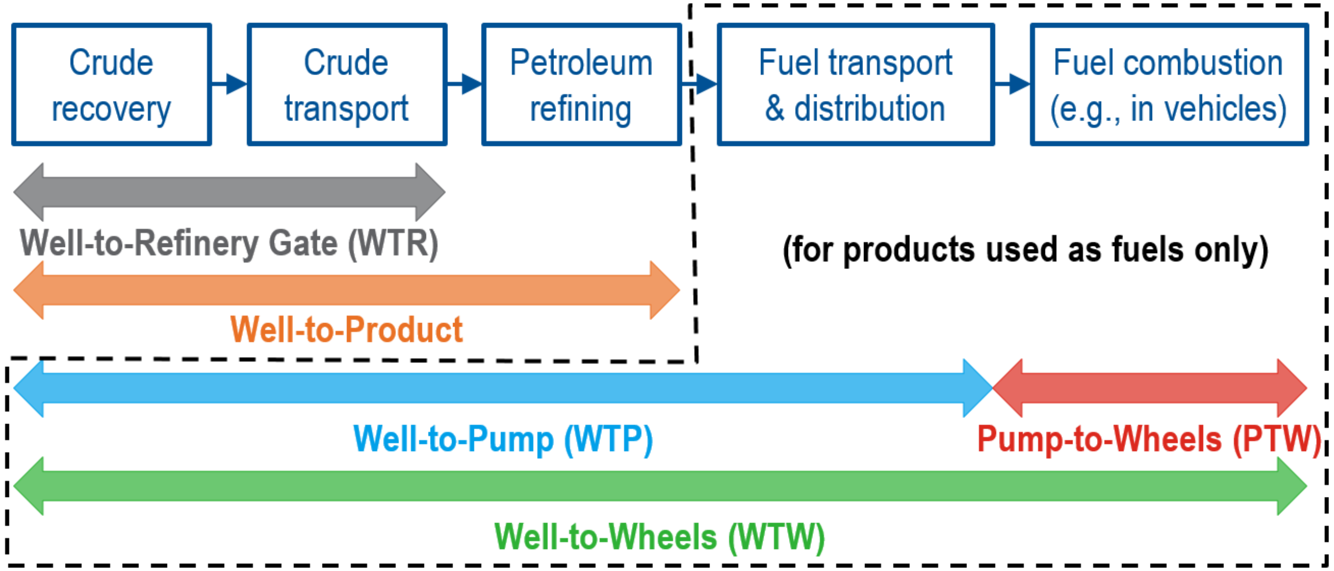
Life Cycle Analysis (LCA) of Petroleum-Based Fuels with the GREET® Model

Amgad Elgowainy, Zifeng Lu, Pingping Sun

Systems Assessment Center
Energy Systems Division
Argonne National Laboratory

The GREET Introduction Workshop
Argonne National Laboratory, October 15, 2019

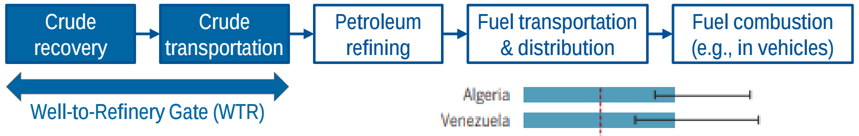
GREET capabilities for LCA of petroleum-based fuels



- **Crude types**
  - Conventional crude (domestic and imported)
  - Canadian oil sands
  - Shale oil (e.g., Bakken and Eagle Ford)
- **Refining products**
  - Gasoline blendstock, diesel, jet, residual oil, LPG, pet coke, crude naphtha
  - Asphalt, propane, butane, propylene (2019)
- **Energy and environmental metrics**
  - Energy intensities of total, fossil (petroleum, gas, coal), renewable (biomass, hydro, wind, solar), nuclear, …
  - Water use intensities
  - GHG emission intensities (and CO_2, CH_4, and N_2O)
  - Air pollutants' emission intensities of VOC, CO, NO_x, PM_{10}, $PM_{2.5}$, SO_x, BC, and OC (2019)
- **Regional results**
  - US PADD zones, selected states (e.g., CA)

Argonne NATIONAL LABORATORY

Crude recovery & transportation

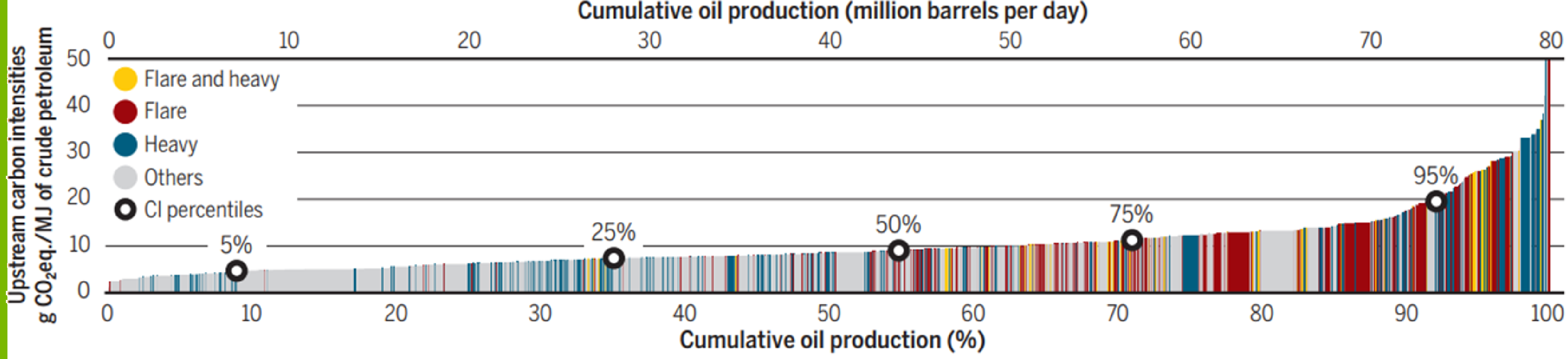


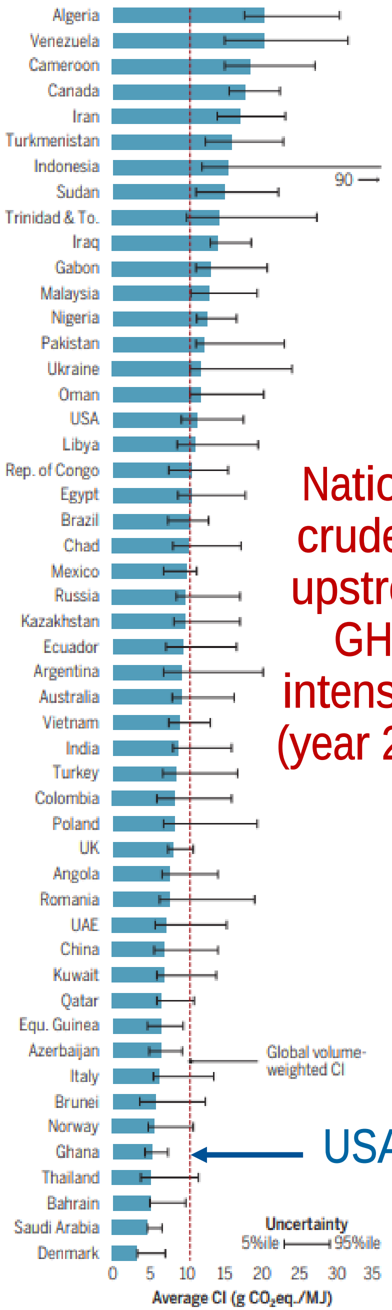
Global field-level carbon intensity of crude oil production

- **Analysis of energy and GHG emission intensities of 8966 oil fields in 90 countries**
  - Use engineering-based model
    - Oil Production Greenhouse Gas Emissions Estimator (OPGEE)
  - Analyze field-specific characteristics
    - Field depth, reservoir pressure, API gravity, gas/oil ratio, water/oil ratio, etc.

Global field-level upstream carbon intensity supply curve (year 2015)

Contribution of high flaring ("Flare" with FOR >75th percentile of all fields) and oil density ("Heavy" with API gravity ≤22°) are shown. Bar width reflects the oil production of a particular field in 2015. Global GHG intensity percentiles (5%, 25%, 50%, 75%, 95%) are 4.7, 7.3, 9.1, 11.2, and 19.5 g CO_2eq./MJ crude oil, respectively.



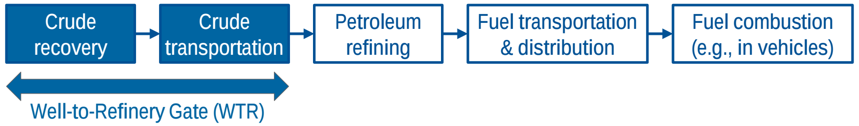


National crude oil upstream GHG intensities (year 2015)

USA

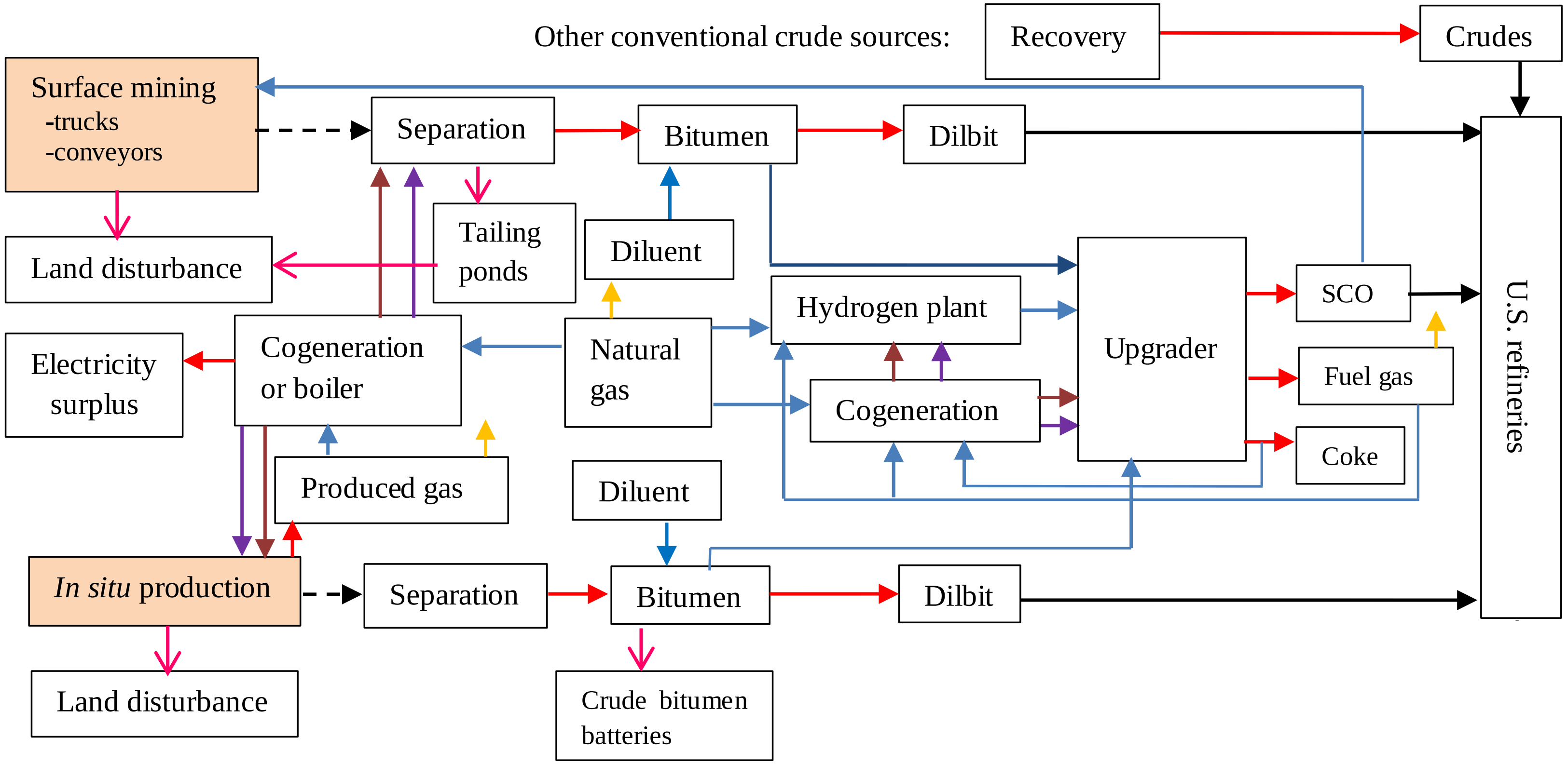
Masnadi et al., "Global carbon intensity of crude oil production", Science 361, 851-853, 2018
Masnadi et al., "Well-to-refinery emissions and net-energy analysis of China's crude-oil supply", Nature Energy, 3, 220-226, 2018

Crude recovery & transportation



Energy use and GHG emissions of Canadian oil sands

- Cover all 27 major oil sands projects since 2008



Legend: Used as process fuel or feedstock; Product output; Flaring; Transportation; Co-produced electricity; Co-produced steam; Process flow; Primary Process; Associated process

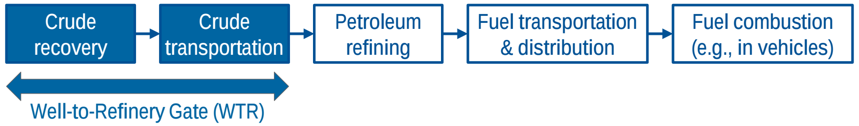
WTR system boundary includes:

- land disturbance by surface mining and *in situ* production
- bitumen recovery & separation
- bitumen upgrading
- flaring of gases
- fugitive emissions from tailing ponds and crude bitumen batteries
- electricity cogeneration in fields
- production/transmission of Canadian natural gas
- production/transportation of diluents

Cai et al., "Well-to-wheels greenhouse gas emissions of Canadian oil sands products: implications for US petroleum fuels", Environ. Sci. Technol. 49, 8219-8227, 2015

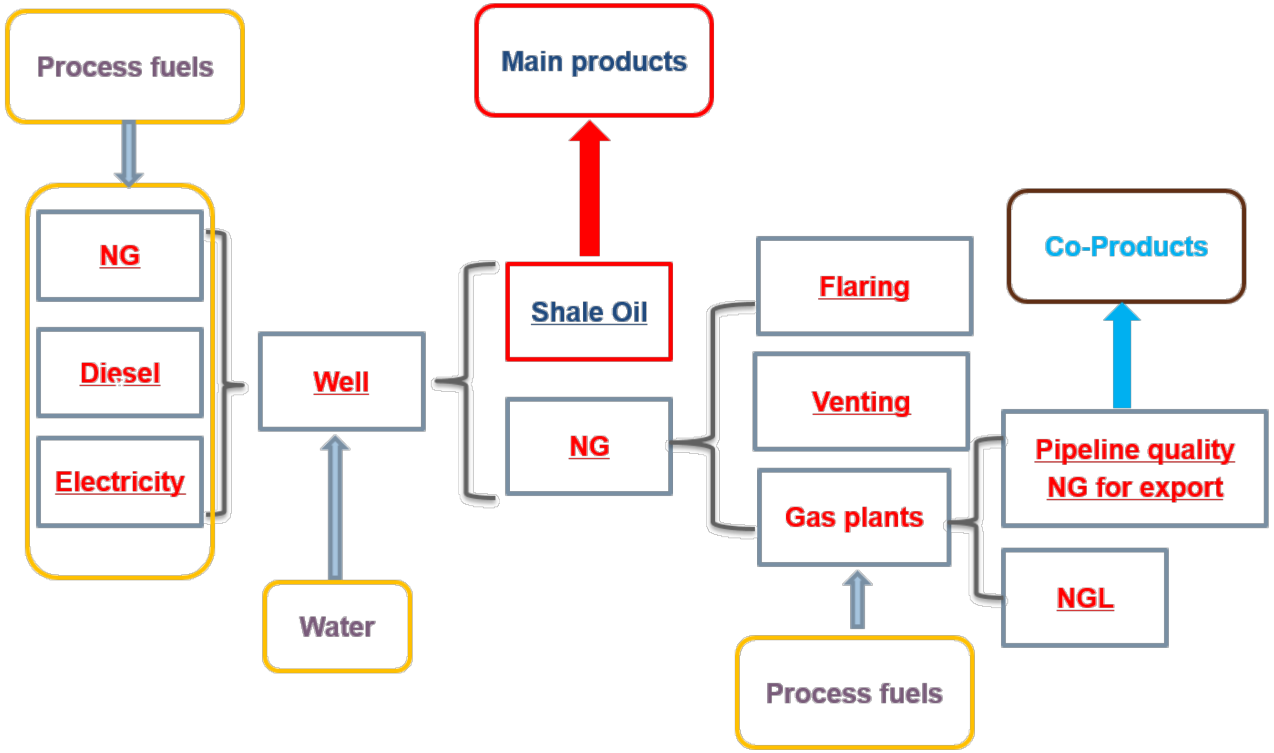
Argonne NATIONAL LABORATORY

Crude recovery & transportation



Energy use and GHG emissions of US shale oil

- **Estimate energy use and GHG emissions associated with the crude oil and NG extraction**
  - Based on data from 18,000+ wells drilled in the Bakken and Eagle Ford formations from 2006 to 2013
  - Using Oil Production Greenhouse Gas Emissions Estimator (OPGEE) model



Crude Types	WTR Energy (MJ/MJ)	WTR GHG (g $CO_{2\text{-eq}}$/MJ)
Bakken shale oil	0.039	9.59
Eagle Ford shale oil	0.031	5.08
US shale oil average	0.035	7.29
US conventional crudes	0.040	5.77

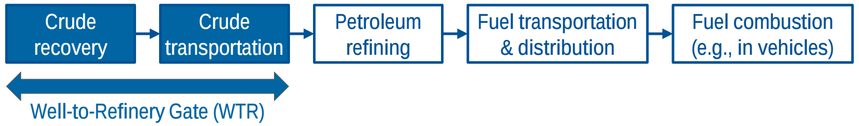
GREET1_2019

US shale oil have similar WTR energy intensities and a slightly higher GHG emissions intensities compared to US conventional crudes

Brandt et al., "Energy Intensity and Greenhouse Gas Emissions from Crude Oil Production in the Bakken Formation: Input Data and Analysis Methods," Argonne National Laboratory, https://greet.es.anl.gov/publication-bakken-oil, 2015.

Ghandi et al., "Energy Intensity and Greenhouse Gas Emissions from Crude Oil Production in the Eagle Ford Region: Input Data and Analysis Methods," Argonne National Laboratory, https://greet.es.anl.gov/publication-eagle-ford-oil, 2015.

Crude recovery & transportation



Summary: Crude oil received by the US refineries in 2018

Crude Types – Sources	Volume Shares (%)	API Gravity	WTR Energy (MJ/MJ)	WTR GHG (g $CO_{2\text{-eq}}$/MJ)
Conventional – US	49.8	32.0	0.04	5.8
Conventional – Canada	9.0	26.5	0.08	8.2
Conventional – Mexico	3.1	26.5	0.05	6.3
Conventional – Middle East	6.8	31.8	0.07	8.4
Conventional – Latin America	5.2	24.8	0.05	6.6
Conventional – Africa	2.2	38.3	0.06	7.1
Conventional – Other regions	1.4	32.0	0.05	6.9
Oil sands – Canada	8.0	17.8	1.32	24.8
Shale oil – US	14.6	45.3	0.04	7.3
Energy-Weighted Average		**31.6**	**0.07**	**8.2**

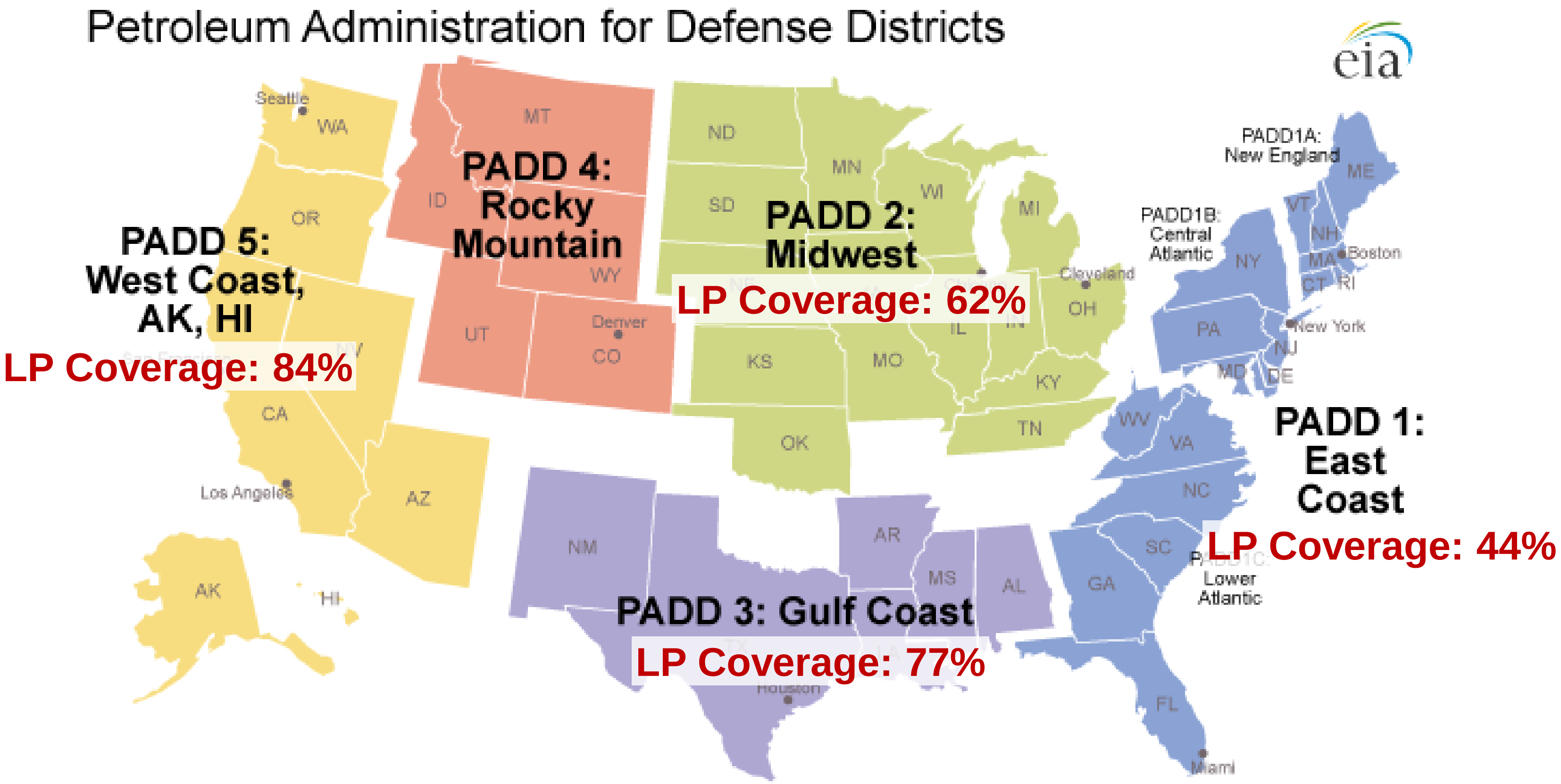
GREET1_2019

- **Differences in well-to-refinery gate (WTR) GHG emissions**
  - Conventional crudes
    - transportation distance (e.g., US domestic vs. Middle East)
    - transportation mode (e.g., Canadian via pipelines vs. Mexico via rail)
  - Canadian oil sands
    - energy-intensive recovery processes, e.g., oil sands extraction, bitumen separation, and bitumen upgrading
  - US shale oil
    - methane flaring and venting, especially for the Bakken formation

Petroleum refining

Characterize refineries at the process/unit level to derive product-specific results

- **Linear programming (LP) models of individual US refineries for process/unit-level analyses**
  - 43 large (>100 k bbl/d) US refineries with different configurations in 4 PADD regions in 2012
  - Close-to-reality process data and configurations
  - Covering 70% of US refining capacity



Crude Input to Refineries (k bbl/day)

PADD region	Total	LP modeling
I	921	404
II	3,451	2150
III	7,755	5983
IV	574	-
V	2,337	1956
Total	15,038	10493

Elgowainy et al., "Energy Efficiency and Greenhouse Gas Emission Intensity of Petroleum Products at US Refineries," Environ. Sci. Technol. 48, 7612-7624, 2014

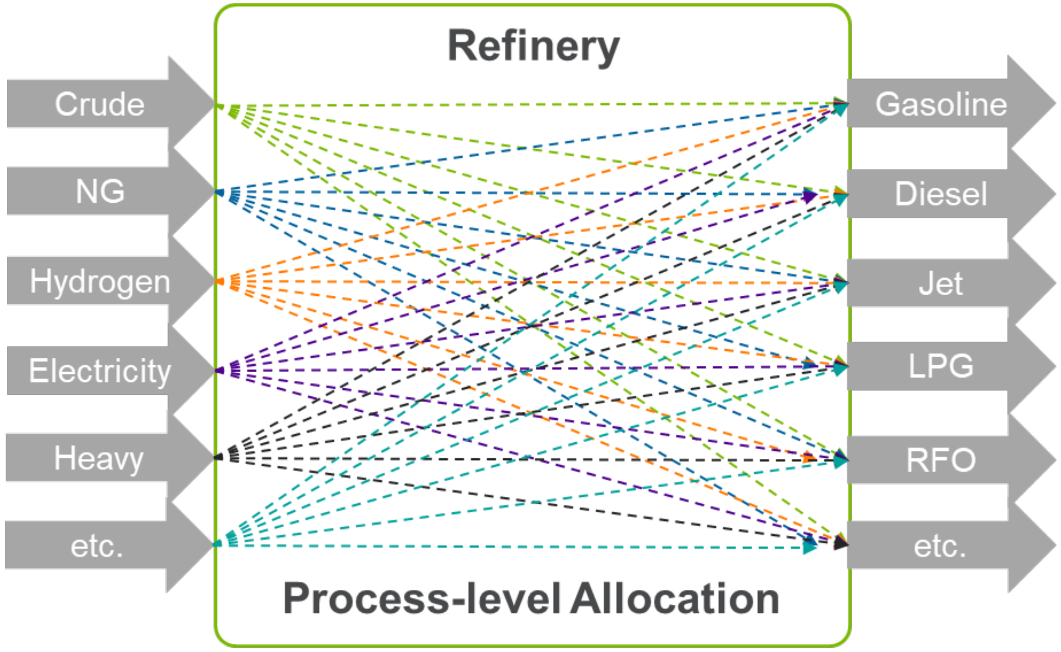
Forman et al., "US Refinery Efficiency: Impacts Analysis and Implications for Fuel Carbon Policy Implementation," Environ. Sci. Technol. 48, 7625-7633, 2014

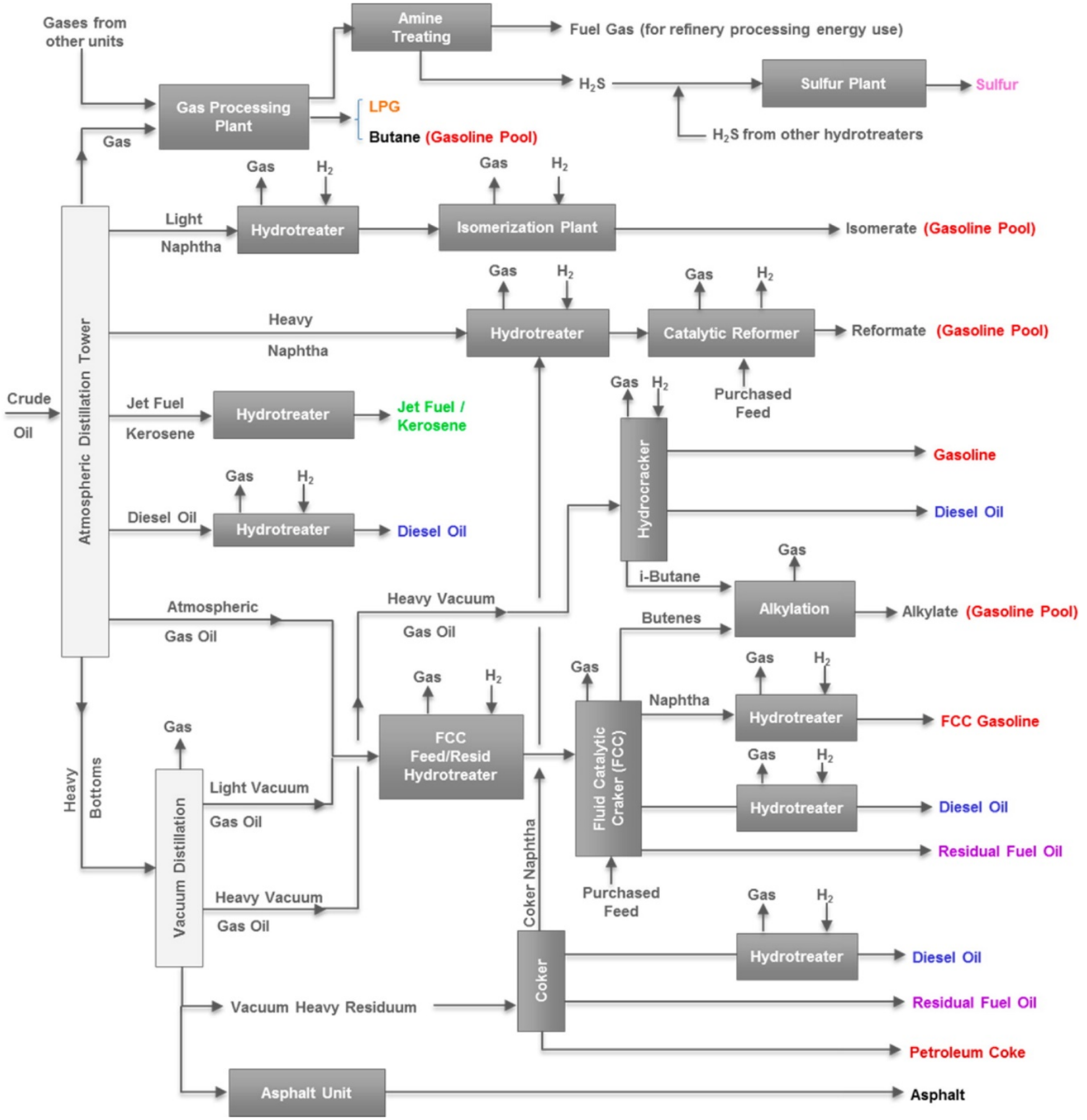
Han et al., "A Comparative Assessment of Resource Efficiency in Petroleum Refining," Fuel, 157, 292-298, 2015

Petroleum refining

Refinery process/unit-level details are important for assigning energy inputs and emissions

- **Purpose: derive product-specific results**
  - Estimate the energy and emissions burdens of individual intermediates within a refinery by allocating the burdens at the process/unit level
  - Energy allocation by default
  - Aggregate allocated burdens to final product pools
  - Track destination of each flow within a refinery

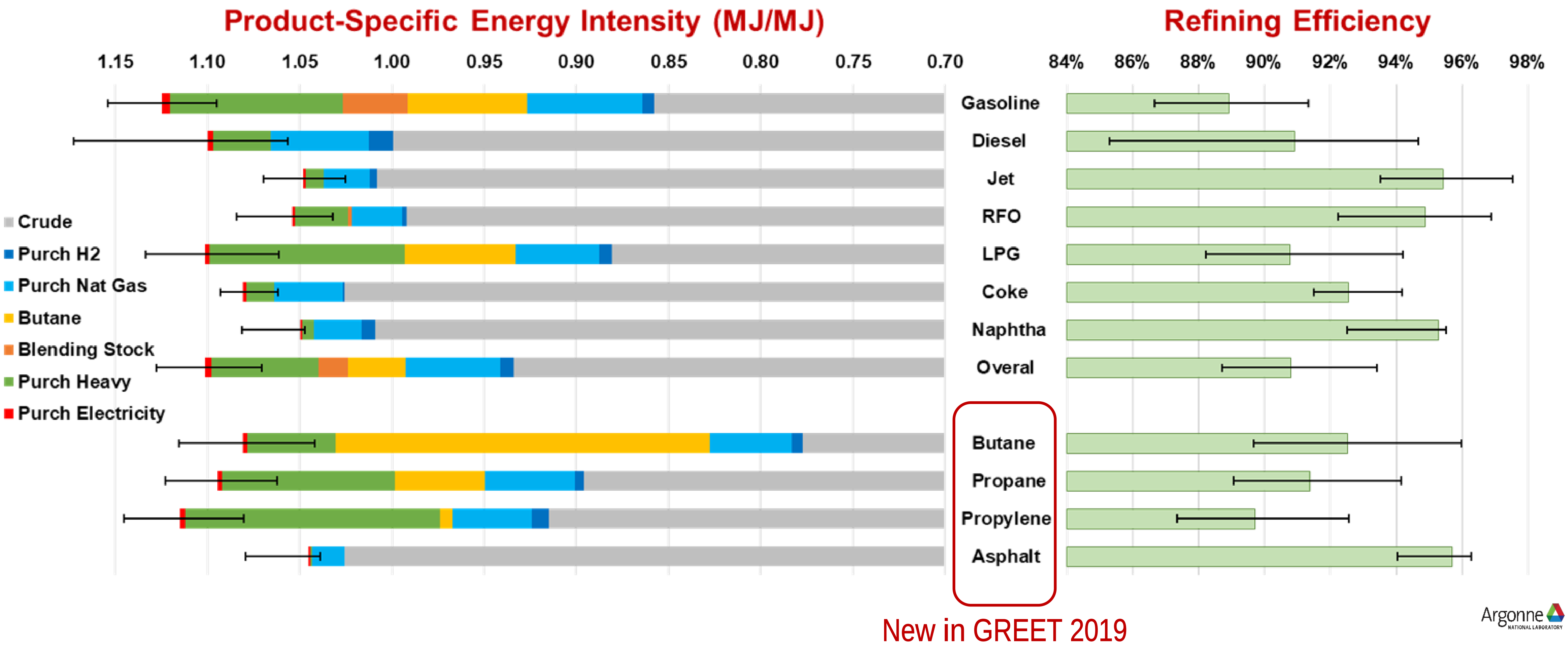




Petroleum refining

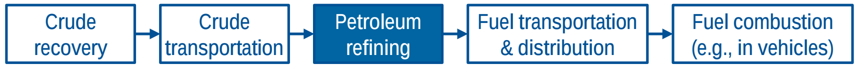
Product-specific refining efficiencies and energy intensities

- Variations in product-specific results reflect the differences in refining pathways and the differences in energy intensities of related processes



Argonne NATIONAL LABORATORY

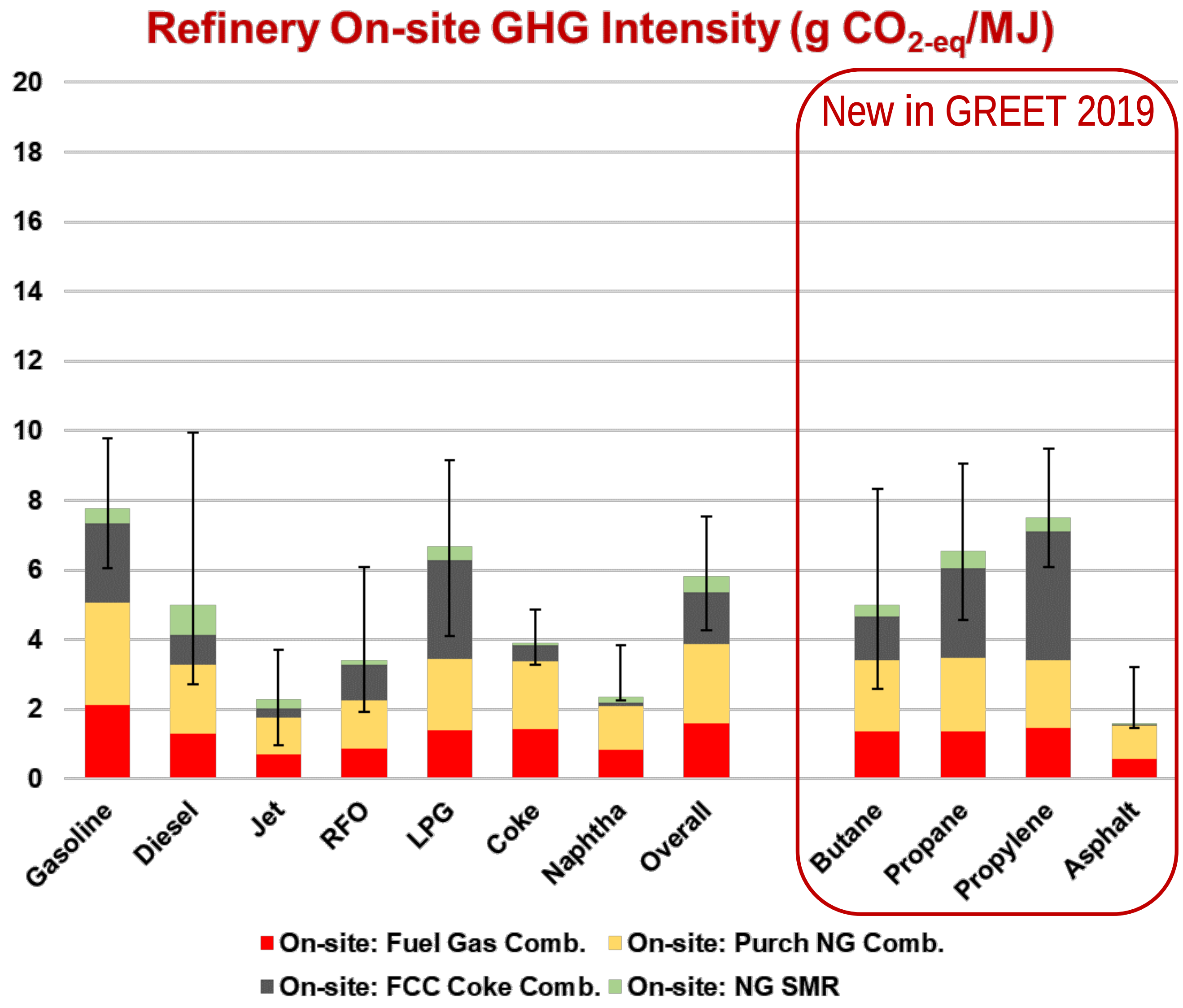
Petroleum refining



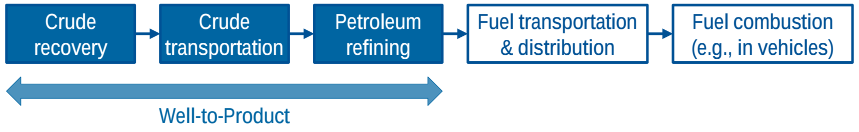
Product-specific GHG emission intensities

Sources of on-site refinery GHG emissions

– Combustion of purchased fuels
  - e.g., purchased NG
– Combustion of internally produced fuels
  - e.g., FCC coke and fuel gas
– Non-combustion emissions
  - e.g., SMR



Well-to-product GHG emissions

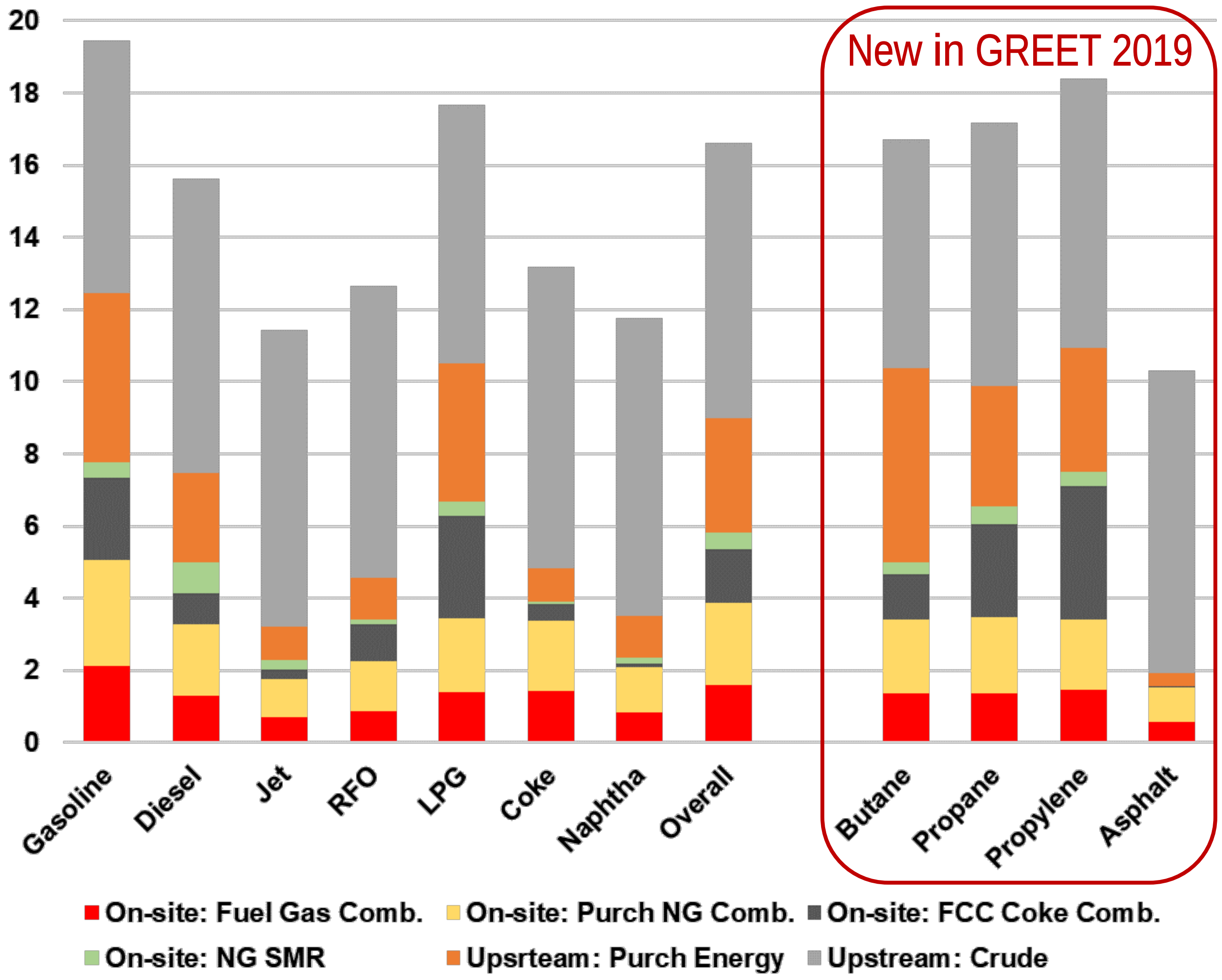


Product-specific GHG emission intensities

- **Sources of on-site refinery GHG emissions**
  - Combustion of purchased fuels
    - e.g., purchased NG
  - Combustion of internally produced fuels
    - e.g., FCC coke and fuel gas
  - Non-combustion emissions
    - e.g., SMR

- **Upstream GHG emissions**
  - Crude oil
  - Purchased hydrogen
  - Purchased natural gas
  - Purchased electricity
  - Purchased heavy
  - Purchased butane
  - Purchased blending stock
  - etc.

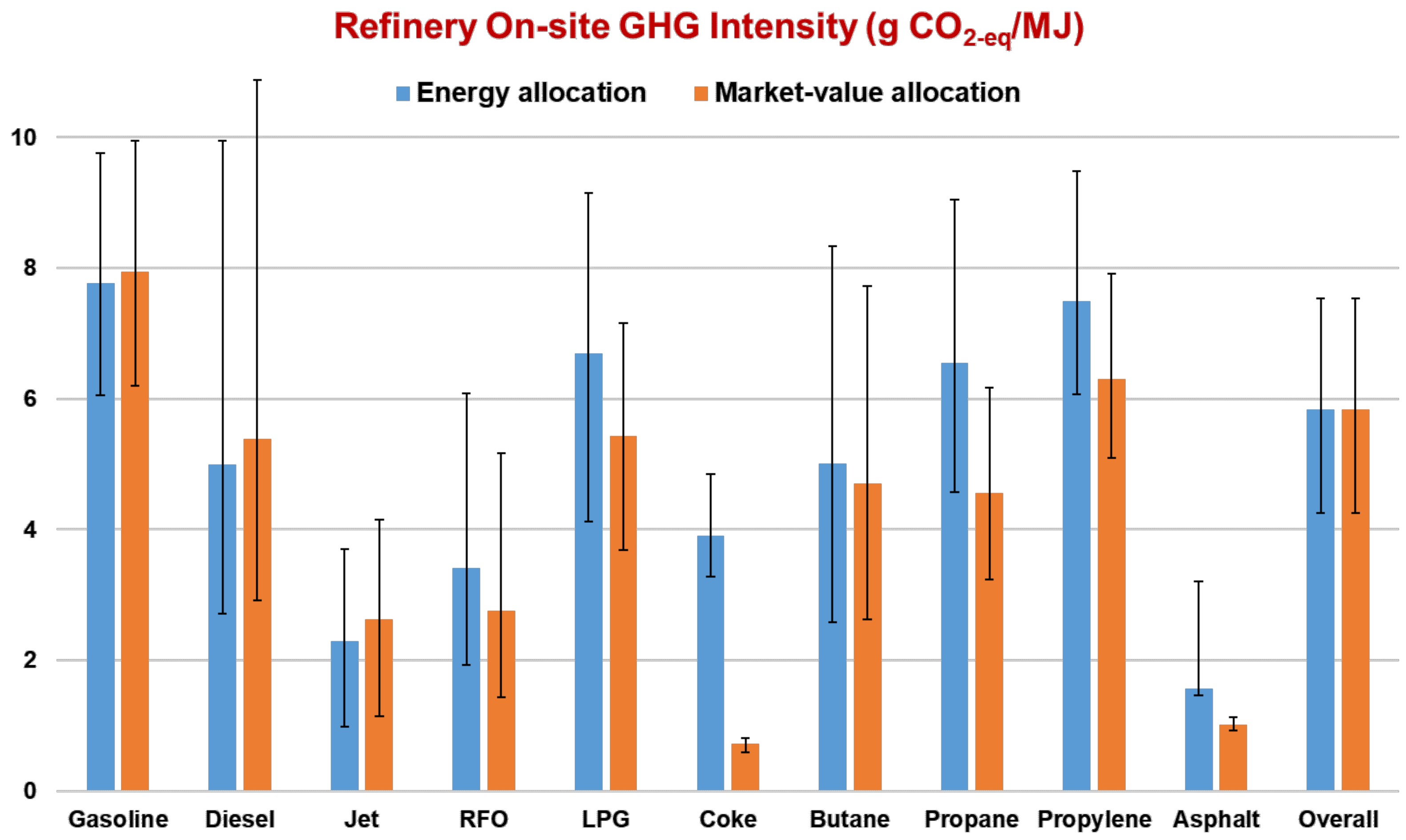
Well-to-Product GHG Intensity (g $CO_{2\text{-}eq}$/MJ)



Petroleum refining

Process/unit–level allocation methods significantly affect product-specific results

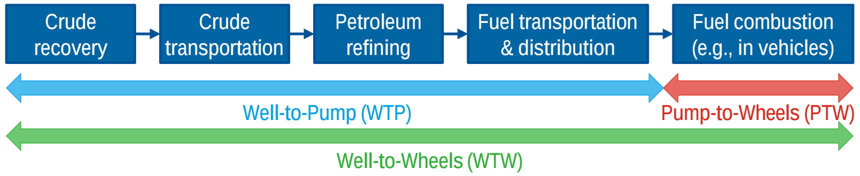
- **Market-value allocation**
  - Lower carbon intensities are assigned to products with lower market values e.g., RFO, LPG, coke, propane, propylene, asphalt, etc.



Product prices in 2018 market (EIA)

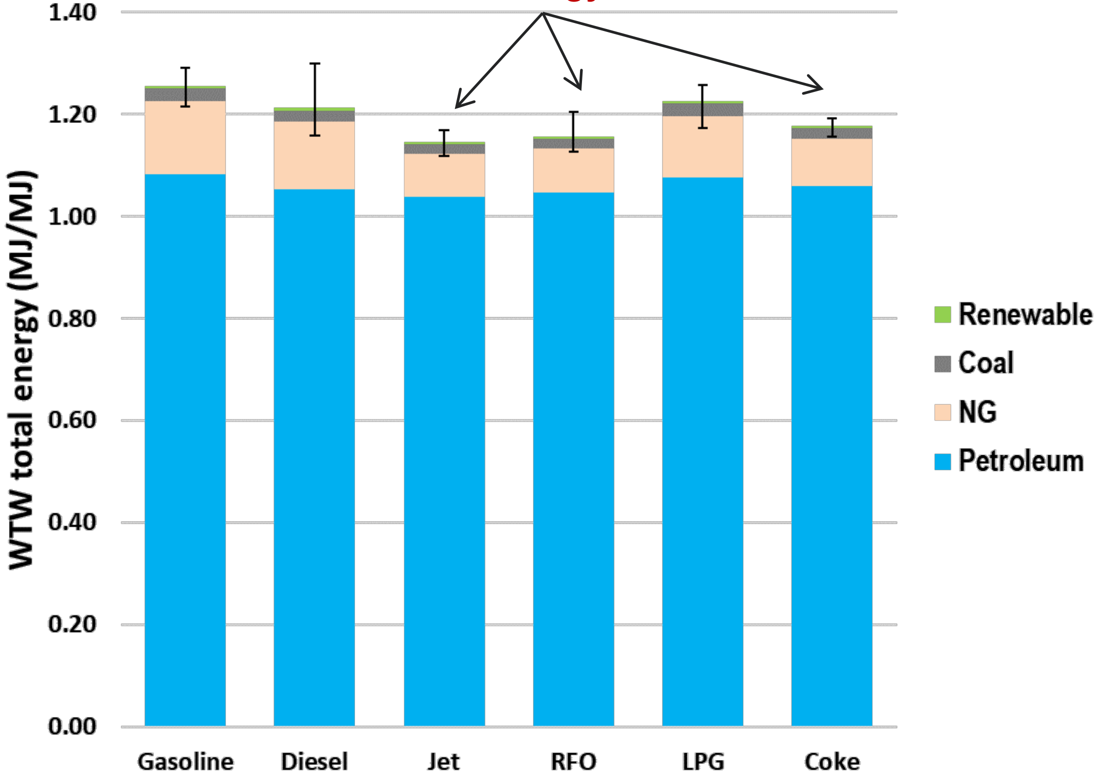
Products	Price ($/mmBtu)
Gasoline BOB	17.7
Diesel	15.5
Jet	15.4
RFO	9.8
LPG	10.7
Coke	2.4
Butane	12.0
Propane	9.4
Propylene	12.0
Asphalt	7.3

Well-to-Wheels results

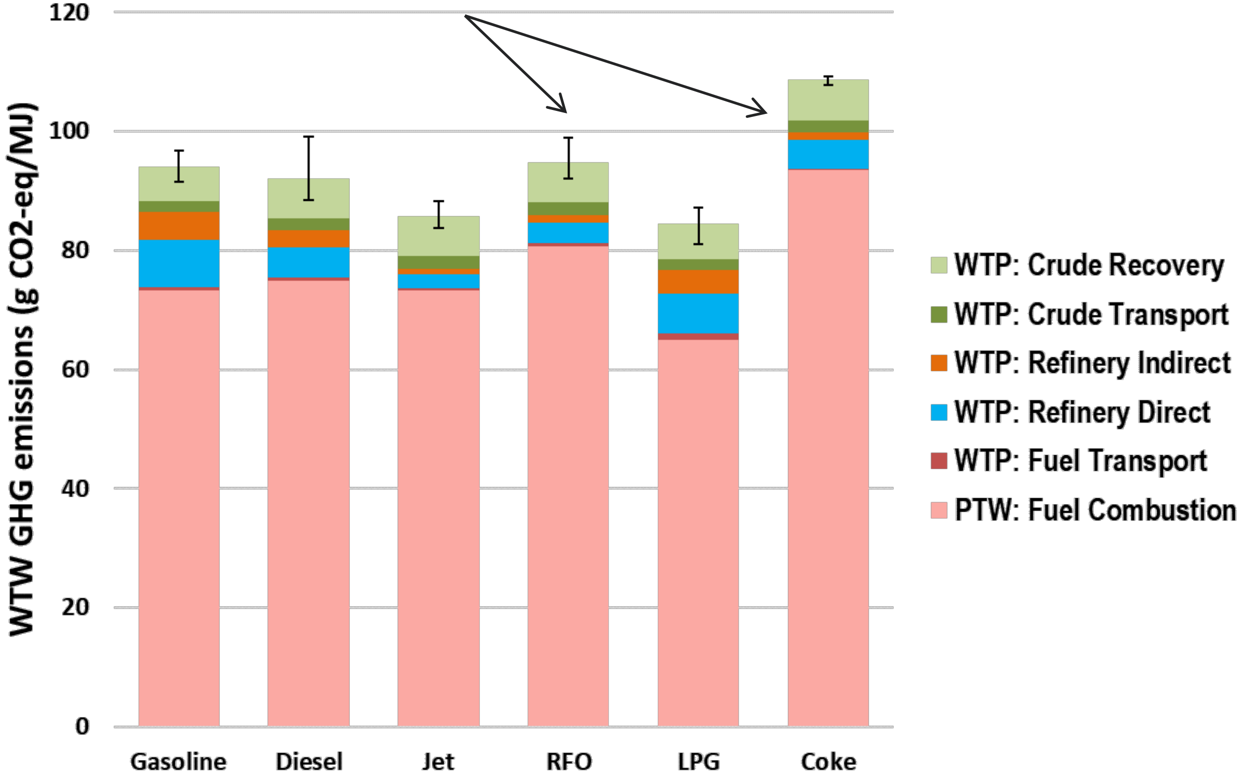


- **WTW GHG emissions of petroleum fuels are dominated by end use release of CO_2; refinery direct/indirect emissions a distant second**

Jet, RFO, and coke are less processed fuels, thus lower energy intensities



High C-content of RFO and coke increases their WTW GHG emission intensities



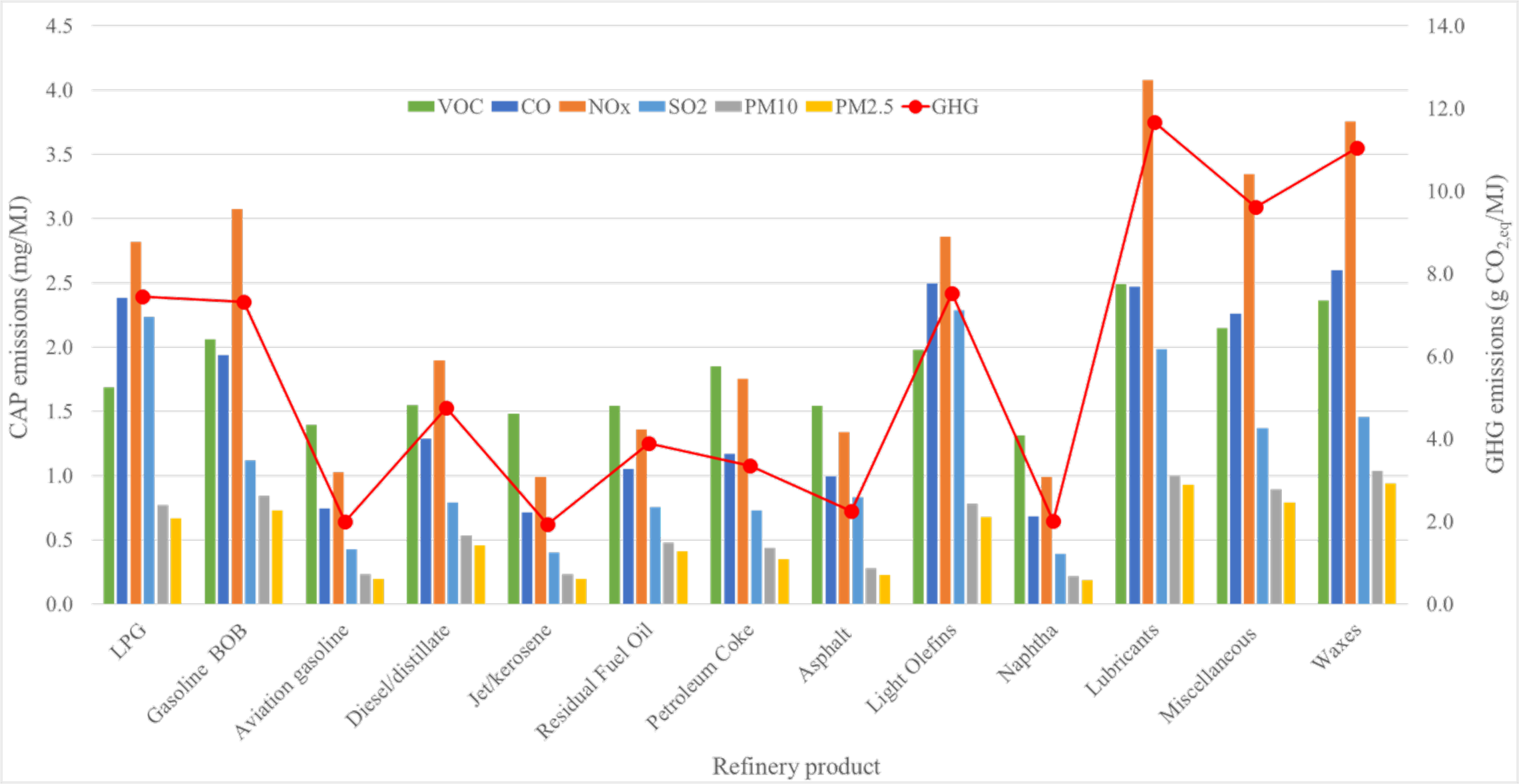
Elgowainy et al., "Energy Efficiency and Greenhouse Gas Emission Intensity of Petroleum Products at US Refineries," Environ. Sci. Technol. 48, 7612-7624, 2014

Argonne NATIONAL LABORATORY

Petroleum refining CAP emissions

Criteria air pollutant (CAP) emissions are updated in GREET 2019

- Using EPA databases National Emission Inventory (NEI) and Greenhouse Gas Reporting Program (GHGRP) for emissions, and EIA database for energy uses and fuel productions



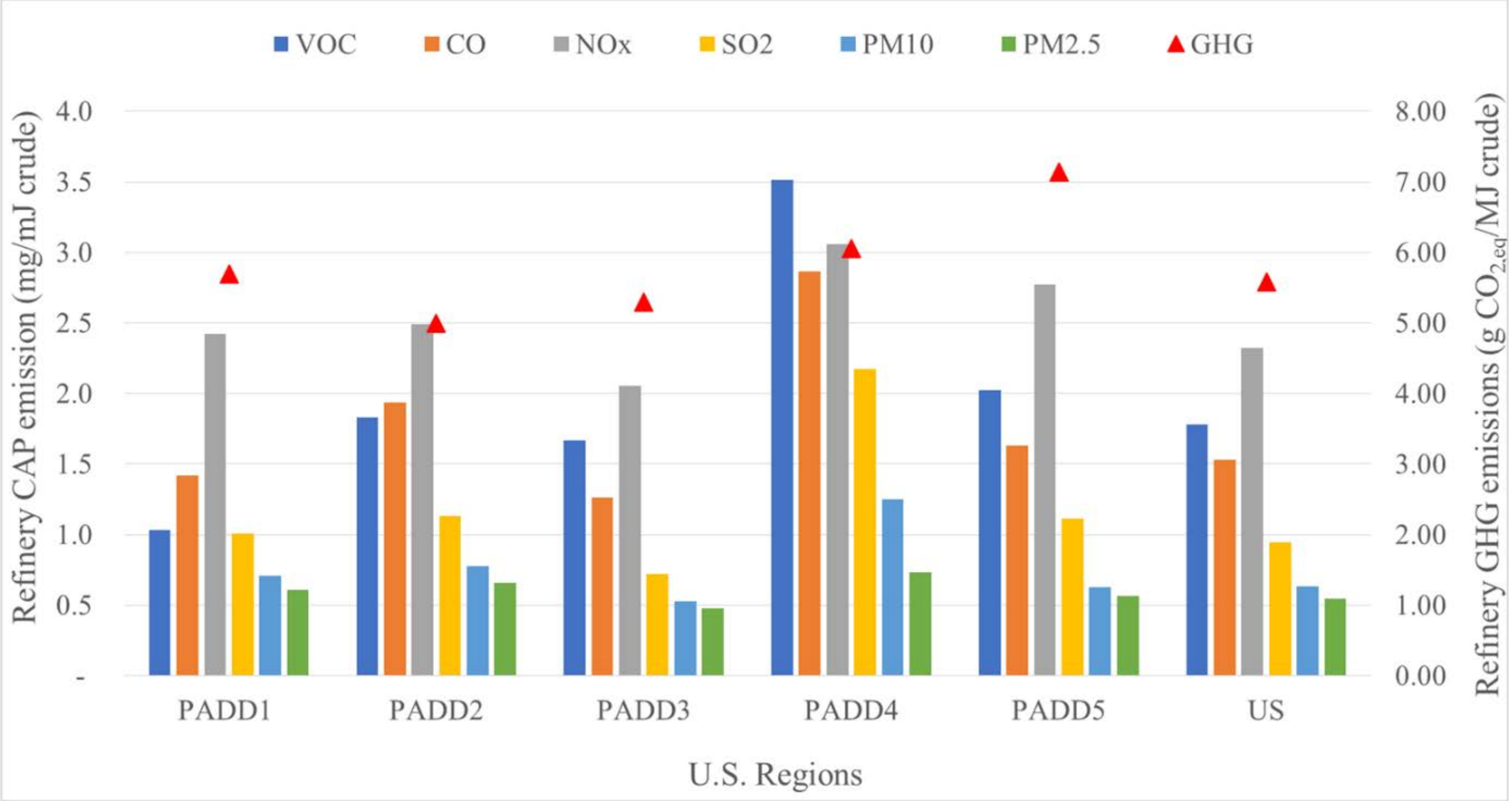
Refinery CAP emissions are allocated to individual refinery products, which are lower than those in previous GREET versions

Sun et al., "Criteria Air Pollutant and Greenhouse Gases Emissions from US Refineries Allocated to Refinery Products," Environ. Sci. Technol. 53, 6556-6569, 2019

Petroleum refining CAP emissions

Criteria air pollutant (CAP) emissions are updated in GREET 2019

- Refinery CAP emissions per crude input and per unit are also investigated



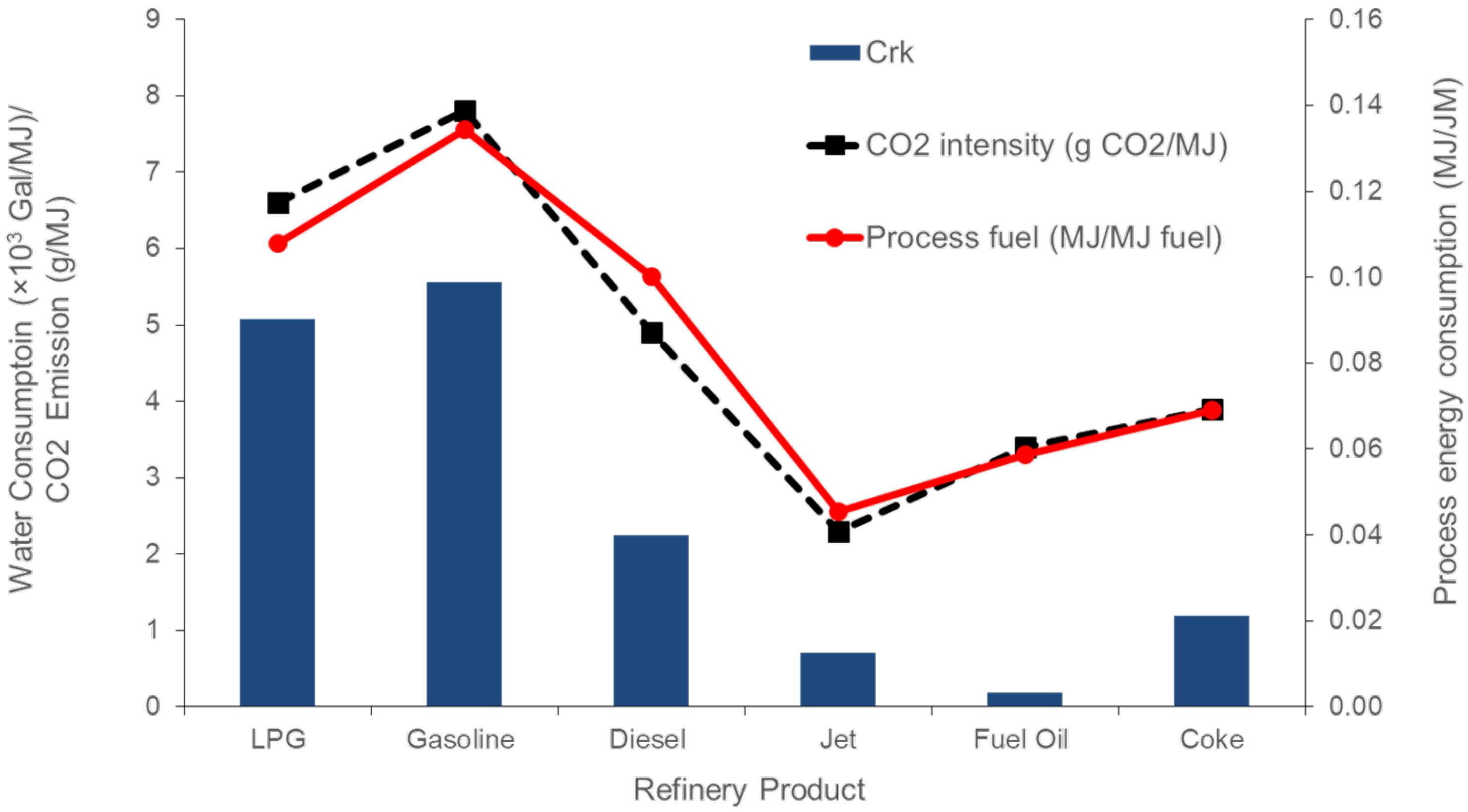
Sun et al., "Criteria Air Pollutant and Greenhouse Gases Emissions from US Refineries Allocated to Refinery Products," Environ. Sci. Technol. 53, 6556-6569, 2019

Argonne NATIONAL LABORATORY

Petroleum refining water consumption

- **Capacity shares**
  - Cracking 17%
  - Light coking 63%
  - Heavy coking 20%

- **Refinery water consumption is directionally proportional to energy consumption and CO_2 emissions**



Sun et al., "Estimation of U.S. refinery water consumption and allocation to refinery products," Fuel 221, 542-557, 2018

GREET petroleum module allows users to change all key input parameters

- **How to change the shares of crude oil sources**
  - “Inputs” tab
  - Section “3.1 a) Share of crude oil sources”
  - Set Cell E21 to 2 (User-defined)
  - Change the user defined share in Row 24 and 32

3.1) Petroleum Recovery Options

3.1.a) Share of crude oil sources

1	Basis of share of crude oil sources: 1 -- EIA projection, 2 -- User defined		
	U.S. Domestic	Canada (Oil Sands)	Canada (Conv. Crude)
EIA projection	64.4%	8.0%	9.0%
User defined	64.4%	8.0%	9.0%
Used in calculation	64.4%	8.0%	9.0%
API gravity	34.8	17.8	26.5
S Content (wt %)	1.4	2.9	1.9
Average transportation distances (mi)	See T&D_Flowcharts tab	1,708	1,708

U.S. Domestic crude	Shale Oil (Bakken)	Shale Oil (Eagle Ford)	Rest of U.S. domestic crude
API gravity	42	48	32.0
Vol. Share (%)	11.0%	11.7%	77.3%

- **How to change refining efficiencies**
  - “Inputs” tab
  - Section “3.3) Petroleum Refining Efficiency”
  - Choose Simulation scenarios (E63) from 0 to 8
  - When 0 is selected, a user can directly enter the refining efficiency of each product to Row 78 (Efficiency defined in the time-series tables)

3.3) Petroleum Refining Efficiency

3.3.a) Simulation scenarios

0	0 -- Efficiency defined in the time-series tables; 1 -- Crude oil mixes defined in 3 -- Low API, high HP%; 4-- Low API, high S%; 5 -- Med. API, high S%; 6 --

3.3.b) Crude Quality, refinery product slate and complexity index

	Used in calculation	User defined	De
API gravity of Average Crude to Refineries	31.6	29.6	
S Content of Average Crude to Refineries (wt %)	1.7	1.7	
Refinery Heavy Product Yield (mmBtu of mmBtu of total refinery products)	11.0%	11.0%	
Refinery Complexity Index	10.8	10.8	

3.3.c) Overall Refinery and Product Specific Efficiency

	Overall	Gasoline	CA
Energy consumption ratio		1.178	
Estimated refinery efficiency by crude/refinery characteristics in Sections 3.3.b)	90.4%	88.8%	
Efficiency defined in the time-series tables		88.6%	
Used in calculation		88.6%	

Amgad Elgowainy *aelgowainy@anl.gov*
Zifeng Lu *zlu@anl.gov*
Pingping Sun *psun@anl.gov*

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

for:

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