Summary Report

6th CRC Workshop on Life Cycle Analysis of Transportation Fuels

Argonne National Laboratory

October 15-17, 2019

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On behalf of the Coordinating Research Council

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Summary of

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

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A. Introduction

On October 15-17, 2019, the Coordinating Research Council (CRC) hosted a workshop at Argonne National Laboratory near Chicago, Illinois, which focused on technical issues associated with life cycle analysis (LCA) of transportation fuels. The workshop was co-sponsored by API, Argonne National Laboratory, California Air Resources Board, Canadian Fuels Association, CONCAWE, National Biodiesel Board, Neste, Renewable Fuels Association, Union of Concerned Scientists, U.S. Department of Agriculture, Bioenergy Technology Office (BETO) of the U.S. Department of Energy, and the U.S. Environmental Protection Agency. This was the sixth in a series of bi-annual LCA Workshops organized by CRC. The four specified goals of this Workshop were very similar to 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.
- Establish priorities for directed research to narrow knowledge gaps and gather experts' opinions on where scarce research dollars would best be spent.

Attendance at the workshop was similar to previous years, with approximately 110 participants, including 16 from Canada and 6 from outside North America. Representatives were present from government bodies (including National Laboratories), industry, academia, and non-governmental organizations (NGOs). Twenty-five technical presentations were given, organized into seven Technical Sessions. At the end of the workshop, a final open session was held to solicit ideas from all attendees about research needs related to LCA of transportation fuels.

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) Overall Workshop Highlights, (C) Highlights and Learnings from Individual Presentations, and (D) Research Needs. A glossary of terms used during the Workshop is included as an appendix.

B. Overall Workshop Highlights

Given below are brief overall impressions and highlights from 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.

- Application of LCA to define carbon intensity (CI) of transportation fuels is increasingly being used by researchers and regulators, while affected parties are determining how to most effectively comply with new regulations. Nevertheless, it is recognized that some of the longstanding problems – such as data quality and model uncertainty – continue to exist and are the subject of on-going work.

- Emission factors and carbon intensities assigned to different land management options over time are complex, influenced by external variables such as weather and prior land management, and difficult to generalize. Lacking explicit documentation of a justified baseline and reference scenario, "change" estimates associated with soil carbon and other land management related emissions become uncertain and subjective.

- While some variations have been noted, total U.S. cropland area has not changed substantially over the past 20 years, as land use conversions into and out of cropland have been of similar size. However, due to variable definitions and data sources, uncertainty remains about certain land use details. Clear agreement on observed measures of actual land cover and land management is a prerequisite for improving consistency of modeling related to LUC.

- The share of land dedicated to major crops in the U.S. has changed over time, with increasing production of corn and soybeans being offset by decreases in other crops, continuing a trend that began in the mid-1980s. Biofuel policies are one possible factor contributing to this trend. Globally, increased crop yields and use of multi-cropping are among several factors contributing to decreasing estimates of the LUC effects simulated by some models.

- The issue of GHG emissions attributed to modeled land use change (LUC) remains controversial. Recent revisions to the GTAP-BIO model utilizing updated global economic databases and more detailed characterization of land use classes have reduced estimates of induced LUC (ILUC) contributions to the carbon intensity (CI) of biofuels in studies using this model. While ILUC emissions are included when estimating a fuel's CI value in the U.S. (according to EPA, CARB, and Oregon regulations), they are not included directly in the EU's Renewable Energy Directive (RED) or Canada's proposed Clean Fuel Standard (CFS).

- While originally applied primarily to conventional fuels and crop-based biofuel pathways, LCA is now being used to evaluate life-cycle GHG impacts of numerous other fuel pathways. These include fuels from waste feedstocks, mixed biological and fossil feedstocks, electro-fuel pathways, and others.

- Compliance with increasingly stringent low carbon fuel standards (LCFS), such as those applied in California, requires simultaneous adoption of many low-carbon strategies – including renewable diesel, renewable natural gas, electric fuels, refinery modifications, and carbon capture and sequestration (CCS). In addition, the CI values of conventional biofuels (ethanol and biodiesel) are being reduced by incorporating low-carbon production processes within their life cycles.

- Estimation of ILUC emissions varies with the models and assumptions being used. Due to differences in assumptions, such as substitution among different oilseeds and LUC in Malaysia and Indonesia, ILUC emissions for U.S. soy biodiesel are higher when calculated using CARB's approach that utilizes the AEZ-EF model as compared to values calculated using the GREET model with the Carbon Calculator for Land Use Change for Biofuels (CCLUB). Similarly, the CARB approach gives higher CI values for U.S. corn ethanol, in part, due to differences in assumptions regarding carbon emission factors associated with transitions among land classes, and due to LUC results from different GTAP versions.

- Considerable efforts are underway to promote and evaluate the GHG reduction benefits of sustainable aviation fuels (SAFs). Currently, the most commonly used SAFs are hydrogenated esters of fatty acids (HEFAs) that are derived from vegetable oils. However, the source of the oil has large effects on the estimated LUC emissions. For example, HEFA produced from palm oil in Malaysia and Indonesia has very high LUC emissions, whereas the same fuel produced from palm oil in South America may have negative LUC emissions.

- Use of waste feedstocks is generally recognized as a way to produce fuels having low CI values. However, many waste materials have other low-value uses, which may need to be satisfied with substituted materials. In cases where displacement emissions result from use of these substituted materials, such emissions should then be attributed to the biofuel being produced from the original waste feedstock, thereby altering its CI value. While different methods for attributing displacement emissions were discussed, no consensus was reached on the best method for each context.

- In efforts to assess the economic and environmental impacts of RFS2 (or other biofuels policies), it is important to compare results observed from the factual case (what really happened) with estimated results that would have occurred in a counterfactual case without the biofuels policy in effect. Development of realistic and clearly documented counterfactual scenarios is an important area that deserves further attention.

- Efforts are underway within ASTM International to develop a procedural standard for reference scenarios to use when performing LCA studies of biofuels. Such a standard will provide guidance on data sources, assessment frameworks, measurable indicators, documentation, and other aspects of scenario development. It is hoped that this will improve the transparency and replicability of LCA studies, thereby fostering improved decision making.

- Stock and Flow Models (SFMs) provide an alternative way to assess the GHG impacts of biofuels. Compared to the traditional, static LCA approach, SFMs investigate time-based flows of carbon between different carbon sinks. Because of significant differences in data requirements, scope of investigation, and type of questions that can be addressed, it is difficult to compare directly the results from LCA and SFM studies.

- The importance of agriculture as a carbon mitigation measure was emphasized by several speakers. However, for effective mitigation, it is important to understand which soils, under which cropping conditions, can increase soil organic carbon (SOC). Consistent and reliable measurements of SOC over time is costly and difficult. Afforestation of retired agricultural land can also lead to carbon sequestration.

- The combination of LCA with techno-economic analysis (TEA) is becoming more widely used to evaluate and compare different fuels and production pathways – including pathways that utilize renewable electricity to produce so-called E-fuels.

- Modeling work has shown that aggressive electrification of both the transportation and non-transportation sectors in California can lead to improvements in air quality and human health, primarily due to reduced concentrations of $PM_{2.5}$.

- A potential E-fuel opportunity was discussed involving use of concentrated CO_2 waste streams at corn ethanol plants throughout the U.S. Modeling has shown that by using renewably-generated H_2 (from electrolysis plants) with this CO_2, and incorporating additional hydrocarbon production via Fischer-Tropsch processes, the final CI value of the ethanol product can be lowered dramatically.

- Another emerging form of carbon capture and utilization (CCU) involves microbial fermentation of waste CO_2 to produce ethanol, which can be further upgraded to higher value hydrocarbon fuels. Considering the wide range of feedstocks, conversion processes, and final products, it is important to utilize TEA/LCA evaluations to focus on the most promising pathways.

- In most LCA models, refinery production of gasoline is assumed to have higher CI values than is production of diesel fuel. This results from use of higher energy intensive processes in the production of gasoline that occurs in refineries where operations are economically optimized. However, if operations were optimized to reduce GHG emissions, the relative gasoline and diesel CI values could change substantially. This suggests that using a marginal CO_2 approach in refinery optimization modeling could give a better indication of CI values as refinery operations change.

- Assessment of GHG emissions associated with oil and gas production is improving as more on-site processes are being represented and more complete data collection is occurring. Over the approximately 9000 oil producing fields represented in the OPGEE model, CI values for oil production range from under 5 to over 40 g CO_{2eq}/MJ. Fields associated with heavy crude, and those that utilize extensive flaring, tend to have the highest CI values. Limiting flaring appears to be an effective GHG mitigation strategy.

- The Petroleum Refining Life Cycle Inventory Model (PRELIM), which is used to estimate life cycle GHG emissions associated with U.S. transportation fuels, is undergoing significant updates. Improvements are being made to better represent changing crude slates in U.S. refineries and to include estimated impacts of additional environmental outcomes (beyond GHG emissions), such as acidification, eutrophication, ozone depletion, and other metrics.

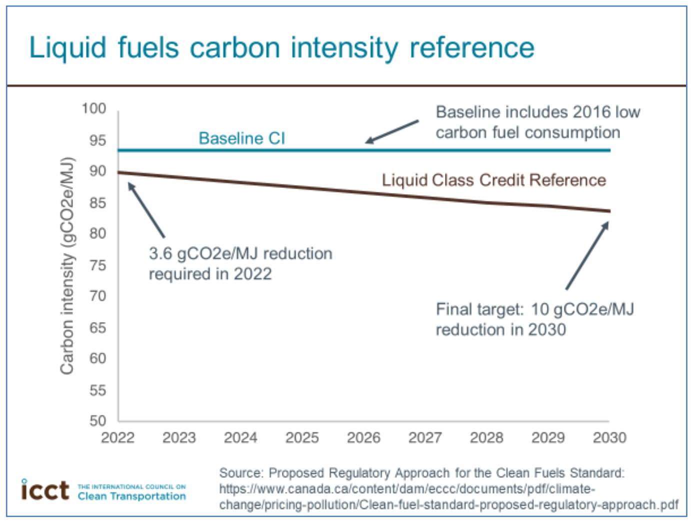
C. Highlights and Learnings from Individual Presentations

<u>Session 1: Transportation Fuel Policy</u>

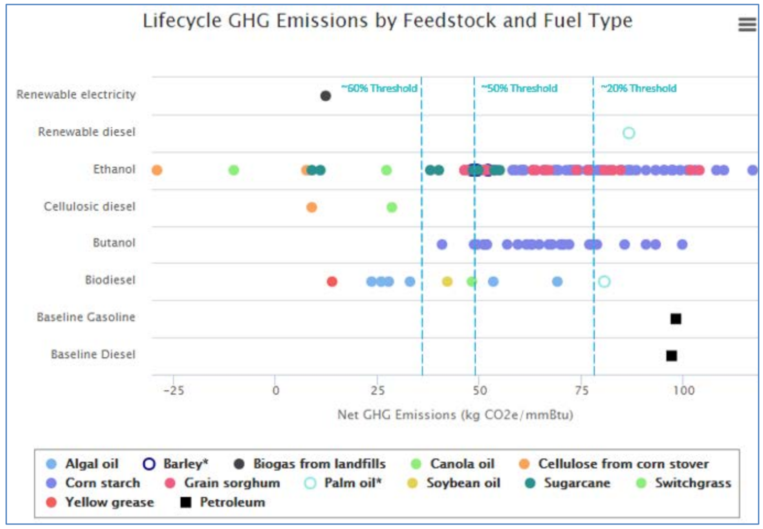
Chairpersons: Devin O'Grady (Natural Resources Canada), Jeremy Martin (Union of Concerned Scientists), and Sari Kuusisto (Neste Corp.)

Session 1 consisted of four presentations that laid the foundation for the rest of the Workshop by providing summaries of policies, and recent policy changes, related to renewable and low-carbon transportation fuels in several regions around the world. Stephanie Searle of the International Council on Clean Transportation (ICCT) discussed the Clean Fuel Standard (CFS) that is proposed for Canada, and options being considered to ensure compliance with the CFS. Aaron Levy of the U.S. EPA explained the U.S. Renewable Fuel Standard Program (RFS2), pointing out several recent developments related to this program. Adrian O'Connell of the European Commission Joint Research Centre (EC-JRC) summarized recent work related to the EU's new Renewable Energy Directive (RED II). Finally, Colin Murphy of the University of California at Davis (UC Davis) provided updates to the Low Carbon Fuel Standard (LCFS) program in California.

Stephanie Searle [International Council on Clean Transportation, (ICCT)] described Canada's proposed Clean Fuel Standard (CFS), which is part of the country's overall strategy to reduce GHG emissions 30% below 2005 levels by the year 2030. While somewhat similar to California's Low Carbon Fuel Standard (LCFS) and the European Union's Fuel Quality Directive (FQD), the proposed CFS is a broader regulation, covering several economic sectors (transportation, industry, and buildings) and fuel types (gaseous, liquid, and solid). All policy elements discussed in this presentation are being considered by the Canadian government, but no final decisions have been made on the DFS. Searle focused on the liquid transportation fuel component of the CFS, which requires a 10-12% reduction in carbon intensity (CI) by 2030. As shown in the figure, this represents a CI reduction of 10 g CO_2eq/MJ. While each fuel type comprising the entire fuel pool is assigned its own CI baseline value, the entire pool must follow the CI reduction trajectory shown in the figure. Induced land use change (ILUC) considerations are not included in determining a fuel's CI value. Compliance with these liquid fuel CI targets can be achieved in various ways, including reducing life-cycle emissions of conventional fossil fuels, substitution of low carbon fuels (e.g. CNG, propane, and hydrogen), and end-use fuel switching [e.g., EVs and fuel cell electric vehicles (FCEVs)]. To address sustainability concerns, the CFS prohibits conversion of forests or wetlands to produce biofuel feedstocks and will not allow use of feedstocks associated with high ILUC – which means that use of palm oil is banned. Overall, the CFS is more complex, but also more flexible than the EU-RED or California LCFS regulations. The current timeline calls for a final regulation for liquid fuels in early 2021, with gaseous and solid fuel regulations following about one year later.



Aaron Levy (U.S. EPA) discussed the U.S. Renewable Fuel Standard (RFS) program, with emphasis on recent developments. RFS was established by the U.S. Energy Policy Act of 2005 (EPACT) and was modified to RFS2 under the U.S. Energy Independence and Security Act of 2007 (EISA). To qualify as a renewable fuel under the RFS program, a fuel must be produced from renewable biomass and meet the statutory GHG emissions reduction requirement, as compared to a 2005 baseline (i.e., GHG reduction thresholds). The threshold requirement is 20% for "Renewable Fuel," 50% for "Advanced Biofuel" and "Biomass-Based Diesel Fuel," and 60% for "Cellulosic Fuels." The required GHG reductions are assessed on a life-cycle basis, "including direct emissions and significant indirect emissions such as emissions from land use changes." In determining compliance with RFS, EPA considers the impacts of an entire renewable fuel pathway, which consists of three components: feedstock, production process, and final fuel. To date, EPA has fully quantified lifecycle GHG results for 144 renewable fuel pathways, which are shown in the figure.



Levy mentioned several EPA developments and accomplishments since the previous CRC LCA Workshop in October 2017. For example, renewable fuel volume obligation (RVO) rulemakings were finalized for 2018 and 2019, and volumes are proposed for 2020. Also, regulatory changes were finalized to allow E15 to take advantage of the same 1-psi Reid Vapor Pressure (RVP) waiver that currently applies to E10 fuel during the summer months. In addition, EPA has published the 2nd Triennial Report to Congress on Biofuels and the Environment. This report noted that between 2007 and 2012, actively managed cropland in the U.S. increased by approximately 4.0-7.8 million acres, although the contribution of biofuel feedstock production to this increase cannot be quantified with precision. It was also noted that ILUC estimates for corn ethanol remain uncertain, and progress in reducing the sources of uncertainty has been limited.

Levy also mentioned several RFS-related activities currently underway at EPA, including rules to set the annual renewable volume obligations and make other regulatory amendments. Along with other agencies, EPA is developing the 3rd Triennial Report to Congress on Biofuels and the Environment. As with the previous triennial reports, consideration of GHG impacts likely will not be included, as this has been considered out of scope of the report by the EISA, and is directly considered by fuel pathway certification.

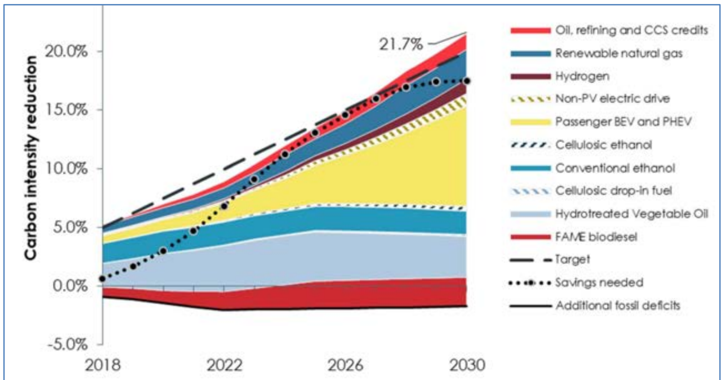
Adrian O'Connell [European Commission Joint Research Centre (JRC)] provided a summary of JRC's work in support of the European Union Renewable Energy Directive (EU-RED). When originally developed in 2009, RED required the EU Member States to achieve at least a 10% share of renewable energy in transport fuels by 2020. Other requirements restricted the type of biofuels to those deemed to be sustainable, with LCA being a tool in assessing sustainability. Updated RED-II requirements, defined in 2018, increase the transport target to 14% of renewable fuels by 2030, with a sub-target of 3.5% advanced biofuels originating from agricultural residues, biowaste, and other defined wastes. LCA is used to determine whether specific fuel pathways satisfy the GHG reduction thresholds established as part of the sustainability requirements under RED-II. These thresholds are shown in the chart.

Greenhouse gas savings thresholds in RED II

Plant operation start date	Transport biofuels	Transport renewable fuels of non-biological origin
Before October 2015	50%	-
After October 2015	60%	-
After January 2021	65%	70%
After January 2026	65%	70%

O'Connell also discussed several RED-II-related issues that the JRC is currently addressing. One involves defining the methodology by which GHG savings are calculated from fuels arising through co-processing operations, in which both renewable and non-renewable feedstocks are utilized. Another involves LCA methodologies for renewable fuels of non-biological origin (ReFuNoBiOs), including e-fuels and fuels derived from industrial exhaust streams. In these cases, it matters whether the feedstocks are elastic (increasing with demand) or rigid (not increasing with demand). When using elastic feedstocks, the GHG impacts of the renewable fuels are estimated based on the incremental increase in supply; with rigid feedstocks, the GHG impacts are estimated based on the diversion of the feedstocks from their existing uses. Finally, O'Connell compared carbon capture and use (CCU) of CO_2 from concentrated waste streams (such as flue gas) vs. capture from the atmosphere. While direct air capture (DAC) may make sense in a few cases where stranded renewable electricity is available, it is preferable to utilize waste industrial CO_2, which otherwise would be emitted.

Colin Murphy (U.C. Davis) presented an update on the 2018 re-adoption of California's Low Carbon Fuel Standard (LCFS). Among the various changes included in this re-adoption is a tightening of the transportation fuel CI reduction target to provide a 20% reduction by 2030, compared to a 2010 baseline. The current year (2019) target of 6.25% CI reduction increases linearly with time over the next 11 years, until the goal of 20% reduction is met in 2030. Conventional fossil fuels, which have CI values higher than the standard for a given year, generate deficits, while alternative fuels having CI values lower than the standard generate credits. A significant component in the modified LCFS program is the ability to generate credits from sources other than the fuels themselves. For example, utilizing carbon capture and sequestration (CCS) in the generation of corn ethanol, renewable diesel, and renewable natural gas (RNG) can lower the CI value of these fuels. In an example mentioned by Murphy, the average corn ethanol CI value of 70 g CO_2/MJ could be reduced to 40 g CO_2/MJ with application of CCS.



Source: Chris Malins "California's Clean Fuel Future" April 2018

Other credit opportunities include production of alternative jet fuel, on-site petroleum refinery modifications (such as co-processing), and infrastructure projects to expand the capacity of hydrogen fuels and DC fast charging stations. The amounts of these credits are capped, and third party verification is required to ensure the credits are warranted and are handled properly. A projected pathway of how California will achieve the 20% CI reduction target by 2030 is shown in the figure, which indicates the expected contributions of several different components. In the near term, compliance will continue to be dominated by diesel substitutes and corn ethanol. By the late 2020s, EVs are expected to be the largest contributor, while RNG, refinery projects, and CCS applications are also expected to become significant.

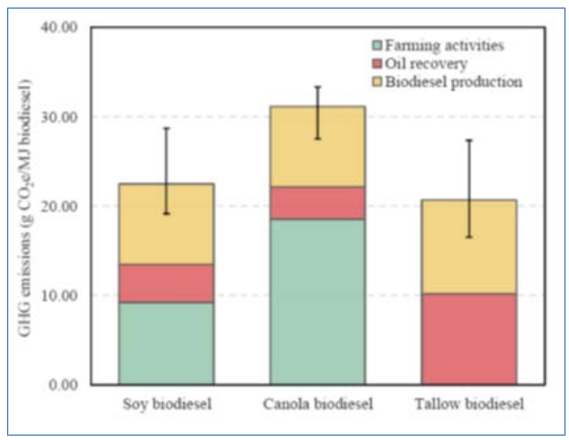
Session 2: Recent Modeling of Crop-Based Biofuels

Chairpersons: Stephanie Searle (ICCT) and Aaron Levy (U.S. EPA)

Session 2 consisted of three presentations that discussed recent work regarding LCA modeling of crop-based biofuels. Rui Chen of the California Air Resources Board (CARB) discussed work he had formerly conducted while at Argonne National Laboratory (ANL) investigating the impacts of different ILUC assumptions on the CI values of biodiesel fuels in the U.S. Farzad Taheripour of Purdue University discussed updates to the GTAP-BIO model and use of this model to assess CI values of various sustainable aviation fuels (SAFs). Hugo Valin of the International Institute for Applied Systems Analysis (IIASA) discussed updates to the GLOBIOM model and use of this model to investigate ILUC impacts of biofuels in Europe.

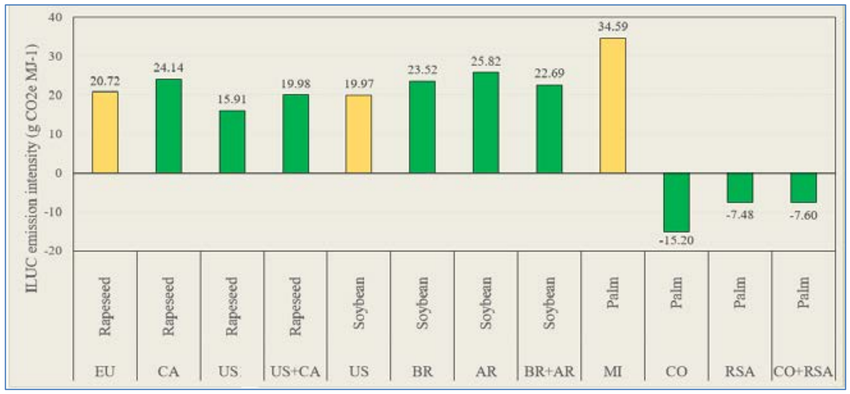
Rui Chen [(California Air Resources Board (CARB)] discussed an LCA study of U.S. biodiesel fuel and the impacts of different ILUC assumptions on the CI results. [This work was not sponsored by CARB, but was conducted by Argonne National Laboratory (ANL) when Chen was employed there.] The study focused on biodiesel because of the growing importance of diesel fuel (and its alternatives) within the overall pool of transportation fuels. While the U.S. Energy Information Administration (EIA) projects that gasoline demand will decline by about 25% from 2005 to 2050, while diesel fuel demand is expected to increase by about 75% over this same period. Well-to-wheels (WTW) LCA modeling was conducted to assess fossil fuel consumption and GHG emissions from three biodiesel pathways - using soy, canola, and tallow as feedstocks. The GREET model was employed, including the Carbon Calculator for Land Use Change from Biofuels (CCLUB) module for determining ILUC impacts. Recent USDA survey data were used to provide updated farming information (acreage, crop yields, fertilizer application, etc.). Model inputs for vegetable oil extraction were obtained from the National Oilseed Processors Association (NOPA), which showed a significant reduction in energy use between 2008 and 2014. Updated model inputs for biodiesel production were obtained through the National Biodiesel Board (NBB) from a survey of current production facilities.

Predicted ILUC emissions were quite variable, depending upon the case being studied, but in every case ILUC values determined by the CCLUB method were much lower than those determined by the AEZ-EF model that is used by CARB. For example, the CARB Average Proxy case for soy biodiesel has an ILUC value of 26.1 g CO_{2e}/MJ, whereas the value from CCLUB is 10.0 g CO_{2e}/MJ. A major factor explaining this discrepancy is the difference in how the two approaches handle land use change in Indonesia. The GREET-CCLUB modeling results showed an approximate 80% reduction in fossil energy consumption compared to petroleum diesel for biodiesels produced from all three feedstocks (soy, canola, and tallow). Total GHG emissions from soy biodiesel were estimated to be 65-70% lower than from petroleum diesel, when including an ILUC value of 10 g CO_{2eq}/MJ. As shown in the figure, differences in GHG emissions were found among the three biodiesel pathways. These are attributed primarily to higher farming emissions for canola (due to greater fertilizer inputs) and higher energy requirements for tallow rendering compared to seed oil crushing. A model sensitivity analysis was also conducted, which showed that the overall GHG results are most sensitive to changes in ILUC assumptions and energy inputs from farming and fuel production processes.



Farzad Taheripour (Purdue University) summarized LCA work being conducted for the International Civil Aviation Organization (ICAO) to investigate ILUC emissions for a variety of sustainable aviation fuels (SAF). The GTAP-BIO model being used represents the world economy in 2011. Several model updates have been included, such as addition of multiple cropping, adjustments to yield-price elasticity (YDEL), and changes to cropland-pasture (C-P) designations. Also, the AEZ-EF model used to determine GHG emissions from land use change (LUC) was revised to account for soil carbon sequestration from dedicated crops. Taheripour summarized several long-term trends occurring within the crop and livestock economic sectors, which have impacts on ILUC. These trends include agricultural intensification, production of more crops with less land, increased production of poultry and pork compared to beef, and increased production of corn and soybeans compared to other crops.

GTAP-BIO was used to examine ILUC emissions arising from a variety of different biojet fuel shocks. The fuel pathways included hydrogenated esters of fatty acids (HEFA), alcohol-to-jet (ATJ), and Fisher-Tropsch to jet (FTJ) from different feedstocks in various countries of origin. Sensitivity tests were performed to examine the effects of expansion of crops on peatlands and variations in the CO_2 emission rates from peatlands. Increasing the peat oxidation factors increased the ILUC emissions intensity of palm HEFA fuel from Malaysia and Indonesia by up to a factor of two, but also increased ILUC emissions from soy- and rapeseed-HEFA pathways in the U.S., Brazil, and EU by 20-30%. Additional modeling was conducted to examine ILUC emissions from several regional pathways, including palm-HEFA fuel from Colombia (CO) and the rest of South America (RSA). In contrast to the high ILUC emissions from palm-HEFA in Malaysia and Indonesia, the fuel pathway in Colombia has negative ILUC emissions (see figure). This is due to a large increase in overall crop biomass resulting from growth of new palm plantations in Colombia.



Hugo Valin [International Institute for Applied Systems Analysis (IIASA)] discussed use of the GLOBIOM model to investigate ILUC impacts of biofuels used in the EU. GLOBIOM is a partial equilibrium model that represents the agricultural, forestry, and bioenergy markets within the 28 EU Member States and across 25 other world regions. The model uses a base year of 2000, and is applied with a 10-year time step up to 2050. Extensive GLOBIOM modeling was done to evaluate different fuel pathways and policy scenarios in support of the EU's Renewable Energy Directive (RED) in 2015. This work showed that depending upon the pathway considered, biofuels can significantly increase LUC and resulting GHG emissions. Particular risks were identified with pathways involving soy and palm biodiesel, due to impacts of deforestation in tropical regions. Understanding gained from this earlier modeling work was influential in setting caps on 1st generation biofuels within the RED policies, and establishing other guidelines regarding sustainability.

Now there is new policy under RED II, which increases the renewable fuel target to 14% by 2030, caps "high ILUC risk" feedstocks, and promotes a variety of other "good practices" for biofuels. Valin discussed several recent updates and applications of GLOBIOM modeling in support of these and other biofuel policies. For example, GLOBIOM, like GTAP-BIO, was used to support the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) program of ICAO. Many of the alternative jet fuel pathways mentioned above by Farzad Taheripour (who used the GTAP-BIO model) were also investigated by IIASA, using the GLOBIOM model. While the ILUC emission results for most pathways were quite similar between these two modeling approaches, GLOBIOM predicted much higher emissions for HEFA fuels produced from vegetable oils – especially soy from Brazil and palm from Southeast Asia.

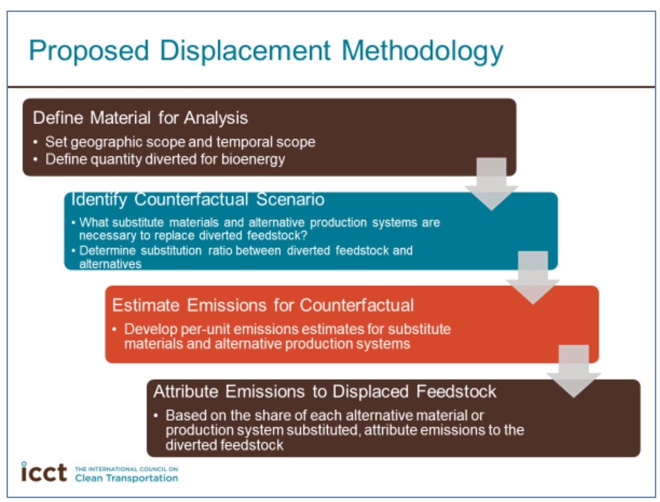
Valin mentioned a large number of recent updates and improvements made to GLOBIOM. For example, the model now includes effects of multi-cropping and it can now account for co-product substitution based on protein and energy content. Considerable work has been done to improve the model with respect to palm oil expansion in various locations. New data sources have been incorporated regarding the share of new palm plantations being developed on peat soils, GHG emission factors from disturbed lands within and outside the new plantations, and other emission sources in palm-growing regions. Valin also commented on future work involving GLOBIOM and biofuels. Additional land use modeling including prospective scenarios and consequential analysis is required to develop informed policy decisions. Further work exploring ILUC emission estimates is also necessary, recognizing that this is an imprecise area. Finally, social and environmental considerations must be combined to address sustainability questions.

Session 3: Biofuels: "Compared to What?" Of Baselines, Reference Scenarios, and Counterfactuals

Chairpersons: Keith Kline (Oak Ridge National Laboratory) and Jeongwoo Han (ExxonMobil)

Session 3 consisted of four presentations that addressed the need to develop and utilize appropriate baselines, reference scenarios, and counterfactual scenarios when assessing environmental impacts of transportation fuels. Nikita Pavlenko of the International Council on Clean Transportation (ICCT) presented a methodology to determine GHG emissions when a waste material is diverted from its current use to serve as a feedstock for biofuels production. Tyler Lark of the University of Wisconsin discussed development of counterfactual scenarios to describe what would have happened to cropland area, crop prices, and other U.S. agricultural parameters since 2007 in the absence of the U.S. RFS program. Chuck Core of CC Consulting (formerly of Archer-Daniels Midland) discussed an ongoing ASTM effort to develop a procedural standard for defining reference scenarios for use in LCA studies of biofuels. Finally, Bill Hohenstein of USDA discussed several trends in U.S. agriculture over the past 20 years, and explained their connections with biofuels polices and trends.

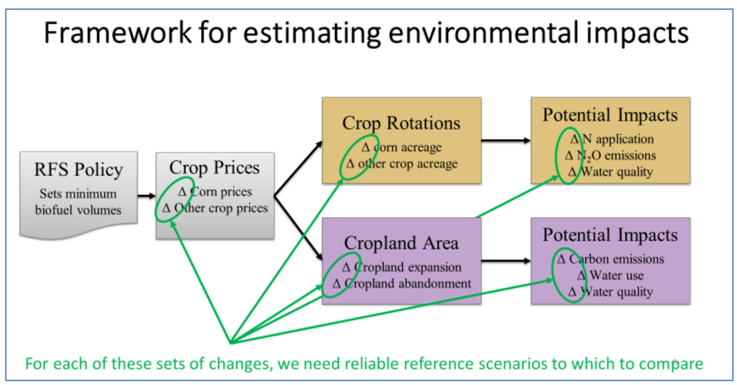
Nikita Pavlenko [International Council on Clean Transportation (ICCT)] discussed issues of displacement emissions that arise when waste and residue feedstocks are used to produce biofuels. While use of waste feedstocks is generally regarded as a favorable way to produce biofuels having low CI values as compared to purpose-grown feedstocks, there are still indirect effects to consider. Used cooking oil (UCO) was presented as a simple example to illustrate these points. Historically, UCO has been used as a supplement to animal feed. However, as UCO is increasingly being diverted for use as a biofuel feedstock, its calorific and nutritional value in animal feed must be replaced. Emissions associated with the replacement animal feed must then be determined and should be attributed to the biofuel being produced from the displaced UCO, thereby increasing the CI value of this biofuel.



Pavlenko explained a 4-step methodology (shown in the figure) to assess displacement emissions in situations where waste feedstocks are utilized. This begins with a careful definition of the situation being considered, including the geographic scope, temporal scope, and amounts of feedstocks and fuels included. Next, a counterfactual scenario is developed to identify the substituted materials, and their production processes that are used to replace the waste feedstock being diverted to biofuel production. For example, in the simple UCO displacement situation mentioned above, it was determined that 1.2 lbs of corn feed was required to replace every 1.0 lb. of UCO diverted from animal feed. The final two steps estimate the emissions associated with the counterfactual scenario, and attribute these emissions to the biofuel produced from the displaced feedstock. When applied to the UCO example, this dramatically increases the CI value of biodiesel produced from UCO in the U.S. from 15 to 40 g CO_{2eq}/MJ, which reduces the carbon savings relative to petroleum diesel from 85% to 60%.

Pavlenko also presented a more complex example involving crude tall oil (CTO), which is a low value by-product of the paper and pulp industry. Currently, some CTO is burned on-site for power generation and some is upgraded through fractional distillation to produce a variety of specialized products. Diverting CTO to biofuel production will upset the current balance of uses, leading to substitution of other materials for on-site power or for displaced specialty products. However, determining how current CTO uses are disrupted, and what the emissions impacts of this are, is complicated. Assuming that all current uses are equally displaced is the simplest approach, but is not very realistic. Determining displacement based on economic value of different end uses is more realistic, but is much more data intensive. Another factor to consider is that markets are not static, even for "waste" materials. Finally, Pavlenko cautioned that we must be careful to not incentivize displacement of waste feedstocks into biofuels if this results in greater fossil fuel consumption in other sectors.

Tyler Lark (Univ. Wisconsin) discussed efforts to understand the economic and environmental impacts of the RFS2 program. In particular, impacts on crop prices, land use change, and GHG emissions are of interest, although the approach used can also be employed to examine other impacts, such as water use and water quality. This approach requires development of counterfactual scenarios that can be compared with the observed, factual scenario. In this case, the factual scenario involves implementation of the RFS2 program in 2007. Based on various measurements and observations, we have a good understanding of how cropland area, crop rotations, crop prices, and other factors have changed since then. A counterfactual scenario describes what we think would have happened over this time period in the absence of the RFS program. Differences between the factual and counterfactual scenarios then represent estimates of the impacts of RFS. A schematic depiction of this approach is shown in the figure.



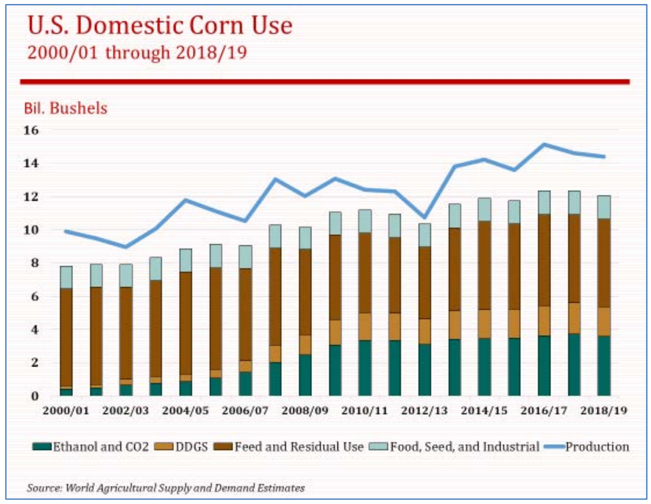
Developing a counterfactual scenario begins with estimating changes in ethanol volume resulting from implementation of the RFS program. Lark used differences in USDA projections made for the RFS1 and RFS2 programs to estimate a 5.5 billion gallon/year impact of RFS2. The size of this ethanol "demand shock" was then used to estimate the change in crop prices from a business as usual (BAU) counterfactual scenario that did not include this shock. Results of this determination estimated increased crop prices for corn, soybeans, and wheat of 30%, 20%, and 21%, respectively. Based on these price differences, Lark estimated the price-response elasticity of planting corn vs. other crops, and used this to calculate the probability of crop switching throughout the contiguous U.S. The final counterfactual mentioned involved cropland area. According to the USDA's National Resources Inventory (NRI), total cropland area increased by 7.5 million acres between 2007 and 2015, with perhaps 5 million acres being attributable to RFS2. However, a counterfactual assessment suggests that the baseline cropland area in the absence of RFS would have been 12 million acres lower in 2015, based on the declining trend in effect since 1992. If this counterfactual were accepted as representing the true baseline, the impacts of RFS on cropland area are much greater than previously believed. Work is continuing to estimate uncertainties (and their propagation) in these counterfactual scenarios, and to estimate outcomes on a per-gallon of ethanol basis, so they can be more easily compared with other results. Lark concluded by urging the research community to work towards development of a set of universally accepted baseline conditions, which could then be used by all in future studies.

Chuck Corr (CC Consulting; formerly of Archer-Daniels Midland) discussed efforts underway within ASTM International to develop a procedural standard for reference scenarios used in conducting LCA investigations of biofuels. This work was stimulated by researchers at Oak Ridge National Laboratory (ORNL) who reviewed different reference scenarios used in the literature. They found that there was no standard for identifying or characterizing an appropriate reference scenario, and that the selection of a particular scenario had a significant effect on the outcome of the LCA study being conducted. In view of this, it was thought that establishment of a procedural standard would be useful in providing guidelines to improve transparency, replicability, communication, and better-informed decisions.

ASTM International is thought to be the most appropriate venue for creating a standard for reference scenarios. ASTM itself does not develop standards, but it provides a committee structure whereby knowledgeable volunteers work together to develop standards. In this case, standard development is being conducted within Committee E48 on *Bioenergy and Industrial Chemicals from Biomass*, under Subcommittee E48.80 on *Sustainability Related to Biomass*. This subcommittee has already developed a related standard, E3066: “Standard Practice for Evaluating Relative Sustainability Involving Energy or Chemicals.”

As is usual with ASTM, the draft standard now being developed for reference scenarios will define the intended use of the standard. In this case, the scope involves situations where one scenario includes biomass or biomass-derived products. The standard will also define the general concepts and principles related to transparency, measurable indicators, equivalency, replicability, iteration, realism, and terminology. Finally, the standard will define practices with respect to the assessment framework, characterization of the test and reference scenarios, documentation of data sources, and documentation of differences between scenarios. As with any ASTM standard, the draft now being developed must be approved by committee vote before being accepted. Corr invited any interested parties to join the ASTM E48 Committee and participate in this effort.

Bill Hohenstein (USDA) discussed U.S. cropland trends over the past 20 years, and the large number of factors influencing these trends – including biofuels policy. Other important factors include international trade relationships, improvements in agricultural technology, and climate change. Since 2000, total U.S cropland acreage has not changed substantially, while major changes in crop distribution have occurred, resulting in more corn and soybeans, and less other crops. Also, although total acreage amounts have not changed, shifts among land classes have occurred, both adding to and subtracting from the cropland acreage. Additions to cropland have come primarily from pasture and retirement of Conservation Reserve Program (CRP) lands. Reductions in cropland primarily reflect transitions to pasture and development. CRP enrollment limits are set by the Farm Bill. The limit decreased from a maximum of 37 million acres allowed in 2007 to about 24 million acres per the 2014 Farm Bill. Most retirements in recent years occurred in the Northern Plains. Since 2000, consumption of corn ethanol in the U.S. has increased from <0.5% of the total gasoline pool to 10% today. This has been accompanied by growth of corn production from about 10 billion bushels to 14 billion bushels. As shown in the figure, the amount of corn used for food and feed has remained nearly constant over this period, while the amounts of DDGS and ethanol have increased.



Hohenstein also presented data showing warmer temperatures over most of the U.S. since the first half of the 20th century, and explained how this has lengthened the growing season by 6-19 days across different regions of the country. Another driver of crop growth is importation of soybeans by China, which has increased from about 15 million tons in 2000 to over 90 million tons today. While the U.S. supplies a significant fraction of these imports, the largest supplier is Brazil. The factors leading to LUC in the Amazon area (and elsewhere) are complex and defy simple explanation. For example, during the time when U.S. corn ethanol production rose most dramatically (2004-2010), the annual rate of Amazon deforestation declined from over 10,000 to under 3000 square miles, which appears inconsistent with the ILUC projections at that time. Research has shown that LUC model predictions failed to accurately account for expansion of multi-cropping and acceleration of new agricultural technology driven by increased crop prices. This intensification has allowed for increased crop production without reducing exports or requiring large-scale LUC.

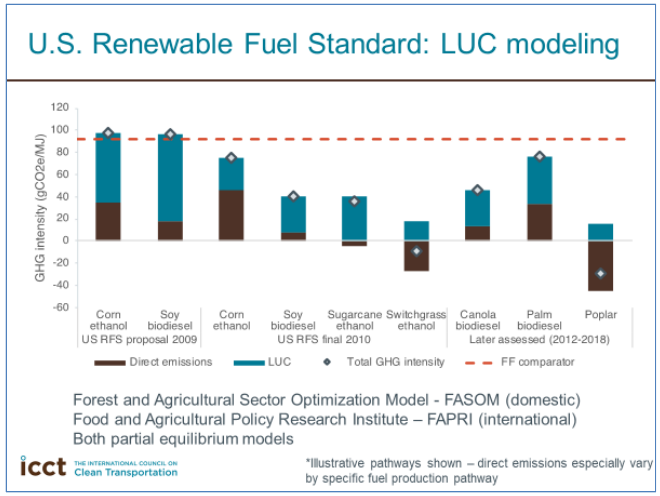
Special Panel Exploring Key Issues in LUC Modeling

Chairpersons: Aaron Levy (EPA) and Michael Wang (ANL)

This special panel provided four presentations that discussed recent developments and controversies regarding LUC modeling. Stephanie Searle of ICCT summarized different LUC modeling approaches being used by the U.S. EPA, the California Air Resources Board (CARB), and the EU – while pointing out the economic drivers/incentives linking these models with the biofuels policies they support. Jim Hileman of the Federal Aviation Administration (FAA) discussed the LUC modeling being used to assess carbon intensity of aviation fuels in support of the International Civil Aviation Organization (ICAO) goal of carbon neutral growth. Chris Malins of Cerulogy discussed changes in the derivation of ILUC emissions estimates over the past decade and questioned whether the sharp decline in ILUC values in studies using the GTAP model may be based, in part, on overly-optimistic assumptions. Mike Griffin of Carnegie Mellon University and Savant Consulting, Inc. compared the structure, data needs, and utility of stock and flow models (SFMs) with LCA models. Following these four presentations, an additional four panelists were invited to offer their thoughts on the topic of LUC modeling. These included Steffen Mueller of UIC, Jennifer Dunn of ANL, Farzad Taheripour of Purdue University, and Hugo Valin of IIASA.

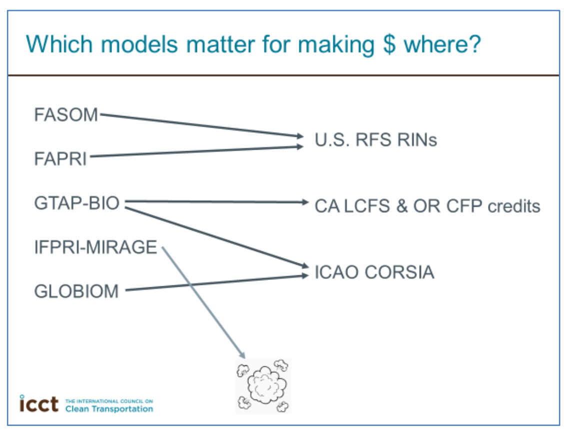
Stephanie Searle (ICCT) reviewed a range of LUC models currently being used by different countries and jurisdictions as part of biofuels policies. Under the U.S. RFS program, EPA used two partial equilibrium agro-economic models – FASOM for domestic and FAPRI for international – to estimate LUC related to biofuel production. GHG emissions associated with these LUC scenarios are then combined with direct emissions to determine the overall GHG intensity of specific biofuel pathways, as shown in the figure. The RFS regulation requires a specific allocation of fuel volumes in four categories having prescribed GHG reduction values: (1) Renewable Fuel (20% GHG reduction), (2) Advanced Biofuel (50% GHG reduction),

(3) Cellulosic Fuel (60% GHG reduction), and (4) Biomass-Based Diesel (50% GHG reduction). Compliance with these renewable fuel volume obligations (RVOs) creates economic incentives to produce more or less of a particular biofuel. These incentives exist and are managed in the form of Renewable fuel Identification Numbers (RINs), which monetize the value of blending a particular renewable fuel. Searle presented time trend data of RIN values over the past 10 years. Currently, D6 RINs (which apply to the Renewable Fuel category, including corn ethanol) have a value of \$0.1-0.2 per gallon, while D5 RINs (Advanced Biofuels, such as sugarcane ethanol) and D4 RINs (Biomass Based Diesel) have values of \$0.4-0.5 per gallon.



The State of California incentivizes increasing usage of renewable fuels through their LCFS regulations, which mandate that the carbon intensity (CI) value of the entire fuel pool – expressed as g CO_2eq/MJ – be reduced following a prescribed timetable. [Oregon now follows a very similar approach as part of their Clean Fuel Program (CFP)]. In this scheme, each fuel pathway is assigned a particular CI value, based on assessments of its direct and LUC emissions. A general equilibrium model, GTAP-BIO, is used to determine the LUC impacts of each pathway. Fuel pathways that result in lower GHG emissions than the target value generate credits, expressed as \$/tonne of CO_{2eq}, whereas pathways with higher GHG emissions generate deficits. Searle presented monthly trend data showing that the current price of these LCFS credits is approximately \$200/tonne of CO_{2eq}.

Under the EU's RED, a general equilibrium model called IFPRI-MIRAGE has been used to estimate indirect effects of biofuels. However, because LUC emissions are only reported, but not used in calculating a fuel's CI value, determination of these emissions is not directly linked to an immediate economic incentive. Finally, Searle discussed LUC modeling by the International Civil Aviation Organization (ICAO). Both the GTAP-BIO model and a partial equilibrium model called GLOBIOM are used to determine LUC emissions. There are direct economic impacts of this approach, as the calculated CI values are used in determining an airline's compliance with its goals as stipulated in the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). Searle concluded with the figure highlighting the economic connections between LUC models and policies/regulations where they are used.



Jim Hileman (FAA) provided more explanation of CORSIA, which is being developed by ICAO. ICAO has set a goal of carbon neutral growth for international aviation from 2021 to 2035. The carbon offsetting requirements, together with other measures, were developed to achieve this goal, which can be met by use of CORSIA Eligible Fuels (CEFs). CEFs are ranked by their CI values that are based on life-cycle emissions as compared to conventional aviation fuel. For several years, ICAO's standing Committee on Aviation

Environmental Protection (CAEP) has been working to define CEFs and the methodologies used to evaluate and approve them. Two types of CEFs have been defined: (1) sustainable aviation fuel (SAF), which is produced from renewable or waste-derived feedstocks, and (2) lower carbon aviation fuels, which are produced from fossil feedstocks, but using processes resulting in lower lifecycle emissions.

Total LCA emissions for a particular fuel pathway are determined by summing the direct emissions (also called core LCA) and the emissions from induced land use change (ILUC). The core LCA value of a particular pathway is determined using an attributional process, with the emissions being allocated to co-products on an energy basis. The ILUC LCA values are determined using two different modeling approaches: (1) GTAP-Bio from Purdue University and (2) GLOBIOM from the International Institute for Applied System Analysis (IIASA). These two ILUC modeling approaches have been used to assess 17 SAF pathways. Results from the two models are in good agreement for most of the sugar and starch fuel pathways, but not for the oilseed pathways, where GLOBIOM predicts much higher values than GTAP-BIO. For example, the ILUC values for soy-derived HEFA produced in the U.S. are 20.0 g CO_{2eq}/MJ from GTAP-BIO, and 50.4 g CO_{2eq}/MJ from GLOBIOM. In cases where the two ILUC values are within a tolerance level of 8.9 g CO_{2eq}/MJ (defined as 10% of the baseline fossil fuel LCA value of 89 g CO_{2eq}/MJ), the CAEP recommends using an average of the two models. When the two models give larger differences, it is recommended to use the lower value plus an adjustment factor of 4.45 g CO_{2eq}/MJ. Based on the methodologies described by Hileman, default LCA emission values have been determined for 28 CORSIA eligible fuels. These draft values must still be approved by the ICAO Council before they are accepted. This work is described in detail in a 2019 CORSIA supporting document report: "CORSIA Eligible Fuels – LCA Methodology," which is available at the following web link: CORSIA Supporting Document.

Chris Malins (Cerulogy Inc.) discussed the derivation of ILUC emissions estimates for conventional biofuels when using the GTAP model, and questioned the robustness of these estimates. He pointed out that when CARB first introduced ILUC determination into its LCFS regulations in 2009, the GTAP modeling framework used to estimate LUC was coupled with a set of LUC emission factors to compute ILUC emissions for a range of ethanol and biodiesel scenarios. When updating the LCFS regulations in 2014, substantially lower ILUC emission values were estimated. Since that time, additional modeling changes in GTAP-BIO have further reduced ILUC values. For example, CARB's median ILUC emission estimate for corn ethanol of about 30 g CO_{2eq}/MJ in 2009 was reduced to 20 g CO_{2eq}/MJ in 2014, with some more recent GTAP-BIO estimates by other researchers being close to 10 g CO_2eq/MJ. Similar reductions have occurred for soy biodiesel.

Malins examined several factors responsible for these ILUC reductions, and argued that in some cases, the underlying evidence to support such changes is not very compelling. For example, the GTAP factor called YDEL is used to represent the crop yield to price elasticity, which has an important influence on estimates of cropping changes in response to biofuel policies. This factor was changed in CARB's 2014 modeling work compared to the 2009 value, thereby contributing to the reduced estimates of ILUC emissions. The "correct" value of YDEL is still a matter of dispute. Malins also questioned establishment of region-specific YDEL values by the GTAP-BIO developers, as well as their use of the corn YDEL value for soy.

Another influential but uncertain factor contributing to reduced ILUC emissions estimates involves the land category called cropland-pasture (C-P). C-P is land that is currently being used as pasture, but was cropland previously, and could be converted back to cropping without improvement. This land category was not included in the GTAP database in 2009, but was included (for the U.S. and Brazil) in CARB's 2014 LCFS update. Malins indicated that there are considerable uncertainties in estimating the amount of C-P lands, as well as the amount of land converted from C-P to cropping. Yet, these estimates have become very important in recent ILUC modeling as some modelers assume that conversion of C-P to cropping results in much lower emissions than does conversion of pasture to cropping. In fact, recent ILUC modeling using the Carbon Calculator for Land Use change for Biofuels (CCLUB) assumes a negative LUC emission rate when C-P is converted to corn cropping. According to Malins, this is one reason why CCLUB-based ILUC outcomes consistently give lower values than those based on emission factors from the AEZ-EF model (which CARB used in their 2014 LCFS update). In conclusion, Malins indicated that some recent modeling changes have been based on subjective decisions rather than compelling data, and that consequently, lower estimates of ILUC emissions from recent modeling may reflect an optimistic bias.

Mike Griffin (Carnegie Mellon University and Savant Consulting Inc.) summarized the recent CRC Project RW-104 that he and his team (including Savant Technical Consulting and the Univ. of Toronto) conducted to assess the use of stock and flow models (SFMs) to investigate GHG impacts of biofuels. In this project, over 130 literature articles related to SFMs were examined, categorized, and summarized. Where possible, SFM modeling approaches and results were compared to LCA models. However, SFM and LCA models address different questions, making direct comparisons difficult. For example, SFMs are useful in predicting changes in carbon stocks (sinks in the atmosphere, biosphere, geosphere, and oceans) and the rates of flows between these sinks. Thus, SFMs can be used to predict changes in carbon stocks over time. The most comprehensive form of SFMs are Earth System Models (ESMs), which incorporate detailed global carbon-cycle models. ESMs include sub-models to represent specific processes, such as carbon uptake by vegetation and decay of vegetation. Because of the extensive data needs and complex data processing requirements, ESMs are typically simplified by excluding certain carbon pools, restricting the geographic regions being studied, decreasing the model resolution, or other means.

In contrast, LCA models have lower data requirements and typically are based on static analyses, i.e., no temporal changes. The scope of LCA models is usually limited to a specific product or process, whereas a SFM has a much broader scope. A simple comparison between SFMs and attributional LCA is provided in the figure. Griffin concluded that for realistic evaluation of biofuels' GHG impacts, both SFM and LCA approaches should be used, and the complementary information they provide could promote better decision making.

Stock and Flow vs. aLCA

Attribute	Stock and Flow Models	aLCA
Data requirements	Very large for non-simplified models, required data often unavailable	Much lower and typically available
Focus	Carbon reservoirs/pools	Products and carbon flows
Treatment of time	Time-based flows easily incorporated	Assumes steady-state and unchanging climate forcing
Scope	Global if not simplified	Production pathway

Comments from Additional Panelists

Following the above four presentations, four additional panelists were invited to offer their inputs and comments regarding the material presented.

Steffen Mueller (UIC) stated that there is substantial evidence from many research groups to support the recent reductions in ILUC emissions estimates for corn ethanol. In several countries, scientists and policy makers have decided against including ILUC emissions at all, because they are believed to be relatively small and highly uncertain. Mueller also explained that the CCLUB model requires knowledge of land use history, which is particularly difficult to provide for the cropland-pasture (C-P) land category. To address this, CCLUB recreates a historical land use record based on USDA census data. It is then assumed that during periods of C-P increase, soil organic carbon (SOC) content is characteristic of pastureland, while during periods of C-P decrease, SOC is more characteristic of cropland. Because some C-P has already been carbon depleted, it is reasonable to believe that putting this land back into active cropping could lead to carbon sequestration. Finally, Mueller cautioned that the debates about ILUC emissions should not cause us to lose sight of the big picture that agriculture can be a very effective GHG mitigation tool.

Jennifer Dunn (ANL) explained that marginal land is a major land category within the U.S., but that its definition is somewhat vague and hence, the amount and location of marginal land vary significantly among different land use data sets. Some marginal land is also C-P land, whose conversion to cropland has important implications with respect to biofuels' LUC emissions. ANL has been involved in several LCA studies investigating GHG emissions of biofuels whose feedstocks have been produced under a variety of LUC scenarios. Changes in SOC can be positive or negative, depending upon the type of land conversion, crop type, and agricultural practices being employed.

Farzad Taheripour (Purdue Univ.) explained that the trend of decreasing ILUC emissions estimates with newer LCA studies is not limited to cases in which the GTAP model is used. Due to documented improvements in modeling approaches and input data, this downward trend should be expected. Taheripour also showed that since 2002, the total amount of U.S. cropland has decreased by 38 million acres (8.8%), while the harvested area has increased by 17 million acres (5.6%). This demonstrates that intensification is the dominant mechanism of U.S. agricultural growth, not extensification. At the same time, increased crop yields have resulted in much higher total harvests of corn and soybeans in the U.S. The increased production of corn ethanol and soy biodiesel over this period has provided a necessary outlet for the excess supply of these commodities.

Hugo Valin (IIASA) pointed out that most of the ILUC debate in the U.S. relates to corn ethanol, which is only of minor importance elsewhere. In several other countries, issues regarding biodiesel are more dominant – including soy-biodiesel from Brazil and palm-biodiesel from several other countries. He also emphasized the dynamic nature of biofuel feedstocks, processes, and policies. ILUC should be considered within a broader context of sustainability. Before debating exact values of ILUC emissions in specific scenarios, a consensus should be reached regarding the significance of ILUC at all. Valin also mentioned that agriculture could be useful for carbon sequestration both directly, through cropping practices, and indirectly by afforestation of land removed from active agriculture.

Session 4: Electrical Pathways

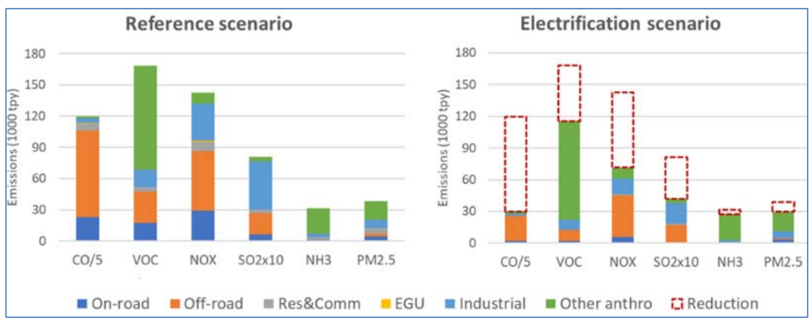
Chairpersons: Amit Kapur (Phillips 66) and Michael Wang (ANL)

Session 4 consisted of three presentations that discussed how renewable electricity – and intermediates produced from this electricity – could play a role in reducing the carbon footprint of transportation fuels. Volker Sick of the University of Michigan discussed commercially-sustainable approaches to convert available CO_2 into useful products, including fuels. Marcus Alexander of the Electric Power Research Institute, (EPRI) presented modeling results showing how aggressive electrification of both the transportation and non-transportation sectors in California could improve air quality and human health. Amgad Elgowainy of ANL presented modeling showing how combining available CO_2 with electrolytically-produced H_2 could be utilized to produce low-carbon liquid hydrocarbon fuels.

Volker Sick (Univ. of Michigan) discussed the global need to reduce atmospheric CO_2 concentration and the utilization of CO_2 as a feedstock for various products as one way to achieve this goal. This approach is becoming more practical as increasing deployment of renewable energy sources is making carbon-free, low-cost energy available. The Global CO_2 Initiative at the University of Michigan is collaborating with other organizations to promote commercially sustainable approaches that convert CO_2 to useful products. Five product sectors identified thus far that show promise of substantial and economic CO_2 reductions are concrete, fuels, aggregates, methanol, and polymers.

Techno-economic assessment (TEA) and LCA are recognized tools for determining the economic viability and carbon footprint of product and production pathways. However, these tools have not been applied widely to CO_2-based products. The Global CO_2 Initiative is now working with many other international experts to develop specific guidance regarding integration of TEA and LCA for such products. Issues being addressed include setting system boundaries, choosing optimum indicators, identifying Technology Readiness Levels (TRLs), selecting appropriate CO_2 prices, and calculating capital and operational expenses. More information about this TEA/LCA toolkit is available at the following link: https://www.globalco2initiative.org/research/techno-economic-assessment-and-life-cycle-assessment-toolkit/.

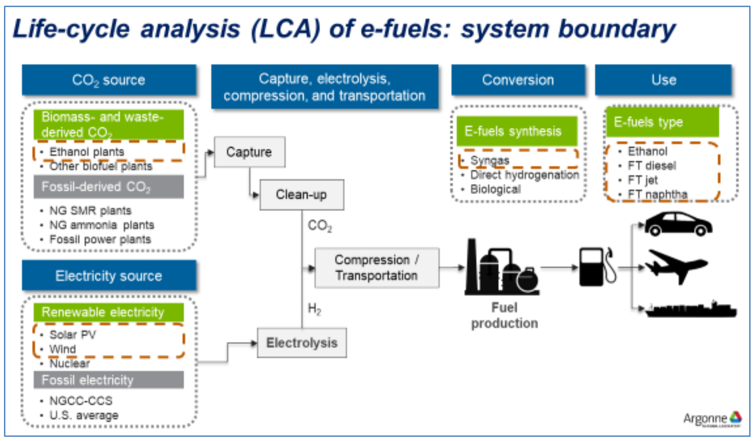
Marcus Alexander [Electric Power Research Institute (EPRI)] discussed a study conducted by EPRI to investigate the effects of electrification throughout California on air quality and human health in the year 2050. The starting point for this study was an earlier California Energy Commission (CEC) project that showed how electrification was an essential component in achieving the State's GHG reduction goals of 40% below 1990 levels by 2030, and 80% below 1990 levels by 2050. The EPRI team then introduced numerous assumptions of increased electrification in the on-road and non-road transportation sectors, as well as in the non-transportation sector. The figure shows the 2050 statewide emissions reductions resulting from the assumptions used in this aggressive electrification scenario.



These scenarios were then used in regional air quality modeling to assess the impacts of electrification on $PM_{2.5}$ and O_3 in the South Coast Air Basin (SoCAB) during both summer and winter. The EPA-recommended Comprehensive Air Quality Model with Extensions (CAMx) was utilized, which allows for source apportionment analysis. Results showed that the electrification scenario reduced $PM_{2.5}$ concentrations throughout the region – particularly in winter – with a major reason being electrification of residential heating sources, including elimination of wood burning. Ozone modeling showed that electrification reduced summertime maximum daily 8-hour O_3 concentrations throughout most of the air basin, with the exception of the shipping port area, due to the well documented phenomenon of "NOx reduction disbenefits."

To estimate the health impacts of the electrification scenario, EPA's Environmental Benefits Mapping and Analysis Program (BenMAP) was used. Differences in modeled pollutant concentrations between the electrification and reference scenarios were coupled with census tract population data to calculate number of avoided mortalities per year, using established concentration response functions (CRFs) for O_3 and $PM_{2.5}$. Results showed annual mortality reduction benefits were much greater for $PM_{2.5}$ than for O_3. In the SoCAB, there were approximately 6200 avoided mortalities due to $PM_{2.5}$ reduction, but only 180 due to O_3 reduction. By applying EPA's Value of Statistical Life (VSL) factor of \$8.7M, these avoided mortalities translate to a health benefit of $56B. Benefits for the entire State of California are approximately double these SoCAB figures.

Amgad Elgowainy (ANL) described work being conducted at ANL to investigate lifecycle energy and GHG impacts of low-carbon electro-fuels (E-Fuels). Interest in E-fuels is driven by the desire to utilize CO_2 to produce valuable products, to make better use of renewably-generated H_2, and to produce low-carbon liquid fuels for heavy-duty vehicles, locomotives, and aircraft. High purity CO_2 sources exist at many locations, particularly at corn ethanol plants, steam methane reformers (SMRs) used to produce hydrogen, and ammonia plants. If renewable H_2 were produced at the same locations (by electrolysis of water), the CO_2 and H_2 could be combined in the reverse water gas shift (WGS) reaction to produce CO and H_2O. With use of additional H_2, the Fischer-Tropsch (FT) process could then be used to produce liquid hydrocarbons. The Aspen Plus model was used to simulate various synthesis processes, and the GREET model was expanded to include various E-Fuel pathways and assess their lifecycle environmental impacts. The system boundaries for the well-to-wheels (WTW) LCA analysis are shown in the figure – beginning with CO_2 and electricity sources and ending with use of the fuels in transportation applications.



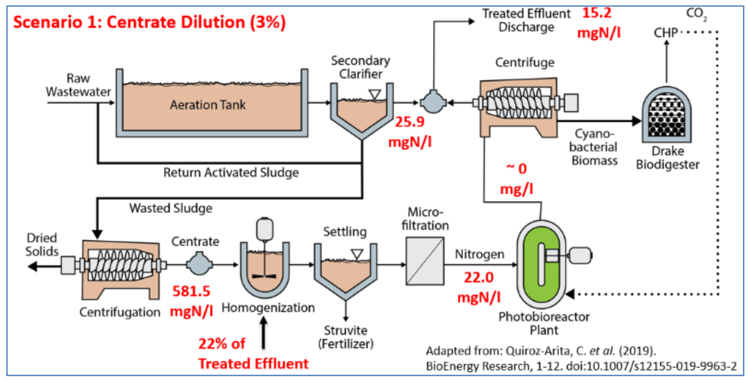
Simulations of a standalone FT plant were conducted, with the plant scaled to accept the biogenic CO_2 produced from a 100 million gallon/year corn ethanol plant. The FT fuel – consisting of a mixture of naphtha, jet fuel, and diesel – had very low WTW GHG emissions, based on the carbon neutrality of the CO_2 feedstock. For simulations in which the FT plant included H_2 recycle, the final fuels had GHG emissions of 6 g CO_{2eq}/MJ; without this recycle, the GHG emissions were -11 g CO_{2eq}/MJ. Additional simulations were conducted to examine integrated operation of the corn ethanol plant and FT plant. In this case, 38% of the initial corn carbon was converted to ethanol and 19% was released as high purity CO_2, with 56% of this CO_2 being converted to FT fuels. The calculated WTW GHG emissions of all the fuels combined (ethanol, naphtha, jet fuel, and diesel) was 38-40 g CO_{2eq}/MJ. In comparison, GHG emissions of ethanol produced from a standalone corn ethanol plant are approximately 53 g CO_{2eq}/MJ.

Session 5: Advanced/Novel/Waste Fuels

Chairpersons: Robb DeKleine (Ford) and Alicia Lindauer (DOE)

Session 5 consisted of three presentations that focused on potential production of low-carbon fuels from a variety of waste or other low-value feedstocks. Carlos Quiroz-Arita of Colorado State University discussed options for integrating algal/cyanobacterial photoreactor systems with wastewater treatment facilities (WWTFs). Laurel Harmon of LanzaTech summarized various approaches to carbon capture and utilization (CCU), by which waste carbon is used as a feedstock to produce high-value fuels, food/feed, and chemicals. Vikas Khanna of the University of Alberta discussed process modeling simulations comparing the energy and GHG reduction benefits of different approaches to lignocellulosic pyrolysis and upgrading.

Carlos Quiroz-Arita (Colorado State Univ.) discussed potential energy and sustainability benefits that could result from integrating algal/cyanobacterial growth systems with wastewater treatment facilities (WWTFs). Such integration can provide the water and nutrients necessary for growth of microalgae/ cyanobacteria, while helping to reduce the nutrient levels of WWTF effluent. Increasingly stringent nutrient discharge limits are creating economic and operational challenges at many WWTFs in the U.S.

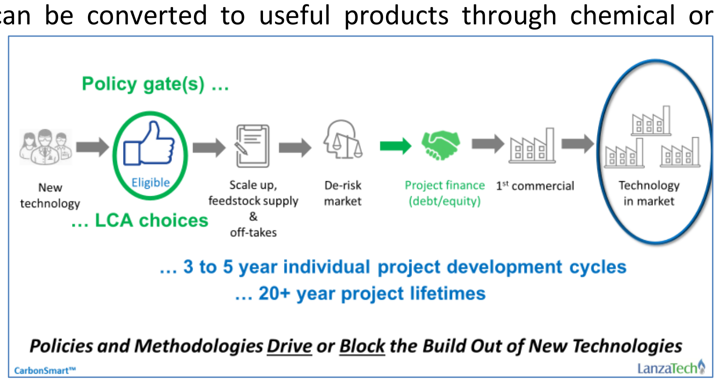


Adapted from: Quiroz-Arita, C. *et al.* (2019). BioEnergy Research, 1-12. doi:10.1007/s12155-019-9963-2

Quiroz-Arita conducted a modeling study to investigate integration of a cyanobacterial side-stream nutrient removal process at the Drake WWTF in Ft. Collins, CO. A schematic of this integrated system is shown in the figure. The cyanobacteria chosen for this integrated system is *Synechocystis* sp. PCC6803, whose growth behaviors in sludge centrate had already been studied. For optimum cyanobacterial growth, the centrate must first be diluted to achieve an acceptable nitrogen concentration range. Effluent from the photobioreactor plant is depleted in nitrogen and can be used to dilute higher-nitrogen containing WWTF effluent streams while still meeting discharge limits. The biomass grown in the photobioreactor is treated in a digester to produce methane (used as a fuel) and CO_2, which is recycled to the photobioreactor. Results from LCA modeling of this integrated system showed that using a 3% dilution concentration of centrate provided optimum performance in terms of maximum nitrogen removal and minimum carbon footprint.

Laurel Harmon (LanzaTech) discussed the importance of recycling waste carbon for reuse as low-carbon fuels, chemicals, and other products. While great progress is being made towards de-carbonizing the electrical grid, the need for carbon-based materials will continue indefinitely for liquid fuels, chemicals, food/feed, and many other products. An important societal goal is to employ a form of carbon capture and utilization (CCU) by using waste carbon sources as feedstocks to produce these needed carbon-based products. LanzaTech has now commercialized a process utilizing a proprietary microbe, Clostridium autoethanogenum, to ferment industrial off-gases (containing CO, CO_2, and H_2) to produce ethanol. This technology is currently being employed at a 16 million gallon/year ethanol plant in China, where off-gases from a steel plant are used as feedstock. While ethanol is a useful product itself, it can be further upgraded into jet fuel by means of various alcohol-to-jet (ATJ) conversion processes.

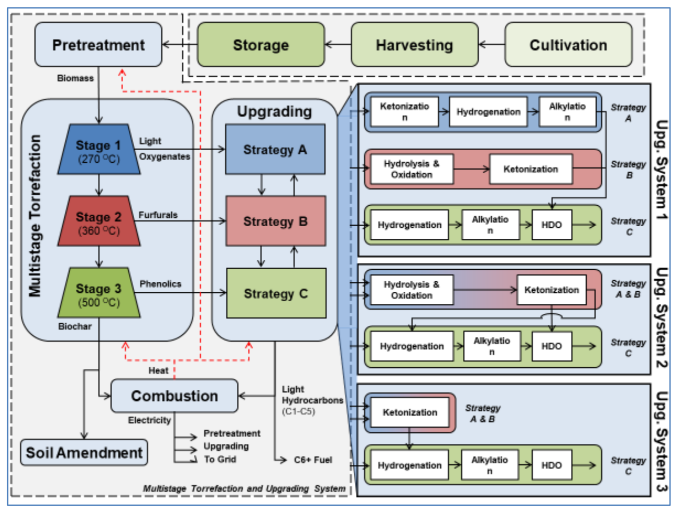
Many other options for carbon recycling are possible. For example, gasification of biomass or municipal solid waste (MSW) produces syngas that can be converted to useful products through chemical or biological conversion processes. Microbe modification can be done to enable utilization across a broader range of feedstocks and to produce a broader range of carbonaceous products. After use, the spent microbes themselves can be repurposed as animal feed. Harmon emphasized that with so many options available, it is critical to make wise choices



regarding which to focus on, and what commercial pathways to follow. As shown in the figure, LCA is an important early step in this process. Due to long project development cycles and even longer commercial plant lifetimes, it is critical to make sound methodological choices today, as the consequences of these choices will remain for several decades.

Vikas Khanna (Univ. of Pittsburgh) described the use of LCA to evaluate energy and GHG impacts of various pathways for converting and upgrading biomass feedstocks into final products. This work is part of a broader effort to develop thermochemical and catalytic platforms for producing renewable transportation fuels and specialty bio-based chemicals. Conventional fast pyrolysis followed by catalytic hydrodeoxygenation (HDO) has attracted considerable interest as a way to convert lignocellulosic feedstocks into renewable fuels and chemicals. However, two major limitations of this single-stage pyrolysis/HDO approach are: (1) the hydrocarbon product distribution is skewed towards light-end gases rather than the desired, heavier liquid components and (2) a large amount of process H_2 is required to conduct the upgrading. As a consequence, the overall lifecycle energy and GHG reductions from this approach are not as large as desired.

Khanna described an alternative approach in which the lignocellulosic constituents are selectively decomposed through a series of increasingly severe torrefaction/pyrolysis processes. The intermediate products from each step are then selectively upgraded to produce a set of final products. The figure shows the overall process scheme for a 3-step system. Based on a combination of experimental data and ASPEN process simulations, this multi-step approach was shown to require less H_2 than a single step pyrolysis/HDO approach. In addition, the product distribution was improved when using the multi-step approach, with 48% of the feedstock carbon resulting in C_{6+} liquid products, as opposed to only 12% carbon efficiency for the single-stage approach. Calculated energy return on investment (EROI) was close to 1.0 for the fast pyrolysis/HDO approach, but was significantly higher for the multi-stage approach – particularly if the biochar product was used as a fuel for heat and power, rather than using it for soil amendment. The life-cycle GHG emissions also varied, depending upon the intended use of the biochar product, with lower emissions when used as a soil amendment rather than as a fuel. In all cases, however, life-cycle GHG emissions were considerably lower with a multi-stage approach than with a single-state pyrolysis/HDO approach. Khanna concluded that such multi-step systems can produce drop-in replacement hydrocarbon fuels capable of achieving over 50% GHG reductions relative to baseline petroleum-derived diesel fuel.



Session 6: Liquid Petroleum Fuels

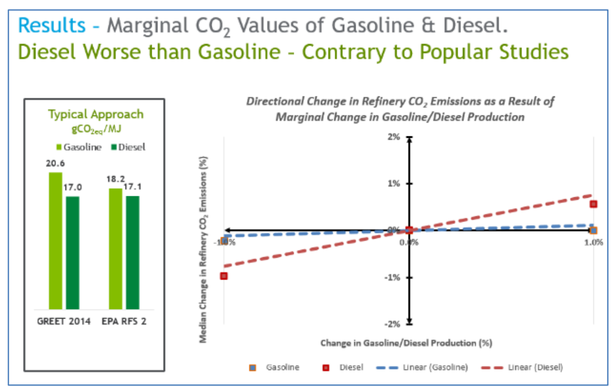
Chairpersons: Babak Fayyaz (Chevron), Suren Rangaraju (CONCAWE), and Robb DeKleine (Ford)

Session 6 consisted of four presentations that addressed the carbon intensity of petroleum-derived fuels. Amir Abdul-Manan of Aramco Asia discussed an LCA study that investigated changes in refining GHG emissions as refinery operations were modified to produce different ratios of gasoline/distillate fuels.

Adam Brandt of Stanford University discussed updates to the Oil Production Greenhouse gas Emission Estimate (OPGEE) model, and use of this model to estimate the CI of oil production around the world. Giovanni Di Lullo of the University of Alberta discussed methods for assessing the sensitivity and uncertainty of various processes within the life cycle of petroleum fuels. Finally, Matt Jamieson of KeyLogic Systems Inc. discussed the U.S. DOE's effort to update the Petroleum Refining Life cycle Inventory Model (PRELIM) to more accurately estimate transportation fuels' life cycle energy requirements and GHG emissions with changes in the overall crude slate.

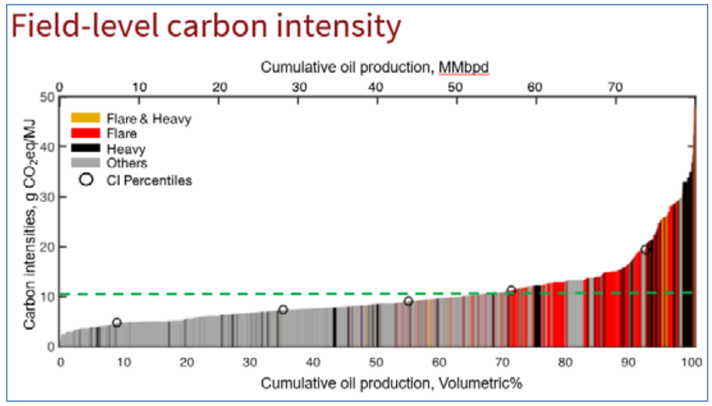
Amir Abdul-Manan (Aramco Asia) described an LCA study that was done to investigate changes in petroleum refinery GHG emissions as refinery operations were modified to produce varying ratios of distillate/gasoline fuel products. Refinery linear program (LP) models were used to represent operations in six regions of the world, with 2014 chosen as the baseline year. When used to optimize refinery operations with respect to economics, these LP models typically show that gasoline is more carbon intensive to produce than is diesel fuel. This is a result of higher energy intensive processes (such as cracking and reforming) that some gasoline streams undergo within the refinery. Consequently, in most LCA models, gasoline production is assigned a higher carbon intensity (CI) value than is diesel production. In GREET, for example, the CI values of refining crude oil to gasoline and diesel fuel are 20.6 and 17.0 g CO_{2eq}/MJ, respectively.

In this study, the refinery LP models were re-optimized to produce minimum CO_2 emissions. This approach could represent the situation in which there are economic incentives to reduce GHG emissions. As the magnitude of the economic stimulus increases, production of both gasoline and diesel decline, but the rate of decline is steeper for diesel. This is driven largely by a shift in the refineries' hydrogen balance. Externally produced H_2, from steam methane reforming (SMR) of natural gas, is highly CO_2 intensive as compared to H_2 produced in a refinery reformer used to manufacture gasoline streams. Thus, to minimize overall refinery CO_2, it is advantageous to produce relatively more gasoline (and co-product H_2) than diesel (which requires H_2). As shown in the figure, the marginal change in CO_2 emissions is much greater for diesel compared to gasoline, which is opposite to what is assumed in GREET and the LCA models used by EPA for RFS2 assessments. To correct this disparity, Abdul-Manan suggested that a marginal CO_2 approach could be used in determining CI values of refinery fuels, as opposed to the current snapshot approach based on overall burden allocation. Alternatively, different CO_2 allocation factors could be incorporated into existing LCA models. Both of these corrective measures have pros and cons. As a final thought, Abdul-Manan suggested that an optimum well-to-wheels (WTW) approach would favor use of a gasoline-like fuel in a compression ignition engine, as this would maximize CO_2 mitigation both on the refinery/fuel side, and on the vehicle.

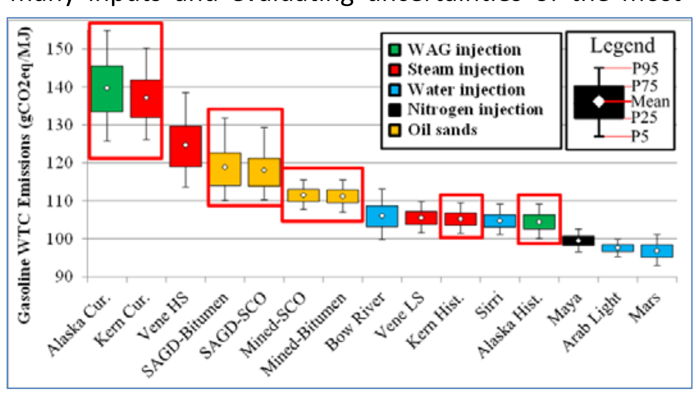


Adam Brandt (Stanford University) discussed updates and improvements to estimating CI values of crude oil production using the Oil Production Greenhouse gas Emissions Estimator (OPGEE) model. This open-source GHG tool provides emissions estimates for approximately 9000 producing oil fields around the world, representing 98% of global oil production. Model inputs include information about production volumes, oil/gas ratios, crude oil properties, processing technologies being employed, flaring, and other parameters. A recent model improvement described by Brandt involves incorporation of Aspen HYSYS chemical process simulation to represent acid gas removal processes. OPGEE is now able to estimate GHG emissions associated with various acid gas removal processes, using different amine solvents.

The extent of gas flaring is a major contributor to the CI value of oil production at a particular field. Satellite infrared imaging data can be used to determine flaring location and estimate the amount of CO_2 emissions. Brandt showed a ranking of oil production CI values by country, which varied from approximately 5 to 20 g CO_2eq/MJ, with much greater variation across the range of oil fields within each country. The CI range across all oil fields is shown in the figure. The volume weighted average CI value from these fields is 10.3 g CO_{2eq}/MJ, with 65% of this attributed to CO_2 emissions and 34% attributed to methane. This figure also shows that oil fields associated with heavy crude and those including flaring have much higher CI values than other fields. Based on these data, Brandt estimated that global oil production was responsible for 1.7 Gt CO_{2eq} in 2015. This figure is approximately 42% higher than the value estimated by the International Association of Oil and Gas Producers (IOGP). Considerable GHG emissions reduction could be realized by minimizing flaring and better control of fugitive emissions. Reducing the volume weighted average CI from its current value of 10.3 g CO_{2eq}/MJ to the current 25th percentile value of 7.3 g CO_{2eq}/MJ could result in reducing global emissions by approximately 18 Gt over the next century. Brandt concluded by briefly describing current work in which microeconomic analysis of oil fields is combined with CI analysis. Among other things, this allows for assessment of how oil production CI varies with crude oil demand and price.



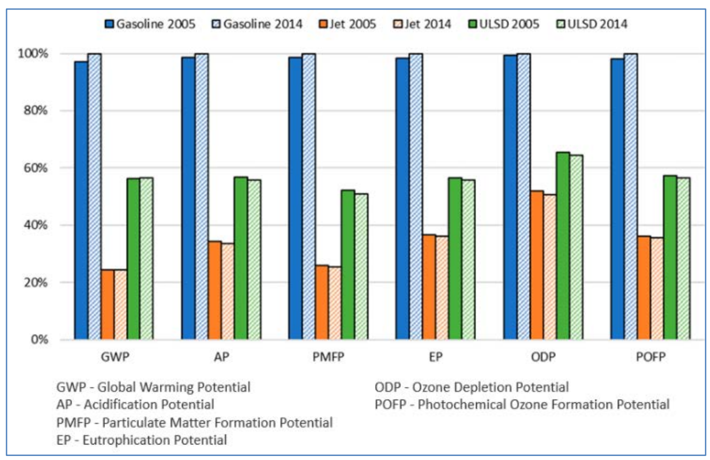
Giovanni Di Lullo (University of Alberta) discussed a framework for implementing sensitivity and uncertainty analyses in process-based LCA within the oil and gas industry. The objective is to use LCA to compare GHG emission intensities of different crude sources and technology pathways. This is done using the FUNdamental Engineering Principles-based Model (FUNNEL), which estimates energy and GHG impacts over the entire life cycle of transportation fuels. Processes accounted for in FUNNEL include preparation of oil production sites, crude extraction, surface processing, crude transportation, refining, fuel distribution, and final combustion. To describe these processes, numerous variables/parameters are required, each having its own variability and uncertainty. Di Lullo described an open-source Regression Uncertainty and Sensitivity Tool (RUST) used to perform sensitivity analysis. The RUST methodology helps reduce data collection workload by screening many inputs and evaluating uncertainties of the most important ones. Besides uncertainties in empirical values for various parameters, it is important to represent uncertainties in the models being used and in the subjective decisions being made about the model domain.



Di Lullo presented WTW GHG results from FUNNEL analyses representing gasoline production from a variety of crude sources using a variety of process technologies. As shown in the figure, the GHG emissions intensity of these scenarios ranged from approximately 97 to 140 g CO_{2eq}/MJ. Using a variance-based sensitivity analysis, some of the most important parameters were determined to be refinery emissions, gas-to-oil ratio, fugitive emissions, and refining yield.

Matt Jamieson (KeyLogic Systems Inc.) described work led by DOE's National Energy Technology Laboratory (NETL) to update the Petroleum Refining Life Cycle Inventory Model (PRELIM). PRELIM is an Excel-based model of petroleum refineries developed at the University of Calgary, which is used to estimate GHG emissions and energy requirements associated with the production of U.S. transportation fuels. Updates are being incorporated to expand the crude and product slates that can be accommodated, increase the number of refinery configurations, and extend the model outputs beyond GHG emissions to include acidification, eutrophication, ozone depletion, and other environmental impacts. In addition, efforts are underway to enable PRELIM to assess environmental impacts of large-scale CO_2 enhanced oil recovery (EOR) deployment. An objective in this update work is to create a modeling tool that can reliably assess the impacts of a changing U.S. crude mix over time. During the past decade, for example, increasing domestic production has displaced significant amounts of imported crude. This change in crude slate results in changes to refinery operations, which in turn affect energy requirements and GHG emissions.

In this PRELIM update effort, NETL utilized publicly-available emissions data from EPA sources and refinery operating data from the U.S. Energy Information Administration (EIA). Because some of these data are provided at a facility level, methodologies were developed to disaggregate the emissions by specific processes within the refinery. PRELIM also includes uncertainty assessments, which are meant to represent the uncertainty of the average emissions value, not the total uncertainty in the underlying data distributions. An application of the updated PRELIM model to investigate changes in environmental impacts of gasoline, jet fuel, and ultra low sulfur diesel (ULSD) between 2005 and 2014 is shown in the figure. All results are normalized to the 2014 gasoline values. This shows that across a wide range of environmental indicators, the magnitude of adverse impacts is in the order of gasoline > diesel > jet fuel. Also, the impacts for gasoline are slightly higher in 2014 compared to 2005 for most indicators, while the opposite is true for diesel and jet fuel.



D. Research Needs

Concluding Panel – Research Needs Discussion

The final session of the Workshop included an open discussion by all attendees regarding perceived research needs in areas related to LCA of transportation fuels. Many thoughts and suggestions were provided electronically, using an audience participation application called Slido. Some (but not all) of the comments obtained by Slido were discussed by the broader group. While many recommendations were offered, no concerted efforts were made to develop consensus or a priority ranking. Listed below are many of the suggestions that were most relevant to the subject of the Workshop, categorized by broad topic areas:

Land Use/Land Use Change

- Better definitions and explicit characterization of carbon and nutrient stocks and flows on each modeled land unit are necessary. The confusion around cropland-pasture (C-P) is symptomatic of larger issues related to the simplifications and assumptions used in models. What are actual carbon and emission dynamics of a defined land parcel under different management practices? How does past land use history affect current carbon storage potential and emissions?
- Further work is needed to clarify what "LUC" means, and to reliably distinguish between the effects from multiple drivers of change, including biofuel policies.
- Data collection and analysis should be a priority to document what actually happened over the past two decades of biofuel growth. Models cannot be improved unless we have agreement on a set of facts and sources for input data.
- Better understanding of land management is needed with respect to spatial and temporal variability. How do vegetative cover, intensity of cultivation, and carbon flows change?
- There is a need to determine and document the historical upstream impacts of oil and gas exploration and production on land cover and carbon emissions.
- What are the real accuracies of satellite imaging? How does this impact our understanding of LUC over time?

LCA Models/Modeling

- Need better regional specificity of LCA results. CI values of biofuels vary depending upon where, when, and how land is managed, and upon the feedstocks used and the biofuels produced.
- Need to develop realistic counterfactual scenarios for other policies/pathways besides just RFS and corn ethanol.
- Continue to examine models that give divergent results. It's important to understand the reasons for the discrepancies, and where possible, to harmonize modeling elements.
- Should emphasize use of holistic LCA to investigate a broader range of environmental impacts (beyond GHG) for different scenarios.
- Considering the variabilities and uncertainties that exist, is it preferable to use LCA to define broad bins or categories for low carbon fuels (as EPA does) rather than calculating seemingly precise CI values (as CARB does)?

Improve Scientific Foundation Underlying ILUC Modeling

- Conduct more econometric analysis of key elasticities used in models – including regional- and crop-specific elasticities.

- Apply causal analysis and statistical tools to review the evidence for the assumed drivers of ILUC and the elasticity values that are used.
- Determine regionally-specific factors that account for varying policies and "on-the-ground" changes in land cover and land management.
- Ensure that investments in transportation fuels include corresponding analyses to identify environmentally sensitive lands at risk and situations where monitoring of carbon stocks and flows should be undertaken.

Economic Issues

- Need more emphasis on determining the lifecycle costs of CO_2 abatement. Need agreement on a common metric (such as $/tonne CO_2) to compare various options.
- Develop accepted methodology to compare environmental and economic tradeoffs of different low-carbon fuel options.
- More work is needed to understand the costs and benefits of electro-fuels.
- Better understanding of the economic options and drivers for LUC are needed, both in developed and developing countries.
- Conduct additional model validation by comparing model results with empirical data.

Policies and Applications

- How can LCA principles/applications be used to promote carbon-reducing agricultural practices?
- How do the sustainability and cost-effectiveness of soil carbon sequestration compare with other CCS options?
- With so many fuel options, markets, technologies, etc., how can we use LCA to help direct a path forward towards the most beneficial options?
- How can we avoid endless LCA debates that delay adoption of positive actions?

Other Issues

- Engage with environmental groups to explain how LCA is being used to estimate low-carbon fuel benefits, and what parameters are most important in these assessments.
- How are the sensitivities/uncertainties of LCA results affected by changes in energy and climate policies?
- Are there other consequential impacts of continued petroleum use, such as military engagements, that should be considered when comparing biofuels with conventional fuels?
- Engage with decision makers/stakeholders to more effectively promote environmentally sound pathways for transportation fuels.

APPENDIX I

Glossary of Terms Used During the Workshop

AEO	Annual Energy Outlook
AEZ-EF	Agricultural Ecological Zone – Emission Factor (model)
ALCA	Attributional Life Cycle Assessment
ANL	Argonne National Laboratory
ATJ	Alcohol-to-Jet
BenMAP	Benefits Mapping and Analysis Program
BEV	Battery Electric Vehicle
CAEP	Committee on Aviation Environmental Protection
CAMx	Comprehensive Air Quality Model with Extensions
CARB	California Air Resources Board
CCLUB	Carbon Calculator for Land Use change for Biofuels
CCS	Carbon Capture and Sequestration
CCU	Carbon Capture and Utilization
CDL	Cropland Data Layer
CEC	California Energy Commission
CEF	CORSIA Eligible Fuel
CFP	Clean Fuel Program
CFS	Clean Fuel Standard
CGE	Computable General-Equilibrium
CI	Carbon Intensity; also Compression Ignition
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
CONCAWE	CONservation of Clean Air and Water in Europe
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
C-P	Cropland-Pasture
CRC	Coordinating Research Council
CRF	Concentration-Response Function
CRP	Conservation Reserve Program
CTO	Crude Tall Oil
DayCent	Ecosystem model for soil carbon
DDGS	Dried Distillers Grains with Solubles
DG ENER	(EC) Directorate General for Energy
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
EIO-LCA	Economic Input-Output- Life Cycle Assessment Model
EISA	(US) Energy Independence and Security Act (2007)
EOR	Enhanced Oil Recovery
EPA	(US) Environmental Protection Agency

EPAct	(US) Energy Policy Act (2005)
EPIC	Environmental Policy Integrated Climate model
EROI	Energy Return on Investment
ESM	Earth System Model
EU	European Union
EV	Electric Vehicle
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
FFC	Fossil Fuel Comparator
FQD	Fuel Quality Directive
FT	Fischer-Tropsch
FTG	Fuel Task Group
FTJ	Fischer-Tropsch Jet (fuel)
FUNNEL	Fundamental Engineering Principles-based Model
g $CO_{2,eq}$ MJ^{-1}	grams of CO_2, equivalents per MJ of fuel
GDP	Gross Domestic Product
GGE	Gasoline Gallon Equivalent
GHG	Greenhouse Gas
GHGRP	(EPA) Greenhouse Gas Reporting Program
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
HDO	Hydrodeoxygenation
HEFA	Hydro-processed Esters and Fatty Acids
IAM	Integrated Assessment Model
ICAO	International Civil Aviation Organization
ICCT	International Council on Clean Transportation
IEA	International Energy Agency
IFPRI	International Food Policy Research Institute
IIASA	International Institute for Applied Systems Analysis
ILUC	Indirect (or Induced) Land Use Change
IOGP	International Association of Oil and Gas Producers
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)
LDV	Light-Duty Vehicle
LMC	Land Management Change
LNG	Liquefied Natural Gas
LP	Linear Program (refinery models)

LPG	Liquefied Petroleum Gas
LUC	Land Use Change
MMT	Million Metric Ton
MSW	Municipal Solid Waste
NBB	National Biodiesel Board
NEI	(EPA) National Emissions Inventory
NETL	(DOE) National Energy Technology Laboratory
NG	Natural Gas
NOPA	National Oil Processors Association
NPV	Net present value
NREL	National Renewable Energy Laboratory
NRI	(USDA) National Resource Inventory
OPGEE	Oil Production Greenhouse gas Emissions Estimator
ORNL	Oak Ridge National Laboratory
PHEV	Plug-in Hybrid Electric Vehicle
PRELIM	Petroleum Refining Lifecycle Inventory Model
RED	Renewable Energy Directive
ReFuNoBiOs	Renewable Fuels of Non-Biological Origin
RFS	Renewable Fuels Standard
RIN	Renewable Identification Number
RNG	Renewable Natural Gas
RUST	Regression Uncertainty and Sensitivity Tool
RVO	Renewable fuel Volume Obligation
RVP	Reid Vapor Pressure
SAF	Sustainable Aviation Fuel
SFM	Stock and Flow Model
SMR	Steam Methane Reforming
SOC	Soil Organic Carbon
SoCAB	South Coast Air Basin
SOM	Soil Organic Matter
TEA	Techno-Economic Assessment
TRL	Technology Readiness Level
UCO	Used Cooking Oil
UIC	University of Illinois-Chicago
ULSD	Ultra-Low Sulfur Diesel
UNFCCC	UN Framework Convention on Climate Change
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
VSL	Value of Statistical Life
WTW	Well-to-Wheels
WWTF	Waste Water Treatment Facility
YDEL	Parameter within GTAP model that reflects yield-price elasticity