Summary Report

8th Biennial CRC Workshop on Life Cycle Analysis of Transportation Fuels

Argonne National Laboratory
October 3-5, 2023

Report Prepared by:

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On behalf of the Coordinating Research Council

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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.

Table of Contents

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A. Introduction

The 8th biennial Coordinating Research Council (CRC) Workshop on Life Cycle Analysis of Transportation Fuels was held at Argonne National Laboratory on October 3-5, 2023. The workshop was co-sponsored by Argonne National Laboratory, Canadian Fuels Association, Clean Fuels Alliance America, Renewable Fuels Association, SCS Global Services, Union of Concerned Scientists, and the U.S. Environmental Protection Agency. The goals of this workshop were similar to previous workshops:

- Outline technical needs arising out of policy actions and ability of LCA analysis 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 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 102 registrants for this workshop, 54 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 noting some changes since the 2021 workshop:

- The 2021 workshop was virtual as a result of the COVID19 pandemic, but travel demand has since rebounded from pandemic lows.
- Global events have led to disruptions in energy markets (e.g., the war in Ukraine).
- Increases in electrification continue and interest in biofuels and sustainable aviation fuel remains strong.
- There have been significant investment activities related to hydrogen production and carbon capture, utilization, and storage (CCUS).

Klaus Daniel, the Associate Lab Director of Argonne's Advanced Energy Technologies Directorate, welcomed the participants to Argonne and to the workshop and noted that life cycle analysis is a key tool to achieving decarbonization. Klaus noted that Argonne was pleased to host the workshop again and welcomed the exchange of ideas.

Chris Tennent (CRC) provided a brief summary of the CRC history and structure, noting that CRC has been active for over 100 years and was formed from a Society of Engineers (SAE) committee working on fuels and vehicles. While much of the early work of CRC focused on engine and fuel performance, CRC has evolved to include separate committees working on emissions, atmospheric impacts, advanced vehicles and fuels, aviation, and most recently, sustainable mobility. Within the Sustainable Mobility Committee, there are subgroups working on electrification, fuels, novel carbon reduction strategies, and life cycle analysis. The CRC LCA Workshop now falls under the purview of the Sustainable Mobility Committee.

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

- Aggressive GHG reduction policies continue to be developed and implemented in the U.S., Europe, and Canada. In addition to the traditional focus on on-road transportation fuels, measures designed to reduce GHG emissions from aviation and marine fuels are being developed and implemented.
- The EU's "Fit for 55" package of policy measures is designed to reduce GHG emissions by at least 55% in 2030 across all sectors, relative to 1990 levels. The ultimate goal is to make Europe the first carbon neutral continent by 2050.
- Canada adopted its Clean Fuel Regulation (CFR) in 2022, which builds on the 2012 Renewable Fuels Regulations (RFR). The CFR calls for a reduction in carbon intensity of transportation fuels produced or imported for use in Canada, with a mandated 15% reduction in 2030 relative to 2016 levels. It is anticipated that the CFR will spur the uptake of clean technologies and low carbon intensity fuels.
- California's Low Carbon Fuel Standard (LCFS) is in the process of revision, with a target hearing date of early- to mid-2024. A primary motivation for this rulemaking is to stabilize credit prices, which dropped significantly beginning in late-2020 as higher volumes of lower-carbon fuels were introduced to the market than expected. It is anticipated that the 2030 carbon intensity reduction target will increase from 20% to 30% in 2030, with an intermediate step-down in the 2025-2026 timeframe. The targets are expected to follow a 4.5% per year increase in stringency beyond 2030, resulting in a 90% carbon intensity reduction target by 2045.

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[1] To maintain consistency in reporting the outcomes of the CRC LCA workshops, the structure of this Summary Report is very similar to the 2021 report prepared by S. Kent Hoekman, which is available at https://crcao.org/wp-content/uploads/2022/04/CRC-2021-LCA-Workshop-Summary.pdf.

- The U.N. International Civil Aviation Organization (ICAO) has developed a Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) with a goal of carbon neutral growth for international aviation. CORSIA compliance can be achieved via offsets or by the use of CORSIA-eligible fuels (CEF), which can be renewable or waste-derived sustainable aviation fuel (SAF) or fossil-based lower carbon aviation fuel (LCAF) that achieves a minimum 10% reduction relative to the fossil baseline. The program is currently in the Pilot Phase; more rigorous sustainability requirements (post Pilot Phase) go into effect in January 2024.
- The International Maritime Organization (IMO) has developed several strategies to reduce GHG emissions from international shipping, which, as a sector, contributed about 3% of global anthropogenic GHG emissions in 2018. IMO's 2023 strategy establishes GHG reduction targets of 20% by 2030, 70% by 2040, and net-zero GHG emissions by 2050. In 2023, the IMO developed LCA guidelines for marine fuel LCA.
- GHG emissions from U.S. agriculture have not declined in recent years, primarily because conservation programs have not prioritized "climate-smart" farming, and there is no commodity standard akin to "organic" farming. In addition, there is a lack of incentives for reducing farm-level emissions in current biofuel programs. Programs that provide incentives to reduce GHG emissions under the USDA Smart-Climate Commodities program will begin to be implemented, but project-level feedstock accounting and verification are not currently permitted under the EPA's Renewable Fuels Standard or California's LCFS, the two major renewable fuel programs in the U.S. As of the Workshop, the Treasury Department had not yet released guidance on whether project-level feedstock accounting would be included in the Inflation Reduction Act tax credits for the sector.

Session 2: Policy Relevant Reports and Analysis

- EPA's Model Comparison Exercise (MCE) compared five different models (GREET/CCLUB, GLOBIOM, GCAM, GTAP, and ADAGE) to address land use changes in the context of biofuel LCA by using similar inputs to estimate the GHG impacts of corn ethanol and soybean oil biodiesel. The results from the MCE showed a wide variation in GHG impacts across model types (supply chain, partial equilibrium, computable general equilibrium, integrated assessment), with more variability observed for soybean oil biodiesel than for corn ethanol.
- Session 2 included a discussion of attributional life cycle analysis (ALCA) versus consequential life cycle analysis (CLCA).[2] In general, it is felt that CLCA introduces significant uncertainty because of the economic modeling required. While ALCA is important as a policy tool (e.g., in implementing the clean hydrogen tax credits spelled out in the Inflation Reduction Act), many experts believe CLCA is useful to establish policy "guardrails" and to give a general idea of where to focus additional analysis efforts or to identify areas of concern.
- Additionality and "counterfactual" scenarios are important considerations in LCA. Common examples include the treatment of avoided methane when assessing renewable natural gas projects as a counterfactual scenario case and the qualification of "green hydrogen" when

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[2] "Consequential" lifecycle analysis assesses how emissions or impacts (including "market-mediated" impacts) may change in response to a decision or action, such as a change in biofuel consumption. This is the approach EPA used in estimating GHG impacts of renewable fuels for the RFS2 rulemaking. "Attributional" lifecycle analysis evaluates emissions along each stage of a supply chain and assigns (or "attributes") emissions to a functional unit such as volume or energy of fuel. This is the methodology applied in Argonne's GREET model.

assessing renewable electricity used for its production as an additionality case. In the latter example, the primary question is whether the renewable electricity is newly added to the grid, or whether shuffling is occurring. One risk of insufficient additionality is the attribution of reductions from outside policies to fuels.

Session 3: Biofuel and Land Use Change

- Data presented by Farzad Taheripour (Purdue) do not support large ILUC values. Early papers that estimated ILUC values dismissed, ignored, or overlooked the magnitude of market-mediated responses and therefore overestimated ILUC emissions. More recent papers have taken into account market-mediated responses and estimated significantly lower ILUC values. U.S. crop data from the past 20 years have shown major yield increases for corn and soybeans, no major change in forest area, and no systematic reduction in agricultural product exports.
- Crop expansion into marginal lands has occurred as crop prices have increased. Better categorization of marginal lands is needed, and carbon stock for marginal lands is very uncertain, perhaps more than the uncertainties in economic models.
- In general, clear and consistent definitions for terminology used in land use change issues are needed. The most simple terms lack consensus across use cases for land use change assessment.

Session 4: Biofuel Methodology

- Session 4 continued the discussion of appropriate baseline, or “counterfactual,” scenarios in assessing avoided emissions in quantifying GHG emissions associated with fuel pathways. Avoided emissions from counterfactual scenarios can significantly impact the carbon intensity of renewable natural gas, and multiple counterfactual scenarios reflecting business-as-usual management practices may need to be considered for some waste feedstocks (e.g., MSW, animal manure, wastewater sludge, etc.).
- It was generally agreed that field-level carbon accounting should be pursued to allow best practices and optimization of farming practices to be reflected in the carbon intensity of biofuels. However, certain important parameters used to assess GHG reductions are very difficult to quantify and to ensure permanence. Soil carbon (including soil organic carbon) was identified as being particularly problematic when assessing permanence and in allocating between crops in common rotations (e.g., soy-corn rotations). Policy is needed to incentivize field-level practices, and communication with growers is important as there is a lot of uncertainty from the growers’ perspective.

Session 5: Hydrogen

- It is unclear if battery electric vehicles can displace all ICEs, so hydrogen is considered a backstop, particularly in the heavy-duty truck sector where the economics are more favorable.
- Hydrogen leakage across the hydrogen supply chain needs to be better characterized, as wide variability is observed in the literature. Current leak rate estimates are 3% - 6% for gaseous hydrogen and 6% - 12% for liquid hydrogen. But these rates are highly uncertain since there are no credible, measured hydrogen leakage data.
- A new analysis tool for estimating GHG emissions from hydrogen production is being developed as part of the Open Hydrogen Initiative (OHI). The model will estimate cradle-to-gate GHG

emissions for many different feedstocks and processes, and it is envisioned that it will be an open-source spreadsheet tool that will be extremely customizable and easy to operate. The model originated to support price benchmarking, not as a regulatory tool.

- Argonne presented results of GREET modeling of hydrogen production, outlining the various feedstock and production processes included in GREET. The impacts of including "embodied" GHG emissions for different pathways showed that hydrogen production from electrolysis using solar PV amounted to 2.1 kgCO2e/kg H2.[3]

Session 6: Carbon Capture, Utilization, and Storage (CCUS) / eFuels

- The energy required to produce power-to-liquid fuels (PtL or eFuels) is staggering. It is estimated that 2.7 MJ of electricity would be needed for each MJ of fuel, which compares to 0.2 MJ of fossil energy per MJ fuel for hydrotreated fatty acids (e.g., canola oil based SAF).
- Approximately 15,000 TWh power generation would be needed for the annual production of jet fuel forecasted to 2050 (jet fuel only).[4]
- Most eFuel pathways assume the large quantity of hydrogen required would be from electrolysis using low-carbon electricity. However, Argonne researchers have estimated the "embodied emissions" for solar PV electricity to be 38 gCO2e/kWh and wind turbines to be 10 gCO2e/kWh, which compares to 0.5 gCO2e/kWh of embodied GHGs for natural gas electricity. It remains an open question as to whether embodied emissions will be included in future regulatory analyses (e.g., the ICAO CORSIA). The current approach for treating electricity in CORSIA does not account for "embodied" emissions. Including embodied emissions for solar electricity to produce PtL jet fuel results in a carbon intensity increase from 0 gCO2e/MJ to 31 gCO2e/MJ. This compares to 40 gCO2e/MJ for SAF produced from canola.
- Direct air capture of CO2 is much more expensive ($200 - $600/ton) than carbon capture from higher concentration, industrial sources ($10 - $60/ton).
- Carbon mineralization was discussed as a means of storing CO2 by converting it into a thermodynamically stable solid, and the products of CO2 mineralization (e.g., magnesium and calcium carbonates) could potentially substitute for conventional products in several industries (e.g., cement manufacturing, which results in a negative carbon footprint). However, the high energy required to overcome the slow reaction kinetics of carbonate formation is potentially a serious roadblock to implementation.

Session 7: Electrification

- According to an analysis conducted by ICCT, battery electric HDVs provide lifetime GHG emissions reductions of 32% - 47% compared to their respective diesel versions. Fuel cell EVs can provide GHG savings compared to fossil fuel ICEVs, but the GHG intensity of the hydrogen feedstock is critical (renewable vs. fossil). Natural gas-powered vehicles provide minor GHG savings compared to fossil fuel ICEVs.

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[3] As a point of reference, GREET2022 estimates that hydrogen produced via steam methane reforming of natural gas with carbon capture has a GHG footprint of approximately 3.4 kgCO2e/kgH2.

[4] As a point of reference, the 2019 total global electricity production was approximately 27,000 TWh (IEA, https://www.iea.org/reports/electricity-information-overview/electricity-production).

- According to an analysis conducted by Phillips 66, renewable diesel and renewable natural gas consistently reduce GHG emissions at relatively low costs, but these pathways depend on low carbon-intensity feedstock. Battery EVs and hydrogen FCEVs are more feasible for work trucks, medium and urban trucks/buses, but may need incentives. There is an opportunity for “blue” hydrogen (SMR with CCS) in addition to “green” hydrogen to contribute to GHG reductions from work trucks and medium-duty trucks.

Closing Remarks

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

- The regulatory, regulated, and research communities are looking for ways to improve inputs and modeling of land use change.
- Farm-level GHG accounting may run into challenges related to allocating emissions among feedstocks grown in a rotation where GHG fluxes depend on the entire rotation.
- The workshop included a session on hydrogen for the first time, highlighting the interest in that topic.
- CCU and associated eFuels will require massive amounts of energy to implement.
- Based on a poll of the audience, the following research ideas were identified as being high priority:
  - Soil carbon science.
  - Well-to-wheels analysis of internal combustion engines and lower-carbon intensity liquid fuels.
  - Embodied emissions; a more holistic approach to life cycle analysis.
  - Non-linearity in land use change impacts.

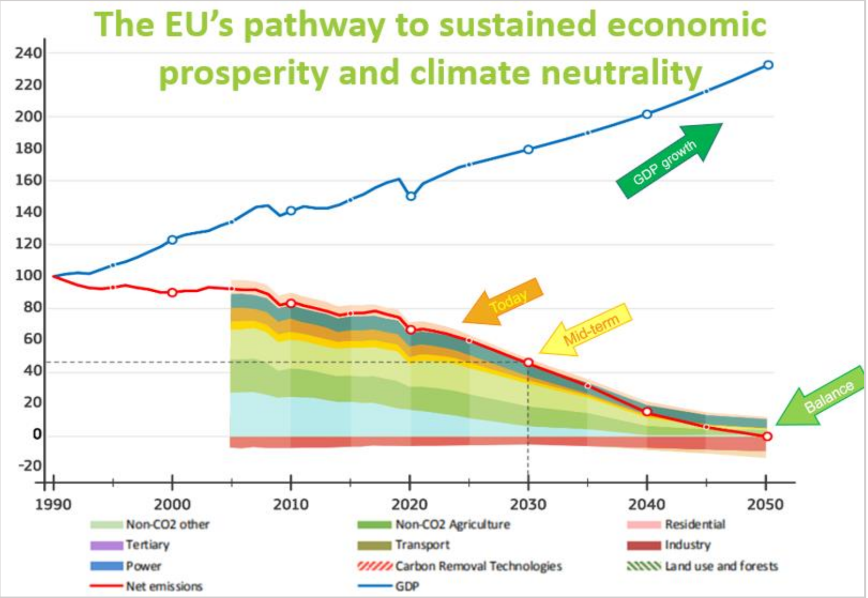
C. Highlights and Learnings from Individual Presentations

<u>Session 1: Policy Updates</u>

Chairpersons: Devin O'Grady (Canadian Fuels Association), Matt Herman (Iowa Soybean Association), Sari Kuusisto (Neste)

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. Laura Lonza from the European Commission presented a summary of the EU’s “Fit for 55” package of policies intended to achieve a 55% reduction in GHG emissions by 2030. Karine Lavertu and Francois Charron-Doucet from Environment and Climate Change Canada (ECCC) presented information on Canada’s Clean Fuel Regulation (CFR) and the fuel life cycle analysis model used in the CFR, respectively. Robert Molina of the Federal Aviation Administration (FAA) presented background information on the International Civil Aviation Organization (ICAO), the associated Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), and how sustainable aviation fuel (SAF) fits within the structure of CORSIA. Satu Kuurma of the Finnish Transport and Communications Agency (TRAFICOM) discussed the International Maritime Organization’s (IMO) efforts to reduce GHG emissions from international shipping. Jeffery O’Hara of the U.S. Department of Agriculture (USDA) discussed conceptual issues with respect to the use of the GREET model in estimating the carbon intensity of biofuels. Finally, Collin Murphy of U.C. Davis gave an update on California's Low Carbon Fuel Standard (LCFS) with an emphasis on changes currently being proposed by CARB staff and expected to be voted on by the Board at a public hearing early in 2024.

Laura Lonza (EU Commission) provided information on the EU's "Fit for 55" package of policies intended to achieve a 55% reduction in GHG emissions by 2030 relative to 1990 levels, with the ultimate goal of making Europe the first carbon neutral continent by 2050. This is a very comprehensive package of polices that impact all economic sectors.



In terms of fuels policies, the Fit for 55 package includes an updated Renewable Energy Directive (RED II+), which increases the target for renewables in transport from 14% to 29% in energy terms and includes a 14.5% reduction in the carbon intensity of transport fuels. RED II+ expands its scope to include "all fuels supplied to the transport sector" and therefore now includes aviation and shipping.

Karine Lavertu (ECCC) presented information on Canada's Clean Fuel Regulation (CFR), which came into effect in June 2022. While the CFR is a national program, several provinces have their own low-carbon fuel requirements. The CFR is targeting a 15% reduction in fuel carbon intensity by 2030. Similar to the California LCFS, there are many opportunities for credit generation under the CFR. Aside from producing and importing low-CI fuels (ethanol, biodiesel, RNG, etc.), credits can be generated from projects that reduce the CI of liquid fossil fuels and by supplying fuel or energy to advanced vehicle technologies (BEVs, hydrogen fuel cell vehicles). Although the CFR does not include induced land use change (ILUC) as part of fuel CI scores, there are Land Use and Biodiversity (LUB) criteria to prevent adverse land-use and biodiversity impacts related to feedstock cultivation and harvesting. The program has gotten off to a good start, with over 200 organizations registering for the program, 250 CI applications submitted, 24 training programs conducted, and over 170 meetings with stakeholders since July 2022.

Francois Charron-Doucet (ECCC) presented information on the Fuel LCA Model used in the CFR, which is used to calculate life cycle CI of fuels and energy sources used and produced in Canada. The Fuel LCA Model was built to meet the following criteria: transparent and traceable CI calculations, representative of Canadian fuel pathways, follow ISO guidelines (e.g., 14040 and 14044), and bilingual. The steps involved in modeling a facility's CI score include:

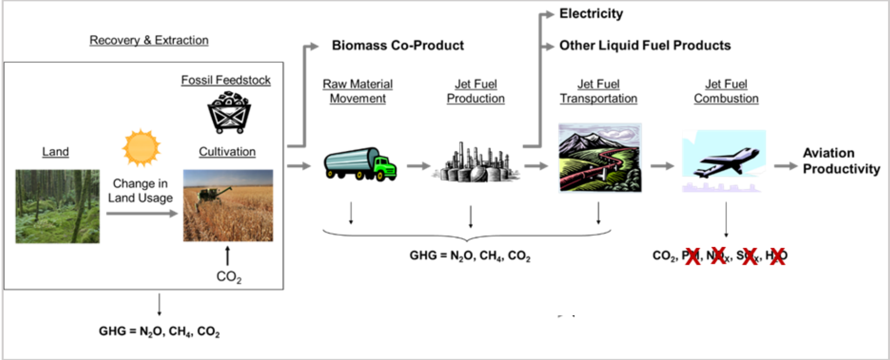
1. Data are collected at the production facility and from the fuel's supply chain.

2. Data are converted to LCA parameters using the data workbook.
3. Parameters are entered in the Fuel LCA Model's database using openLCA software.
4. The openLCA software calculates the CI and provides a detailed analysis of the fuel's life cycle.

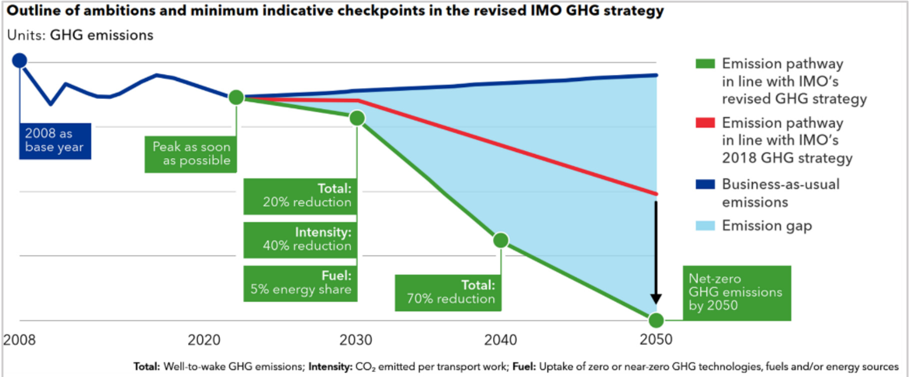
The Fuel LCA Model offers high flexibility and improved transparency, but that comes at the cost of a steeper learning curve as it requires users to learn the basic concepts of LCA modeling and the use of openLCA. It is anticipated that the Fuel LCA Model will be updated on a two-year cycle, with the first update coming in June 2024.

Robert Malina (FAA) presented information on ICAO, CORSIA, and how sustainable aviation fuel (SAF) fits within the structure of CORSIA. Two options for CORSIA compliance are available: (1) offsetting with emission units, and (2) claiming emission reductions from CORSIA eligible fuels (CEF). A CEF can be CORSIA Sustainable Aviation Fuel (SAF), which is a renewable or waste-derived fuel, or CORSIA Lower Carbon Aviation Fuel, which is a fossil-based fuel having 10% lower CI than baseline fossil jet fuel.

Calculation of CEF life cycle emissions follows a traditional attributional LCA approach in which GHG emissions for each step of the fuel pathway are evaluated, from feedstock cultivation through fuel combustion. Default "core" LCA values have been established for CORSIA based on work performed by an international team of researchers and scientists. An ILUC "adder" is applied to the core LCA values to arrive at the total CI score for a fuel pathway. The default ILUC values are based on modeling performed by Purdue University using GTAP-BIO and by the International Institute for Applied Systems Analysis using GLOBIOM. Airline operators/fuel producers can use the default CI values or they can work with an eligible Sustainability Certification Scheme (SCS) to seek a core LCA value representative of their specific fuel production pathway.



Satu Kuurma (TRAFICOM) discussed IMO's efforts to reduce GHG emissions from international shipping, which contributed about 3% of global anthropogenic emissions in 2018. IMO has several existing regulations in place to reduce GHG emissions, including energy efficiency improvements for existing and new ships, reporting of fuel oil consumption data, and carbon intensity reporting in units of grams CO2 per capacity-mile. IMO is targeting a 20%


Outline of ambitions and minimum indicative checkpoints in the revised IMO GHG strategy

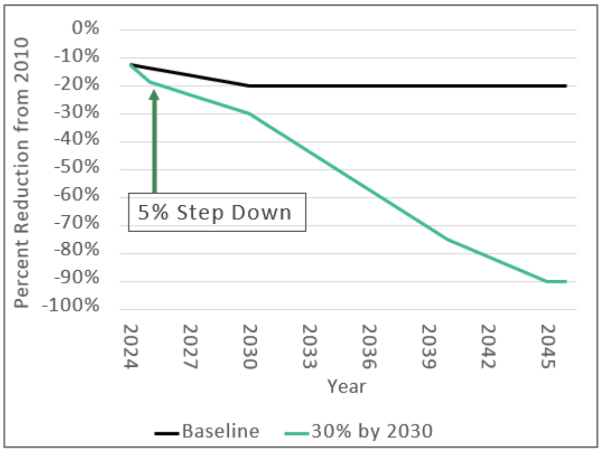
Total: Well-to-wake GHG emissions; **Intensity:** CO_2 emitted per transport work; **Fuel:** Uptake of zero or near-zero GHG technologies, fuels and/or energy sources

Figure: DNV, Energy Transition Outlook 2023, MARITIME FORECAST TO 2050 reduction in GHG emissions by 2030, 70% by 2040, and net zero GHG emissions by 2050. Interim guidance on the use of biofuels was issued in July 2023, which will require well-to-wake life cycle GHG emission reductions of at least 65% relative to fossil marine fuel (94 gCO2e/MJ). IMO's LCA guidelines will apply a qualitative risk-based approach to ILUC, where feedstocks are identified as low-ILUC risk or high-ILUC risk within the framework of sustainability criteria.

Jeffery O'Hara (USDA) discussed conceptual issues with respect to the use of the GREET model in estimating the CI of biofuels, with a focus on farm-level emissions. He noted that GHG emissions from U.S. agriculture have not declined in recent years, primarily because conservation programs have not prioritized "climate-smart" farming, and there is no commodity standard akin to "organic" farming. In addition, there is a lack of incentives for reducing farm-level emissions in current biofuel programs. For example, the federal RFS is not premised on CI scores, and while state LCFS programs use CI scores, average values are used for feedstock production. Programs that provide incentives to reduce GHG emissions could potentially be implemented, but project-level feedstock accounting and verification is likely to be difficult and costly to implement.

Land use change issues were also discussed during this presentation. While the core GREET model is attributional, ILUC values are appended onto the core values. However, different versions of GREET give different results (e.g., soybean SAF ILUC from ICAO-GREET is 24.5 gCO2e/MJ, whereas the ANL-GREET value is 9.3 gCO2e/MJ). EPA's MCE was also discussed, and it was noted that the MCE was agnostic on which models were most realistic/accurate, which is in tension with the pragmatic need to implement CI methodologies. Finally, the observed land-use patterns in the past 10 to 15 years have been less than predicted due to intensification, and from USDA's perspective, the technique employed for estimating LUC emissions should be the one that is most realistic and consistent with observed data.

Collin Murphy (U.C. Davis) gave an update on California's Low Carbon Fuel Standard (LCFS) with an emphasis on changes currently being proposed by CARB staff. A primary motivation for this rulemaking is to stabilize credit prices, which dropped significantly beginning in late-2020 as higher volumes of lower-carbon fuels were introduced to the market than expected. It is anticipated that the 2030 carbon intensity reduction target will increase from 20% to 30% in 2030, with an intermediate step-down in the 2025-2026 timeframe. The targets are expected to follow a 4.5% per year increase in stringency beyond 2030, resulting in a 90% carbon intensity reduction target by 2045.



Dr. Murphy went on to discuss modeling that was performed to test the feasibility of the targets, which showed that the 30% reduction target for 2030 is achievable under a wide range of scenarios, and that the step-down is feasible and can reduce banked credits in 2030, helping to stabilize credit prices at higher levels. Major areas of uncertainty include the EV deployment rate, gasoline consumption trend, and the availability and carbon intensity of hydrotreated fuels (renewable diesel and SAF). More aggressive targets (35% or greater) in 2030 are feasible only with rapid, likely unsustainable, levels of hydrotreated fuel growth. Targets will need to increase much faster in the 2030-2035 time period due to high EV sales fractions.

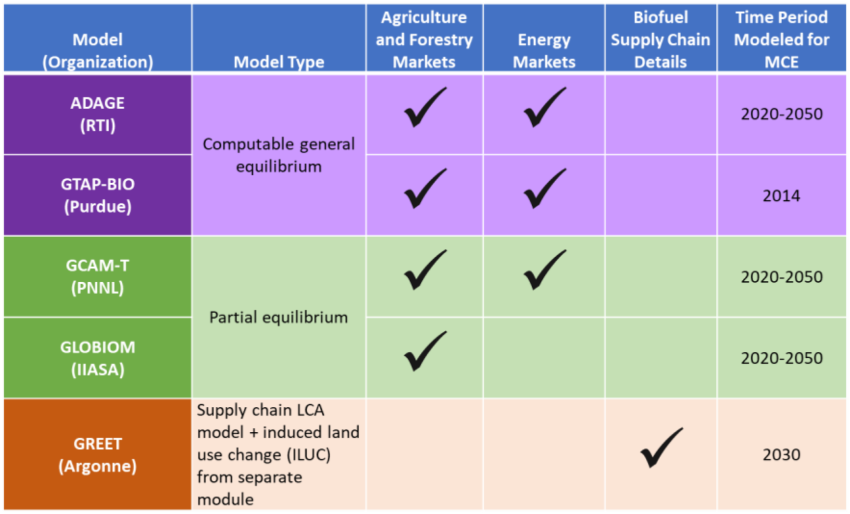
Session 2: Policy Relevant Reports and Analysis

Chairpersons: Aaron Levy (US EPA), Jeremy Martin (Union of Concerned Scientists)

Session 2 consisted of four presentations that summarized recent reports related to policy issues and analyses. Aaron Levy of the U.S. Environmental Protection Agency (EPA) provided a summary of EPA's recently released "Model Comparison Exercise" in which five different GHG models were assessed using consistent inputs across models. The other three presentations focused on different aspects of the 2022 National Academies LCA report.[5] Steffen Mueller (University of Illinois, Chicago) and Jennifer Dunn (Northwestern University) discussed attributional life cycle analysis (ALCA), Valerie Thomas (Georgia Tech) and Jeremy Martin (Union of Concerned Scientists) discussed consequential life cycle analysis (CLCA), and Nikita Pavlenko (ICCT) discussed the topic of additionality.

Aaron Levy of the U.S. Environmental Protection Agency (EPA) provided a summary of EPA's recently released "Model Comparison Exercise" (MCE). The goals of the MCE were to (1) advance the science in the area of analyzing the lifecycle greenhouse gas emissions impacts from increasing use of biofuel, (2) identify and understand differences in scope, coverage, and key assumptions in each model, and, to the extent possible, the impact that those differences have on the appropriateness of using a given model to evaluate the GHG impacts of biofuels, and (3) understand how differences between models and data sources lead to varying results. The impacts of corn ethanol and soybean oil biodiesel were evaluated in the MCE.

Five different models were included in the MCE as shown in the table to the right. To the extent possible, the models were configured to run common scenarios with key inputs aligned. For example, the corn ethanol "shock" was assumed to be 1 billion gallons per year of additional consumption in the U.S. from a baseline of 14.8 billion gallons.



Model (Organization)	Model Type	Agriculture and Forestry Markets	Energy Markets	Biofuel Supply Chain Details	Time Period Modeled for MCE
ADAGE (RTI)	Computable general equilibrium	✓	✓		2020-2050
GTAP-BIO (Purdue)		✓	✓		2014
GCAM-T (PNNL)	Partial equilibrium	✓	✓		2020-2050
GLOBIOM (IIASA)		✓			2020-2050
GREET (Argonne)	Supply chain LCA model + induced land use change (ILUC) from separate module			✓	2030

Results from the MCE showed that there remains a large degree of variation and uncertainty in life cycle GHG estimates that consider significant market-mediated "indirect" emissions. In addition, economic modeling of the energy sector may be required to avoid overestimating the emissions reduction from fossil fuel consumption. Finally, models included in the MCE produced a wider range of carbon intensity

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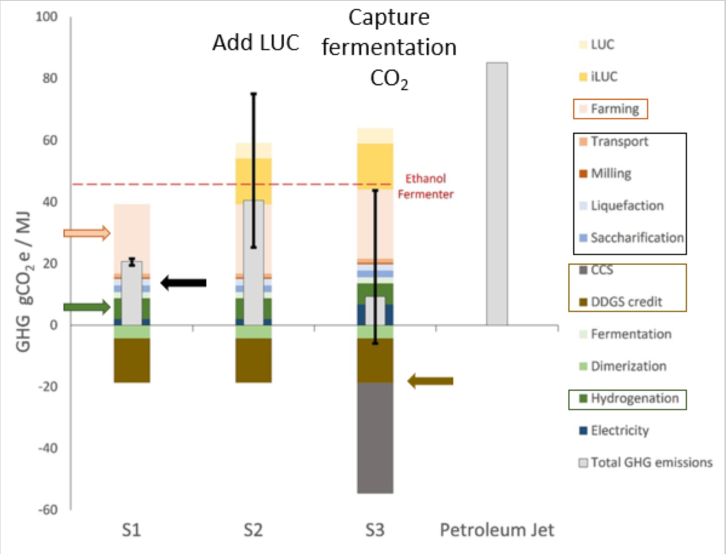
[5] See https://nap.nationalacademies.org/catalog/26402/current-methods-for-life-cycle-analyses-of-low-carbon-transportation-fuels-in-the-united-states

estimates for soybean oil biodiesel than for corn ethanol. For example, land use change results ranged from -1 to 31 kgCO2e/MMBtu for corn ethanol and from 10 to 295 kgCO2e/MMBtu for soy biodiesel.

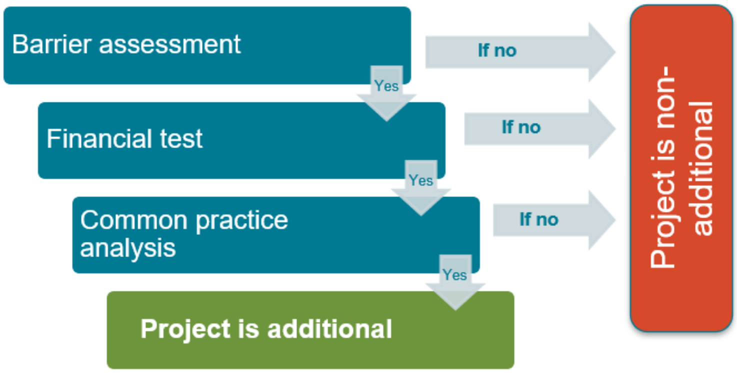


R. Batten, O. Galant, M. Karanjikar, S. Spatari. *Fuel.* **2023**, 333: 126294

Steffen Mueller (University of Illinois, Chicago) and **Jennifer Dunn** (Northwestern University) discussed attributional life cycle analysis (ALCA). As noted above, "attributional" life cycle analysis evaluates emissions along each stage of a supply chain and assigns (or "attributes") emissions to a functional unit such as volume or energy of fuel. ALCA methods yield actionable insights in low-carbon fuel supply chains. For example, biorefineries that include a hydrogenation step should focus on improving that process (e.g., via low-carbon hydrogen) to decrease that portion of GHG emissions. The figure to the right shows LCA results for producing jet fuel from corn ethanol (ferment sugars to isoprene, dimerize, hydrogenate).

Many low-carbon fuel policies are implemented with an ALCA approach because that allows for comparison against actual values, which often require verification. For this, one needs to "assign emissions to products or activities" which is much more consistent with ALCA practices. However, ILUC is often added as a consequential element outside of the ALCA boundary.

Valerie Thomas (Georgia Tech) and **Jeremy Martin** (Union of Concerned Scientists) discussed consequential life cycle analysis (CLCA), which assesses how emissions or impacts (including "market-mediated" impacts) may change in response to a given policy or set of actions, such as mandated biofuel volumes. CLCA is used when one needs to know the consequences of a policy and wants to ensure that the consequences reduce emissions. One criticism of CLCA is that the uncertainties are larger than the effect. While that could be true, a better effort is needed to understand various elements of CLCA models. Generally, it is thought that CLCA is complimentary to ACLA, and the CLCA results can help to identify potential outcomes that are to be avoided versus those that can be supported. Simply relying on a gram-per-megajoule value from ALCA does not tell the whole story. CLCA results are useful to inform safeguards in policy decisions.



Nikita Pavlenko (ICCT) addressed the role of additionality in fuels policies. The basic concept is whether a given project goes beyond what is legally required. A project that would be following the law, such as renewable electricity under a renewable portfolio standard, would be non-additional. A second test would be to determine whether the project needs climate financing (e.g., credits) to be viable, and finally, consideration of whether the type of project is common practice in a region. If it passes those tests, the project is considered additional.

A common example of additionality is an assessment of diary biogas in which the CI depends on the counterfactual behaivor in the absense of the fuel policy. The CI of fuels derived from methane that would otherwise be released (e.g., methane from manure or landfill) are strongly influenced by assumptions in the LCA of the alternative fate of methane pollution and are subject to dramatic change if relevant regulations or practices change (e.g., rules put in place requiring control of diary manure methane emissions). Another common example is renewable electricity used for green hydrogen and eFuels production. Electricity from direct-connect projects (i.e., behind-the-meter) is clearly additional, but using grid electricity to backfill for capacity limitations introduces issues on how to ensure that the grid-purchased electricity is also additional. The risks of insufficient additionality include GHG reductions from fuel policies that fall short of the intended or credited reductions, attributing GHG reductions from outside polices to fuel policies, and dilution of the policy signal, i.e., crowding out in-sector reductions from fuels with out-of-sector credits.

Session 3: Biofuel and Land Use Change

Chairpersons: Scott Richman (Renewable Fuels Association), Veronica Bradley (Clean Fuels Alliance America)

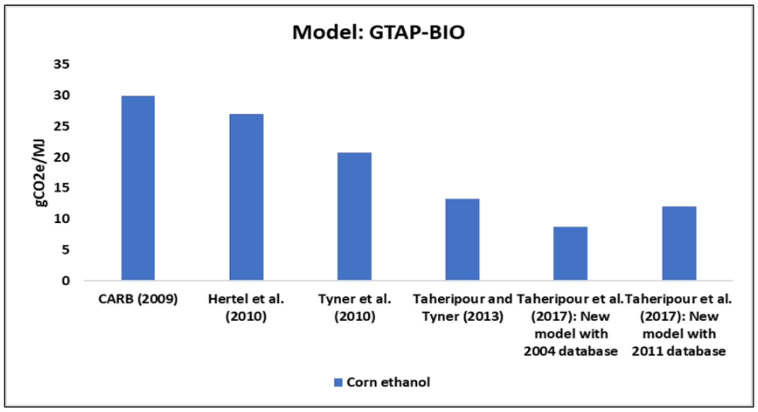
Session 3 included three presentations discussing issues related to biofuel production and associated land use change. Farzad Taheripour (Purdue University) presented issues related to induced land use change (ILUC) emissions, including modeling practices and historical evidence for ILUC. Nick Goeser (CAL Consulting) discussed harmonization of land use classifications, and Madhu Khanna (University of Illinois, Urbana-Champaign) presented an assessment of land use change due to biofuels in the U.S.

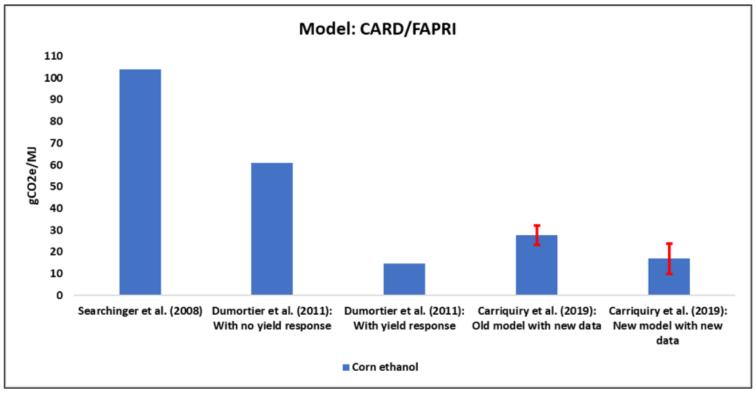
Farzad Taheripour (Purdue University) discussed a variety of issues related to induced land use change emissions. Early papers published on ILUC estimated that corn ethanol would result in huge GHG emissions, but since then, major efforts have been made to assess ILUC emission values for biofuels following a consequential LCA approach. The early ILUC estimates dismissed, ignored, or overlooked market-mediated responses and used problematic modeling frameworks and therefore over-estimated ILUC impacts. Some of the more important market-mediated responses include:

- Higher demands for crops could be satisfied due to yield improvements – partially induced by better commodity markets.

- Changes in crops' relative prices generate competition among crops and that leads to crop switching.
- Higher demands for feed crops (e.g., corn) induces efficiency gains in the livestock industry.
- Additional demand for cropland could be satisfied by using marginal land and multiple cropping.

More recent papers have accounted for market-mediated responses and have estimated significantly lower ILUC values.





This presentation also covered historical data on crops and crop production, observing that over the past two decades, U.S. agriculture continued to grow with major intensification in crop production and higher efficiency in livestock sector, with no major expansion in cropland area. While some marginal land returned to crop production, deforestation has not been observed in the U.S. Finally, no systematic reduction in exports of agricultural products has been observed. These observations do not support the claims made by the initial ILUC theory and published literature.

Nick Goeser (CAL Consulting) discussed harmonization of land classifications as related to direct land use change (DLUC), the results of which came out of a series of workshops and meetings with the agriculture industry, academia, food producers, national labs, and NGOs. The current "flexible" definitions confuse the discussion and have cascading consequences for the agricultural supply chain. Examples of confusion regarding land cover and land management terminology include land use, land management, marginal lands, native or intact, grasslands, etc. Key gaps that were identified included over-simplification of complex mosaics of multi-layered land uses into monolithic classes, different definitions that are not clearly stated, and that land use change should be allocated to the drivers of the issue, not the crop that happens to be at the "scene of the crime."

Madhu Khanna (University of Illinois, Urbana-Champaign) presented an assessment of land use change due to corn ethanol in the U.S. using two different methods: (1) econometric (empirical) methods with county level data on crop acreage from 2003 to 2014, and (2) using a numerical simulation model (BEPAM) to examine land use change from 2007 to 2018. Using the first method, results were found to be very sensitive to the time period analyzed, with the 2003 to 2014 time period resulting in 0.61 million acres/billion gallons of ethanol per year, and the 2008 to 2014 resulting in 0.43 million acres/billion gallons of ethanol per year.[6] The second method (numerical simulation) resulted in corn ethanol requiring 0.41 to 0.57 million acres of cropland conversion per billion gallons without including pasture land, and 0.71 to 0.75 million acres of cropland conversion per billion gallons with pasture land is included. Despite land use change emissions, the carbon intensity of corn ethanol is 19-41% lower than for gasoline.

Session 4: Biofuel Methodology

Chairpersons: Scott Richman (RFA), Veronica Bradley (Clean Fuels)

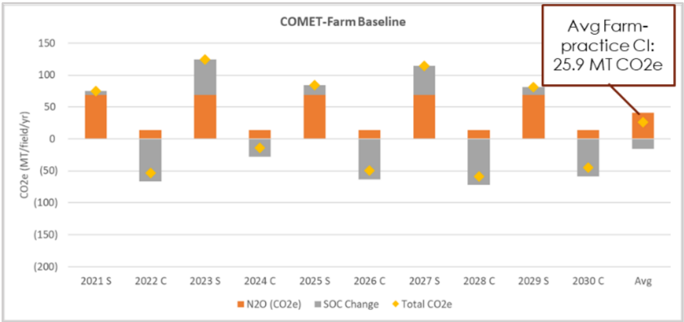
Session 4 included four presentations focused on issues related to methodologies used in the application of life cycle analysis to biofuels. Hao Cai (Argonne) discussed quantification of displacement credits, particularly related to the business-as-usual (BAU), or "counterfactual," scenario used in the assessment. Sharon Bard (Terra Economics) presented information on farm-based allocation approaches. Marie Coffin (CIBO Technologies) presented details of a model used for feedstock carbon evaluation. Finally, Bin Peng (University of Illinois) discussed a framework for quantifying field-level agricultural carbon outcomes.

Hao Cai (Argonne) discussed counterfactual scenarios used to estimate displacement credits in the GREET model. This is a particularly important aspect of certain waste-to-energy pathways, where the conversion of waste to fuel can result in a significant decrease in GHG emissions relative to the business-as-usual scenario. A common example of this is a manure-based anaerobic digestion pathway in which methane release under the counterfactual management practices (a mix of anaerobic lagoon, deep pit, solid storage, liquid/slurry, and pasture application) are considered fugitive methane emissions and are not recovered. Those fugitive methane emissions are assigned as a credit to the anaerobic digestion pathway and can result in negative emissions from production of renewable natural gas in some cases.

Important issues to consider in the selection of counterfactual scenarios include:

- The need to focus on causality when waste is diverted from BAU management practices to energy production.
- Multiple counterfactual scenarios reflecting various BAU management practices may need to be considered for certain waste feedstocks.
- BAU management practices may be evolving, and the counterfactual scenario may be shifting over time, requiring revisiting of the issue.

Sharon Bard (Terra Economics) discussed two models for field-level analysis: GREET's Feedstock Carbon Intensity Calculator (FD-CIC) and COMET-Farm, which is a whole farm carbon accounting system managed by the USDA and Colorado State University. Results of a case study of a soybean/corn cropping system were compared between



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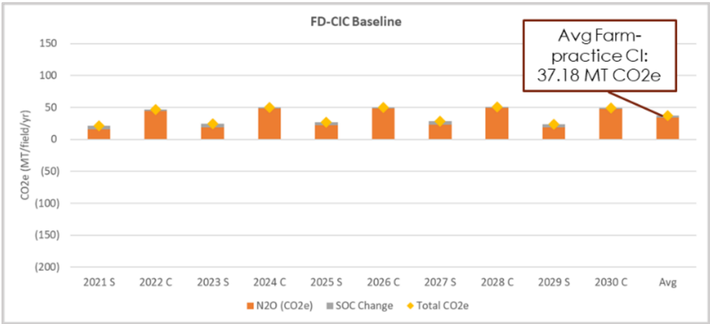
[6] For reference, corn planted area for all purposes in 2021 was estimated to be 92.7 million acres. See https://www.nass.usda.gov/Publications/Todays_Reports/reports/acrg0621.pdf#:~:text=Corn%20planted%20area%20for%20all%20purposes%20in%202021,percent%20or%201.87%20million%20acres%20from%20last%20year.

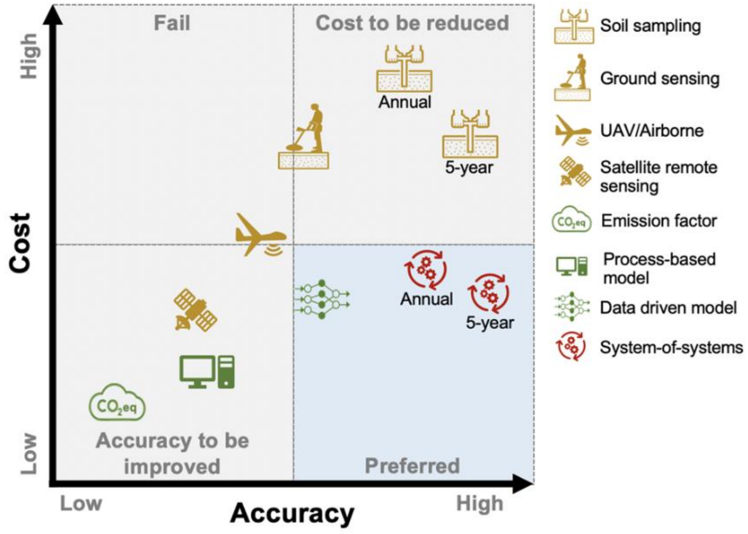
the two models. The tools quantify emissions and soil organic carbon (SOC) sequestration differently. FD-CIC quantifies all farming activities associated with production of the feedstock, regardless of when the activity is performed. On the other hand, COMET-Farm predicts CO2e based on activities in a calendar year; not explicitly attributed to a specific crop (however, activities occurring in one year do have some impact on GHG emissions in the following calendar year).



During the Q&A session, it was recommended that corn-corn versus soybean-corn rotations could serve as a good test case to establish guardrails to look at more than just the GHG carbon intensity of a fuel pathway, and that would be a good use of consequential LCA. In response to a question regarding how best to allocate SOC between crops, Dr. Bard noted that she was not sure, but there is a need to have consensus on the approach to get uptake by all in the clean fuels space.

Marie Coffin (CIBO Technologies) discussed the Systems Approach to Land Use Sustainability (SALUS) crop modeling system developed by CIBO that can be used to quantify the carbon footprint of a field. The model uses a mechanistic approach that models the growth of a plant and its interaction with all elements including water, sun, fertilizer, and soil carbon on a daily basis. Outputs from the model include soil carbon and yield based on management practices. This is a process-based model that farmers can use to evaluate the impacts of various farming practices. SALUS includes both a crop module and a soil module, and it can evaluate hypothetical farming practices from conventional to regenerative.

Bin Peng (University of Illinois) discussed a framework for quantifying field-level agricultural carbon outcomes. A key question in the analysis is: How can an accurate, scalable, and cost-effective solution for agricultural carbon evaluation at the field level be achieved? A system-of-systems approach is proposed to handle the complexities of this type of analysis as a single sensor alone, or modeling alone, cannot solve the problem. Additionally, innovative data collection at scale will be important to successfully quantify field-level agricultural carbon emissions.

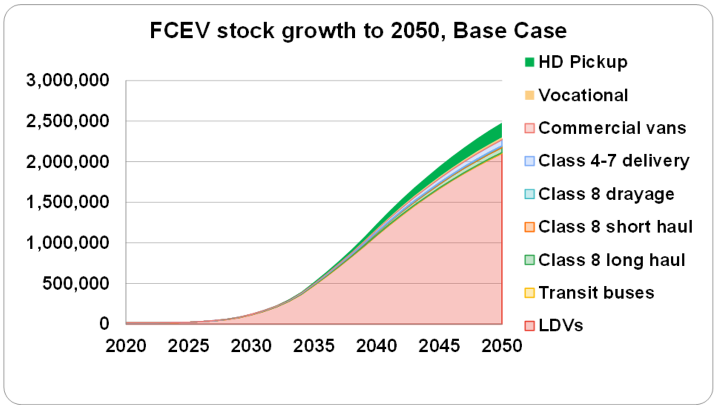


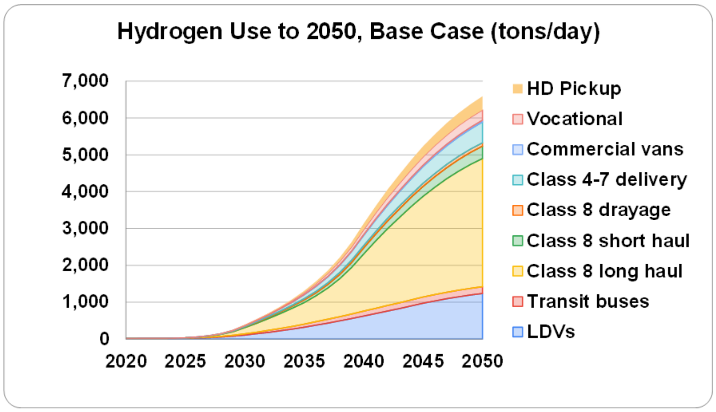
Session 5: Hydrogen

Chairpersons: Anil Prabhu (CARB), Diep Vu (Marathon)

Session 5 included four presentations focused on issues related to hydrogen production and life cycle analysis. Lew Fulton (U.C. Davis) gave a presentation on the California Hydrogen Analysis Project. Rosa Dominguez-Faus (GTI Energy) summarized the Open Hydrogen Initiative (OHI) and the development of an open-source LCA model that will estimate cradle-to-gate GHG emissions from hydrogen production. Paul Doucette (University of Houston) discussed the prospects for building a hydrogen economy in Texas. Finally, Pradeep Vyawahare (Argonne) presented information on modeling GHG emissions from hydrogen production with the GREET model.

Lew Fulton (U.C. Davis – Institute of Transportation Studies) presented the results of an analysis of the potential for hydrogen growth in the on-road transportation sector in California. U.C. Davis is part of the Alliance for Renewable Clean Hydrogen Energy Systems (ARCHES), which is intended to lead California's hydrogen development efforts and participate as part of California's DOE-funded "Hydrogen Hub" project.[7] Large hydrogen demand increases are driven by rapid growth of hydrogen fuel cell vehicles in the California fleet – from near zero today to 100,000+ light-duty vehicles in 2030 and 2 million by 2050; trucks are assumed to grow by similar percentages. ZEV mandates will lead to demand for FCVs as battery electric vehicles may not entirely fill consumer needs, particularly in heavy-duty trucking. Large reductions in hydrogen costs are being predicted as a result of economies of scale, from $12 per kg in 2023 to $5 per kg in 2030.





Some of the key recommendations from this study included:

- Work must progress rapidly, across agencies and stakeholders, to align vehicle/fuel/station rollout to 2030, with ambitious targets.
- Must incentivize both fleet purchases of trucks/buses and construction of stations to serve these; with at least 50 large stations state-wide by 2030.
- Station siting should be established to enable state-wide truck travel.

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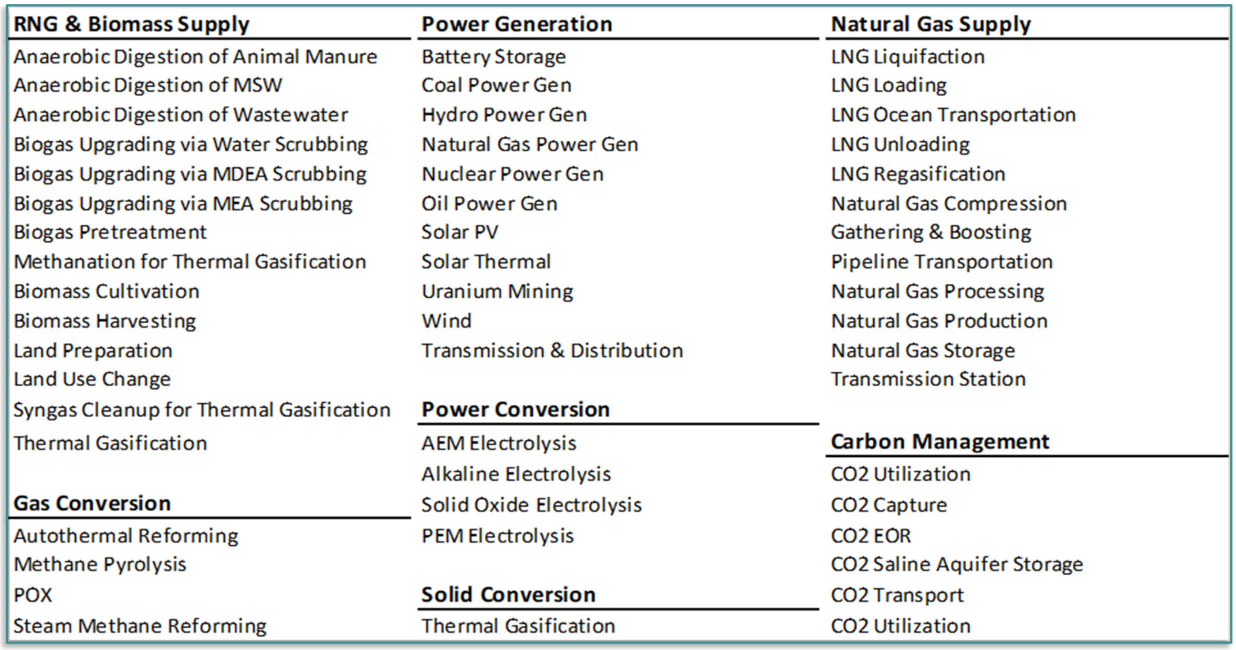
[7] Note that subsequent to the LCA workshop, California was selected as a national Hydrogen Hub, receiving up to $1.2 billion in funding from DOE. See the governor's press release here: https://www.gov.ca.gov/2023/10/13/california-selected-as-a-national-hydrogen-hub/

- Consider encouraging liquid management of hydrogen, with liquid hydrogen being delivered by tanker trucks to larger stations.

Rosa Dominguez-Faus (GTI Energy) summarized the Open Hydrogen Initiative (OHI), which is developing an open-source, spreadsheet-based LCA tool ("OHI Tool") to estimate cradle-to-gate GHG emissions from hydrogen production. The OHI Tool was originally intended to support price benchmarking, not as a regulatory tool. The tool is extremely customizable and models GHG emissions from three primary feedstock conversion routes: (1) solid conversion (e.g., biomass), (2) gas conversion (e.g., natural gas, RNG), and (3) power conversion (i.e., electrolysis). Within each of these pathways, a user can select many different options to best represent the facility being analyzed, as shown in the table below. In addition, different options for carbon management can be modeled. Public availability of the tool is anticipated in the first quarter of 2024.



RNG & Biomass Supply

- Anaerobic Digestion of Animal Manure
- Anaerobic Digestion of MSW
- Anaerobic Digestion of Wastewater
- Biogas Upgrading via Water Scrubbing
- Biogas Upgrading via MDEA Scrubbing
- Biogas Upgrading via MEA Scrubbing
- Biogas Pretreatment
- Methanation for Thermal Gasification
- Biomass Cultivation
- Biomass Harvesting
- Land Preparation
- Land Use Change
- Syngas Cleanup for Thermal Gasification
- Thermal Gasification

Gas Conversion

- Autothermal Reforming
- Methane Pyrolysis
- POX
- Steam Methane Reforming

Power Generation

- Battery Storage
- Coal Power Gen
- Hydro Power Gen
- Natural Gas Power Gen
- Nuclear Power Gen
- Oil Power Gen
- Solar PV
- Solar Thermal
- Uranium Mining
- Wind
- Transmission & Distribution

Power Conversion

- AEM Electrolysis
- Alkaline Electrolysis
- Solid Oxide Electrolysis
- PEM Electrolysis

Solid Conversion

- Thermal Gasification

Natural Gas Supply

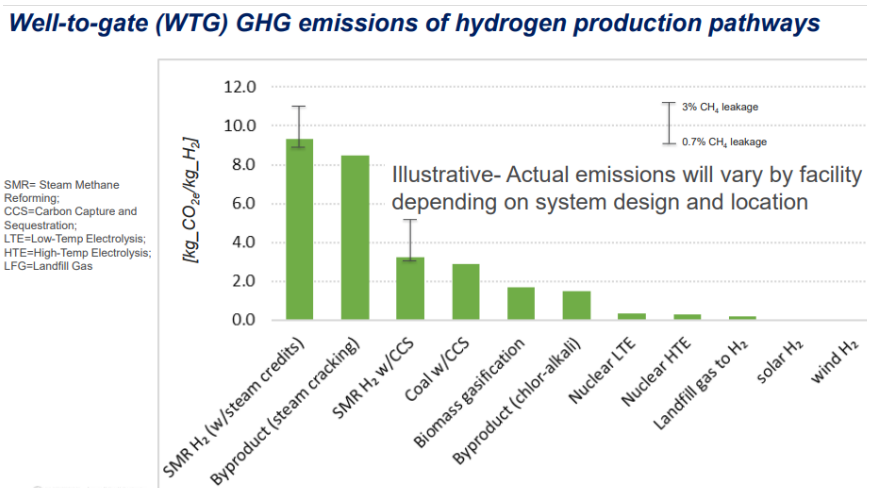
- LNG Liquifaction
- LNG Loading
- LNG Ocean Transportation
- LNG Unloading
- LNG Regasification
- Natural Gas Compression
- Gathering & Boosting
- Pipeline Transportation
- Natural Gas Processing
- Natural Gas Production
- Natural Gas Storage
- Transmission Station

Carbon Management

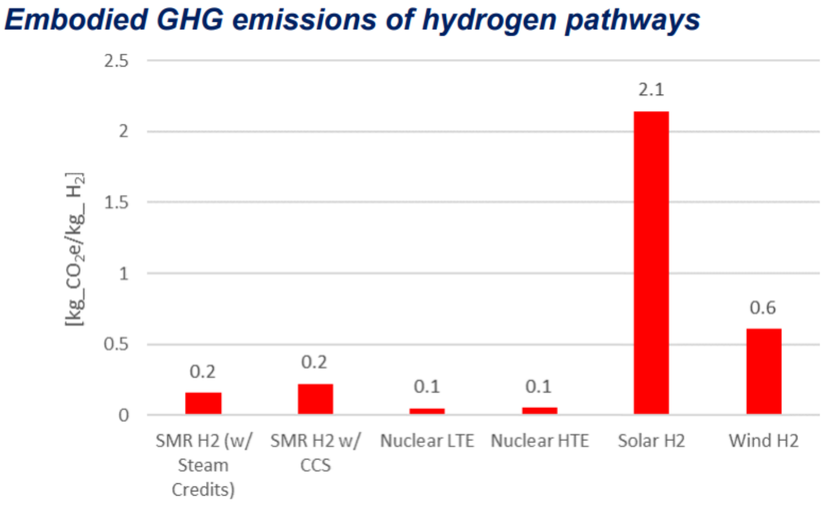
- CO2 Utilization
- CO2 Capture
- CO2 EOR
- CO2 Saline Aquifer Storage
- CO2 Transport
- CO2 Utilization

Paul Doucette (University of Houston) discussed the prospects for developing a hydrogen economy in Texas, which is likely to be kick-started with the $1.2 billion DOE award of the Gulf Coast Hydrogen Hub centered in the Houston region. Dr. Doucette noted that hydrogen is not without its challenges, highlighting the permitting process as being a key element in the build-out of a hydrogen network. Also discussed was the need to engage and develop an energy workforce in disadvantaged communities (DAC), noting the requirement for 40% DAC labor to receive federal funding. While the issues related to the energy transition may be difficult, society needs to find a way to solve them.

Pradeep Vyawahare (Argonne) presented information on modeling GHG emissions from hydrogen production with the GREET model. Highlighted were two federal pieces of legislation that will allow for significant funding for hydrogen projects: the Bipartisan Infrastructure Law (BIL) allocates $8.5 billion for clean hydrogen production and deployment and the Inflation Reduction Act (IRA) provides up to $3 per kg of hydrogen based on well-to-gate carbon intensity, with credits available for a CI less than 4.0 kgCO2e/kgH2.



IRA credits would be available for fossil-based feedstocks (natural gas and coal) as long as CCS is employed. Of note is that the results shown in the figure above do not account for "embodied" emissions, which can be significant for solar-based hydrogen production. This could potentially have implications for credits available through the IRA, although it is not clear if the IRA will consider embodied GHG emissions.[8]



Session 6: Carbon Capture and Utilization (CCU) / eFuels

Chairpersons: Babak Fayyaz (Chevron), Jane O'Malley (International Council on Clean Transportation)

Session 6 consisted of four presentations that addressed various aspects of carbon capture and utilization and eFuels production. Robert Malina (University of Hasselt) and Florian Allroggen (MIT) discussed Power-to-Liquid (PtL) fuels analyzed under the CORSIA guidelines and methodologies. Uisung Lee of Argonne presented information on how carbon utilization in eFuel production is treated in the GREET model. Mihri Ozkan (U.C. Riverside) summarized approaches for direct air capture of CO2. Finally, André Bardow (ETH Zurich) discussed LCA of carbon capture and utilization by carbon mineralization.

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[8] Note that the December 2023 proposed rule implementing "45V" credits for clean hydrogen production does not include embodied emissions in calculating the GHG footprint of hydrogen.

Robert Malina (University of Hasselt) and **Niamh Keogh** on behalf of **Florian Allroggen** (MIT) presented information on PtL fuels and carbon utilization under the CORSIA core LCA method. Net-zero technologies are needed for the aviation sector to achieve climate goals, and strategies to move away from fossil energy carriers will play a significant role in decarbonization strategies. While CORSIA analyses of SAF include drop-in fuels from biomass and waste streams, PtL fuels with alternative carbon sources are insufficiently covered in current CORSIA guidelines. For example, synthetic fuels based on CO2 from DAC or from industrial waste streams are not credited for the CO2 captured, only biogenic CO2 is excluded from the combustion of the fuel.

Two key issues that need to be explored to enable PtL fuels include electricity sourcing and carbon sourcing:

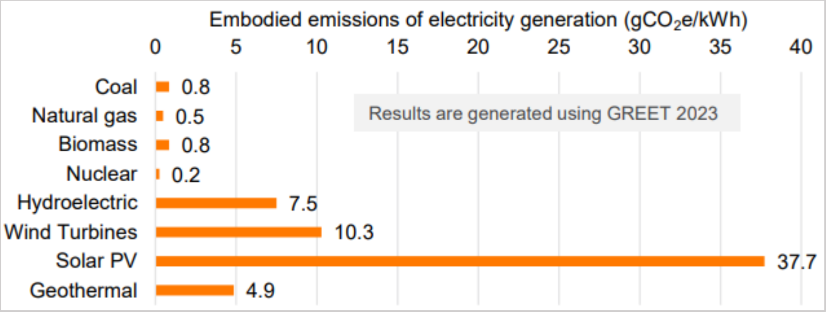
- Electricity sourcing – how should full lifecycle GHG emissions be captured, and how is the source of electricity identified along with implications on the grid (e.g., how to ensure renewable sources are from new generation facilities, i.e., proof of "additionality")?
- Carbon sourcing – limitations in biomass availability may require the use of alternative carbon sources. Should carbon captured from point sources be eligible under CORSIA?

With the increasing use of PtL technologies, a substantial increase in electricity use is expected. For example, ~15,000 TWh of power generation would be needed for the annual production of jet fuel in 2050.[9]

Uisung Lee of Argonne National Laboratory presented options for LCA estimates of CO2 utilization using the eFuel module in GREET. The CCUS pathways in GREET include all applicable supply chains:

- CO2 source (ethanol plants, biomass gasification, natural gas processing, cement plants, natural gas SMR plants, atmospheric DAC, etc.).
- CO2 capture, purification, compression, transmission to fuel production site.
- Conversion of CO2 to fuel via direct methanol synthesis, reverse water gas shift (RWSG) followed by Fischer-Tropsch (FT) synthesis or indirect methanol synthesis, and CO2 electrolysis followed by FT synthesis or gas fermentation.
- Use of the end-product (vehicle, aviation, marine).

The eFuel conversion process requires a significant amount of hydrogen, therefore it is essential to have renewable electricity and hydrogen available. An important issue to consider in the GHG footprint of electricity generation is embodied emissions of the corresponding infrastructure. Fossil-based electricity generation systems generally have a negligible infrastructure impact because of the substantial lifetime of electricity generation. On the other hand, embodied emission impacts of renewable electricity are significant compared to conventional electricity generation systems. In particular, solar PV embodied emissions amount to 37.7 gCO2e/kWh, which,



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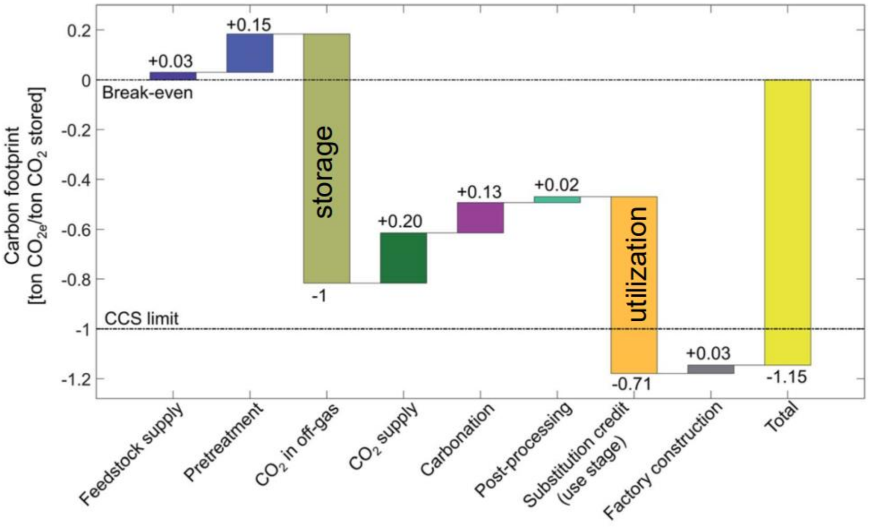
[9] For reference, this reflects about one-half of global electricity production in 2019.

when used for electrolysis of water to produce hydrogen, results in a GHG footprint of 2.1 kgCO2e/kg H2.

Mihri Ozkan (U.C. Riverside) summarized recent literature on direct air capture of CO2. She highlighted the five “pillars” of DAC: (1) capture technology, (2) energy demand, (3) cost, (4) environmental impact, and (5) political support. On a global basis, there are 130 DAC projects currently under development (a couple quite large[10]), with 18 having been completed that capture a total of 11,000 metric tons of CO2 annually.[11] CO2 capture by DAC is much more expensive ($200-$600 per ton) than for industrial sources ($10-$60 per ton) that have much higher CO2 concentrations in flue gas streams. A significant issue in the development of a project is the selection of the heat source for CO2 removal from the collection media as it needs to be continuously available. A choice also needs to be made with respect to the CO2 collection technology, which can be liquid (typically amine-based systems) or solid sorbents. Sold sorbent materials generally require less heat for CO2 extraction but get worn out over time, while liquids can be more readily recycled.

André Bardow (ETH Zurich) presented LCA results of carbon capture and utilization by CO2 mineralization. Rather than input large amounts of energy to “invert” combustion via endothermic reaction(s), e.g., via reverse water gas shift, a mineralization pathway requires much less energy to drive the reaction(s), which are exothermic but have very slow reaction kinetics. In carbon capture by mineralization, CO2 is reacted with metal-oxide and silicon bearing materials (MO-Si) to produce carbonates (MCO3) and silica (SiO2). If the mineralized CO2 is used as input to cement manufacturing, a large negative carbon footprint can be achieved because benefits are realized in the CO2 capture phase and the CO2 utilization phase that is credited with displacing conventional cement feedstock.



Session 7: Electrification

Chairpersons: Robb De Kleine (Ford), Xiaoyi He (Phillips 66)

Session 7 consisted of four presentations that addressed issues related to electric vehicle life cycle analysis, electricity generation, and impacts of the battery supply chain. Nikita Pavlenko (ICCT) compared

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[10] See, for example, the 500,000 tonne-per-year project in the Permian Basin (https://carbonengineering.com/news-updates/direct-air-capture-groundbreaking/)

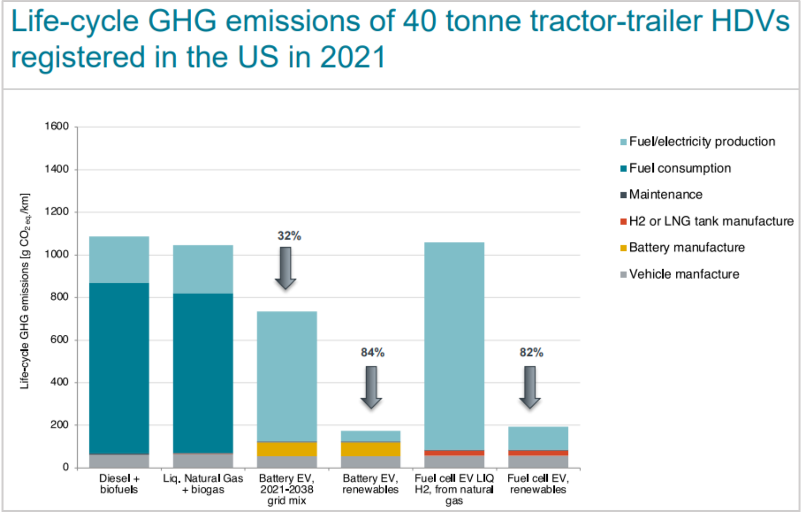
[11] To put 11,000 annual metric tons of CO2 into perspective, that represents tailpipe CO2 emissions from about 3,600 gasoline cars that get 35 mpg and travel 12,000 miles per year.

life cycle analysis of electrification pathways for light-duty and heavy-duty vehicles. Xiaoyi He (Phillips 66) presented an LCA comparison of various fuel pathways for medium-duty and heavy-duty trucks and buses. Ayomipo Arowosola (MIT) compared the impacts of average versus marginal electricity generation for EV recharging. Finally, Fanran Meng (University of Sheffield) presented an analysis of the environmental impacts of the global lithium-ion battery supply chain.

Nikita Pavlenko (ICCT) presented an update to ICCT's 2021 report on a global comparison of life cycle GHG emissions of combustion engine and electric passenger cars.[12] The updated analysis compared the impacts of different light-duty and heavy-duty vehicle powertrains that could be used to decarbonize the U.S. road transport sector. The analysis was performed on a well-to-wheels basis using the GREET model, with updates to better reflect real-world operation of plug-in hybrid electric vehicles (PHEVs) and new assumptions regarding HDV lifetime and performance. Four fuels were assessed: diesel/biofuel blends, natural gas, hydrogen, and electricity.

The primary findings of the study were:

- Battery electric HDVs registered in 2021 provide lifetime GHG emissions reductions of 32% to 47% compared to their respective diesel versions.
- Fuel cell EVs can provide large GHG savings compared to fossil fuel ICEVs but the GHG intensity of the hydrogen feedstock is critical. Using fossil natural gas hydrogen in fuel cell EVs can result in GHG savings as small as 4% compared to the fossil fuel version (specifically, the 40 tonne tractor-trailer).
- Natural gas-powered vehicles – at best – provide minor GHG savings compared to fossil fuel ICEVs; at worst they cause GHG emission increases.



Xiaoyi He (Phillips 66) presented results of a GHG life cycle analysis and total cost of ownership (TCO) analysis for diesel, renewable diesel, battery electric, hydrogen fuel cell, natural gas, and renewable natural gas (RNG) technologies used in heavy- and medium-duty vehicles.

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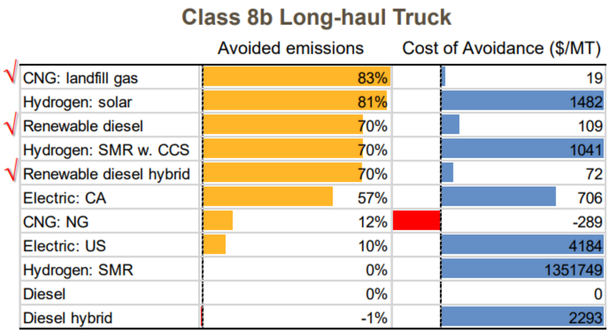
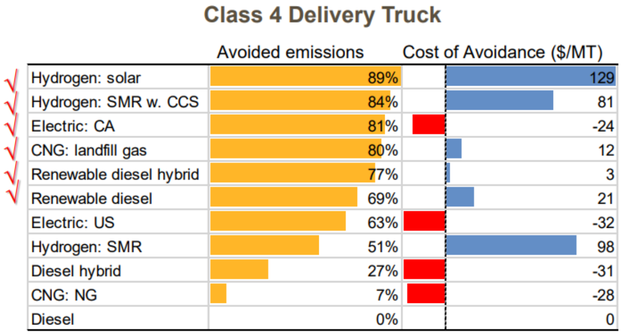
[12] See https://theicct.org/sites/default/files/publications/Global-LCA-passenger-cars-jul2021_0.pdf.



Class 8b Long-haul Truck

		Avoided emissions	Cost of Avoidance ($/MT)
✓	CNG: landfill gas	83%	19
	Hydrogen: solar	81%	1482
✓	Renewable diesel	70%	109
	Hydrogen: SMR w. CCS	70%	1041
✓	Renewable diesel hybrid	70%	72
	Electric: CA	57%	706
	CNG: NG	12%	-289
	Electric: US	10%	4184
	Hydrogen: SMR	0%	1351749
	Diesel	0%	0
	Diesel hybrid	-1%	2293

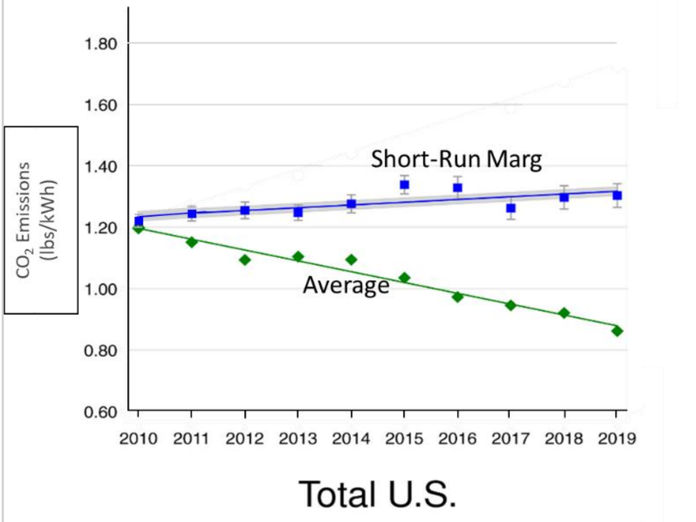


Class 4 Delivery Truck

		Avoided emissions	Cost of Avoidance ($/MT)
✓	Hydrogen: solar	89%	129
✓	Hydrogen: SMR w. CCS	84%	81
✓	Electric: CA	81%	-24
✓	CNG: landfill gas	80%	12
✓	Renewable diesel hybrid	77%	3
✓	Renewable diesel	69%	21
	Electric: US	63%	-32
	Hydrogen: SMR	51%	98
	Diesel hybrid	27%	-31
	CNG: NG	7%	-28
	Diesel	0%	0

The analysis included embodied emissions associated with vehicle manufacturing as well as fuel pathway emissions. The study found that renewable diesel and renewable natural gas consistently reduce GHG emissions at a relatively low cost and do not require change of powertrain, but these pathways are dependent on low-CI feedstock. Given the difficulties in electrification of heavy, long-distance vehicles (e.g., compromised fuel economy advantages because of large battery packs and highway driving), renewable diesel and renewable natural gas are appealing options for heavy, long-distance applications. Battery EVs and hydrogen FCVs are feasible for work trucks, medium-duty trucks, and urban trucks and buses. However, incentives may be needed for hydrogen FCVs to balance their higher fuel costs.

Ayomipo Arowosola (MIT) discussed the impacts of average versus marginal electricity generation on the GHG footprint of electric vehicles. While average electricity emission rates have been decreasing over time, demand is increasing, and fossil sources are often used to make up for the shortfall on a marginal basis. The short-run marginal electricity emission rates are almost always higher than the average emission rate in an area because natural gas is typically the marginal source. That said, continuous grid decarbonization will lead to reductions in the short-run marginal emission rates, and EV charging presents opportunities for optimization, leading to potential emissions savings.



Emission Rates trend in the U.S. – Average & Short-Run Marg

Fanran Meng (University of Sheffield) presented estimates of the environmental impacts of the global lithium-ion battery supply chain from a temporal, geographical, and technological perspective. As policies are put in place that incentivize or require the implementation of EVs, there will be a massive demand for lithium-ion batteries. As a result, understanding and mitigating the environmental impacts is essential for a sustainable low-carbon economy transition. In general, nickel-based chemistries[13] (NCX) have a GHG footprint of about 80 kgCO2e/kWh, whereas lithium-iron-phosphate (LFP) batteries have a

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[13] For example, lithium-nickel-manganese-cobalt-oxide and lithium-nickel-cobalt-aluminum.

GHG footprint of about 55 kgCO2e/kWh.[14] Emissions are highly regionally specific, with NCX battery emissions concentrated in China (45%), Indonesia (13%) and Australia (9%), and LFP battery emissions concentrated in China (57%), Australia (17%) and Chile (5%). Over time, it is expected that the GHG emissions of both battery chemistries will decrease, primarily as a result of electricity sector decarbonization in the regions where the batteries are produced.

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[14] To put these numbers into perspective, an 80 kWh battery pack (~250-mile range @ ~0.30 kWh/mi) would have a GHG footprint of 64 gCO2e/mi for the NCX battery and 44 gCO2e/mi for the LFP battery over a 100,000-mile life.

Appendix
Glossary of Terms Used During the Workshop

ADAGE	Applied Dynamic Analysis of the Global Economy (model)
AEO	Annual Energy Outlook
AEZ	Agricultural Ecological Zone
ALCA	Attributional Life Cycle Assessment
ANL	Argonne National Laboratory
ATR	Auto Thermal Reformer
BEPAM	Biofuel and Environmental Policy Model
BEV	Battery Electric Vehicle
CAEP	Committee on Aviation Environmental Protection
CTG	Cradle-to-Grave
CARB	California Air Resources Board
CCLUB	Carbon Calculator for Land Use and Land Management Change from Biofuels Production (GREET module)
CCS	Carbon Capture and Sequestration
CCUS	Carbon Capture, Utilization and Storage
CEF	CORSIA Eligible Fuel
CFR	Clean Fuel Regulation (Canada)
CGE	Computable General-Equilibrium
CI	Carbon Intensity (also Compression Ignition)
CI-LUC	Carbon Intensity from Land Use Change
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
DAC	Direct Air Capture and Disadvantaged Communities
DOE	(US) Department of Energy
EC	European Commission
ECCC	Environment and Climate Change Canada
EDF	Environmental Defense Fund
EF	Emission Factor
EIA	(US) Energy Information Administration
EISA	(US) Energy Independence and Security Act (2007)
EPA	(US) Environmental Protection Agency
EPAct	(US) Energy Policy Act (2005)
ETS	(EU) Emission Trading System
EU	European Union
EV	Electric Vehicle
FAA	(U.S.) Federal Aviation Administration
FAO	(UN) Food and Agricultural Organization
FAPRI	Food and Agricultural Policy Research Institute

FASOM	Forest and Agricultural Sector Optimization Model
FCEV	Fuel Cell Electric Vehicle
FD-CIC	Feedstock Carbon Intensity Calculator (GREET module)
FT	Fischer-Tropsch
gCO2e/MJ	grams of CO2 equivalents per MJ of fuel
GCAM	Global Change Assessment Model
GDP	Gross Domestic Product
GGE	Gasoline Gallon Equivalent
GHG	Greenhouse Gas
GLOBIOM	Global Biomass Optimization Model (LCA model used in EU)
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model
GTAP	Global Trade and Analysis Project (econometric model)
GTAP-BIO	GTAP model modified to represent biofuels
GWI	Global Warming Intensity
GWP	Global Warming Potential
HDV	Heavy Duty Vehicle
HEFA	Hydro-processed Esters and Fatty Acids
HEV	Hybrid Electric Vehicle
ICAO	International Civil Aviation Organization
ICCT	International Council on Clean Transportation
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
IEA	International Energy Agency
IFPRI	International Food Policy Research Institute
IIASA	International Institute for Applied Systems Analysis
ILUC	Indirect (or Induced) Land Use Change
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
IRA	Inflation Reduction Act
ISO	International Organization for Standardization
JRC	(EC) Joint Research Centre
kgCO2e/kgH2	Kilograms CO2-equivalents per kilogram Hydrogen
LCA	Life Cycle Assessment
LCAF	Lower Carbon Aviation Fuel
LCFS	Low Carbon Fuel Standard (California regulation)
LCI	Life Cycle Inventory
LCOD	Levelized Cost of Driving
LDV	Light-Duty Vehicle
LFP	Lithium-Iron-Phosphate battery chemistry
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LUB	Land Use and Biodiversity
LUC	Land Use Change
MCE	(EPA) Model Comparison Exercise

MMT	Million Metric Ton
MSW	Municipal Solid Waste
NBB	National Biodiesel Board
NCX	Nickel-based Li-Ion battery chemistries
NEEA	(Brazil) Energy-Environment Efficiency Grade
NETL	(DOE) National Energy Technology Laboratory
NGV	Natural Gas Vehicle
NGO	Non-Governmental Organization
NRC	Natural Resources Canada
NREL	National Renewable Energy Laboratory
OHI	Open Hydrogen Initiative
PHEV	Plug-in Hybrid Electric Vehicle
PNNL	Pacific Northwest National Laboratory
PtL	Power-to-Liquids
PV	Photo-Voltaic (solar electricity)
RD	Renewable Diesel
RED	Renewable Energy Directive
RFA	Renewable Fuels Association
RFR	Renewable Fuels Regulation (Canada)
RFS	Renewable Fuels Standard
RIN	Renewable Identification Number
RNG	Renewable Natural Gas
SAE	Society of Automotive Engineers
SAF	Sustainable Aviation Fuel
SCS	Sustainability Certification Scheme
SMC	(CRC) Sustainable Mobility Committee
SMR	Steam Methane Reforming
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
TEA	Techno-Economic Assessment
UCS	Union of Concerned Scientists
UNFCCC	U.N. Framework Convention on Climate Change
USDA	U.S. Department of Agriculture
WTG	Well-to-Gate
WTW	Well-to-Wheels (or Well-to-Wake)