Life Cycle Analysis (LCA) of Biofuels and Land Use Change with the GREET® Model

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Biofuel Pathways in GREET and
Land Use Change and Land Management Effects in CCLUB

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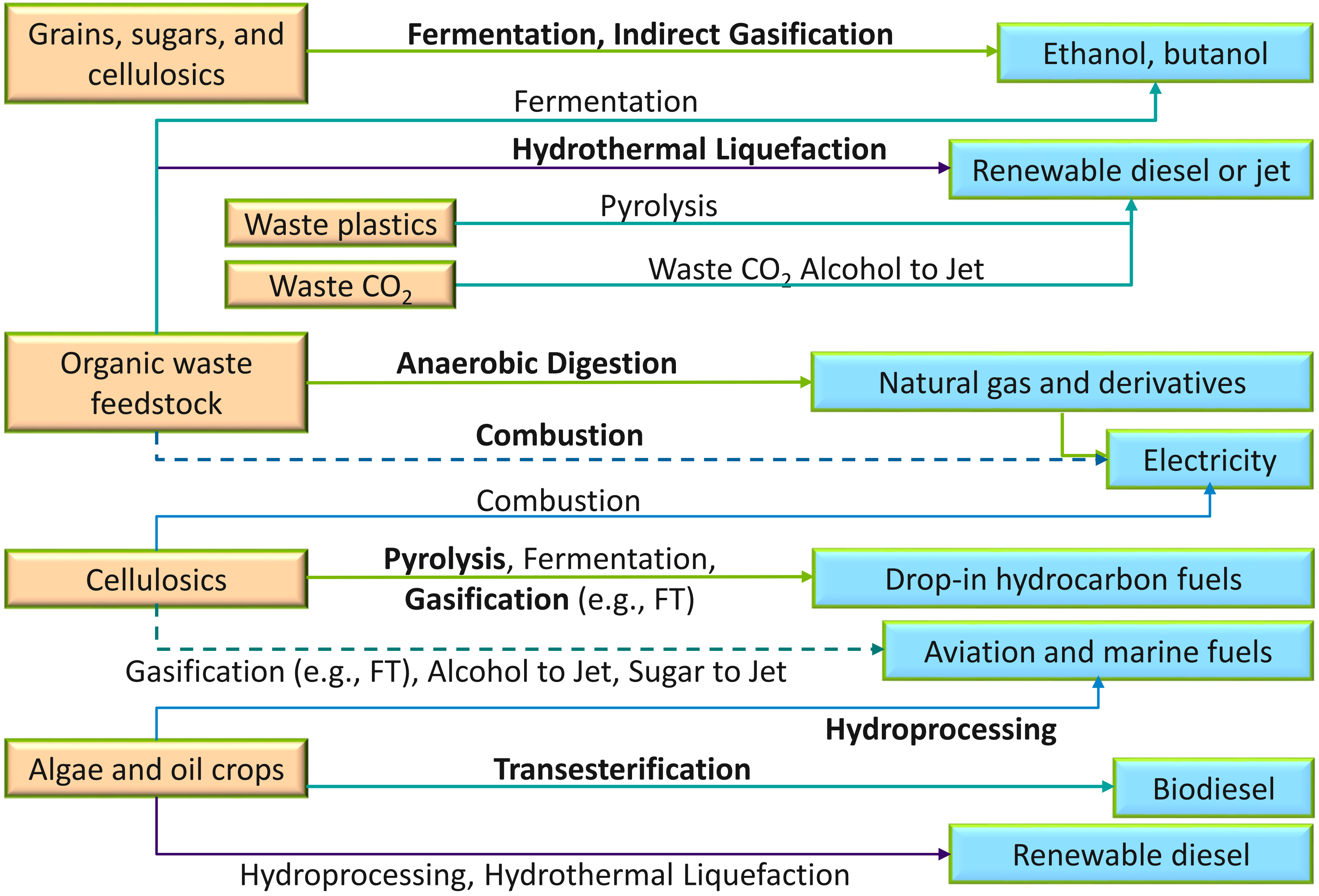
GREET includes various biomass feedstocks, conversion technologies, and fuels for biofuel LCA



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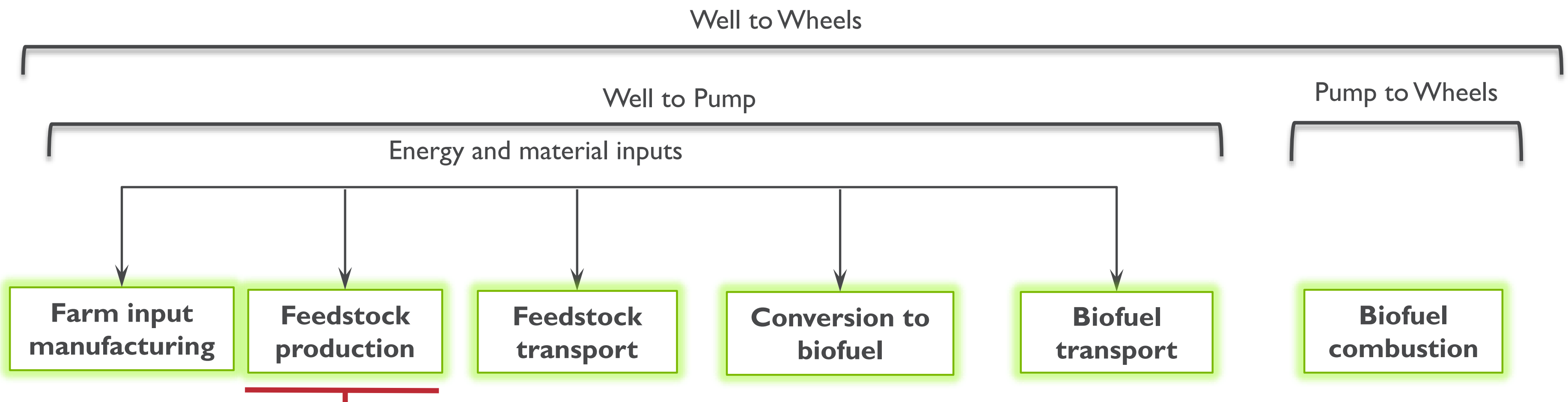
The system boundary of biofuel LCA



Considers GHG emissions from LUC for different biofuel pathways

Land Use Change

- Carbon Calculator for Land Use change from Biofuels production (CCLUB)
- Feedstock average soil C and soil nitrous oxide (N_2O)

Land Management Practices

Carbon Calculator for Land Use change from Biofuels production (CCLUB) relies on GTAP and emission factors

Biofuel scenarios

- An increase in corn ethanol production from its 2004 level (3.41 billion gallons[BG]) to 15 BG

Computable general equilibrium economic model (GTAP)

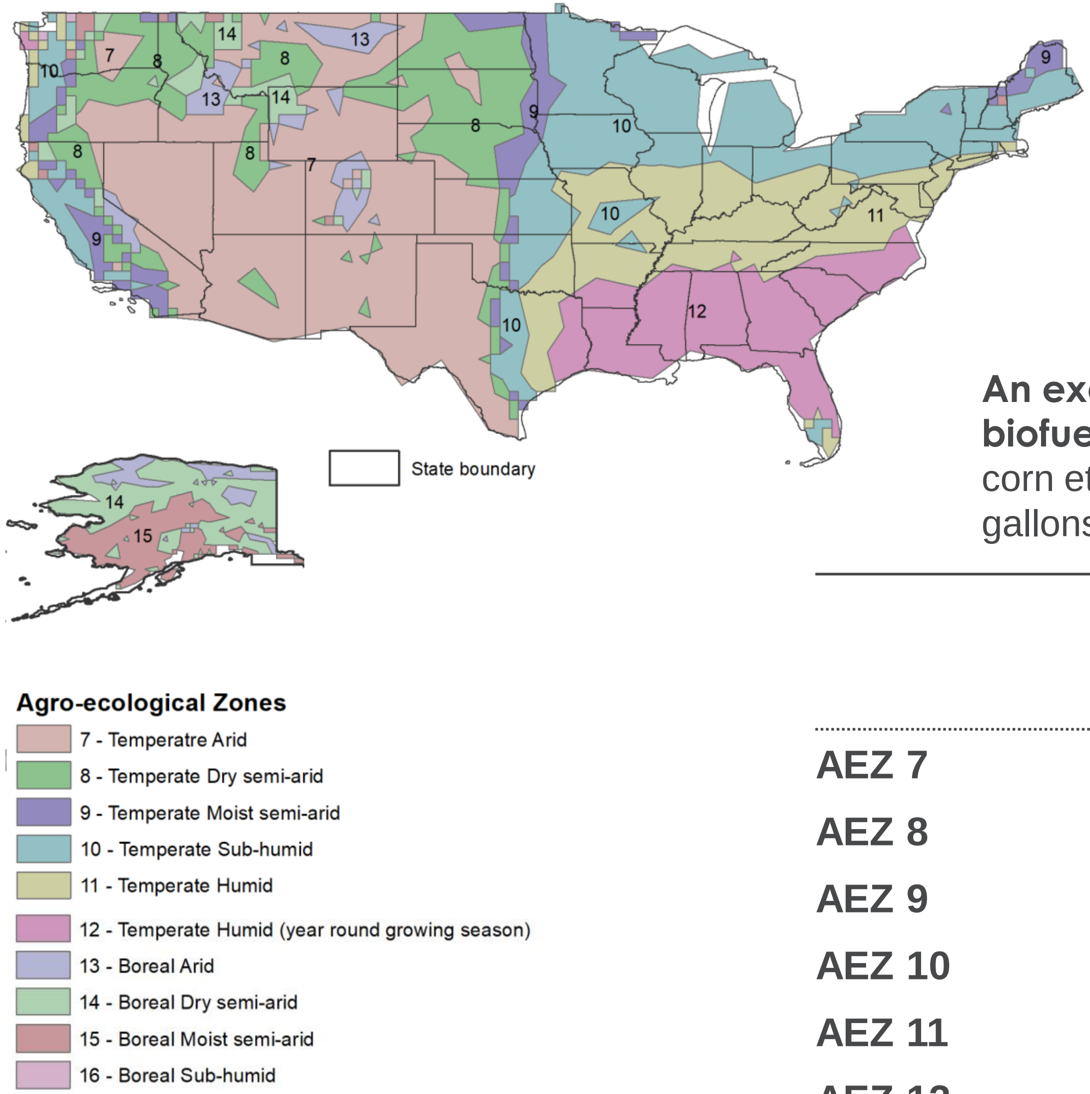
- Estimate land conversion associated with scenarios

Soil C and N_2O emission factors related to LUC

- International/domestic emission factors are derived from Winrock / Woods Hole database
- Domestic emission factors can be modeled using US county-level soil C simulations

Biofuel scenarios include nine different cases *(CCLUB manual, 2018)*

Case	Case Description	BG
1	An increase in corn ethanol production from its 2004 level (3.41 BG) to 15 BG (Corn Ethanol 2011)	11.59
2	An increase of ethanol from corn stover by 9 BG, on top of 15 BG corn ethanol	9
3	An increase of ethanol from Miscanthus by 7 BG, on top of 15 BG corn ethanol	7
4	An increase of ethanol from switchgrass by 7 BG, on top of 15 BG corn ethanol	7
5	An increase in corn ethanol production from its 2004 level (3.41 BG) to 15 BG with GTAP recalibrated land transformation parameters (Corn Ethanol 2013)	11.59
6	Increase in soy biodiesel production by 0.812 BG (CARB case 8)	0.812
7	Increase in soy biodiesel production by 0.812 BG (CARB average proxy)	0.812
8	Increase in soy biodiesel production by 0.8 BG (GTAP 2004)	0.8
9	Increase in soy biodiesel production by 0.5 BG (GTAP 2011)	0.5



GTAP estimates land use impacts on three land types by agricultural ecological zones (AEZ)

An example of domestic land use impacts of biofuels based on case 1 scenario: An increase in corn ethanol production from its 2004 level (3.41 billion gallons [BG]) to 15 BG

	Land Cover (ha)		
	Forest	**Grasslands**	**Cropland/Pasture**
AEZ 7	-3,479	-340,320	-224,128
AEZ 8	-16,931	-133,912	-102,281
AEZ 9	-2,022	-10,238	-64,792
AEZ 10	-179,636	-82,626	-403,376
AEZ 11	-93,360	-42,881	-298,278
AEZ 12	-30,064	-14,111	-74,470

Three land types are available for conversion to feedstock production

- ✓ Forest: primarily private forest land
- ✓ Grasslands
- ✓ Cropland/pasture:
  - USDA: Generally is considered to be in long-term crop rotation. This category includes acres of crops hogged or grazed but not harvested and some land used for pasture that could have been cropped without additional improvement.
  - CCLUB: Pasture (past) ⟶ Cropland (past) ⟶ cropland/pasture (present)
- ✓ Questions for cropland/pasture
  - The frequency of switches between cropland and pastureland phases influences soil C levels, but this frequency is not well understood (Emery *et al.* 2017).
  - Soil C stock of cropland/pasture
    - Medium SOC of grasslands (CCLUB prior 2014)
    - Low SOC for low productivity cropland (CCLUB post 2014)
    - High SOC for grasslands (Others)
  - CCLUB domestic emission factors vs. other domestic emission factors

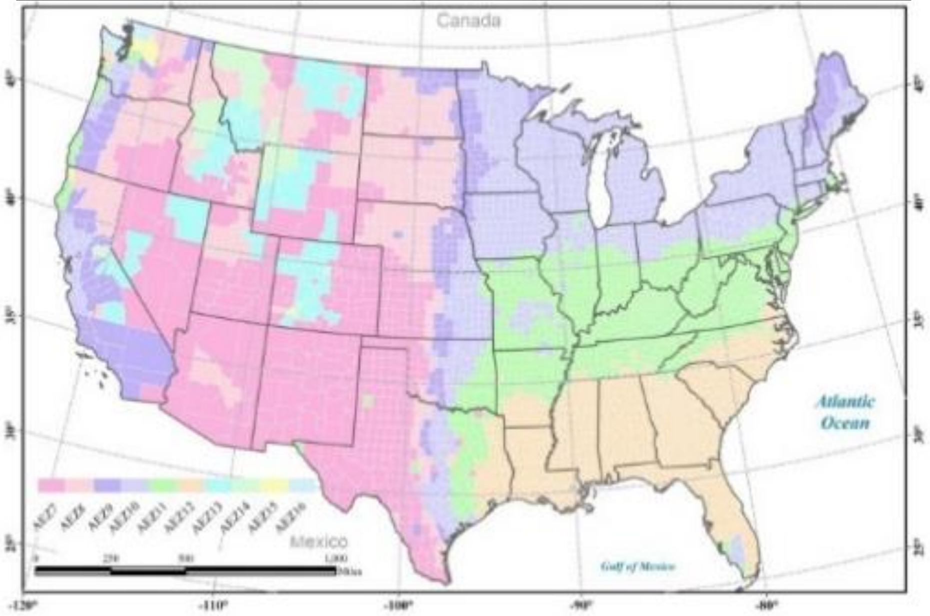
Land use history is considered in modeling domestic soil C emission factors
(Parameterized CENTURY, Kwon et al. Biomass Bioenergy 2013)

Scenario	Pristine (prior to 1880)	Early Agriculture (1880-1950)	Modern Agriculture (1951-2010)	Land Use Change (2011-2040, a 30 yr time-frame)	
1	Grasslands	Croplands	Croplands	Corn	Conventional Tillage
3					Reduced Tillage
5					No Till
11	Grasslands	Grasslands	Grasslands	Corn	Conventional Tillage
13					Reduced Tillage
15					No Till
21	Forest	Forest	Forest	Corn	Conventional Tillage
23					Reduced Tillage
25					No Till
31	Grasslands	Cropland	Grasslands(1951-1975) /Cropland (1976-2010)	Corn	Conventional Tillage
33					Reduced Tillage
35					No Till

Spatiotemporal database along with land use history are key inputs for a process-based soil C modeling

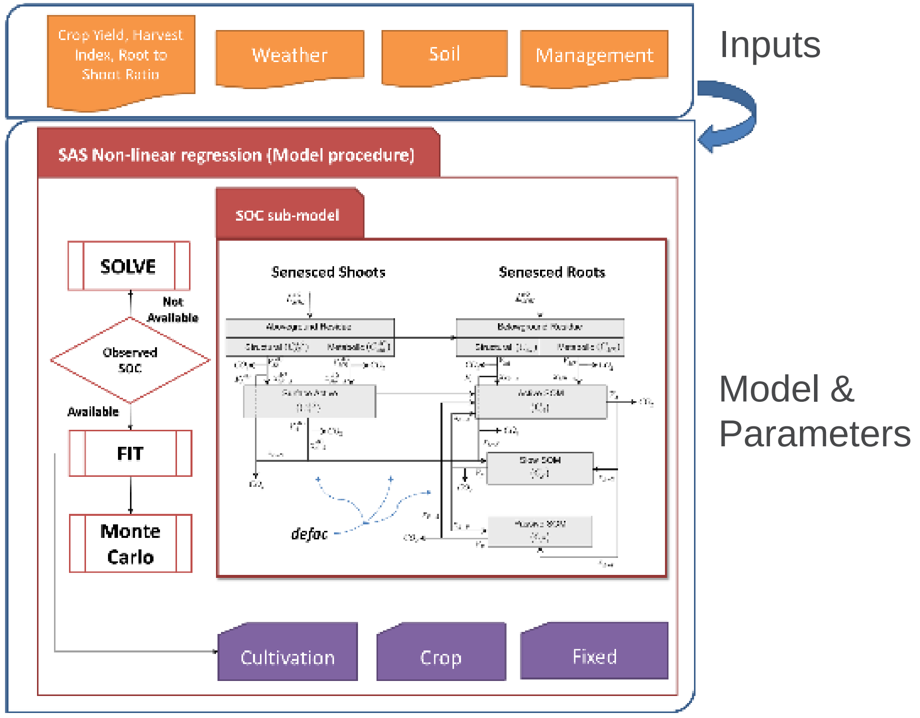
Spatiotemporal database

Monthly climate data
Soil characteristics
Historical corn yields by county

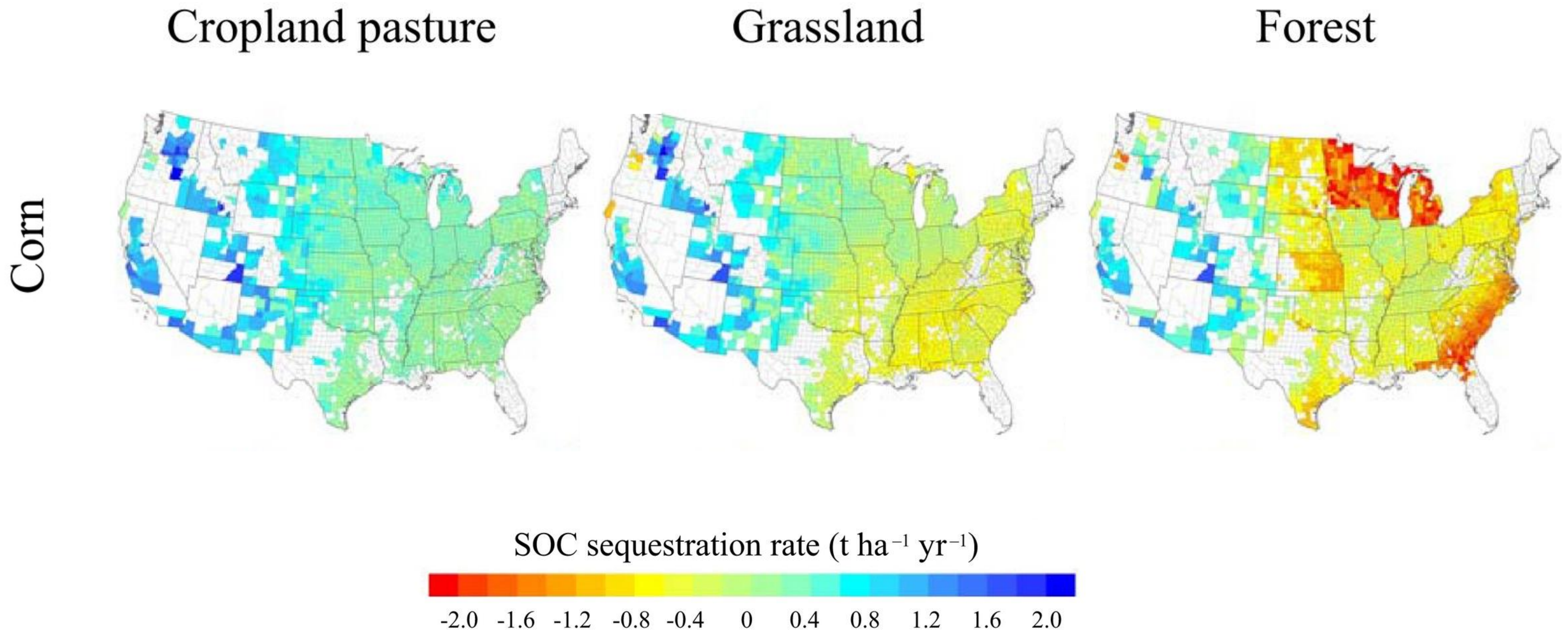


Process-based model (Parameterized CENTURY)

Monthly soil C change

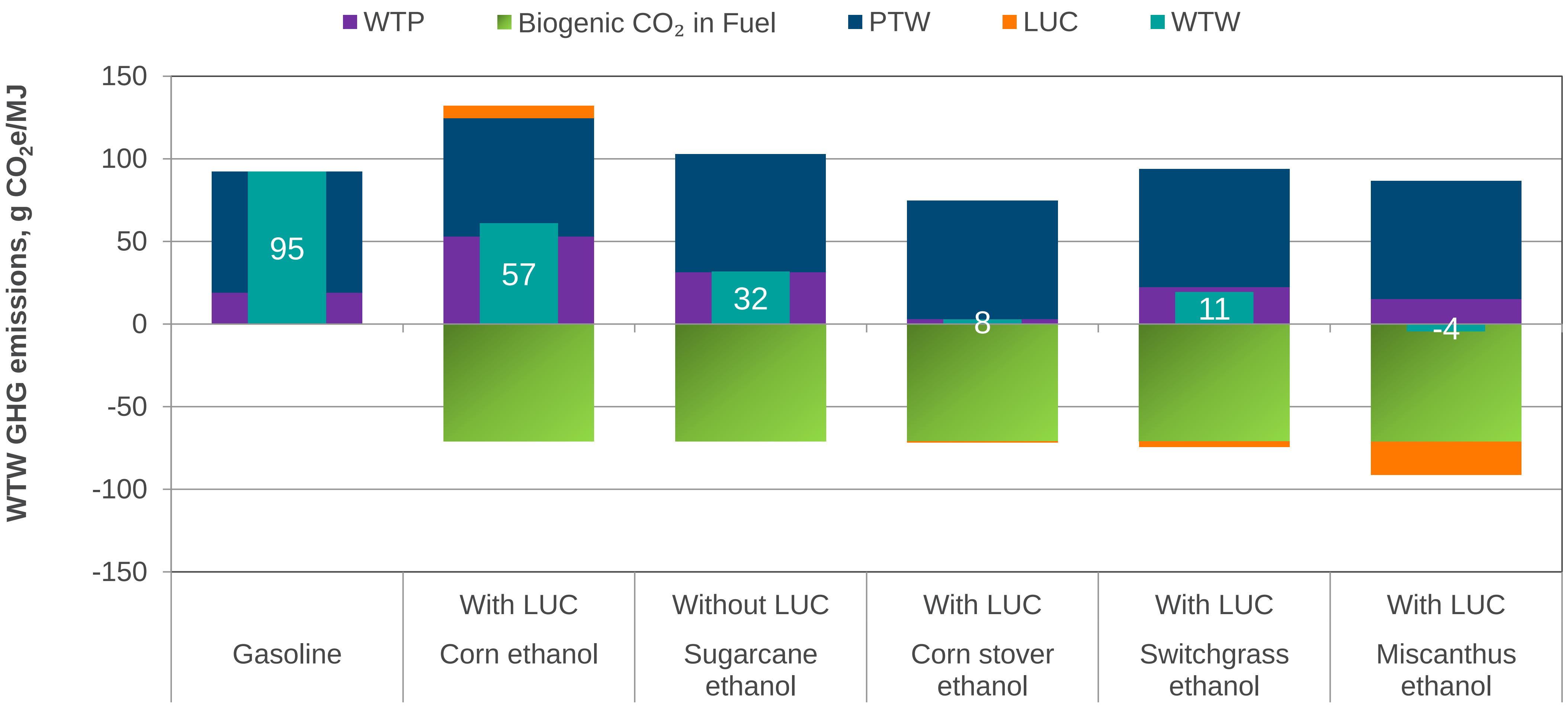


US county-level soil C sequestration rate are employed as domestic soil C emission factors



Qin et al., *GCB Bioenergy*, 2016

Estimated LUC and life-cycle GHG emissions for corn ethanol are 5.4 (international) and 1.4~4.3 (domestic) g CO_2e/MJ, respectively



Based on GREET 2018

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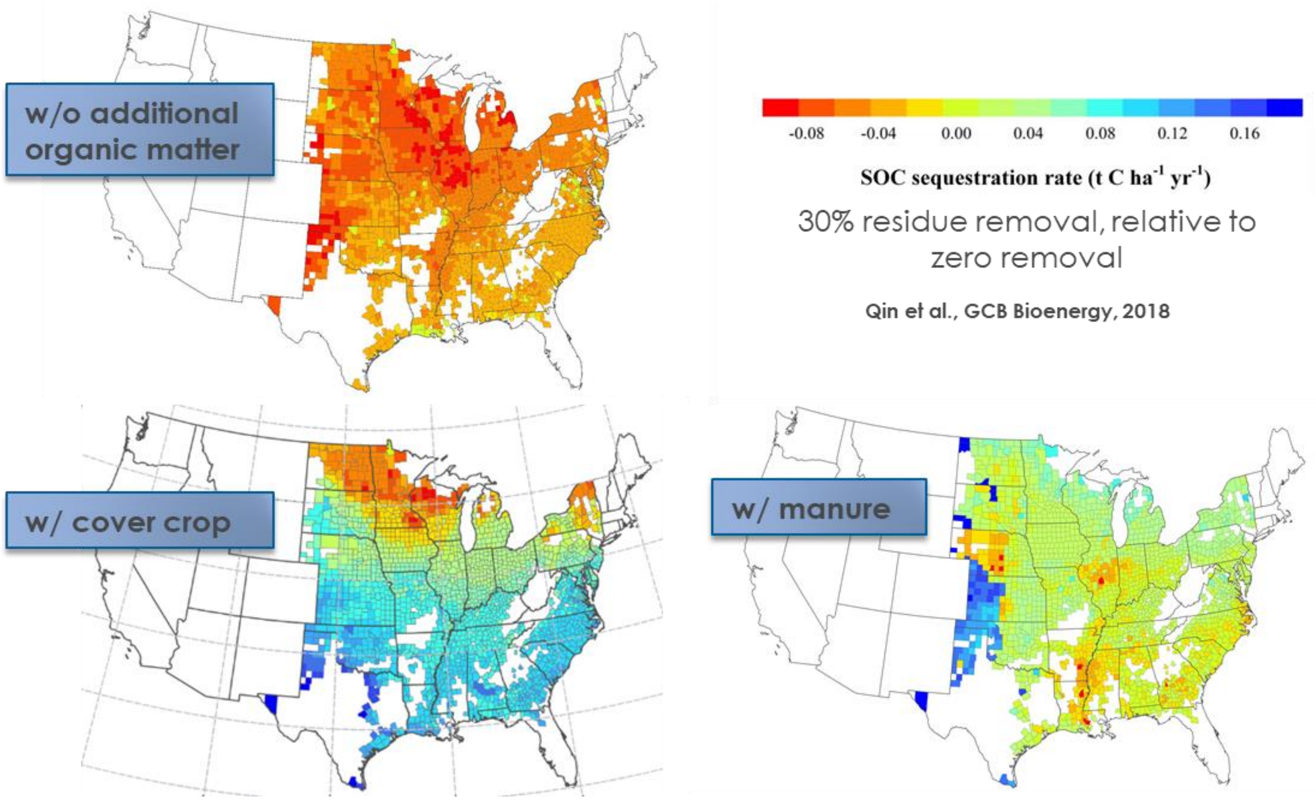
CCLUB assesses land management impacts on corn stover biofuels' GHG emissions

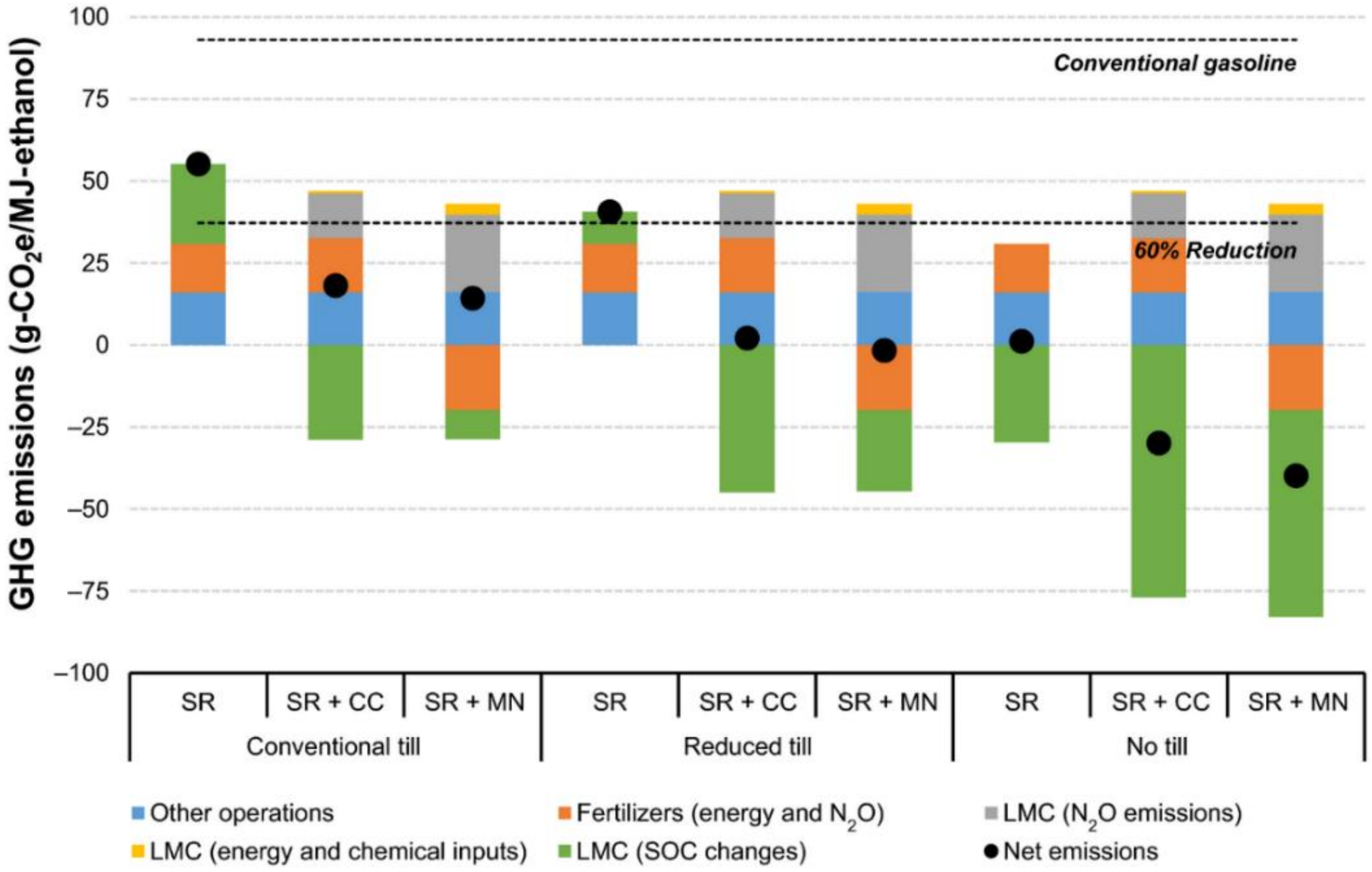
Farming Scenarios

Corn stover removal with
- Tillage
- Cover cropping
- Animal manure

Soil C emission factors associated with a 30% corn stover removal



Soil C change upon LMC may dramatically affect corn stover ethanol GREET LCA GHG results



Soil C impacts

SR: Stover removal
MN: manure
CC: cover crop

The results are based on the marginal allocation approach where all burdens and benefits of the LMC practices are assigned to stover ethanol (Qin et al., GCB Bioenergy 2018)

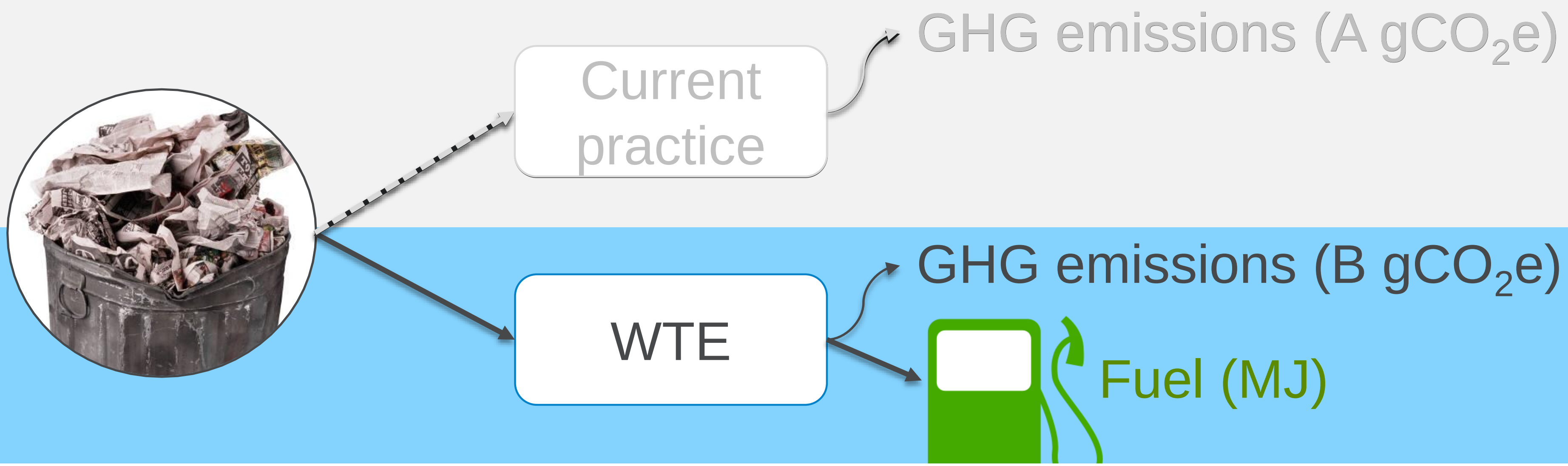
Waste-derived Fuel Production Pathways in GREET

Life-cycle GHG emissions of WTE pathways compared to conventional waste management practices

Conventional Waste Management	WTE
+ Carbon in waste is partly sequestered - Non-collected CH_4 emission influences global warming significantly	+ Generates fuels displacing fossil fuel + Avoid emissions from conventional waste management - Carbon in waste is released into atmosphere

Avoided emissions are considered for the LCA of WTE pathways

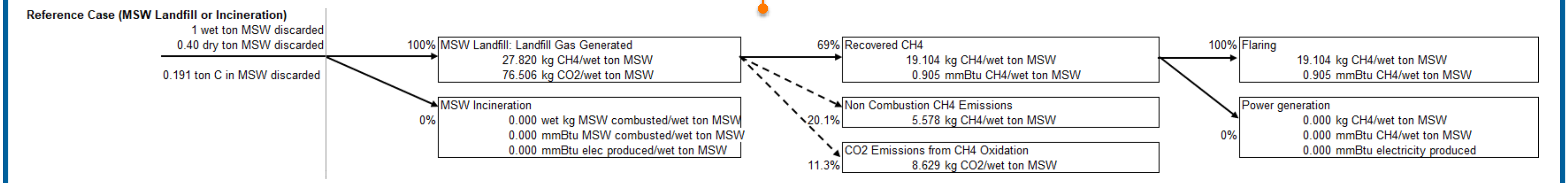
- Using waste avoids emissions from conventional waste management practices.
  - Waste is not intentionally produced.
  - Waste management is regulated.

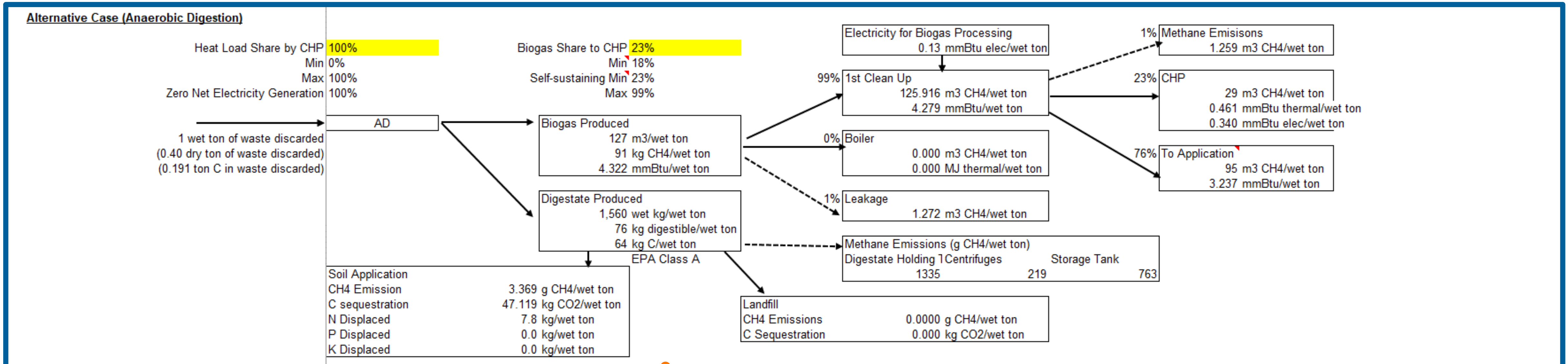


- Fuel production and combustion emissions: B gCO_2e/MJ.
- By diverting waste, emissions associated with current waste management A gCO_2e can be avoided.
- (B-A) gCO_2e/MJ indicates the GHG impact of MJ of fuel produced and used.

GREET renewable natural gas tab

Consider BAU energy use and emissions avoided due to diversion for fuel production





Consider all associated energy use and emissions for waste-derived fuel production

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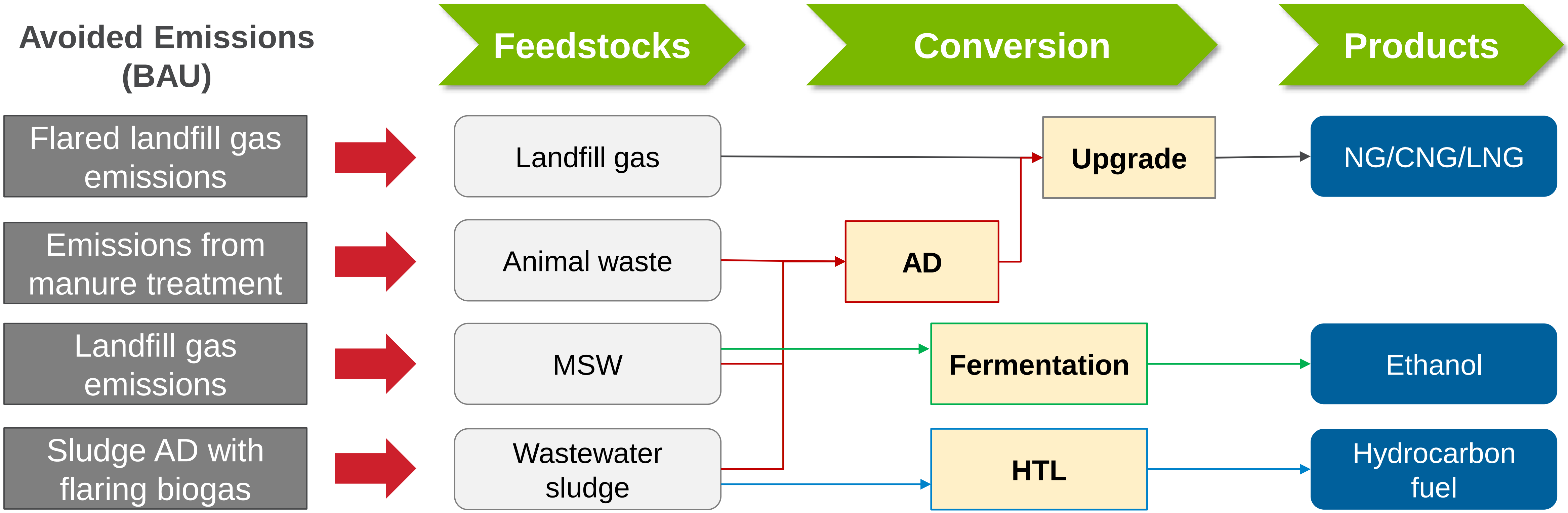
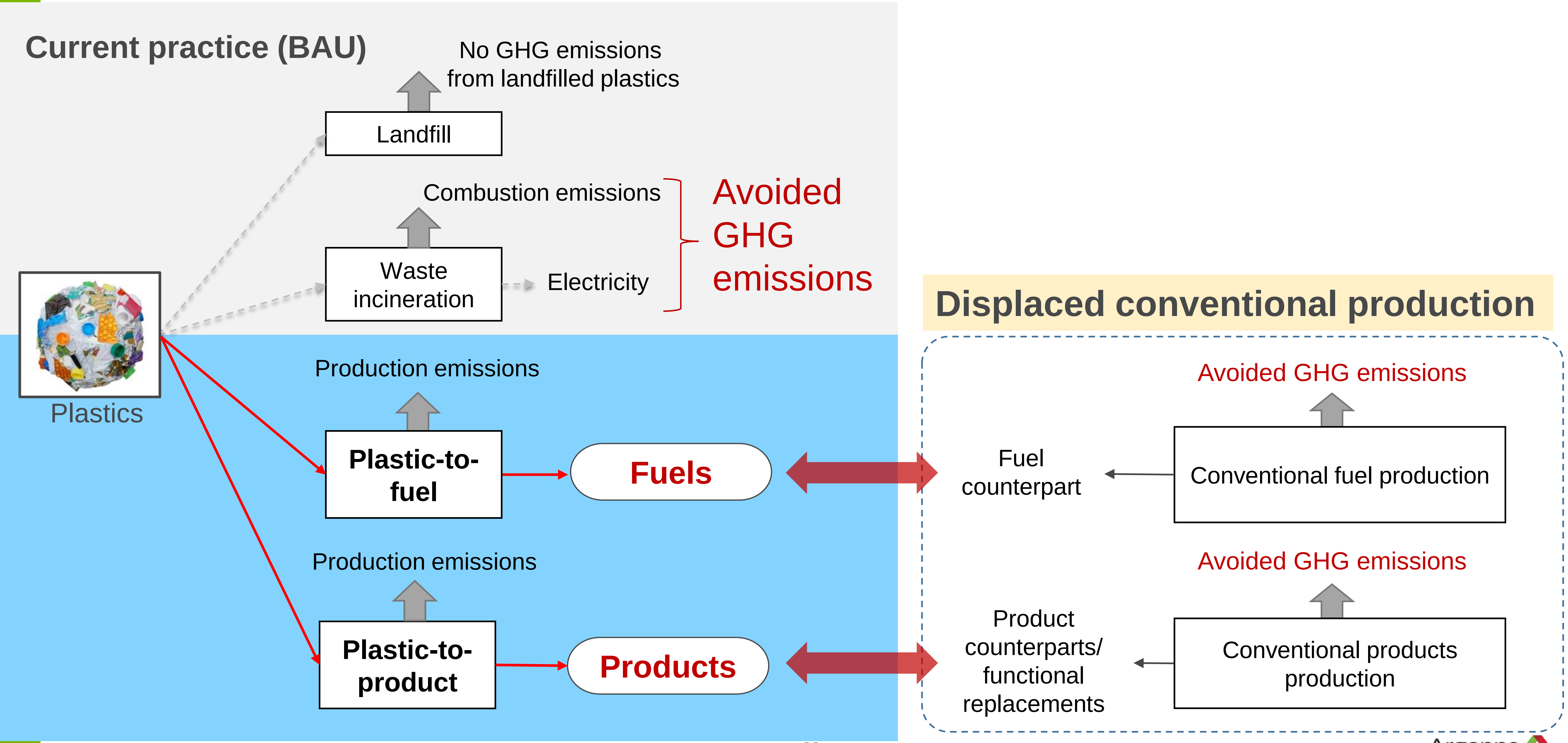
WTE pathways can provide significant WTW GHG reductions due to no upstream emission burdens and avoided BAU emissions

- Diverting waste from current practices with high GHG emissions brings the highest environmental benefits.

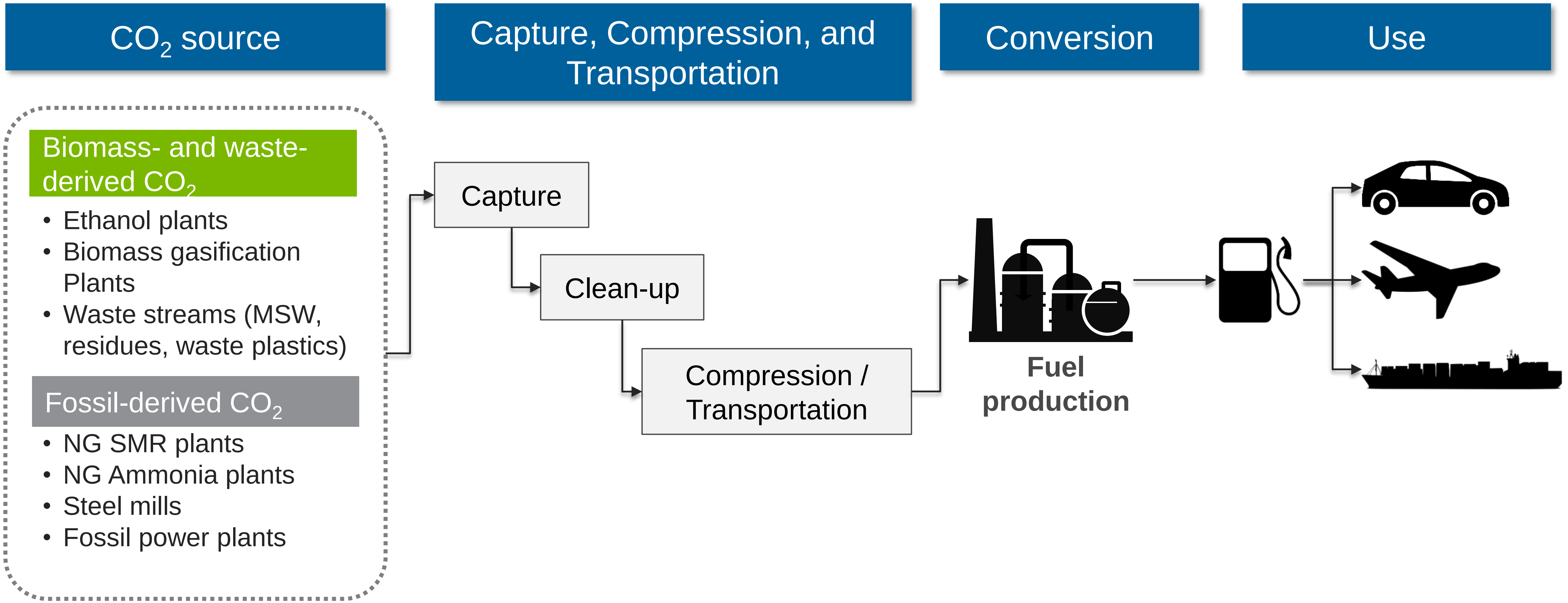
Pathways in GREET



LCA for waste plastic-based fuels and products



LCA of CO_2 utilization (on-going, FY20)



- In FY20, Argonne plans to incorporate a CO_2 utilization module, converting CO_2 from corn ethanol plants into fuels using NREL's conversion technologies.
- It will further include other CO_2 sources and conversion technologies.

GREET for ICAO (International Civil Aviation Organization) Fuels Task Group for Sustainable Jet Fuel Pathways

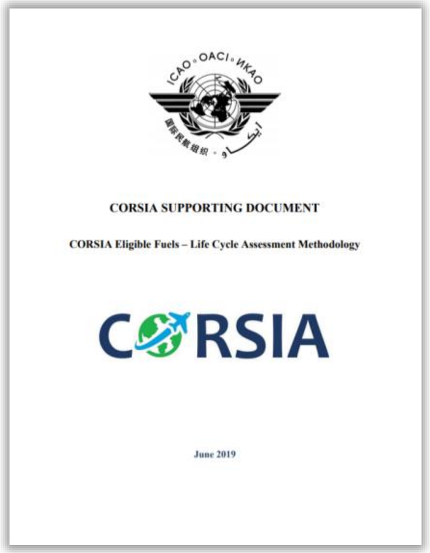
UN ICAO's CORSIA: solutions for sustainable growth of international aviation

- Fuel consumption reduction: More efficient aircraft, shorter routing, and optimized management and planning
- GHG emissions reduction: Low-carbon bio-based jet fuels, such as hydroprocessed renewable jet (HRJ), biomass-based Fischer-Tropsch jet (FTJ), Sugar-To-Jet (STJ), Alcohol-To-Jet (ATJ), etc.

- ICAO and international airline operators are committed to have carbon growth neutral from 2020 through Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).

Argonne supported ICAO to evaluate life-cycle GHG emissions of various jet fuel production pathways

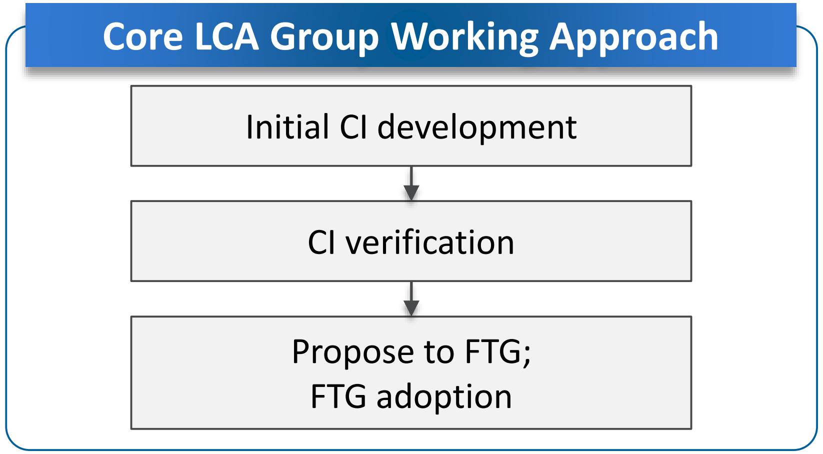
- Argonne is a member of the ICAO Fuels Task Group (FTG) tasked with modeling carbon intensities for CORSIA.
- Argonne is part of FTG's core LCA group with MIT, EC JRC, & U of Toronto
  - developing core LCA values for alternative jet fuels
  - writing the guidance document for LCA data submission


CORSIA SUPPORTING DOCUMENT

CORSIA Eligible Fuels – Life Cycle Assessment Methodology

CORSIA

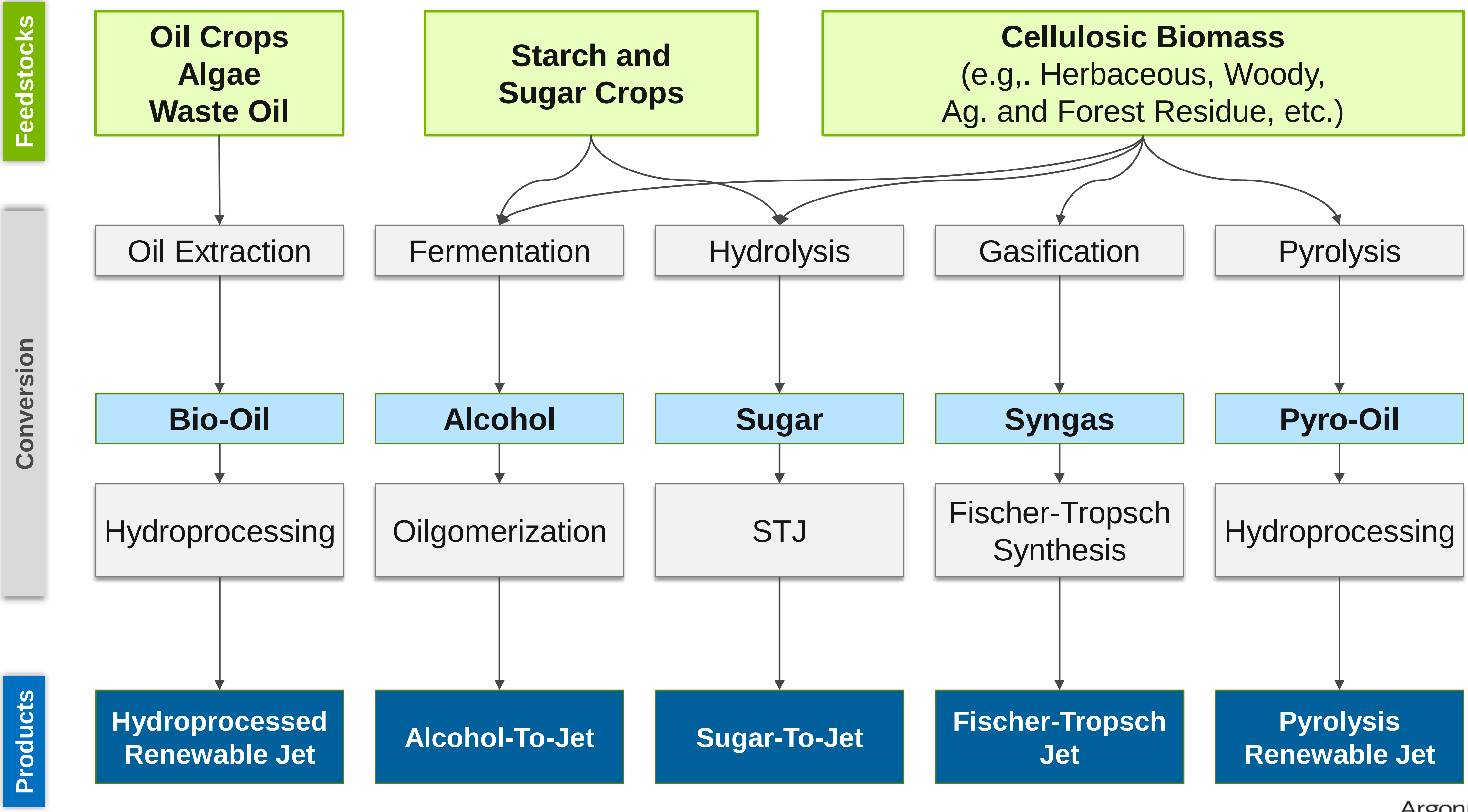
June 2019



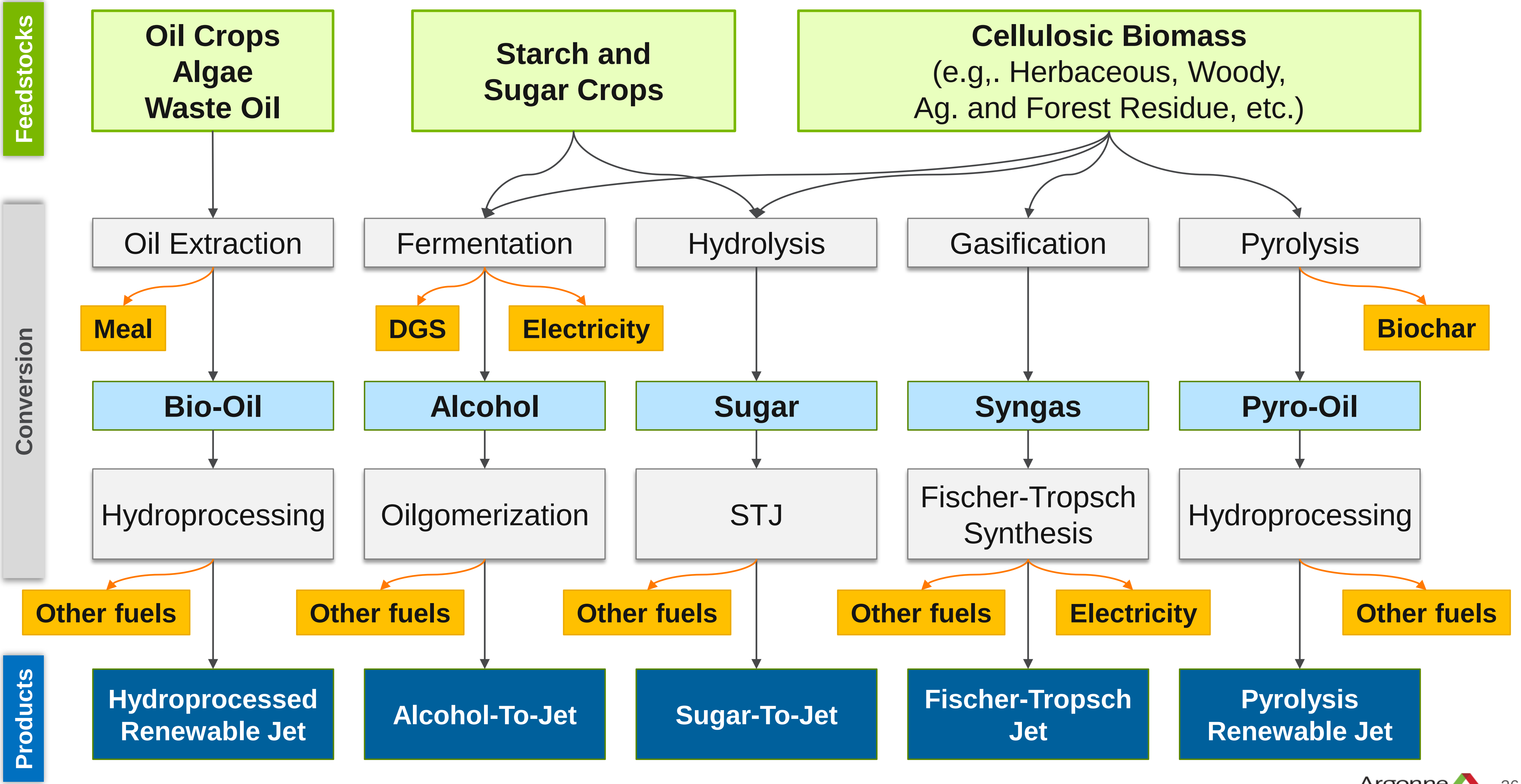
	Feedstock	Core LCA value [gCO_2e/MJ]
Fischer-Tropsch	Agricultural residues	7.7
	Forestry residues	8.3
	MSW, 0% NBC	5.2
	MSW, NBC as % of total C	NBC*170.5 + 5.2
	Short-rotation woody crops	12.2
	Herbaceous energy crops	10.4
Hydro-processed Esthers & Fatty Acids (HEFA)	Tallow	22.5
	Used cooking oil	13.9
	Palm fatty acid distillate	20.7
	Corn oil	17.2
	Soybean	40.4
	Rapeseed/canola	47.4
	Camelina	42
	Palm oil - closed pond	37.4
	Palm oil - open pond	60.0
	Brassica carinata	34.4
SIP	Sugarcane	36.6
	Sugarbeet	32.4
Isobutanol to Jet	Sugarcane	27.8
	Agricultural residues	29.3
	Forestry residues	23.8
	Corn grain	55.8
	Herbaceous energy crops	43.4
	Molasses	27.0
EtOH to Jet	Sugarcane	24.1
	Corn grain	65.7

Note: NBC – Non-biogenic carbon

Bio-aviation fuel pathways by feedstock



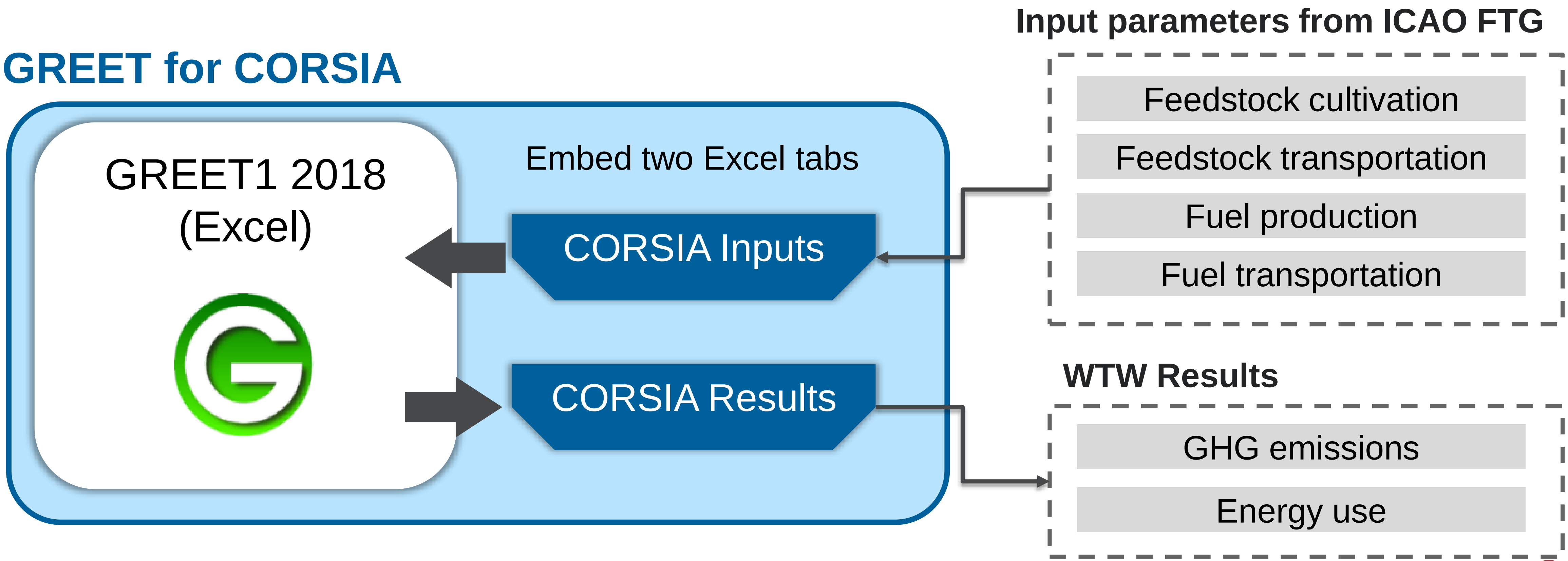
Co-products in the bio-aviation fuel pathways



Note: DGS denotes Distillers' Grains with Solubles. Other fuels include fuel gas, naphtha and distillates

Overview of ‘GREET for CORSIA’

- ICAO approved sustainable aviation fuel production pathways are implemented in GREET 2018.
- Using the GREET version for CORSIA, the LCA parameters and results of sustainable aviation fuel pathways can be observed in a transparent way.
- Argonne plans to build an upgraded version in GREET 2019.



GREET for CORSIA inputs tab

[Preliminary] GREET for CORSIA Input Parameters for LCA of Sustainable Aviation Fuels

Electricity grid: 1 — 0: User-defined, 1: US, 2: Eurpoe, 3: Latin America, 4: Canada

Data Sources

Conversion	Feedstock	Selected Data	0	1	2	3	4
FTJ	Switchgrass	1	User-defined	ANL/MIT (US)	ANL/MIT (EU)	JRC	
	Miscanthus	1	User-defined	ANL/MIT (US)	ANL/MIT (EU)		
	Poplar	1	User-defined	ANL/MIT (US)	ANL/MIT (EU)	JRC	
	Willow	1	User-defined	ANL/MIT (US)	ANL/MIT (EU)		
	Eucalyptus	1	User-defined	ANL/MIT (US)	JRC		
	Corn Stover	1	User-defined	MIT	JRC		
	Wheat Straw	1	User-defined	MIT	JRC		
	Forest Residue	1	User-defined	ANL/MIT	JRC		
	MSW	1	User-defined	MIT			
HEFA	Tallow	1	User-defined	MIT	JRC		
	Used cooking oil	1	User-defined	MIT	JRC		
	Palm fatty acid distillate	1	User-defined	ANL	JRC		
	Corn oil	1	User-defined	ANL	JRC		
	Soybean	1	User-defined	GREET (US)	BioGrace (EU)	Latin America	JRC (EU)
	Rapeseed/canola	1	User-defined	GREET (US)	BioGrace (EU)	GHGenius (Canada)	JRC (EU)
	Camelina	1	User-defined	GREET (US)	GHGenius (Canada)	JRC (EU)	
	Palm oil - closed pond	1	User-defined	ANL	JRC		
	Brassica carinata	1	User-defined	ANL/U of T (N.America)			
SIP	Sugarcane	1	User-defined	MIT	JRC	CTBE	
	Sugarbeet	1	User-defined	MIT	JRC		
Isobutanol_ATJ	Sugarcane	1	User-defined	MIT	JRC	CTBE	
	Agricultural residues	1	User-defined	MIT	JRC		
	Forestry residues	1	User-defined	MIT	JRC		
	Corn grain	1	User-defined	MIT	JRC		
	Switchgrass	1	User-defined	MIT	ANL/MIT (EU)	JRC	
	Miscanthus	1	User-defined	MIT	ANL/MIT (EU)	JRC	
	Molasses	1	User-defined	MIT	JRC	CTBE	
Ethanol_ATJ	Sugarcane	1	User-defined	MIT	JRC	CTBE	
	Corn grain	1	User-defined	MIT	JRC		

Data selection : Datasets can be selected from lookup tables:

- ICAO FTG input parameters
- or stakeholder own input parameters

Major Parameters

FT

Selected Parameters

Conversion pathways	FTJ - Herbaceous energy crops		FTJ - Short rotation woody crops			FTJ - Agricultural residues		FTJ - Forest residue	FTJ - MSW
Feedstocks	Switchgrass	Miscanthus	Poplar	Willow	Eucalyptus	Corn stover	Wheat Straw		
Data sources:	ANL/MIT (US)	ANL/MIT (US)	ANL/MIT (US)	ANL/MIT (US)	ANL/MIT (US)	MIT	MIT	ANL/MIT	MIT
Cultivation and Collection	per dry kg	per dry kg	per dry kg	per dry kg	per dry kg	per dry kg	per dry kg	per dry kg	per dry kg
Total N (g)	5.38	5.12	2.17	1.61	3.08				
P2O5 (g)	2.54	1.15	0.65	0.72	2.47				
K2O (g)	3.53	[illegible]	[illegible]	[illegible]	0.52				
CaCO3 (g)	6.45	[illegible]	[illegible]	[illegible]	4.32				
Herbicide (g)	0.06	[illegible]	[illegible]	[illegible]	0.01				
Insecticide (g)	0.00	[illegible]	[illegible]	[illegible]	0.00				
Diesel (Btu)	69.02	[illegible]	[illegible]	[illegible]	[illegible]	246.47	254.96	145.70	
Natural gas (Btu)	0.00	[illegible]	[illegible]	[illegible]	0.00	0.00	0.00	0.00	
Electricity (Btu)	5.36	4.10	0.00	0.46	0.00	0.00	0.00	0.00	
Feedstock Transportation									

Selected parameters

Lookup tables

FTJ - Herbaceous			
Switchgrass			
User-defined	ANL/MIT (US)	ANL/MIT (EU)	JRC
per dry kg	per dry kg	per dry kg	per dry
5.38	5.38	5.80	
2.54	2.54	0.90	
3.53	3.53	4.10	
6.45	6.45	0.00	
0.06	0.06	0.03	
0.00	0.00	0.00	
69.02	69.02	69.02	
0.00	0.00	0.00	
5.36	5.36	5.36	

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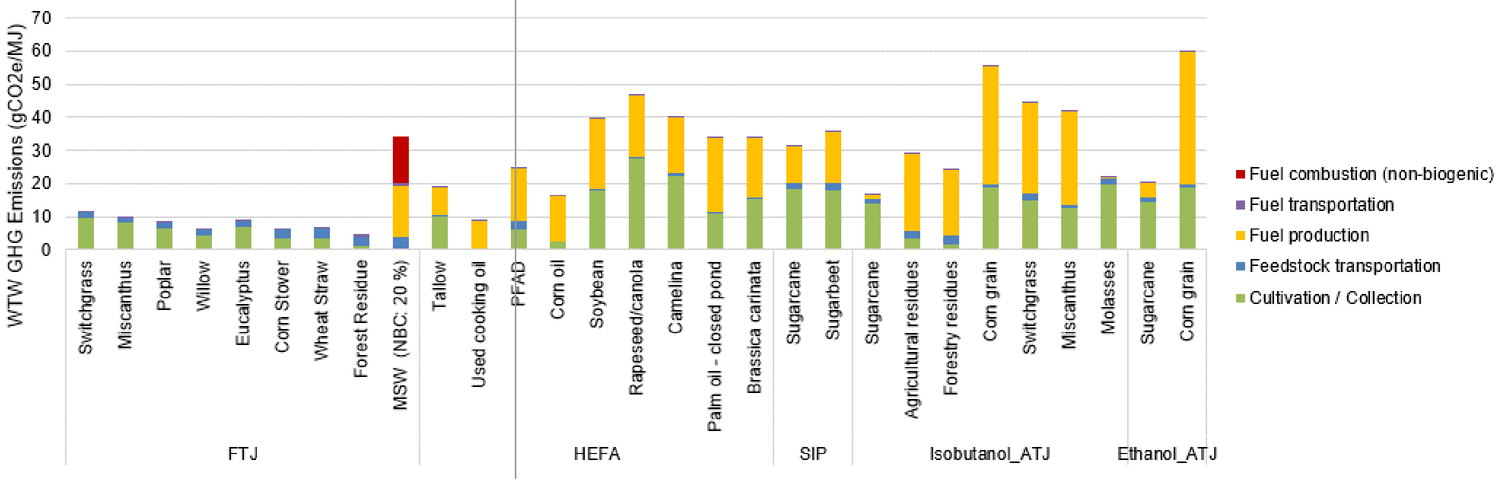
GREET → **LCA results**

GREET for CORSIA results tab

[Preliminary] GREET for CORSIA, LCA Results for Sustainable Aviation Fuels

Selected electricity grid: US

		Selected Dataset	Life-cycle GHG Emissions (gCO2e/MJ) Cultivation / Collection	Feedstock transportation	Fuel production	Fuel transportation	Fuel combustion (non-biogenic)	Life-cycle GHG Emissions (gCO2e/MJ)
	Forest Residue	ANL/MIT	1.40	2.46	0.04	0.70		**4.59**
	MSW (NBC: 20 %)	MIT		4.02	15.23	0.70	14.08	**34.03**
HEFA	Tallow	MIT	10.03	0.34	8.37	0.39		**19.13**
	Used cooking oil	MIT		0.34	8.37	0.39		**9.10**
	PFAD	ANL	6.10	2.66	15.98	0.39		**25.12**
	Corn oil	ANL	2.42	0.34	13.59	0.39		**16.74**
	Soybean	GREET (US)	17.74	0.79	21.09	0.39		**40.01**
	Rapeseed/canola	GREET (US)	27.48	0.58	18.62	0.39		**47.07**
	Camelina	GREET (US)	22.50	0.65	16.74	0.39		**40.27**
	Palm oil - closed pond	ANL	10.81	0.46	22.51	0.39		**34.17**
	Brassica carinata	ANL/U of T (N.America)	15.22	0.54	17.81	0.39		**33.96**
SIP	Sugarcane	MIT	18.34	1.79	11.14	0.39		**31.65**
	Sugarbeet	MIT	17.92	2.02	15.44	0.39		**35.77**
Isobutanol_ATJ	Sugarcane	MIT	13.89	1.26	1.48	0.39		**17.02**
	Agricultural residues	MIT	3.57	1.86	23.71	0.39		**29.52**
	Forestry residues	MIT	1.77	2.40	19.92	0.39		**24.48**
	Corn grain	MIT	18.77	0.98	35.48	0.39		**55.61**
	Switchgrass	MIT	14.89	2.34	27.29	0.39		**44.91**
	Miscanthus	MIT	12.48	1.23	28.03	0.39		**42.12**
	Molasses	MIT	19.74	1.78	0.34	0.39		**22.25**
Ethanol_ATJ	Sugarcane	MIT	14.33	1.30	4.66	0.39		**20.68**
	Corn grain	MIT	18.88	0.98	39.99	0.39		**60.23**

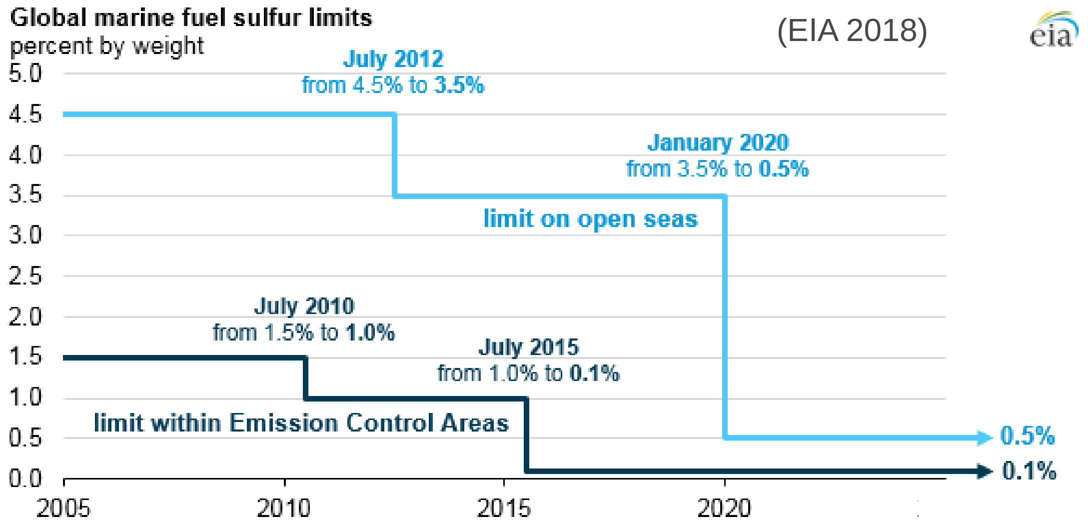


Life-cycle GHG emission results for sustainable aviation fuel pathways: Core LCA values are presented for LCA stages. New results would be generated if different datasets are selected in the input tab.

Marine Applications of GREET

Life-cycle GHG and CAP emissions of conventional and bio-based marine fuels

- Global shipping contributes 13% of human-caused emissions of sulfur oxides (Sofiev 2018) and 2.6% of human-caused carbon dioxide emissions (Olmer 2017)
- Global marine fuel consumption is expected to double in the next 20 years.
- The International Maritime Organization (IMO) has set emission targets to reduce global marine fuel sulfur content from current 3.5% to 0.5% by weight in 2020.
- The California Air Resources Board (CARB) and other state agencies have established regulations limiting the sulfur content of fuel used in coastal regions to 0.1%.



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Developed a new marine module including 19 marine fuel production pathways for GREET 2019

- Added new marine fuel production pathways including both fossil and biomass derived marine fuels in Collaboration with NREL and PNNL.
- Updated combustion emission factors in marine vessels.
  - Third IMO Greenhouse Gas Study 2014 (IMO 2015)
  - 2014 National Emissions Inventory (EPA 2018)
  - Natural gas as a marine fuel (Thomson et al. 2015)
- The results can be expressed in terms of per energy (MJ of fuel) or per trip (or per tonne-km).

Pathways	Note
HFO (2.7% sulfur)	Residual oil in GREET
HFO (0.5% sulfur)	Residual oil in GREET + Desulfurization
HFO (0.1% sulfur)	Residual oil in GREET + Desulfurization
MGO (1.0% sulfur)	Unfinished oil in GREET
MGO (0.5 % sulfur)	Unfinished oil in GREET+ Desulfurization
MGO (0.1 % sulfur)	Unfinished oil in GREET+ Desulfurization
MDO (1.92% sulfur)	Mixture of HFO 2.7%S and MGO 1.0%S
MDO (0.5% sulfur)	Mixture of HFO 0.5%S and MGO 0.5%S
MDO (0.1% sulfur)	Mixture of HFO 0.1%S and MGO 0.1%S
LNG	LNG in GREET
FT-Diesel (NG)	Newly added; data provided by NREL
FT-Diesel (biomass)	Newly added; data provided by NREL
FT-Diesel (biomass/NG)	Newly added; data provided by NREL
FT-Diesel (biomass/coal)	Newly added; data provided by NREL
Pyrolysis oil (woody biomass)	Newly added; data provided by PNNL
Renewable diesel (yellow grease/HFO)	Newly added; data provided by PNNL
Renewable diesel (yellow grease)	Newly added; data provided by PNNL
Straight Vegetable Oil (SVO)	Soy oil in GREET
Biodiesel	Biodiesel in GREET

New GREET marine module

Marine Module

1) Scenario Selection

1.1) Engine Type and Emisson Regulation

Select and change all diesel main engine type:	MSD	(SSD - Slow Speed Diesel; MSD - Medium Speed Diesel; ST: Steam Turbine; GT: Gas Turbine)
Select and change all diesel aux. engine type:	MSD	(MSD - Medium Speed Diesel; HSD - High Speed Diesel)
Select and change all IMO emisison regulation tier:	3	Tier 0: non-regulated engines (pre 2000), Tier 1: 2000-2011, Tier 2: 20112015, Tier 3: after 2016

1.2) Trip Characteristics

Selected trip: Bulk-Foreign, Pacific (Domestic-International)

Pre-defined (Regional characteristics)

Vessels:	Bulk
Travel:	Foreign
Region:	Pacific
	Domestic-International

	Selected: Pre-defined (Regional characteristics)				User-defined							
	Distance (nm)	Speed (knots)	Time in Mode (hours)	Load Factors	Distance (nm)	Speed (knots)	Time in Mode (hours)	Load Factors	Urban emission share (%)	Engine	Engine Rating (kW)	Total fuel consumption (MJ per trip)
Cruise (Global waters)	4,421	14	309	0.8	584	14	41	0.8	0%	Main Engine	8,698	18,917,669
Cruise (CA waters)	0	14	0	0.8	0	14	0	0.8	0%	Main Engine	8,698	0
RSZ (1)	81	14	6	0.8	69	14	5	0.8	0%	Main Engine	8,698	359,906
RSZ (2)	25	14	2	0.8	85	14	6	0.8	0%	Main Engine	8,698	110,594
Hotel (1)			117	0.1			117	0.1	0%	Aux. Engine	1,852	201,156
Hotel (2)			117	0.1			117	0.1	0%	Aux. Engine	1,852	201,156
Payload (wet ton)	57,541				57,541							
million tonne-km	438				71							

2) Summary Results

2.1.) Selected Fuels: Energy Consumption, Water Consumption, and Emissions

Selected fuel type	HFO (0.5% sulfur)	
Engine type	1	1--Main engine, 2--Aux engine
Energy Unit:	MJ	mission Unit: g
		Energy Functional Unit: MJ

	Units	Feedstock	Conversion	Combustion	WTH
Total energy	MJ/MJ	0.07	0.09	1.00	1.16
Fossil fuels	MJ/MJ	0.07	0.09	1.00	1.16
Coal	MJ/MJ	0.01	0.00	0.00	0.01
Natural gas	MJ/MJ	0.05	0.06	0.00	0.10
Petroleum	MJ/MJ	0.01	0.04	1.00	1.05
Water consumption	gal/MJ	0.02	0.00	0.00	0.02
VOC	g/MJ	0.00	0.00	0.06	0.07
CO	g/MJ	0.01	0.00	0.13	0.14
NOx	g/MJ	0.02	0.01	0.31	0.33
PM10	g/MJ	0.00	0.00	0.09	0.09
PM2.5	g/MJ	0.00	0.00	0.08	0.08
SOx	g/MJ	0.01	0.00	0.25	0.26
BC	g/MJ	0.00	0.00	0.01	0.01
OC	g/MJ	0.00	0.00	0.03	0.03
CH4	g/MJ	0.09	0.01	0.00	0.10
N2O	g/MJ	0.00	0.00	0.00	0.00
CO2	g/MJ	5.47	5.88	80	92
CO2 (w/ C in VOC & CO)	g/MJ	5.49	5.89	81	92
GHGs	g CO2e/MJ	8.15	6.29	82	96
VOC: Urban	g/MJ	0.00	0.00	0.00	0.00
CO: Urban	g/MJ	0.00	0.00	0.00	0.00
NOx: Urban	g/MJ	0.00	0.00	0.00	0.00

2.2) Selected Trips: Energy Consumption, Water Consumption, and Emissions

Energy Unit:	MJ	mission Unit: kg
	Functional Unit:	1 — 1--Per Trip, 2--Per million tonne-km

Units	Cruise (Global waters)	Cruise (CA waters)	RSZ (1)	RSZ (2)	Hotel (1)	Hotel (2)	Trip
Selected fuels:	2	17	17	17	17	17	
MJ/Trip	22,024,111	0	737,897	226,746	412,421	412,421	23,813,595
MJ/Trip	21,927,523	0	27,679	8,505	15,470	15,470	21,994,649
MJ/Trip	196,887	0	1,251	384	699	699	199,922
MJ/Trip	1,903,418	0	7,840	2,409	4,382	4,382	1,922,430
MJ/Trip	19,827,218	0	18,588	5,712	10,389	10,389	19,872,297
gal/Trip	394,552	0.00	21,551	6,622	12,045	12,045	446,815
kg/Trip	1,232	0.00	22	6.65	9.30	9.30	1,278
kg/Trip	2,669	0.00	48	15	26	26	2,783
kg/Trip	6,311	0.00	137	42	60	60	6,610
kg/Trip	1,696	0.00	6.80	2.09	3.61	3.61	1,713
kg/Trip	1,558	0.00	6.20	1.91	3.29	3.29	1,573
kg/Trip	4,891	0.00	15	4.50	8.19	8.19	4,926
kg/Trip	234	0.00	1.08	0.33	0.58	0.58	237
kg/Trip	605	0.00	2.36	0.72	1.25	1.25	611
kg/Trip	1,927	0.00	3.73	1.14	2.03	2.03	1,936
kg/Trip	79	0.00	1.43	0.44	0.80	0.80	83
kg/Trip	1,732,711	0	1,800	553	1,017	1,017	1,737,098
kg/Trip	1,740,744	0	1,943	597	1,086	1,086	1,745,456
kg CO2e/Trip	1,819,513	0	2,435	748	1,359	1,359	1,825,415
kg/Trip	37	0.00	0.07	0.02	0.04	0.04	37
kg/Trip	25	0.00	0.12	0.04	0.07	0.07	25
kg/Trip	47	0.00	0.29	0.09	0.16	0.16	48

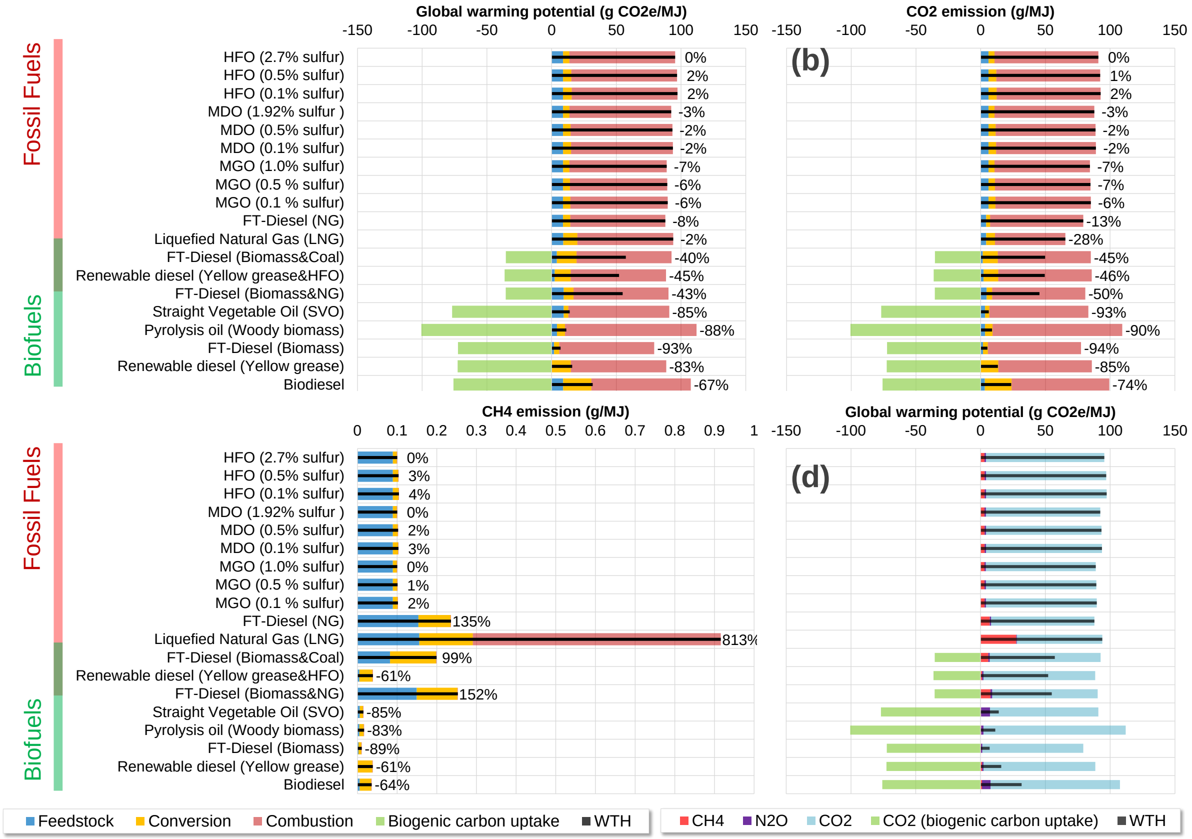
--> Fuel selection for each trip segment

1 -- HFO (2.7% sulfur)
2 -- HFO (0.5% sulfur)
3 -- HFO (0.1% sulfur)
4 -- MDO (1.92% sulfur)
5 -- MDO (0.5% sulfur)
6 -- MDO (0.1% sulfur)
7 -- MGO (1.0% sulfur)
8 -- MGO (0.5 % sulfur)
9 -- MGO (0.1 % sulfur)
10 -- FT-Diesel (NG)
11 -- Liquefied Natural Gas (LNG)
12 -- FT-Diesel (Biomass&Coal)
13 -- Renewable diesel (Yellow grease&HFO)
14 -- FT-Diesel (Biomass&NG)
15 -- Straight Vegetable Oil (SVO)
16 -- Pyrolysis oil (Woody biomass)
17 -- FT-Diesel (Biomass)
18 -- Renewable diesel (Yellow grease)
19 -- Biodiesel

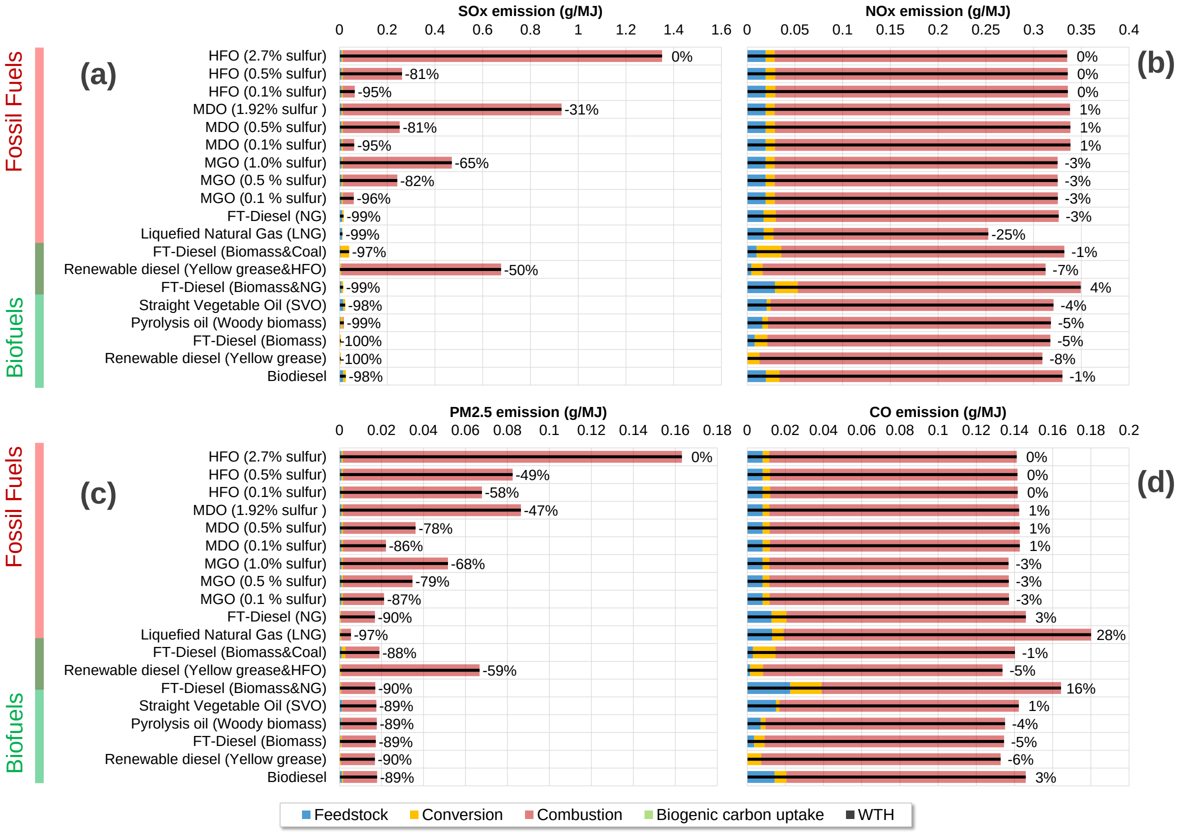
Pretreatment | Catalyst | Bioproducts | E-D Additives | OilGasCoalInfra | ElecInfra | Woody | HDV_TS | HDV_WTW | JetFuel_WTP | JetFuel_PTWa | JetFuel_WTWa | Rail_PTW | Rail_WTW | Chart1 | Marine_WTH | Di ...

Marine fuels' Well-to-Hull (WTH) results

GHG Emissions



CAP Emissions



- Low-sulfur petroleum fuels can reduce life-cycle SOx emission with minor increase in WTH GHG emissions.
- Biomass-derived marine fuels can reduce both WTH GHG and CAP emissions significantly.
- CH_4 slip during downstream combustion significantly influences LNG's WTH GHG emissions.

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