2015 DOE BETO Project Peer Review

GREET Life-Cycle Analysis of Biofuels

March 24, 2015

Analysis and Sustainability

Michael Wang, Jennifer B. Dunn

Argonne National Laboratory

Key acronyms list

AD	Anaerobic digestion	FR	Forest residue
AEO	Annual Energy Outlook	FTD	Fischer Tropsch Diesel
AEZ	Agricultural Ecological Zone	FN	Fuel gas/natural gas
AGE	Air emissions, greenhouse gas emissions, energy consumption	FY	Fiscal year
ALU	Algal lipid upgrading	GHG	Greenhouse gas
AHTL	Algal hydrothermal liquefaction	GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
BD	Biodiesel	GTAP	Global Trade Analysis Project
BETO	Bioenergy Technologies Office	GV	Gasoline vehicle
BEV	Battery electric vehicle	HTL	Hydrothermal liquefaction
CARB	California Air Resources Board	LCA	Life cycle analysis
CHG	Catalytic hydrothermal gasification	PM	Particulate matter
CCLUB	Carbon Calculator for Land Use Change from Biofuel Production	PTW	Pump-to-wheels
CS	Corn stover	RA	Resource assessment
DGS	Distillers' grains solubles	SCO	Synthetic crude oil
EIA	Energy Information Administration	SOC	Soil organic carbon
EPA	Environmental Protection Agency	SOT	State of technology
FCEV	Fuel cell electric vehicle	WTP	Well-to-pump
		WTW	Well-to-wheels

Goal statement

- Develop a life-cycle analysis (LCA) model that supports BETO Sustainability and Strategic Analysis by quantifying energy and environmental impacts of biofuels
  - Energy security
  - Greenhouse gas (GHG) emissions
  - Air pollutant emissions
  - Water consumption
- Conduct LCAs and disseminate LCA results
  - Provide LCA results to agencies and industries for R&D and policy decision making
  - Examine critical issues affecting biofuel LCA results and biofuel sustainability

Quad chart overview

Timeline

- Project start date: FY2007
- Project end date: Annual
- Percent complete: On schedule

Budget

	Total Costs FY 10 –FY 12	FY 13 Costs	FY 14 Costs	Total Planned Funding (FY 15-Project End Date
DOE Funded	$3.8 M	$1.3 M	$1.3 M	$3.6 M

Barriers

- Barriers addressed
  - At-B: limitations of analytical tools and capabilities for system-level analysis
  - At-A: lack of comparable, transparent, and reproducible analysis
  - St-F: systems approach to bioenergy sustainability

Partners

- In-kind
  - NREL, ORNL, PNNL, INL, MIT, Purdue
  - Other agencies (FAA, EPA, USDA, DOD-DLA-Energy, CARB)
  - Industry stakeholders (energy companies, biofuel producers/tech developers, auto companies)
  - Research institutions and NGOs
- Supported
  - U. of IL at Chicago and at Urbana-Champaign, U. of WI Madison, UC Davis, Stanford
  - ERG, Great Plains Institute

Project overview

- Develop GREET^{TM} LCA model to address energy and environmental impacts of biofuels and conventional fuels
  - Advance LCA methodologies especially to deal with technology uncertainties, LCA system boundary, co-products, indirect effects, etc.
  - Develop extensive, reliable data for LCAs of biofuel and petroleum fuel pathways
  - Maintain model openness and transparency and provide tool training
- Conduct LCAs of key biofuel production pathways
  - Update existing biofuel pathways in GREET
  - Examine emerging LCA issues and add new biofuel pathways to GREET
  - Publish biofuel LCA studies and review/evaluate relevant studies
- Interact with stakeholders (researchers, agencies, industries) to provide LCA results and to improve LCAs

GREET overview

- Several DOE programs have supported GREET development since 1995
- A publicly available LCA tool for consistently examining life-cycle energy and emissions of vehicle/fuel systems
  - Available for free download at greet.es.anl.gov
  - Fuel types include petroleum fuels, NG-based fuels, hydrogen, electricity, and many biofuel types
  - End use transportation applications
    - Over 85 on-road vehicle/fuel systems (conventional tech., hybrids, plug-in hybrids, battery electric vehicles, fuel cell vehicles)
    - Marine transportation, air transportation, and rail transportation
- GREET produces results for
  - Greenhouse gas emissions (CO_2e of CO_2, CH_4, N_2O, black carbon)
  - Criteria pollutant emissions (VOC, CO, NO_x, SO_x, $PM_{2.5}$, and PM_{10}); separated into total and urban emissions
  - Energy use by total energy, fossil energy, petroleum energy
  - Water consumption
- Biofuels have been an important fuels group in GREET development and applications

GREET includes many biofuel production pathways

- Ethanol via fermentation from
  - Corn
  - Sugarcane
  - Sorghum (grain, juice, cane)
  - Cellulosic biomass
    - Crop residues
    - Dedicated energy plants: switchgrass, miscanthus, willow, poplar
    - Forest residues

- Cellulosic biomass via gasification to
  - Fischer-Tropsch diesel
  - Fischer-Tropsch jet fuel
  - Hydrogen

- Cellulosic biomass via pyrolysis to
  - Renewable gasoline
  - Renewable diesel
  - Renewable jet fuel

- Renewable natural gas from
  - Landfill gas
  - Anaerobic digestion of animal wastes, municipal solid waste, and other feedstocks

- Corn to butanol

- Soybeans, other oil seeds, and corn oil to
  - Biodiesel
  - Renewable diesel
  - Renewable gasoline
- Soybeans and other oil seeds
  - Renewable jet and marine fuel

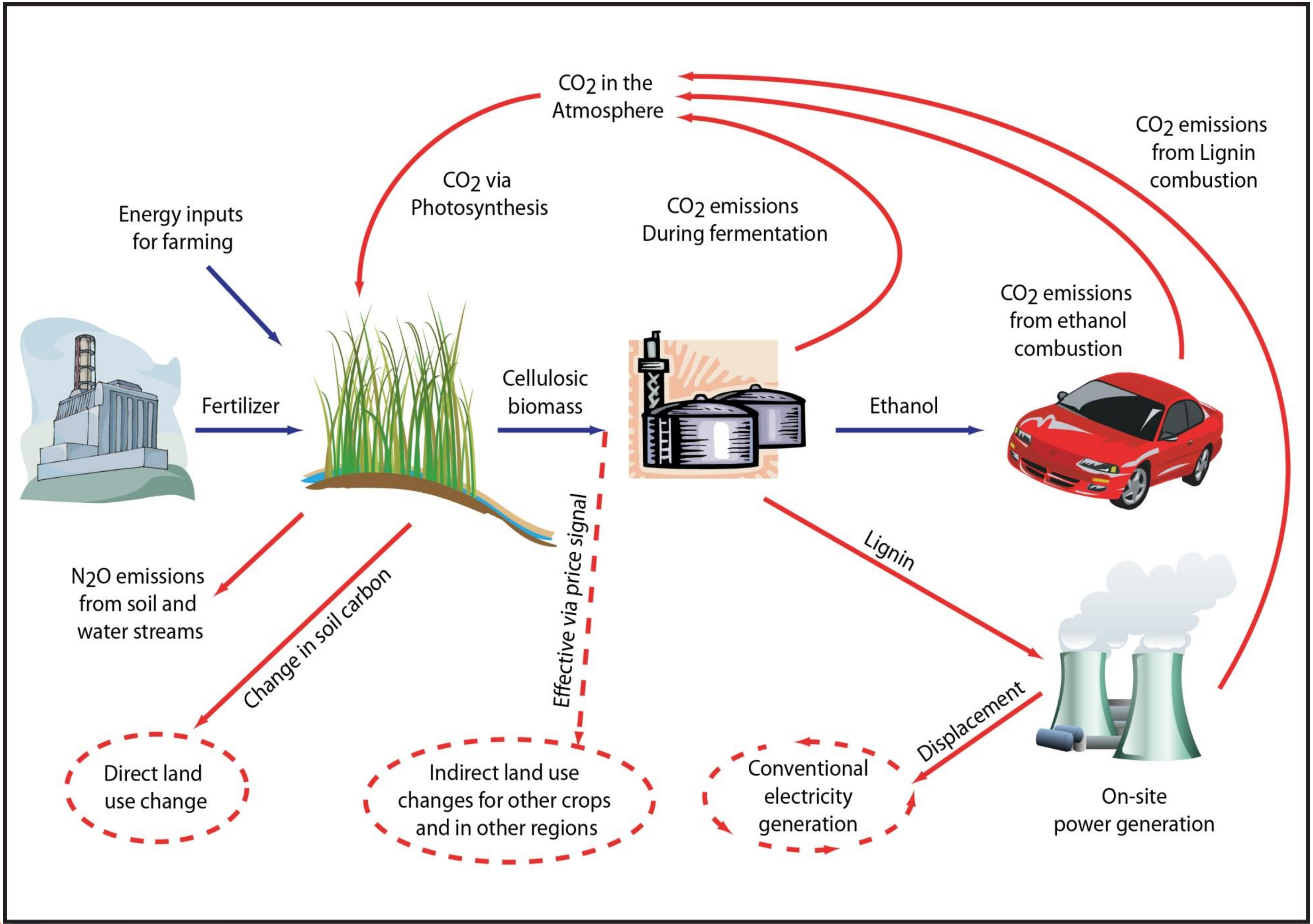
- Algae to
  - Biodiesel
  - Renewable diesel
  - Renewable gasoline
  - Renewable jet and marine fuel

- Ethanol to jet fuel

Approach, data sources, and key issues with GREET LCA

- 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
- Data Sources
  - Open literature and results from other researchers
  - Simulations with models such as Aspen Plus for fuel production and Argonne Autonomie and EPA MOVES models for vehicle operation
  - 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

GREET biofuel LCA system boundary example: switchgrass to ethanol



Approach: project management

- Annual plan determined via discussions with BETO
- Multi-step quality control process
  - Internally,
    - First researcher conducts initial analysis/calculations
    - Second researcher checks and verifies initial analysis/calculations
    - A team reviews and documents analysis and results
  - External experts review results/publications
- Community engagement for data availability, representativeness, and reliability
- Feedback through external interactions and communication
  - Interact with agencies, industry, researchers, and others to identify key issues and exchange data
  - Communicate via peer-reviewed publications, presentations, and public outreach for broad dissemination of LCA results
- Project progress and deliverables
  - Tracking through monthly and quarterly written reports, quarterly conference calls with sponsor to track milestone completion
  - Biweekly internal team meetings to review technical progress and gain feedback

Critical success factors of GREET development and applications

- Critical LCA issues need to be addressed with science and thoroughness
  - LCA system boundary: determined by LCA scope and broad policy context
  - Methods for co-products in biofuel LCAs: need to address broad issues (e.g., food and fuels; synergy of different energy products)
  - LCA output attributes should be relevant to energy and environmental concerns
- LCA models should address technology advancements and technical variability and uncertainties
  - Temporal and spatial variations in data should be accommodated in LCAs to reflect
    - Technology advancement over time
    - Geographic differences
  - Technical variability of pathway parameters are addressed with stochastic simulations in GREET
  - Technical uncertainties are addressed with scenario analysis and a variety of technology paths for a given supply chain
- Reliable data and transparent models/analyses are key to success of LCA including GREET
  - GREET and its publications are fully accessible at its website
  - Community can conduct detailed computations with GREET and provide detailed critiques

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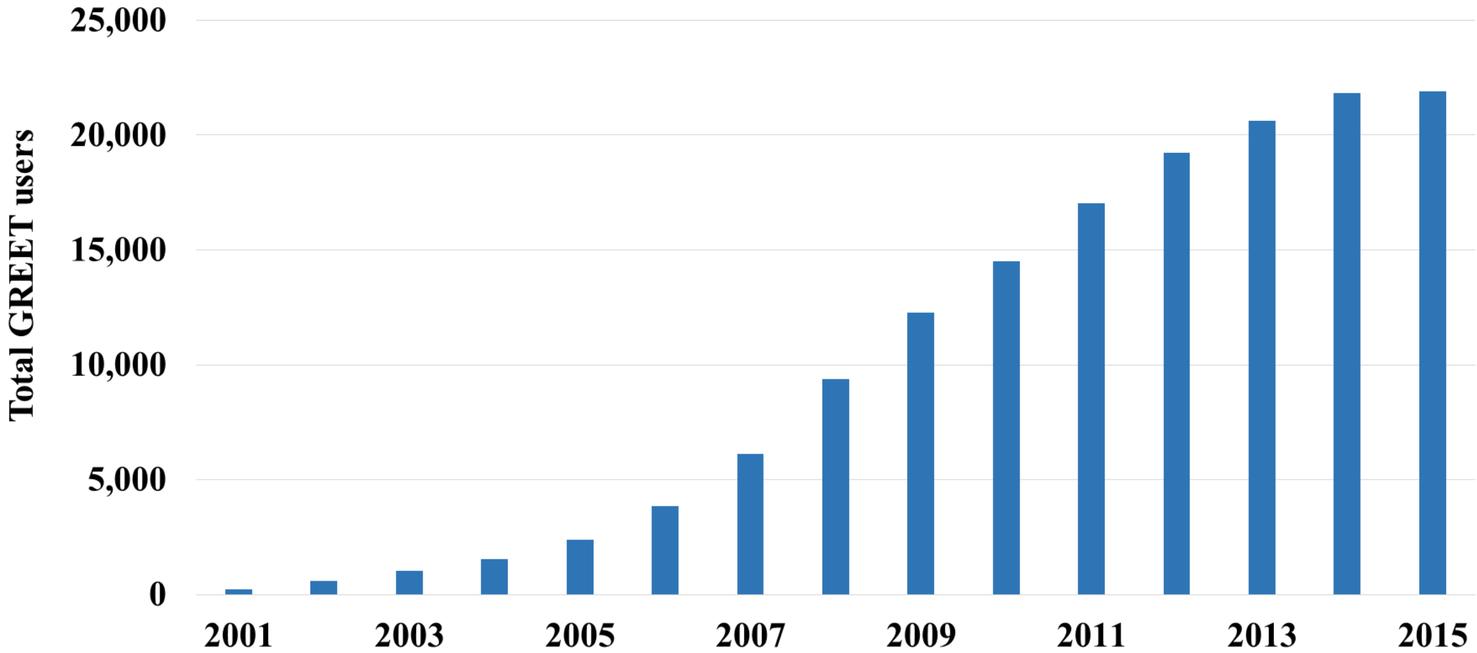
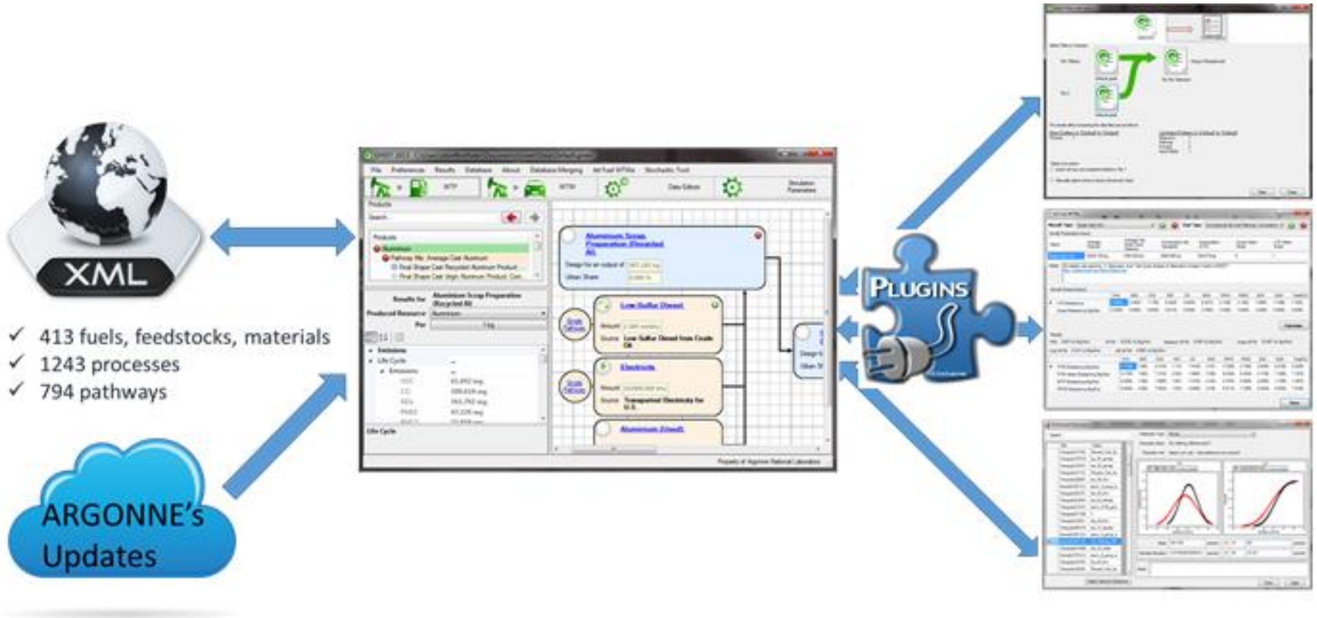
There are more than 23,000 registered GREET users globally

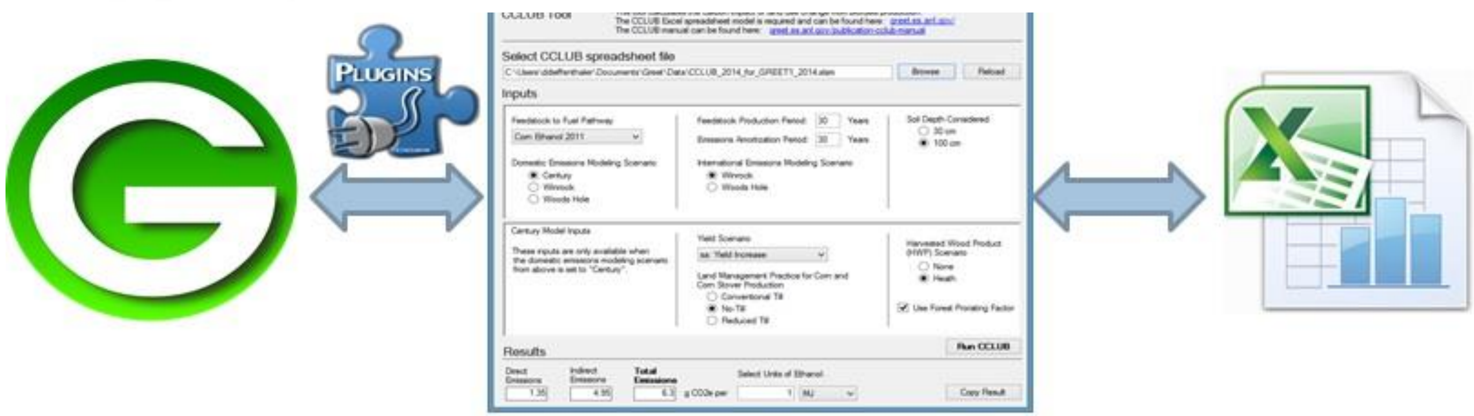


- **Geographically, 71% in North America, 14% in Europe, 9% in Asia**
- **51% in academia and research, 23 % in industry, 8% in governments**

Modular user interface and structured database

- ❑ Provides efficient and standardized LCA model and database sharing
- ❑ Minimizes time to add new data or update from Argonne's data server



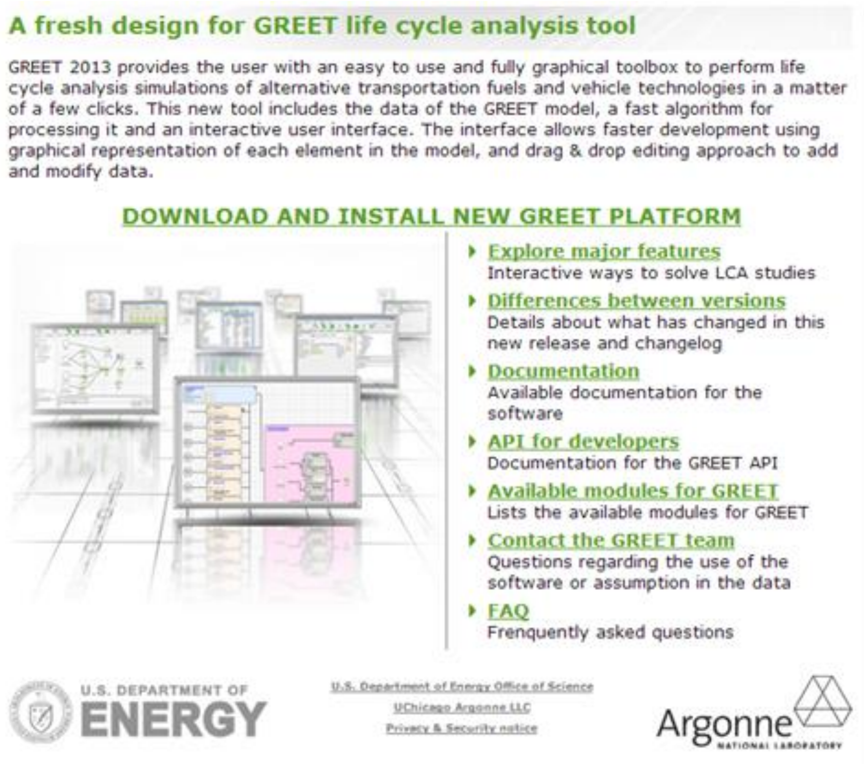


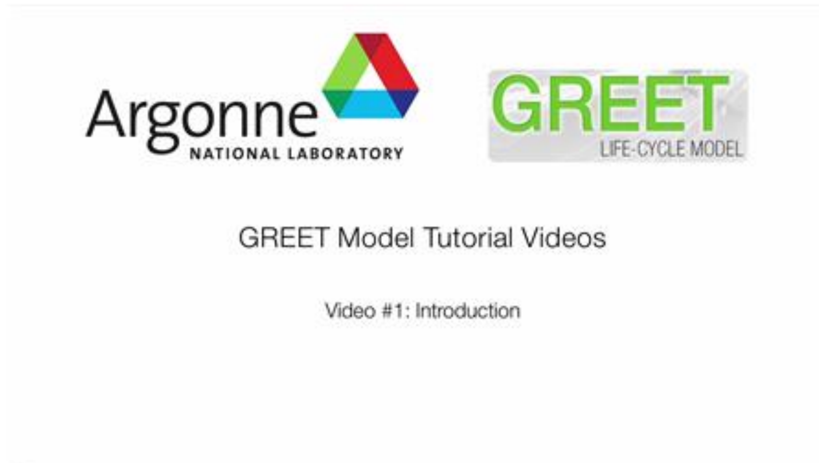
Example: Update land-use change GHG emissions using CCLUB module (Excel)

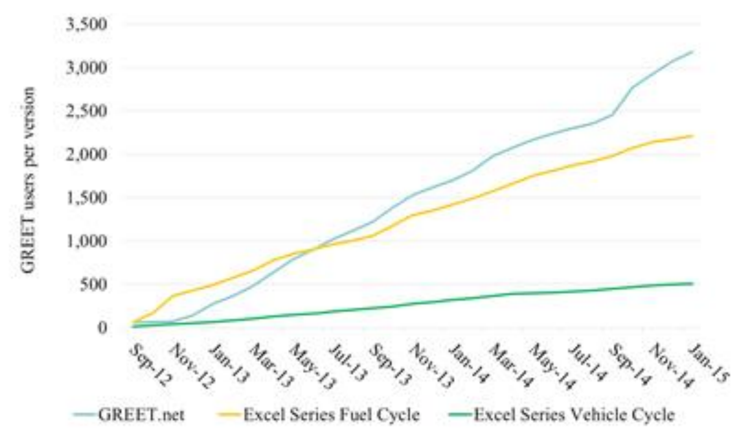
Online presence and support for GREET

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

GREET Model Tutorial Videos







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Argonne participates in key stakeholder groups, provides analyses of emerging reports and issues

- Co-chair LCA Subgroup of International Civil Aviation Organization's Alternative Fuel Task Force to develop LCA methodology and assimilate LCA results of renewable jet fuels
- Participate in ISO 248 Committee to develop sustainability standard for bioenergy
- Member of the US-China Advanced Biofuel Working Group to examine biofuel sustainability in US and China
- Provide analyses and comments on emerging reports/issues

Comments on

Ethanol's Broken Promise by the Environmental Working Group (May 2014)

Michael Wang†, Jennifer B. Dunn†, Steffen Mueller‡, Zhangcai Qin†, Wally Tyner*, and Barry Goodwin+

June 9, 2014

† Energy Systems Division, Argonne National Laboratory
‡ Energy Resource Center, University of Illinois at
* Purdue University College of Agriculture
+ North Carolina State University Department of A

Summary

In their recent report,[1] the Environmental Working
emissions of corn ethanol are greater than those of

Response to "Biofuels from crop residue can reduce soil carbon and increase CO_2 emissions"

Jennifer B. Dunn, Zhangcai Qin, Michael Wang

Energy Systems Division, Argonne National Laboratory

In their recent paper[1] Liska et al. examine the potential for corn stover removal from corn fields
reby releasing CO_2 into the atmosphere.
esidue removal are considered, life-cycle
anol are much higher than previously

Comments on

Avoiding Bioenergy Competition for Food Crops and Land by Searchinger and Heimlich

By Michael Wang and Jennifer B. Dunn
Systems Assessment Group
Energy Systems Division
Argonne National Laboratory

February 16, 2015

The report by Searchinger and Heimlich expresses concern that bioenergy cannot contribute significantly to the fuel supply for the transportation and power sectors without compromising

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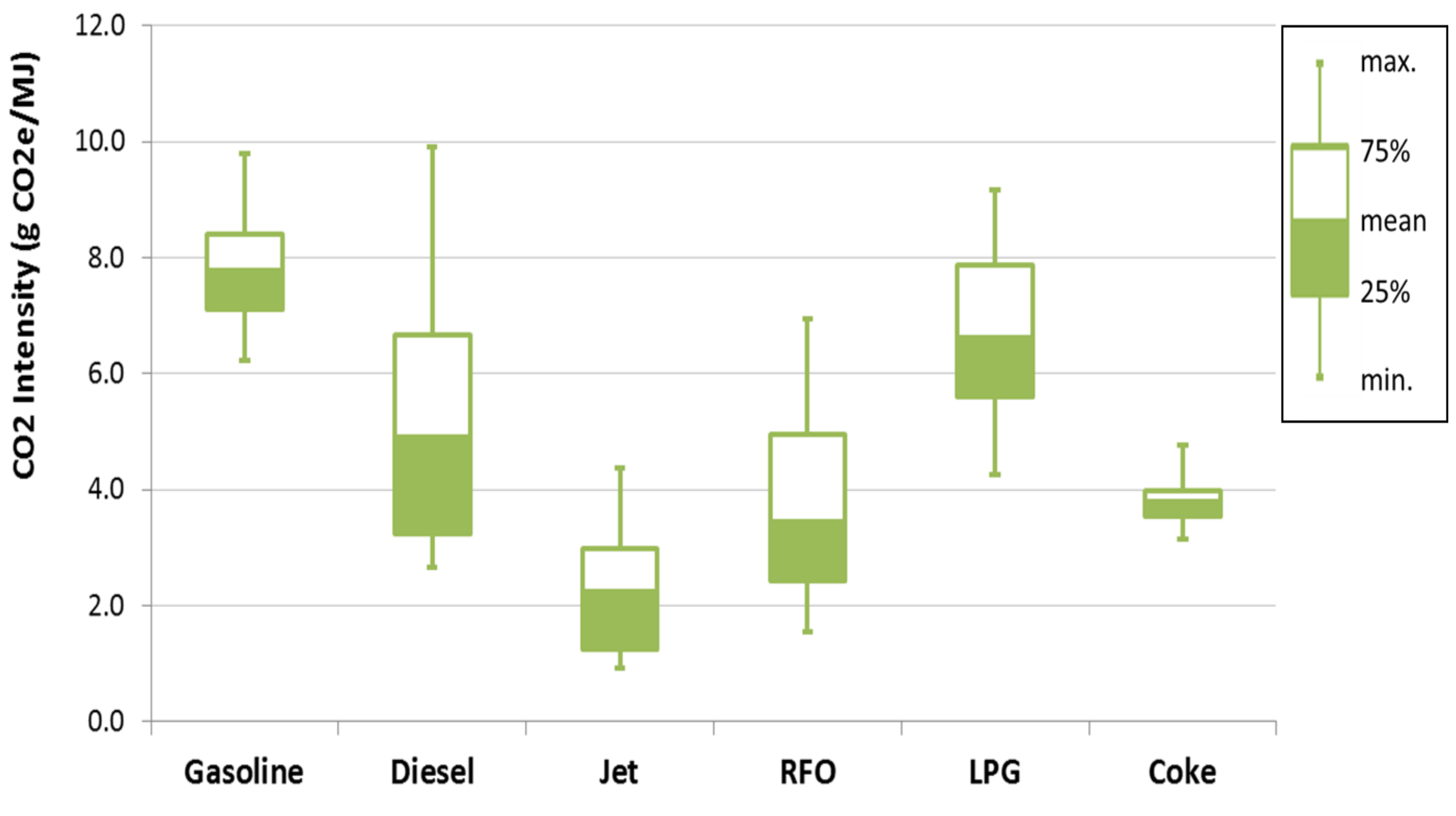
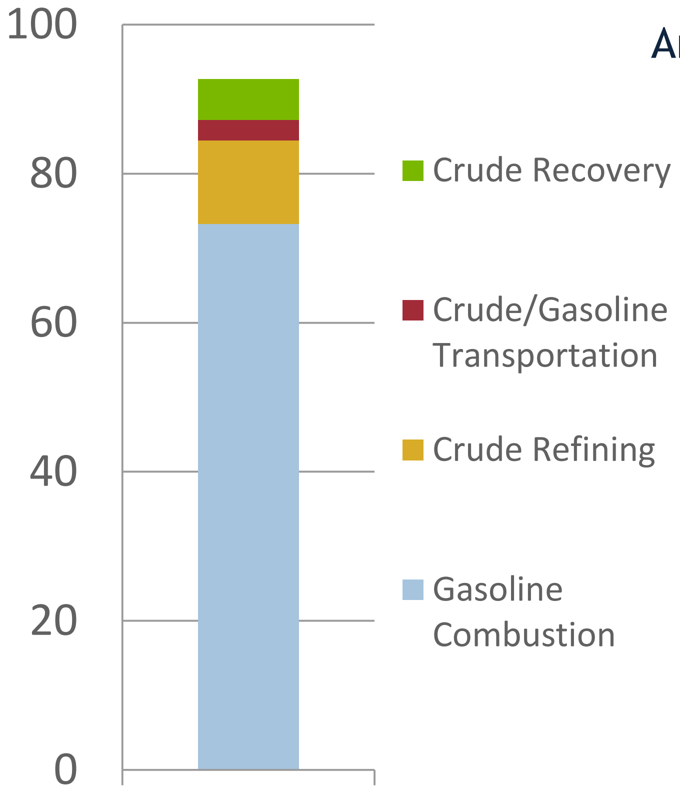
Petroleum refinery CO_2 intensity was modeled with 43 U.S. refineries (~70% U.S. refining capacity)

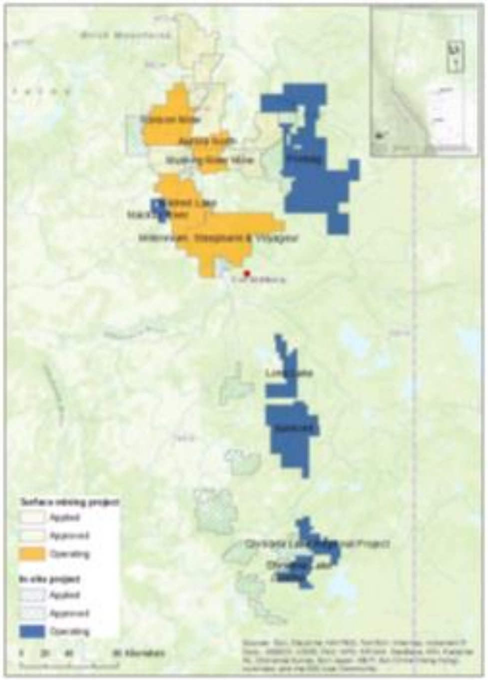


Elgowainy et al. *Environmental Science and Technology*, 2014
Forman et al. *Environmental Science and Technology*, 2014

Gasoline Well-to-Wheel GHG emissions: grams/MJ



Argonne addressed GHG emissions of oil sands



Oil sand land disturbance GHG (Yeh et al. 2014)

Pay-as-you –go
- ✓ 3.4-3.4 g/MJ for surface mining
- ✓ 1.8-2.8 g/MJ for in-situ

Amortization
- ✓ 1.9 g/MJ for surface mining
- ✓ 0.56-0.89 g/MJ for in-situ

	Conventional Crude	Mining SCO (53%)	Mining Dilbit (4%)	In-Situ SCO (8%)	In-Situ Dilbit (35%)
Recovery	4.1	20	7.0	24	13
Land Disturbance	—	1.9	1.5	0.70	0.56
Refining	15	18	17	19	19
Transport. & Distribution	2.3	3.7	3.9	3.7	3.9
Total Well-to-Pump	**21**	**44**	**29**	**47**	**36**

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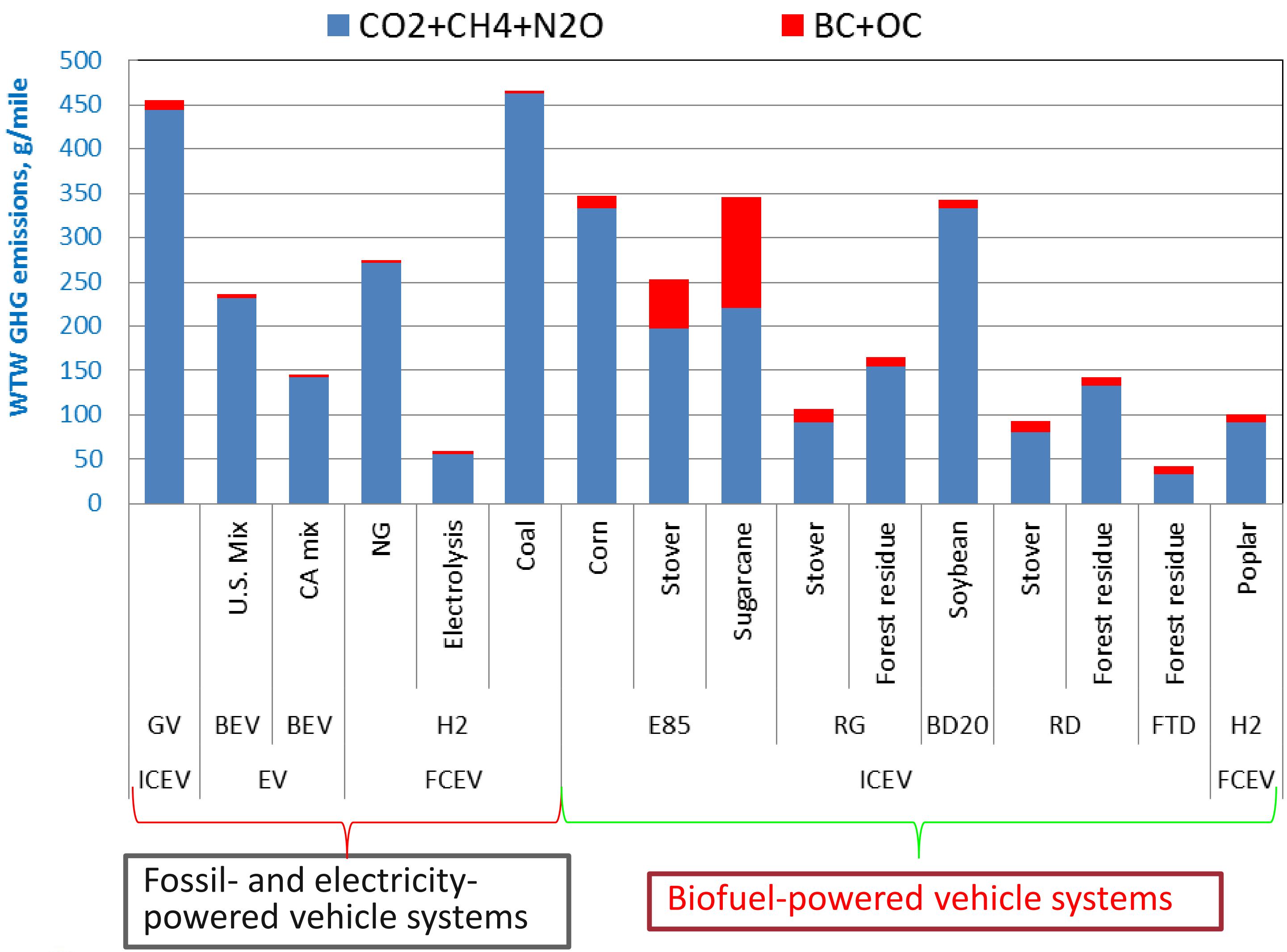
Black and organic carbon significantly influence sugarcane and cellulosic ethanol, but minimally affect fossil- and electricity-powered vehicle systems



BC emissions from biomass (and diesel) combustion are a major contributor to stover and sugarcane ethanol

Cai and Wang, *Environmental Science and Technology*, 2014

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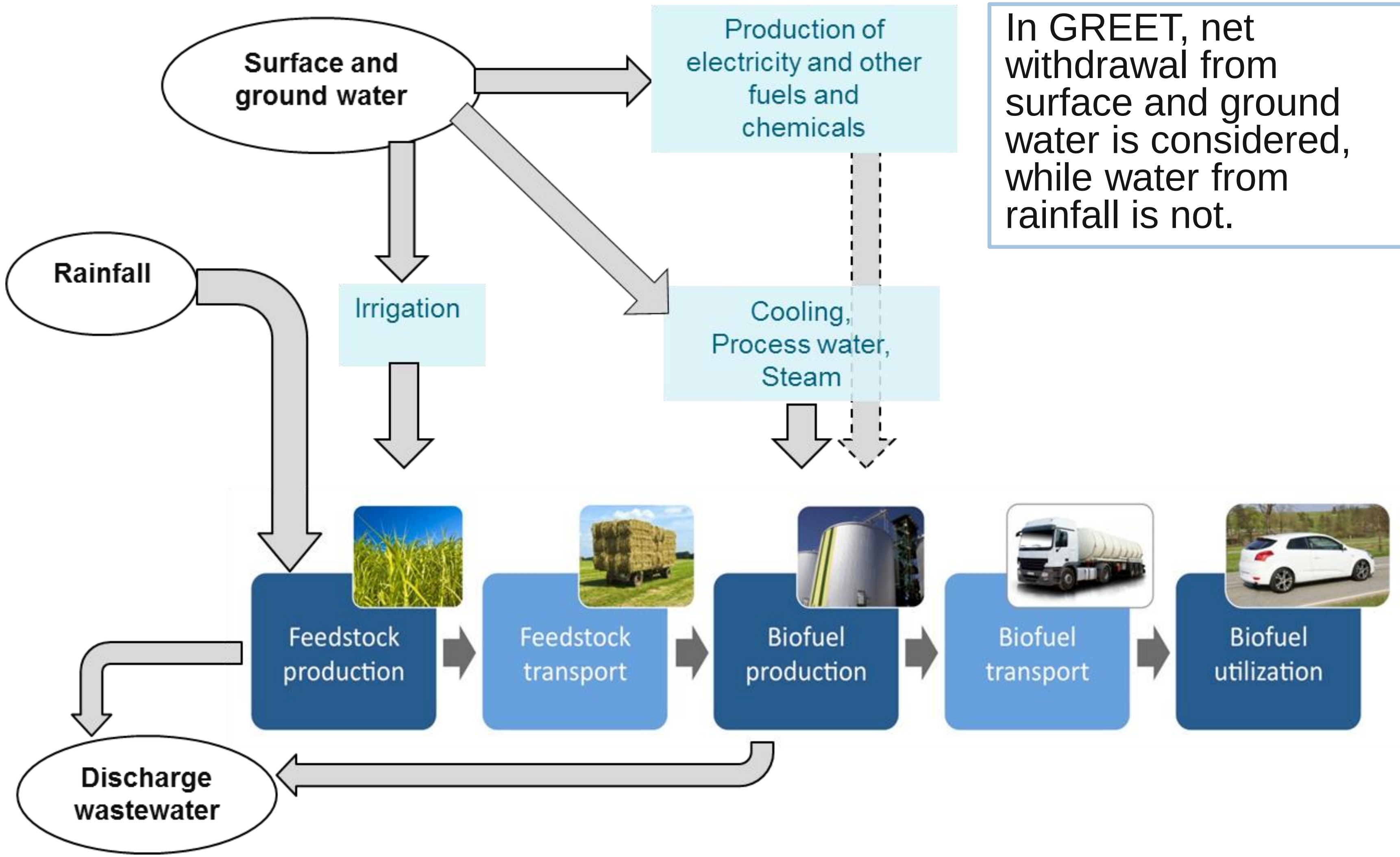
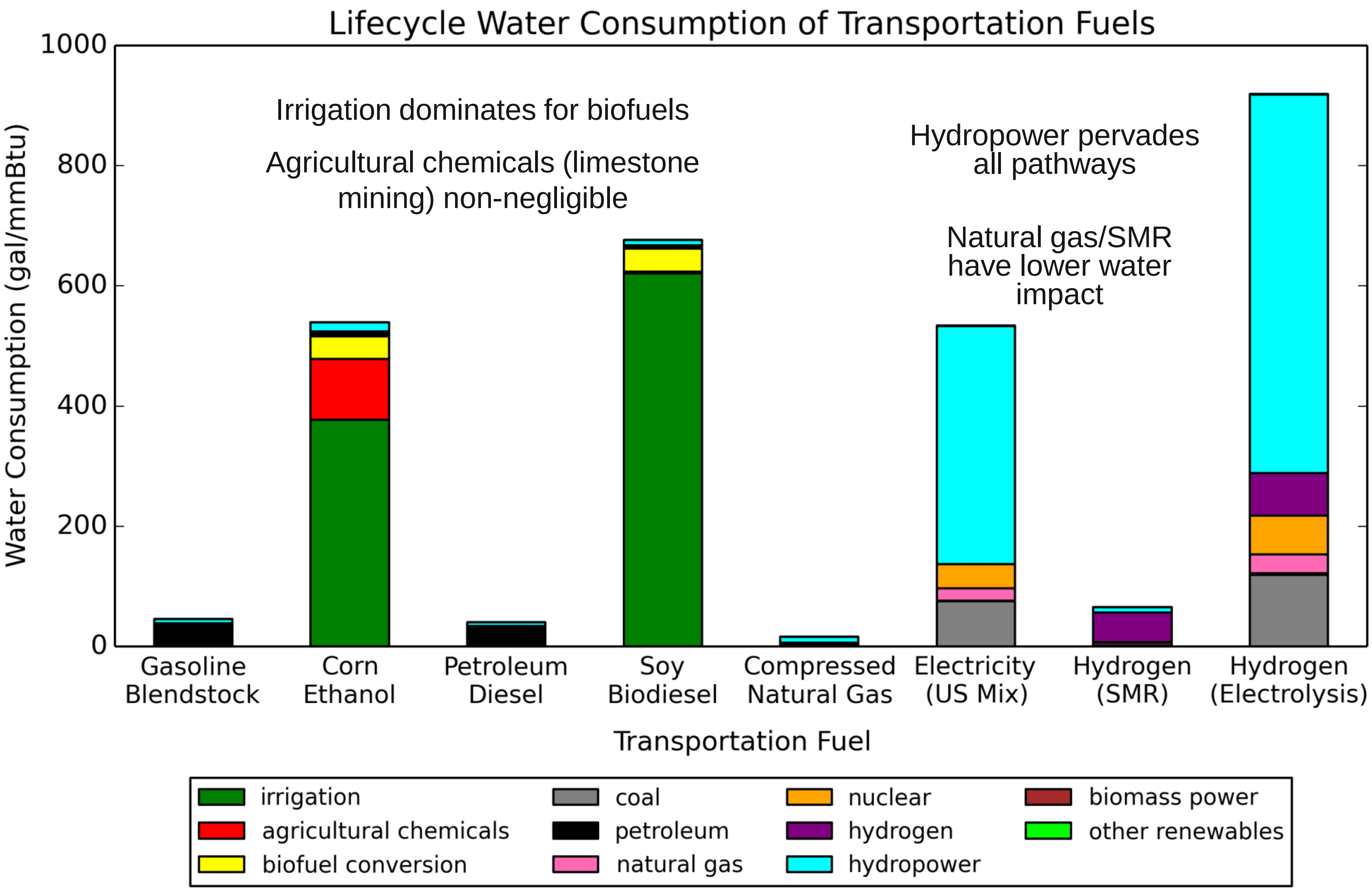
Biofuel water use accounting



In GREET, net withdrawal from surface and ground water is considered, while water from rainfall is not.

Detailed water life-cycle analysis of fuel pathways



For biofuels, data sources and approach build on WBS 4.2.1.10, incorporate analysis directly into GREET with most recent data.

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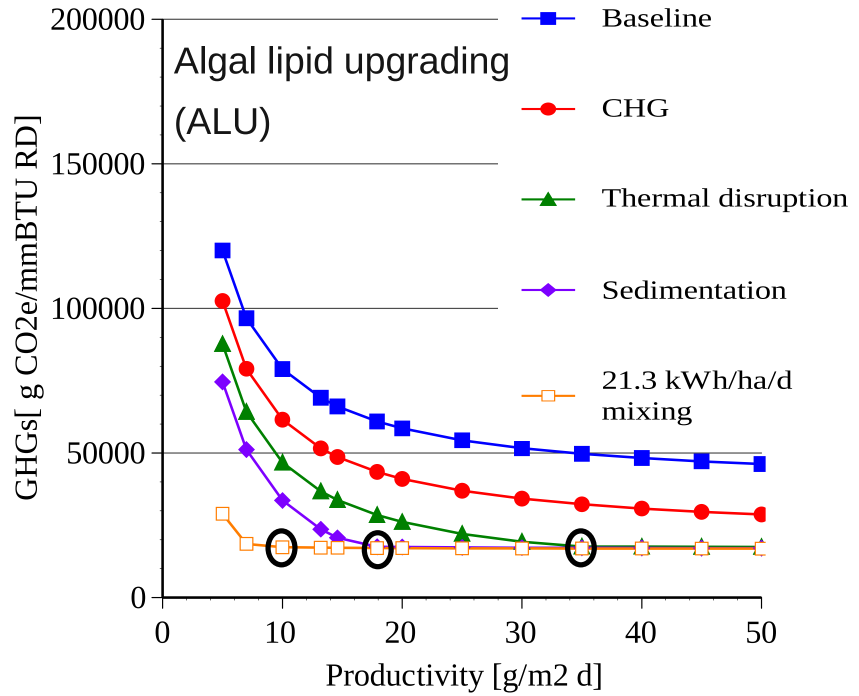
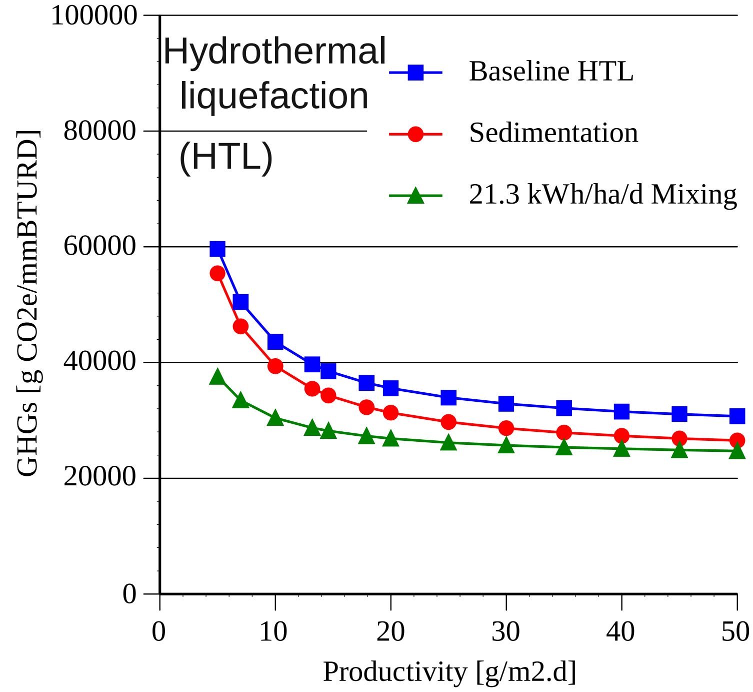
Algae: Ways to Achieve GHG Targets in ALU and AHTL Pathways





R&D Guidance from LCA:

- Must achieve productivity *at low mixing energy*. All 4 seasons must be considered.
  - Energy use must be reported with productivity data
  - Harvest at or above ~0.5 g / L
- Establish CHG or immediate return of AD digestate to ponds to avoid CH_4 & N_2O
- Must demonstrate a low energy primary harvest. (Huge water movement).

Algae: Examined pathways with Improved Economics

Scenario	Year	MFSP ($2011/GGE)		Seasons	Productivity (g/m²/d)	WTW GHG (gCO2$_2$e / MMBTU)		
						Fuel cycle	Infrastructure	Total
Baseline ALU	FY12	$	20.79	3	15.5	67500	8300	75800
National Scale HTL	FY13	$	11.34	4	14.6	40100	-	-
HTL design case	FY14	$	4.49	4	30	35700	1700	37400
ALU design case	FY14	$	4.35	4	30	34900	2100	37000

MFSP - Minimum fuel selling price
GGE - Gallons of gasoline equivalent
WTW GHG - Well to wheels (whole lifecycle) greenhouse gas emissions

The TEA / LCA / RA collaboration guides BETO's system integration and design

- Algae project metrics
  - Approximately 1.5 FTE
  - 3 journal articles and 3 conference presentations in 2 yrs
  - Principal is co-leading system integration in an Algal Biomass Yield collaboration

Key technical accomplishments

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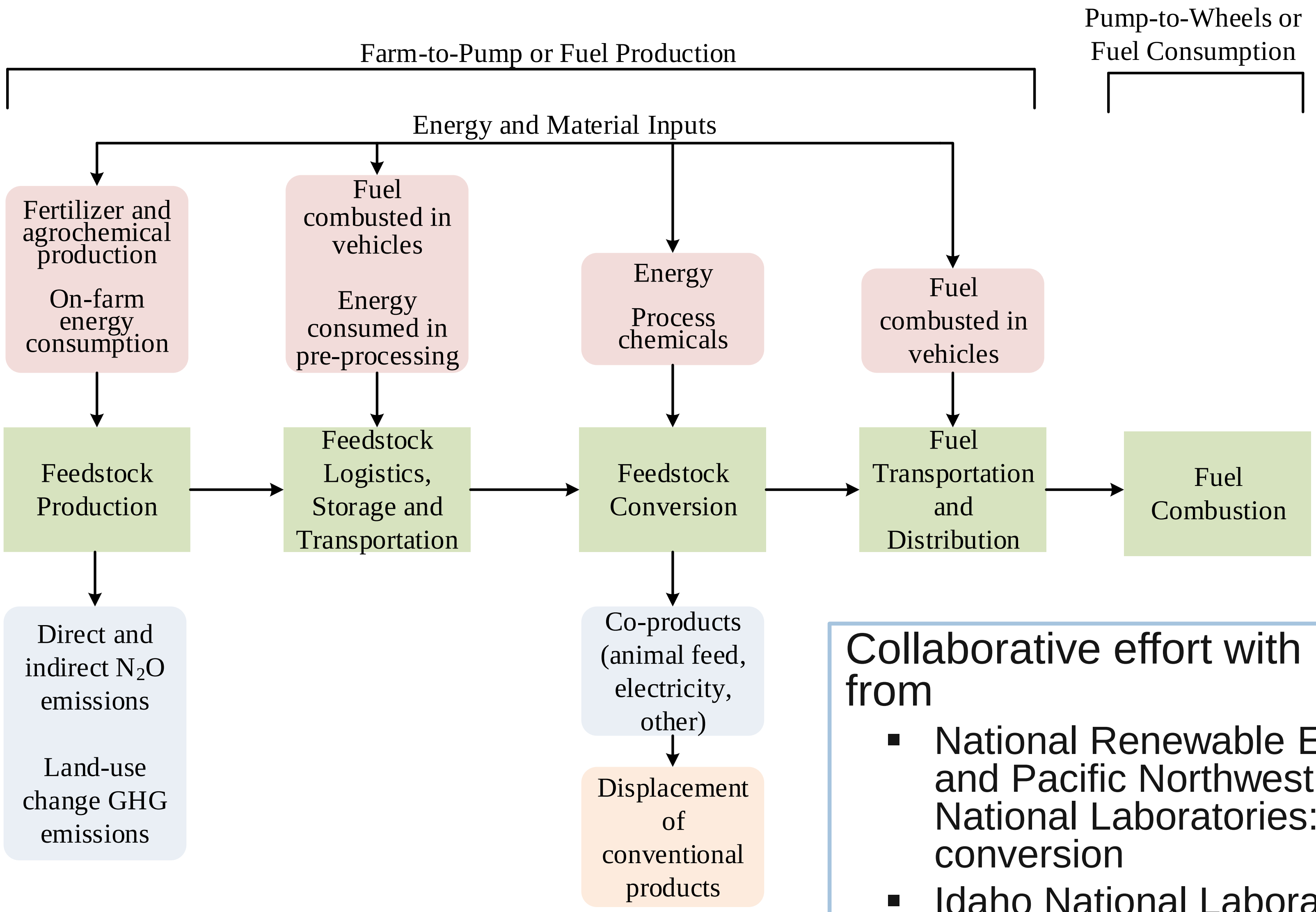
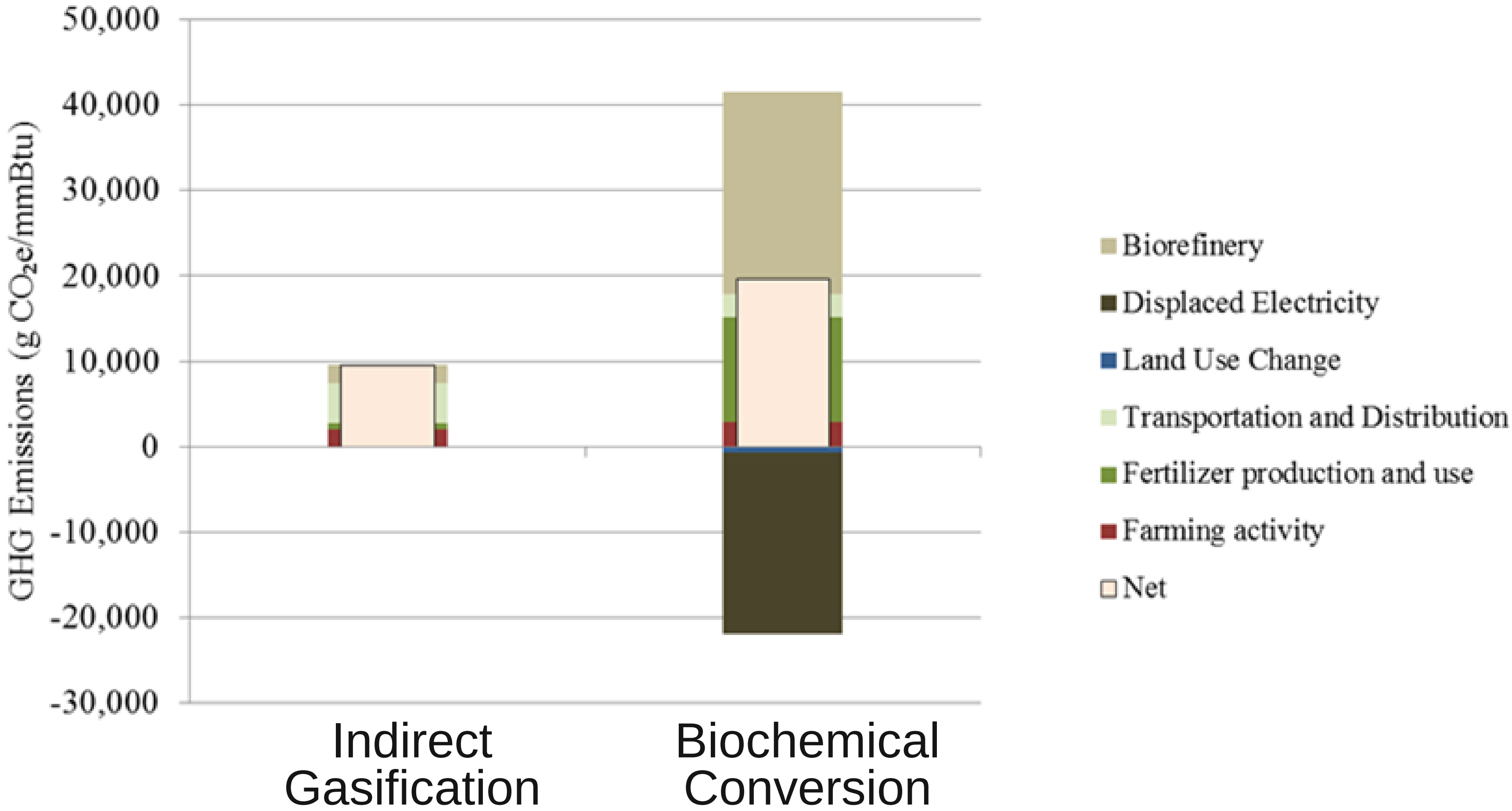
Argonne supply chain sustainability analysis for BETO key pathways



Collaborative effort with input from

- National Renewable Energy and Pacific Northwest National Laboratories: conversion
- Idaho National Laboratory: feedstock logistics

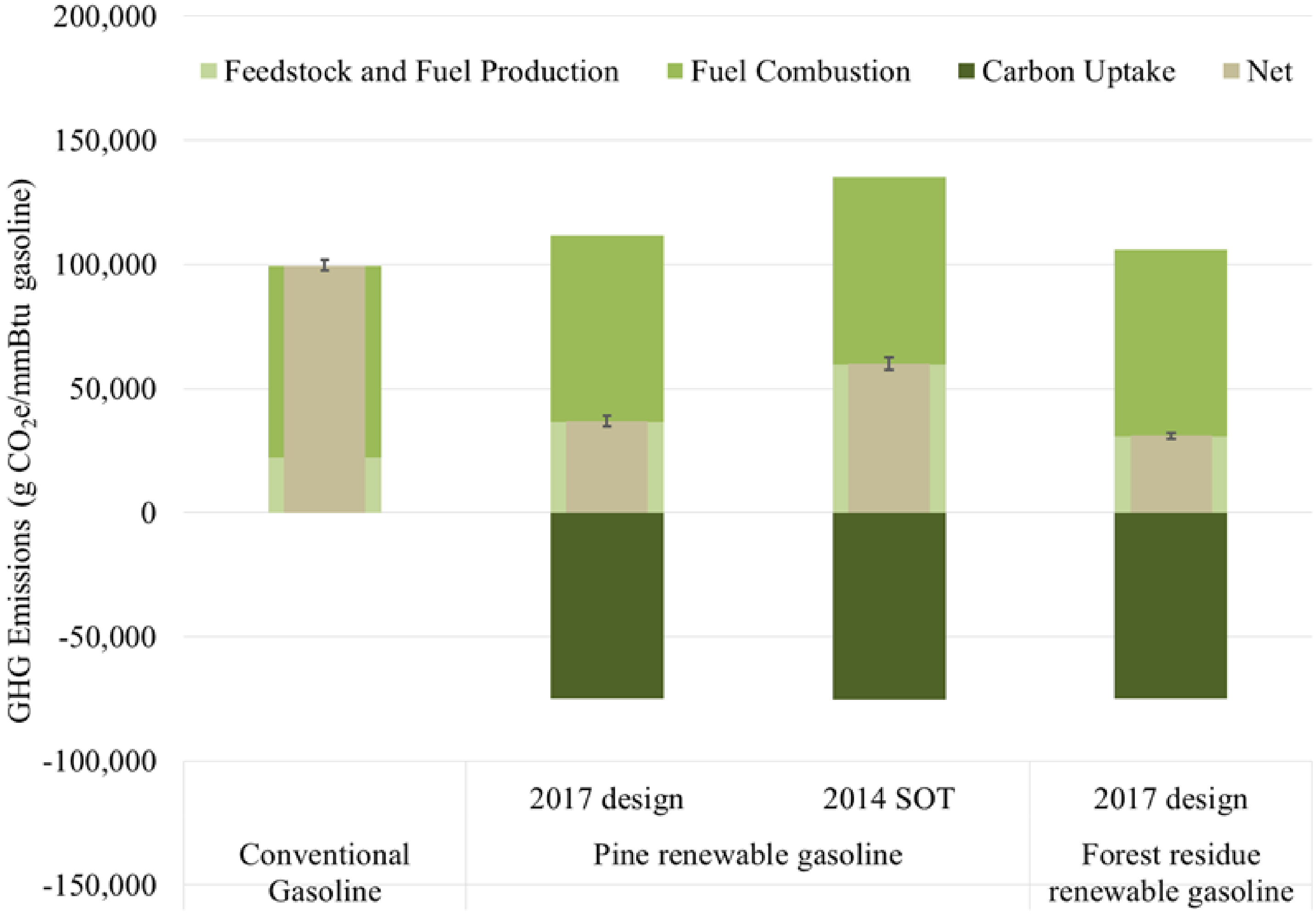
SCSA identifies GHG drivers for BETO priority pathways



FY13 analyses

- Corn stover to ethanol via fermentation
- Southern pine to ethanol via gasification
- Hybrid poplar to renewable gasoline and diesel by fast pyrolysis

BETO MYPP includes FY14 SCSA results by citing the SCSA report



Separately, Algae HTL SCSA in FY14 shows 65% reduction compared to low-sulfur diesel

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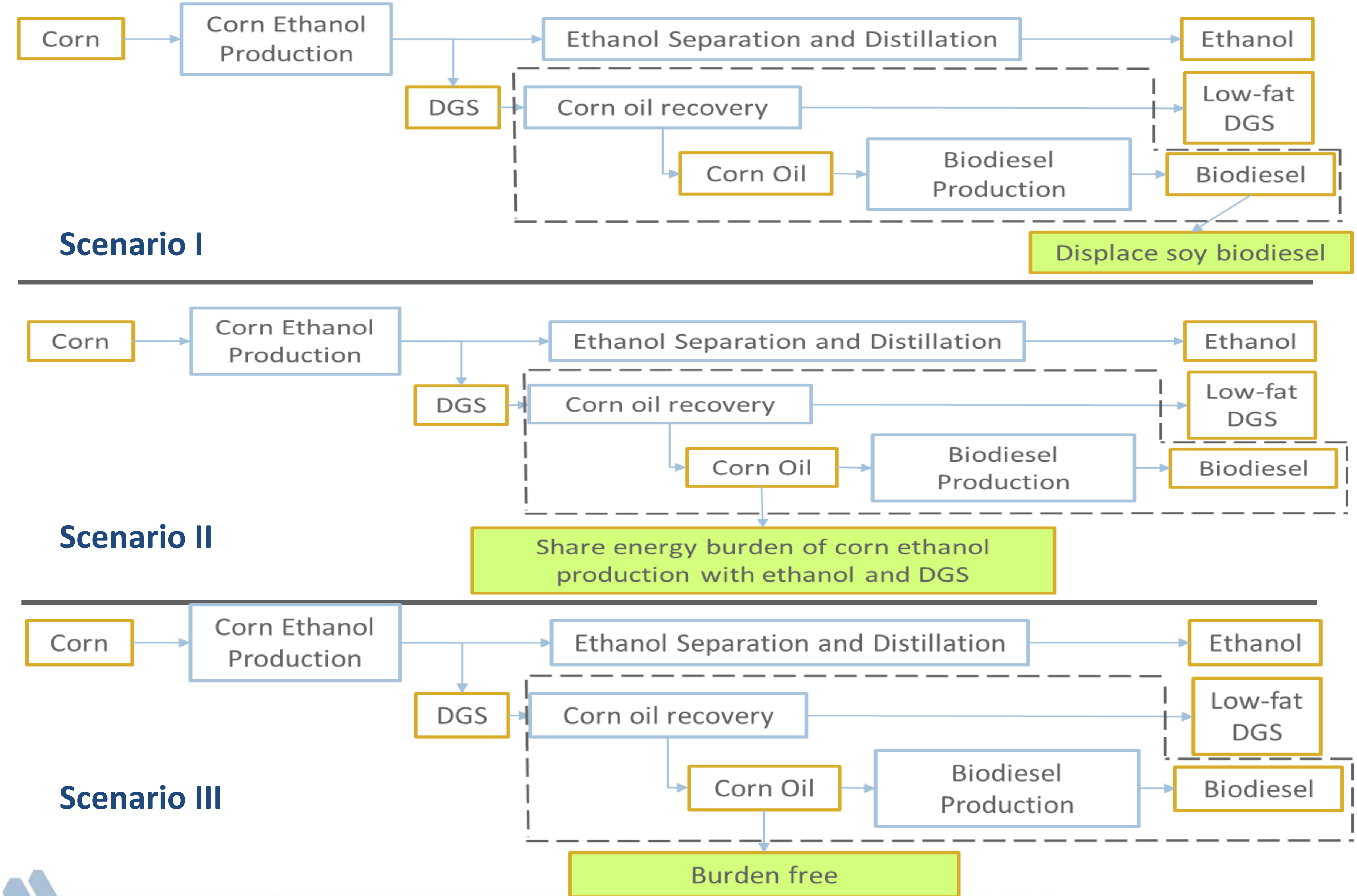
Corn ethanol plant co-production - ethanol, DGS, and corn oil: three co-product treatment scenarios



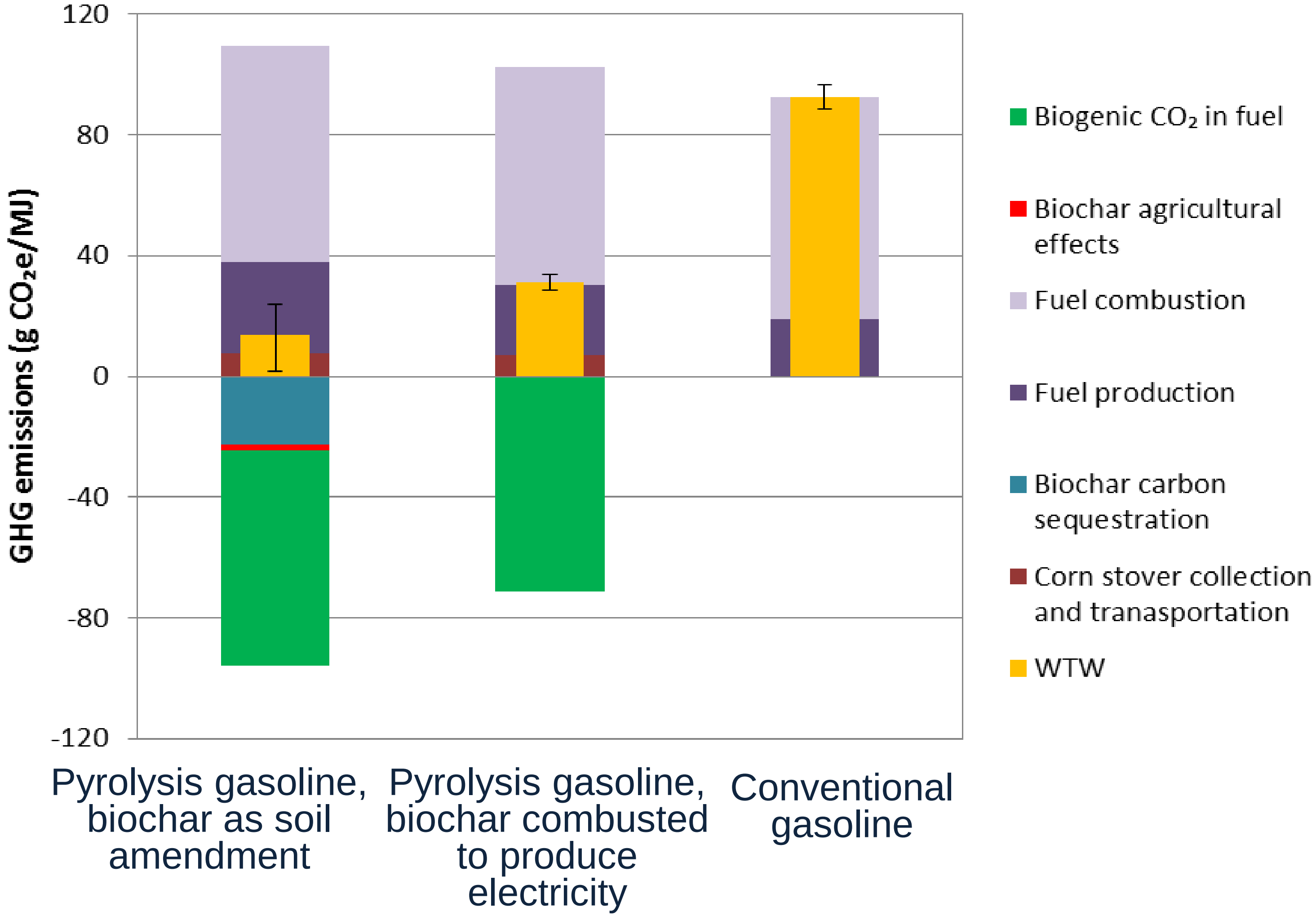
The three co-product treatment scenarios result in different WTW GHG emissions

	WTW GHG Emissions (g CO_2e/MJ)	
	Ethanol	Corn Oil Biodiesel
Scenario I	61	None*
Scenario II	46	45
Scenario III	61	10
CA Air Resources Board**	60	34

* Biodiesel GHG credit is fully assigned to ethanol, thus no biodiesel volume to avoid double counting.

** CARB values are tentative and for comparison only, the final values from CARB may be subject to change.

Life-cycle GHG emissions of gasoline from fast pyrolysis is lower when biochar is used as a soil amendment



Wang et al. *Biofuels, Bioproducts, and Biorefining*, 2013.

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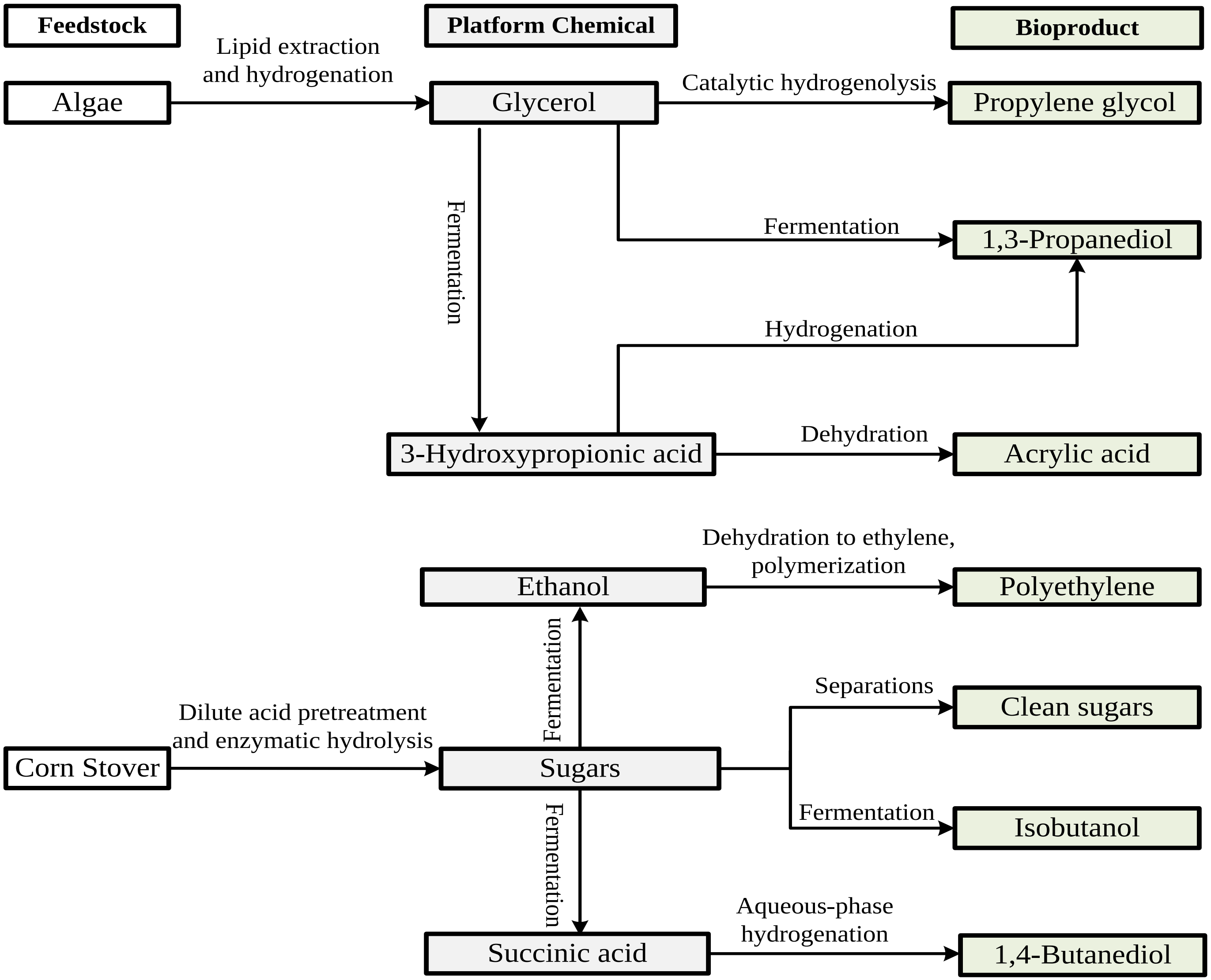
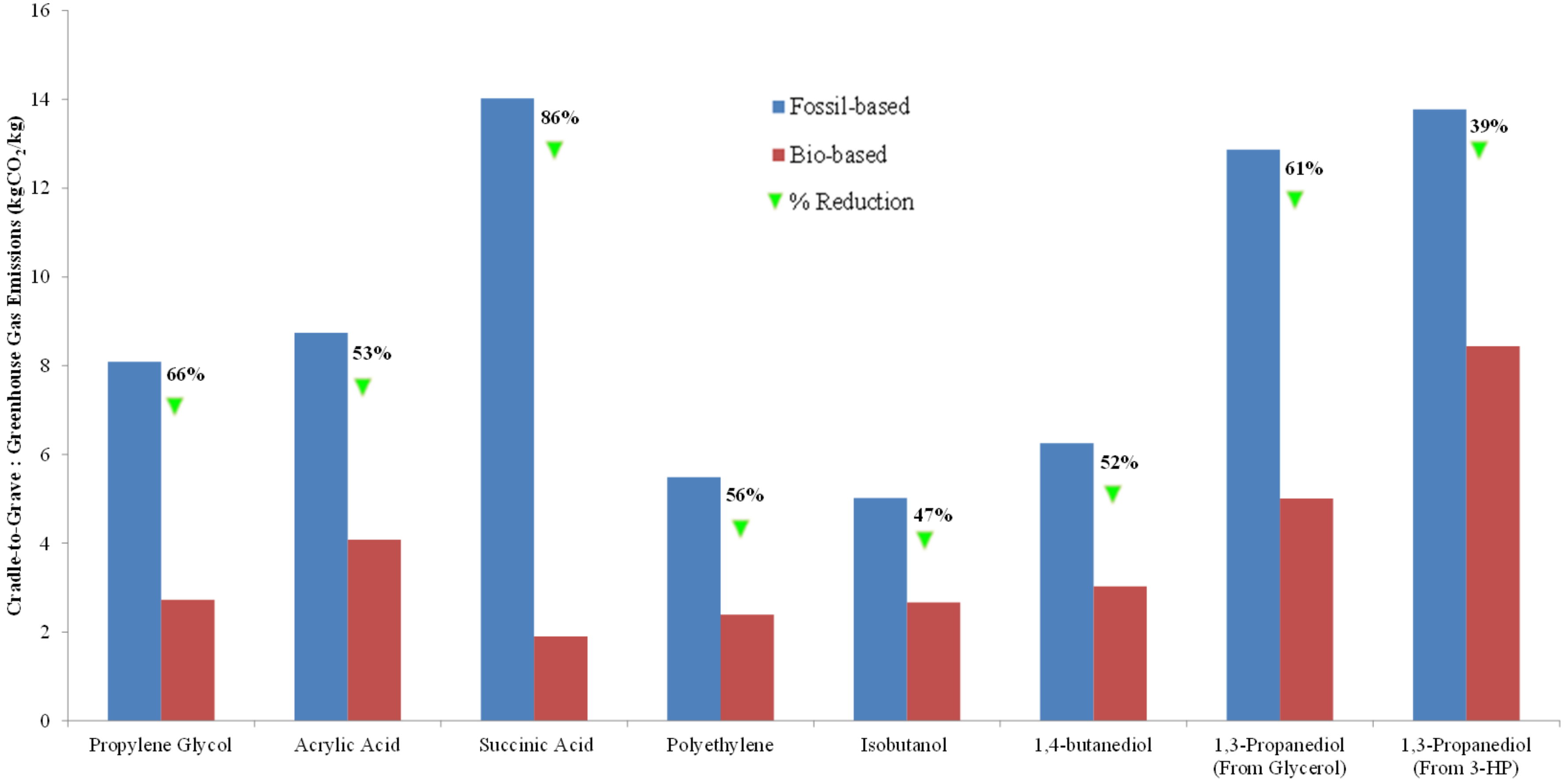
Selection of bioproducts was based on a high-level market analysis



Bioproducts uniformly showed reductions compared to their fossil-derived counterparts



Adom et al. *Environmental Science and Technology*, 2014.

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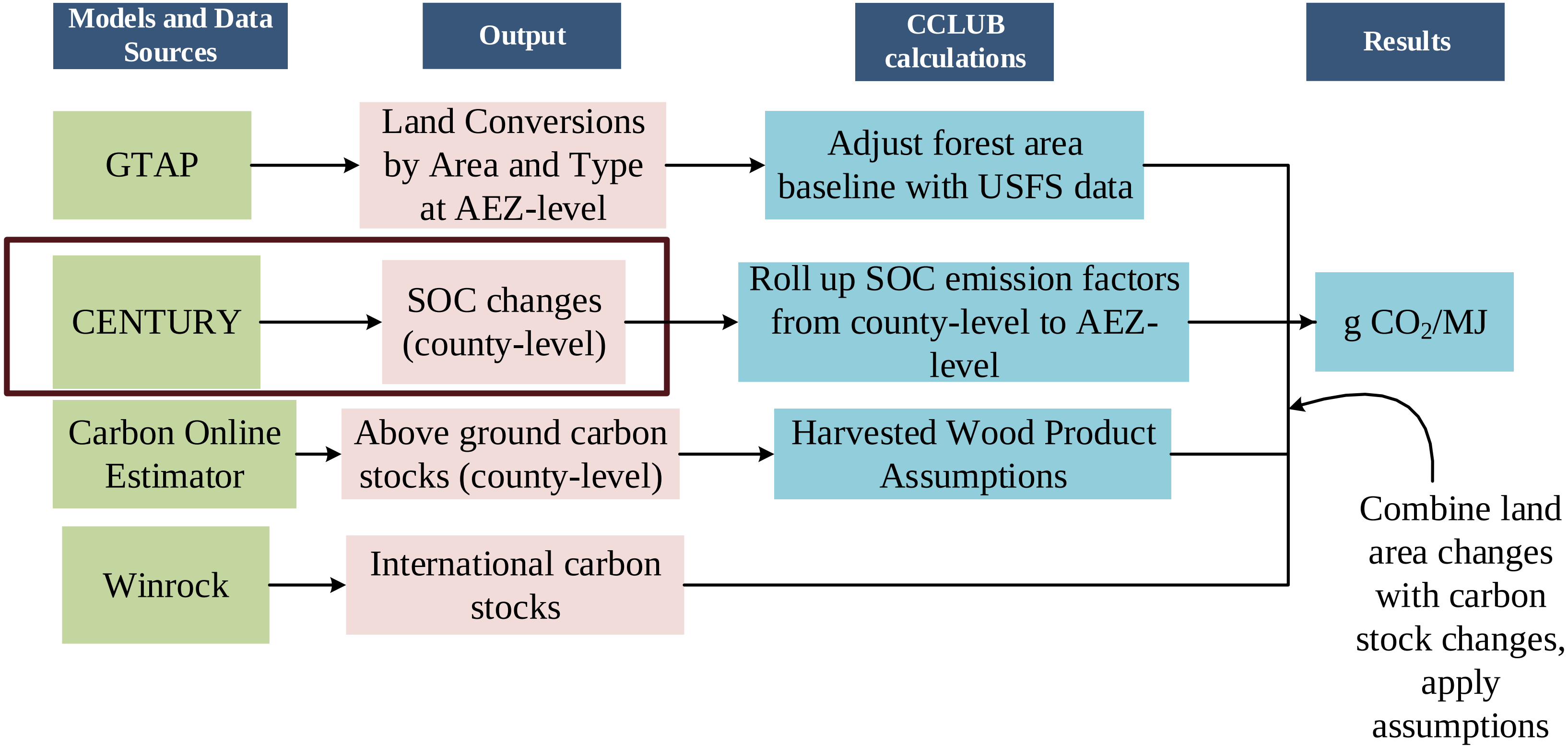
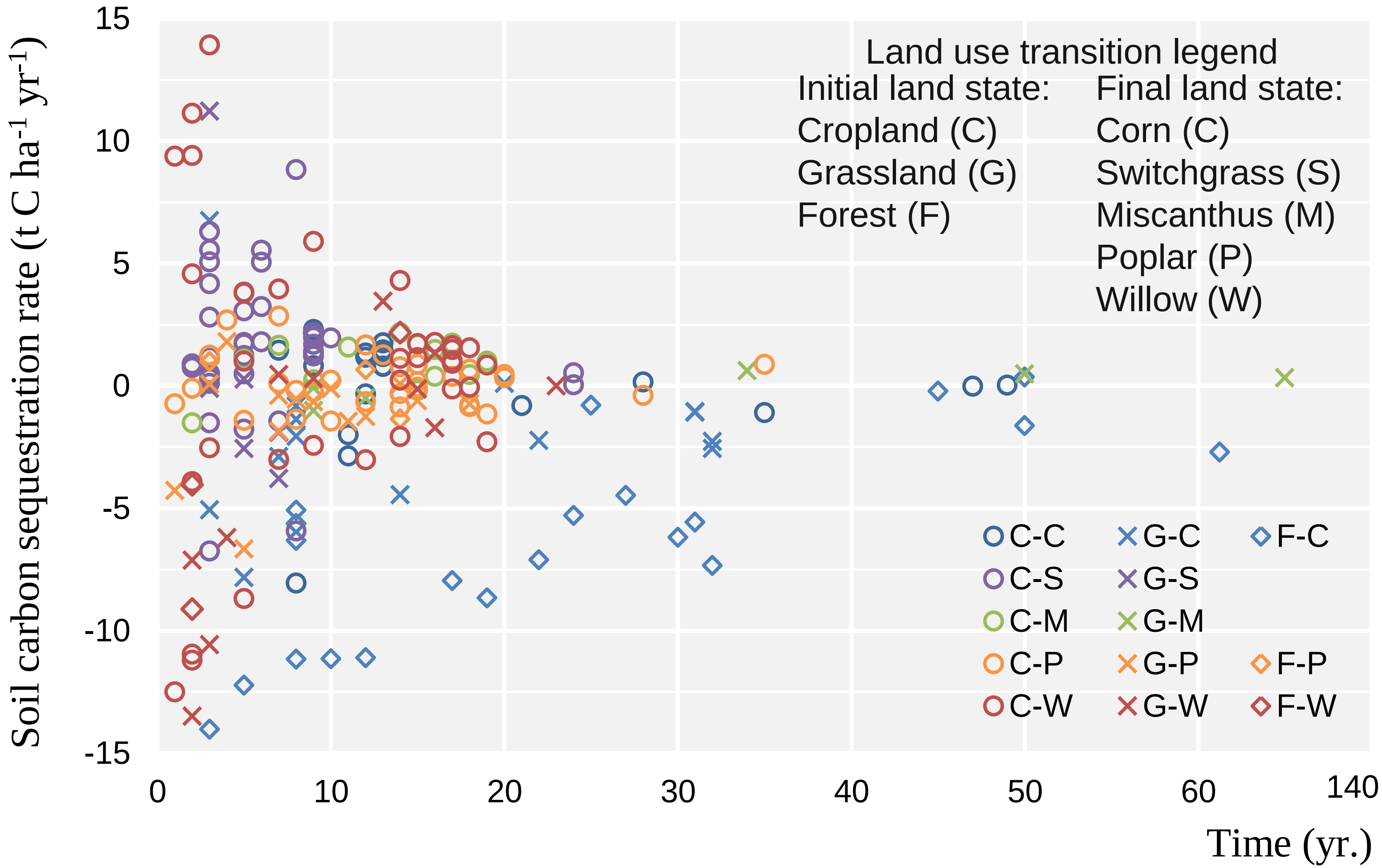
Carbon stock implications of land-use change is a key issue in biofuel life cycle analysis



Soil organic carbon (SOC) modeling improvements and expansions

- Modeling is at county-level
- Poplar and willow added as feedstocks
- User selects 30-cm or 100-cm soil depth results

SOC change rates for LCAs should be based on a time horizon of 20 to 30 years in most cases

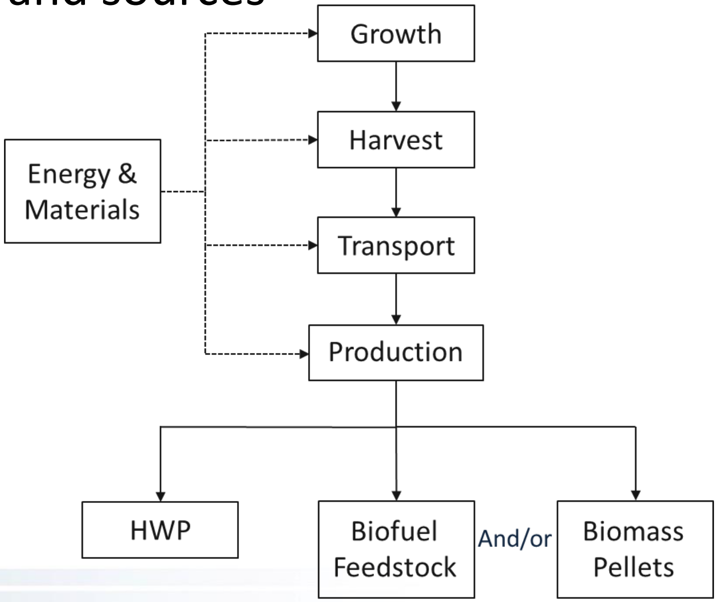


Qin et al., *GCB Bioenergy*, 2015

Critical LCA issues for woody bioenergy

- ❑ Current debate on carbon neutrality and biomass additionality for biofuels
- ❑ Composition of different types of woody feedstocks
- ❑ Carbon cycle dynamics over time
  - Carbon absorption from forest growth model
  - Above- and below-ground biomass after harvest
- ❑ Carbon sinks and sources of forests
  - Validity of carbon neutrality assumption for different forest types and different woody feedstock types
  - Discounting over time of carbon sinks and sources
- ❑ Counterfactual scenarios


Credit: Elaine Oneil, CORRIM



Relevance of GREET development and applications

- GREET is an integral part of BETO's Sustainability and Strategic Analysis mission
  - Develop a consistent model to advance understanding of biofuel sustainability
  - Produce high-quality, consistent, peer-reviewed analyses
  - Outreach and engage agencies and stakeholders with LCA results to promote clean, efficient biofuels and biofuel production
- Sustainability criteria are critical for BETO in technology/pathway down-selection; analysis with GREET quantifies and clarifies:
  - Energy security benefits of biofuels
  - GHG emission reduction potentials of biofuels
  - Air pollutant effects of biofuels
  - Water consumption
  - Identification of key energy and environmental sources and mitigation measures for adverse effects
- Supply chain analysis is an important area of BETO efforts
  - GREET provides a platform to integrate life cycle stages of biofuel pathways and TEA results to address their overall energy and environmental benefits
- Sustaining program funding to GREET by BETO (and other EERE programs) results in an open, transparent LCA tool for consistent comparisons among fuels and in continuing advances in LCAs

Future work

- GREET model development and LCAs
  - Analyze carbon dynamics of woody feedstocks including pine, fir, forest residue, willow, poplar to address concerns of carbon neutrality and biomass additionality
  - Analyze air emissions for biofuel pathways in collaboration with NREL on feedstock production and conversion
  - Examine additional farming practices such as manure application and cover crops to mitigate possible SOC loss from crop residual removal
  - Continue to expand key GREET modules, including pretreatment, catalyst, bioproducts
  - Add heavy-duty vehicles, detailed refinery model at process unit level into GREET.net
- GREET LCA applications
  - Carry out Supply Chain Sustainability Analysis for BETO priority pathways
  - Upgrade and update the Bioeconomy AGE model to estimate economy-wide biofuel benefits
  - Apply GREET approach and data to Billion Ton Study Sustainability Chapter in collaboration with other laboratories

Summary

- GREET is a widely-accepted LCA tool that industry, agencies, and academia use to assess life-cycle energy and environmental metrics of biofuels. These users apply the model for a range of purposes including developing R&D strategies, identifying energy/environmental issues and solutions, and developing/evaluating biofuel policies.
- GREET and supporting technical documentation are publicly available, enabling users to examine critical issues, develop their own analyses, and provide critical feedback to Argonne LCA research.
- Argonne develops publications and presentations that address key issues in biofuel sustainability and disseminate LCA results in the national and international debate of biofuel sustainability.
- Argonne is developing applications of GREET that address biofuel sustainability at an economy-wide level, expanding GREET application beyond per-fuel-level analysis.
- Argonne develops LCA results for BETO priority pathways through collaboration with NREL, INL, and PNNL, laboratories that develop TEAs for feedstock logistics and conversion technologies. BETO uses the resulting supply chain sustainability analyses to select biofuel technology options and guide R&D.

Additional Slides

Selected comments from BETO 2013 GREET review and ANL responses

Apply GREET LCA results to inform policy

We engage in the dissemination of GREET LCA results and biofuel LCA key issues through stakeholder engagement, publications, and public speaking. We continue to seek engagement with a diverse stakeholder base that can include policy makers and their staff.

Consider data repository development distinct from Excel modeling that can incorporate input from external users

We continue to explore transparent and clear ways to display data in GREET, which is a significant database of the material and energy intensity of biofuel pathways. We will continue to make GREET serve that role and function as an LCA model. While GREET is designed for users to incorporate their own data, we have a vigorous process to choose GREET default data for data representation and reliability because, as GREET developers, we shoulder the responsibility for the model's data quality.

Expand beyond Excel platform relying on software engineering expertise and maintaining transparency

In our development of the .net platform, our team of software engineers is striving to retain transparency while optimizing ease of use. We continue to solicit feedback from users of GREET.net to improve it.

Publications

Peer Reviewed Journal Articles and Book Chapters

- C. Canter, R Davis, M. Urgun-Demirtas, and E Frank, "Infrastructure associated emissions for renewable diesel production from microalgae." 2013**.** *Algal Research* 5:195-203
- H Cai, JB Dunn, Z Wang, J Han, MQ Wang. "Life-cycle energy use and greenhouse gas emissions of production of bioethanol from sorghum in the United States." 2013. *Biotechnology for Biofuels*, 6:141.
- Z Wang, JB Dunn, J Han, MQ Wang. "Effects of co-produced biochar on life cycle greenhouse gas emissions of pyrolysis-derived renewable fuels." 2013. *Biofuels, Bioproducts, and Biorefining*, 8: 189-204.
- M.C. Johnson and E Frank, "Energy consumption during the manufacture of nutrients for algae cultivation." 2014 *Algal Research* 2: 426-436
- R Davis, D Fishman, et al. (2014). "Integrated Evaluation of Cost, Emissions, and Resource Potential for Algal Biofuels at the National Scale." 2014 *Environmental Science & Technology* 48: 6035-6042.
- I Emery, JB Dunn, J Han, M Wang. "Biomass Storage Options Influence Net Energy and Emissions of Cellulosic Ethanol." 2014. *Bioenergy Research*, doi: 10.1007/s12155-014-9539-0
- J Elliott, B Sharma, N Best, et al. "A Spatial Modeling Framework to Evaluate Domestic Biofuel-Induced Potential Land Use Changes and Emissions." 2014. *Environmental Science and Technology*, 48: 2488-2496.
- GS Forman, VB Divita, J Han, et al.. "U.S. Refinery Efficiency: Impacts Analysis and Implications for Fuel Carbon Policy Implementation." 2014. *Environmental Science and Policy*, 48: 7625-7633.
- A Elgowainy, J Han, H Cai, et al. "Energy Efficiency and Greenhouse Gas Emissions Intensity of Petroleum Products at US Refineries." 2014. *Environmental Science and Technology*, 48: 7612 – 7624.
- F Adom, JB Dunn, J Han, N Sather. "Life-cycle Fossil Energy Consumption and Greenhouse Gas Emissions of Bioderived Chemicals and Their Conventional Counterparts." 2014**.** *Environmental Science and Technology*, 48: 14624-14631.
- Z Qin, JB Dunn, H Kwon et al. "Soil carbon sequestration and land use change associated with biofuel production: Empirical Evidence." 2014. *GCB Bioenergy*, doi: 10.1111/gcbbb.12237

Selected Technical Reports (http://greet.es.anl.gov/publications)

- Z Wang, JB Dunn, J Han, MQ Wang. "Material and Energy Flows in the Production of Cellulosic Feedstocks for Biofuels for the GREET Model." 2013. ANL/ESD-13/9.
- F Adom, JB Dunn, A Elgowainy, et al. "Life Cycle Analysis of Conventional and Alternative Marine Fuels in GREET." 2013. ANL/ESD-13/10.
- JB Dunn, MC Johnson, Z Wang, et al. "Supply Chain Sustainability Analysis of Three Biofuel Pathways." 2013. ANL/ESD-14/5.
- F Adom, JB Dunn, J Han. "GREET Pretreatment Module." 2014. ANL/ESD-14/13.
- JB Dunn, F Adom, N Sather, et al. "Life-cycle Analysis of Bioproducts and Their Conventional Counterparts in GREET." 2014. ANL/ESD-14/9.
- H Cai, MQ Wang. "Estimation of Emission Factors of Particulate Black Carbon and and Organic Carbon from Stationary, Mobile, and Non-point Sources in the United States for Incorporation into GREET." 2014. ANL/ESD-14/6.

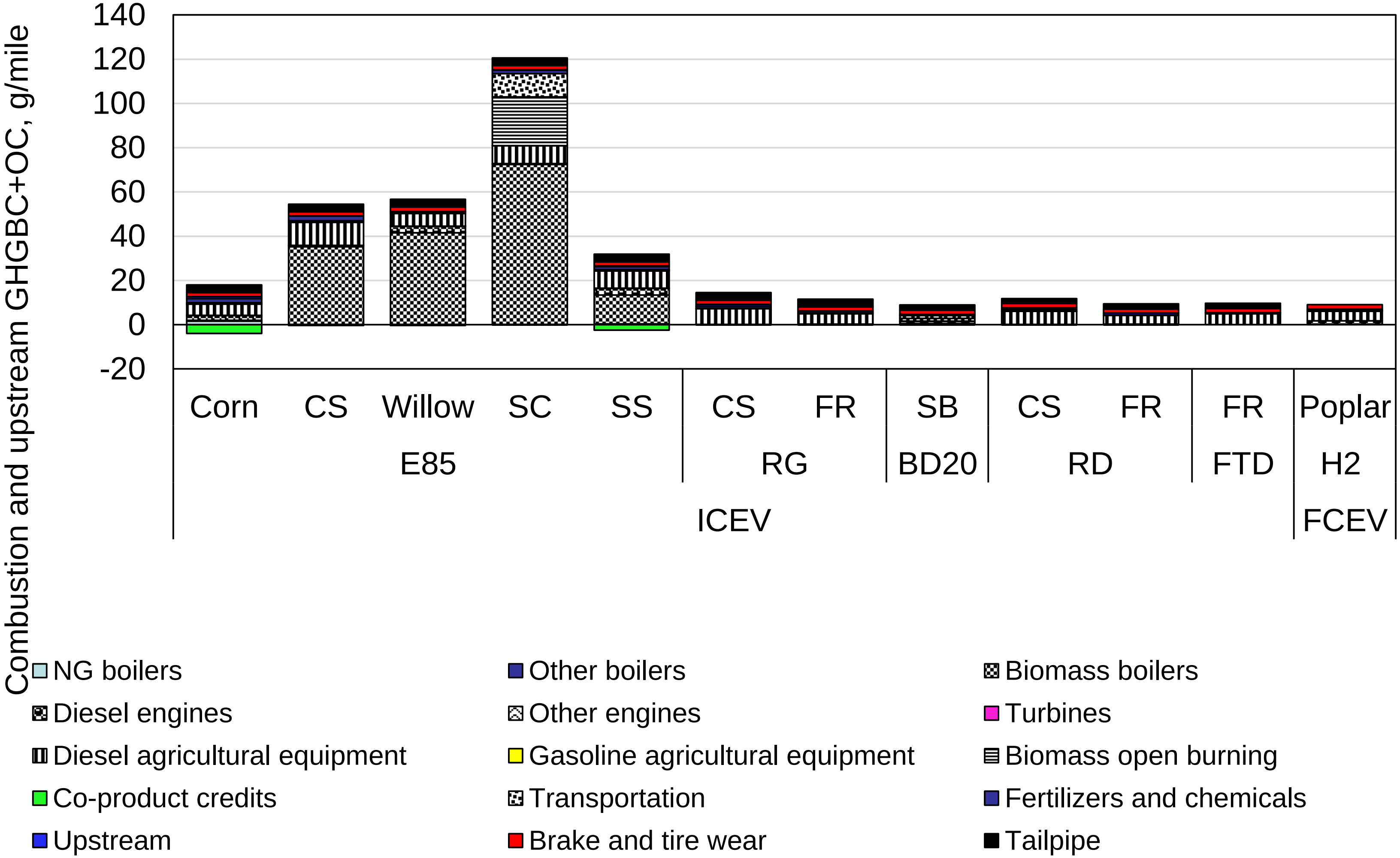
Additional Technical Memoranda at http://greet.es.anl.gov/publications

Selected presentations

- M Johnson, E Frank, Y Zhu, et al., Life Cycle Analysis of Algal Biofuels: Implications of NAABB R&D, 3rd Inter. Conference on Algal Biomass, Biofuels, and Bioproducts, Toronto, Canada, June 16-19, 2013
- Z Wang, JB Dunn, J Han, M Wang, How Does Biochar Application to Soil Influence Life-Cycle GHG Emissions of Biofuels Generated from Pyrolysis? 2013 American Society of Agri. and Biological Engineers Annual Meeting, Kansas City, Missouri, July 21-24, 2013
- S Mueller, JB Dunn, H Kwon et al., Land-Use Change GHG Emissions for Corn and Cellulosic Ethanol from High-Resolution US Soil Organic Carbon Emission Dactors, LCA XIII, Orlando, Florida, Oct. 1-3, 2013
- MQ Wang, Key Issues for GREET Transportation Fuel LCA, CRC Workshop on Life Cycle Analysis of Transportation Fuels, Argonne, IL., Oct. 16-17, 2013
- MQ Wang, Biofuel Life Cycle Analysis and Regulatory Applications, 2013 AIChE Annual Meeting, San Francisco, CA, Nov. 6, 2013
- MQ Wang, Biofuel Life Cycle Analysis Results, 2013 SAE Fuels, Lubricants and Aftertreatment Symposium, Long Beach, CA, Nov. 19, 2013
- MQ Wang, Biofuel Life Cycle Analysis Results, HEI SCET Workshop, Chicago, Dec. 5, 2013
- M.Q. Wang, R. McCormick, B. West, et al., Air Pollutant Emission Effects of Biofuels vs. Petroleum Gasoline and Diesel, 3rd Sino-US Advanced Biofuels Forum, Beijing, China, Dec. 9-10, 2013
- R Malina, M Staples, M Wang, et al., A Comparison of LC GHG Accounting for Alternative Fuels in the US and EU, CAAFI Environmental Workshop, Washington, DC, Jan. 27, 2014
- JB Dunn, Advancements in the Analysis of Land-Use Change Greenhouse Gas Emissions, 9th Annual World Biomarkets Conference, Amsterdam, Netherlands, March 4-6, 2014
- E Frank, R Davis, D Fishman, et al., National Scale Modeling of Algal Biofuels: Resources, Cost, and Emissions." Algae Strategy Workshop. Charleston, SC, March 26-27, 2014
- MQ Wang, Bioethanol Energy and Environmental Effects, Guangdong Bioethanol Industry Development Workshop, Guangzhou, China, May 29, 2014
- E Frank, R Davis, D Fishman, et al., National Scale Modeling of Cost, Emissions, and Resource Assessment in the United States, 4th Inter. Conference on Algal Biomass, Biofuels, and Bioproducts. Santa Fe, NM, June 15-18, 2014
- MQ Wang, GREET Bioenergy Life Cycle Analysis and Key Issues for Woody Feedstocks, Biomass 2014, Washington, DC, July 30, 2014
- MQ Wang, Life-Cycle Greenhouse Gas Emissions of Corn Ethanol with the GREET Model, EESI Congressional Briefing, Washington, DC, Sept. 18, 2014
- JB Dunn, Land-Use Change Greenhouse Gas Emissions in US Biofuel Life Cycle Analysis, Les Rencontres IAR, Reims France, Sept. 30, 2014
- JB Dunn, F Adom, NF Sather, Bioproduct Life Cycle Analysis: Key Results and Methodological Issues." LCA XIV, San Francisco, Calif., Oct. 6-8 2014

Backup Slides

Biomass combustion was identified to be a key contributor to black carbon emissions (g/mi in FFVs)

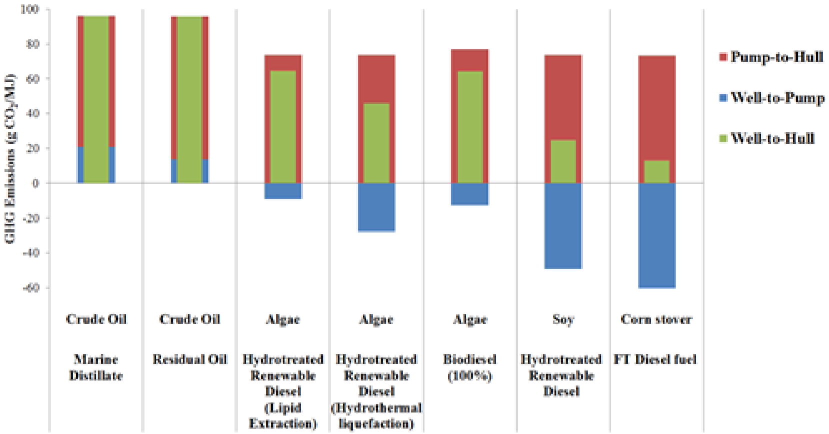


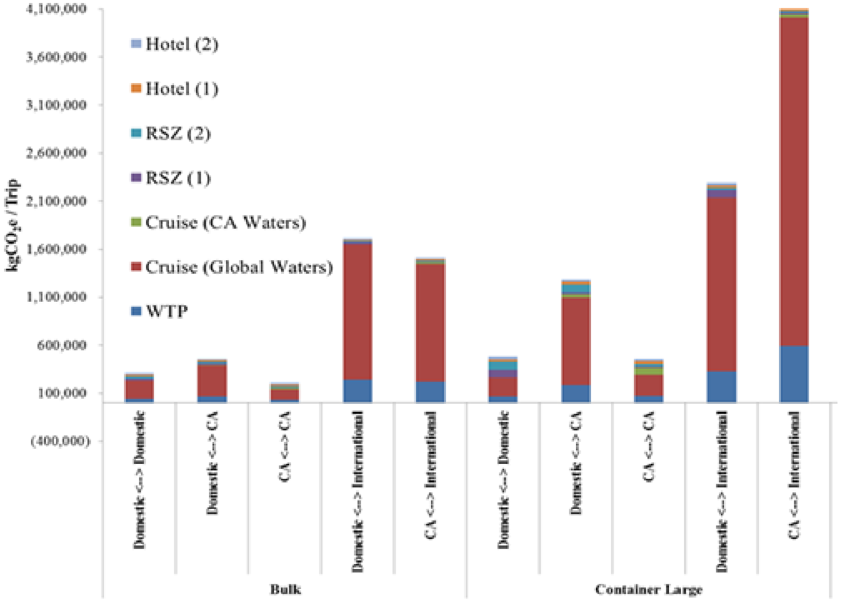
CS: Corn stover ; SC: sugarcane; SS: Sweet sorghum; FR: Forest residue; SB: Soybean; RG: Renewable gasoline; FTD: Fischer-Tropsch diesel; RD: Renewable diesel; FCEV: Fuel cell electric vehicle

Cai and Wang, *Environmental Science and Technology*, 2014

The marine module contains well-to-hull and per energy functional unit results

- Bio-based marine fuels offer GHG reductions
- Transit in international waters largest contributor to well-to-hull emissions.





- Vessel types:
  - •Bulk Container
  - •Large Container
  - •Crude Carrier
- Regions
  - •Atlantic
  - •Pacific
  - •Great Lakes
  - •Gulf of Mexico