9TH CRC LIFECYCLE ANALYSIS WORKSHOP SUMMARY ARTICLE

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COORDINATING RESEARCH COUNCIL, INC.
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Summary Report

9th Biennial CRC Workshop on Life Cycle Analysis of Transportation Fuels

Argonne National Laboratory
October 7-9, 2025

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On behalf of the Coordinating Research Council

Disclaimer: This report aims to accurately summarize presentations and discussions from the Workshop. The author is responsible for the content of this report, which does not necessarily represent the views of any particular individual, organization, or agency.

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Summary Report

9th Biennial CRC Workshop on Life Cycle Analysis of Transportation Fuels

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A. Introduction

The 9th biennial Coordinating Research Council (CRC) Workshop on Life Cycle Analysis of Transportation Fuels was held at Argonne National Laboratory on October 7-9, 2025. The workshop was sponsored by the American Petroleum Association, Canadian Fuels Association, Clean Fuels Alliance America, and the Renewable Fuels Association. The goals of this workshop were similar to previous workshops:

- Outline technical needs arising out of policy actions and ability of life cycle analysis (LCA) to meet those needs.
- Identify data gaps, methodology issues, areas of uncertainties, validation/verification, model transparency, and data quality issues.
- Identify research results and activities that have come to light in the past two years, especially ones that have helped to close data gaps previously outlined as outstanding issues.
- Establish priorities for directed research to narrow knowledge gaps and gather experts' opinions on where scarce research resources would best be spent.

There were 130 registrants for this workshop, 64 of whom were first-time attendees to the workshop. Registrants were from six different countries and represented government bodies (including National Laboratories), industry, academia, and non-governmental organizations (NGOs). Thirty technical presentations were given, organized into seven technical sessions.

Robb De Kleine (Ford) opened the workshop by welcoming the participants and thanking the workshop sponsors and Argonne for again hosting the workshop. He noted that the federal government shutdown created travel difficulties for some participants, and therefore some presentations would be on-line rather than in-person. He reiterated the workshop goals and noted that the workshop has done a lot of good for the understanding of life cycle analysis and indirect land use change. He closed by highlighting several uncertainties around policies moving forward:

- Credit mechanisms in some programs are being scaled back;
- Trade is potentially becoming an issue for fuels and feedstocks; and
- Previous strong battery electric vehicle (BEV) growth is moderating, which would be balanced by conventional internal combustion engine (ICE) vehicles.

Chris Tennent (CRC) provided a brief summary of the CRC history and structure, noting that CRC has been active for over 100 years and is a 501(c)(3) nonprofit organization. As such, CRC does not lobby, and research is the key to the organization – CRC's work informs regulations based on sound science. The

CRC LCA workshop falls under the purview of the Sustainable Mobility Committee, which consists of CRC sustaining members as well as other agencies and organizations.

Following the introductory remarks, the workshop presentations began. This Workshop Summary Report[1] highlights the topics discussed in each session as well as the knowledge gaps identified by the speakers, the session chairs, and other workshop participants. The report is organized into the following sections: (A) Introduction, (B) Workshop Highlights, and (C) Highlights and Learnings from Individual Presentations. A glossary of terms used during the workshop is included as an appendix. All figures shown in this Summary Report were taken from the presentation materials used by the speakers.

B. Workshop Highlights

Below is a summary of the impressions, highlights, and conclusions from the technical sessions of the LCA Workshop. This list is not comprehensive, but it attempts to capture important observations, significant take-home messages, and common themes that emerged from the information presented.

Session 1: Policy Updates

- Volume requirements for EPA's Renewable Fuel Standard (RFS) have been proposed for 2026 and 2027 under the "Set 2" rule, with biomass-based diesel experiencing the largest growth during this timeframe. It was noted that the RFS may be at an inflection point with the Set 2 rule, continued expansion of state-level policies, and continuing interest in a national low-carbon fuel standard.
- A major update to California's Low Carbon Fuel Standard (LCFS) became effective on July 1, 2025. The goal of the revised regulations is to reduce the carbon intensity (CI) of the transportation fuel pool by at least 30% by 2030 and 90% by 2045 from a 2010 baseline. Also included with this update is an auto-acceleration mechanism that could trigger additional target increases if the market is oversupplied with credits.
- Updates to "Section 45Z" clean fuel production credit regulations as part of the One Big Beautiful Bill Act (OBBBA) included preservation of 45Z credits and extension to 2029, elimination of a special credit rate for sustainable aviation fuel (SAF), and elimination of indirect land change (ILUC) from the CI calculations beginning in 2026. The latter change significantly increases anticipated credit values ($/gallon) for soybean and canola oil based fuels.
- Canada's Clean Fuel Regulations (CFR), similar in structure to California's LCFS, continue implementation, requiring reductions in carbon intensity from 3.5 gCO2e/MJ (4% below 2016 levels) in 2023 to 14.0 gCO2e/MJ (15% below 2016 levels) in 2030. These regulations use the Government of Canada's Fuel Life Cycle Assessment Model which runs on the openLCA platform. The model was first published in 2022 and is updated every two years. The next formal update of the model is planned for fall 2026; stakeholders are encouraged to review and provide feedback on the model update.
- The European Union's (EU) Renewable Energy Directive III (RED III), with more aggressive targets, has been adopted into national law by member states as of 2025. Some of the challenges

[1] To maintain consistency in reporting the outcomes of the CRC LCA workshops, the structure of this Summary Report is very similar to previous workshop summaries available on CRC's website at https://crcao.org/life-cycle-analysis-lca-of-transportation-fuels-workshop/.

associated with RED implementation and fuel certification include auditing of waste and residue feedstocks, identifying virgin palm oil being sold as used cooking oil, and using satellite images to support claimed processing plant volumes.

- The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) continues implementation, with a baseline defined as 2019, and emissions increases from 2024 to 2035 need to be offset. It is anticipated that in the 2025-2026 timeframe there will be a need for airlines to begin to reduce and offset emissions, and therefore significant activity in this space is expected moving forward.
- International Maritime Organization's (IMO) efforts to reduce GHG emissions from international shipping were reviewed, which include a goal of 20% GHG reduction by 2030 (striving for 30%); and net zero GHG emissions by about 2050

Session 2: Methodology

- Questions remain regarding appropriate allocation methods when using recycled or waste feedstocks for biofuels. Used cooking oil (UCO) was used as an example, where the carbon intensity (CI) of biodiesel from UCO ranged from 18 to 28 gCO2e/MJ, depending on selection of allocation/analysis method.
- Standardization of mass balance and other methods for chain of custody accounting in life cycle assessment is needed and is particularly important for circular economy technologies such as chemical recycling of plastics and in some bio-feedstock technologies.
- Methodological barriers exist in carbon accounting for bio-based products, including: (1) carbon accounting systems lack attributional LCA harmonization; (2) carbon accounting systems lack consequential LCA harmonization; and (3) government GHG accounting incentives focus on fuels rather than products.
- Reference land use is an important concept for biofuel and bioenergy lifecycle analysis. Five reference land use options from ISO 14067 (carbon footprint of products) were discussed: business as usual (BAU), projected future, target, potential natural regeneration, and historic baseline. For attributional LCA, it was argued that potential natural regeneration is a coherent reference land use. For consequential LCA, BAU or a projected counterfactual future were put forward as defensible choices for reference land use in most cases.

Session 3: Biofuels

- Modeling of soil organic carbon (SOC) under different conditions of tillage, soil type, and cover crops is an important consideration in implementing policies to support sustainable farming practices. Increased adoption of these practices is needed for achieving significant co-benefits in agriculture, and models are needed as a supplement to measurements because SOC measurements can be cost-prohibitive at scale with currently available technologies. Multi-model ensemble (MME) analysis provides an opportunity to benchmark models, develop dynamic baselines, and reduce uncertainty.
- Farming practices such as no-till and cover crops can increase SOC relative to conventional practices and are considered an avoided emissions practice.

Session 4: Land Use Change

- National inventories show much different land use change emissions than do global models, and this difference is referred to as the "Grassi Gap" after the researcher who first identified the discrepancy. Understanding and reconciling these differences is crucial for improving LUC emission estimates and tracking progress toward long-term climate goals.
- Opportunities to mitigate emissions from agriculture include reducing nitrogen emissions and increasing soil organic carbon (SOC) stocks. Reducing use of nitrogen fertilizer would result in GHG reductions because of the high global warming potential of nitrous oxide. To overcome concerns about permanence in crediting SOC accumulation, system thinking was recommended because carbon stocks in soil fluctuate regularly, where total SOC is a "bank" and the net change is simply in - out. Uncertainties in cradle-to-farmgate carbon intensity include unknown plant trait parameters (e.g., photosynthesis, which impacts yield) and fertilizer information.
- Significant uncertainties remain in modeling indirect land use change (ILUC). As a solution to the ILUC problem, it was suggested that we get back to basics – science and causal analysis. Incentives are needed for better land management, and more data are needed from the areas of concern. There are irreducible uncertainties associated with ILUC modeling, and shifting to a risk-based approach for dealing with ILUC was recommended.

CRC Project SM-LCA-17

- This project was intended to address the question: *Why do different models give different results for the same feedstock/fuel pathway?* Eight LCA methodologies were considered (RFS, LCFS, CORSIA, etc.) and two specific fuel pathways were analyzed: dry mill corn ethanol and soybean oil renewable diesel. A range of results across models was observed for the two feedstock/fuel pathways, with treatment of land use change and co-product accounting being identified as significant sources of those differences.

Session 5: Negative Emissions

- The counterfactual, or business-as-usual (BAU), scenario is critically important in assessing negative emissions that can arise in manure-based renewable natural gas (RNG) production when the avoided emissions in the BAU scenario (primarily methane) are greater than emissions associated with production of the RNG, typically in a digester.
- There is concern that treatment of biomethane in CARB's LCFS regulations could have unintended consequences. In the 4th quarter of 2024, RNG from manure digesters accounted for 21% of the credits under California's LCFS, but it contributed just over 1% of the state's transportation energy. The very low CI of manure-based RNG (e.g., -270 gCO2e/MJ) is creating a new profit center in the feedstock industries where up to 40% of revenue in dairy farms can come from biogas. It was suggested that to overcome these issues, methane crediting should be capped and phased out in favor of regulating emissions directly.
- Carbon dioxide removal (CDR) consists of activities that remove CO2 from the atmosphere and store it in products or geological, terrestrial, and oceanic reservoirs. It was argued that CDR is

needed to achieve mid-century net-zero CO2 objectives. However, building CDR into life cycle analysis suffers from a lack of policy frameworks and appropriate biogenic carbon accounting.

Session 6: Natural Gas and Hydrogen

- Upstream emissions associated with natural gas production, particularly methane leakage, continue to be an important element of transportation fuel LCA.
- A recent study using a "bottom-up" (BU) methodology found large differences in processing across regions, which shows up as clear differences in carbon intensity across regions. In general, methane losses were estimated to be lower than in other studies that were mainly based on a top-down approach.
- It was argued that decision-relevant LCAs must incorporate measurement data (i.e., top-down data) even at the expense of reduced resolution, and measurement-informed LCAs are especially critical for supply chains with significant contribution from methane or fugitive CO2.
- The carbon intensity of hydrogen produced via methane pyrolysis (i.e., of $CH_4 \rightarrow 2H_2 + C$, where the carbon ends in the form of carbon black or coke) is significantly impacted by the method selected for treatment of carbon black co-product, with system expansion resulting in a negative carbon intensity.
- A transparent method of accounting for GHG emissions across the value chain is needed for product-level carbon intensity standards. LCA practitioners can help integrate chemical engineering principles (e.g., mass and energy balances) with accounting principles to develop standardized guidelines for carbon accounting.

Session 7: Electrification

- A number of uncertainties exist with respect to grid decarbonization, including: (1) renewables (wind and solar) are being deployed at increasing rates, but unknowns exist about the future extent, regional balancing mix, and reliability; (2) policy designs shape energy outcomes, but there is uncertainty about future form, timing, and affordability impacts; and (3) there is higher-than-expected load demand growth than observed in recent decades, but the extent of load growth, spatial and sectoral differences, and load profiles are uncertain.
- With respect to grid emission modeling for electric vehicles (EVs), it was argued that attributional LCA is ill-suited to model the massively connected power system, and that consequential LCA is needed to estimate the effect of a decision, action, or policy, particularly those related to EV charging.
- CRC Project No. SM-E-20 found that plug-in electric vehicle (PEV) GHG reductions are robust across a range of assumptions and increase over time with increasing grid decarbonization. However, if battery availability is limited, decarbonization would be limited. Securing battery supplies will be important to achieve the deepest GHG reductions from PEVs.
- Critical minerals are the backbone of decarbonization, and standardization of critical mineral mining LCA is needed. A review of current studies showed that large

inconsistencies exist in functional unit, system boundary, co-product allocation, indicator choice, and uncertainty analysis.

Closing Remarks

Robb De Kleine closed out the workshop with the following comments and observations:

- He reiterated thanks to the organizing committee, sponsors, Argonne, and CRC staff that led to a great exchange of ideas and information during the workshop.
- He noted that there remain policy uncertainties and uncertainties around BEV deployment and the electric grid, stressing that this workshop helps to inform policy.
- He cautioned against unintended consequences, particularly around how to properly draw boundaries, citing one of the panel members in saying, “Let’s stay humble.”

C. Highlights and Learnings from Individual Presentations

Session 1: Policy Updates

Chairpersons: Hanna Alve (Neste), Brent Heard (National Academies), Devin O'Grady (Canadian Fuels Association), Michael Wang (Argonne)

Session 1 consisted of seven presentations that provided summaries of policies and recent policy changes related to the use of LCA in assessing the carbon intensity (CI) of transportation fuels in several regions around the world. Brent Heard of the National Academies presented background and an update on the U.S. Renewable Fuel Standard (RFS), with an emphasis on the “Set 2 Rule” and supporting LCA work that has been proposed by EPA. Colin Murphy of U.C. Davis gave an update on California's Low Carbon Fuel Standard (LCFS), summarizing the main features of the rulemaking approved by the California Air Resources Board (CARB) in November 2024 that became effective on July 1, 2025. David Cobb of the Clean Fuels Alliance America discussed provisions of the “Section 45Z” clean fuel production credit set forth in the 2022 Inflation Reduction Act (IRA) and modified by the 2025 One Big Beautiful Bill Act (OBBBA). Francois Charron-Doucet from Environment and Climate Change Canada (ECCC) presented information on Canada’s Clean Fuel Regulation (CFR) and the Government of Canada’s Fuel Life Cycle Assessment Model used in the CFR. Norbert Schmitz of the International Sustainability and Carbon Certification (ISCC) discussed the implementation of the EU’s Renewable Energy Directive III and the role of certification in that program. Jon Obnamia of the Transport Canada Civil Aviation presented background information on the International Civil Aviation Organization (ICAO), the associated Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), and how CORSIA eligible fuels can be used to offset emissions from the aviation sector. Finally, Selma Brynolf of Chalmers University (Sweden) discussed the International Maritime Organization’s (IMO) efforts to reduce GHG emissions from international shipping.

Brent Heard (National Academies) presented background information on the U.S. Renewable Fuel Standard (RFS), including how life cycle analysis was used within the framework of the RFS, the threshold reductions needed to qualify for the different RIN or "D" codes, and the original renewable volume obligations as laid out in the 2007 Energy Independence and Security Act (EISA). He then discussed the shortfalls in meeting the volume requirements as set out in EISA, noting that the high cost of cellulosic biofuels relative to petroleum fuels was a key barrier to achieving the RFS volumes (i.e., the mandated 16 billion gallons of cellulosic biofuel in 2022).

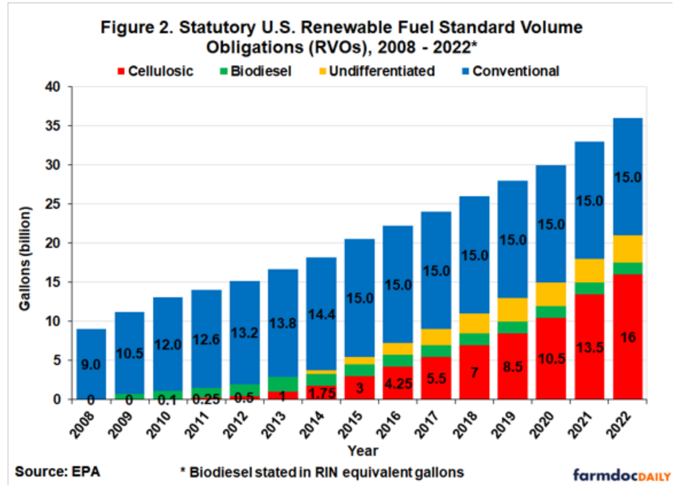


Figure 2. Statutory U.S. Renewable Fuel Standard Volume Obligations (RVOs), 2008 - 2022*

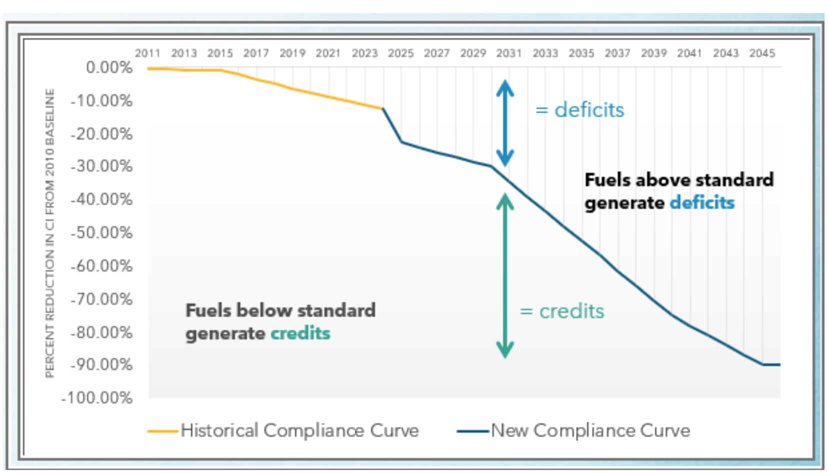
He went on to discuss EPA's proposed RFS "Set 2" rule, noting that biomass-based diesel would experience the largest growth in 2026-2027, and that the majority of cellulosic biofuel for transportation would continue to be renewable natural gas, with smaller volumes of ethanol produced from corn kernel fiber. Dr. Heard explained that the RFS seeks to balance multiple objectives, including U.S. energy security, incentivizing next-generation, low-GHG fuels, and supporting rural and agricultural communities by creating and expanding demand for their products. Finally, he noted that the RFS may be at an inflection point with the proposed Set 2 rule, continued expansion of state-level policies, and continuing interest in a national low-carbon fuel standard.

Proposed Volume Requirements 2023 – 2027 (billion RINs)

Billion RINs	Volume Requirement Established in Set 1 Rule			Proposed Volume Requirements	
	2023	2024	2025	2026	2027
Cellulosic biofuel	0.84	1.09	1.38	1.30	1.36
Biomass-based diesel (RINs)	4.51	4.86	5.36	7.12	7.50
Biomass-based diesel (gallons) – projected	2.82	3.04	3.35	5.61	5.86
Advanced biofuel	5.94	6.54	7.33	9.02	9.46
Total renewable fuel	20.94	21.54	22.33	24.02	24.46
Conventional (implied mandate)	15.00	15.00	15.00	15.00	15.00

https://www.epa.gov/system/files/documents/2025-06/420f25006.pdf

Colin Murphy (U.C. Davis) gave an update on California's LCFS with an emphasis on the revisions adopted by the Board at the end of 2024, which became effective on July 1, 2025. He noted that the program will likely continue to evolve via regular updates. The goal of the revised regulations is to reduce the carbon intensity (CI) of the transportation fuel pool by at least 30% by 2030 and 90% by



2045 from a 2010 baseline. In addition to the CI reductions, the more stringent CI standards were intended to stabilize credit prices in the short-term. The rulemaking also added an Automatic Acceleration Mechanism (AAM) that will increase the program's carbon intensity target if the total amount of banked credits in 2027 or later exceeds three quarters of deficit generation. This is intended to prevent future credit price declines of the type that occurred in 2020-2022, and it can be implemented without a formal rulemaking. The AAM may be triggered as early as 2027 (based on 2026 data), but the modeling used to support this was performed prior to recent changes in federal fuel policy and so needs updating.

David Cobb of the Clean Fuels Alliance America gave an update of the "Section 45Z" clean fuel production credit set forth in the 2022 Inflation Reduction Act (IRA) and modified by the 2025 One Big Beautiful Bill Act (OBBBA). Important revisions coming out of the OBBBA included: 45Z preservation and extension to 2029; elimination of special credit rate for SAF; elimination of indirect land change (ILUC) from the CI calculations beginning in 2026; and eligibility limited to only fuels made from feedstocks grown or produced in the U.S., Canada, or Mexico. The elimination of ILUC results in significantly increased credit values for soybean oil based fuels and allows canola oil based fuels to qualify for credits in 2026-2029. Mr. Cobb indicated that the industry is still awaiting future guidance related to procedures to request a Provisional Emission Rate (PER) and additional CI reductions for Climate Smart Agriculture practices.

Representative §45Z Values ($/gal) – 2025

Fuel\Feedstock	U.S. Soybean	U.S./ Canada Canola	Tallow	U.S. DCO	U.S. UCO
Biodiesel	$0.32 or $0.42	DQ	$0.64 or $0.74	$0.85	$0.64 or $0.74
Renewable Diesel	$0.21	DQ	$0.64 or $0.74	$0.74 or $0.85	$0.64 or $0.74
Sustainable Aviation Fuel	$0.37	DQ	$1.12 or $1.30	$1.30 or $1.49	$1.12 or $1.30

Representative §45Z Values ($/gal) – 2026-2029

Fuel\Feedstock	Soybean	Canola	Tallow	DCO	UCO
Biodiesel	$0.64	$0.32	$0.64 or $0.74	$0.85	$0.64 or $0.74
Renewable Diesel/SAF	$0.53	$0.21	$0.64 or $0.74	$0.74 or $0.85	$0.64 or $0.74

Francois Charron-Doucet (ECCC) presented information on Canada's Clean Fuel Regulations (CFR) and the Fuel LCA Model used in the CFR. The CFR, which operates much like the California LCFS, is a key part of Canada's climate plan. It is a market-based program, requiring continued reductions in CI from 3.5 gCO2e/MJ (4% below 2016 levels) in 2023 to 14.0 gCO2e/MJ (15% below 2016 levels) in 2030. The CI values and targets in the CFR are based on higher heating value (HHV) and are therefore not directly comparable to the LCFS. Reductions beyond 2030 will be subject to review and potential future amendments.

	2022	2023	2024	2025	2026	2027	2028	2029	2030
Reduction requirement (g/MJ)	0	3.5	5.0	6.5	8.0	9.5	11.0	12.5	14.0
% below 2016 levels	0%	4%	5%	7%	8%	10%	12%	13%	15%
Expected reduction requirements* (Mt)	0	4.7	13.7	17.5	21.2	24.7	28.0	31.2	34.3

The Fuel LCA model uses OpenLCA as its computation platform, along with a database of fuel pathways and inputs that are specific to Canada. The Fuel LCA model supports the CFR as well as the Clean Hydrogen Investment Tax Credit and the Clean Fuels Fund. The Clean Hydrogen Investment Tax Credit is similar to the 45V credits in the U.S., where credit values increase as the hydrogen GHG footprint is reduced. The Clean Fuels Fund seeks to de-risk the capital investment required to build new or expand existing clean fuel production facilities. The Fuel LCA Model is used to determine eligibility for funding against specific threshold values for liquid biofuels, sustainable aviation fuel, hydrogen, and gaseous fuels.

Norbert Schmitz (ISCC) discussed the implementation of the EU's Renewable Energy Directive III and the role of certification in that program. He noted that ISCC had over 15 years of experience in certifying global value chains and that over 14,600 valid certificates had been issued. ISCC certification extends beyond energy and transportation fuels to industrial applications, food markets, feed markets, and others. Dr. Schmitz stepped through the timeline of when RED II became effective (December 2018) to when member states were to have transposed RED III into national law (May 2025). An overview of the targets for RED III are tabulated below. (Note that RFNBO refers to renewable fuels of non-biological origin, such as hydrogen and efuels produced via electrolysis using renewable electricity.) Some of the challenges associated with RED implementation and fuel certification include auditing of waste and residue feedstocks, identifying virgin palm oil being sold as used cooking oil, and using satellite images to support claimed processing plant volumes.

Overall RED saving target		**RED II**	**RED III (Directive (EU) 2023/2413)**
		At least 32%	**At least 42.5% (joint effort to reach 45%)**
	Transport target	At least 14%	**At least 14.5% GHG savings or 29% renewable energy** for all transport modes, including aviation and shipping
Renewable Energy for transport	Crop based feedstocks	7% cap (2020 consumption level, MS may reduce 7% to zero	No changes
	Targets for Annex IX, Part A (advanced fuels)	0.2 % (2022), 1 % (2025), 3.5 % (2030)	**At least 1% in 2025 and 5.5% in 2030** (shared with RFNBOs), with potential for increase if more feedstock is available
	Target for Annex IX, Part B	Limit of 1.7% (modifiable by MS with Commission approval)	No change
	RFNBOs	No target included	**At least 1% in 2030** (renewable hydrogen for petrol and diesel counts towards the transport target)
	Sustainability criteria	Land and land-use related requirements for agricultural and forest biomass	**Follow the cascading system to be respected,** prioritizing biomass for material use over energy use

Jon Obnamia of Transport Canada's Civil Aviation group presented background information on the International Civil Aviation Organization (ICAO), the associated Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), and how CORSIA eligible fuels can be used to offset emissions from the aviation sector. Dr. Obnamia stressed that CORSIA is not a carbon tax, but rather a global carbon offsetting scheme. The baseline is defined as 2019, and emissions increases from 2024 to 2035 need to be offset. The offsetting scheme applies to airlines for international operations only. There are two means for an airline to comply: (1) offsetting with emissions units, and (2) claiming emission reductions from CORSIA eligible fuels (CEF). Two types of CEFs are defined: (1) CORSIA sustainable aviation fuel produced from renewable or waste-derived feedstocks, and (2) CORSIA lower carbon aviation fuel, which is a fossil-based fuel. CEFs require a minimum 10% reduction from the 89 gCO2e/MJ fossil baseline. In addition to meeting GHG limits, CEFs must also comply with other CORSIA sustainability criteria. A total of 14 sustainability criteria are defined in the program. It is anticipated that in the 2025-2026 timeframe there will be a need for airlines to begin to offset emissions, and therefore significant activity in this space is expected moving forward.

Selma Brynolf of Chalmers University (Sweden) discussed the International Maritime Organization's (IMO) efforts to reduce GHG emissions from international shipping. Dr. Brynolf reviewed the timeline of IMO regulatory action to reduce GHG emissions from shipping, which included: (1) IMO's strategy for reducing GHG emissions from ships in 2023; (2) creation in 2024 of the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) that provides advice to the UN; (3) a goal of 20% GHG reduction by 2030 (striving for 30%); and (4) net zero GHG emissions by about 2050.

GESAMP has convened a work group to study LCA of marine fuels, which includes refinement of methodologies for well to tank (WTT) and well to wake (WTW) carbon intensity estimates. In addition, the GESAMP work group is considering sustainability themes, including indirect land use change. Under the IMO guidelines, ILUC would be treated with a risk-based approach (similar to RED III) because of uncertainties rather than an actual value as in the CORSIA methodology.

Panel Discussion and Q&A – the following ideas and themes emerged during the panel discussion and Q&A session following the presentations:

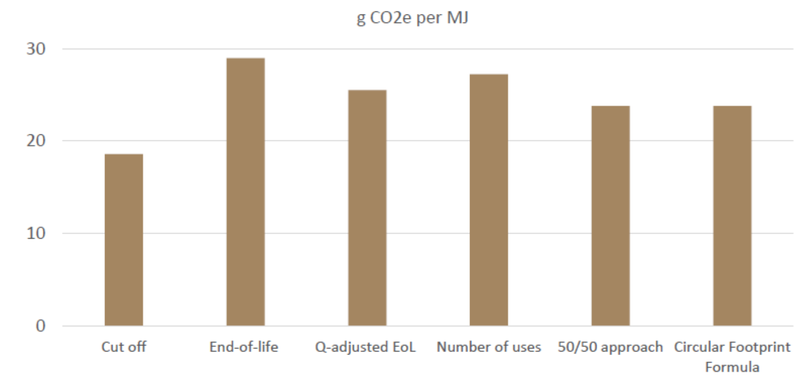
- Responding to a question regarding conversion of refineries to bio-feedstocks rather than closing, Colin Murphy noted that two refineries in California had converted to produce renewable diesel, so that is an option. However, feedstock availability could be an issue if volumes increase. It was also noted that while co-processing is an option under some regulatory schemes, it is not universally available (e.g., co-processed fuels are not available for 45Z credits).
- Colin Murphy also noted that two additional petroleum refineries had announced plans to close in the past year, leading to concerns about gasoline supply and price. He stated that the LCFS is not a leading driver in these closures.
- Accounting for ILUC continues to be a policy decision because of uncertainties around modeling assumptions. A single value can be problematic because of the limitations and uncertainties inherent in ILUC modeling. As an alternative, risk-based approaches that limit the use of crop-based biofuels (e.g., EU RED and IMO) are preferred by some.
- Responding to a question about climate smart agriculture, the panel noted that 45Z does more to recognize climate smart agriculture than other policies, but additional guidance is needed. The panel also noted that while there may be interest, it is a difficult topic because agriculture practices could potentially be regulated in the future. Under the RED, there is no explicit accounting for climate smart agriculture, but it would be captured more globally via default modeling inputs, e.g., reduced fertilizer usage.
- Finally, in response to a question regarding guidelines for defining wastes used as feedstocks, the panel noted that some regulatory schemes had better definitions than others. For example, under CORSIA it needs to be proven that a "waste" is not intentionally being produced and that there is no economic value associated with the waste. However, this may create a conflict if demand then creates a value to the waste. It was also noted that ISCC has a decision tree, but sometimes regulators have different opinions on how to define a waste.

Session 2: Methodology

Chairpersons: Aaron Levy (US EPA), Matt Herman (Iowa Soybean Association), Susan Sanchez (UL Solutions)

Session 2 consisted of four presentations on methodological issues related to life cycle modeling. Tomas Ekvall (TERRA) discussed allocation methods for recycled feedstocks in biofuel production. Connie Hensler (Interface, Inc. and American Center for Life Cycle Assessment) presented information on standardizing the chain of custody and mass balance methods in life cycle assessments. Tristan Brown (SUNY College of ESF) discussed how to overcome barriers to carbon accounting in bio-based products. Finally, Sampo Soimakallio (Finnish Environment Institute) presented information on reference land use in life cycle assessment.

Tomas Ekvall of TERRA discussed allocation methods for recycled feedstocks in biofuel production, using used cooking oil (UCO) as an example. Six different allocation methods were analyzed, and the resulting carbon intensity of biodiesel from UCO ranged from 18 gCO2e/MJ to 28 gCO2e/MJ. The minimum value was based on the "cut-off" approach in which the initial manufacturing and potential alternative fate of cooking oil is ignored, which is the standard approach in many regulatory schemes (e.g., California LCFS). In this approach, UCO is truly considered a waste, and only emissions associated with collection and pre-treatment are considered prior to processing. The maximum value was based on an "end-of-life" approach in which the initial production of cooking oil is assigned to the biodiesel fuel. The rationale for this approach is that there is a need to produce the primary material that is lost to transportation fuel. This approach is stipulated in some guidance documents (e.g., ISO 20915, WorldSteel Association). Several attendees discussed the fact that most regulatory treatments of UCO-based fuels assume the feedstock would otherwise have had no productive use, which contrasts to the common use of UCO for animal feed or other purposes prior to the adoption of policies to incentivize its use as a fuel.



Connie Hensler of Interface, Inc. and the American Center for Life Cycle Assessment (ACLCA) presented information on standardizing the mass balance and chain of custody methods in life cycle assessments. This presentation was focused at product life cycle analysis rather than fuel LCAs, nonetheless, many of the same issues apply. In particular, it was argued that specific standards for mass balance chain of custody are needed so that duplicate infrastructure is not needed to keep sustainable materials physically segregated, e.g., the need to segregate soybeans by field. She noted that mass balance is currently a hot topic because it is needed for circular economy technologies such as chemical recycling of plastics and in some bio-feedstock technologies. She also noted that guidance is under development by the ACLCA for both rolling average and credit-based mass balance methods.

Tristan Brown of SUNY College of Environmental Science & Forestry presented information on methodological barriers to carbon accounting for bio-based products. Dr. Brown identified three key barriers to carbon accounting: (1) carbon accounting systems lack attributional LCA harmonization; (2) carbon accounting systems lack consequential LCA harmonization; and (3) government GHG accounting incentives focus on fuels rather than products. Expanding on Barrier #3, "carbon negative" biofuels such as RNG create confusion when considered alongside biogenic carbon products that are not combusted.

Dr. Brown offered several suggestions for overcoming the carbon accounting barriers above:

- Remove end-of-life (EOL) uncertainty through contractual solutions (e.g., RECs for biogenic products) which incentivizes continued storage in biogenic products by purchaser and production by producer.
- Separating biogenic products with EOL removals and sequestration from natural and technological removals and sequestration – companies have more control over carbon fate in

biogenic products than in other forms of removal/sequestration (e.g., wildfires and forest carbon; droughts/floods and soil carbon).

- Development of government policies that include biogenic products alongside existing GHG accounting systems and policies for biofuels – the EU is starting to move in this direction under RED II, but the U.S. largely treats biofuels and bioproducts separately at the federal and state levels.

Sampo Soimakallio of the Finnish Environment Institute presented information on reference land use in life cycle assessment. Reference land use is required to assess GHG impacts of land use or decisions related to land use. ISO 14067 presents five options for reference land use: (1) business as usual (continuation of current practice based on historical data); (2) projected future; (3) target (e.g., based on policy targets for land use); (4) potential natural regeneration (e.g., in the absence of human activity); and (5) historic baseline (land use patterns at a specific point in time). Assessing the impacts of any activity requires a reference scenario without the studied activity. The choice of reference land use is critical and can lead to completely different conclusions regarding the GHG performance of bioenergy. The most coherent choice of reference land use depends on whether an attributional or consequential LCA is being conducted:

- Attributional LCA – potential natural regeneration is a coherent choice for reference land use.
- Consequential LCA – business as usual or projected future are coherent choices for reference land use.

Dr. Soimakallio closed by noting that uncertainties cannot be avoided, but it is better to be approximately right than completely wrong.

Panel Discussion and Q&A – the following ideas and themes emerged during the panel discussion and Q&A session following the presentations:

- A question was asked about how to assess ILUC given the uncertainties involved. The panel responded that data and models are needed because ILUC cannot be directly observed. Empirical data may improve models, but models are needed. ILUC is difficult to assess because the world is changing with or without biofuels.
- A question was asked about ILUC uncertainties and what research would be useful to reduce those uncertainties. The panel noted that more data are useful, noting that the field has come a long way since the original Searchinger paper. As an example, Brazil saw an 80% decrease in deforestation based on satellite imagery. It's difficult to get a precise answer because we do not have the actual counterfactual. Although we may eventually agree on methods and models, the uncertainty will still be there.
- In response to a question about the choice of allocation methods, Tomas Ekvall offered the following: (1) it needs to be feasible and simple; (2) there needs to be acceptability to a lay audience; (3) the results need to point in the right direction to improve the environment; and (4) it needs to be robust to avoid the risk that LCAs are misused.
- In response to a question related to Dr. Soimakallio's presentation, he responded that dynamic modeling should be used in LCA, especially short-term analyses. He suggested that both ALCA and CLCA approaches are valuable, but issues arise if they give directionally different answers.
- A question was asked about whether there was a consensus on methodologies, e.g., via the use of ISO standards. While ISO standards provide guidance, a big challenge is politicization.

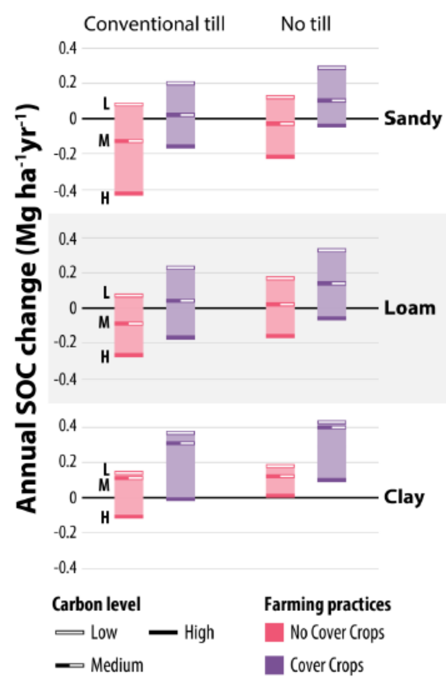
Researchers are using similar methods, but assumptions make a big difference. A member of the panel expressed concern that ILUC was being used to make EVs look better relative to biofuels.

Session 3: Biofuels

Chairpersons: Scott Richman (Renewable Fuels Association), Veronica Bradley (Clean Fuels Alliance America), Sara Herman (Cargill), Corinne Scown (UC Berkeley)

Session 3 included three presentations discussing issues related to biofuel production and associated agricultural modeling. Bruno Basso (Michigan State University) presented results of modeling soil organic carbon (SOC) accumulation on agricultural land in the U.S. Luke Monhollon (First Environment) described an agricultural model intercomparison project. Finally, Jeffrey O'Hara (USDA) discussed opportunities for low carbon feedstocks in clean transportation fuel programs via a pre-recorded video (presentation materials not available).

Bruno Basso of Michigan State University presented results of modeling the potential for soil organic carbon accumulation on agricultural lands using the SALUS model (System Approach to Land Use Sustainability), which is a process-based crop model that simulates interactions between soil, climate, genetics, and management at a daily time-step for multiple crops, including perennials. The SOC impacts of planting cover crops (e.g., prairie grass, switchgrass, rye) on various land types were presented (e.g., marginal land, abandoned crop land, CRP land, etc.). Using a multi-model ensemble (MME) analysis, which included SALUS, the impacts of different agricultural practices were assessed. Conventional till versus no till, soil type, and whether winter cover crops were planted all impacted the modeled change in SOC. No till with cover crops resulted in a net increase in SOC across all soil types. Dr. Basso closed by noting that increased adoption of climate-smart practices is essential for achieving significant co-benefits in agriculture, and that models are needed because we cannot measure SOC at scale.

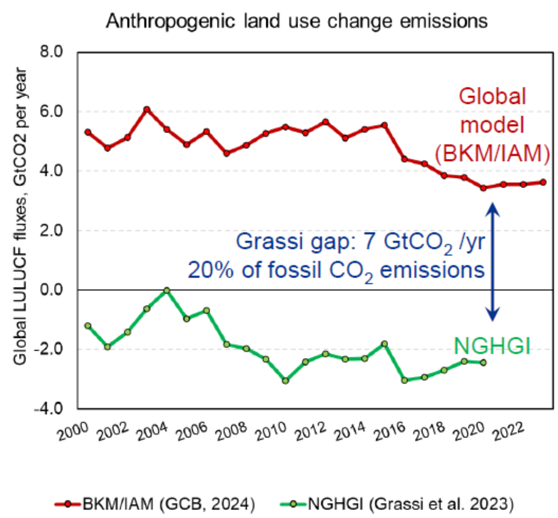


Luke Monhollon of First Environment described an agricultural model intercomparison project (AgMIP). He started out by summarizing the USDA definition of sustainable agriculture, which over the long term will result in human food and fiber needs being met, enhance environmental quality, make efficient use of nonrenewable resources, and sustain the economic viability of farm operations. He then presented information on the AgMIP, which compiled information on multiple growing systems and extensive data from 139 studies over 16 years. He showed visual projections indicating that climate change is expected to negatively impact corn yields, which would increase feedstock prices and therefore fuel-based ethanol prices.

Session 4: Land Use Change

Chairpersons: Veronica Bradley Clean Fuels Alliance America), Colin Murphy (UC Davis), Michael Wang (Argonne National Lab), Jeremy Martin (Union of Concerned Scientists), Sarah Ohrel (US EPA)

Session 4 included four presentations focused on issues related to land use change associated with biofuel production. Xin Zhao (Pacific Northwest National Lab) discussed the "Grassi Gap" in land use change and recent advances in modeling. Gray Martin (RTI International) presented information on cropland transitions in the U.S., while Kaiyu Guan (University of Illinois) discussed cradle-to-farmgate MRV (measurement, reporting, and verification) for biofuel crop emissions with an emphasis on soil organic carbon and N2O emissions. Finally, Keith Kline (Oak Ridge National Lab) presented a science-based analysis of land use change and a risk-based approach to ILUC.



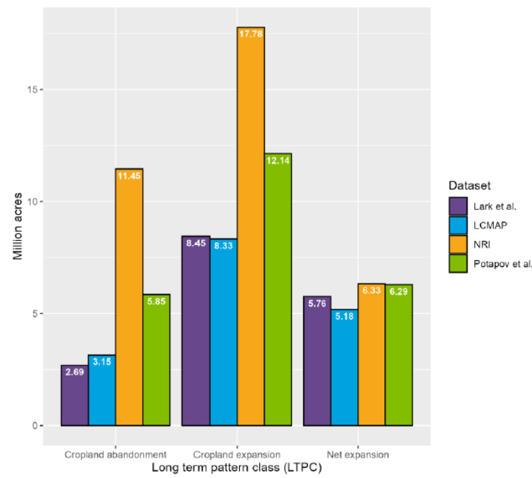
Xin Zhao of Pacific Northwest National Lab discussed the "Grassi Gap" in land use change and recent advances in modeling. The Grassi Gap, first identified by Giacomo Grassi et al. (2018; Nature Climate Change), refers to major discrepancies in anthropogenic land use change emissions between official national inventories and global model estimates. The national greenhouse gas inventories (NGHGI) show decreases in LUC fluxes, while the global models – bookkeeping models (BKM) and integrated assessment models (IAM) – show increases in LUC fluxes, with the difference amounting to about 20% of global fossil CO2 emissions. Dr. Zhao noted that one of the key differences in methodologies is that the NGHGI estimates include indirect anthropogenic effects (i.e., human-induced environmental impacts) on managed land, and one way to bridge the Grassi Gap is to reattribute indirect effects, i.e., attribute 60% of land sink to LUC, globally. Dr. Zhao closed by highlighting several implications related to biofuels ILUC, including:

- There is uncertainty in vegetative and soil carbon densities because of different emission accounting approaches,
- Static versus dynamic modeling makes a difference, and
- Comparison of empirical/historical data versus projections – are LCA/ILUC emissions observable?

Understanding and reconciling these differences is crucial for improving LUC emission estimates and tracking progress toward long-term climate goals.

Gray Martin of RTI International presented information on cropland transitions in the U.S., noting that there are multiple U.S. datasets that track agricultural land change, but they vary widely in source data, resolution, frequency, and class definitions. This study focused on the analysis of four datasets, using the Land Change Monitoring, Assessment, and Projection (LCMAP) dataset as the primary comparison point because of its consistent, long long-term national coverage. Net cropland expansion between 2008 and 2016 was similar across datasets, but the spatial distribution of the changes differed. LCMAP cropland expansion may better capture conversion of natural areas, while other sources capture transitions from managed pasture to cropland, which is not captured by LCMAP.

Cropland Change (2010-2016)



Kaiyu Guan of the University of Illinois discussed cradle-to-farmgate MRV (measurement, reporting, and verification) for biofuel crop emissions with an emphasis on soil organic carbon and N2O emissions. Dr. Guan presented two primary themes: (1) cutting back on nitrogen fertilizer represents an opportunity for GHG reductions, and (2) system thinking should be applied to SOC because it is a cycle, where SOC is a "bank" and the net change is simply in - out. The largest uncertainties in cradle-to-farmgate carbon intensity are unknown plant trait parameters (e.g., photosynthesis, which impacts yield) and fertilizer information. Advanced modeling techniques that integrate models with data ("Model-Data Fusion") can potentially reduce the uncertainties. In closing, Dr. Guan noted that SOC sequestration remains an important opportunity to lower CI, and further opportunities will become available through knowledge-guided AI.

Keith Kline of Oak Ridge National Lab presented a science-based analysis of land use change and a risk-based approach to ILUC. Dr. Kline opened his presentation with a summary of recommendations that came from a technical workshop on carbon accounting of biofuels associated with the G20 summit held in Brazil in 2024. Among those recommendations were:

- Apply life cycle assessment with input data and methods that are transparent, evidence-based, and verifiable.
- Continue collaborations to improve the transparency and consistency of LCA methods, including allocation, carbon removals, and carbon credits.
- Avoid quantitative indirect land-use change (ILUC) values as they cannot be directly measured or scientifically verified; quantitative ILUC factors have not provided consistent results and have not been shown to support effective actions to reduce LUC emissions.
- Consider alternative approaches to address ILUC concerns, such as risk-based approaches or direct measurements of effects.

Dr. Kline went on to highlight programs implementing risk-based approaches for ILUC, including the European Commission where food crops and feedstocks from areas with high deforestation rates are considered high-risk and are limited, a Brazilian proposal that would establish a tiered risk approach (e.g., low-ILUC risk would include production from integrated systems of multi-cropping, production generated by higher yields, production from improving conditions on abandoned or degraded land), and the Roundtable for Sustainable Biomaterials that recognizes credible low-ILUC certification schemes and restricts high-ILUC risk feedstocks. As a solution to the ILUC problem, Dr. Kline suggested we get back to basics – science and causal analysis. Incentives are needed for better land management, and more data are needed from the areas of concern. Finally, there are irreducible uncertainties associated with ILUC, and shifting to a risk-based approach for dealing with ILUC is needed.

Panel Discussion and Q&A – the following ideas and themes emerged during the panel discussion and Q&A session following the presentations:

- In response to a question about how to connect what is changing to why it is changing (causal analysis), the panel responded with the following remarks:
  - Causal analysis started with health and epidemiology (e.g., health effects of smoking). Need to study both populations – look at areas with deforestation and those without deforestation and determine cause of each and linkages. Analyze data on crop exports to see if that is driving deforestation. Need a causal chain and time sequence (cause and effect).
  - Econometric models are about identification but also need experiments (ground data) to compare modeling results with historical changes.
- In response to a question of how trade policies are accounted for in these models, the panel noted that there are limitations to the current models and many issues are not accounted for, including government subsidies. Models are a simplification of a complex process. It is difficult to tease out causality in model results. An audience member added that economic models have been used to inform policy for many years, and not just for ILUC. The main contribution of economic models is to understand the potential impacts of a policy.
- A question was asked about whether a second crop of soybeans in Brazil is a risk. The panel noted that a primary question is where the second crop is located – can be beneficial but could also be detrimental. Site-specific factors on where deforestation is happening is very important. We should not be putting faith in a model where we cannot observe an outcome (e.g., where changes are happening).
- In response to a question of whether U.S. data can be expanded globally, one panelist noted that validation is important, and global datasets make that easier. Another panelist responded that it depends – some models at a global level are useful, but crop conditions and management practices are important. It is hoped that in five years a global tillage map will be available.
- A question was asked as to whether it was possible to implement a "true-up" for the LCFS if it is found that ILUC values in the regulation are overstated. The response was that it would be difficult to do within the structure of the LCFS. A primary challenge is that the targets are based on the credit market, and a true-up could negatively impact the targets and could temper investment.

CRC Project SM-LCA-17

Between Sessions 4 and 5, Phil Heirigs (independent consultant teaming with Trinity Consultants and Life Cycle Associates) summarized the results of CRC Project SM-LCA-17: "Literature Review of Models Used for Biofuels GHG Emissions Modeling and Comparison of Results on Some Commonly Available Fuels." The basic premise of this work was to address the question: *Why do different models give different* *results for the same feedstock/fuel pathway?* Eight LCA methodologies were considered (RFS, LCFS, CORSIA, etc.) and two specific fuel pathways were analyzed: dry mill corn ethanol and soybean oil renewable diesel. Models were run in their default configurations and using a common set of inputs based on GREET1_2022. Carbon intensity values from the same biofuel production pathway vary substantially across the different LCA methodologies:

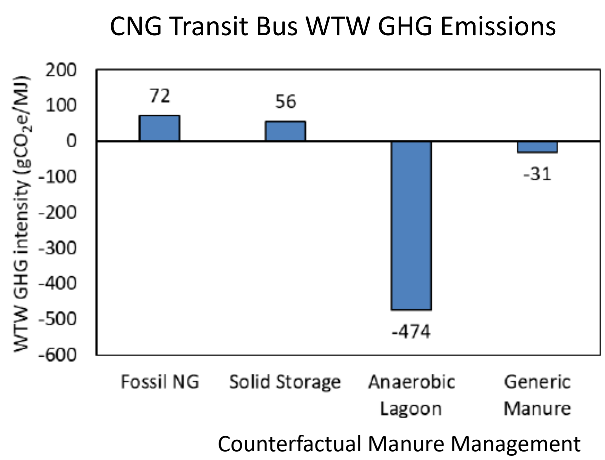
- Dry mill corn ethanol CI estimates with default LCA inputs ranged from about 53 to 75 gCO2e/MJ.
- Dry mill corn ethanol CI estimates ranged from about 38 to 69 gCO2e/MJ using GREET1_2022 inputs.
- Renewable diesel from soybean oil CI estimates with default LCA inputs ranged from about 34 to 66 gCO2e/MJ.
- Renewable diesel from soybean oil CI estimates ranged from about 18 to 57 gCO2e/MJ using GREET1_2022 inputs.

Treatment of land use change and co-product accounting were identified as significant sources of differences in the modeled results.

Session 5: Negative Emissions

Chairpersons: Jeremy Martin (Union of Concerned Scientists), Gonca Seber Olcay (ICCT), Corinne Scown (UC Berkeley), Andrea Strzelec (USCAR)

Session 5 included three presentations focused on issues related to negative emissions in LCA modeling. Branden Leonhardt (Argonne National Lab) discussed assessment of "counterfactuals" in manure management and renewable natural gas production. Kevin Fingerman (Cal Poly Humboldt) presented information on how biomethane is treated in CARB's LCFS regulations. And Michael Shell (Isometric) gave a pre-recorded presentation on applying life cycle analysis to carbon dioxide removal (CDR).

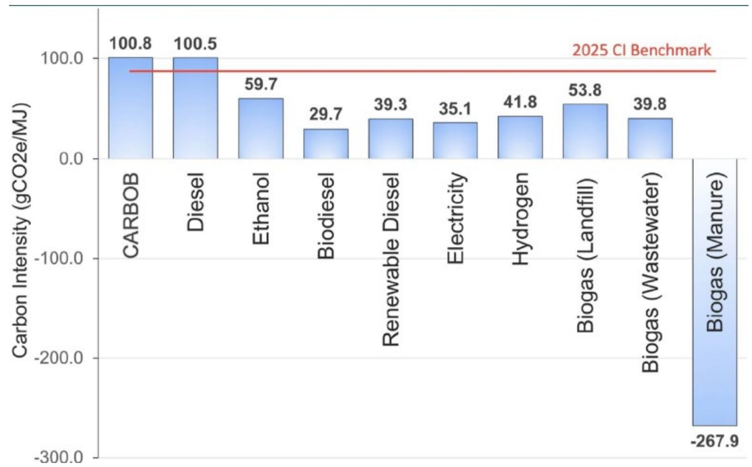


Branden Leonhardt of Argonne National Lab discussed assessment of "counterfactuals" in manure management and renewable natural gas (RNG) production. The counterfactual, or business-as-usual (BAU), scenario is critically important in assessing negative emissions,[2] and for some counterfactual scenarios, the CI score can be comparable to fossil natural gas (e.g., solid storage of manure). Dr. Leonhardt listed several important characteristics in the selection of counterfactuals in this context: technically sound, representative of all BAU practices, agnostic to different animal types and manure management methods, consistency and data transparency, could change over time as the industry develops, and could be revised to expand or contract the system boundary. Based on this work, a "generic manure"

[2] Note that negative emissions can arise in manure-based RNG production when the avoided emissions in the BAU scenario (primarily methane) are greater than emissions associated with production of the RNG, typically in a digester.

counterfactual was developed to provide a simple, defensible, and broadly applicable counterfactual scenario. As observed in the figure, the generic manure counterfactual resulted in a less aggressive negative carbon intensity score than if an anaerobic lagoon was selected as the BAU practice.

Kevin Fingerman of Cal Poly Humboldt presented information on how biomethane is treated in CARB's LCFS regulations, noting that the large crediting of carbon offsets (i.e., avoided methane from BAU manure management practices) could have unintended consequences. He noted that in the 4th quarter of 2024, RNG from manure digesters accounted for 21% of the credits under California's LCFS, but it only contributed just over 1% of the transportation energy. While the installation of digesters is a net climate win, he and his colleagues believe that the LCFS policy should be reconsidered. The current policy has the potential for the following distortions:



- *<u>In the feedstock industries</u>*, as it creates a new profit center where up to 40% of revenue can come from biogas;
- *<u>In the market for negative-carbon feedstocks</u>*, where high-mitigation feedstocks go only to transport fuel systems, whether or not this is the highest and best use of a given feedstock supply; and
- *<u>In carbon offset markets</u>*, where offsets go to the biomethane transport fuel rather than the most efficient methane abatement, and a higher carbon price is offered without evaluating or requiring additionality, potentially undermining other mitigation pathways.

To overcome these issues, methane crediting should be capped and phased out in favor of regulating emissions directly. Additionally, manure and other valorized wastes should be treated as co-products rather than "true" wastes. Finally, the avoided emissions crediting should be restructured to divide it from the LCFS.

Michael Shell of Isometric gave a pre-recorded presentation on applying life cycle analysis to carbon dioxide removal (CDR). He began the presentation by defining CDR as activities that remove CO2 from the atmosphere and store it in products or geological, terrestrial, and oceanic reservoirs. This would include direct air capture, but it excludes natural CO2 update not caused by human intervention. Biomass carbon removal and storage (BiCRS) is a subset of subset of CDR technologies, including bioenergy with carbon capture and storage (BECCS), bio-oil, biochar, and direct biomass burial. He argued that CDR is needed to achieve mid-century net-zero CO2 objectives. However, building CDR into life cycle analysis suffers from a lack of policy frameworks and appropriate biogenic carbon accounting. Additionally, for BiCRS the counterfactual fate of biomass is a key consideration. Robust life cycle analysis is needed in CDR to provide consistency and confidence in quantifying removals.

Panel Discussion and Q&A – the following ideas and themes emerged during the panel discussion and Q&A session following the presentations:

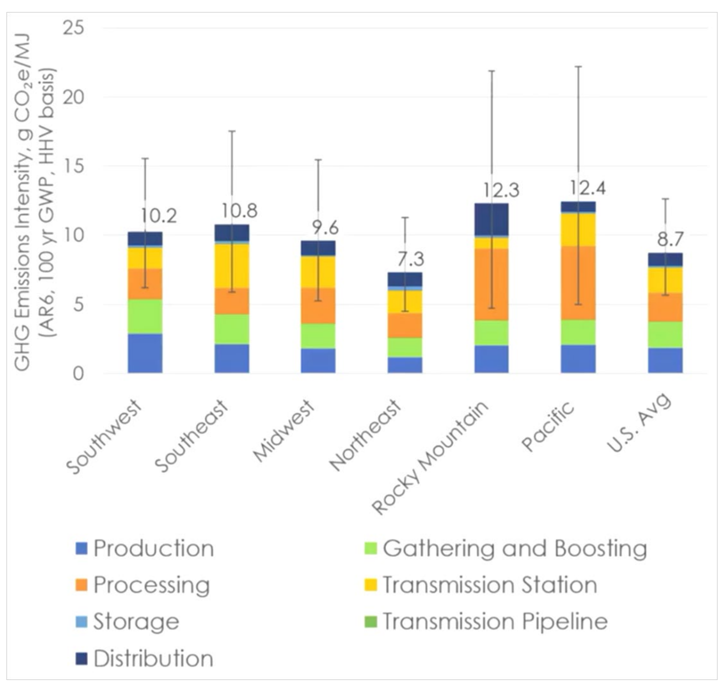
- In response to a question of whether California should mandate cattle methane reductions, one panelist noted that if controls were required, there would be no need to worry about additionality. Another panelist suggested that direct regulation is a policy question with different opinions among stakeholders.
- An audience member offered the following with respect to dairy digesters and biogas: (1) a generic economic model does not apply to California dairies; (2) the capital cost of a digester is equal to or greater than the cost of cattle at a dairy, representing a significant economic risk for the operator; and (3) income from biogas helps mitigate fluctuating milk prices over which dairies have no control.
- In response to a question about how long it took for the build-out of diary digesters in California, Dr. Fingerman noted that it was very rapid, and he wouldn't suggest immediate elimination of credits – there needs to be a phase-out period. Avoided emissions crediting should be developed with a sunset built in.

Session 6: Natural Gas and Hydrogen

Chairpersons: Anastasia Behr (UL Solutions), Diep Vu (Marathon), Susan Sanchez (UL Solutions)

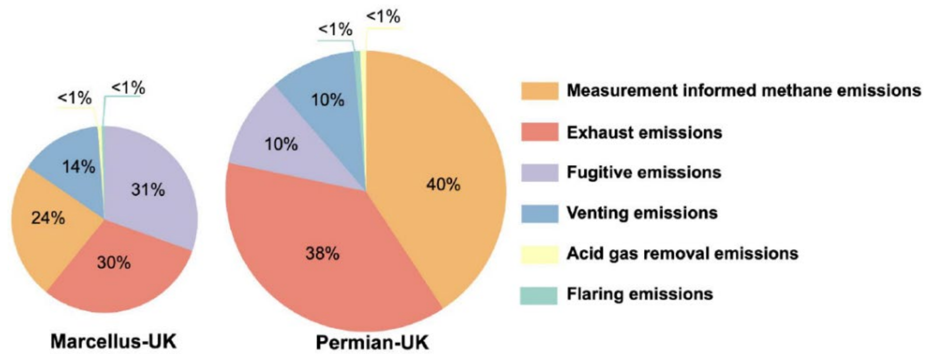
Session 6 consisted of four panelists discussing issues related to the life cycle analysis of natural gas and hydrogen. Each of the panelists opened with brief presentations. Matt Jamieson (National Energy Technology Laboratory) gave a pre-recorded presentation on NETL's life cycle analysis of natural gas. Arvind Ravikumar (University of Texas at Austin) discussed measurement-based life cycle assessments of the LNG and hydrogen supply chains. Amgad Elgowainy (Argonne National Laboratory) presented LCA insights across natural gas and hydrogen, with a summary of R&D GREET updates. Finally, Michael Kerby (ExxonMobil) discussed carbon accounting and product-level carbon intensity standards. Joule Bergerson (Notre Dame) joined the panel discussion in Matt Jamieson's absence. Hong Jin (AmSpec Group) moderated this session.

Matt Jamieson of the National Energy Technology Laboratory gave a pre-recorded presentation on NETL's most recent life cycle analysis of natural gas. This analysis is a very detailed bottom-up assessment of upstream emissions associated with natural gas production, processing, and transmission. A variety of data sources were used, including EPA's Greenhouse Gas Reporting Program (GHGRP), EPA's Greenhouse Gas Inventory (GHGI), EIA data on gas production, and Enverus DrillingInfo and RigData databases to estimate recovery and county-level well counts. The evaluation found large differences in processing across regions, which shows

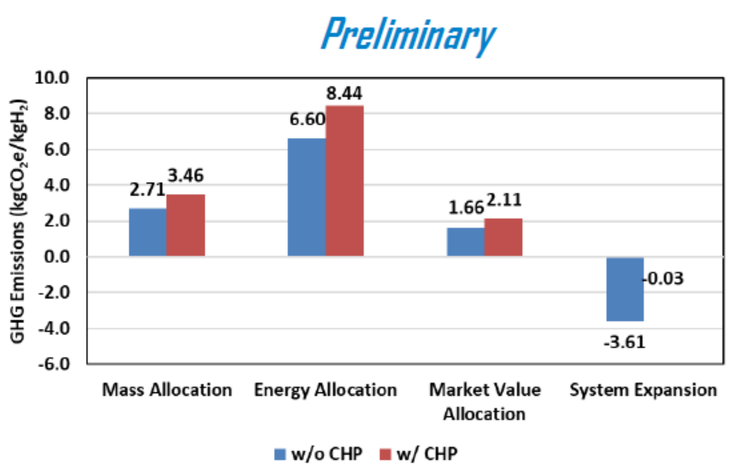


up as clear differences in carbon intensity across regions. In general, methane losses were estimated to be lower than in other studies.

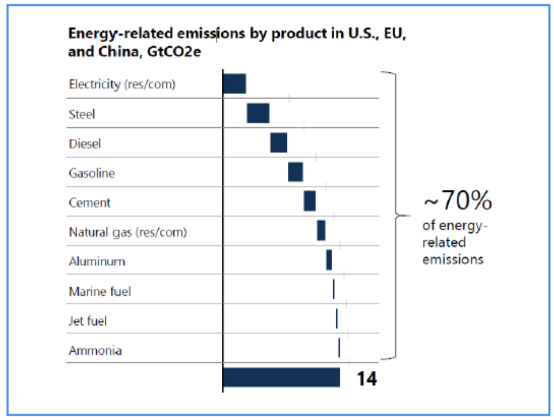
Arvind Ravikumar of the University of Texas at Austin discussed measurement-based life cycle assessments of the LNG and hydrogen supply chains. Dr. Ravikumar began by noting two key challenges with LCA approaches: (1) simultaneously too much and too little detail (too much time on minor contributors and limited incorporation of direct measurement via remote sensing); and (2) limited characterization of uncertainty. He argued that official inventories underestimate methane emissions by 50% to 60%. When including measurement-based data, methane emissions contribute 24% to 40% of total GHG intensity that is not included in inventory-based LCAs. Similar discrepancies are found in “blue hydrogen” supply chains from the Marcellus and Permian basins. He closed by arguing that decision-relevant LCAs must incorporate measurement data even at the expense of reduced resolution and that measurement-informed LCAs are especially critical for supply chains with significant contribution from methane or fugitive CO2.



Amgad Elgowainy of Argonne National Laboratory presented on LCA insights across natural gas and hydrogen, with a summary of R&D GREET updates. One of the more significant updates to R&D_GREET2024_rev1 (released May 2025) is the addition of the NETL data described above for natural gas production, which gives users flexibility in selecting specific regions for modeling GHG emissions from natural gas. In addition, a methane pyrolysis pathway was added for hydrogen production in which hydrogen is produced directly from methane in the form of CH4 → 2H2 + C, where the carbon product is in the form of carbon black or coke rather than CO2 produced in a typical steam methane reforming method. Treatment of co-products (H2, carbon black, and coke) has a significant impact on the calculated CI of hydrogen produced from methane pyrolysis, with system expansion resulting in a negative carbon intensity.



Michael Kerby of ExxonMobil discussed carbon accounting and product-level carbon intensity standards, stating that there currently is no transparent method of accounting for GHG emissions across the value chain. LCA practitioners can help integrate chemical engineering principles (e.g., mass and energy balances) with accounting principles to develop standardized guidelines for carbon accounting. He identified several successful product-level carbon intensity standards, including the Montreal Protocol to phase out CFCs to address ozone layer depletion, IMO sulfur reductions in marine fuel to reduce SOx from shipping, and California's LCFS to reduce transportation fuel carbon intensity. He argued that significant emission reductions are possible by prioritizing the top 10 emitting products globally.



Panel Discussion and Q&A – the following ideas and themes emerged during the panel discussion and Q&A session following the presentations:

- In response to a question on methane measurement, the panel made the following points:
  - Accurate data by region and timeframe are needed – EPA data are accessible and complete. Measurement data can be incorporated with a top-down adjustment to bottom-up estimates (TD/BU).
  - There is a mismatch in scales between TD and BU estimates, as TD measurements capture large facility emissions. Where to measure methane and how to integrate into life cycle analysis is still an ongoing question.
  - There is still a lot of work to be done on fossil-based natural gas and hydrogen – there are a lot of assumptions in going from satellite data to life cycle analysis. A recent study was cited where three research teams evaluated an operating facility and got very different results – boundary conditions, differences in methods, and different assumptions all contributed to the difference in results.
  - At the end of the day, operators need reasonable policy based on science or the policy falls apart. While there is 24-hour coverage of the Permian with drones, the best way to use those data is not clear. Need to determine appropriate technology and method to use globally.
  - Michael Wang of Argonne thanked the panel for making methane leakage a priority issue, noting that Argonne's GREET model had used a hybrid TD/BU approach for 10 years. Both TD and BU approaches have problems. The U.S. has extensive TD data, but not other countries, so significant knowledge gaps exist globally. As a result, the continued use of BU is recommended. All biofuels use natural gas, so the impact of this issue is broad.
- In response to a question on how best to integrate LCA into policy and decision-making, the following points were made by the panel:
  - It goes back to science, technology, and collaboration on the best techniques to measure methane to bring certainty to a large uncertainty. Need continued collaboration with national labs and academia.

- Need to get better on uncertainty – should not be moving forward with one number. Need to convince policymakers to look at a range of values and better explain variability.
    - Need operator-specific data; average values are not useful. Consider risk assessment frameworks historically used for safety to deal with variability.
    - There is a practical side to life cycle analysis – averages are used for a reason, e.g., you can't track electrons.
- In response to the indirect impact of hydrogen emissions, the following points were made:
    - Need data and an accurate assessment of indirect H2 emissions (e.g., via leakage). Most H2 releases are controlled releases based on storage losses – the economics are not there to capture H2.
    - There are little data on H2 leakage – most values in the literature point to the same 1-2 studies. If new value chains for hydrogen are developed, it gives us a chance to do it right and reduce fugitives from the value chain. While hydrogen does not have a signature like methane, we can borrow from our natural gas experience.
- The following "key messages" were offered by the panel:
    - Need to implement carbon accounting into life cycle analysis, perhaps with a broad-based, cross-sector consortium to develop a robust, transparent accounting system. If we can't count carbon, policy falls apart.
    - Standards can get you to a certain level, but need expert reviews and transparency, particularly around variability. Allocation methods are important and impact policy if allocation methods change. Transparency is very important alongside standardization efforts.
    - Verification and auditing are needed using reasonable but strict standards.
    - LCA needs a framework and methods. Data need to be robust to fill gaps, and transparency is important.

Session 7: Electrification

Chairpersons: Brent Heard (National Academies of Science), Robb De Kleine (Ford), Andrea Strzelec (USCAR)

Session 7 consisted of four presentations that addressed issues related to electric vehicle life cycle assessment and electricity generation. Arin Kaye (EPRI) discussed grid de-carbonization and the carbon intensity of electric vehicles. Jeremy Michalek (Carnegie Mellon University) presented information on grid emission modeling for electric vehicles. Jeff Gonder (National Renewable Energy Lab) summarized the results of a CRC-sponsored study on GHG impacts from plug-in electric vehicles. Finally, Jennifer Dunn (Northwestern University) presented information on the life cycle assessment of minerals used in the electric vehicle production life cycle.

Arin Kaye of EPRI discussed modeling that EPRI had done related to how grid decarbonization might impact power sector emissions and electricity demand growth. She highlighted three key takeaways and uncertainties: (1) renewables (wind and solar) are being deployed at increasing rates, but unknowns exist about the future extent, regional balancing mix, and reliability; (2) policy designs shape energy outcomes, but there is uncertainty about future form, timing, and affordability impacts; and (3) there is higher-than-expected load demand growth than observed in recent decades, and uncertainties about the extent of load growth, spatial and sectoral differences, and load profiles exist. EPRI modeling of annual household expenditures showed that in 2050 electricity expenditures are expected to increase, but overall household expenditures on energy could be reduced by 36-42% as a result of technological change, especially EV adoption.

Jeremy Michalek of Carnegie Mellon University presented information on grid emission modeling for EVs. Dr. Michalek began by noting the differences between attributional and consequential lifecycle modeling (citing the 2022 NAS study[3]), which are especially distinct for the power grid. Most early LCA studies of EVs used average emissions rates (attributional) with little thought to how system boundaries were drawn. This is important because where boundaries are drawn can change the answer. A key takeaway from this work is that EV charging can have surprising consequences. Specifically:

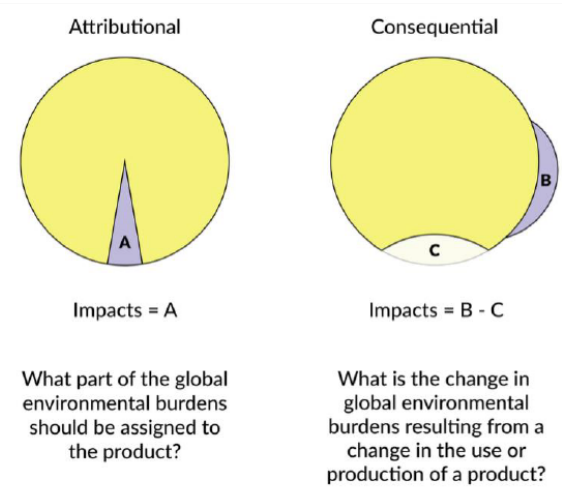
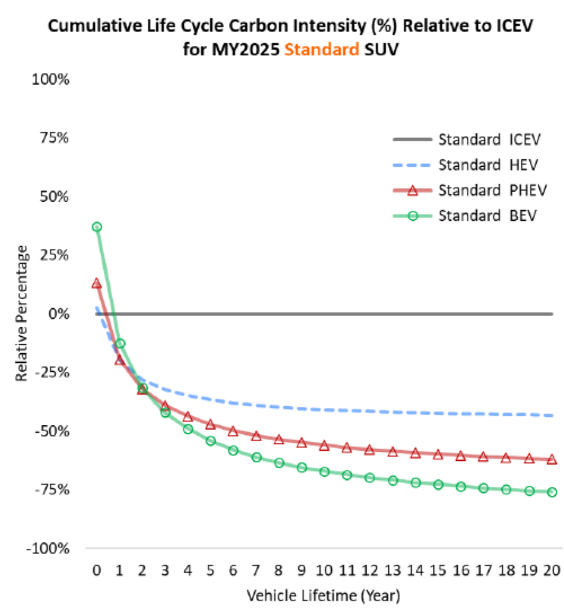


Figure Source: http://nap.nationalacademies.org/26402

- Attributional LCA is ill-suited to model the massively connected power system – electricity flows across nearly any boundary, and demand changes in one region cause investment and production changes in other regions.
- Consequential LCA is needed to estimate the effect of a decision, action, or policy – marginal emissions are for small changes, short-run estimates should be used if EV charging impacts operations but not infrastructure, while long-run estimates should be used if EV charging impacts operations and infrastructure.

Finally, his modeling shows that when EV load is flexible (especially vehicle-to-grid capability), EVs can induce so much wind/solar investment that adding EV load can *reduce* total grid emissions.

Jeff Gonder of the National Renewable Energy Lab (NREL) summarized the results of a CRC-sponsored study on GHG impacts from plug-in electric vehicles (CRC Project No. SM-E-20). Battery manufacturing emissions result in HEVs, PHEVs, and PEVs having higher emissions than ICEs early in their life, but in the long-term, GHG reductions increase from HEVs to PHEVs to BEVs. The study found that PEV GHG reductions are robust across a range of assumptions and increase over time with increasing grid decarbonization. Under the reference battery growth assumptions, all U.S. LDVs could become



BEVs and achieve the deepest decarbonization result. However, if battery availability is more limited,

[3] See Current Methods for Life-Cycle Analyses of Low-Carbon Transportation Fuels in the United States | The National Academies Press.

decarbonization would be more limited. Securing battery supplies will be important to achieve the deepest GHG reductions from PEVs.

Jennifer Dunn Northwestern University presented information on the life cycle assessment of minerals used for battery and EV production, noting that critical minerals are the backbone of decarbonization. Her team reviewed 74 critical mineral mining LCAs and found large inconsistencies in functional unit, system boundary, co-product allocation, indicator choice, uncertainty analysis, etc. As a result, they have developed a set of recommendations to standardize approaches intended to improve comparability across analyses.

- Functional unit: recommend a mass-based functional unit of “one ton of mineral equivalent” to help eliminate biases from different product compositions.
- Co-product allocation: recommend co-product allocation based on the mass of contained minerals within products.
- System boundary: recommend cradle-to-grave system boundary (mine perspective), including all processing of the entire mine life cycle.
- Data collection: recommend that, when possible, obtain data pertaining directly to the mine and its operations.

Dr. Dunn closed by noting that standardization is a tough ask but any progress would be helpful. Finally, she recommended that “when in doubt, leave it out” to avoid decision-making based on results calculated with low quality data.

Appendix
Glossary of Terms Used During the Workshop

AgMIP	Agricultural Model Intercomparison Project
ALCA	Attributional Life Cycle Assessment
ANL	Argonne National Laboratory
BAU	Business as Usual
BECCS	Bioenergy with Carbon Capture and Storage
BEV	Battery Electric Vehicle
BiCRS	Biomass Carbon Removal and Storage
BKM	Bookkeeping Model
BU	Bottom Up
BU/TD	Bottom Up/Top Down
CARB	California Air Resources Board
CCS	Carbon Capture and Sequestration
CDR	Carbon Dioxide Removal
CEF	CORSIA Eligible Fuel
CFAA	Clean Fuels Alliance America
CFR	Clean Fuel Regulation (Canada)
CI	Carbon Intensity
CLCA	Consequential Life Cycle Assessment
CNG	Compressed Natural Gas
CO2e	Mass of a specified GHG expressed as a mass of CO2 having equivalent GWP
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CRC	Coordinating Research Council
CRP	Conservation Reserve Program
CSA	Carbon Smart Agriculture
DOE	(US) Department of Energy
EC	European Commission
ECCC	Environment and Climate Change Canada
EIA	(US) Energy Information Administration
EISA	(US) Energy Independence and Security Act (2007)
EOL	End of Life
EPA	(US) Environmental Protection Agency
EPRI	Electric Power Research Institute
EU	European Union
EV	Electric Vehicle
gCO2e/MJ	grams of CO2 equivalents per MJ of fuel
GHG	Greenhouse Gas
GHGI	Greenhouse Gas Inventory
GHGRP	Greenhouse Gas Reporting Program
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies Model
GESAMP	Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection
HEV	Hybrid Electric Vehicle

IAM	Integrated Assessment Model
ICAO	International Civil Aviation Organization
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
IEA	International Energy Agency
ILUC	Indirect (or Induced) Land Use Change
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
IRA	Inflation Reduction Act
ISCC	International Sustainability & Carbon Certification
LCA	Life Cycle Assessment
LCAF	Lower Carbon Aviation Fuel
LCFS	Low Carbon Fuel Standard (California regulation)
LCMAP	the Land Change Monitoring, Assessment, and Projection
LNG	Liquefied Natural Gas
LUC	Land Use Change
MME	Multi-Model Ensemble
NETL	(DOE) National Energy Technology Laboratory
NGHGI	National Greenhouse Gas Inventories
NGV	Natural Gas Vehicle
NGO	Non-Governmental Organization
NREL	National Renewable Energy Laboratory
OBBBA	One Big Beautiful Bill Act
PER	Provisional Emission Rate
PEV	Plug-in Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
PNNL	Pacific Northwest National Laboratory
RED	Renewable Energy Directive
RFA	Renewable Fuels Association
RFS	Renewable Fuels Standard
RNG	Renewable Natural Gas
SAF	Sustainable Aviation Fuel
SMC	(CRC) Sustainable Mobility Committee
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
TD	Top Down
TERRA	Tomas Ekvall Research, Review & Assessment
UCO	Used Cooking Oil
UCS	Union of Concerned Scientists
USDA	U.S. Department of Agriculture
USCAR	U.S. Council for Automotive Research
WTG	Well-to-Gate
WTW	Well-to-Wheels (or Well-to-Wake)