Summary Report

7^{th} CRC Workshop on Life Cycle Analysis of Transportation Fuels

Virtual Workshop

October 19-22, 2021

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.

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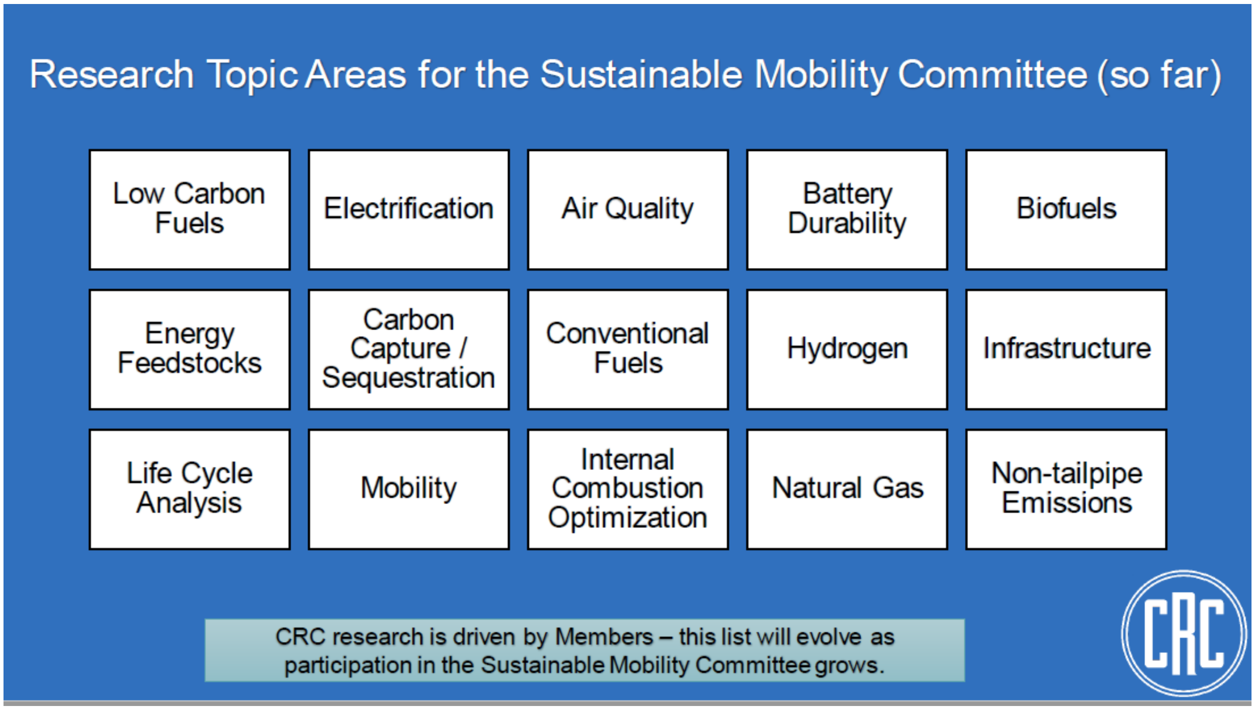
A. Introduction

The 7th bi-annual Coordinating Research Council (CRC) Workshop on Life Cycle Analysis of Transportation Fuels was held as a virtual event on October 19-22, 2021. The workshop was co-sponsored by Argonne National Laboratory, Canadian Fuels Association, National Biodiesel Board, Ohio Soybean Council, Renewable Fuels Association, Union of Concerned Scientists, Bioenergy Technology Office (BETO) of the U.S. Department of Energy, and the U.S. Environmental Protection Agency. The four generalized goals for this Workshop were the same as those of previous Workshops:

- Outline technical needs arising out of policy actions and the ability of LCA analysis to meet those needs.
- 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.
- Identify data gaps, areas of uncertainties, validation/verification, model transparency, and data quality issues.
- Present LCA results of emerging vehicle technologies and fuels.
- Establish priorities for directed research to narrow knowledge gaps and gather experts' opinions on where scarce research dollars would best be spent.

There were 161 registrants for this Workshop, which is about 50% higher than the number of attendees at previous, in-person workshops. A large majority of registrants were from the U.S., although significant numbers also were from Canada (~20%) and Europe (~8%). These registrants represented government bodies (including National Laboratories), industry, academia, and non-governmental organizations (NGOs). Twenty-eight technical presentations were given, organized into six Technical Sessions. Following each Technical Session, a number of Interactive Sessions were held, allowing the Workshop speakers and attendees to interact directly. Although a Friday session on land-use change (LUC) was optional, it attracted 95 participants and considerable interactive discussion, underscoring the enduring interests to improve understanding and estimation of LUC effects of transportation fuels.

Prior to the first Technical Session, a brief introduction to CRC's new Sustainable Mobility Committee (SMC) was provided by Heather Hamje of ExxonMobil (and current Chair of CRC). The SMC, which was formed in March 2021, expands the focus of CRC beyond the traditional topics of mutual interest to the vehicle/equipment manufacturers and fuel industries. The Committee intends to focus on research related to carbon-neutral transportation. In addition to the CRC sustaining Members, other technical organizations from government, industry, and academia are invited to join the SMC. An initial list of research topic areas being considered by the Committee is shown in the figure below. The CRC LCA Panel, which has been responsible for organizing this series of bi-annual LCA Workshops, will now become the Life Cycle Analysis Working Group of the SMC.



Research Topic Areas for the Sustainable Mobility Committee (so far)

Low Carbon Fuels	Electrification	Air Quality	Battery Durability	Biofuels
Energy Feedstocks	Carbon Capture / Sequestration	Conventional Fuels	Hydrogen	Infrastructure
Life Cycle Analysis	Mobility	Internal Combustion Optimization	Natural Gas	Non-tailpipe Emissions

CRC research is driven by Members – this list will evolve as participation in the Sustainable Mobility Committee grows.

This Workshop Summary Report 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

Given below are brief overall impressions, highlights, and conclusions from each Technical Session of the LCA Workshop. This list is not comprehensive, but attempts to capture the most important observations, significant take-home messages, and common themes that emerged from the information presented.

Session 1: Policy Updates

- LCA-based policies to promote low-carbon transportation fuels are becoming more widespread throughout the world. At this workshop, programs within the U.S., Canada, Europe, Brazil and international organizations (ICAO and IMO) were discussed.

- The U.S. federal Renewable Fuel Standard (RFS) Program has now been in effect for 10-years. The EPA is expected to make several decisions about the future of the program related to the eligibility of bio-intermediate feedstocks, renewable electricity, renewable hydrogen, and setting volumes beyond 2022.

- California's Low Carbon Fuel Standard (LCFS) program has stimulated growth of many low-CI fuels, both within and outside the State, including renewable diesel (RD), renewable natural gas (RNG), and sustainable aviation fuels (SAF). Additionally, ultra-low CI fuels, which are produced from waste materials and may include carbon capture and sequestration (CCS), are becoming more common.

- The Canadian Clean Fuel Standard (CFS), which has many similarities to the LCFS program, is expected to be finalized in the first half of 2022, and become effective near the end of 2022. This will require a 13% CI reduction compared to the 2016 baseline to be met by 2030.

- A Brazilian national biofuels policy, called RenovaBio, has been in place for two years. This policy has several similarities to LCFS, including requirements for gradual CI reduction and establishment of a financial market for biofuels credits.

- The Renewable Energy Directive (RED II) calls for CI reduction of European transportation fuels. A number of changes are now being considered to RED II to address the EC's recently announced climate change package, called "Fit for 55."

- The International Maritime Organization (IMO) is considering various approaches to reduce the carbon footprint of the global shipping sector. Options being discussed include use of LCA to assess GHG emissions on a full well-to-wake (WTW) basis.

- The CORSIA program of the International Civil Aviation Organization (ICAO), implemented to help the international aviation sector achieve its carbon neutral growth goal, is continuing to evolve. LCA methods are used to determine both direct (core) and indirect CI values for aviation fuels. This approach is being used to evaluate the GHG reduction benefits of SAF produced from different feedstocks and production pathways.

Session 2: Biofuel

- The lifecycle carbon intensity assigned to biofuels produced from forest residues depends upon the type of forest management practices that are assumed in counterfactual cases. Allowing these residues to remain on the forest floor results in the highest overall GHG emissions for the system, due to methane produced through normal decay processes.

- Increasing soil carbon by sustainable farming practices is an increasingly attractive GHG mitigation strategy. Improved measurement and modeling methods are being developed to estimate soil carbon levels in different situations, and to reduce the uncertainties in these estimates.

- Through their ARPA-E organization, DOE is supporting work that could transform the agricultural sector from a net contributor of GHG emissions to a net sink. The TERRA/ROOTS and SMARTFARM programs are intended to increase carbon sequestration in soil and mitigate emissions through various improvements in farming practices. The program also funds efforts to monitor and measure N_2O fluxes and SOC changes on different farms.

Session 3: Sustainable Farming

- The importance of agriculture with respect to GHG mitigation is gaining attention. The California Department of Food and Agriculture (CDFA) has implemented a Healthy Soils Program (HSP) that incentivizes farmers and ranchers to utilize prescribed management practices that improve soil health, sequester carbon in the soil, and reduce GHG emissions.

- Considerable work is underway to improve understanding of how farming practices and land management changes impact soil carbon levels and GHG emissions at the farm level. This degree of specificity is necessary to support an effective incentive/credit program (either via biofuel regulations or standalone programs) that rewards farmers for adopting improved agricultural practices.

- A soil organic carbon (SOC) modeling tool is being developed by Argonne National Laboratory (ANL) for use with their GREET model in calculating a biofuel's lifecycle CI value. This tool utilizes a parameterized version of the process-level CENTURY model to relate SOC changes to land management changes (LMC). With further development, it is possible that this approach could be used to quantify (and monetize) reduced CI benefits of farm-level LMC.

Session 4: Carbon Capture and Utilization

- Carbon capture, utilization, and storage (CCUS) is increasingly being emphasized as a significant GHG emissions mitigation strategy. In the International Energy Agency (IEA) roadmap to achieve a net zero global energy system, CCUS is projected to remove about 11% of all energy-related GHG emissions by 2035, and 21% by 2050.

- An LCA study has been conducted to investigate the CI value of diesel fuel produced by Fischer-Tropsch synthesis using CO_2 from direct air capture (DAC) and H_2 from electrolysis. Results ranged from 10 to 30 g CO_{2eq}/MJ of diesel, depending upon the type of calciner used in the DAC process. Sensitivity analyses showed the results to depend upon the carbon intensity of the grid electricity used in the various processes.

- The term "Blue Hydrogen" is used to describe H_2 produced from methane using the steam methane reforming (SMR) process with the SMR-produced CO_2 being captured. An LCA study has shown that the carbon intensity of Blue H_2 varies greatly, depending upon the processes and assumptions that are used. Without CCS, existing SMR processes produce H_2 with a CI value of approximately 80 g CO_{2eq}/MJ H_2. This could be reduced by 50% (or more) by using an autothermal refining (ATR) process in place of SMR.

- Production of industrial chemicals using CO_2 captured from readily-available sources is being investigated (using LCA) as a possible GHG mitigation strategy. Ten of 12 production pathways investigated showed some potential for GHG reduction, but only two (polyether polyols and formic acid from hydrogenation) indicated large enough reductions to be commercially attractive.

Session 5: Electrification

- Increasingly complex LCA modeling is being used to assess GHG emissions and other environmental impacts of potential vehicle electrification scenarios. The results are highly dependent upon modeling assumptions. In general, significant lifecycle GHG emission reductions are projected to result from electrification – for both plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs). These benefits are projected to increase in the future, as the carbon intensity of the electrical grid is reduced.

- Three different LCA studies presented by Ricardo, ICCT, and ANL all indicated that lifecycle GHG emissions of current generation gasoline ICE, PHEV, and BEV midsize vehicles are approximately 250, 150, and 100 g CO_{2eq}/km traveled, respectively. Current hydrogen fuel cell electric vehicles (HFCEVs) have lifecycle GHG emissions ranging from 50 to 150 g CO_{2eq}/km, depending upon the process used to produce the hydrogen.

- An economic assessment by ANL indicated that the levelized cost of driving (LCOD) for current technology midsize gasoline vehicles is approximately \$0.45/mile (excluding taxes), while LCOD of BEVs and FCEVs is \$0.60-0.80/mile. However, this disparity is expected to narrow in the future, reaching near parity by 2030 due to significant reductions in battery costs.

Session 6: Land Use Change

- Emission factors and carbon intensities assigned to different land management options over time are complex and difficult to generalize. Several studies are underway to improve understanding of where and how much land use change (LUC) really occurs, distinguish the degree of attribution among multiple social, political, and economic drivers for this LUC, and how actual behaviors differ from assumptions used in earlier LUC modeling.

- Because induced (or indirect) land use change (ILUC) is not directly observable, models must be used to estimate ILUC and its GHG impacts. The GTAP-BIO model and database, which have long been used in conducting ILUC assessments, are undergoing significant updates that are expected to improve applicability and reliability in LCA studies of biofuels policies. Recent statistical analyses of the relationships among ethanol production and markets over the past 30 years raise questions about several ILUC modeling assumptions.

- While ILUC modeling continues to improve with respect to methodologies, data, and applications, a significant amount of inherent uncertainty remains. An example of this relates to variations in how land uses are categorized in different model applications. The choices made regarding land representation can result in large differences in calculated lifecycle CI values of biofuels.

C. Highlights and Learnings from Individual Presentations

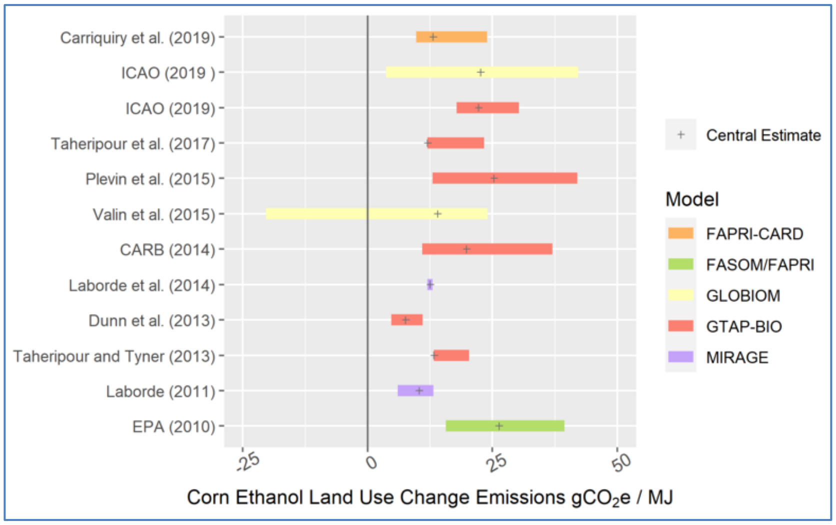
Session 1: Policy Updates

Chairpersons: Aaron Levy (EPA) and Michael Wang (Argonne National Laboratory)

Session 1 consisted of eight 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. Aaron Levy of the U.S. EPA discussed the Renewable Fuel Standard (RFS) and provided his thoughts about progress over the past decade. Cheryl Laskowski of the California Air Resources Board (CARB) presented an update on California's Low Carbon Fuel Standard (LCFS) program. Don O'Connor (independent consultant) summarized the Canadian Clean Fuel Standard (CFS) program that is expected to become effective next year. Jacob Teter of the International Energy Agency (IEA) provided an update on fuels regulations within the European Commission's (EC) climate package. Marcelo Morandi of Embrapa Environment explained the Brazilian national fuels policy, called RenovaBio. Bryan Comer of the International Council on Clean Transportation (ICCT) discussed efforts by the International Maritime Organization (IMO) to reduce GHG emissions from the shipping sector. Jim Hileman of the U.S. Federal Aviation Administration (FAA) summarized efforts to offset GHG emissions by the International Civil Aviation Organization (ICAO). Finally, Stephanie Searle of ICCT summarized land use change (LUC) emissions results from application of various low-carbon fuel policies around the world.

Aaron Levy (U.S. EPA) provided an update on the U.S. Renewable Fuel Standard (RFS) program. The basic structure of this program is unchanged since its origination under the 2005 Energy Policy Act (EPAct) and revision under the 2007 Energy Independence and Security Act (EISA). To qualify under the RFS program, a fuel must be produced from renewable biomass feedstocks and must meet specified GHG emission reduction targets – on a lifecycle basis – compared to a 2005 baseline. According to the statutory definition, "The term 'lifecycle GHG emissions' means the aggregate quantity of GHG (including direct emissions and significant indirect emissions, such as significant emissions from land use changes), as determined by the Administrator, related to the full fuel lifecycle …" To date, EPA has approved over 200 renewable fuel pathways for generation of Renewable Identification Number (RIN) credits. Each pathway involves semi-consequential LCA modeling of a unique combination of feedstock, production process, and final fuel.

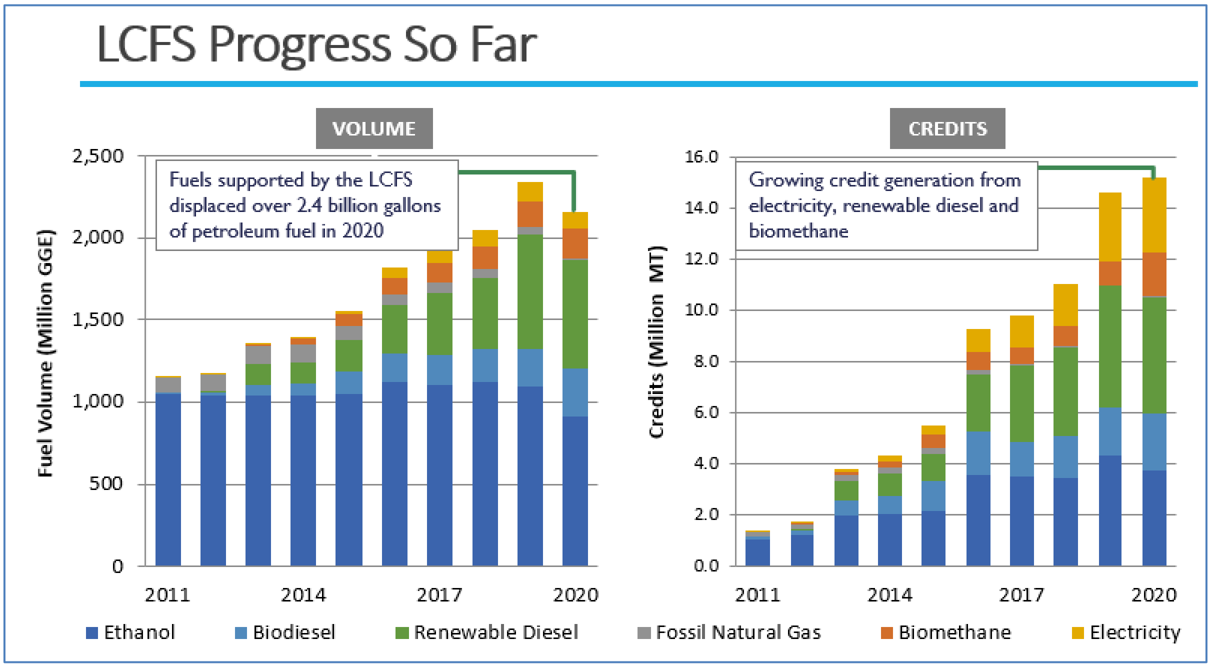
Levy mentioned a few general observations from over 10-years of experience with the RFS Program. Over this period, progress has been made in many areas of modeling, although the greatest sources of uncertainty continue to be modeling of land use change (LUC) and market-mediated effects. Certain long term agricultural trends are occurring, such as crop yield increases and more efficient uses of fertilizers and pesticides. These trends should be considered in



future, updated LCA modeling. Additionally, if farm-level practices for reducing GHG emissions are to be incentivized, some reliable means of monitoring and verification must be developed. Despite all the changes in modeling approaches and assumptions, the direct carbon intensity (CI) of corn ethanol originally determined by EPA in 2010 (45-48 g CO_{2eq}/MJ) remains a reliable estimate. Much more variation (and controversy) surrounds the portion of CI resulting LUC. The figure shows the range (and central estimates) of CI values attributed to induced (or indirect) land use change (ILUC) for corn ethanol as modeled by numerous individuals and organizations. EPA's original 2010 estimate lies towards the high end, but is not extremely different from most of the other estimates.

EPA continues to be involved in advancement of LCA modeling tools and applications. Pathways including production of hydrogen and electricity from renewable biomass are being considered. Considerable effort is underway within EPA and DOE to incorporate sustainable aviation fuel (SAF) within the RFS Program. In addition, LCA is being utilized in efforts to decarbonize marine fuels, evaluate incentive policies, and consider GHG emissions associated with vehicle production.

Cheryl Laskowski [California Air Resources Board (CARB) presented a status report on California's Low Carbon Fuel Standard (LCFS) Program. LCFS was adopted in 2009 and first implemented in 2011. The primary goals of LCFS are to reduce the carbon intensity (CI) of transportation fuels and to diversify the fuel mix within California. Additionally, LCFS supports a broad range of climate-related goals within the State, including promotion of zero emission vehicles (ZEVs), cleaner freight and goods movement, increased use of renewable power, and more. The program requires gradual, year-by-year reductions in CI of California's total transportation fuel pool, until reaching 20% reduction in the year 2030 (compared to a 2010 baseline). The CI reduction target for the current year (2021) is 8.75%. Achieving the required CI reduction for each year is accomplished by combining sufficient volumes of low CI fuels (which generate credits) with high CI fuels (which generate deficits). A market for LCFS credits has been established, whereby fuel suppliers can purchase available excess credits to help meet their LCFS requirements. In 2020, over $4 billion in credit transfers occurred within California, with an average credit price of approximately $200/ton CO_{2eq}.


LCFS Progress So Far

Fuels supported by the LCFS displaced over 2.4 billion gallons of petroleum fuel in 2020

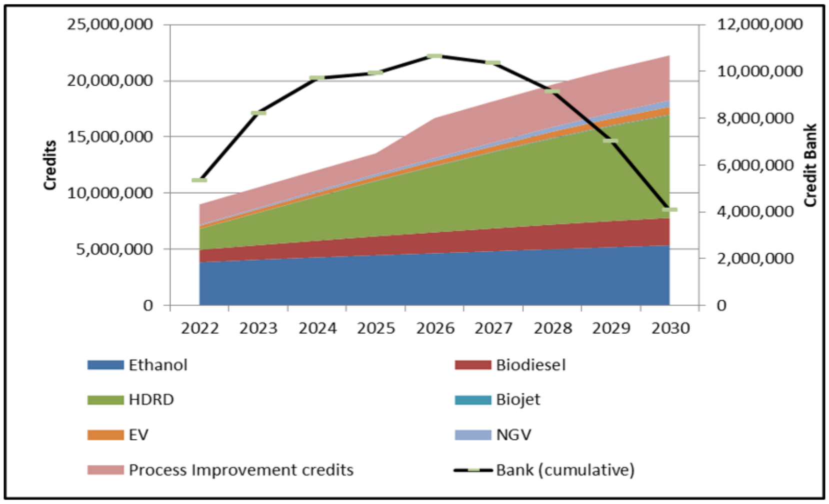
Growing credit generation from electricity, renewable diesel and biomethane

As shown in the figure above, the volume of credit-generating fuels and the total value of credits have both grown substantially since the LCFS Program began. Initially, ethanol was the dominant credit-generating fuel, but now biodiesel, renewable diesel (RD), biomethane, and electricity have all become significant. Currently, there is great momentum for growth of both RD and SAF in California, with several major fuel providers (ExxonMobil, Phillips 66, Marathon, and others) having announced plans to enter this market.

Ultra-low CI fuels are also beginning to enter the market. Most of these fuel pathways involve anaerobic digestion of animal manure for production of renewable natural gas (RNG), electricity, and H_2. Due to the avoidance of methane emissions otherwise resulting from manure decomposition, these fuels can have negative CI values, making them extremely valuable in meeting LCFS requirements. Carbon capture and sequestration (CCS) is also being used in fuel pathways to lower the CI value of fuels. For example, the CI value of corn ethanol can be reduced by 25-30 g CO_{2eq}/MJ by recovering and sequestering the CO_2 that is emitted during the fermentation process. Finally, a critical component of the LCFS Program is the requirement for 3rd party verification of all fuel pathways, which includes the application of LCA. Currently, 624 fuel pathways have been certified in California.

Don O'Connor (Consultant) described the Canadian Clean Fuel Standard (CFS) Program that was first outlined in 2016 and is expected to become effective by the end of 2022. Although a draft regulation was published in 2020, the final regulation is not yet approved, so some details are still likely to change. This program will require a 13% reduction in CI of liquid fuels, relative to a 2016 baseline, by 2030. Similar to the California LCFS, credits can be generated for fuels and processes that reduce CI values. In the CFS Program, three categories of credits are defined:

1. Category 1 credits apply to the actions that reduce the CI of fossil fuels throughout their lifecycle. Examples include use of CCS, integration of renewable electricity into the lifecycle, application of enhanced oil recovery (EOR), and co-processing of biocrude materials in refineries.
2. Category 2 credits apply to the generation and supply of low-carbon fuels, such as ethanol, biodiesel (BD), renewable diesel (RD), and biojet fuel. To qualify, fuels must meet a CI reduction threshold value, as determined using either an LCA model for a particular facility/ pathway or default values defined in the regulation. The Fuel LCA Model (which is not yet released) will contain pre-defined fuel pathways, but will also allow users to create new pathways based on their specific processes. Because the Fuel LCA Model uses higher heating values (HHV) rather than lower heating values (LHV), and uses an energy allocation scheme for co-products (in most cases), the CI values for biofuels are expected to differ from those derived using the GREET model and in California LCFS.



3. Category 3 credits apply to end-user fuel switching, such as conversion to vehicles operating on natural gas (NG), renewable natural gas (RNG), H_2, electricity, etc.

The Canadian CFS Program will included a compliance funds mechanism somewhat similar to California's LCFS credit market. However, the credit price will be capped in the regulation. The proposed regulation set a price cap of $350 (Canadian) per ton of CO_{2eq}. One potential market response to the CFS Program is shown in the figure above. Dramatic growth in renewable diesel (here called HDRD) is projected. Total available credits are expected to grow during the first few years, then decline as they are used to satisfy compliance requirements in later years.

Jacob Teter [International Energy Agency (IEA)] discussed several proposed revisions to alternative fuel legislation that are part of the European Commission's (EC's) recently announced climate package known as "Fit for 55." (This name refers to the goal of 55% GHG reduction by 2030.) Revisions affecting three transportation sectors were summarized: road and rail, aviation, and marine. To address the road and rail sector, the Renewable Energy Directive (RED) was originally introduced in 2009, and was modified to RED II in 2018. Among other requirements, RED II called for Member States (MS) to reduce the CI of transport fuels by 6% (relative to a 2010 baseline) by 2020, with LCA being used to assess attainment of this goal. RED II also includes requirements regarding use of renewable fuels of non-biological origin (RFNBO), use of advanced biofuels, caps on food- and feed-based fuels, and numerous other provisions. Changes to many of the RED II provisions are now being proposed as part of the Fit for 55 effort. The table below was presented to summarize many of these proposed changes.

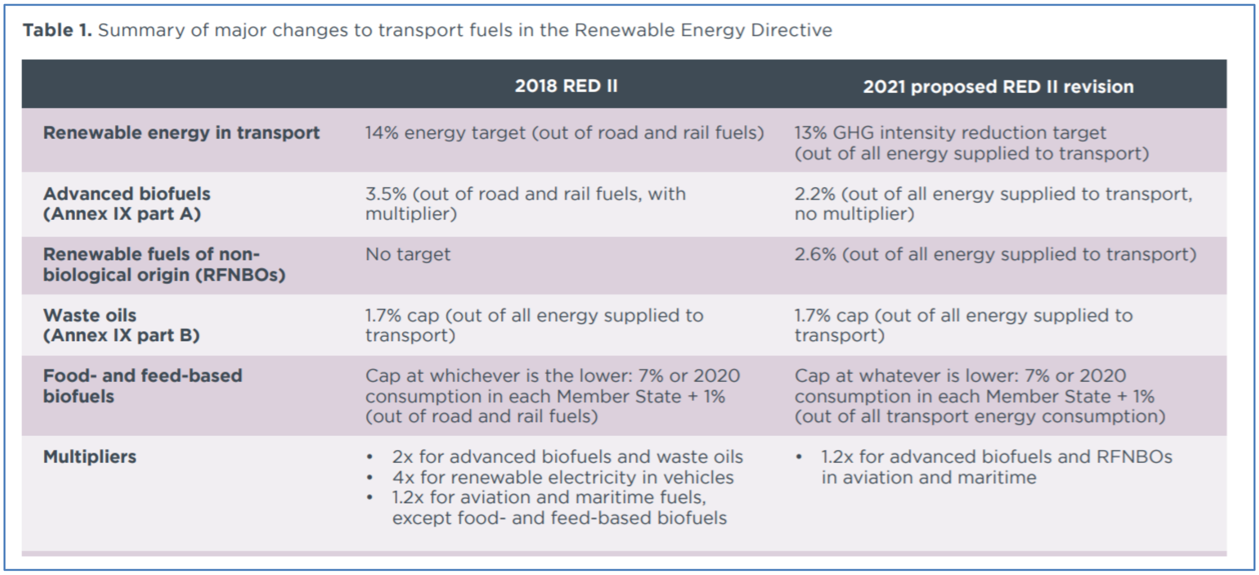


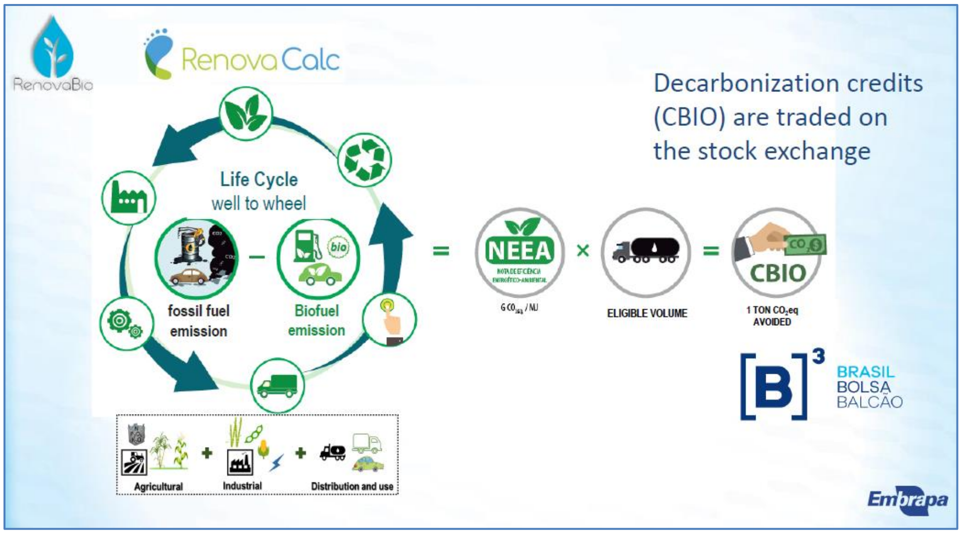
Table 1. Summary of major changes to transport fuels in the Renewable Energy Directive

	2018 RED II	2021 proposed RED II revision
Renewable energy in transport	14% energy target (out of road and rail fuels)	13% GHG intensity reduction target (out of all energy supplied to transport)
Advanced biofuels (Annex IX part A)	3.5% (out of road and rail fuels, with multiplier)	2.2% (out of all energy supplied to transport, no multiplier)
Renewable fuels of non-biological origin (RFNBOs)	No target	2.6% (out of all energy supplied to transport)
Waste oils (Annex IX part B)	1.7% cap (out of all energy supplied to transport)	1.7% cap (out of all energy supplied to transport)
Food- and feed-based biofuels	Cap at whichever is the lower: 7% or 2020 consumption in each Member State + 1% (out of road and rail fuels)	Cap at whatever is lower: 7% or 2020 consumption in each Member State + 1% (out of all transport energy consumption)
Multipliers	• 2x for advanced biofuels and waste oils • 4x for renewable electricity in vehicles • 1.2x for aviation and maritime fuels, except food- and feed-based biofuels	• 1.2x for advanced biofuels and RFNBOs in aviation and maritime

Within the aviation sector, the ReFuel EU Aviation program is developing regulations to increase use of sustainable aviation fuels (SAF). Similarly, the Fuel EU Maritime program is developing regulations to reduce the CI of fuels used by large ships. Summaries of these goals are shown in the table below.

Program	Proposed Requirement	2025	2030	2035	2040	2045	2050
Refuel EU Aviation	Minimum SAF Share, %	2	5	20	32	38	63
	Minimum synthetic fuels share	-	0.7	5	8	11	28
Fuel EU Maritime	Fuel CI reduction, %	2	6	13	26	59	75

Marcelo Morandi (Embrapa Environment) described the Brazilian national biofuels policy, called RenovaBio. This policy was established in 2017, and went into effect in 2020. Annual targets for increasing reductions in transportation-related GHG emissions have been set for the period of 2020-2030. This translates to an approximate 11% reduction in fuel CI over the decade. Similar to California's LCFS program, decarbonization credits, called CBIO, are generated in the RenovaBio Program by eligible fuels that have low CI values. A life-cycle model, called RenovaCalc, is used to determine the Energy-Environmental Efficiency Grade (NEEA) for each approved biofuel pathway. The overall process for calculating credits is summarized in the figure below. Through LCA (using RenovaCalc), the CI of a qualified fuel is calculated (as NEEA), which is then multiplied by the fuel volume to calculate the number of credits (CBIOs).



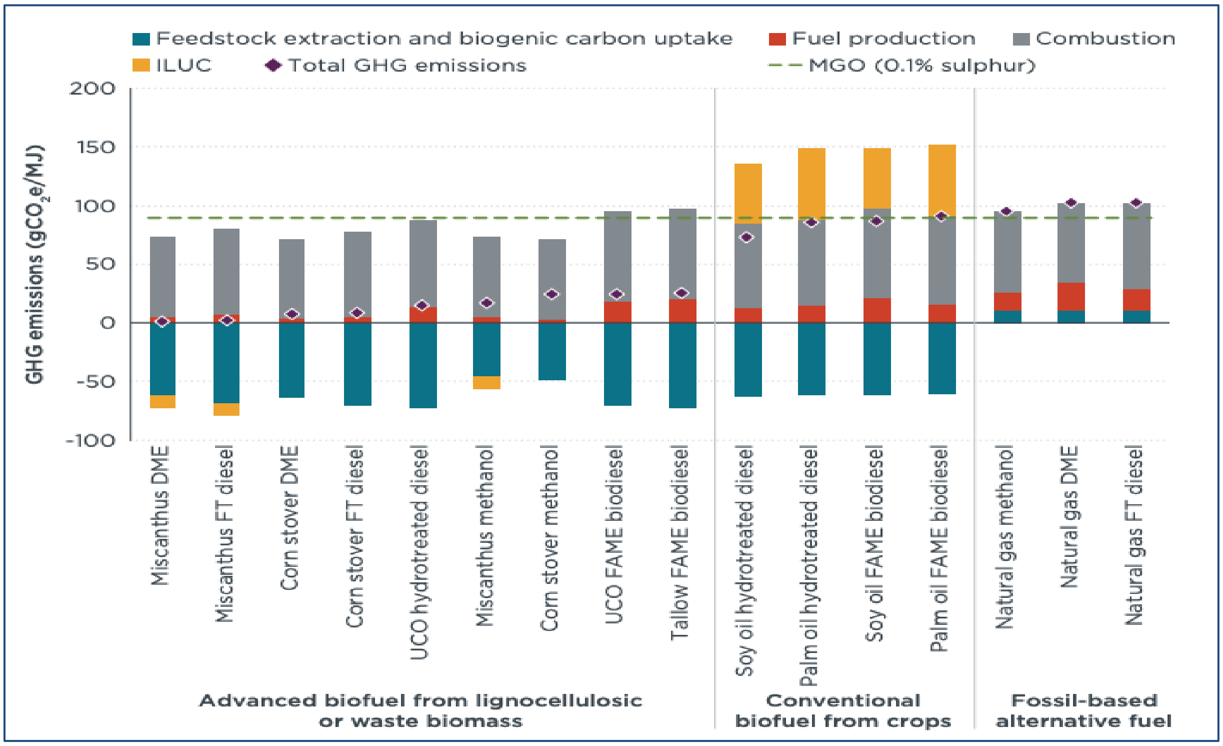
At this point, nine approved biofuel pathways are included in the RenovaCalc model, with additional pathways expected to be added in the future. A certification process is included in RenovaBio policy to ensure that the biofuel credits being generated accurately reflect the feedstocks and processes that are used. Biofuel production in Brazil is dominated by ethanol (357 plants) and biodiesel (51 plants). Currently, 73% of the ethanol plants and 59% of the biodiesel plants are certified under the RenovaBio Program, representing about 84% of the total biofuels produced in the country. After the first two years of operation, the program has generated approximately 42 million CBIOs, representing 42 million tons of CO_2eq avoided. The current CBIO price is about \$7/ton (U.S.). [Note: the current LCFS credit price is about \$200/ton.]

Bryan Comer [International Council on Clean Transportation (ICCT)] discussed the contribution of the shipping sector to global GHG emissions and efforts underway to reduce this. Currently, global shipping emissions are about 1 billion tons CO_2/year, which represents 3% of total anthropogenic CO_2 emissions, with this amount increasing annually. Even larger increases in methane emissions are occurring, as use of LNG-fueled ships is growing rapidly. Additionally, black carbon (BC) emissions are responsible for about 7% of GHG emissions from shipping (using 100-year GWP values).

In 2018, the International Maritime Organization (IMO) developed an initial GHG strategy to achieve GHG emissions reductions from the shipping sector. However, current regulations arising from this strategy are focused on direct CO_2 emissions (not CO_{2eq}) resulting from fuel combustion – so-called tank-to-wake (TTW) emissions. It is now recognized that to reduce shipping's climate impacts will require a revised and more aggressive GHG strategy. In current discussions, a potential low GHG fuel standard (LGFS) is being proposed by some IMO member states and the importance of incorporating LCA is being considered. This would enable more reliable estimates of shipping's overall GHG footprint by including upstream processes necessary to determine well-to-wake (WTW) emissions, not just TTW emissions. Comer outlined three principles that ICCT is promoting during these discussion to revise the IMO's GHG strategy:

1. Consider CO_{2eq}, not just CO_2
2. Consider GWP_{20}, not just GWP_{100}
3. Consider WTW emissions, not just TTW

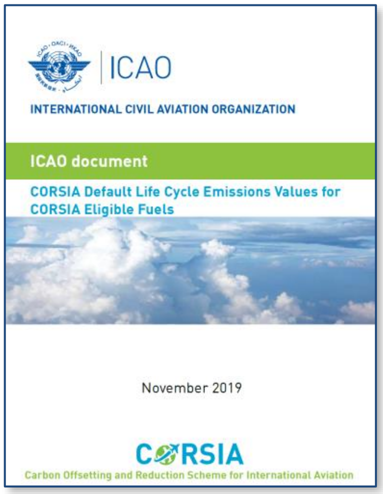
The first two principles are important to address potential adverse impacts arising from increased use of LNG (with methane slip) in shipping. The third principle is important to incentivize advanced, low-CI biofuels as opposed to crop-based biofuels or fossil-based alternative fuels that provide minimal (if any) CI benefits. This is illustrated in the figure below, taken from a recent, comprehensive WTW LCA study by ICCT.



Jim Hileman [the U.S. Federal Aviation Administration (FAA)] provided an update on the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) developed by the Committee on Aviation Environmental Protection (CAEP) of the U.N. International Civil Aviation Organization (ICAO). CORSIA applies to aircraft operators who provide international service. The objective is to use emissions offsetting and reduction measures to help international aviation meet its carbon neutral growth goal, relative to a 2019 baseline. An initial pilot phase of CORSIA is now in effect (2021-2023), with revisions to the program expected after 2023. One way to comply with CORSIA requirements is to use CORSIA-eligible fuels (CEFs), of which there are two types:

1. CORSIA Sustainable Aviation Fuel (SAF): produced from renewable or waste-derived feedstocks
2. CORSIA Lower Carbon Aviation Fuel (LCAF): produced from fossil-based feedstocks with lower CI

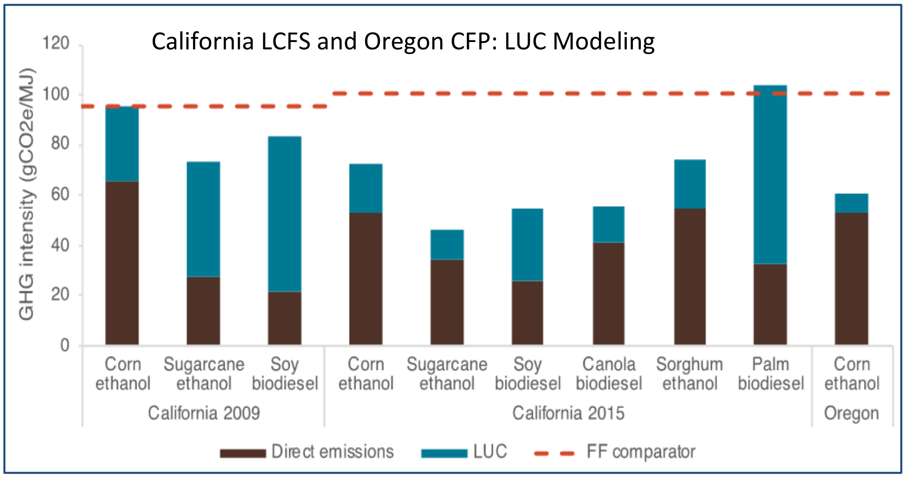
To be eligible, a fuel must meet the CORSIA Sustainability Criteria, as certified by ICAO's Sustainability Certification Scheme (SCS). These criteria include requirements pertaining to feedstock sourcing and extent of GHG reductions on a life cycle basis. Discussions are now underway regarding further sustainability criteria to apply in the future, including a number of additional environmental, social, and economic metrics.


ICAO
INTERNATIONAL CIVIL AVIATION ORGANIZATION
ICAO document
CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels
November 2019
CORSIA
Carbon Offsetting and Reduction Scheme for International Aviation

Life cycle emissions for CORSIA eligible fuels include both direct (core) and indirect (ILUC) LCA values, which are determined in one of two ways: (1) default values or (2) calculated using a CORSIA-defined methodology. Core LCA values are obtained using an attributional approach, with emissions being attributed to co-products based on energy allocations. ILUC LCA values are obtained using GTAP-BIO and GLOBIOM modeling approaches. Default life cycle emissions have been defined for approximately 30 pathways, including processes involving Fischer-Tropsch (FT), hydroprocessed esters and fatty acids (HEFA), alcohol-to-jet (ATJ), and others.

Stephanie Searle [International Council on Clean Transportation (ICCT)] provided an overview of how land use change (LUC) modeling is being used in LCA determinations under different biofuels policies. Within the U.S. RFS program, EPA uses two partial equilibrium agro-economic models to estimate LUC from biofuel production: FASOM is used for the domestic sector and FAPRI is used for the international sector. Carbon stock changes resulting from LUC are estimated by Winrock with MODIS satellite data. LUC modeling is critical in the RFS program because it impacts the final GHG score of each fuel, which determines the biofuel category (and RIN value) into which the fuel is placed.

California's LCFS and Oregon's CFP require that the lifecycle CI value of the transportation fuel pool be reduced year-by-year until achieving an overall reduction of 20% by 2030 (in California) or 10% by 2025 (in Oregon). ILUC emissions contributing to a fuel's CI value are modeled using the GTAP-BIO general equilibrium model, along with GHG emission factors defined for various agricultural ecological zones (AEZs). CI values for a few illustrative fuel pathways under the California and Oregon programs are shown in the figure. It is noteworthy that the LUC component (and hence the total CI) of several pathways decreased substantially in 2015, compared to the original 2009 assessment. Lower CI values for a particular pathway translates to higher monetary value for that fuel.



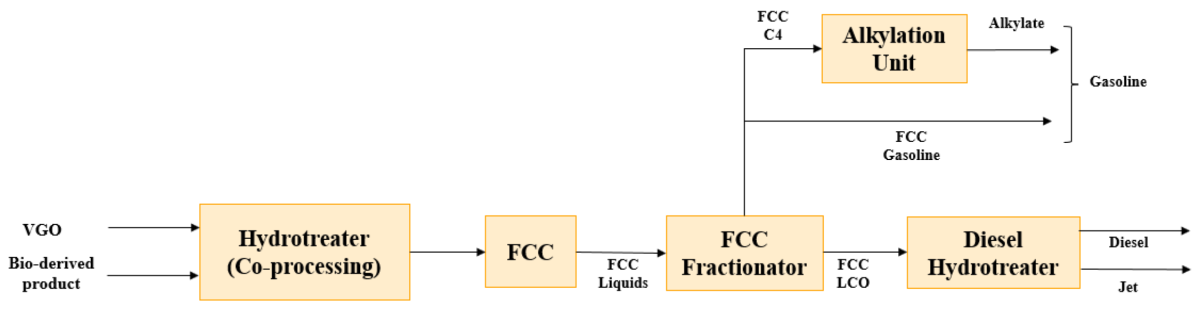
LUC modeling is included within the EU's Renewable Energy Directive (RED), but the results are used only for reporting purposes, not for determination of fuel eligibility or credits. A general equilibrium model called IFPRI-MIRAGE, combined with Winrock emission factors, is used to calculate LUC emissions. Finally, LUC modeling is used by ICAO to determine the CI value of aviation fuel pathways that are used under CORSIA. Two different LUC modeling approaches are utilized (GTAP and GLOBIOM), with the final CI value based on either the average of the two or on the lower value plus an adjustment.

Session 2: Biofuel

Chairpersons: Zia Haq (EPA), Anil Prabu (CARB), and Scott Richman [Renewable Fuels Association (RFA)]

Session 2 consisted of four presentations related to LCA of biofuels. Joule Bergerson of the University of Calgary discussed how co-processing of biocrude with fossil feedstocks within a petroleum refinery impacts the process conditions and CI of the resulting fuel products. Kevin Fingerman of Humboldt State University presented preliminary results showing how the lifecycle GHG emissions and CI of biofuels produced from forest residues depend upon the forest management practices being utilized. Stephen Ogle of Colorado State University discussed models (and their uncertainty) that are used to estimate changes in soil carbon stock as a result of agricultural changes. Finally, David Babson of U.S. DOE discussed programs intended to reduce CO_2 emissions from the U.S. agricultural sector, resulting in this sector becoming a net carbon sink.

Joule Bergerson (Univ. of Calgary) described modeling efforts underway to understand the GHG impacts of co-processing bio-based feedstocks with fossil feedstocks within a petroleum refinery. The specific case being investigated involves co-processing a biocrude derived from hydrothermal liquefaction (HTL) treatment of woody biomass with vacuum gas oil (VGO) derived from Canadian oil sands bitumen. Hydroprocessing of pure VGO was considered first, to establish a baseline of process conditions, energy requirements, product yields and compositions, etc. This was followed by co-processing of a blend containing 7.5% biocrude in VGO. Modeling of both conditions was performed with the Aspen HYSYS process simulation model, using hydroprocessing experimental data provided by Natural Resources Canada (NRC). A schematic of this co-processing through a hydrotreater, followed by further processing and upgrading to produce conventional hydrocarbon products (gasoline, diesel, and jet) is shown below.

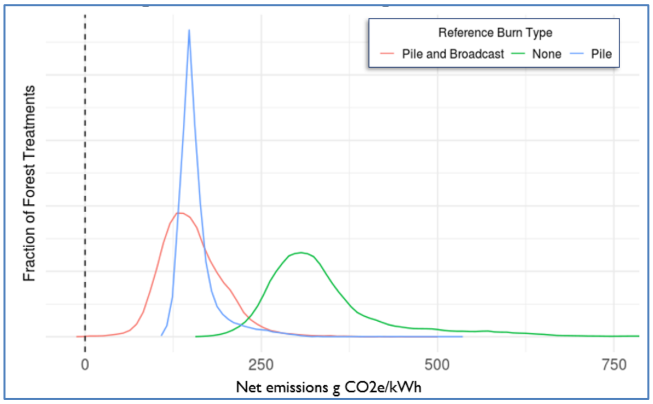


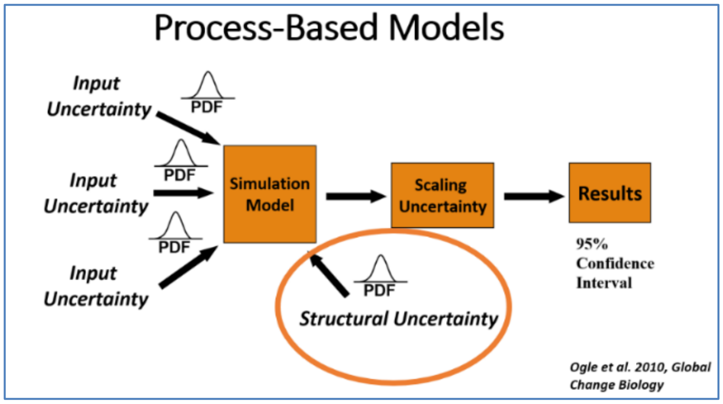
Hydrotreater co-processing of bio-derived product and VGO in a refinery

Products from the co-processing hydrotreater include light gas oil (LGO), naphtha, and light ends. To generate these products at the same sulfur level when co-processing requires higher temperature operation and increased use of H_2. This higher severity is required because the biocrude components are believed to have inhibitory effects on the catalyst. Consequently, greater energy use and CO_2 emissions result from co-processing. For the biocrude/VGO case examined here, the CI values for producing gasoline/diesel/jet increased from 10.6/14.5/14.5 g CO_{2eq}/MJ to 11.0/15.0/15.0 g CO_{2eq}/MJ when co-processing of 7.5% biocrude was included. Though not yet determined, it is likely that this small fuel production CI increase with co-processing will be offset when considering the GHG reduction benefits of biocrude on a full lifecycle basis.

Kevin Fingerman (Humboldt State University) discussed efforts to estimate lifecycle environmental impacts of California forest residues that are removed and used for energy production. Forest thinning that produces these residues is a management option being utilized to mitigate fire risk and enhance carbon sequestration in California's forests. Typically, these residues remain on site, where they undergo prescribed burns (in piles or as broadcast fuel) or are left untreated to undergo normal decay. Another option is to remove the residues and use them as a solid fuel for power production or as a feedstock for thermochemical production of liquid hydrocarbon fuels.

Fingerman and his colleagues have developed the California Biomass Residue Emission Characterization (C-BREC) model that provides a spatially-explicit LCA framework to examine environmental impacts of various forest management options throughout the state. Different residue treatment scenarios are modeled over a 100-year timespan to include normal biomass decay and exposure to wildfires over this period. Methane emissions occur during residue decay, with the emission rates varying by tree species and location. Emissions from residue burning (either prescribed or wildfires) include GHGs, CO, NOx, SOx, $PM_{2.5}$ and PM_{10}. LCA results indicate that the type of burning assumed in the counterfactual cases is the dominant determinant of the carbon footprint of the bioenergy system. As shown in the figure, net emissions from bioenergy systems are highest if the biomass in question would otherwise have been left to decay (unburned) on site. If this biomass had been subject to prescribed burning, the net emissions effect of diverting it to bioenergy production is lower by about ½. For reference, burning of natural gas for power generation has a carbon intensity of about 450 g CO_{2eq}/kWh. If the removed residues are used as feedstock for liquid biofuel products (through a Fischer-Tropsch process), the net emissions from the different cases shown in the figure can be expressed as CI of the fuel, with the peak of the green curve (no burn counterfactual case) occurring at approximately 45 g CO_{2eq}/MJ, which is about ½ the CI value of conventional, petroleum-derived fuels. Fingerman concluded that C-BREC has sufficient rigor and reliability to use in policy applications and in calculation of biofuel pathway CI values.

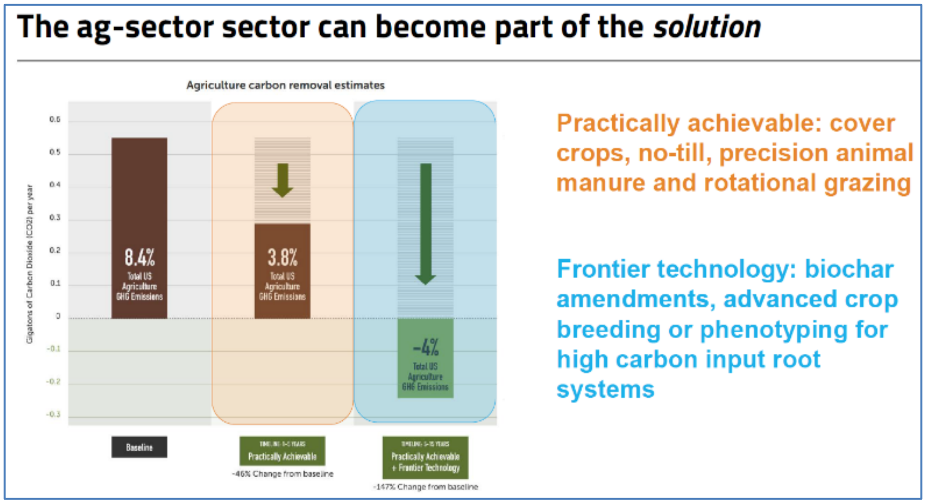




Stephen Ogle (Colorado State Univ.) emphasized the importance of quantifying and reducing the uncertainties in soil carbon determinations. Changes in agricultural practices – including production of biofuel feedstocks – offers the possibility of increasing soil carbon content, thereby representing a GHG mitigation strategy. But determining changes in soil carbon stock over time, and predicting future changes, are very difficult and fraught with high uncertainty. Direct measurements of soil carbon changes are possible, but are expensive and are done on a very limited basis. Model-based assessments are more common, and can account for a wider range of locations and situations. Ogle argued that the most useful approaches utilize process-based models, which are coupled with actual measurements. Because process models are based on physical/biological mechanisms that drive changes in carbon stocks, they can be used to predict potential impacts of future events, such as climate change.

The uncertainties inherent in a process-based model are depicted in the figure above. Each input is associated with a probability distribution function (PDF). The overall uncertainty can be estimated using Monte Carlo or other analysis techniques. Model uncertainty is reduced by aggregating results across larger spatial domains, i.e., going from a single field to multiple fields, then to a larger region (county), and finally to an entire state or country. Further advancements being made in defining mechanistic elements within the process model are helpful in reducing overall uncertainties, but more work is needed in this area.

David Babson (U.S. DOE) began by explaining the structure and mission of the DOE organization known as Advanced Research Projects Agency – Energy (ARPA-E). Current areas of focus within ARPA-E include resilient energy infrastructure, sustainable energy, and climate change mitigation. Babson emphasized that any pathway to achieving the goal of limiting global temperature rise to 2 °C must include both carbon mitigation and carbon removal. The agricultural sector can contribute to both areas. As shown in the figure, agricultural activities currently contribute approximately 8.4% of total U.S. CO_2 emissions. It is projected that this contribution could be reduced to 3.8% within 5 years, by adoption of several available technologies and practices. Further advancements of so-called "frontier technologies" could enable the agricultural sector to become a net sink for U.S. CO_2 emissions within a 5-15 year time frame.



The ag-sector sector can become part of the *solution*

Practically achievable: cover crops, no-till, precision animal manure and rotational grazing

Frontier technology: biochar amendments, advanced crop breeding or phenotyping for high carbon input root systems

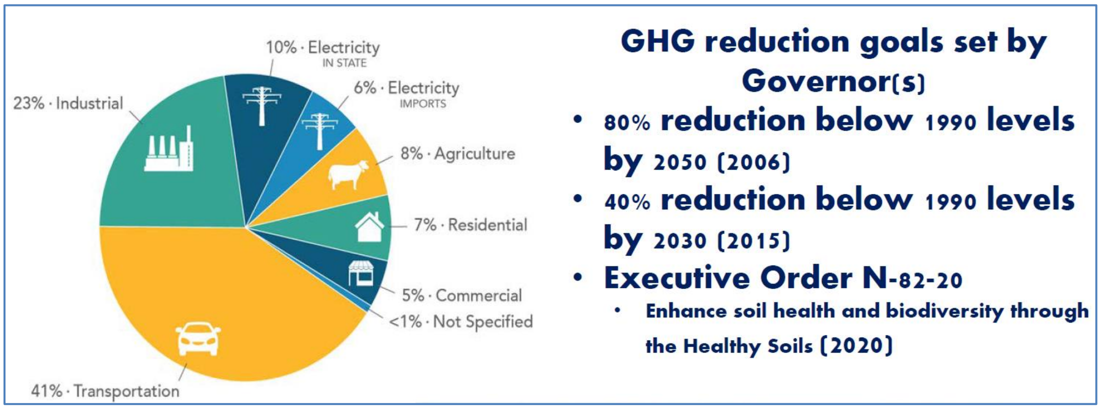
Two programs within ARPA-E are focused on feedstock production and have the potential to significantly reduce agriculture's carbon footprint. The TERRA/ROOTS program supports accelerated plant breeding and crop genetic gain through the convergence of biology, engineering, and computer science. The SMARTFARM program is focused on optimizing crop yield and CI at the farm level. This requires development and application of reliable analytical tools to determine nitrous oxide (N_2O) emissions and soil carbon levels. Utilization of remote sensing by means of drones, aircraft, and satellites, as well as in-situ sensors, is a promising area of development. An important aspect, not yet in place, is a financial mechanism to appropriately compensate farmers for GHG reduction practices that they implement.

Session 3: Sustainable Farming

Chairpersons: Diep Vu (Marathon Petroleum) and Heather Hamje (ExxonMobil)

Session 3 consisted of three presentations and a panel discussion that were all focused on various aspects of sustainable farming. Amrith Gunasekara of the California Department of Food and Agriculture (CDFA) described his state's efforts now underway to promote sustainable farming. Kaiyu Guan of the University of Illinois discussed his group's progress in developing and implementing methods to determine GHG and soil carbon changes at the field level. Hoyoung Kwon of Argonne National Laboratory (ANL) described soil organic carbon (SOC) modeling being done to support LCA of biofuels from feedstocks produced under different agricultural practices. Finally, Jan Lewandrowski of USDA led a panel discussion – including audience questions – with the three other presenters in Session 3.

Amrith Gunasekara [California Dept. of Food and Agriculture (CDFA)] described efforts underway in California to promote sustainable farming. These activities, being coordinated by the CDFA's Office of Environmental Farming and Innovation (OEFI) include incentive programs, demonstration projects, and other information sharing and research. California's overall carbon reduction goals are summarized in the figure below. In the baseline year of 2016, agriculture was responsible for approximately 8% of California's total 429 million metric tons (MMT) CO_{2eq} emissions.

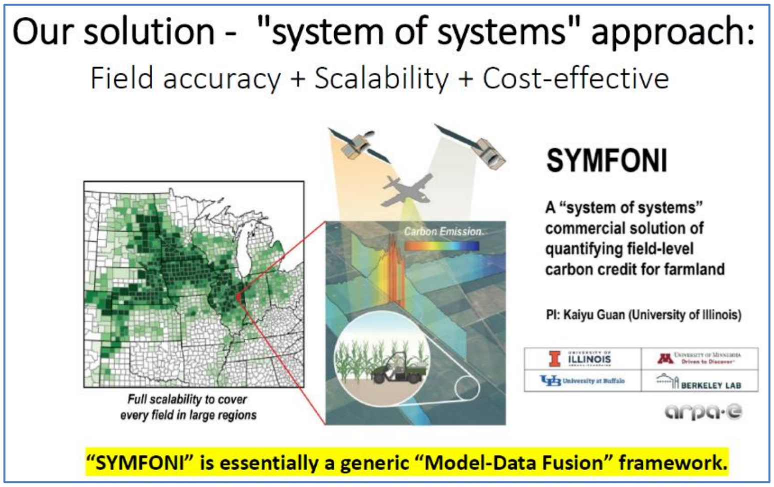


GHG reduction goals set by Governor(s)

- **80% reduction below 1990 levels by 2050 (2006)**
- **40% reduction below 1990 levels by 2030 (2015)**
- **Executive Order N-82-20**
  - **Enhance soil health and biodiversity through the Healthy Soils (2020)**

Overall GHG reduction goals have already been in place for several years. More recently (2020), the Healthy Soils Program (HSP) was initiated to promote conservation management that improves soil health, sequesters carbon, and reduces GHG emissions. Through this program, farmers and ranchers are incentivized to implement one or more of 27 recognized management practices, such as compost application, use of cover crops, no-till farming, improved nutrient management, and several others. The program also provides technical assistance to non-profit organizations and higher education, and assists farmers in accessing the program and reporting the results of their management practices. Thus far, the Healthy Soils Program has been limited to the farm level, but it is recognized that broader lifecycle considerations must be included in the future.

Kaiyu Guan (Univ. of Illinois at Urbana-Champaign) discussed work being done to develop data collection methodologies for GHG emissions and soil carbon at the farm level. To support carbon credit programs, these estimates must be accurate, scalable, and cost-effective. Improved methodologies are required to address the tradeoffs that usually exists between cost and accuracy. As part of the ARPA-E SMARTFARM program, Guan and his team at Univ. Illinois are partnered with a private firm, Aspiring Universe, to integrate a variety of measurement systems into simulation models to predict carbon and nutrient fluxes on agricultural land with high spatial and temporal resolution. Measurements include soil sampling, flux towers, and remote sensing-based systems. This “system of systems” approach is intended to provide sufficiently accurate data to serve as the basis for determining financial compensation to farmers who may introduce agricultural practices that enhance carbon sequestration and/or reduce GHG emissions. Using artificial intelligence and supercomputing techniques, Guan believes this approach could be scaled up to the millions of agricultural fields in the U.S., and eventually to a global scale.



Our solution - "system of systems" approach:

Field accuracy + Scalability + Cost-effective

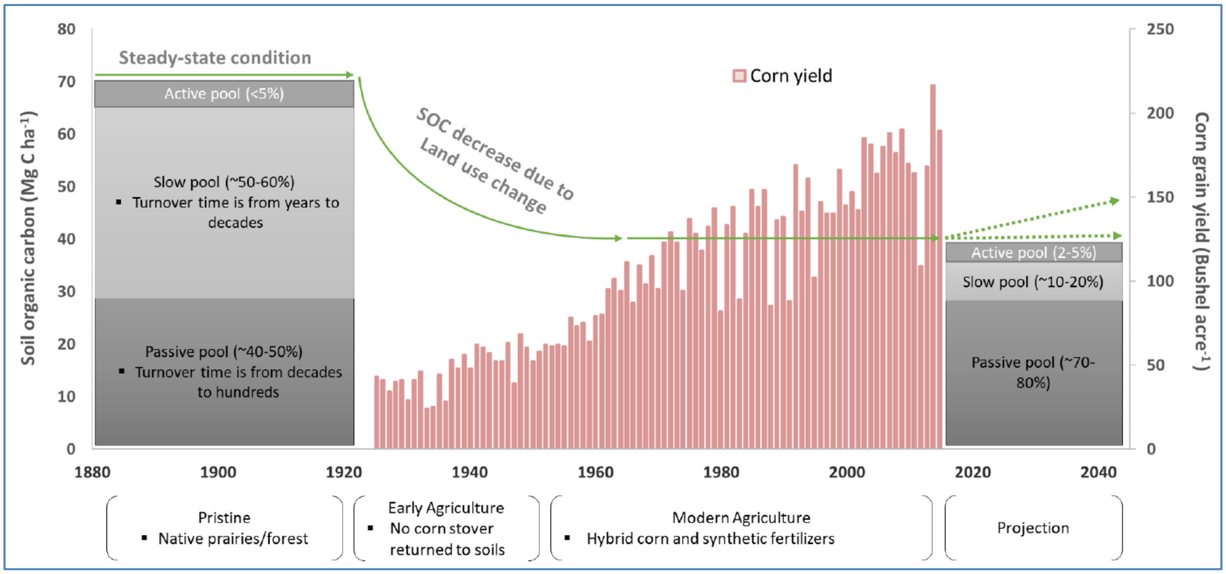
SYMFONI

A “system of systems” commercial solution of quantifying field-level carbon credit for farmland

PI: Kaiyu Guan (University of Illinois)

“SYMFONI” is essentially a generic “Model-Data Fusion” framework.

Hoyoung Kwon [Argonne National Laboratory (ANL)] described soil organic carbon (SOC) modeling work being done in support of the ARPA-E SMARTFARM program and the GREET biofuel LCA. ANL’s GREET model has long been used to conduct LCA determinations of biofuels’ CI values. Important components in the overall CI are the specific agricultural practices used to produce the biofuel feedstock – including amount and type of fertilizer used, tillage practices, use of cover crops, etc. In this work, ANL has developed an extensive database of SOC changes with different farming practices and land management changes. The database was developed using a parameterized CENTURY model with simulations at the U.S. county level. The database is included in GREET to enable determination of how specific farming practices and land management changes (LMC) will impact a biofuel’s CI value. SOC dynamics in this model are driven by factors such as the amount of crop residues left on the field, SOC decay rates, tillage practices, and other field operations.



To determine an appropriate SOC baseline against which the effects of LMC can be judged, the model simulation must be run over a long time period. This is illustrated in the figure abpve. Steady-state SOC conditions are assumed prior to 1920. SOC then decreased during the early agriculture period, until it reached a stable, current level during the modern agriculture period. Introduction of new LMCs will lead to projected changes in SOC, which could be incentivized/monetized by generating carbon credits related to the reduced CI of the biofuel products. Kwon concluded by highlighting a few outstanding issues related to SOC modeling and feedstock verification that must be addressed before this approach can be adopted.

Jan Lewandrowski (USDA) moderated a roundtable discussion with the other three panelists in Session 3 on the topic of integrating SOC modeling with sustainable farming. He began by noting that the issue of carbon sequestration by agricultural practices is now receiving considerable attention within USDA. Many efforts are aimed at developing suitable measurement, modeling, and economic tools to incentivize and reward farmers for adopting beneficial new practices. Much of this discussion was prompted by questions from the audience. Some participants noted that, at present, the uncertainties in determining SOC impacts are so large that including this factor in adjusting a biofuel's CI value is not credible. Others suggested that rather than granting full CI benefit to practices believed to enhance SOC, a discounted benefit should be granted, with the size of the discount being based on the level of uncertainty. This approach would continue to incentivize beneficial practices, while encouraging additional effort to reduce uncertainty. It was also pointed out that while increasing SOC is helpful, this is really a very small factor in overall efforts to reduce GHG emissions. Also, there are many other reasons to pursue sustainable farming beyond GHG considerations.

Session 4: Carbon Capture and Utilization

Chairpersons: Robb De Kleine(Ford), Babak Fayyaz (Chevron), and Xiaoyi He (Phillips 66)

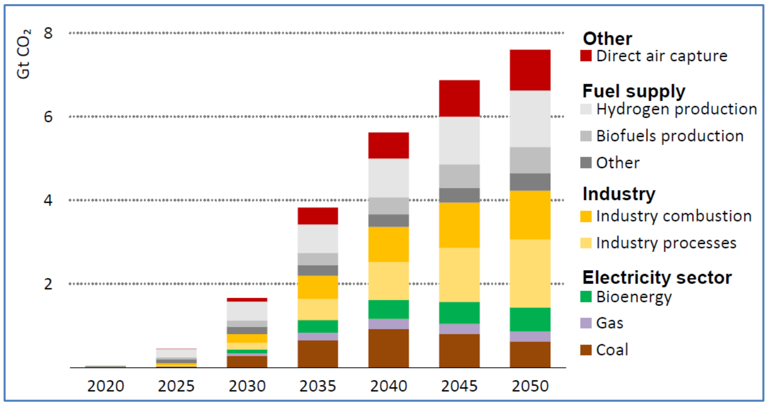
Session 4 consisted of four presentations related to the topic of carbon capture and utilization (CCU). Mathilde Fajardy of the International Energy Agency (IEA) began by describing a roadmap developed by IEA to achieve global net-zero GHG emissions by 2050, and explained how carbon capture, utilization, and storage (CCUS) is an important part of this plan. Joule Bergerson of the University of Calgary discussed an LCA study focused on direct air capture (DAC) of CO_2, followed by Fischer-Tropsch synthesis to produce diesel fuel. Jan Gorsky of the Pembina Institute discussed life-cycle GHG emissions associated with blue H_2, produced from natural gas through processes that include carbon capture and storage (CCS). Finally, Nils Thonemann of the Technical University of Denmark (DTU) discussed a consequential LCA study performed to assess the Global Warming Intensity (GWI) of commercial chemical products produced by a variety of CCU processes.

Mathilde Fajardy [International Energy Agency (IEA)] discussed the importance of carbon capture, utilization, and storage (CCUS) in achieving the goal of a global net-zero energy system. She explained four strategic roles that CCUS can play in reaching this goal:

1. Reduce GHG emissions from existing infrastructure, such as power plants
2. A solution for hard-to-abate GHG emissions, such as steel and cement production
3. A platform for production of low carbon hydrogen
4. Direct removal of CO_2 from the atmosphere by biomass energy with carbon capture and storage (BECCS), and direct air capture (DAC)

IEA has developed a detailed, long-term roadmap to reach net-zero by 2050. This roadmap includes numerous shorter-term milestones to guide GHG reductions in the major sectors of electricity production, industry, transportation, and buildings. Deployment of CCUS is anticipated at various points along the pathway. Of the 35 GT/year CO_2 emission represented by these sectors in 2020, CCUS is expected to remove 4 GT/year by 2035, and 7.5 GT/year by 2050. While CCUS facilities have been operating since the

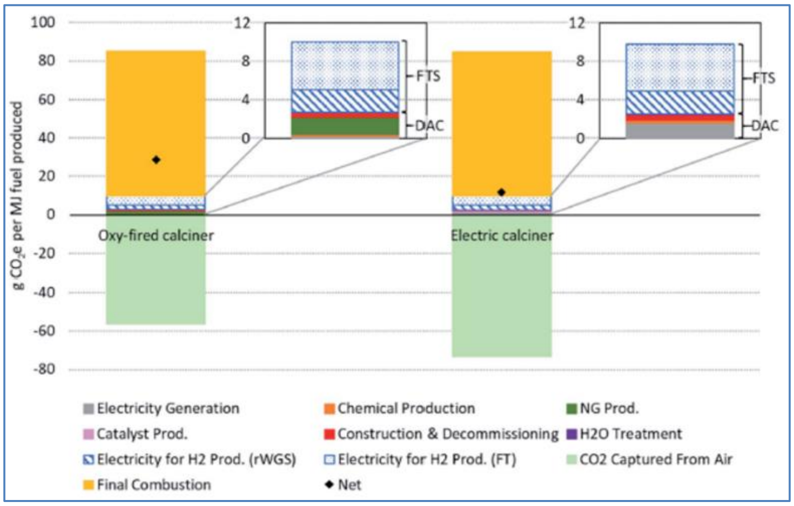
1970s, they have been very few and very small. Current total global capacity of CCUS is approximately 0.05 GT/year, with most of this coming from natural gas production. However, interest in CCUS is now expanding rapidly, with over 100 new projects having been announced thus far in 2021. The figure shown here represents the dramatic ramp-up of CCUS as included in the IEA roadmap to global net-zero emissions. Fajardy identified 4 government and industry actions necessary to make this happen:



1. Create the necessary (economic) conditions for CCUS investment
2. Target development of industrial hubs with shared CO_2 infrastructure (including pipelines)
3. Identify and encourage development of CO_2 storage
4. Boost innovation (and reduce costs) for critical CCUS technologies

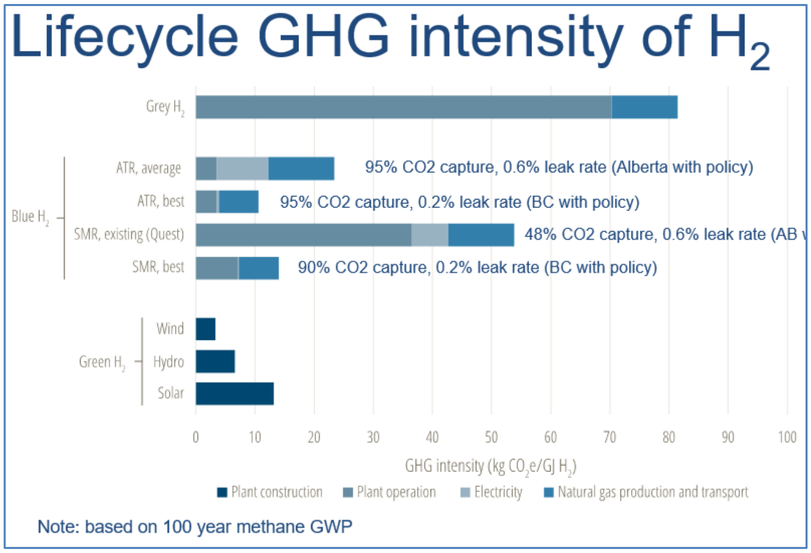
Joule Bergerson (Univ. of Calgary) presented results from an LCA study involving direct air capture (DAC) of CO_2 followed by Fischer-Tropsch synthesis (FTS) to produce low carbon diesel fuel. The baseline scenario assumes a British Columbia (BC) location and uses average carbon intensity (CI) of electricity from the BC grid. Hydrogen production comes from electrolysis. Two different calciner options were examined – one in which natural gas (NG) is combusted to generate heat; the other involves an electric calciner, with no combustion. (A calciner is necessary to drive collected CO_2 off an adsorbent and regenerate fresh adsorbent.) CO_2 emissions from NG combustion in the calciner were captured and incorporated into the FTS process.

Fuel life-cycle GHG emissions results were expressed in two ways: (1) g CO_{2eq}/g CO_2 captured from air and (2) g CO_{2eq}/MJ diesel fuel produced. Results using the first functional unit were approximately 0.5 g CO_{2eq}/g CO_2 captured when using the oxy-fuel calciner, and 0.2 CO_2eq/g CO_2 captured when using an electric calciner. Results using the second functional unit are shown in the figure: the oxy-fired calciner gave approximately 30 g CO_{2eq}/MJ diesel, whereas the electric calciner gave about 10 CO_{2eq}/MJ diesel. These values can be compared with CI values for conventional diesel fuel (~100 g CO_{2eq}/MJ) and biodiesel from vegetable oil (~55 g CO_{2eq}/MJ). Sensitivity analysis was also performed, showing that the CI of electricity inputs was the most impactful parameter. Electricity from the BC grid already has relatively low CI, but use of net-zero electricity would reduce the final diesel fuel CI even further.



Jan Gorski (Pembina Institute) discussed the GHG intensity of low-carbon H_2 production – so called Blue H_2 – which is considered critical to achieve net-zero emissions from energy production systems. Today, virtually all H_2 is produced via steam methane reforming (SMR) processes, which can be chemically depicted as: $CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$. Separating and capturing CO_2 from the SMR process gas is done to provide relatively low GHG intensity "Blue H_2." However, considerable heat energy is required to drive the SMR process. Commonly, this energy is derived from combustion of natural gas, which results in CO_2 emissions in flue gas that may not be captured. With typical SMR operation, the ratio of flue gas CO_2 to process gas CO_2 is about 40/60, so only about 60% of the overall GHG products are available for capture. This situation can be improved by replacing SMR with a process called autothermal reforming (ATR). With ATR, the heat to drive the process is generated internally, by partial oxidation of methane, not by combustion. Thus, in an ATR process, all of the CO_2 products are available for capture.

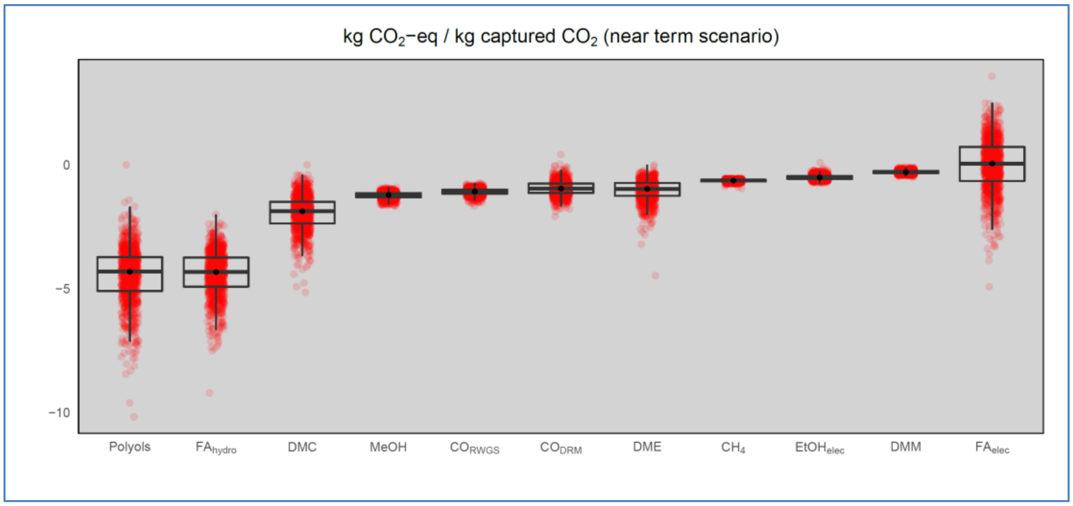
Gorski described an LCA study recently conducted to quantify the GHG intensity of H_2 produced by several different methods. The results, summarized in the figure, show that the GHG intensity of Blue H_2 can vary substantially, depending upon the processes and assumptions that are used. Blue H_2 produced from ATR has considerably lower GHG intensity than that produced from SMR. Important variables influencing the results include assumed CO_2 capture rates, assumed level of upstream methane leaks, the source of electricity used in the processes, and the choice of GWP metrics for methane (100-year, 20-year, etc.) Blue H_2 from any process has considerably lower GHG intensity than Grey H_2 (produced by SMR without any CCS). Results for Green H_2 scenarios are also shown in the figure. (Green H_2 is produced by electrolysis, using low-carbon sources of electricity.) The large variations in GHG intensity results among the Blue and Green H_2 categories suggest that referring to H_2 by color may be overly simplistic.



Note: based on 100 year methane GWP

Nils Thonemann [Technical Univ. Denmark (DTU)] described an LCA study in which carbon capture and utilization (CCU) was used within the chemical industry to reduce GHG emissions associated with 12 specific industrial chemicals within a European context. A consequential LCA approach was used (as opposed to an attributional approach) to better understand system-wide environmental consequences. Near-term supplies of CO_2 for CCU included fermentation processes, bioenergy production, and H_2 production; longer-term CO_2 supplies included production of iron and steel, ammonia, and cement. Hydrogen must also be generated to react with the captured CO_2 using defined conversion technologies to produce the intended chemical product. In the near-term scenario, H_2 was produced from methane using SMR technology; in the long-term scenario, H_2 was produced via electrolysis.

Conversion technologies to produce the desired chemical products from CO_2, H_2, and CH_4 – along with appropriate mass and energy inputs – were obtained primarily from the literature. This was necessary because most of these technologies have never been deployed commercially. Only conversion technologies that had advanced beyond a Technology Readiness Level (TRL) of 3 were considered. The 12 chemical products investigated were the following: (1) polyether polyols, (2) formic acid from hydrogenation (FA_{hydro}), (3) dimethyl carbonate (DMC), (4) methanol, (5) CO from reverse water gas shift (CO_{RWGS}), (6) CO from dry reforming of methane (CO_{DRM}), (7) dimethyl ether (DME), (8) methane, (9) ethanol, (10) dimethoxy methane (DMM), (11) formic acid from electrochemical reduction (FA_{elec}), and (12) Fischer-Tropsch jet (FT_{jet}).



To compare all 12 chemicals on an equivalent basis, the same functional unit – treatment of 1 kg of captured CO_2 – was used in each LCA examination. The lifecycle global warming intensity (GWI) results were then expressed as kg CO_{2eq} per kg of captured CO_2, as shown in the figure above, which represents the near-term scenario. This figure shows 11 of the 12 chemical products, ordered as in the list given above. The FT_{jet} product is not shown, as it gave a much higher GWI result than all other chemical products. The two left-most chemicals shown in the figure (polyether polyols and FA_{hydro}) have strongly negative GWI values, meaning that it would be environmentally beneficial to produce these products via a CCU process. The rest of the chemicals would provide lesser GWI benefits (if any) from a CCU process. Results from the long-term scenarios are very similar to those from the short-term scenarios, with the ordering of the chemical products being identical in both cases.

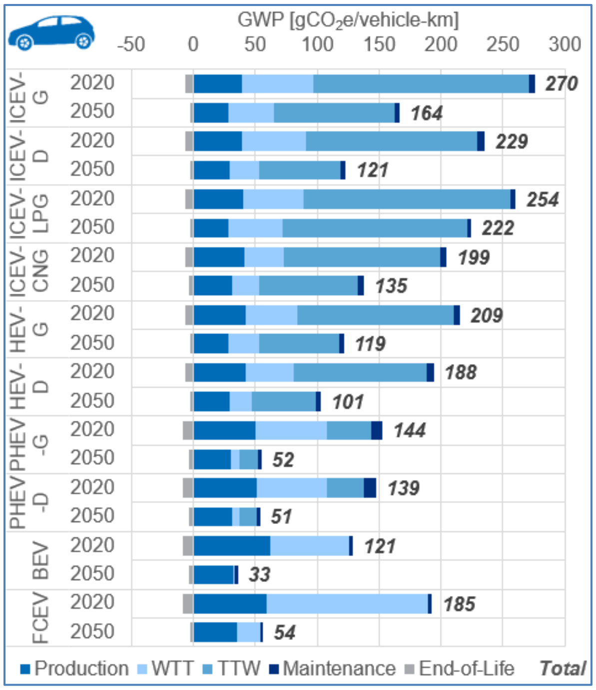
Session 5: Electrification

Chairpersons: Jeremy Martin [Union of Concerned Scientists (UCS)] and Robb De Kleine (Ford)

Session 5 consisted of three presentations dealing with LCA of electrification options. Sofia Amaral of Ricardo discussed a large European LCA study investigating a range of current and future vehicle options with respect to GHG emissions and other environmental outcomes. Georg Bieker of ICCT presented an LCA study investigating GHG emissions of different vehicle types in 2021 and 2030 in four major market locations: U.S., Europe, China, and India. Amgad Elgowainy of ANL described a large U.S. LCA study investigating cradle-to-grave (C2G) GHG emissions and levelized costs of driving (LCOD) for a wide range of fuel/powertrain combinations in 2020 and 2030. A fourth, planned presentation, by Hanjiro Ambrose of CARB was not given, due to scheduling problems.

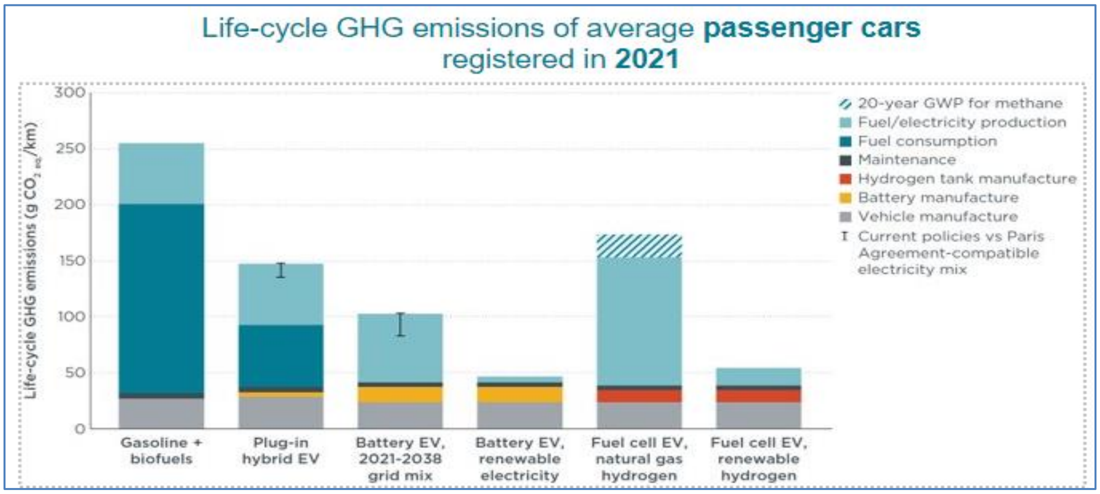
Sofia Amaral (Ricardo) summarized a large LCA study that Ricardo, in collaboration with two European research institutes (E4Tech and ifeu) has recently conducted for the European Commission (EC). Lifecycle environmental impacts were assessed across a wide range of vehicle types, powertrains, and energy chains in both 2020 and 2050. The purpose of this work was to support EC strategies and policy-making. Both light-duty (LD) and heavy-duty (HD) vehicles were considered and a wide range of environmental outcomes were investigated. A well-to-wheel (WTW) analysis was performed to evaluate numerous fuel and electricity production chains, along with their use over the life of the vehicle. Over 60 generic vehicle/powertrain combinations across 7 vehicle types were considered. In addition, the study boundaries included impacts of vehicle production (cradle-to-gate) and end of life options (recycle, re-purpose, and disposal).

Because this policy LCA study included so many dimensions, it was necessary to develop a streamlined, modularized modeling framework to explore the impacts of different options. This Ricardo Lifecycle Protocol (RLP) was utilized to generate global warming potential (GWP) results, as well as 6 other environmental impacts, for many vehicle/powertrain combinations. As an example, GWP results for mid-size passenger vehicles are shown in the figure. Substantial GWP reductions are projected in 2050 compared to 2020, for all vehicle/powertrain cases. Regional variation across the 28 EU countries was examined, showing that GWP of battery electric vehicles (BEVs) in 2020 ranged from about 75 to 290 g CO_{2eq}/vehicle-km. However, the vast majority of EU countries already show significant GWP benefits, which will increase in the future as the electric grid becomes cleaner. It was also shown that fuel cell electric vehicles (FCEVs) have higher GWP impacts than BEVs, both now and in the future. This is due mainly to the GHG emissions associated with hydrogen production. Amaral concluded by highlighting a few areas for improvement within the Ricardo LCA modeling framework: (1) further standardization is needed to facilitate various comparisons, (2) resource issues (such as battery metals) are not addressed very well, and (3) the impacts of future battery recycling are not well understood.



Georg Bieker (ICCT) discussed an LCA study of GHG emissions for passenger cars in the four regions that dominate the new vehicle market: U.S., Europe, China, and India. In each region, relevant powertrain types were considered – including internal combustion engine vehicles (ICEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs). The cradle-to-grave (C2G) vehicle portion of the LCA estimated GHG emissions associated with vehicle and battery production, maintenance, and end-of-life activities. The WTW fuel portion of the LCA estimated GHG emissions associated with production of fuels and electricity in each region, and use of these throughout the vehicle's life. For biofuels, emissions associated with ILUC were included. Recent, real-world data were used to define actual fuel consumption in PHEVs. These data show much higher fuel consumption (and less electricity use) than originally expected – especially outside the U.S. GHG emissions associated with battery production were obtained from current, industrial-scale plants, which show significantly lower emissions than earlier-generation battery production. Because of the near-term focus of this study, 20-year GWP values for methane were used in assessing the global impacts of lifecycles that involve natural gas leaks.

Results for 2021-technology vehicles were presented for each of the 4 regions studied; results for the U.S. are shown in the figure below. The significant reduction in fuel consumption shown for the PHEV case compared to baseline gasoline results from these vehicles being used in an electricity-only mode much of the time. Lifecycle GHG emissions from BEVs were lower than from the PHEVs when assuming an average grid mix over the life of the vehicle (2021-2038). Use of renewable electricity reduced these emissions even more. Thus, extending this study to 2030 showed further emissions reductions for the grid mix BEV cases.

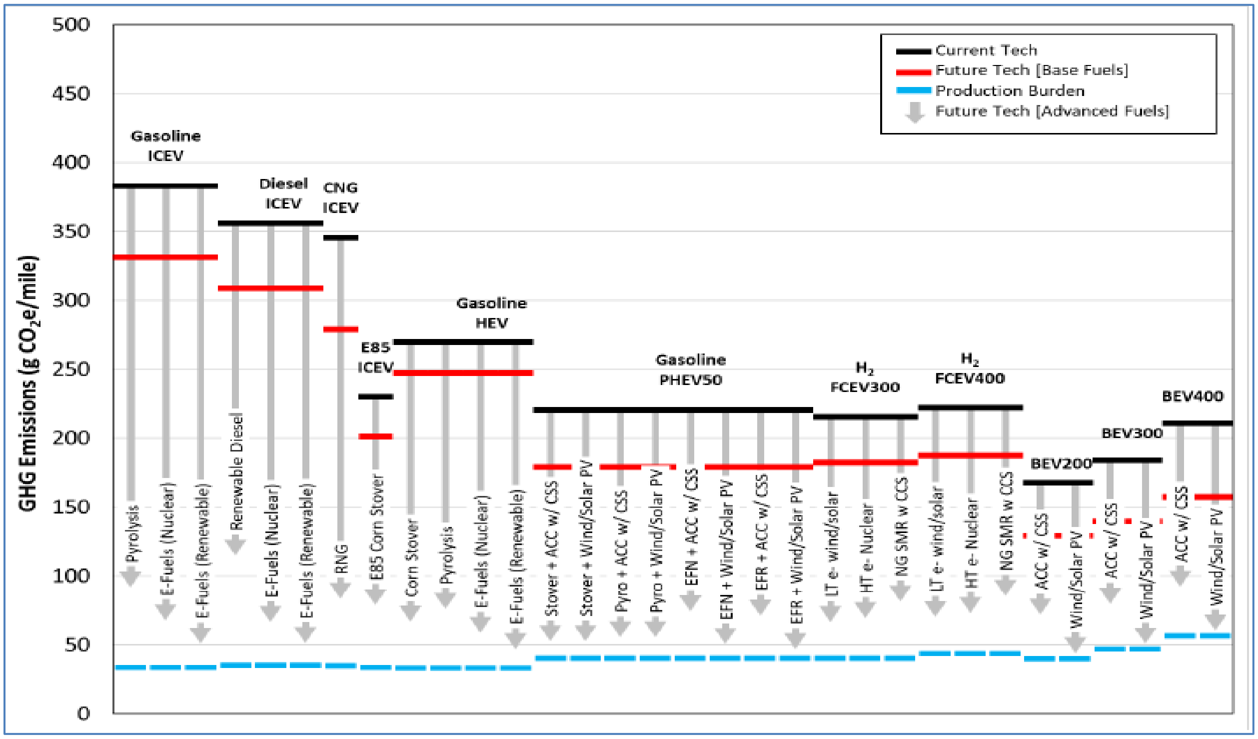


Lifecycle emissions from FCEVs varied greatly, depending upon the source of hydrogen. Bieker explained that while e-fuels could be produced and used in ICEVs, the lifecycle GHG reductions do not approach those from BEVs. Furthermore, e-fuels are too limited and expensive to contribute significantly to the decarbonization of road transport. It was concluded that to address the global warming goal of 1.5 °C would require a largely electric global vehicle fleet by 2050.

Amgad Elgowainy (ANL) described an extensive cradle-to-grave (C2G) analysis of GHG emissions and levelized cost of driving (LCOD) for LD vehicles in the U.S. Both current technology (2020) and future technology (2030) vehicles and fuels were considered. Numerous fuel/powertrain combinations were investigated – including ICEVs, HEVs, PHEVs, BEVs, and FCEVs. The Autonomie model was used to provide information about vehicle component sizing and cost, and fuel economy for different options. The GREET model (version 2020) was used to assess energy use and GHG emissions per mile for both WTW fuel lifecycles and C2G vehicle lifecycles. Cost details for fuels and vehicles were obtained from existing literature sources, as well as techno-economic assessments (TEA) for future fuels (e.g., for H_2, e-fuels, and some biofuels.

In this study, numerous scenarios were examined, in which different assumptions were made regarding the degree of technology advancements occurring on both the vehicle and fuel sides. Given this complexity, a large array of results was generated. In the example of midsize sedans shown below, C2G GHG emissions of various current and future vehicle/fuel technologies are depicted. The current situation is represented by the black horizontal lines; the red horizontal lines indicate GHG emissions reductions achievable in 2030 due to modest improvements in vehicle technology; the gray arrows indicate GHG reductions achievable in 2030 due to use of advanced fuels in advanced vehicles.

Detailed energy and vehicle cost data were assembled to establish LCOD for all the fuel/powertrain combinations that were examined – both now and in the future. For current technology vehicles, LCOD for gasoline and diesel midsize sedans (excluding taxes) was approximately $0.45-0.50/mile, while that of BEVs and FCEVs was higher, at about $0.60-0.80/mile. However, with all future technologies and fuels, the range of LCOD across the various options narrowed considerably, suggesting that future advanced powertrains could reach cost parity with conventional ICEVs as battery costs will be reduced significantly.



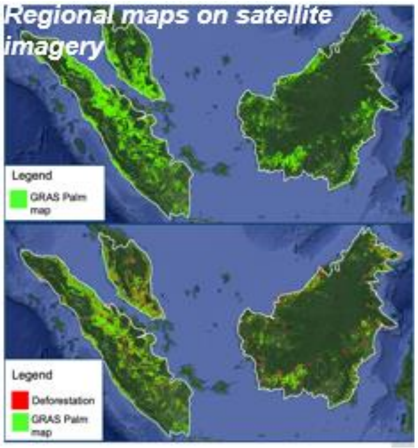
Session 6: Land Use Change

Chairpersons: Keith L. Kline [Oak Ridge National Laboratory (ORNL)] and Stephanie Searle (ICCT)

Session 6 consisted of five presentations that focused on land use change (LUC) issues related to biofuels. Michèle Koper of Guidehouse described the EC High-ILUC risk biofuels project that is currently underway. Gbadebo Oladosu of ORNL summarized a causal analysis study of corn use for ethanol in the U.S. Farzad Taheripour discussed updates being incorporated into the GTAP-BIO database that is used in modeling impacts of biofuel production and use. Hugo Valin of the International Institute for Applied Systems Analysis (IIASA) discussed use of the GLOBIOM model in assessing LUC from biofuels policies. Finally, Rich Plevin (independent consultant) discussed how biofuel CI values are influenced by the choices made in representing land use.

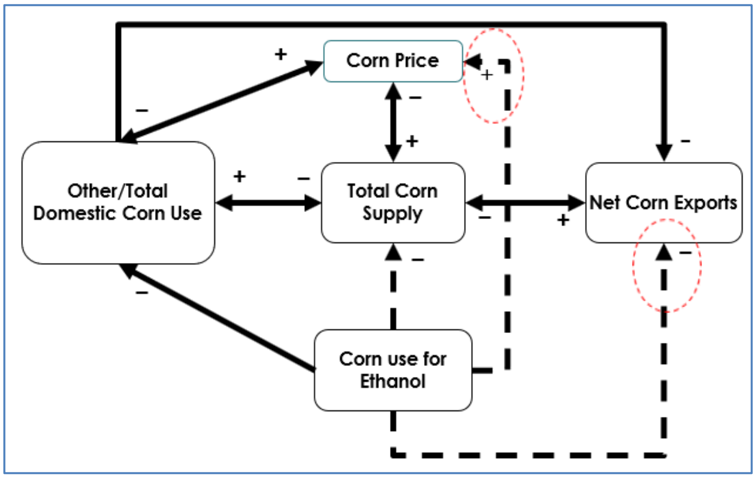
Michèle Koper (Guidehouse) described a project now underway to review high ILUC-risk biofuels for the European Commission (EC). The EC has defined high ILUC-risk fuels as "Biofuels, bioliquids and biomass fuels produced from food and feed crops for which a significant expansion of the production area into land with high-carbon stock is observed." The volume of high ILUC-risk fuels is currently limited by the EC, and these limits will be strengthened gradually in the future. Criteria for determining high ILUC-risk feedstocks involve (1) rate of expansion of the feedstock and (2) fraction of the expansion into land having high carbon stock.

The methodologies for assessing these criteria and defining high ILUC-risk fuels are explained in an EC report. This HILUC project was undertaken to review all relevant aspects of the EC report on feedstock



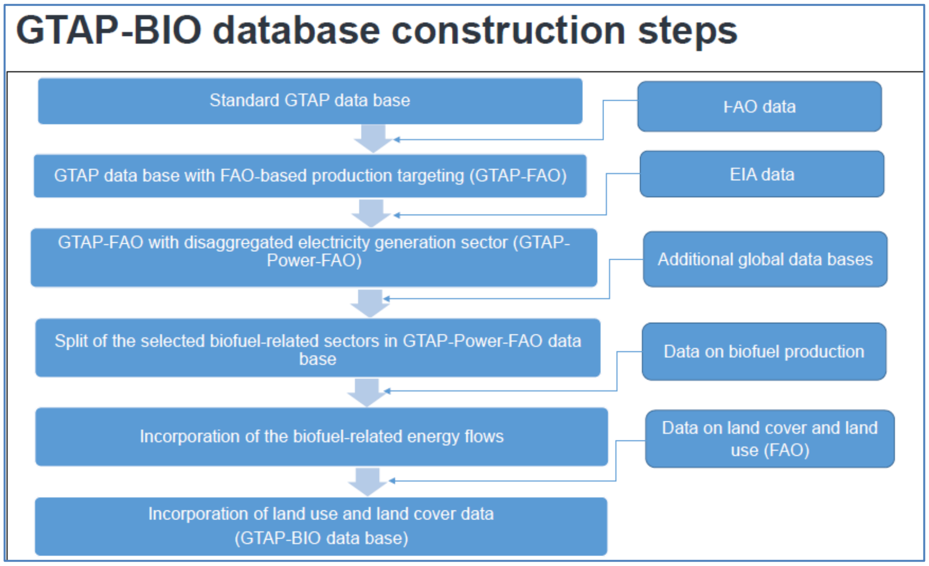
expansion used to set high ILUC-risk limits. In particular, HILUC is examining (1) feedstock expansion shares in high-carbon stock lands, such as forests and peatland, (2) GHG emissions related to this feedstock expansion, and (3) energy yield data. Various databases and mapping techniques are being used to quantify commodity-driven expansion into high carbon stock lands. These mapping results are then combined with GHG emissions values to define impacts of the expansion by crop, by region, by country, etc. Finally, various statistical analyses are being used to examine multi-year trends, explain anomalies, and investigate methodological improvements. The HILUC project is expected to continue until January 2023.

Gbadebo Oladosu (ORNL) described a causal analysis modeling study to better understand the various drivers leading to ILUC resulting from U.S. biofuel policies. ILUC remains a crucial aspect of the RFS program, but its occurrence is not observable; hence, it must be modeled. Estimates of ILUC depend upon various market parameters and assumptions, which may not accurately reflect the true drivers. Thus, this study performed empirical causal analysis tests of potential channels of global ILUC effects of U.S. corn ethanol. A schematic of the relationships investigated is shown in the figure below.



The model variables include total corn supply, corn use for ethanol, other domestic corn use, net corn export, and corn price. Quarterly values for each of these variables were obtained over a 30-year period (1986-2017). Bi-variate linear causality tests were then applied to these data to investigate both one-period ahead (one-quarter ahead) interactions using Grainger causality (GC) tests, and instantaneous causality (IC) during the same period. GC results indicated that some pathways are consistent with common assumptions; for instance, total corn supply positively affects other domestic corn use and negatively affects corn price. However, the results for other pathways are not consistent with common ILUC model assumptions; for instance, corn use for ethanol has no influence on corn prices or on net corn exports. These findings based on historical data raise doubts about two primary mechanisms assumed to induce indirect land-use change, i.e., the effects of biofuel production on global prices and exports. Instantaneous causality results also showed the significance of total corn supply as a key market driver. Oladosu argued that the significant pathways identified in this study should be considered in the broader market models of U.S. corn ethanol. At the same time, additional work should be undertaken to examine more than one-period ahead relationships, and non-linear aspects of these relationships.

Farzad Taheripour (Purdue Univ.) presented work being done to update the GTAP-BIO database that is used by computable general equilibrium (CGE) models to study various economic and environmental topics, including the impacts of biofuels. The latest public version of the database represents the global economy in 2014. All economic activities are aggregated into 65 sectors, with input-output (IO) tables provided for 141 countries/regions. A major limitation of the standard GTAP database is its lack of explicit representation of liquid biofuels. Instead, information about biofuel production and use must be obtained separately from each country where these activities occur. This became increasingly challenging as the biofuel industry grew in size and complexity. Earlier efforts to overcome these challenges involved aggregating biofuels into regional databases, but this also had severe limitations. The current updating effort has now removed these limitations by representing biofuels in the fully disaggregated database.

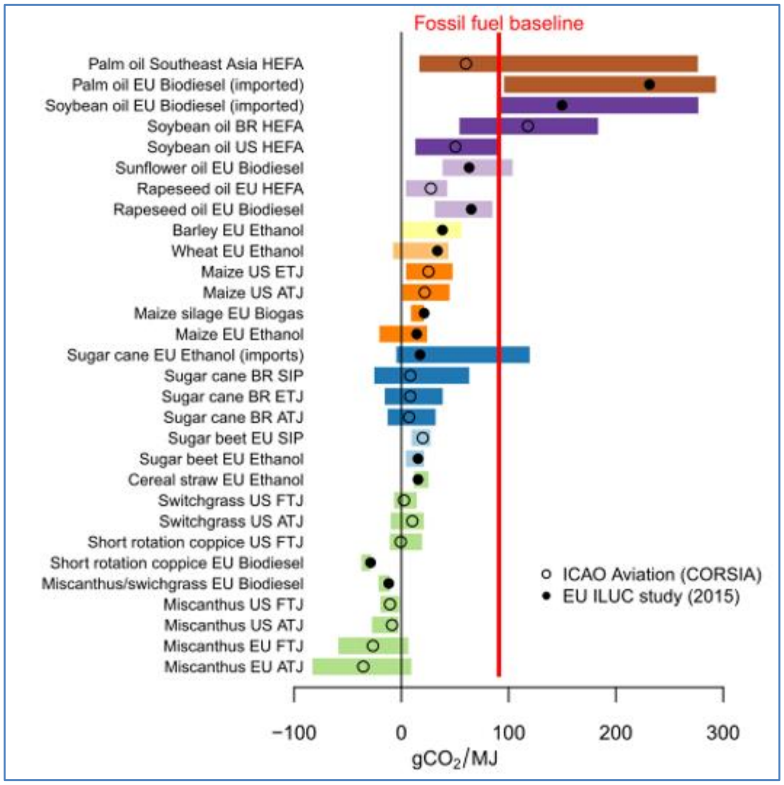


A schematic showing the overall process in constructing this updated database is shown in the figure. Additional upgrades to the GTAP-BIO model include (1) representation of the cropland-pasture (C-P) land classification in all countries, not just 4 countries as was done earlier, (2) greater flexibility in converting GTAP-BIO land use results to ILUC values, and (3) greater flexibility in dealing with agricultural ecological zone emission factors (AEZ-EF) and how they impact ILUC values. Once the database construction is complete, Taheripour intends to use it in various ways to assess the economic and environmental impacts of biofuel products and policies.

Hugo Valin [International Institute for Applied Systems Analysis (IIASA)] discussed ways in which the Global Biomass Optimization Model (GLOBIOM) has been used to assess ILUC issues within the European context. GLOBIOM is a partial equilibrium model that represents agricultural, forestry, and bioenergy markets. It has been used extensively to investigate the lifecycle GHG impacts of biofuel policies within the EU's Renewable Energy Directive (RED) and ICAO's CORSIA program. The figure below illustrates carbon intensity results from numerous biofuel pathways investigated under these programs. Valin summarized five conclusions from this GLOBIOM modeling work:

1. Biofuel consumption policies can have unintended consequences on land use.
2. Market effects resulting from biofuel policies depend upon the feedstock, with high yield feedstocks usually performing better (except for palm oil). Vegetable oil-based biofuels still have a high risk of leakage to high carbon stock areas due to oil market substitution.
3. Establishing a biofuels certificate standard does not safeguard against ILUC.
4. ILUC results are highly sensitive to changing factors such as deforestation and peatland conversion patterns, degree of vegetable oil substitution, use of co-products, feedstock yield changes, and other factors.
5. Overall model uncertainty cannot be resolved beyond a certain level.

Valin also suggested that future ILUC-related work be focused on three areas:

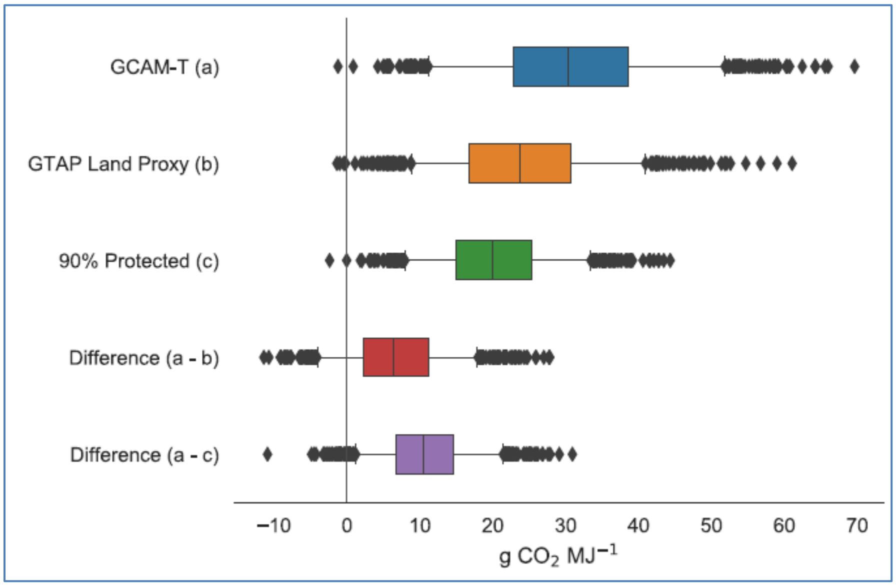


1. Investigate whether current land use observations are consistent with earlier ILUC assumptions.
2. Utilize counterfactual analyses to investigate the most efficient uses of land from the perspective of climate change mitigation.
3. Consider how to move from consumption-based biofuel policies, which can promote undesirable LUC, to supply-side policies that focus on emissions at the source.

Valin concluded that consequential analysis is the key to capture economic market responses to biofuels policies. While ILUC modeling continues to improve with respect to methodologies, data, and applications, inherent uncertainty remains. Thus, biofuel policies should incorporate provisions to account for this uncertainty.

Rich Plevin (Independent consultant) presented an analysis showing how land representation choices in different models can affect the calculated CI of corn ethanol attributable to land use change (CI-LUC). LCA models use various approaches to aggregate land into categories such as agricultural (cropland and pasture), forest (commercial and non-commercial), and other lands (grassland and shrubland). Additionally, there are variations in allocating these land types into protected and unprotected areas. (Protected areas are not available for LUC resulting from changes in biofuel demand.) In this study, the Global Change Assessment Model (GCAM), as customized for improved modeling of transportation fuels (GCAM-T) was used. Two other versions of this model were created to investigate the effects of different land representations. In one case, 90% of non-commercial land in all regions was assumed to be protected – as compared to the 36% assumed in GCAM-T. In the other case, assumptions about land representation were modified to mimic those used in the GTAP-BIO model. These three versions of the model were then used to calculate CI-LUC for corn ethanol cases in the U.S. A Monte Carlo sampling process involving 40 model parameters and 1000 draws was used to produce the distributions of results shown in the figure below. The same parameter draw was used for each of these three model versions.

The results show that CI-LUC is reduced, compared to the GCAM-T case, when the GTAP-BIO land representation is used or when 90% of non-commercial land is assumed to be protected. Plevin suggested that GTAP-BIO's assumption that only commercial land can change results in a reduced CI value. Also, available empirical evidence does not support an assumption of 90% protection. Taken together, these imply that the higher CI-LUC value calculated from the GCAM-T model may be more reliable. Plevin's final conclusion was that land representation in LUC models deserves more attention.



APPENDIX I

Glossary of Terms Used During the Workshop

AEO	Annual Energy Outlook
AEZ	Agricultural Ecological Zone
ALCA	Attributional Life Cycle Assessment
ANL	Argonne National Laboratory
ARPA-E	(DOE) Advanced Research Projects Agency - Energy
ATJ	Alcohol-to-Jet
ATR	Auto Thermal Reformer
BC	Black Carbon
BECCS	Bio-Energy with Carbon Capture and Storge
BEV	Battery Electric Vehicle
CAEP	Committee on Aviation Environmental Protection
C2G	Cradle-to-Grave
CARB	California Air Resources Board
CBIO	(Brazil) Decarbonization Credit
C-BREC	California Biomass Residue Emission Characterization (model)
CCS	Carbon Capture and Sequestration
CCUS	Carbon Capture, Utilization and Storage
CDFA	California Department of Food and Agriculture
CEF	CORSIA Eligible Fuel
CFP	Clean Fuel Program
CFS	Clean Fuel Standard (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
$CO_{2,eq}$	Mass of a specified GHG expressed as a mass of CO_2 having equivalent GWP
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
C-P	Cropland-Pasture
CRC	Coordinating Research Council
DAC	Direct Air Capture
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)
EOR	Enhanced Oil Recovery
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
FCC	Fluidized Catalytic Cracker
FCEV	Fuel Cell Electric Vehicle
FFC	Fossil Fuel Comparator
FT	Fischer-Tropsch
FTJ	Fischer-Tropsch Jet (fuel)
g $CO_{2,eq}$ MJ^{-1}	grams of CO_2, equivalents per MJ of fuel
GC	Grainger Causality
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
GT	Giga-Tonne (10^9 tonne)
GTAP	Global Trade and Analysis Project (econometric model)
GTAP-BIO	GTAP model modified to represent biofuels
GWI	Global Warming Intensity
GWP	Global Warming Potential
HD	Heavy Duty
HDN	Hydro-denitrification
HDO	Hydro-deoxygenation
HDS	Hydro-desulfurization
HEFA	Hydro-processed Esters and Fatty Acids
HEV	Hybrid Electric Vehicle
HSP	Healthy Soils Program
ICAO	International Civil Aviation Organization
ICCT	International Council on Clean Transportation
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
IO	Input-Output
IIASA	International Institute for Applied System Analysis
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
JRC	(EC) Joint Research Centre
LCA	Life Cycle Assessment
LCFS	Low Carbon Fuel Standard (California regulation)
LCI	Life Cycle Inventory

LCOD	Levelized Cost of Driving
LDV	Light-Duty Vehicle
LGO	Light Gas Oil
LMC	Land Management Change
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LUB	Land Use and Biodiversity
LUC	Land Use Change
MMT	Million Metric Ton
MODIS	Moderate resolution Imaging Spectroradiometer (satellite)
NBB	National Biodiesel Board
NEEA	(Brazil) Energy-Environment Efficiency Grade
NEI	(EPA) National Emissions Inventory
NETL	(DOE) National Energy Technology Laboratory
NG	Natural Gas
NRC	Natural Resources Canada
NREL	National Renewable Energy Laboratory
OEFI	(CFDA) Office of Environmental Farming and Innovation
ORNL	Oak Ridge National Laboratory
PDF	Probability Distribution Function
PHEV	Plug-in Hybrid Electric Vehicle
PNNL	Pacific Northwest National Laboratory
PRELIM	Petroleum Refining Lifecycle Inventory Model
RD	Renewable Diesel
RED	Renewable Energy Directive
RFA	Renewable Fuels Association
RFNBO	Renewable Fuel of Non-Biological Origin
RFS	Renewable Fuels Standard
RIN	Renewable Identification Number
RLP	Ricardo Lifecycle Protocol
RNG	Renewable Natural Gas
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
TRL	Technology Readiness Level
UCO	Used Cooking Oil
UNFCCC	U.N. Framework Convention on Climate Change
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
VGO	Vacuum Gas Oil
WTW	Well-to-Wheels (or Well-to-Wake)