jet fuel production scenarios
  - Refine key considerations for CBTL development/demo
  - Evaluate jet fuel production scenarios from economic and life cycle environmental standpoints
  - Assess/validate potential for compliance with EISA Section 526
  - **Create a tool that gives the user access to key parameters that affect the LC GHG emissions and perform uncertainty analysis**

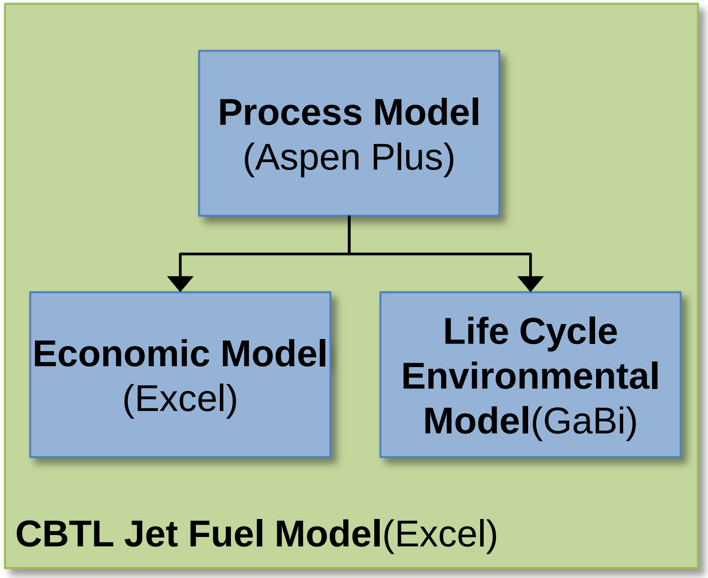
Study Background

- **Six F-T jet fuel production scenarios were evaluated**
- **Mix of field-chipped or torrefied woody biomass (10% to 20%) and coal**
- **Single and dual separate gasifiers**
- **Carbon management via enhanced oil recovery and eventual sequestration**
- **50,000 bbl/day production scenarios including F-T jet fuel plus co-products**
  - F-T diesel, F-T naphtha, F-T LPG, F-T electricity, CO_2, EOR Crude, EOR NGL

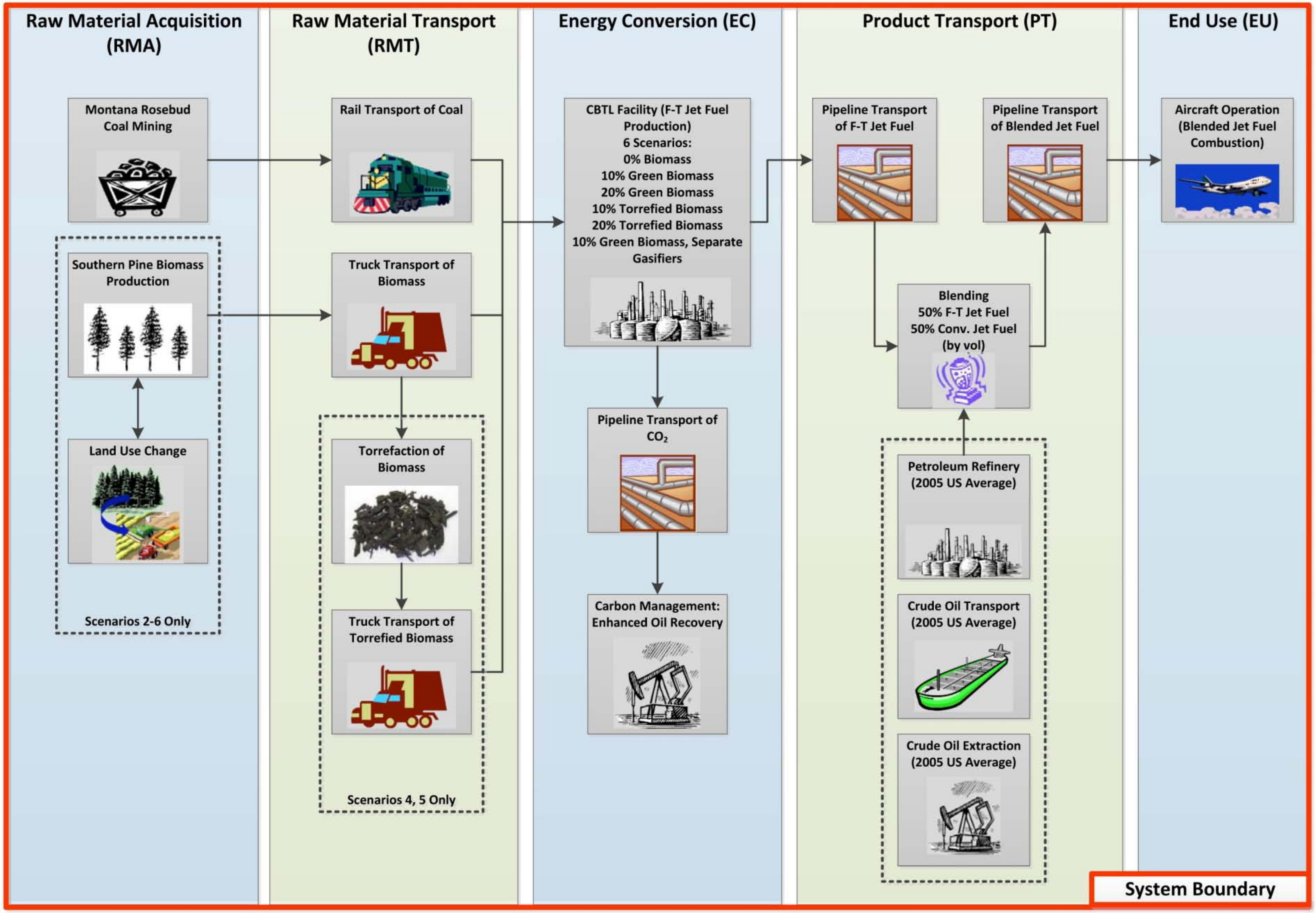
Scenario Property	Scenario Number and Name					
	1: CBTL, 0% Biomass	2: CBTL, 10% Biomass, Chipped	3: CBTL, 20% Biomass, Chipped	4: CBTL, 10% Biomass, Torrefied	5: CBTL, 20% Biomass, Torrefied	6: CBTL, 10% Biomass, Microchipped, Separate Gasifiers
CBTL Facility Location	Southeastern U.S.					
Biomass Type	N/A	Short Rotation Woody Crops (Southern Yellow Pine)				
Coal Type	Montana Rosebud					
Biomass Pretreatment	N/A	Dry and Grind (from Wood Chips)		Torrefaction		Separate Gasifier
Biomass Feed (by weight)	0%	10%	20%	10%	20%	10%
Gasifier Type	Single Feed, Transport, O_2 Blown (using Transport Integrated Gasification [TRIG])					Single Feed, Transport, O_2 Blown, Separate Gasifier
Liquefaction Type	Indirect					
F-T Reactor Type	Slurry Iron Catalyst					
Product Slate	Maximize F-T Jet Fuel Production					
CO_2 Capture	Acid Gas Removal (H_2S and CO_2 – i.e., Selexol)					
Default CO_2 Management	Carbon Capture and CO_2 Enhanced Oil Recovery					

Modeling Approach

- **Three analyses completed for each of the six scenarios**
  - Process model, economic model, life cycle environmental model
- **Process Model (Aspen Plus)**
  - Three representative cases for each scenario
  - Results from 3 cases defined uncertainty in CBTL facility result
- **Life Cycle Environmental Model (GaBi)**
  - Raw materials acquisition through end use (combustion) of fuel
  - GHG emissions evaluation (CO_2, CH_4, N_2O, SF_6), air and water pollutants, and water consumption
- **CBTL Jet Fuel Model (Microsoft Excel®)**
  - Summarizes results of all models
  - Stochastic analyses using @RISK software
  - Results based on 1 MJ of blended jet fuel combusted in a jet aircraft (50:50 blend of F-T jet and conventional jet fuel)
- **Uncertainty in Key Parameters**
  - Modeled for all three analyses
  - Ability to meet EISA Section 526

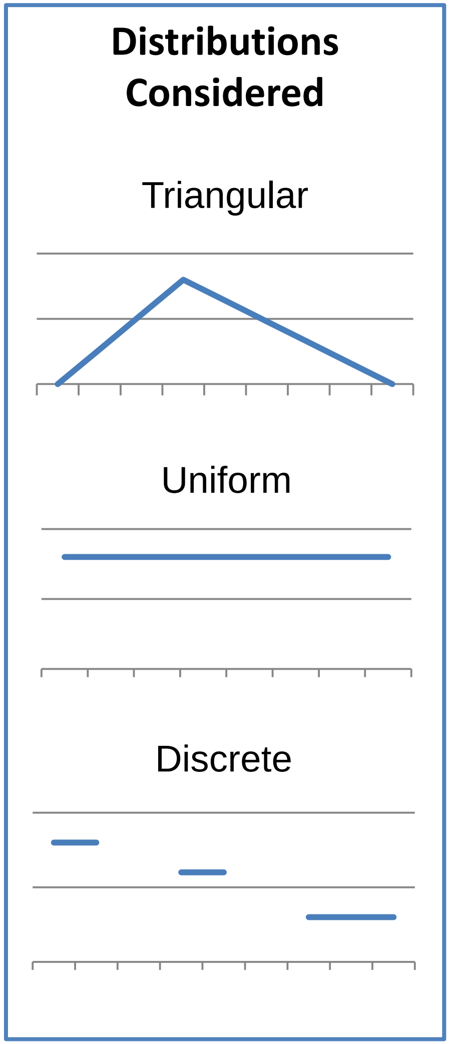


System Boundary



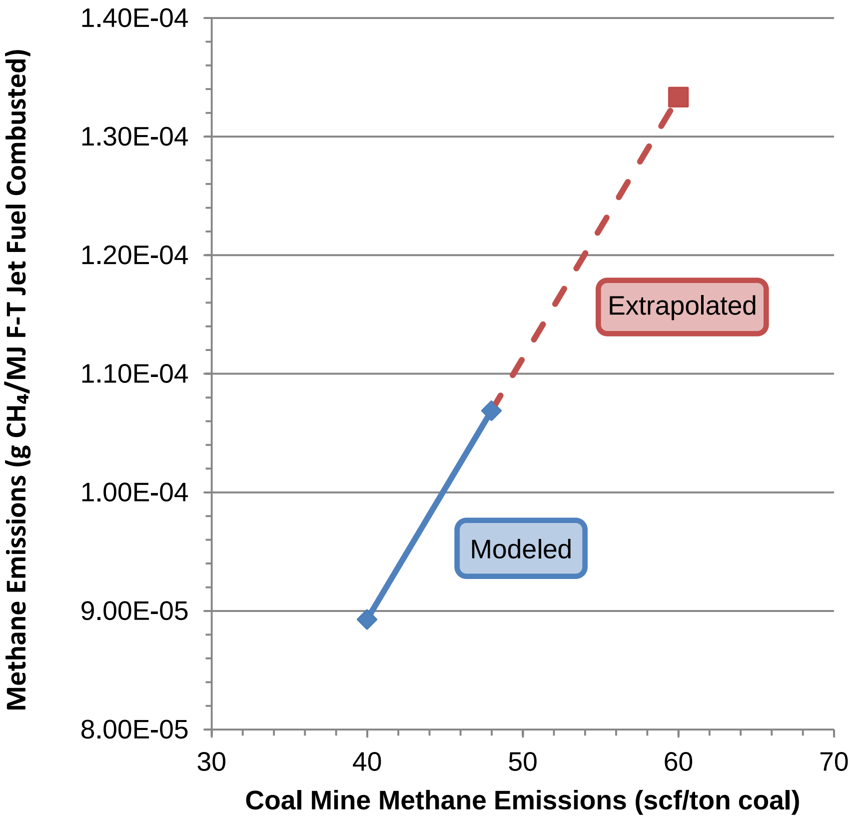
Stochastic Analysis: Parameter Distributions

- **Stochastic analyses performed within the technological/process, economic, and environmental models**
  - Process stochasticity
    - Low/Expected/High RSP
  - Economic stochasticity
    - 18 parameters
  - Environmental stochasticity
    - 14 parameters
- **Stochastic analysis modeled using licensed Microsoft Excel add in @RISK (Palisade)**
  - Latin Hypercube sampling with a seed value
  - Focused on three main distributions: triangular, uniform, and discrete
  - None of the parameters were modeled with a normal distribution due to data limitations
- **Stochastic analyses inform all subsequent results**



Stochastic Analysis: Parameter Relationships

Environmental Parameters	Default Distribution
Coal Mine Methane	Triangular
Biomass Yield	Triangular
Chip Type	Uniform
Direct Land Use	Triangular
Indirect Land use	Triangular
Rail Distance	Triangular
Biomass Truck Distance: Farm to CBTL Facility	Triangular
Biomass Truck Distance: Farm to Torrefaction Facility	Triangular
Biomass Truck Distance (Torrefaction Facility to CBTL Facility)	Triangular
CBTL Plant Operations Scenario	Discrete – 20/60/20 (Low/Expected/High)
CO_2 Pipeline Distance	Triangular
CO_2 Pipeline Loss Rate	Triangular
Blended Jet Fuel Transport Pipeline Length	Triangular
Blended Jet Fuel Transport Scenario	Uniform
Combined Co-Product Mgt.	Discrete



- Linear relationships developed for each of the life cycle model parameters to allow user customization of scenarios
- Assume these relationships are additive
- Limitation for non-linear parameters and interaction

Stochastic Analysis: Co-Product Management

- **Two co-product management schemes**
  - **System expansion:** expands boundary analysis until the functional unit is the only product that exits the system; all other co-products are contained within the system
  - **Energy Allocation:** allocation of environmental burdens based on energy content of co-products; all co-products exit the system boundary
- **Combined Co-Product Management Scheme**
  - No clear choice between results from system expansion and energy allocation; both equally likely to occur
  - Calculated using a 50/50 split between system expansion and co-product allocation results; assumed equally likely for uncertainty
  - Combined co-product management scheme used as study default because there is no clear choice between energy allocation results and system expansion results

Co-Product Energy Breakdown:

F-T Diesel – 3.2%

F-T Jet – 16.4%

F-T LPG – 2.0%

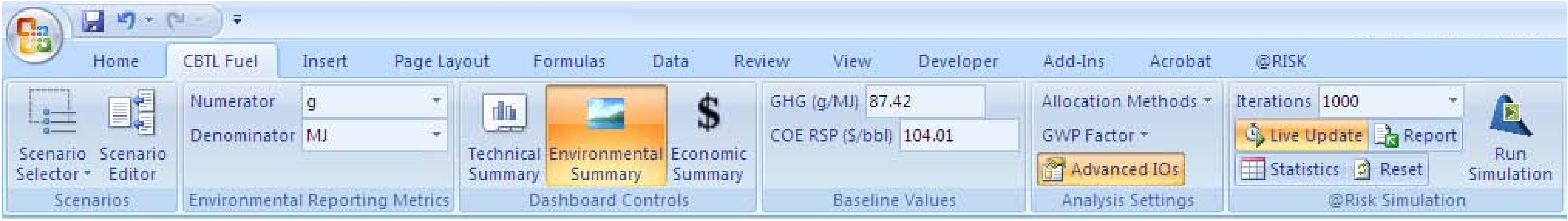
F-T Naphtha – 10.6%

F-T Electricity – 2.4%

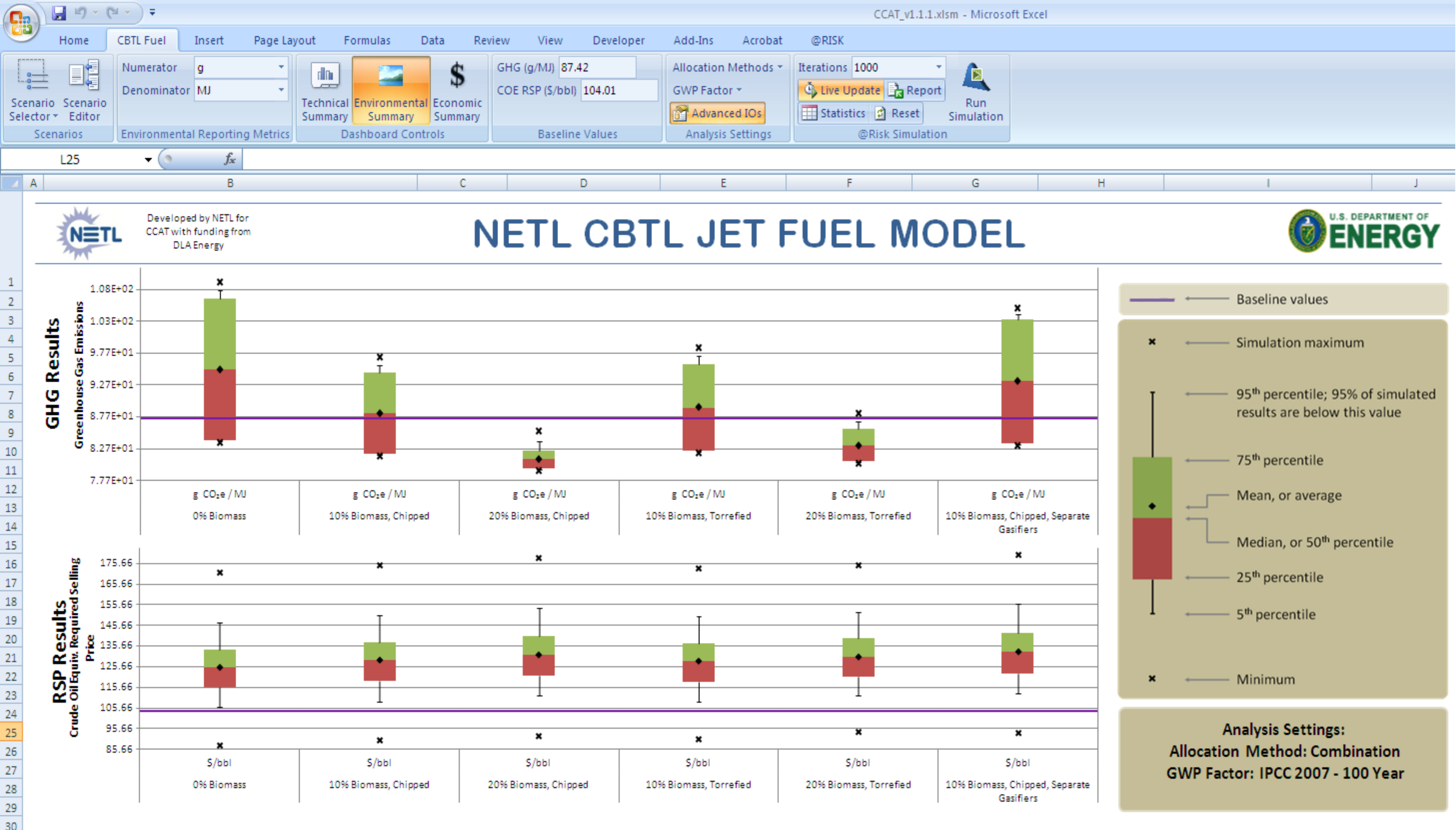
EOR Crude – 63.7%

EOR NGL – 1.8%

CBTL Jet Fuel Model Overview: Functions



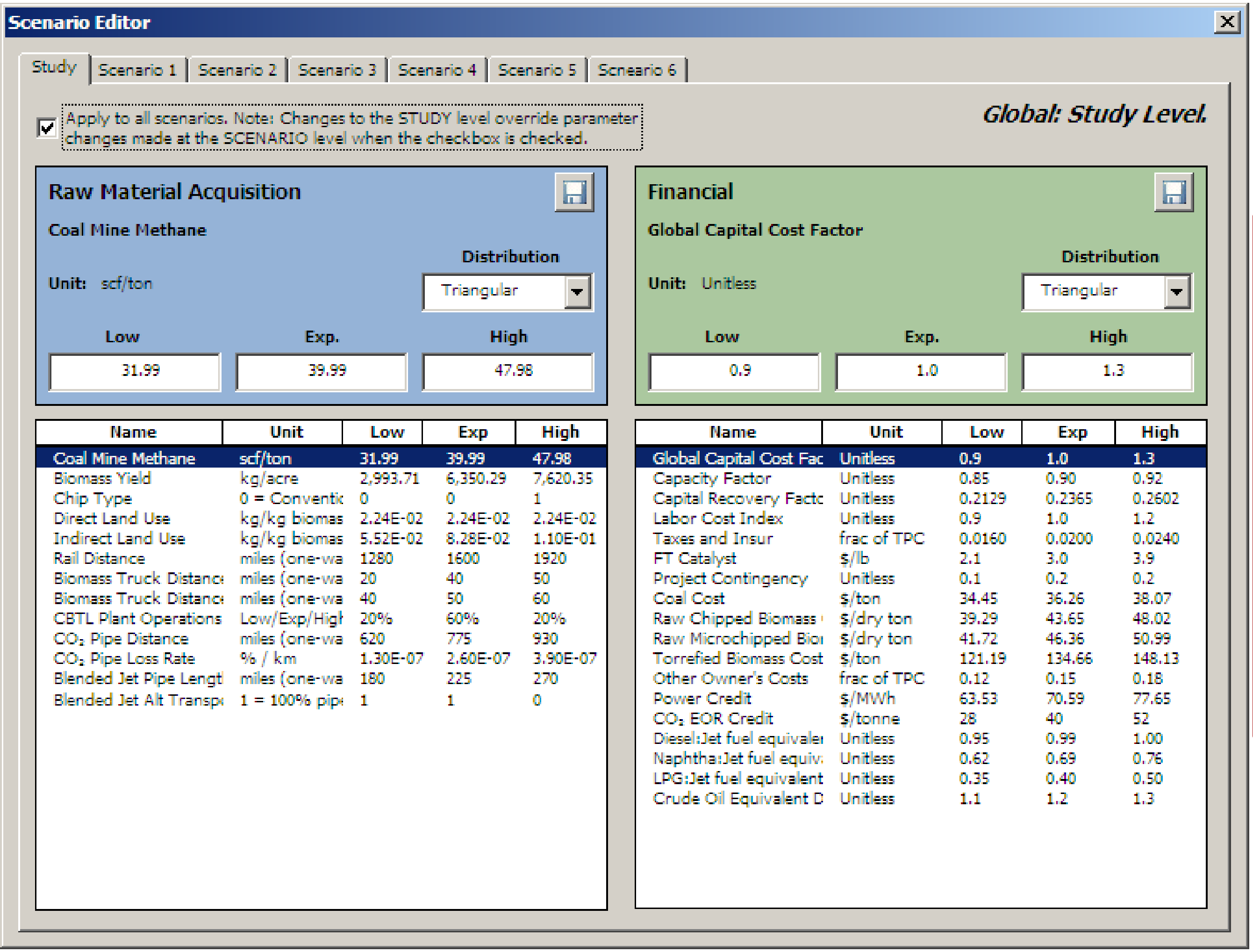
- **NETL CBTL Jet Fuel Model**
  - Excel-based model developed to allow in-depth user access to the technological process, economic, and life cycle environmental results
  - Incorporates stochastic analysis of model parameters with @RISK
- **Model Functionality**
  - **Scenario Selector:** Visualization of results
  - **Scenario Editor:** Parameter values and distributions
  - **Reporting Units:** SI/US – energy/mass/volume
  - **Baseline Values:** Reference value for visualization
  - **Allocation Methods:** Energy, System Expansion, Combined
  - **GWP Factor:** IPCC 2007/2010 – 20, 100, 500 year time horizon
  - **Report:** Detailed statistics complete with parameter histograms



Environmental (Greenhouse Gas) Performance

Proprety	Units	Scenario 1: 0% Biomass	Scenario 2: 10% Biomass, Chipped	Scenario 3: 20% Biomass, Chipped	Scenario 4: 10% Biomass, Torrefied	Scenario 5: 20% Biomass, Torrefied	Scenario 6: 10% Biomass, Microchipped, Separate Gasifiers
Raw Material Acquisition	g CO_2e / MJ	1.90E+00	-6.12E+00	-1.45E+01	-4.04E+00	-9.85E+00	-6.56E+00
Coal Mining, Surface	g CO_2e / MJ	1.90E+00	1.75E+00	1.59E+00	1.69E+00	1.49E+00	1.79E+00
Biomass Production and Field Chipping	g CO_2e / MJ	0.00E+00	-8.91E+00	-1.83E+01	-6.48E+00	-1.29E+01	-9.46E+00
Biomass Direct Land Use Change	g CO_2e / MJ	0.00E+00	2.21E-01	4.54E-01	1.61E-01	3.19E-01	2.35E-01
Biomass Indirect Land Use Change	g CO_2e / MJ	0.00E+00	8.25E-01	1.69E+00	5.99E-01	1.19E+00	8.76E-01
Raw Material Transport	g CO_2e / MJ	3.24E+00	3.01E+00	2.78E+00	3.33E+00	3.41E+00	3.09E+00
Biomass Transport to Torrefaction Facility	g CO_2e / MJ	0.00E+00	0.00E+00	0.00E+00	1.86E-02	3.70E-02	0.00E+00
Biomass Torrefaction	g CO_2e / MJ	0.00E+00	0.00E+00	0.00E+00	4.00E-01	7.92E-01	0.00E+00
Transport of Chipped or Torrefied Biomass to CBTL Plant	g CO_2e / MJ	0.00E+00	2.95E-02	6.03E-02	2.14E-02	4.24E-02	3.13E-02

Model Overview: Scenario Editor

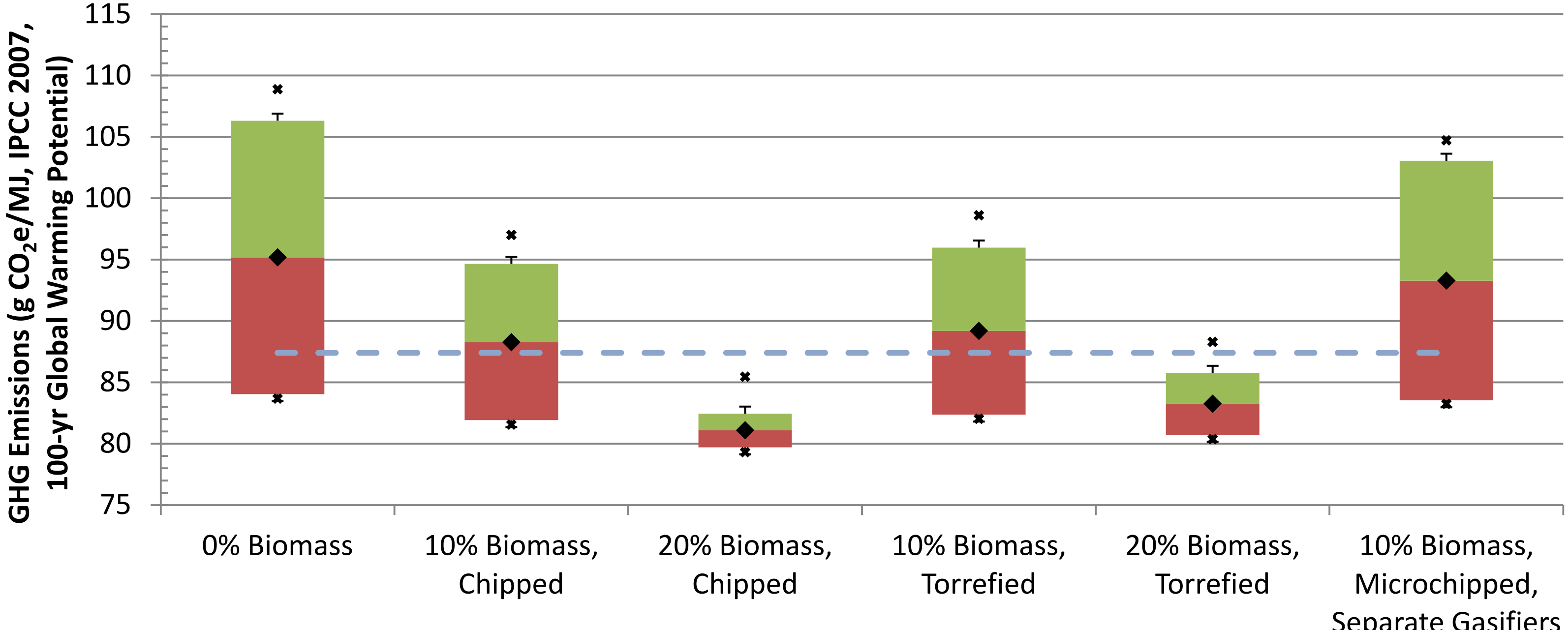


Name	Unit	Low	Exp	High
Coal Mine Methane	scf/ton	31.99	39.99	47.98
Biomass Yield	kg/acre	2,993.71	6,350.29	7,620.35
Chip Type	0 = Conventic	0	0	1
Direct Land Use	kg/kg biomas	2.24E-02	2.24E-02	2.24E-02
Indirect Land Use	kg/kg biomas	5.52E-02	8.28E-02	1.10E-01
Rail Distance	miles (one-wa	1280	1600	1920
Biomass Truck Distanc	miles (one-wa	20	40	50
Biomass Truck Distanc	miles (one-wa	40	50	60
CBTL Plant Operations	Low/Exp/High	20%	60%	20%
CO_2 Pipe Distance	miles (one-wa	620	775	930
CO_2 Pipe Loss Rate	% / km	1.30E-07	2.60E-07	3.90E-07
Blended Jet Pipe Lengt	miles (one-wa	180	225	270
Blended Jet Alt Transp	1 = 100% pip	1	1	0

Name	Unit	Low	Exp	High
Global Capital Cost Fac	Unitless	0.9	1.0	1.3
Capacity Factor	Unitless	0.85	0.90	0.92
Capital Recovery Facto	Unitless	0.2129	0.2365	0.2602
Labor Cost Index	Unitless	0.9	1.0	1.2
Taxes and Insur	frac of TPC	0.0160	0.0200	0.0240
FT Catalyst	$/lb	2.1	3.0	3.9
Project Contingency	Unitless	0.1	0.2	0.2
Coal Cost	$/ton	34.45	36.26	38.07
Raw Chipped Biomass	$/dry ton	39.29	43.65	48.02
Raw Microchipped Bio	$/dry ton	41.72	46.36	50.99
Torrefied Biomass Cost	$/ton	121.19	134.66	148.13
Other Owner's Costs	frac of TPC	0.12	0.15	0.18
Power Credit	$/MWh	63.53	70.59	77.65
CO_2 EOR Credit	$/tonne	28	40	52
Diesel:Jet fuel equivale	Unitless	0.95	0.99	1.00
Naphtha:Jet fuel equiv.	Unitless	0.62	0.69	0.76
LPG:Jet fuel equivalent	Unitless	0.35	0.40	0.50
Crude Oil Equivalent D	Unitless	1.1	1.2	1.3

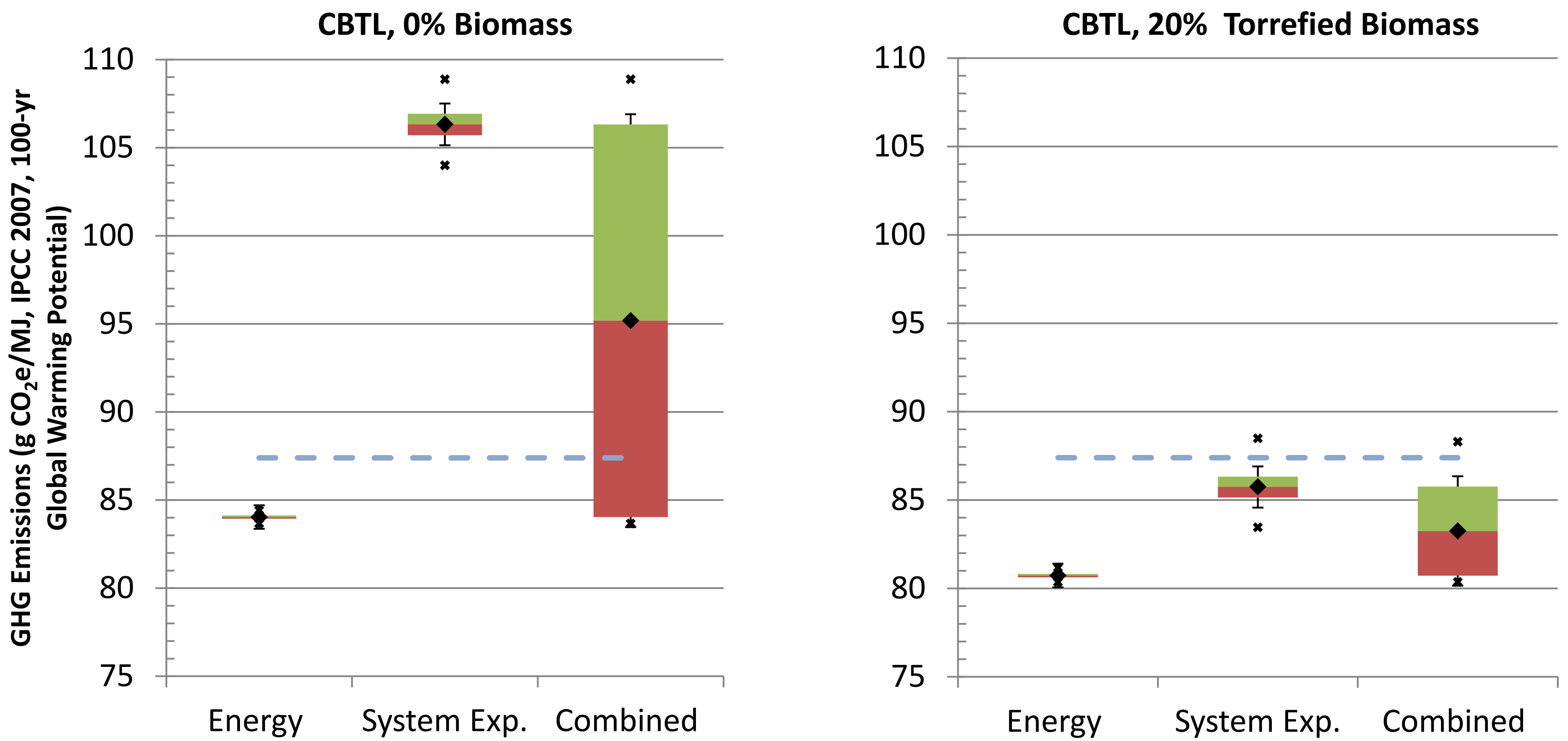
- Scenario Editor allows the user to change parameter values and statistical distributions at the global level or down at the individual scenario level
- Parameters are organized by life cycle stage
- Distribution choices include discrete, uniform, and triangular

Model Output: Comparison of Scenario Life Cycle GHG Emissions



- Horizontal line: Conventional Petroleum Based Jet Fuel Baseline = 87.4 g CO_2e/MJ of fuel combusted
- Only CBTL, 20% Chipped Biomass is always under EISA baseline; however all scenarios could meet or exceed the EISA baseline
- CBTL, 20% Chipped Biomass = 15% reduction in GHG emissions over CBTL, 0% Biomass, on average; separate gasifiers GHG emissions 6% higher than CBTL,10% Chipped Biomass scenario
- Chipped Biomass = slightly lower GHG emissions than Torrefied Biomass
- Combined Co-Product Management = System Expansion plus Energy Allocation

Results for Co-Product Management Scenario



- Key consideration for other scenarios is co-product management strategy
  - Energy allocation is always below the baseline value, system expansion generally spans or is entirely above the baseline value (within the context of this study)
- Primary driver of GHG emissions uncertainty is the choice of co-product management strategy
- Technical modeling properties and model choices drive comparatively minimal variability in life cycle GHG emissions results

Study Conclusions

- Co-product management is a key GHG emissions consideration
  - System expansion consistently results in higher life cycle GHG emissions than energy allocation within this study
  - Optimizing life cycle performance, including CBTL facility performance, also causes variability in life cycle GHG emissions
  - Variability from co-product management accounting procedure drives the greatest uncertainty in GHG emissions (Improvements in current technical and environmental modeling data uncertainty will not change this conclusion)
  - EISA does not specify a co-product management method for LCA
- Biomass feed rate also a key emissions consideration
  - Two scenarios that utilized 20% biomass had lowest life cycle GHG emissions
  - CTL 0% Biomass scenario had highest life cycle GHG emissions
  - Biomass uptake of atmospheric carbon partially offsets carbon emissions during energy conversion and fuel combustion

All scenarios modeled have the potential to have life cycle GHG emissions less than or equal to the life cycle emissions from conventional jet fuel based on uncertainty analysis of the results.

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