Updated Life-cycle Analysis of Biofuels with the GREET Model

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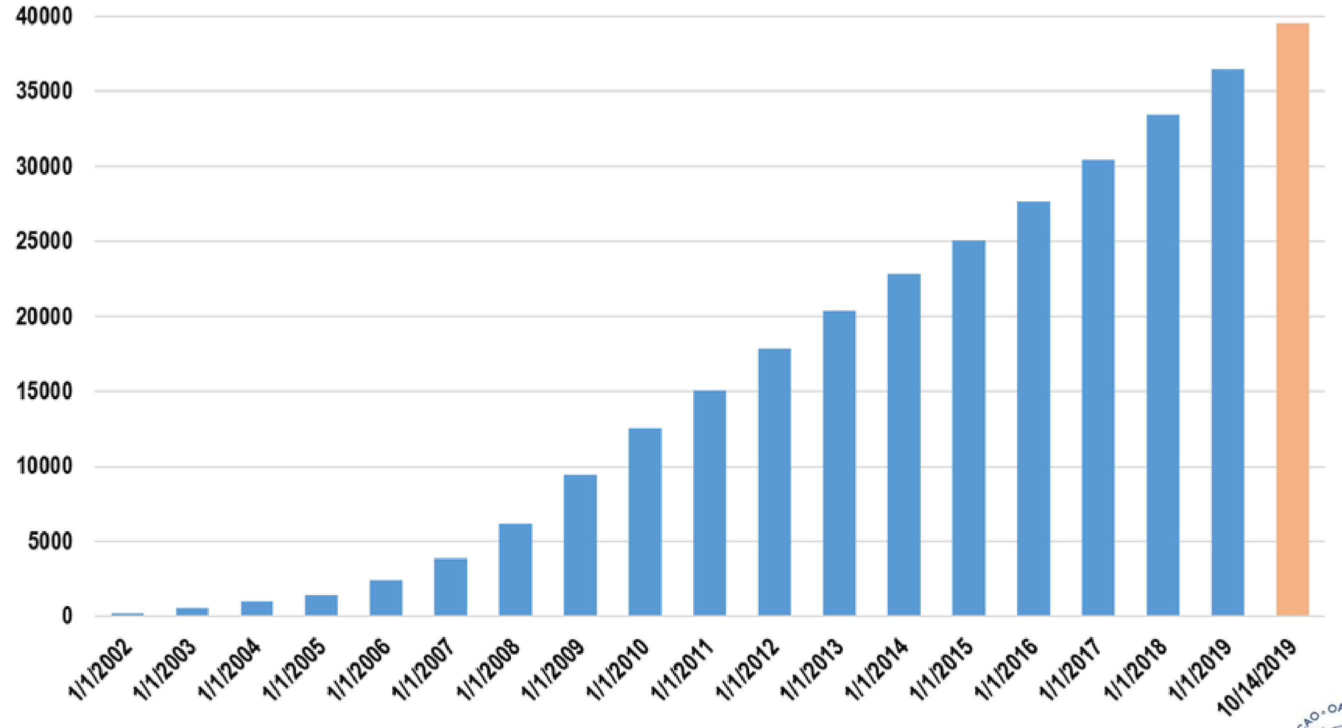
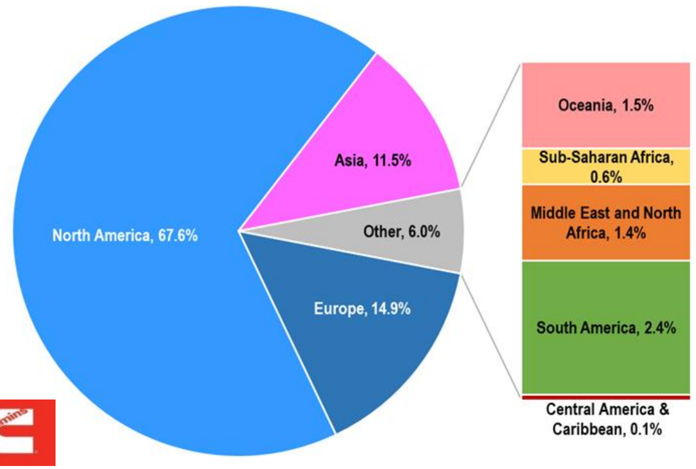
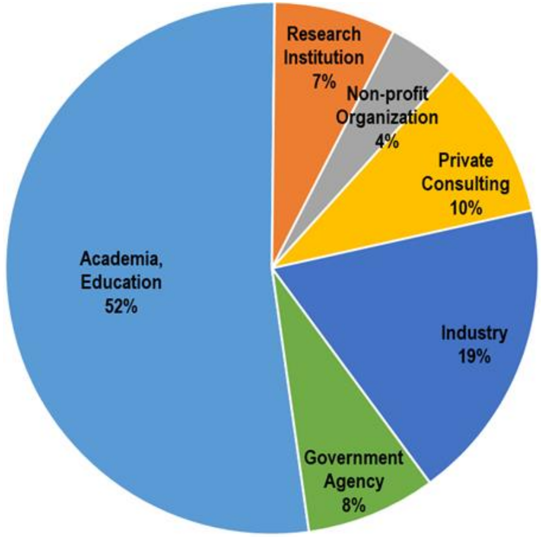
There are ~ 40,000 registered GREET users globally including automotive industry and government agencies







GREET includes a suite of models and tools

- GREET coverage
  - ✓ GREET1: fuel cycle (or WTW) model of vehicle technologies and transportation fuels
  - ✓ GREET2: vehicle manufacturing cycle model of vehicle technologies
- Modeling platform
  - ✓ Excel
  - ✓ .net
- GREET derivatives
  - ✓ **ICAO-GREET** by ANL, based on GREET1
  - ✓ **China-GREET** by ANL, with support of Aramco
  - ✓ **CA-GREET** by CARB, based on GREET1
  - ✓ **AFLEET** by ANL: alternative-fuel vehicles energy, emissions, and cost estimation
  - ✓ **EverBatt** by ANL: energy, emissions, and cost modeling of remanufacturing and recycling of EV batteries

GREET applications by agencies

California Environmental Protection Agency Air Resources Board CA-GREET3.0 built based on and uses data from ANL GREET

State of Oregon Department of Environmental Quality DEQ Oregon Dept of Environ. Quality Clean Fuel Program

EPA RFS2 used GREET and other sources for LCA of fuel pathways; GHG regulations

NHTSA National Highway Traffic Safety Administration (NHTSA) fuel economy regulation

FAA and ICAO AFTF using GREET to evaluate aviation fuel pathways

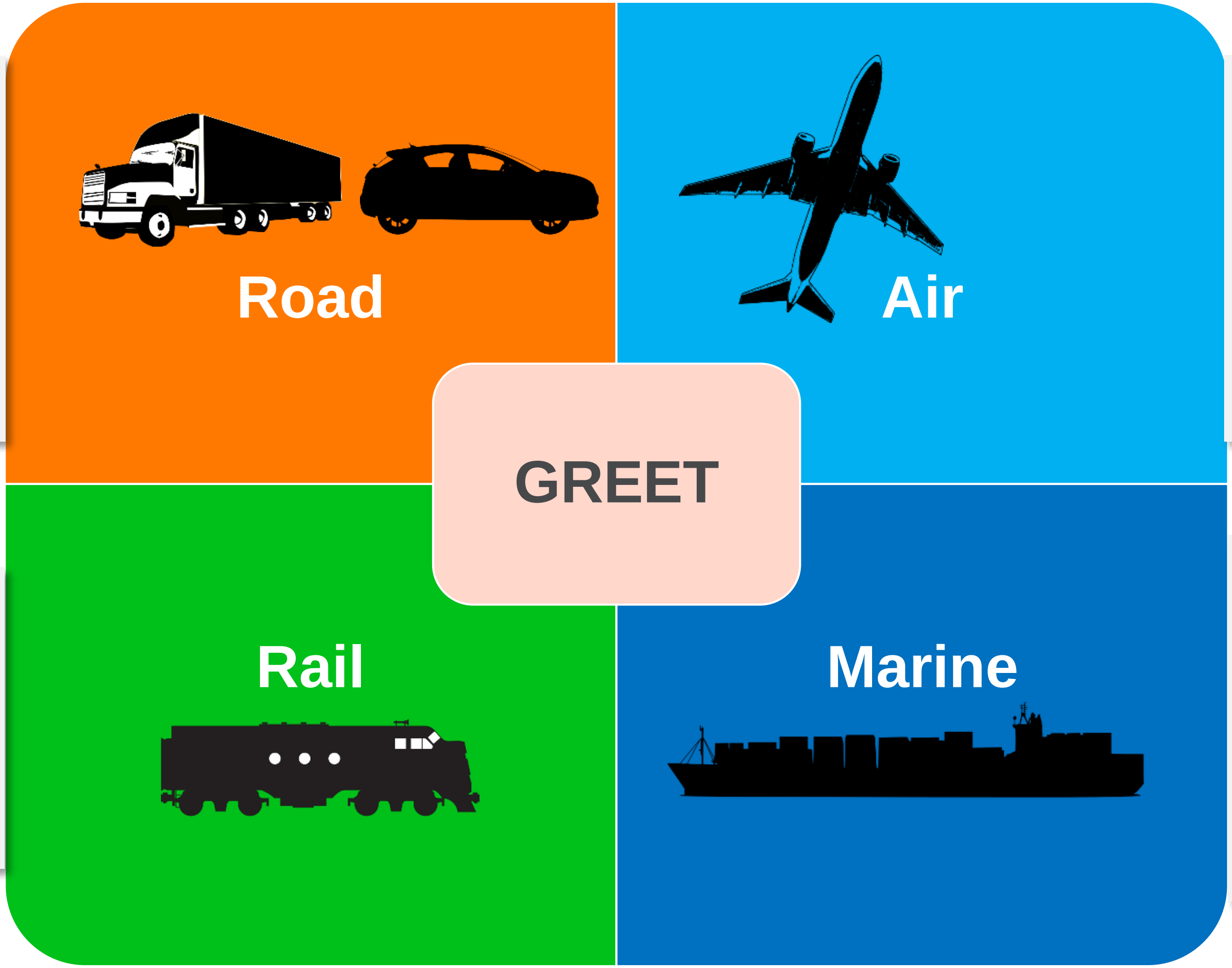
USDRIVE Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability GREET was used for the US DRIVE Fuels Working Group Well-to-Wheels Report

MARAD Maritime Administration LCA of renewable marine fuel options to meet IMO 2020 sulfur regulations for the DOT MARAD

USDA US Dept of Agriculture: ARS for carbon intensity of farming practices and management; ERS for food environmental footprints; Office of Chief Economist for bioenergy LCA

GREET includes all transportation subsectors

- Light-duty vehicles
- Medium-duty vehicles
- Heavy-duty vehicles
- Various powertrains:
  - Internal combustion
  - Battery electric
  - Fuel cells



Globally, a fast growing sector with GHG reduction pressure. GREET includes
- Passenger and freight transportation of various alternative fuels blended with petroleum jet fuels

Freight transportation GREET includes
- Diesel
- Electricity
- CNG/LNG

The sector is under pressure to reduce air emissions and GHG emissions. GREET includes
- Ocean and inland water transportation
- Baseline diesel and alternative marine fuels

GREET includes LCA of five energy systems

Petroleum Sector
- Conventional oil
- Shale oil
- Oil Sands

Gasoline
Diesel
Jet fuel
Liquefied petroleum gas
Naphtha
Residual oil

Electric Sector:
- Electricity generation at US plant level
- Aggregate to national, NERC, and state level
- With CCS, if applicable

Natual gas
Coal
Residual oil
Biomass
Nuclear
Hydro
Wind
Solar

Natural Gas Sector
- Conventional NG
- Shale gas

- NG end use in electric, industrial, and residential sector
- Transportation sector: CNG, LNG
- Alternative fuels: LPG, methanol, DME, FT diesel, FT jet

Renewable Energy/Fuels
- Ethanol
- Biodiesel
- Renewable diesel
- Renewable gasoline
- Renewable jet fuel
- Renewable natural gas

1st Gen Feedstocks:
- Corn
- Soybeans
- Rapeseeds
- Sugarcane
- Palm

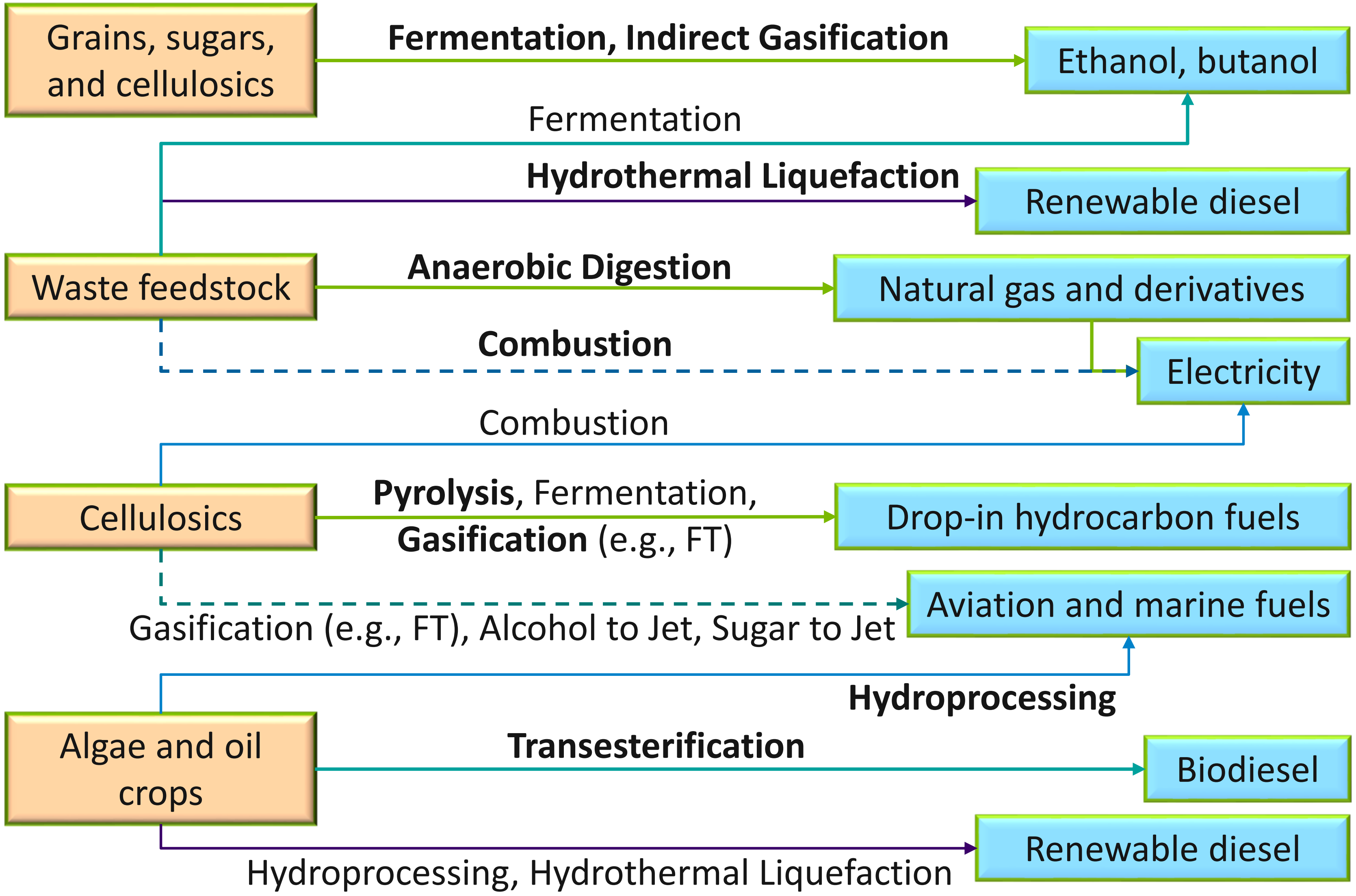
2nd Gen Feedstocks:
- Dedi. energy crops
- Crop residues
- Forest residues
- MSW
- Animal wastes

Algae

Hydrogen Economy:
- Gaseous hydrogen
- Liquid hydrogen
- With CCS, if applicable

Natural gas
Biomass
Coal
Petroleum coke
Coke oven gas
Electrolysis with electricity
Nuclear energy

Biofuels can be produced from various biomass feedstocks via different conversion technologies

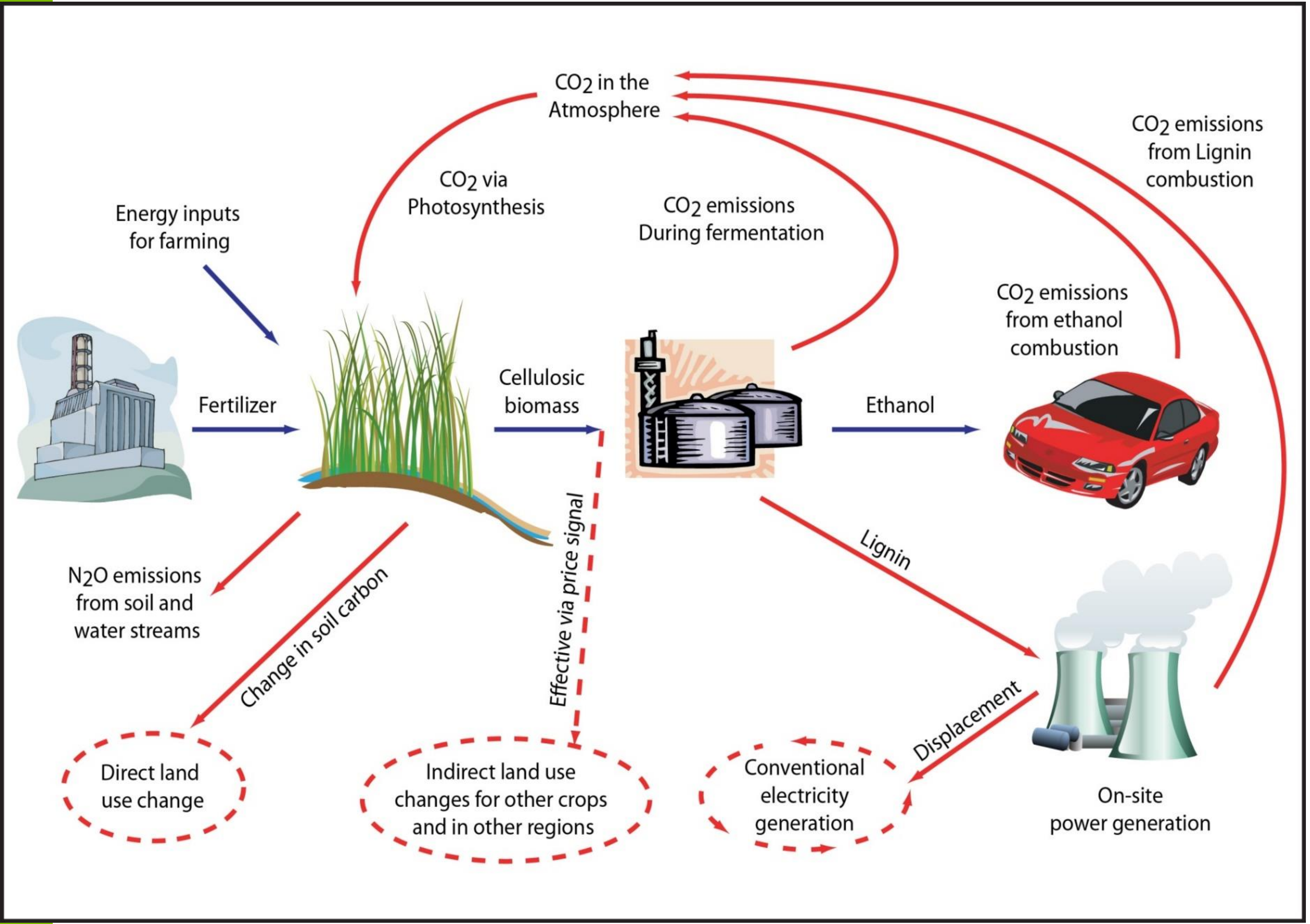


Reductions in GHG emissions can be monetary values

Alternative Fuel Premiums at Sample LCFS Credit Prices ($/gal gasoline-equivalent for fuels used as gasoline substitutes)					
	Credit price				
CI Score (gCO2e/MJ)	$80	$100	$120	$160	$200
10	$0.77	$0.96	$1.16	$1.54	$1.93
20	$0.68	$0.85	$1.02	$1.36	$1.70
30	$0.59	$0.73	$0.88	$1.17	$1.46
40	$0.49	$0.62	$0.74	$0.99	$1.23
50	$0.40	$0.50	$0.60	$0.80	$1.00
60	$0.31	$0.38	$0.46	$0.62	$0.77
70	$0.22	$0.27	$0.32	$0.43	$0.54
80	$0.12	$0.15	$0.18	$0.25	$0.31
90	$0.03	$0.04	$0.04	$0.06	$0.07
100	-$0.06	-$0.08	-$0.09	-$0.13	-$0.16
110	-$0.16	-$0.19	-$0.23	-$0.31	-$0.39
120	-$0.25	-$0.31	-$0.37	-$0.50	-$0.62
130	-$0.34	-$0.43	-$0.51	-$0.68	-$0.85
140	-$0.43	-$0.54	-$0.65	-$0.87	-$1.08
150	-$0.53	-$0.66	-$0.79	-$1.05	-$1.32

(CARB 2019)

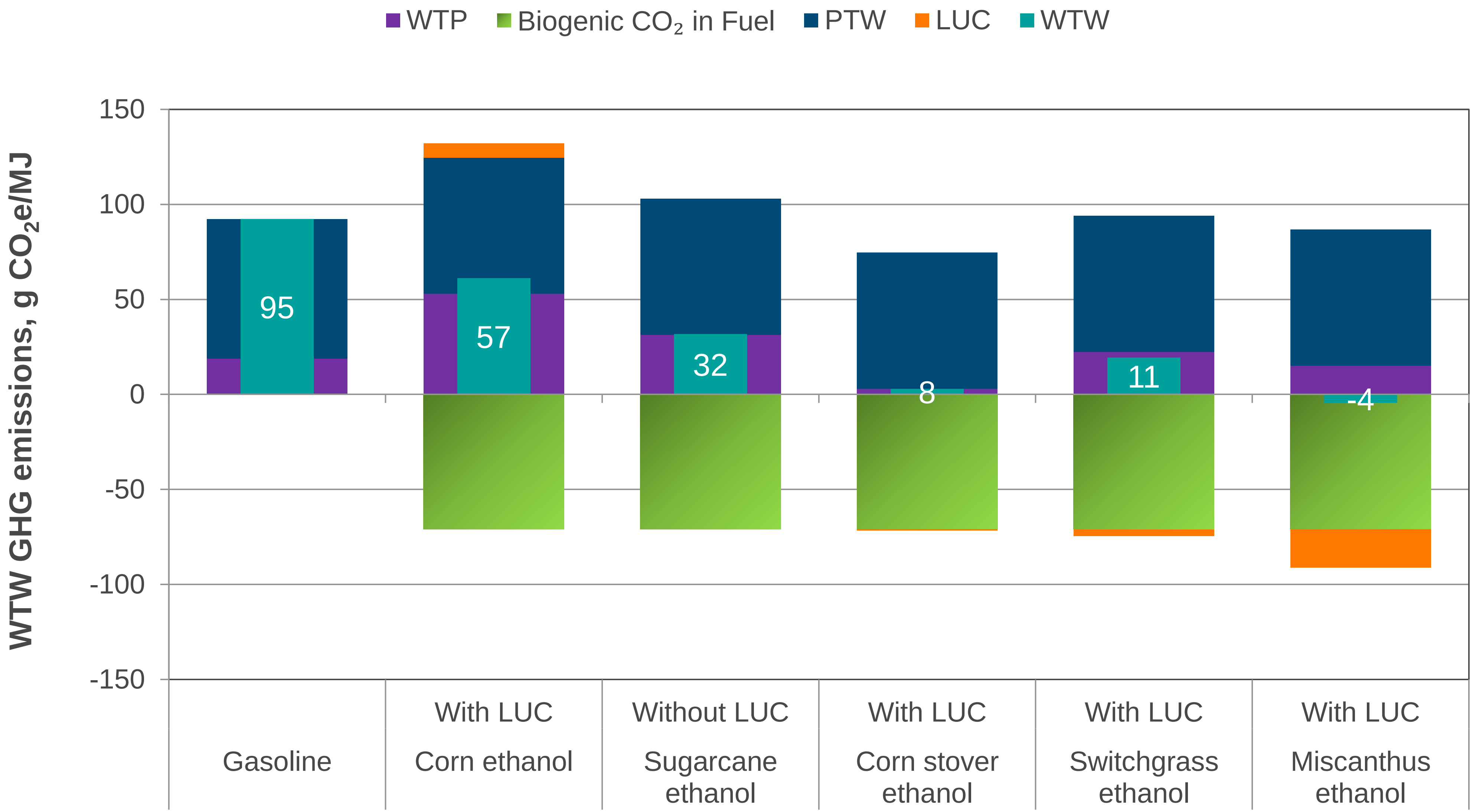
GREET system boundary for biofuel LCA: direct activities and indirect effects are included



Key factors determining biofuel LCA results

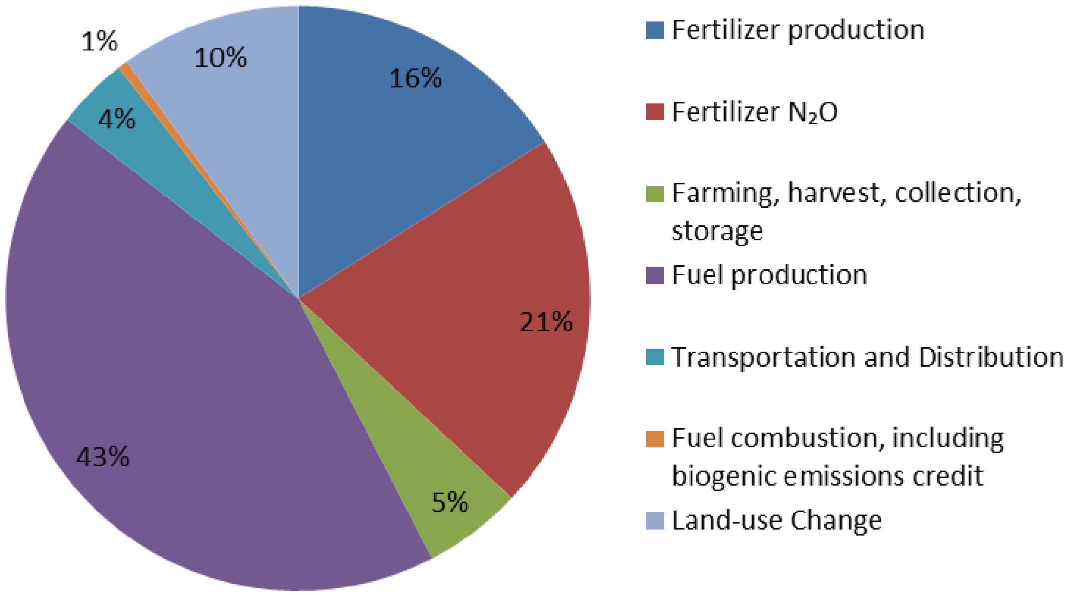
- LCA system boundary
- Feedstock types
- Conversion technologies: energy balance and materials inputs such as enzyme and catalyst
- Technology improvement over time
- Biorefineries with distinctly different products: co-product methods
- Direct and indirect land use changes

GREET life-cycle GHG emissions of ethanol: feedstock is the main driver

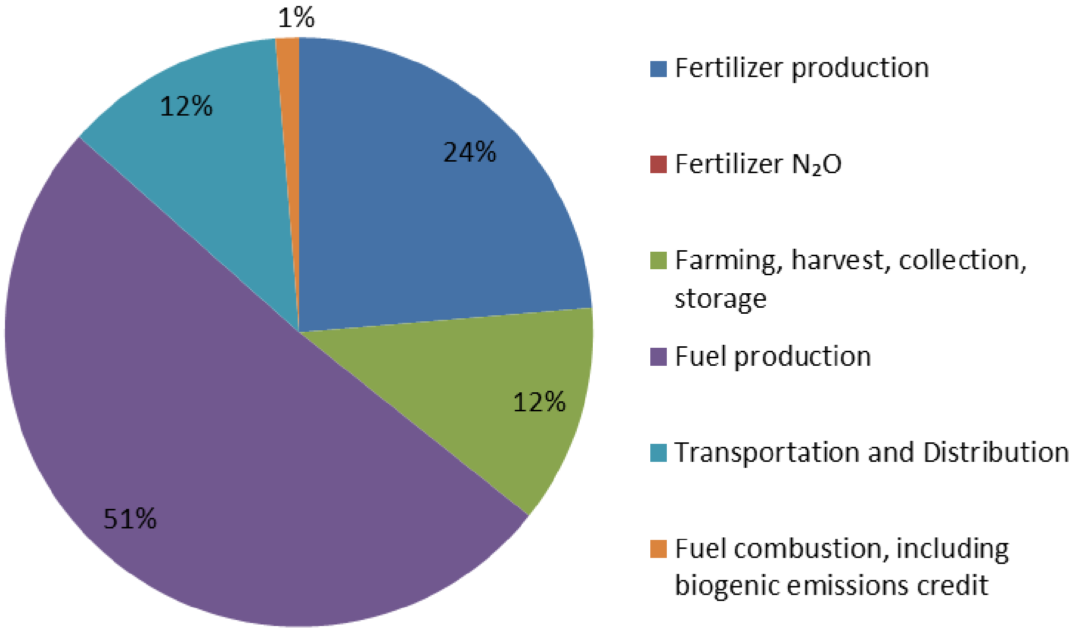


Emission breakdowns for two ethanol types

Corn Ethanol



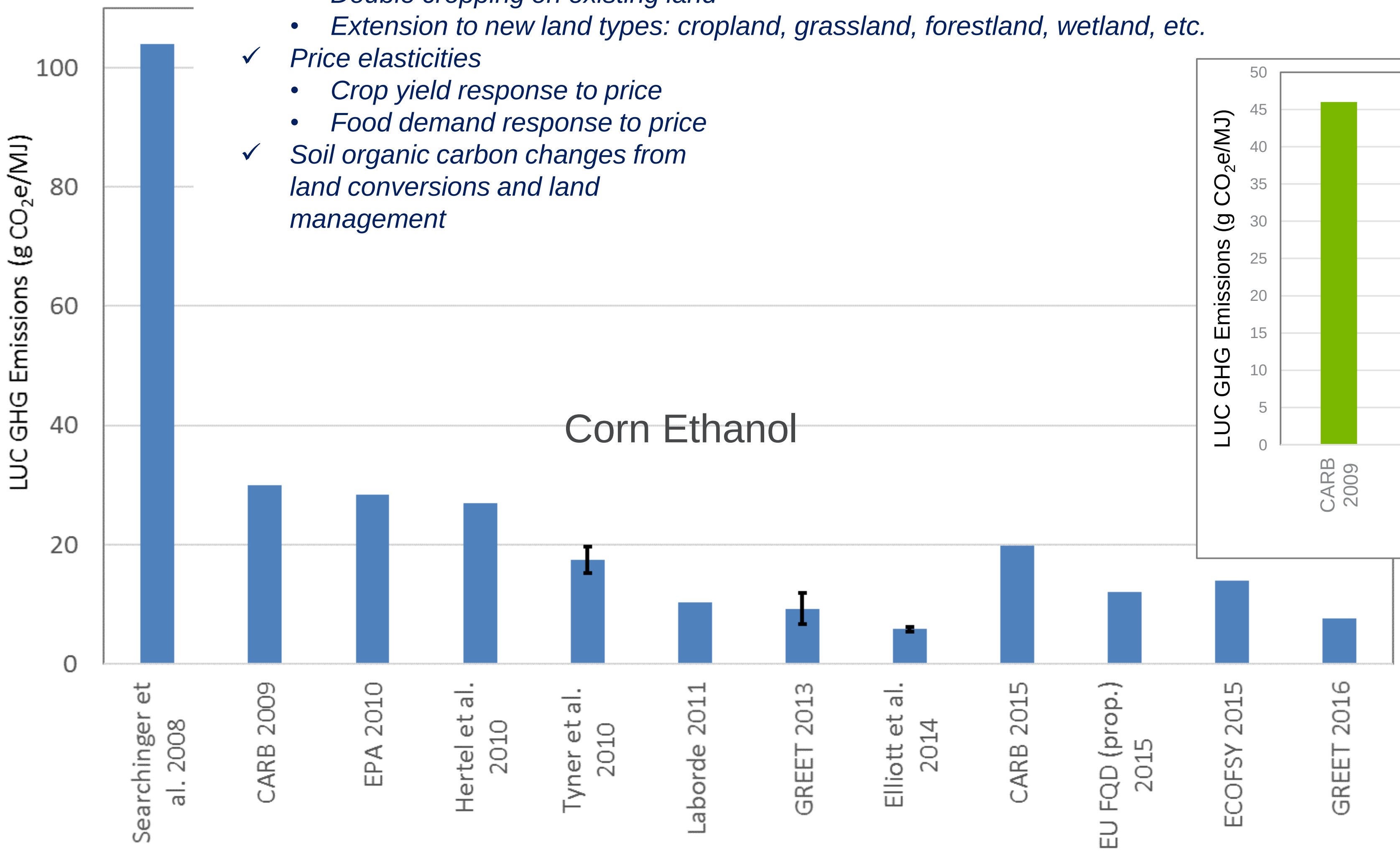
Corn Stover Ethanol

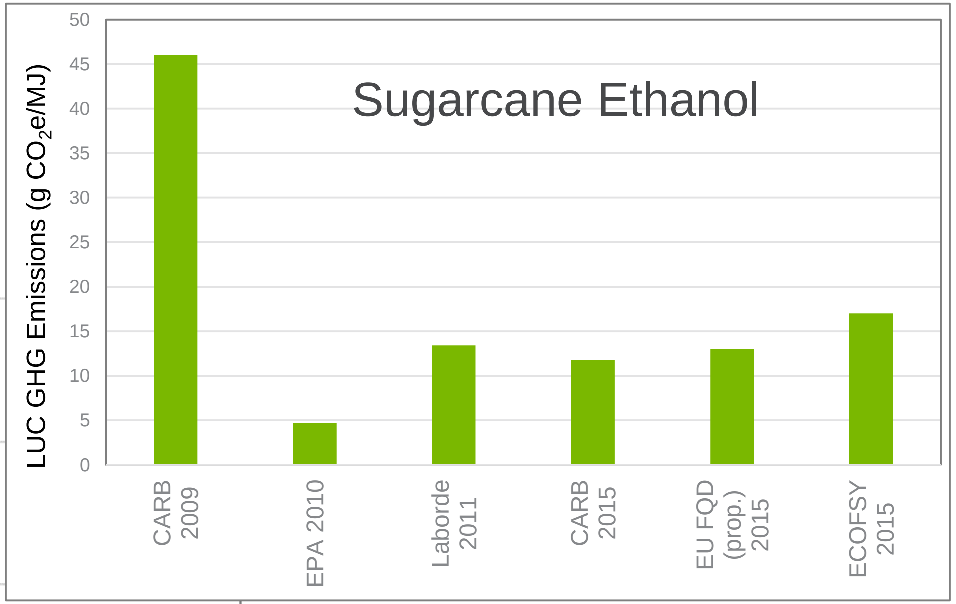


Trend of estimated LUC GHG emissions for corn and sugarcane ethanol

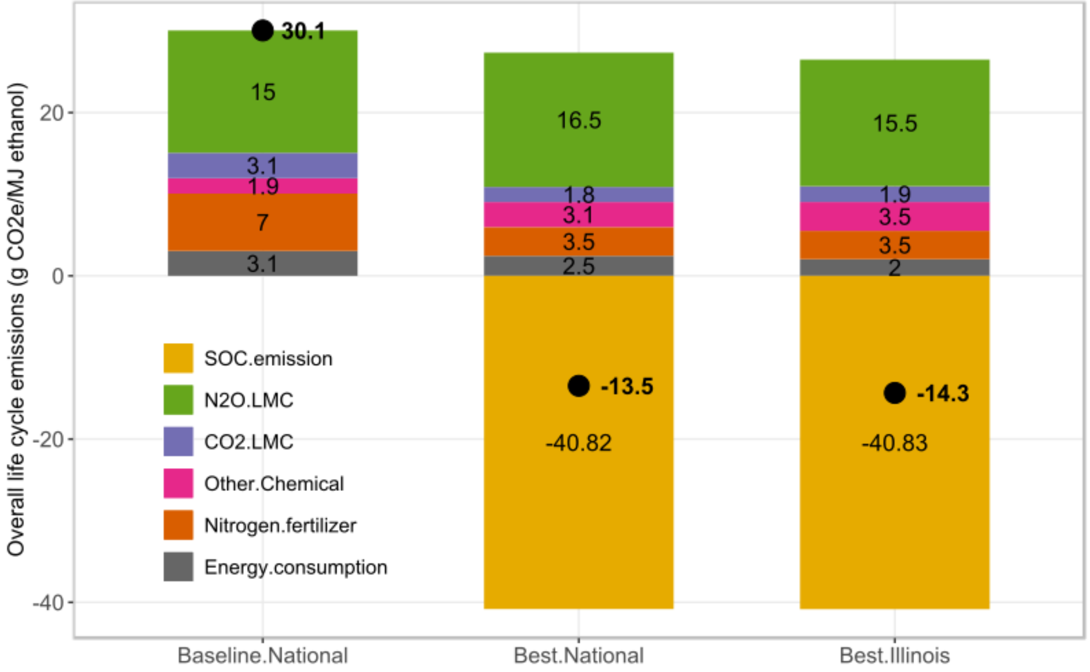
Critical factors for LUC GHG emissions:

- ✓ *Land intensification vs. extensification*
    - *Crop yields: existing cropland vs. new cropland; global yield differences and potentials*
    - *Double cropping on existing land*
    - *Extension to new land types: cropland, grassland, forestland, wetland, etc.*
- ✓ *Price elasticities*
    - *Crop yield response to price*
    - *Food demand response to price*
- ✓ *Soil organic carbon changes from land conversions and land management*





Development of regionalized LCA for corn cradle-to-farm gate GHG emissions including SOC changes



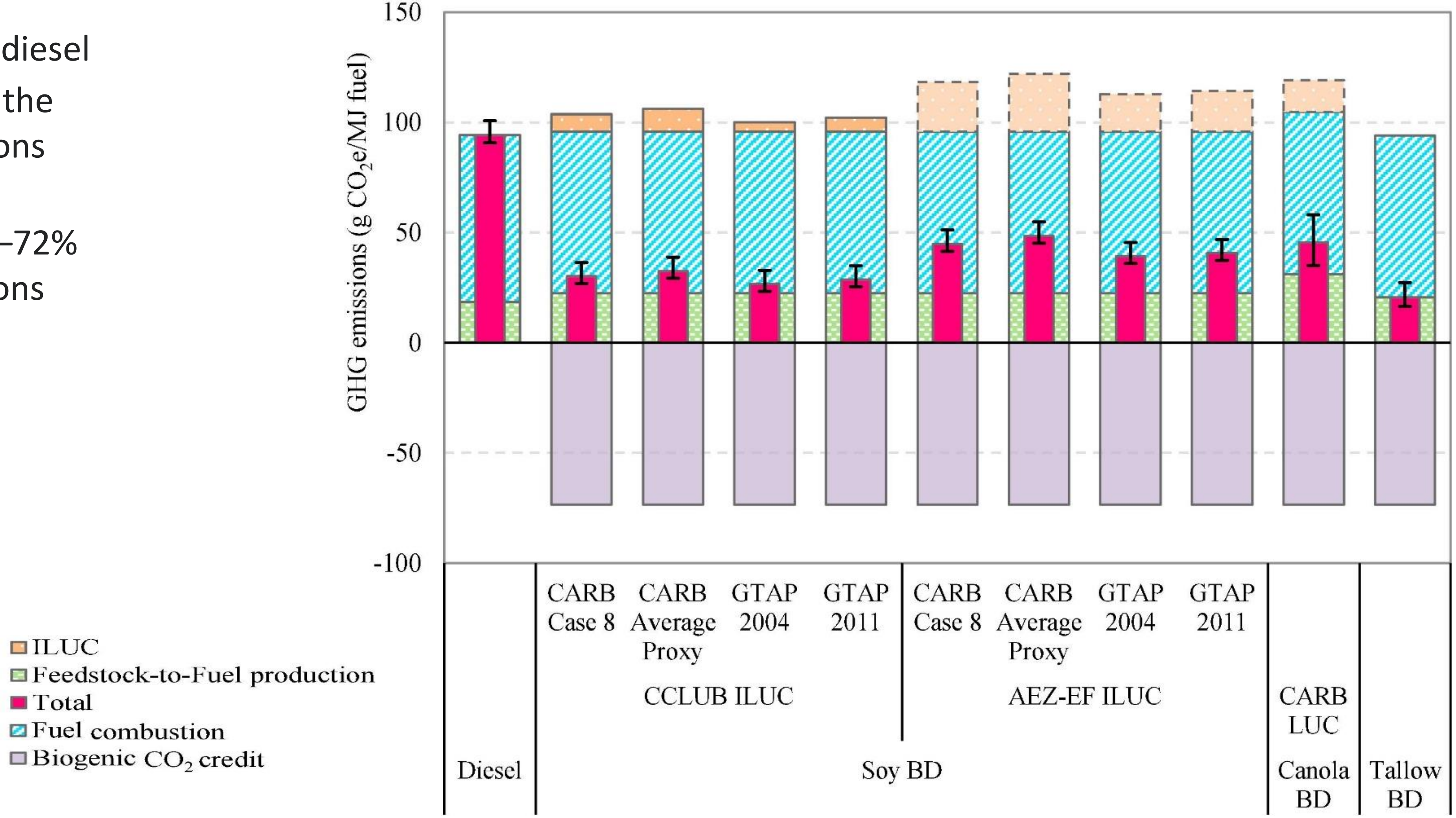
Scenarios	Best	Baseline
Yield improvement	Increase	Current level
Cover crop (CC)	Rye & vetch CC	No CC
Tillage type	No till	Average till
Stover harvest rate	0%	0%
N fertilizer reduction	N credit due to legume CC	No
Manure application	Yes	No
N inhibitor	Yes	No
Deep rooting corn	Yes	No

- N_2O emissions contribute to 50% of the cradle-to-farm gate GHG emissions, indicating the importance of soil N management in reducing overall GHG emissions
- N fertilizer use accounts for 23% of the cradle-to-farm gate GHG emissions, which can be reduced by 50% if potential N credits from legume cover crop is considered
- Farming practices also have significant impacts on SOC changes, resulting in 40.8 g CO_2e reduction per MJ
- In terms of monetary value, the best practice is worth $168/acre under CA LCFS with CO2 price of $100 /metric ton

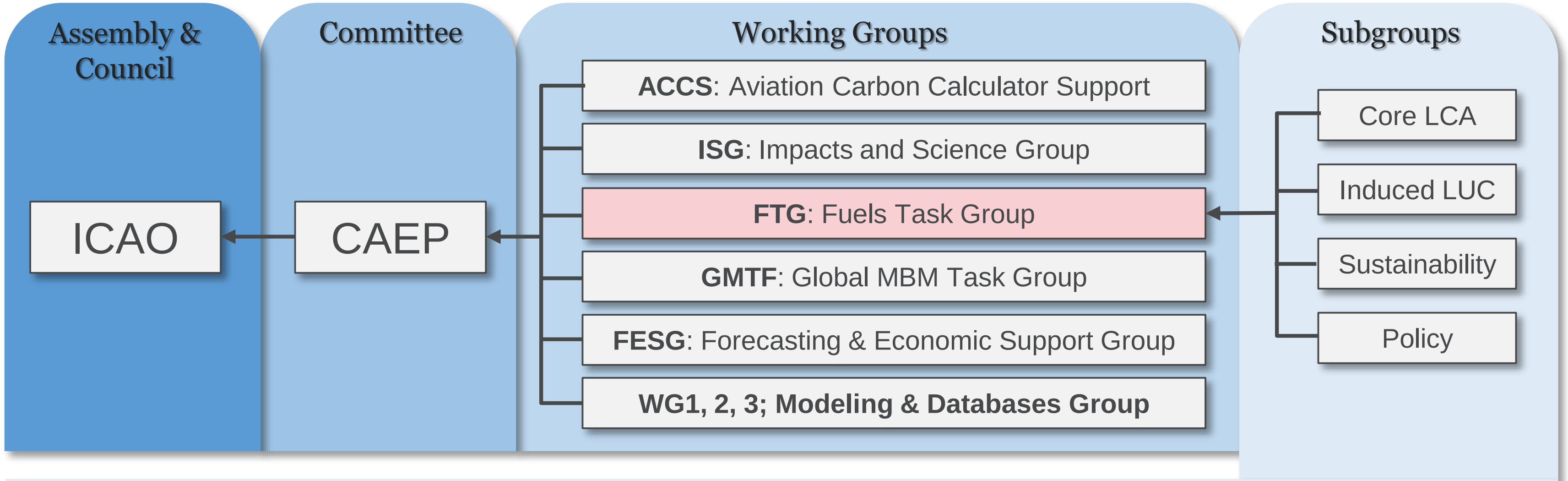
Evaluated WTW GHG emissions of soybean biodiesel including induced land use change emissions

- New LCA results for energy use and GHGs of biodiesel from soy, canola, tallow-based)

  - Addressed iLUC of soy biodiesel
  - Examined discrepancy on the estimation of ILUC emissions related to peatland loss
  - Soy biodiesel achieves 66–72% reductions in GHG emissions when ILUC is considered



Argonne has been working with other organizations to address carbon intensities of sustainable aviation fuels



FTG Subgroups	Key Contributors*	Major Objectives
Core LCA	**ANL**, MIT, JRC	To establish **default core LCA values** for AJF and **Guidance Document** for LCA data submission.
ILUC	Purdue, IIASA	To quantify the **induced land use change** and **associated emissions** due to global aviation biofuels production.
Sustainability	IATA, EDF	To develop recommendations on **sustainability criteria (environmental, social and economic)** for AJF globally.
Policy	IATA, ICAO	To develop **guidance** for States considering introducing **policy support** to advance the deployment of AJF.

* **MIT**: Massachusetts Institute of Technology **ANL**: Argonne National Laboratory **JRC**: Joint Research Centre of the European Commission
IIASA: International Institute for Applied Systems Analysis **IATA**: International Air Transport Association **EDF**: Environmental Defense Fund

Aviation fuel and aircraft options in ICAO-GREET

Fuels and Feedstocks

- **Petroleum Jet Fuel**
  - Conventional Crude
  - Oil Sand
- **Pyrolysis Oil Jet Fuel**
  - Crop Residues
  - Forest Residues
  - Dedicated Energy Crops
- **Hydrotreated Renewable Jet Fuel (HRJ)**
  - Soybeans
  - Palm Oil
  - Rapeseeds
  - Jatropha
  - Camelina
  - Algae
- **Ethanol-To-Jet (ETJ)**
  - Corn
  - Crop Residues
  - Forest Residues
  - Dedicated Energy Crops
- **Sugar-To-Jet (STJ)**
  - Crop Residues
  - Forest Residues
  - Dedicated Energy Crops
- **Fischer-Tropsch Jet Fuel (FTJ)**
  - North American Natural Gas
  - Non-North American Natural Gas
  - Renewable Natural Gas
  - Shale Gas
  - Biomass via Gasification
  - Coal via Gasification
  - Coal/Biomass via Gasification
  - Natural Gas/Biomass via Gasification

Aircraft Types

- **Passenger Aircraft**
  - Single Aisle
  - Small Twin Aisle
  - Large Twin Aisle
  - Large Quad
  - Regional Jet
  - Business Jet
- **Freight Aircraft**
  - Single Aisle
  - Small Twin Aisle
  - Large Twin Aisle
  - Large Quad

- **LCA Functional Units**
  - Per MJ of fuel
  - Per kg-km
  - Per passenger-km

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

Core LCA Group Working Approach

Initial CI development

↓

CI verification

↓

Propose to FTG;
FTG adoption

Conversion process	Feedstock	Core LCA value [gCO_2e/MJ]
FT	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
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 ATJ	Sugarcane	27.8
	Agricultural residues	29.3
	Forestry residues	23.8
	Corn grain	55.8
	Herbaceous energy crops	43.4
	Molasses	27.0
Ethanol ATJ	Sugarcane	24.1
	Corn grain	65.7

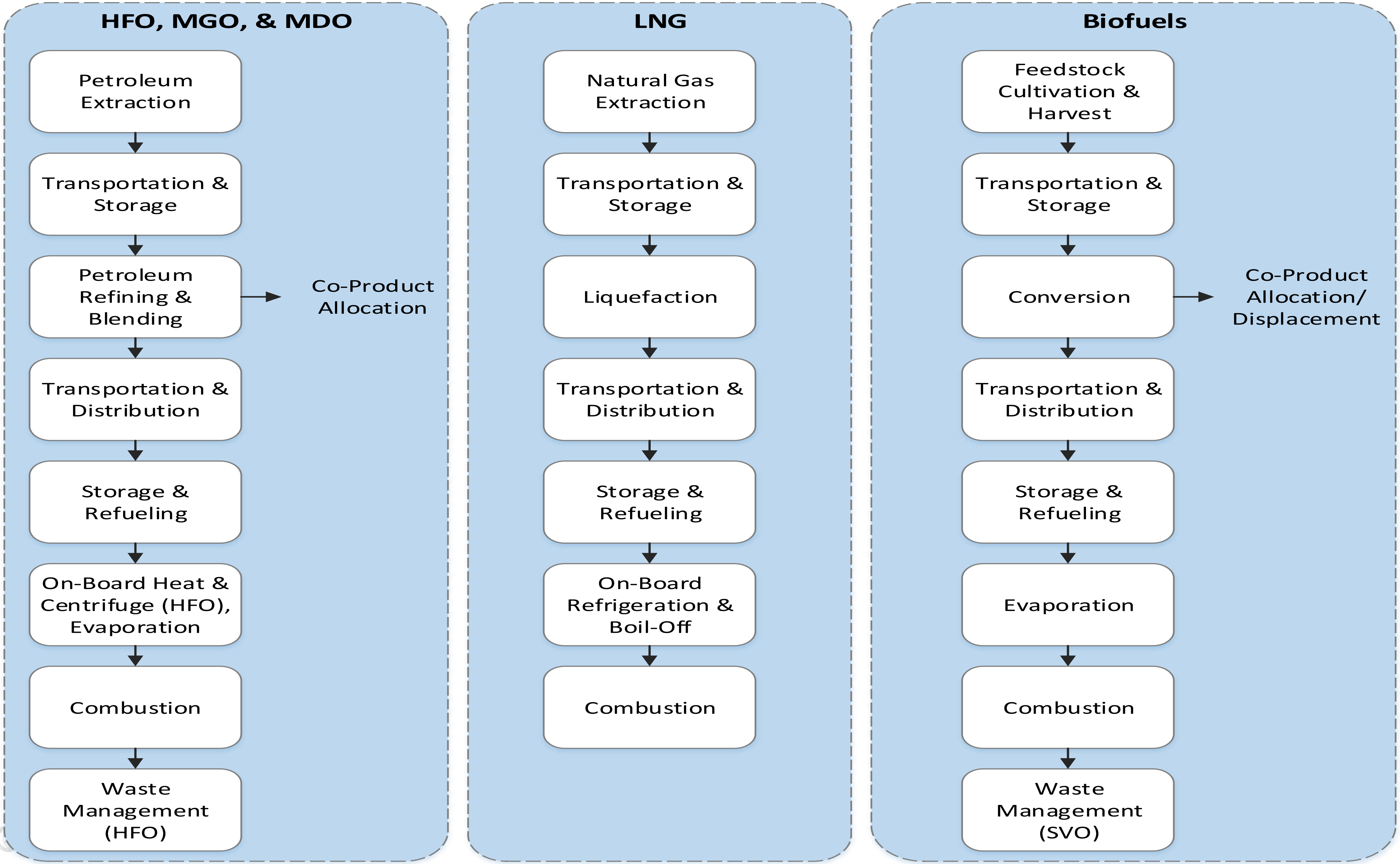
Note: MSW – Municipal solid waste, NBC – Non-biogenic carbon

Interest in alternative marine fuel options

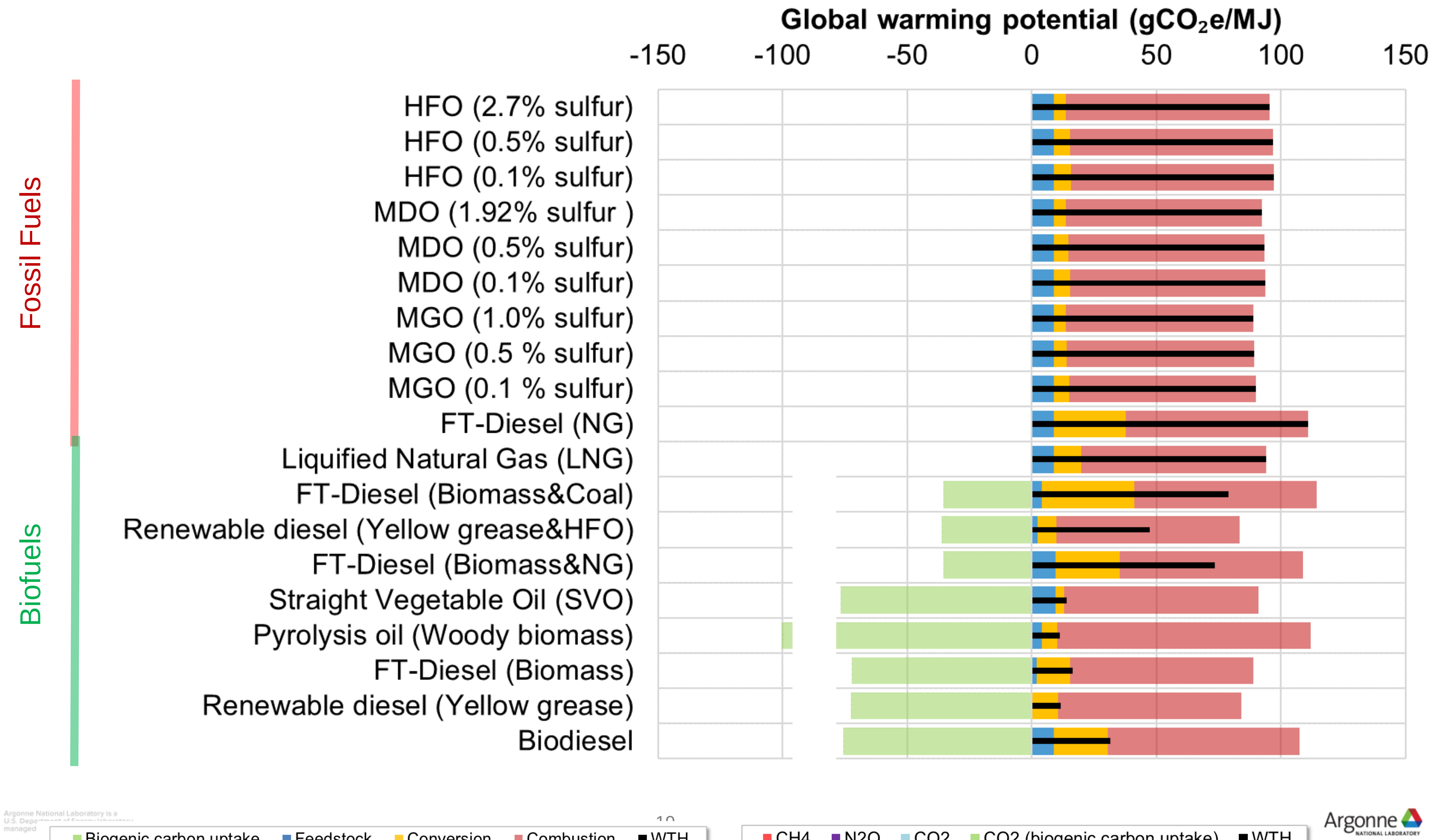
- International Maritime Organization agreement limits marine fuel to 0.5% S wt. beginning January in 2020 (down from the current limit of 3.5%)
  - Further reduced to 0.1% for Emission Control Areas (ECA), coastal regions of US and northern Europe
  - On-highway diesel fuel has a sulfur limit of 15 ppm, or 0.0015%.
- Pressure to reduce carbon intensity
  - IMO framework to reduce CO2 per ton-mile by 30% for new ships beyond 2025 [IMO 2016].
- Ship operators looking for alternatives [Wiesmann 2010]
  - Extremely slim operating margins
  - Alternatives include expanded use of distillates, LNG, biofuels, and employing S scrubbers amongst others
- Biofuels could offer emissions reductions, improved energy security, and reductions in the carbon intensity of marine shipping.

Image source: https://commons.wikimedia.org/wiki/File:LNG_Tanker_ARCTIC_PRINCESS_vor_Hammerfest_(N)_-_Juni_2015.jpg

Marine fuel pathways in GREET

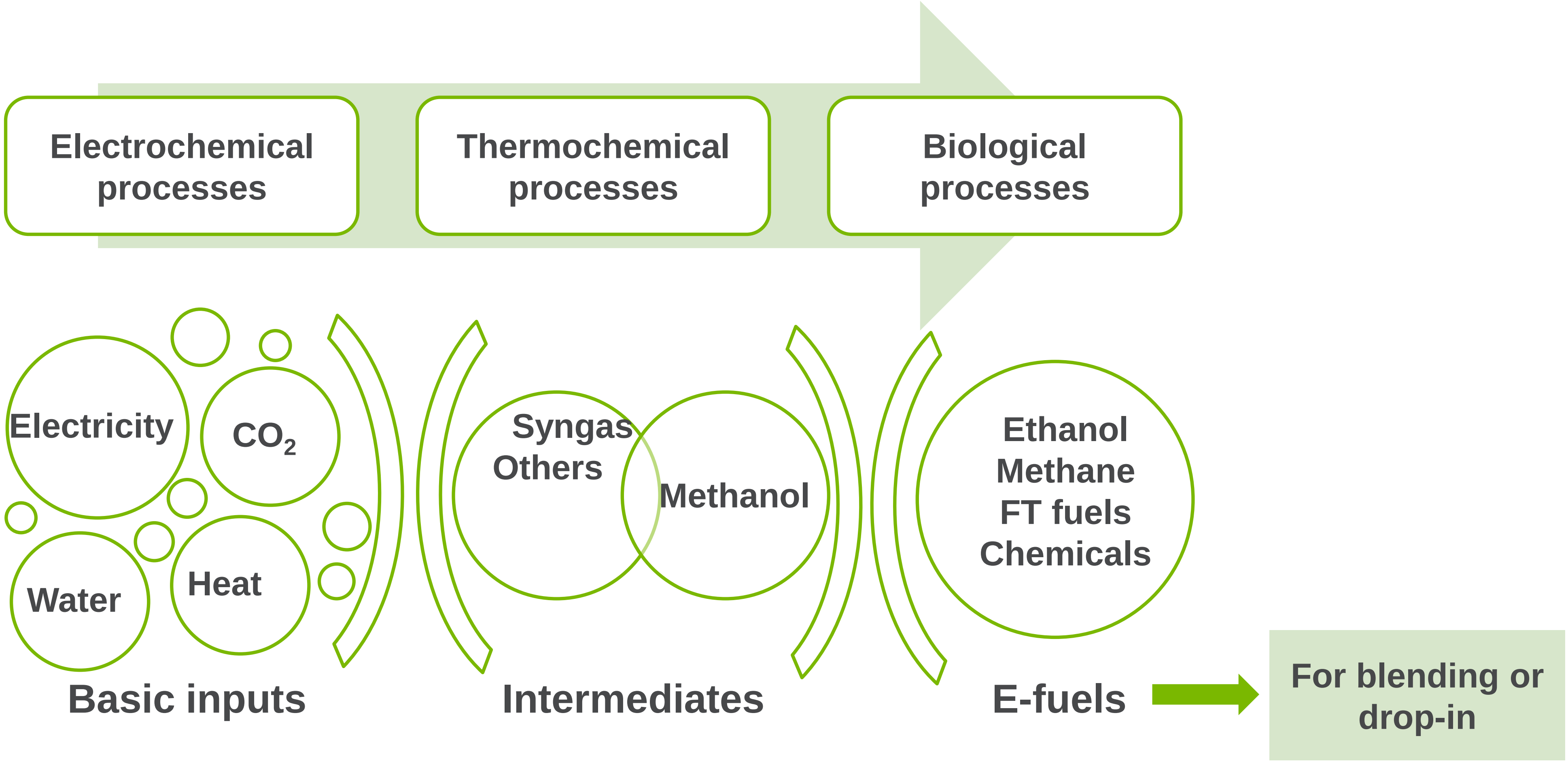


Biofuels for marine applications offer GHG benefits



E-Fuels: $H_{2,e}$ + CO_2 → liquid hydrocarbon (LHC) fuels

- Electro-fuels or “e-fuels” encompass energy carriers and their intermediates synthesized primarily using a carbon source and electricity (for hydrogen)



Major carbon and electricity sources to consider

Carbon Sources

High purity sources of CO_2

- **Ethanol plants**
- **Refineries**
- **Ammonia plants**
- Cement plants
- Iron & steel plants

Other sources of CO_2/CO

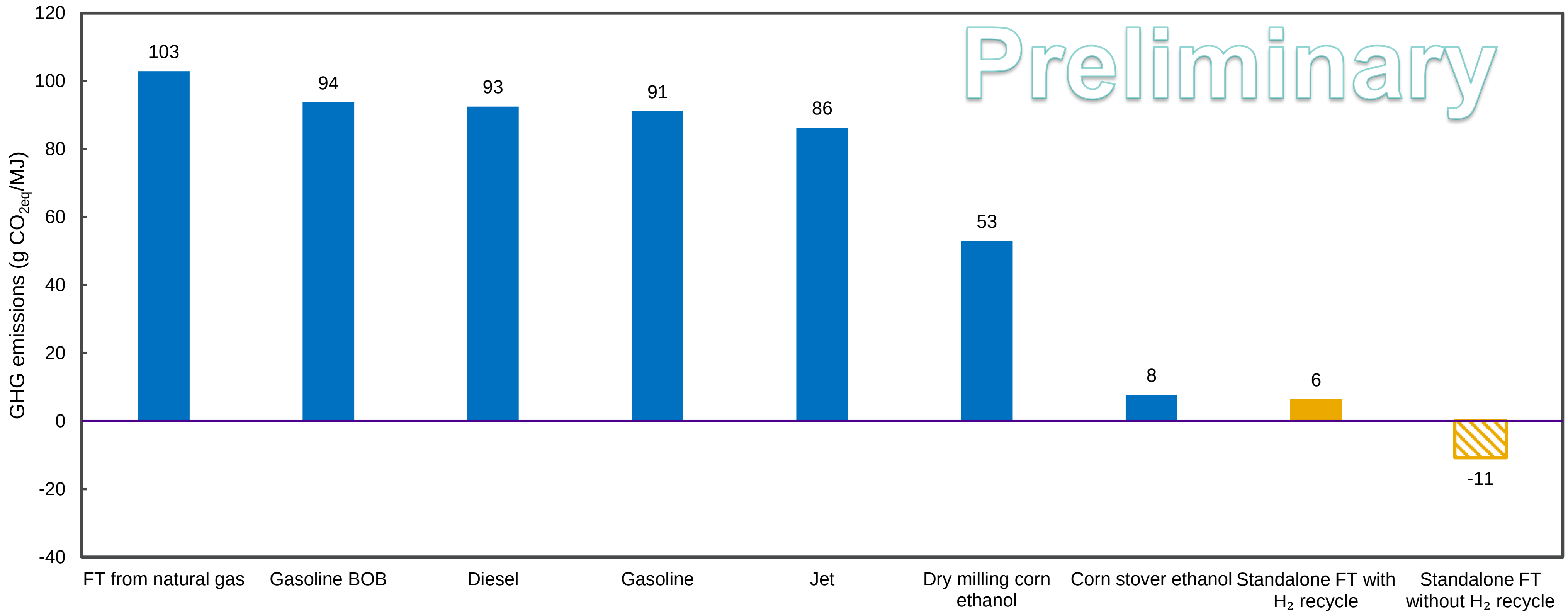
- **Natural gas combined cycle power plants**
- **Biomass power/gasification plants**
- Coal power/gasification plants
- Ambient air

Electricity Sources

- **Wind**
- **Solar**
- **Nuclear**
- **NG combined cycle**

***Standalone* FT fuel WTW GHG emissions with corn ethanol plant CO2**

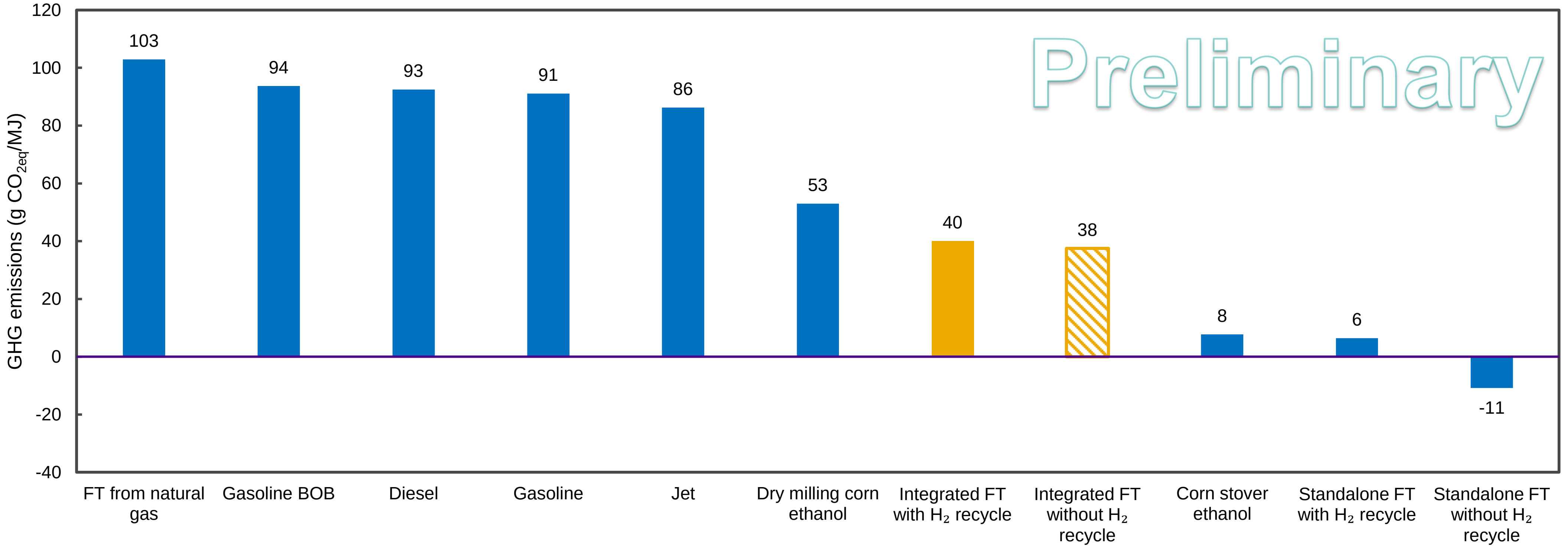
- FT fuel (the mixture of naphtha, jet fuel, and diesel) production without H_2 recycle has the lowest WTW GHG emissions of -11 g CO_{2eq} /MJ [a]
- Based on carbon neutrality of fermentation CO_2 in ethanol plants, GHG emissions reductions of the standalone FT fuel pathway are estimated to be 93% to 113% compared with petroleum pathways



[a] GHG emissions are evaluated based on GREET 2018, we will update the data using GREET 2019

<u>Integrated</u> ethanol and FT fuel WTW GHG emissions with corn ethanol plant CO2

- WTW GHG emissions of for all fuels combined together (<u>ethanol, naphtha, jet fuel, and diesel)</u> are reduced to 38-40 g/MJ from 53 g/MJ of standalone ethanol plant; with 25% to 28% reductions



Please visit http://greet.es.anl.gov for:

- ***GREET models***
- ***GREET documents***
- ***LCA publications***
- ***GREET-based tools and calculators***