GREET® Life-Cycle Analysis of Transportation Fuels and Vehicle Technologies

Amgad Elgowainy and **Michael Wang**
Systems Assessment Group
Energy Systems Division
Argonne National Laboratory

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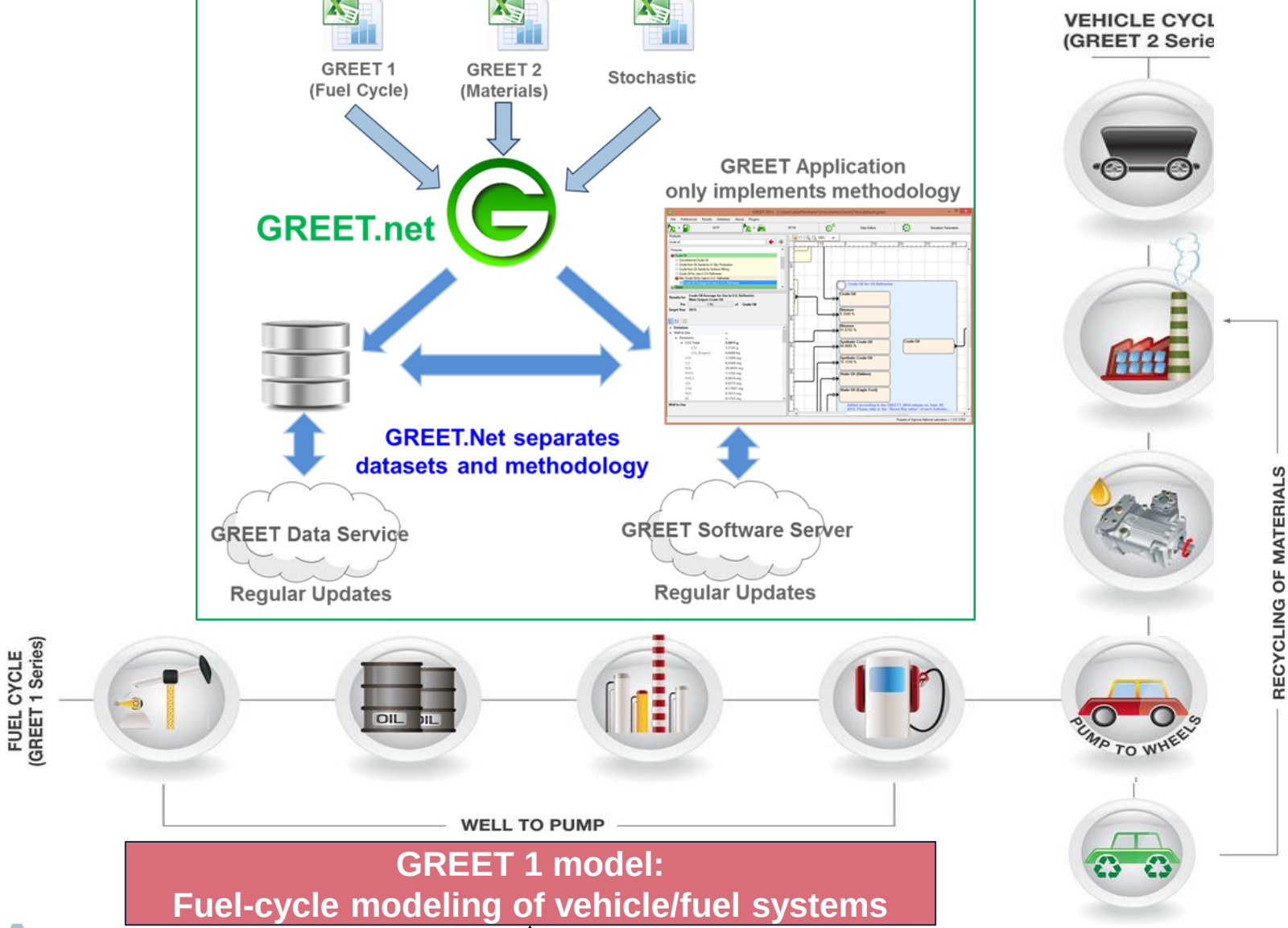
The GREET® (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) Model



GREET 2 model:
Vehicle cycle modeling for vehicle manufacturing

GREET 1 model:
Fuel-cycle modeling of vehicle/fuel systems

Stochastic Simulation Tool

GREET development has been supported by several DOE Offices since 1995

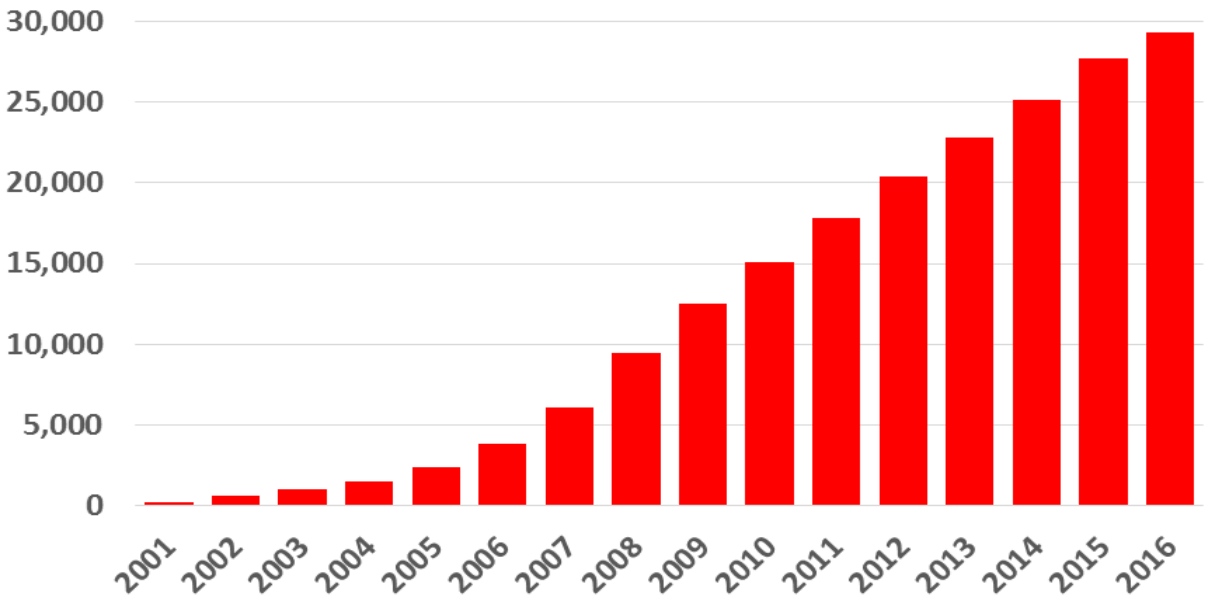
- Vehicle Technology Office (VTO)
- Fuel-Cell Technology Office (FCTO)
- Energy Policy and Systems Analysis (EPSA)
- Bioenergy Technology Office (BETO)
- Geothermal Technology Office (GTO)

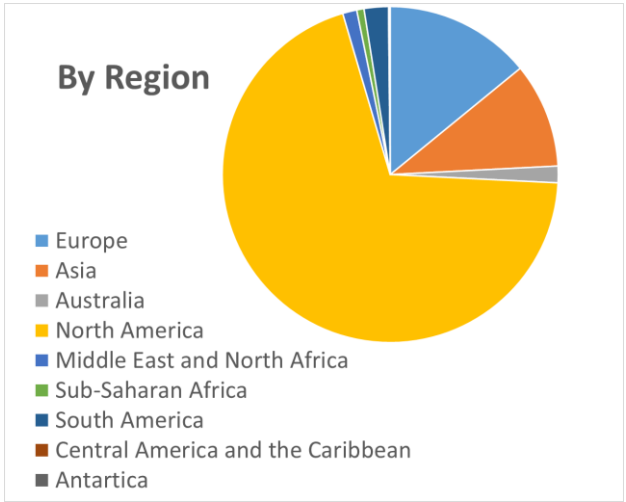
GREET has been in public domain and free of charge - Updated annually

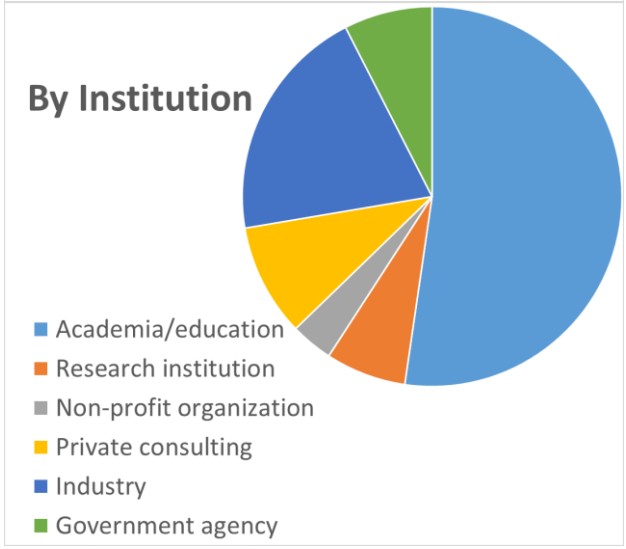
Examples of major uses of GREET

- US EPA used GREET for RFS and vehicle GHG standard developments
- CARB developed CA-GREET for its Low-Carbon Fuel Standard compliance
- DOE, USDA, and the Navy use GREET for R&D decisions
- DOD DLA-Energy uses GREET for alternative fuel purchase requirements
- Auto industry uses it for R&D screening of vehicle/fuel system combinations
- Energy industry (especially new fuel companies) uses it for addressing sustainability of R&D investments
- Universities uses GREET for education on technology sustainability of various fuels

There are 30,000 registered GREET users globally







GREET outputs include energy use, greenhouse gases, criteria pollutants and water consumption for vehicle and energy systems

- **Energy use**
  - Total energy: fossil energy and renewable energy
    - Fossil energy: petroleum, natural gas, and coal (they are estimated separately)
    - Renewable energy: biomass, nuclear, hydro-power, wind, and solar energy
- **Greenhouse gases (GHGs)**
  - CO_2, CH_4, N_2O, and black carbon
  - CO_2e of the three (with their global warming potentials)
- **Air pollutants**
  - VOC, CO, NO_x, PM_{10}, $PM_{2.5}$, and SO_x
  - They are estimated separately for
    - Total (emissions everywhere)
    - Urban (a subset of the total)
- **Water consumption**
- **GREET LCA functional units**
  - Per mile driven
  - Per unit of energy (million Btu, MJ, gasoline gallon equivalent)
  - Other units (such as per ton-mi for transportation modes)

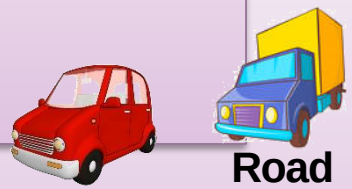
GREET includes more than 100 fuel production pathways from various energy feedstock sources

Feedstock	Fuel
Petroleum Conventional Oil Sands	Gasoline Diesel Jet Fuel Liquefied Petroleum Gas Naphtha Residual Oil
Coal	Hydrogen Fischer-Tropsch Diesel Fischer-Tropsch Jet Methanol Dimethyl Ether
Natural Gas North American Non-North American Shale gas	Compressed Natural Gas Liquefied Natural Gas Liquefied Petroleum Gas Methanol Dimethyl Ether Fischer-Tropsch Diesel Fischer-Tropsch Jet Fischer-Tropsch Naphtha Hydrogen
Renewable Natural Gas Landfill Gas Animal Waste Waste water treatment	
Coke Oven Gas Petroleum Coke Nuclear Energy	Hydrogen

Feedstock	Fuel
Corn	Ethanol Butanol
Sugarcane	Ethanol
Soybeans Palm Rapeseed Jatropha Camelina Algae	Biodiesel Renewable Diesel Renewable Gasoline Hydroprocessed Renewable Jet
Cellulosic Biomass Switchgrass Willow/Poplar Crop Residues Forest Residues Miscanthus	Ethanol Hydrogen Methanol Dimethyl Ether Fischer-Tropsch Diesel Fischer-Tropsch Jet Pyro Gasoline/Diesel/Jet
Residual Oil Coal Natural Gas Biomass Other Renewables	Electricity

GREET includes all transportation subsectors

- Light-duty vehicles
- Medium-duty vehicles
- Heavy-duty vehicles
- Various powertrains:
  Internal Combustion Engines
  Electrics
  Fuel cells



Road transportation

- Globally, a fast growing sector with GHG reduction pressure
- Interest by DOD, ICAO, FAA, and commercial airlines
- GREET includes
  - ✓ Passenger and freight transportation
  - ✓ Various alternative fuels blended with petroleum jet fuels

Air transportation

Rail transportation

- Interest by FRA, railroad companies
- Potential for CNG/LNG to displace diesel

Marine transportation

- Desire to control air pollution in ports globally
- Interest by EPA, local governments, IMO
- GREET includes
  - ✓ Ocean and inland water transportation
  - ✓ Baseline diesel and alternative marine fuels

GREET examines more than 80 on-road vehicle/fuel systems for both LDVs and HDVs

Conventional Spark-Ignition Engine Vehicles
- Gasoline
- Compressed natural gas, liquefied natural gas, and liquefied petroleum gas
- Gaseous and liquid hydrogen
- Methanol and ethanol

Spark-Ignition, Direct-Injection Engine Vehicles
- Gasoline
- Methanol and ethanol

Compression-Ignition, Direct-Injection Engine Vehicles
- Diesel
- Fischer-Tropsch diesel
- Dimethyl ether
- Biodiesel

Fuel Cell Vehicles
- On-board hydrogen storage
  - Gaseous and liquid hydrogen from various sources
- On-board hydrocarbon reforming to hydrogen

Battery-Powered Electric Vehicles
- Various electricity generation sources

Hybrid Electric Vehicles (HEVs)
- Spark-ignition engines:
  - Gasoline
  - Compressed natural gas, liquefied natural gas, and liquefied petroleum gas
  - Gaseous and liquid hydrogen
  - Methanol and ethanol
- Compression-ignition engines
  - Diesel
  - Fischer-Tropsch diesel
  - Dimethyl ether
  - Biodiesel

Plug-in Hybrid Electric Vehicles (PHEVs)
- Spark-ignition engines:
  - Gasoline
  - Compressed natural gas, liquefied natural gas, and liquefied petroleum gas
  - Gaseous and liquid hydrogen
  - Methanol and ethanol
- Compression-ignition engines
  - Diesel
  - Fischer-Tropsch diesel
  - Dimethyl ether
  - Biodiesel

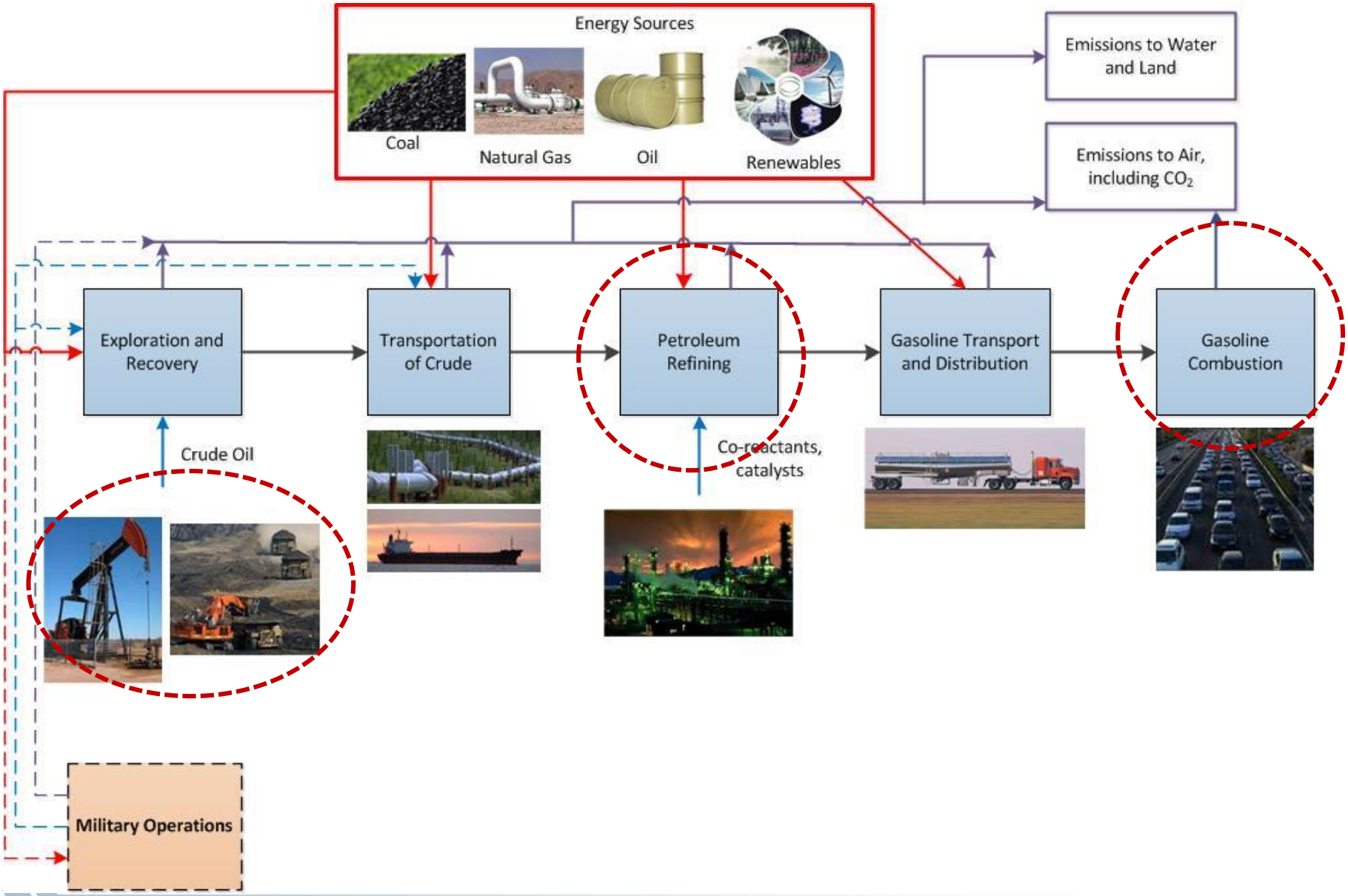
GREET approach and data sources

- **Approach: build LCA modeling capacity with the GREET model**
  - Build a consistent LCA platform with reliable, widely accepted methods/protocols
  - Address emerging LCA issues
  - Maintain openness and transparency of LCAs by making GREET publicly available
  - Primarily process-based LCA approach (the so-called attributional LCA); some features of consequential LCA are incorporated

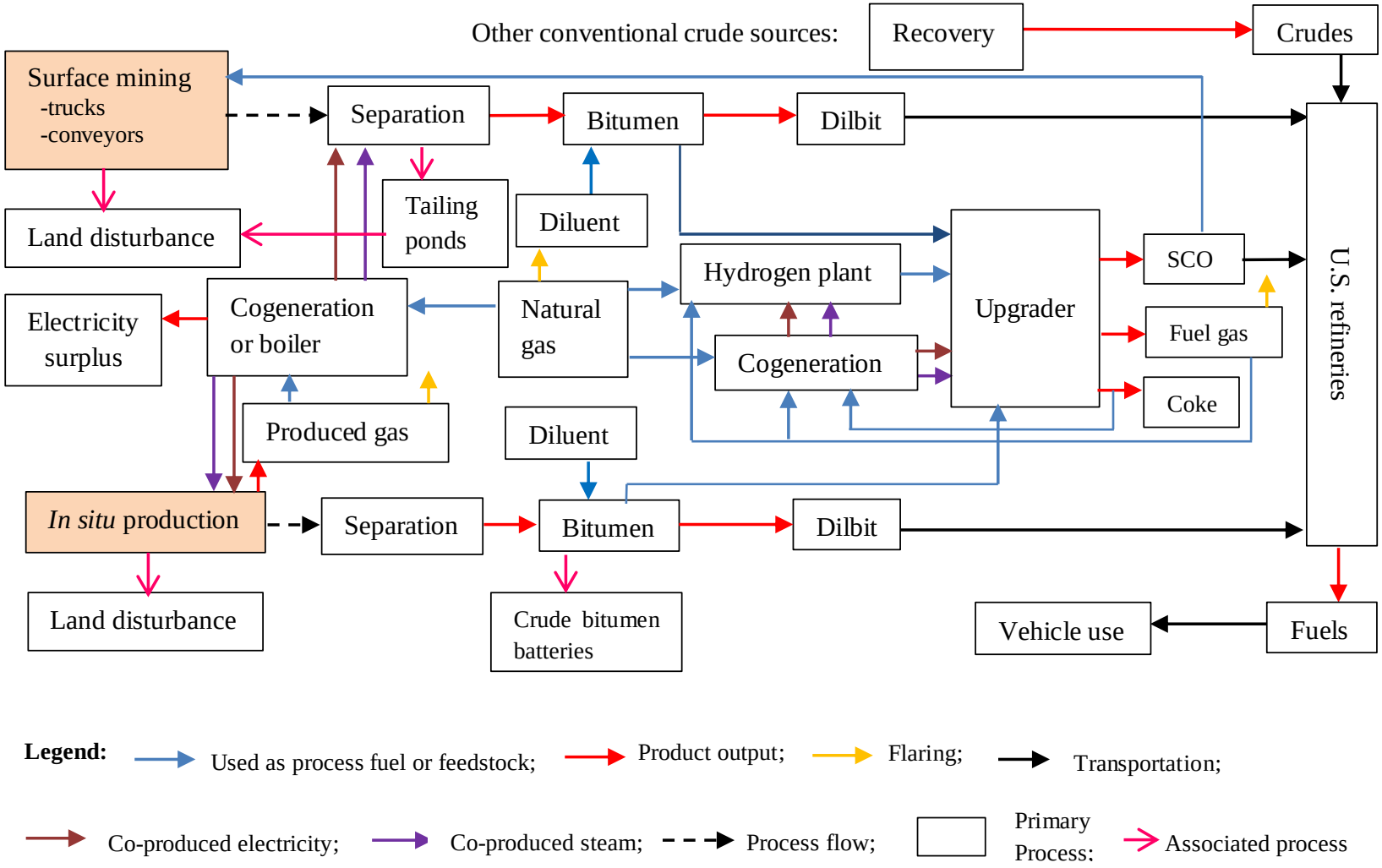
- **Data sources**
  - Field data and open literature
  - Simulations with models such as ASPEN Plus for fuel production and ANL Autonomie and EPA MOVES for vehicle operations
  - Fuel producers and technology developers for fuels and automakers and system components producers for vehicles
  - Baseline technologies and energy systems: EIA AEO projections, EPA eGrid for electric systems, etc.
  - Consideration of effects of regulations already adopted by agencies

LCA GHG Emissions of Petroleum Fuels

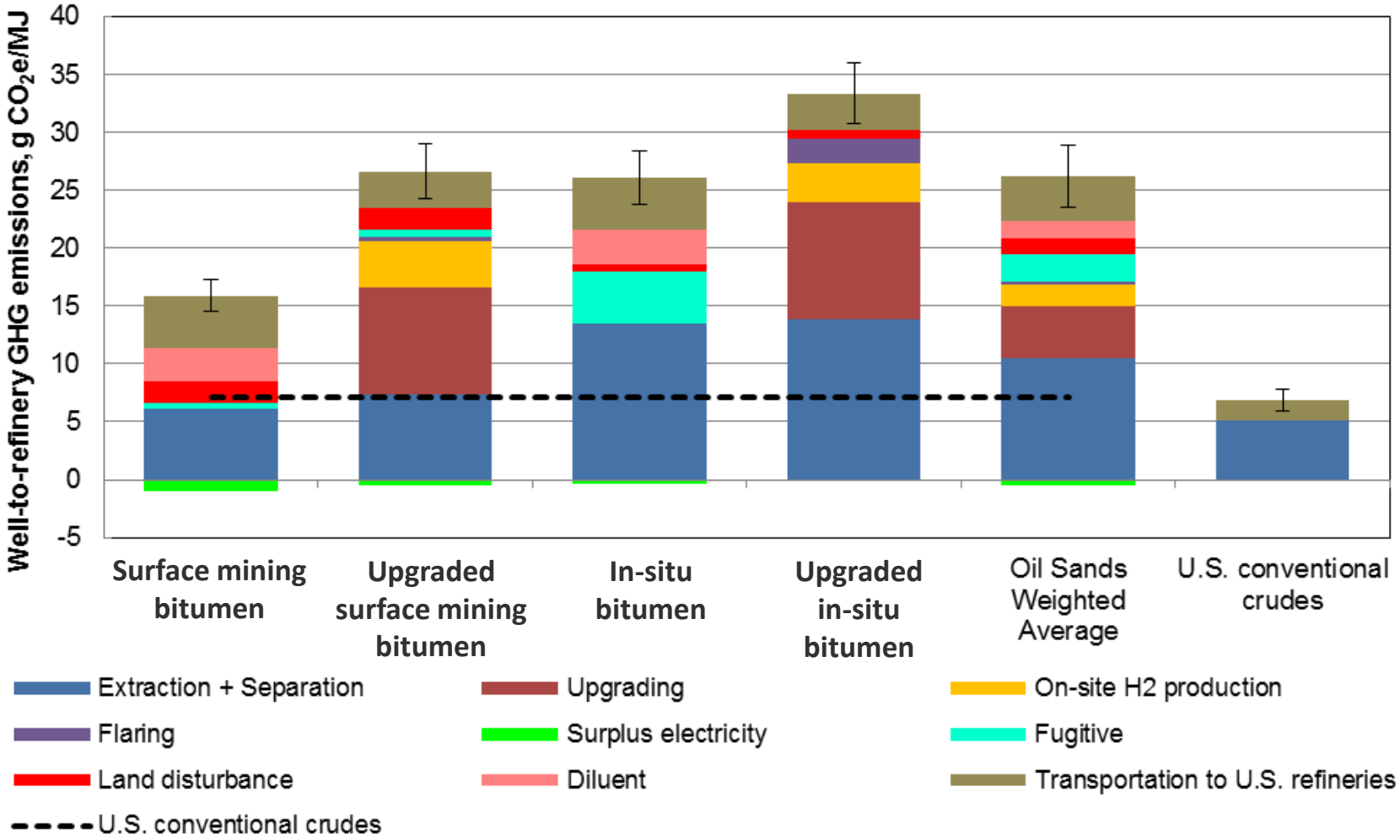
LCA system boundary: petroleum to gasoline



Examined GHG emissions of Canadian oil sands covering all 27 major projects since 2008



Updated GHG emissions of oil sands for 4 major pathways



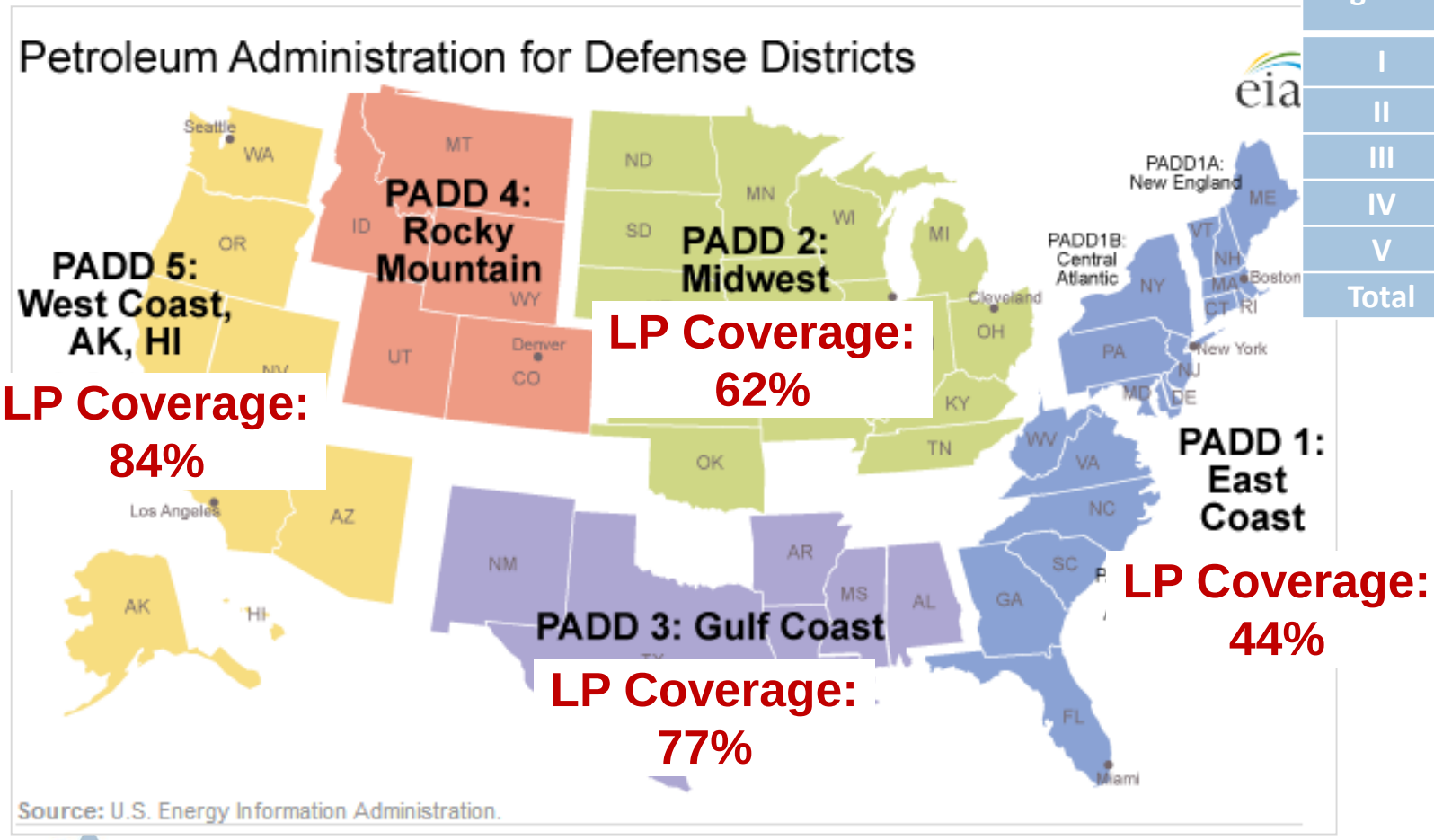
Oil sand operations are 3 to 6 times more carbon intensive than average US conventional crudes

http://pubs.acs.org/doi/abs/10.1021/acs.est.5b01255

ANL study covered 70% of U.S. refining capacity

- LP modeling of 43 large (>100k bbl/d) refineries in four PADD regions
  - Typical summer and winter days in 2010

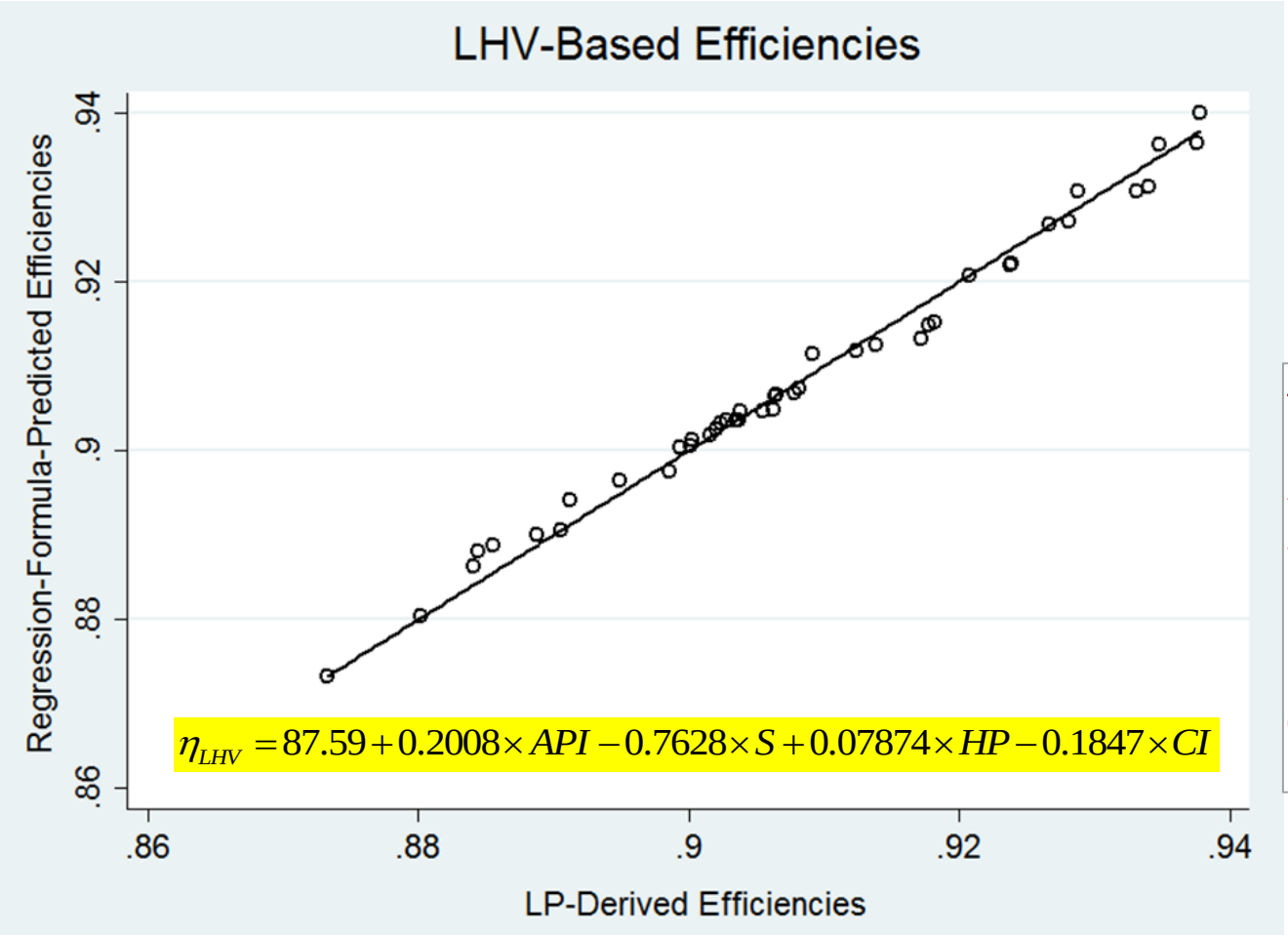
PADD Region	Crude Input to Refineries (1000 bbl/day)[a]
I	921
II	3,451
III	7,755
IV	574
V	2,337
Total	15,038



Source: U.S. Energy Information Administration.

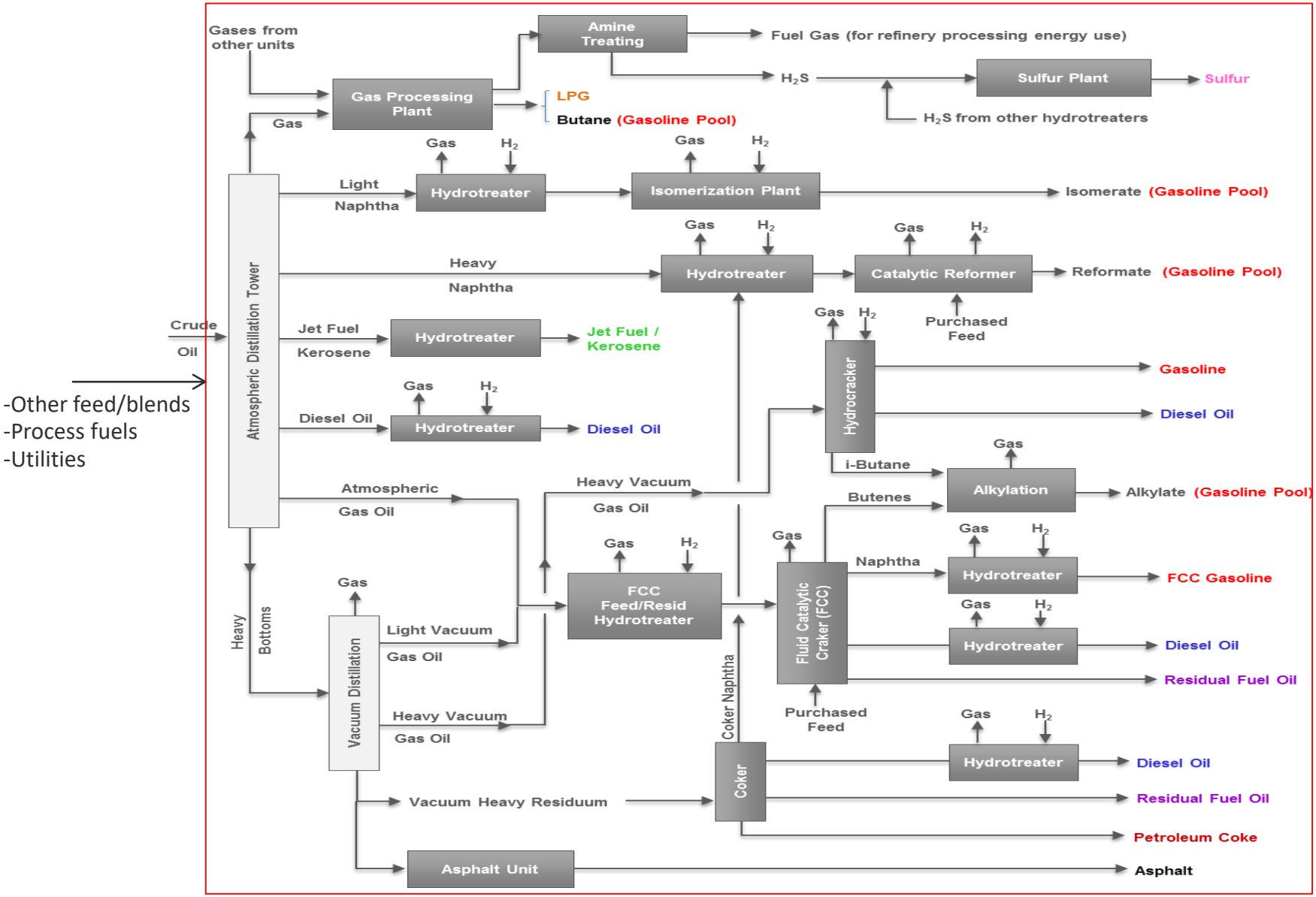
Developed linear regression model that correlates refinery overall efficiency with key refinery parameters

Efficiency=f(API, sulfur%, heavy product yield, refinery complexity index)

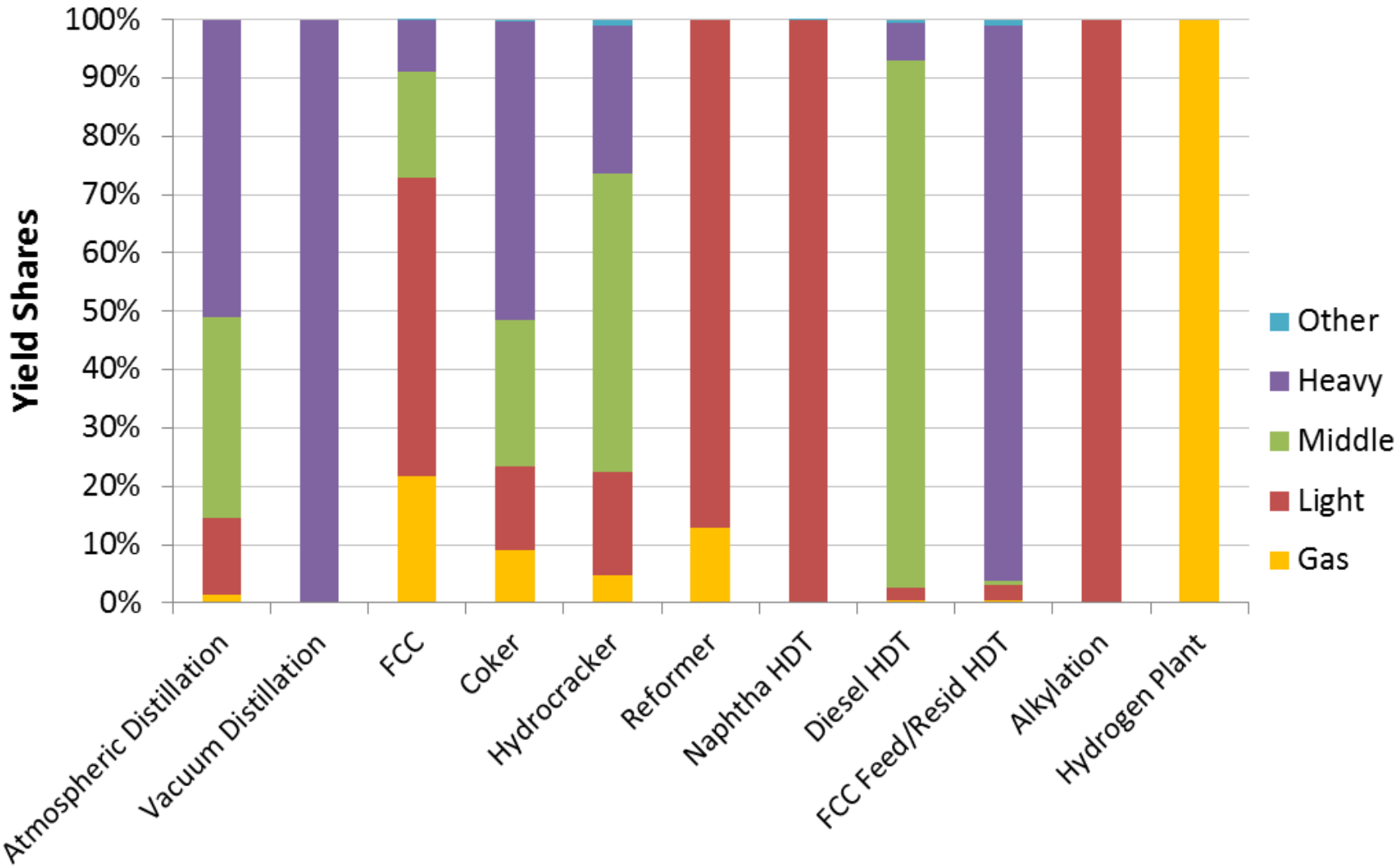


η_{LHV}	is the refinery's overall efficiency (on an LHV basis) in %;
API	is the API gravity of crude oil;
S	is the sulfur content of crude oil in % by weight;
HP	is the heavy products yield in % by energy;
CI	is the actual utilized Complexity Index of the refinery.

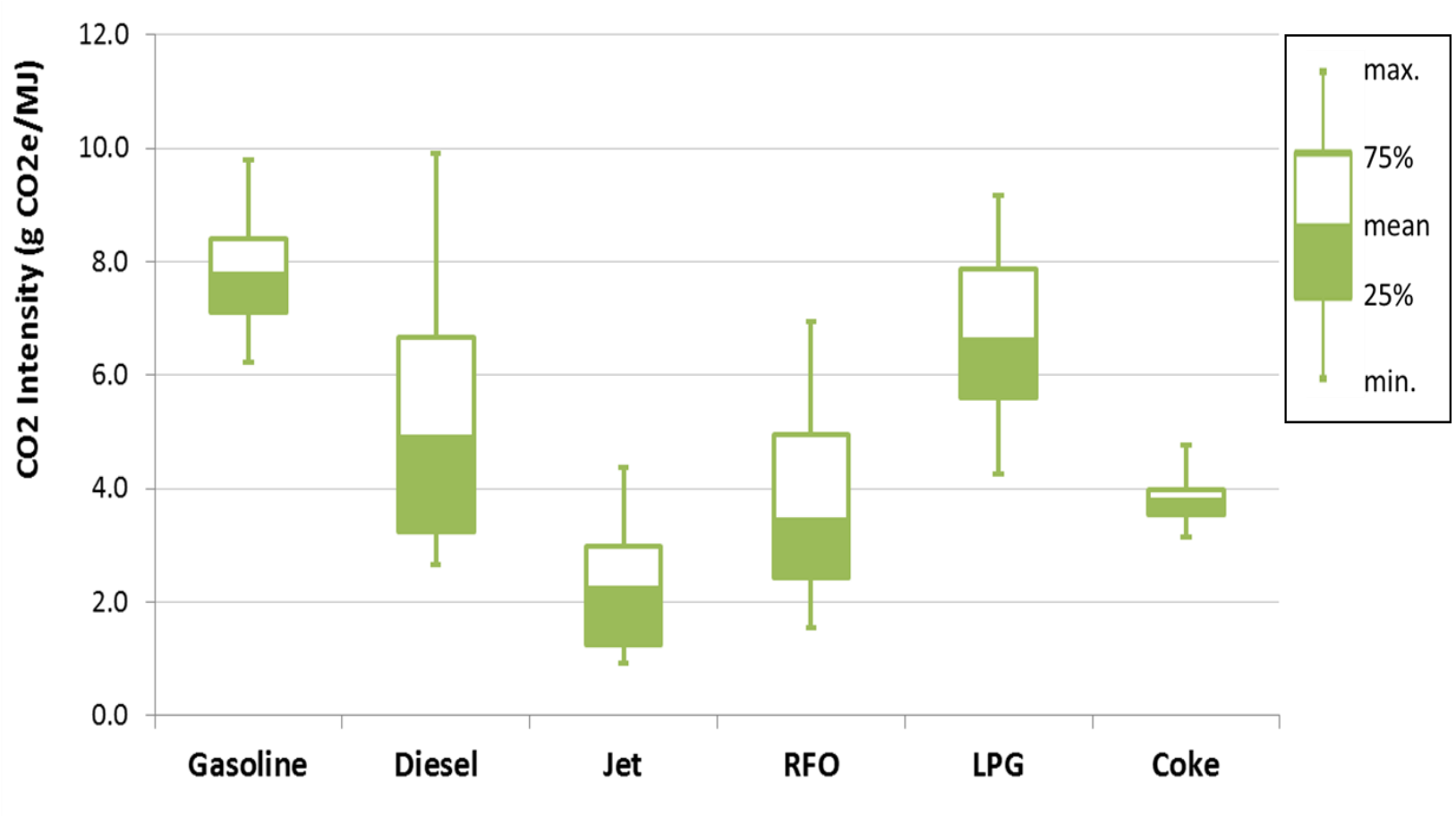
Refinery analysis - data are key for proper LCA



Refinery analysis - product yield by process unit

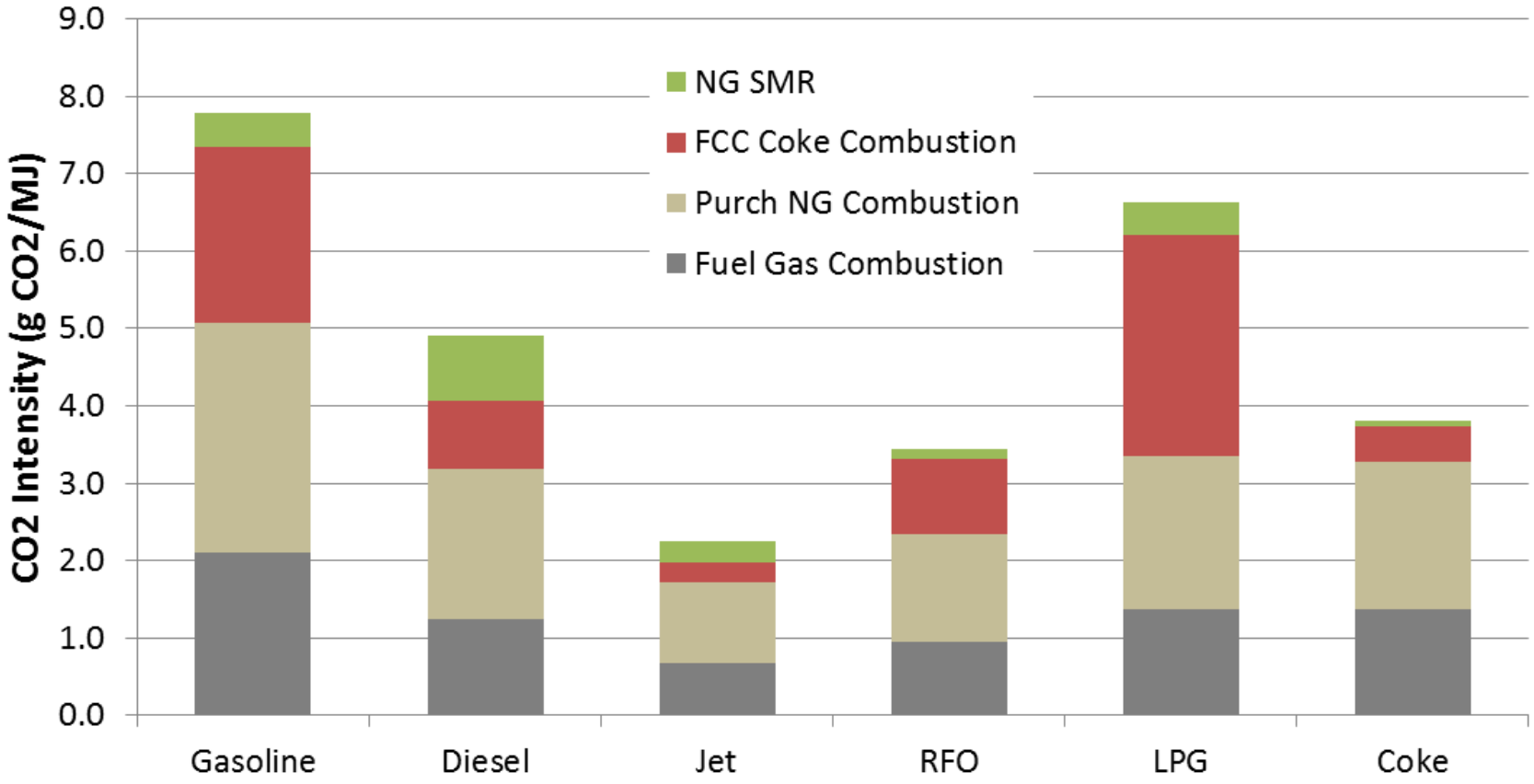


CO_{2e} intensity of refinery fuels with data from 43 large U.S. refineries

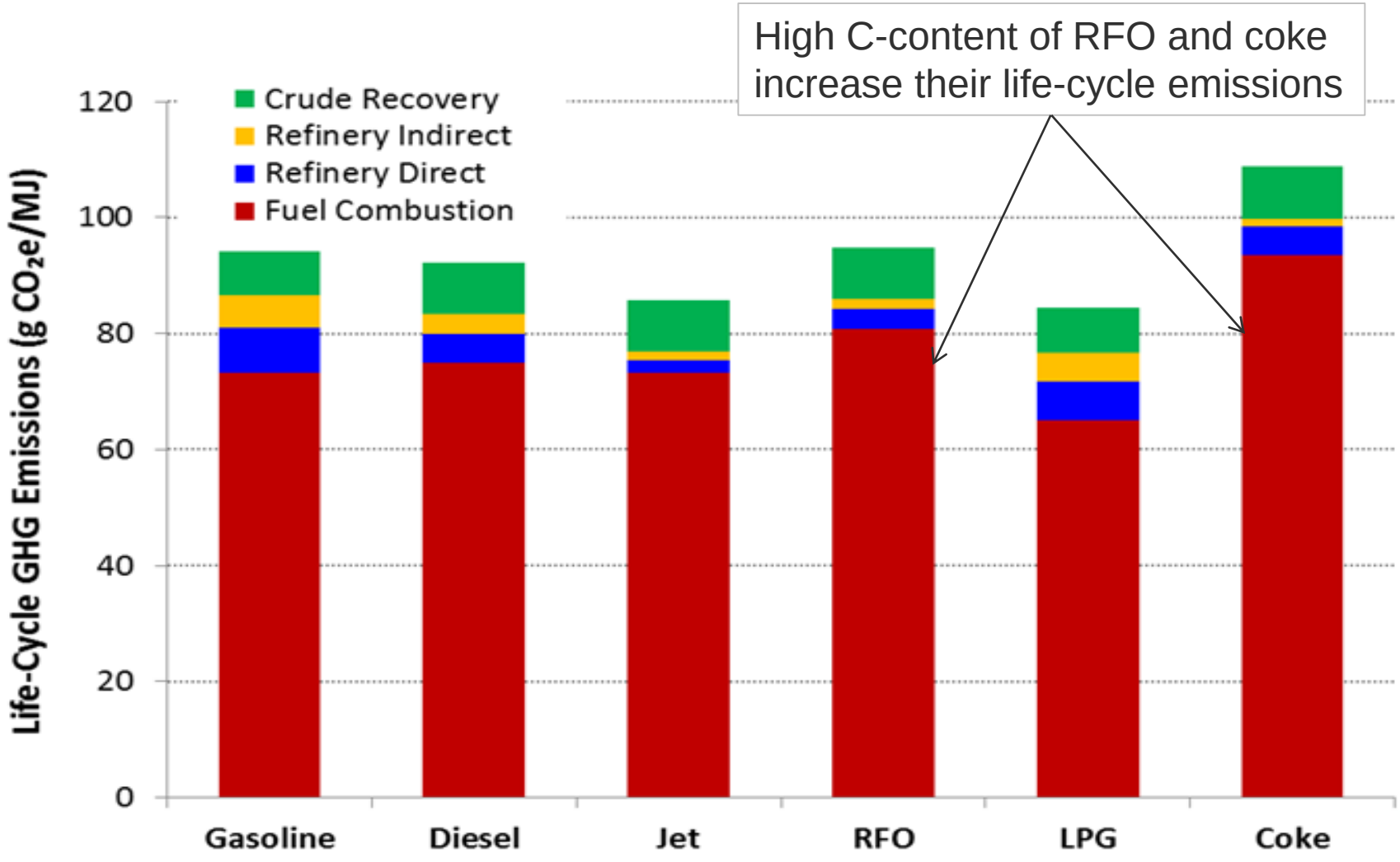


- ✓ Elgowainy et al. *Environmental Science and Technology*, 2014
- ✓ Forman et al. *Environmental Science and Technology*, 2014
- ✓ Han et al. *Fuel*, 2015

Sources of CO_{2e} emissions associated with refinery fuels



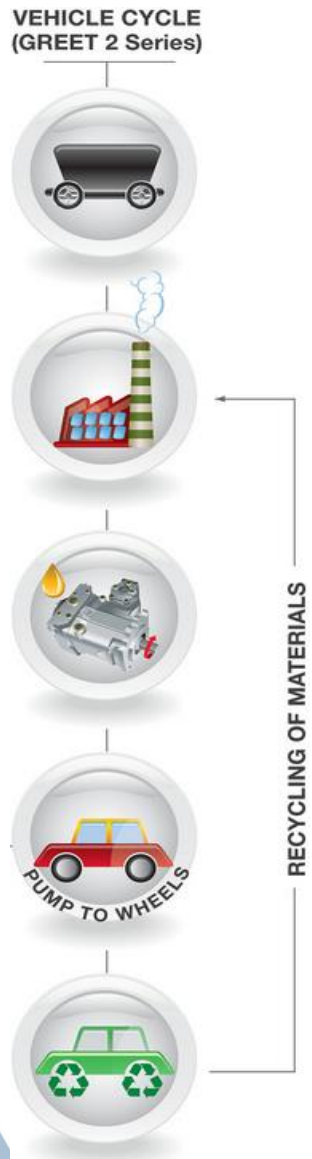
WTW GHG emissions of petroleum fuels is dominated by end use release of CO_2; refinery emissions is a distant second



WTW= well-to-wheels

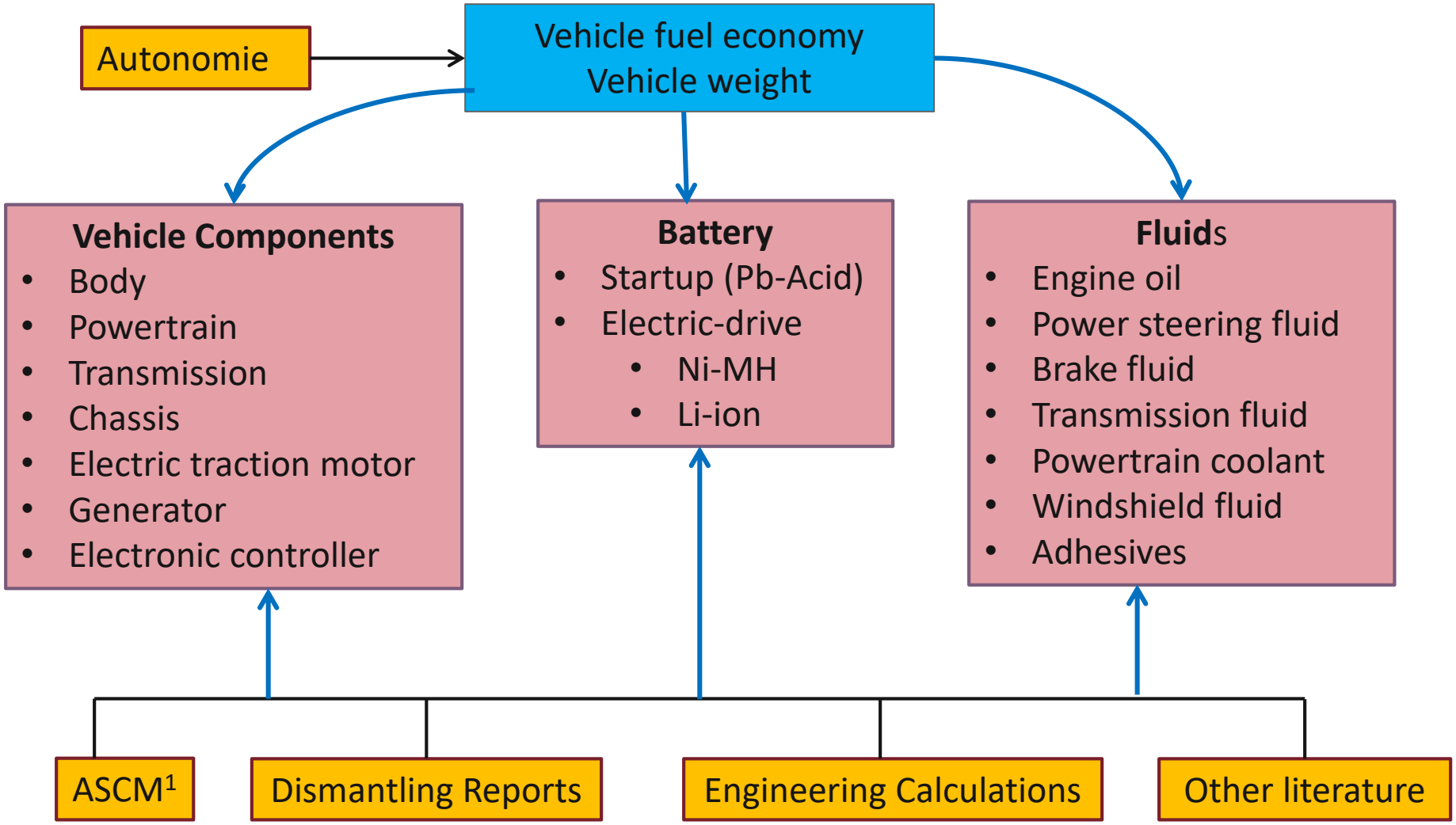
LCA of Vehicle Manufacturing

GREET 2 simulates vehicle cycle energy use and emissions from material recovery to vehicle disposal



- Raw material recovery
- Material processing and fabrication
- Vehicle component production
- Vehicle assembly
- Vehicle disposal and recycling

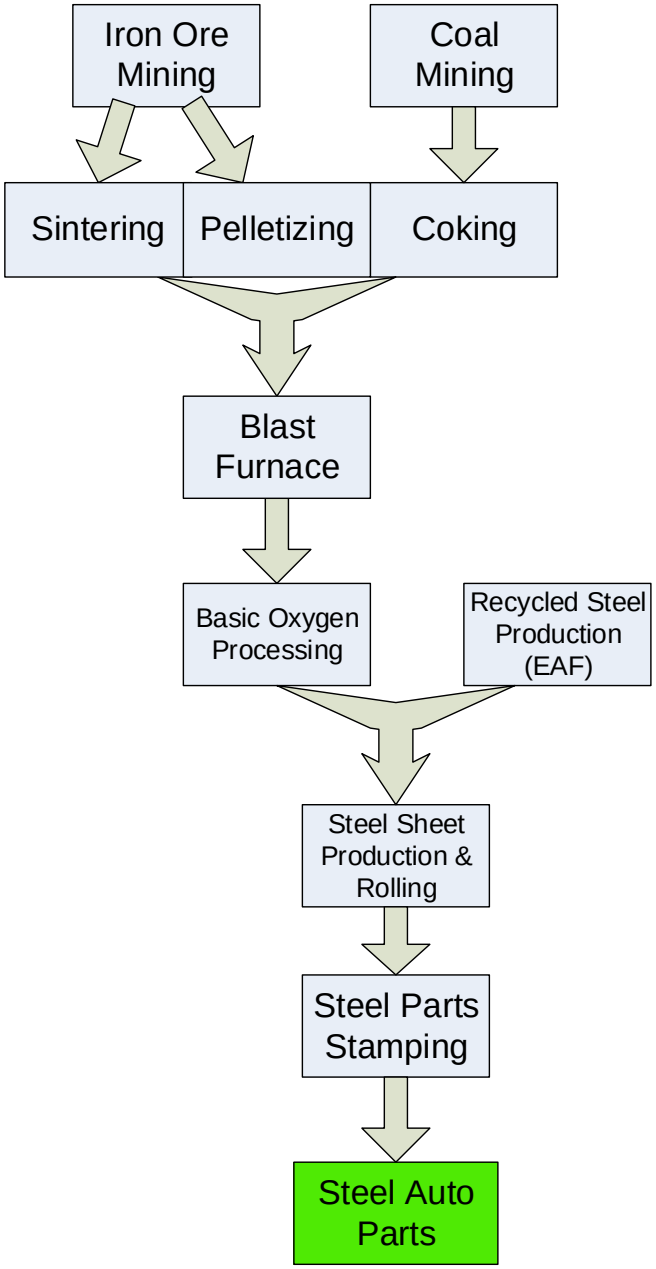
Developing a materials inventory for vehicles



1. Automotive System Cost Model, IBIS Associates and Oak Ridge National Laboratory

Key Parameters for Material Production

- Both steel and aluminum are modeled step-by-step from ore mining to part stamping
- Other metals are examined in three stages
  - Mining
  - Primary (virgin) production
  - Secondary (recycled) production
- Non-metals only examined production



Life Cycles of 60+ materials are included in GREET2

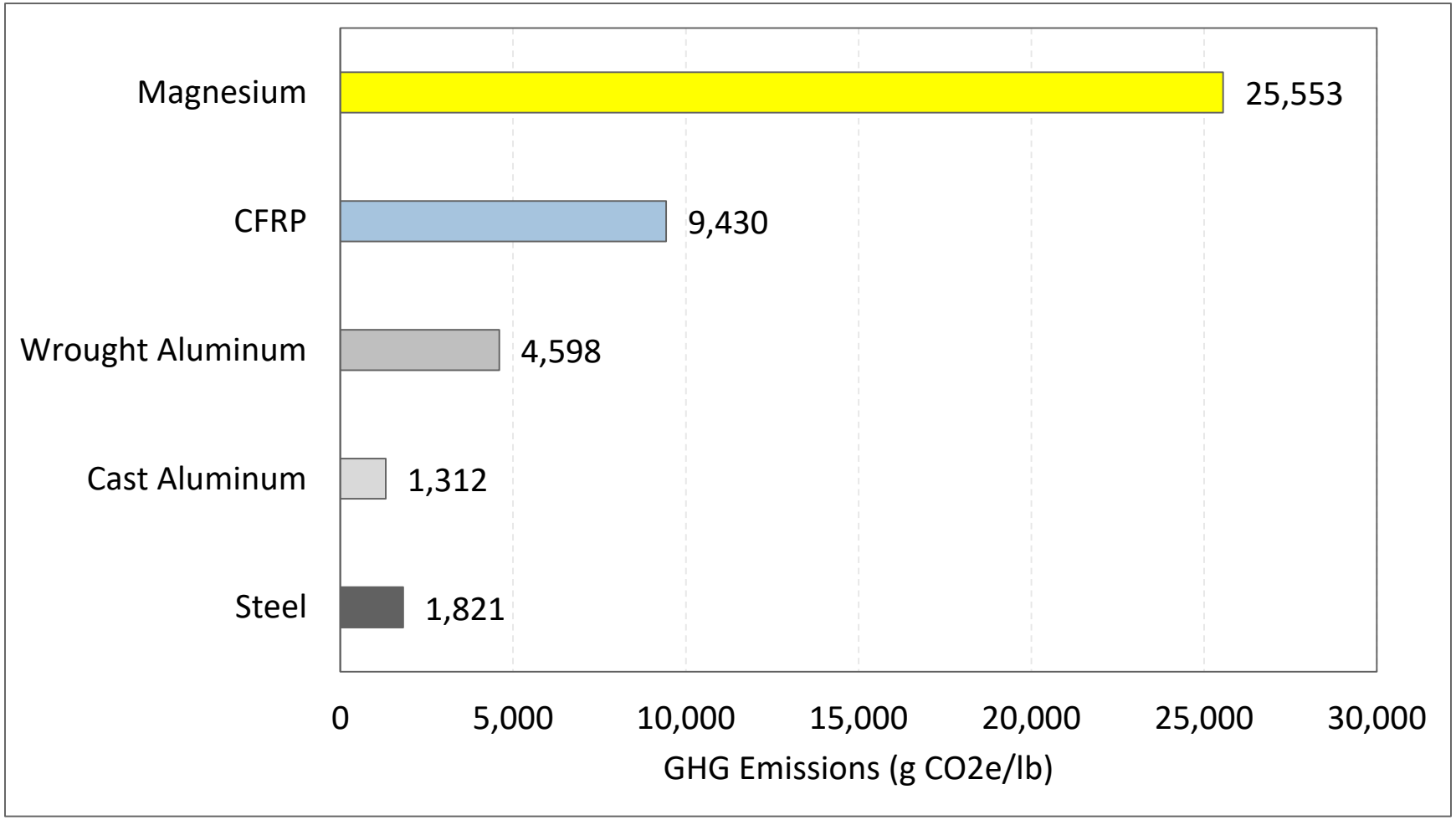
Material Type	Number in GREET	Examples
Ferrous Metals	3	Steel, stainless steel, iron
Non-Ferrous Metals	12	Aluminum, copper, nickel, magnesium
Plastics	23	Polypropylene, nylon, carbon fiber reinforced plastic
Vehicle Fluids	7	Engine oil, windshield fluid
Others	17	Glass, graphite, silicon, cement
Total	**62**	

Key issues in vehicle-cycle analysis

- ❑ Use of virgin vs. recycled materials
- ❑ Vehicle weight and lightweighting
- ❑ Vehicle lifetime, component rebuilding/replacement

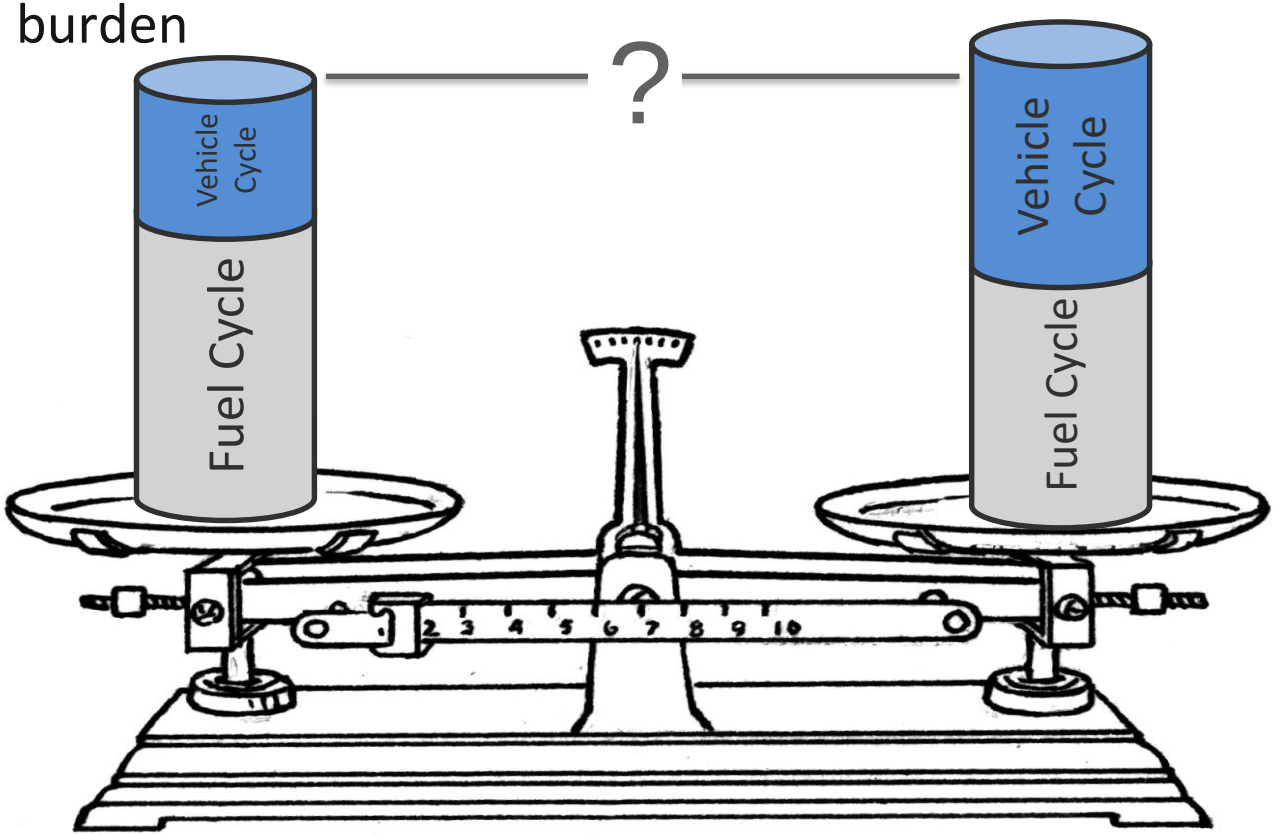
GREET Examination of Vehicle Materials

GHG intensity of lightweight automotive materials vary significantly



Material Burdens and Life Cycle Analysis

- We have examined the GHG burden of materials
  - Addressed the potential trade off between fuel cycle and vehicle cycle
  - Tailpipe GHG reduction vs. increased material embedded GHG burden

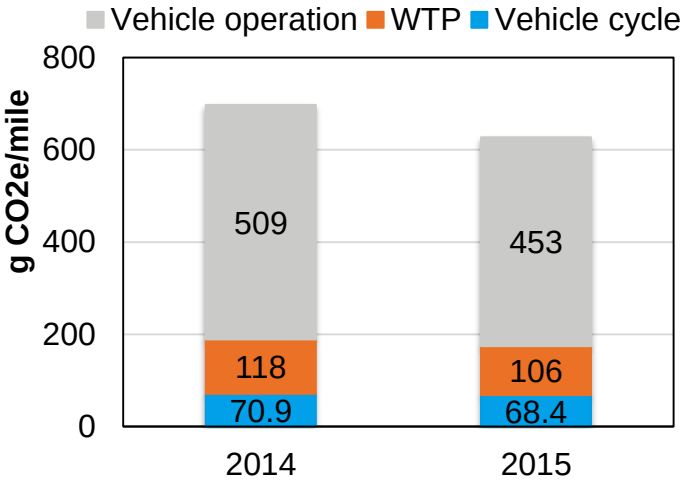


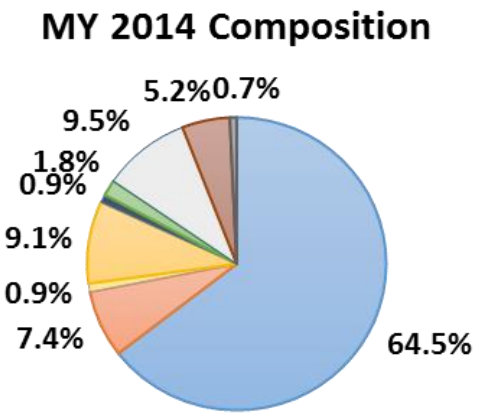
Al-intensive Light-duty Truck Case Study

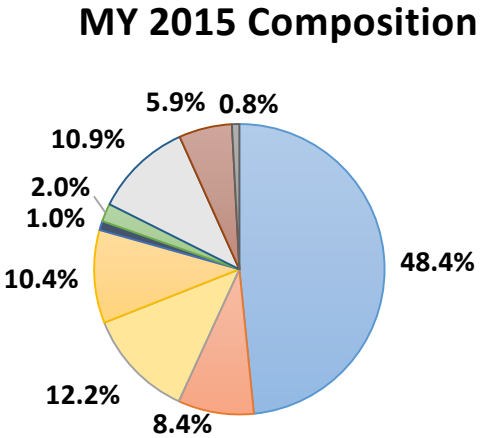
F150 Super Crew 4WD 3.5L Specifications

	MY 2014	MY 2015
Curb Weight (lbs)	5615	4937
Fuel economy (MPG)	17 (15/21)	19 (17/23)
Al content (lbs)	545	1080

Vehicle lifetime miles: 180,000







Steel
Cast Iron
Wrought Aluminum
Cast Aluminum
Copper/Brass
Glass
Average Plastic
Rubber
Others

Findings

- The high Al/steel substitution ratio (~0.44) observed in F150 leads to a net vehicle cycle GHG reduction of 3.5%.
- Fuel cycle GHG decreases by 9.9% as a result of improved fuel economy.
- Lightweighting reduces life-cycle GHG by 10%.

Example of C2G analysis with GREET

- Current and future (2030) vehicle-fuel pathways
  - GHG emissions
  - Levelized cost of driving for each pathway (at volume)
  - Cost of avoided GHG emissions relative to a conventional gasoline vehicle
  - Technology readiness level (TRL) assessment
- Fuel cycle and vehicle cycle
- Report published June 2016

ANL/ESD-16/7

Cradle-to-Grave Lifecycle Analysis of U.S. Light-Duty Vehicle-Fuel Pathways: A Greenhouse Gas Emissions and Economic Assessment of Current (2015) and Future (2025–2030) Technologies

Amgad Elgowainy,[1] Jeongwoo Han,[1] Jacob Ward,[2] Fred Joseck,[2] David Gohlke,[2] Alicia Lindauer,[2] Todd Ramsden,[3] Mary Biddy,[3] Marcus Alexander,[4] Steven Barnhart,[5] Ian Sutherland,[6] Laura Verduzco,[7] and Timothy J. Wallington[8]

[1]Argonne National Laboratory
[2]United States Department of Energy
[3]National Renewable Energy Laboratory
[4]Electric Power Research Institute
[5]FCA US LLC
[6]General Motors
[7]Chevron Corporation
[8]Ford Motor Company

June 2016

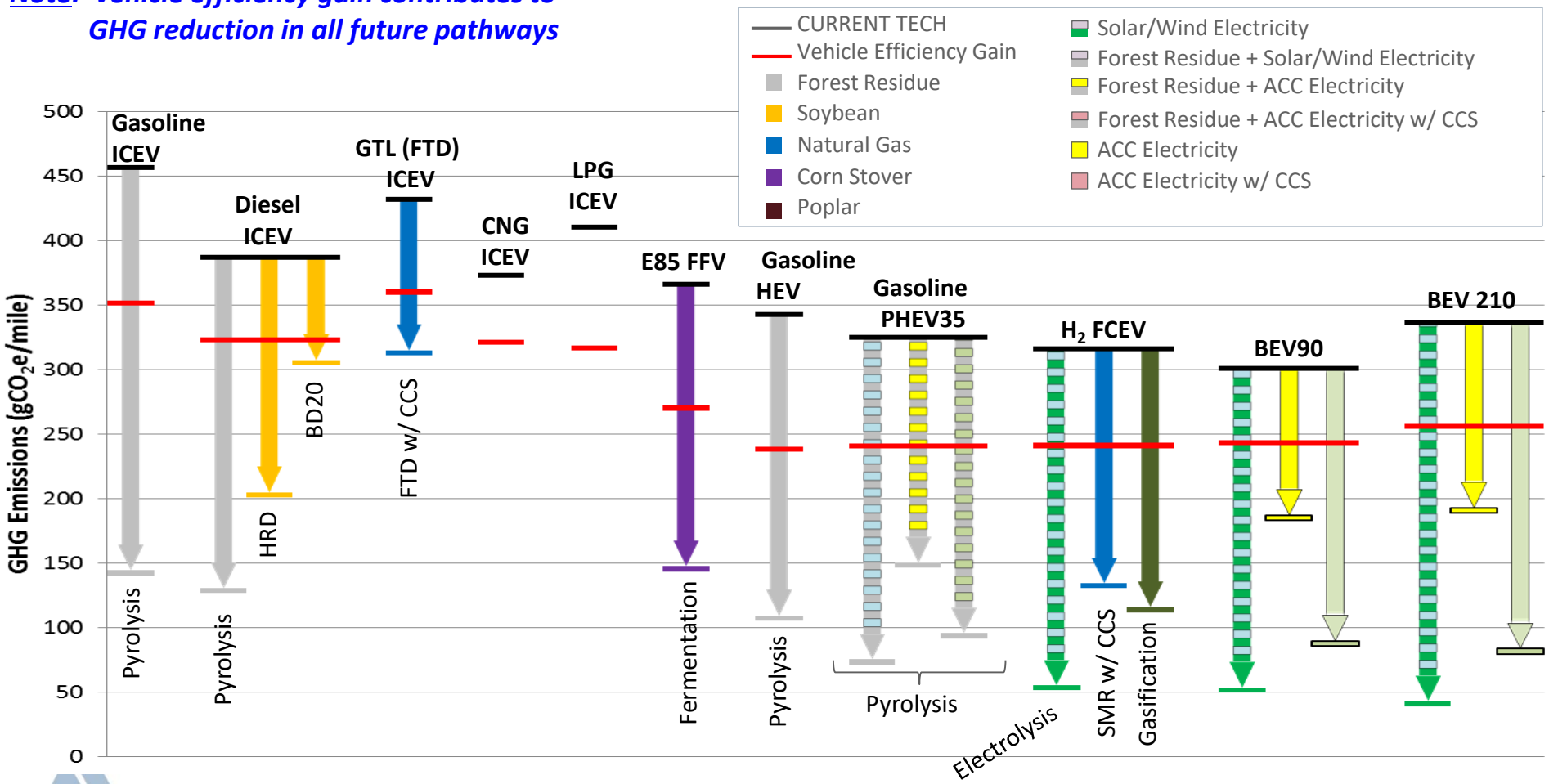
U.S. DRIVE Cradle-to-Grave Working Group members contributed to this report in a variety of ways, ranging from full-time work in multiple study areas to involvement on a specific topic, to drafting and reviewing proposed materials. Involvement in these activities should not be construed as endorsement or agreement with all of the assumptions, analysis, statements, and findings in the report. Any views and opinions expressed in the report are those of the authors and do not necessarily reflect those of Argonne National Laboratory, Chevron Corporation, the Electric Power Research Institute, Exxon Mobil Corporation, FCA US LLC, Ford Motor Company, General Motors, the National Renewable Energy Laboratory, Phillips 66 Company, Shell Oil Products US, or the U.S. Department of Energy.

https://greet.es.anl.gov/publication-c2g-2016-report

C2G GHG Emissions for current and future vehicle-fuel pathways

Large GHG reductions for light-duty vehicles are challenging and require consideration of the entire lifecycle, including vehicle manufacture, fuel production, and vehicle operation.

***Note:* Vehicle efficiency gain contributes to GHG reduction in all future pathways**



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

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

aelgowainy@anl.gov