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Well-to-Wheels Carbon Intensity for Ethanol Blended Fuels

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Executive Summary

The objective of this report is to compare the greenhouse gas (GHG) impact of petroleum gasoline, ethanol, and their blends when used in light duty spark ignited vehicles. Well-to-wheels (WTW) modeling seeks to quantify the carbon dioxide (CO_2) or CO_2 equivalency (including other GHG) produced by a fuel or energy source. Typically, this is presented as a WTW carbon intensity (CI) with units of grams of CO_2 per MJ of energy (g/MJ).

For petroleum fuels, the inherent chemical carbon content of the fuel is added to carbon associated with the production, transportation and refining that occur before the fuel is purchased at the pump. In contrast, bioethanol is considered to be carbon free at the source, because all of the carbon is fixed from the atmosphere and is renewable. US bioethanol is produced primarily from corn. Only the upstream emissions associated with farming, processing and transportation represent a carbon footprint that must be assigned to the ethanol. In addition, CI debits are applied to the ethanol for land use changes (LUC) that affect carbon level in the soil, and credits are applied for useful by-products made available from the corn processing.

The LUC component is difficult to quantify and represents the component with highest variability between studies. The literature presents changes in farming practice and in production energy demands that have reduced the CI for ethanol over the last decade. The GREET model from Argonne National Laboratory of the US Department of Energy has an established history in quantifying CI of fuels. GREET presents a CI of 92.6 g/MJ for gasoline and 52.4 g/MJ for ethanol. These GREET predictions, along with values from a study for the US Department of Agriculture and the current values used by the California Air Resources Board, yield an average CI for ethanol that is 40.4% below the value for petroleum gasoline. Using the 40.4% ethanol advantage, and assuming a CI of 93 g/MJ for gasoline, the CI of ethanol for the three study average is 55.5 g/MJ. A recent study led by Harvard presents a best estimate CI for ethanol of 51.4 g/MJ. The lower reduction in CI for ethanol relative to petroleum from the Environmental Protection Agency (EPA) dates back to 2010 and is used a threshold for recognition of renewable fuels.

When ethanol, with a low CI, is blended with petroleum gasoline to form E10 (a 10% blend of ethanol by volume), the ethanol reduces the CI of the mixture by displacing some gasoline. Beyond this advantage, the ethanol also offers a high octane contribution to the mix and permits the reduction by about 8% of the aromatics in the petroleum fraction while maintaining the same octane rating of the final blend. Aromatics have a high CI, and their reduction in the petroleum fraction further decreases the GHG impact of the E10. The blending effect is similar for E15 and E20 blends. This advantageous blending attribute has been neglected in prior GHG literature.

Both direct displacement and aromatic reduction can be assigned to ethanol as the enabling additive. If a pure ethanol CI of 55.5 g/MJ is adopted from the three study average, a blending CI (BCI) of 43.4 g/MJ is found for ethanol when it is used in E10. If a GREET pure ethanol CI of 52.4 g/MJ is used as the basis, the BCI of ethanol is 40.4 g/MJ. The low BCI values represent the overall benefit of using ethanol in a market gasoline blend, due

to the blending octane number (BON) of the ethanol. Similarly, for anticipated market blending, both E15 and E20 also exhibit low BCI values. BCI may be computed using any specific upstream CI value, and any comparative petroleum blend compositions. If the current GREET estimation that pure ethanol CI is 43.4% lower than petroleum gasoline CI, the BCI values for E10 and E15 average at 40 g/MJ, while the BCI for E20 is 41.7 g/MJ. While the CI of pure ethanol is very attractive from a climate change perspective, the "per gallon" CI benefits of ethanol are higher in a blending strategy.

The EPA has recognized that certain fuels may offer efficiency advantage over others when a vehicle is operated through a driving cycle. The efficiency advantage reduces CO_2 production beyond that expected from the fuel composition alone. A recent EPA study showed that a Tier 3 E10 certification fuel offered an efficiency advantage over a Tier 2 purely petroleum fuel, revealing an additional GHG advantage of the ethanol blend. If this third CO_2 reduction mechanism is also assigned to ethanol, the ethanol BCI is lowered further. The low BCI of ethanol in E10, E15 and E20 encourages optimized blending of ethanol in gasoline motor fuels for immediate GHG reductions, and teaches that ethanol has GHG benefits that are greater than those traditionally recognized in prior well-to-wheels studies of the pure ethanol CI.

Introduction

The USA produces over 50% of the ethanol that is used as fuel in the world, primarily from corn. Peak production, in 2018, was over 16 billion gallons (RFA, 2021). The US Department of Agriculture Feed Grains Yearbook shows that approximately one third of US corn production is used to make fuel ethanol. Co-products from the ethanol production include about one million tons of condensed distillers solubles (corn syrup), and 2.5 million tons of captured carbon dioxide annually, serving to reduce the net environmental impact of the energy required to mill, ferment, distill and dehydrate during the production process. Almost 90% of the production employs dry milling (RFA, 2021). Production energy is provided by burning natural gas, coal or low value fiber, and by using electricity which itself has varying sources for GHG assessment. Ethanol generally is not conveyed in pipelines, due to concerns over corrosion and the routing of existing petroleum fuel pipelines, and is rather moved by truck, rail or barge to terminals for blending (DOT, 2021). This transportation adds to the energy required to bring the product to the end user.

A carbon intensity (CI) based purely on chemical composition of a fuel can be calculated by dividing the fuel carbon content by the energy content of the fuel. Direct hydrocarbon analysis (DHA) facilitates this calculation, although it may also be determined by measuring the carbon content and net heating value of a fuel sample directly. The carbon content is often presented as a CO_2 equivalent, and the units employed for CI are grams of CO_2 per megajoule of net heating energy (g/MJ). Often this ratio is also presented as a tank-to-wheels (TTW) CI for a vehicle, using the approximations that all of the fuel carbon is burned to CO_2, and that the vehicle uses a constant amount of energy to travel some distance. Strictly speaking, TTW CI should take into account both the small amount of incomplete combustion of the fuel, and the vehicle engine efficiency, that could vary slightly with respect to energy content per unit mass or volume of the fuel. In this way a true TTW CI value is also related to the measured mass of CO_2 produced over the distance that a vehicle travels. TTW emissions are considered in vehicle efficiency regulations (EPA, 2021TP). If an equivalent TTW CI is considered, one must include influence of tailpipe methane and nitrous oxide, using accepted GHG equivalencies. For fuel-based CI and TTW calculations, the carbon content is considered for petroleum gasoline, for ethanol, and for blends of the two.

However, from a global greenhouse gas (GHG) perspective the energy required for all aspects of production and transportation of a fuel should be considered. This more holistic view represents a well-to-wheels (WTW) perspective and is the major topic of this report. For corn-based bioethanol, the carbon capture from the atmosphere associated with growing the corn represents a major reduction in WTW CI impact. The term WTW is applied to describe the total CI of all fuels due to the historical predominance of the petroleum well as the fuel source.

Total contribution of CO_2 emissions associated with the burning of petroleum fuels in spark ignited vehicles includes sources associated with the production, transportation and refining that occur before the fuel is purchased at the pump. Also included is all of the carbon in the petroleum fuel, because that carbon source is not renewable, and the CO_2 is introduced into the atmosphere from an original source (where it was previously sequestered).

From a WTW perspective, bioethanol from corn is considered to be carbon free at the source, because all of the carbon is fixed from the atmosphere and is renewable. However, all of the upstream emissions associated with farming, processing and transportation represent a carbon footprint that must be assigned to the ethanol. In addition, corrections are applied for changes to carbon level in the soil (as if that were being mined), the quantities of useful by-products made available in the processing, land use impacts and certain agricultural economic effects attributed to the farming activity.

For both ethanol and petroleum gasoline, the currency for their GHG contribution is termed carbon intensity (CI), often expressed as grams of CO_2 per MJ of net energy available from combustion of the fuel. The energy metric is favored because one may argue that equal energy will produce substantially similar useful work or heat. When ethanol is blended into gasoline and used as a fuel, the resulting CI of the finished fuel can be determined by a weighted sum of the carbon contribution and energy contribution of each source. In some cases, the CO_2 produced by a mass or a volume of gasoline or ethanol may also be employed as a metric, and translation of units for the mixtures must be carefully considered when comparing two fuels.

In the literature, CI values are modeled and presented for ethanol and for petroleum gasoline separately. Customarily neglected in evaluating the CI of the mixture are the blending strategies employed to match the required properties of the finished market fuel. A noteworthy effect is that ethanol raises the octane rating when blended with gasoline, so that a petroleum “blendstock for oxygenate blending” (BOB) with a lower octane rating may be used to produced the finished market fuel. The BOB has different properties and composition than a finished gasoline that is purely from petroleum sources, and its CI is typically lower than for petroleum gasoline because its aromatic content is reduced by the blender.

Aromatic content enhances the octane rating of a finished fuel but is reduced when ethanol is blended because ethanol offers substantial octane enhancement to the blend. Blending strategies and their effect on CI are evaluated in this report and result in an additional low-CI credit for the ethanol as the enabler. This credit is substantial for finished fuels with 10% ethanol by volume (E10), which is the staple fuel of the US, as well as higher blends such as E15 or E20.

The report below does not attempt to develop a new ground-up WTW, or source-to-wheels, model. Existing WTW models for corn-based US ethanol production are considered and evaluated in the light of improving farming and production practices and combined with consideration of blending CI effects to yield a CI for ethanol that is used for E10 to E20 reduced carbon fuels. Since these models do not dwell on the blending effects and combustion of the fuel, they are essentially evaluating upstream effects without considering a changing BOB. Assuming that the CI of the gasoline is assigned to include innate carbon and its refinery and transportation footprint, the term WTW is employed below.

CI values in many studies include carbon equivalency of other species to capture total GHG effects. One example is the characterization of methane associated with natural gas energy use, associated with methane losses to the atmosphere. Another is nitrous oxide release from use of farming fertilizer, which is managed to varying degrees by nitrification inhibitors (Yang et al., 2016; Woodward et al., 2021). Tailpipe emissions of both methane and nitrous oxide from recent model year spark-ignited light duty vehicles are on the order of 0.015 g/mile and 0.005 g/mile respectively. Noting the CO_2 production of about 350 g/mile at the tailpipe and the GHG equivalency of these species, they represent about 1% of the total GHG. Methane and nitrous oxide GHG differences at the tailpipe due to different levels of ethanol in gasoline are therefore not substantive in calculation of CI differences. In reviewing WTW literature that includes equivalent contributions from other molecular species, it is important to realize that there is no consensus on the exact global warming potential (GWP) equivalency to carbon dioxide, in part because determination is complex, and in part because both 100 year and 20 year equivalencies are employed (Cain et al., 2019; IPCC, 2021; EPA, 2021GWP).

This report presents a review of recent WTW studies that evaluate relative upstream carbon intensity of petroleum gasoline and corn-derived ethanol and presents an average 40.4% reduction for the ethanol that is the consensus of three major sources, and 43.4% that is the estimate of the most widely recognized model (GREET). Further GHG reduction benefit is demonstrated by evaluating the difference in chemical CI of the fuel as it is combusted in light duty vehicles. This 40.4% reduction, arising from displacement of high CI aromatics by the ethanol addition, is attributed to the ethanol, reducing its CI to a value of about 43 g/MJ if compared to a petroleum gasoline (E0) of 93 g/MJ. This is termed a blending CI in this report. Using GREET input, the blending CI is reduced to about 40 g/MJ. Alternately, if two fuels such as E0 and E15 are compared as finished market products, the ethanol blend offers an overall reduction of 5.7% GHG. If this is applied to the approximately 1.6

billion US tons of WTW CO_2 produced annually from gasoline combustion, the difference between and E0 scenario and an E15 scenario is estimated to be 94 million tons of WTW CO_2 annually.

Production of Bioethanol

Although there is increasing interest in producing ethanol from cellulosic material, most ethanol is currently produced from sugar (Brazil) or starch (USA) (Bušić et al., 2018, Goldemberg, 2007). Typical US production is from corn, and this is used as the basis for the CI estimation in the studies presented below.

Corn is transported from the farmland to a production facility. Co-location of the agriculture and industrial production is attractive in reducing CI by reducing transportation emissions. Most US ethanol production commences with dry milling of the corn to produce flour, using a hammer mill. The flour and water are then slurried and the enzyme amylase is added. Some wet milling is employed in more costly plants where ethanol is co-produced with other products, such as high fructose corn syrup, cooking oil and food additives (Mosier & Ileleji, 2006). With we milling, remaining starch is processed in the same way as for the dry milling pathway.

The slurry from dry milling is cooked using steam injection and sheared to break starch granules, resulting in a corn mash, and glucoamylase is added to the mash, followed by a fermentation period of about 48 hours that yields a beer with 8 to 12% ethanol by weight (Mosier & Ileleji, 2006).

Distillation to produce anhydrous ethanol is made difficult by the formation of an azeotrope of the ethanol and water at 89.4 mole percent of ethanol. At this point the composition of the liquid and vapor are the same, and the boiling point is below the boiling points of both pure ethanol and water (Kumar et al., 2010). Several methods are known for removal of the water to yield dry ethanol, including distillation with addition of a third component. In modern fuel production molecular sieves are favored to dehydrate the azeotrope (Mosier & Ileleji, 2006; Kumar et al., 2010). An innovative water separation technique using pre-blending with gasoline followed by phase separation has been proposed by Stacey et al. (2016), but in the USA ethanol is still transported separately to terminals for blending with the BOB.

Anhydrous fuel ethanol is denatured with petroleum after production to dissuade human consumption.

Review of Studies and Models

Numerous studies exist to predict the overall CI for both gasoline and ethanol production.

Gasoline WTW CI

The chemical CI of finished petroleum gasoline based on composition is approximately 73 g/MJ. About 80 percent of WTW CI for gasoline is attributed to the carbon in the fuel that is derived from carbon in petroleum crude oil produced by from wells. The remainder is associated with refining and transportation impacts.

Although some studies of relative CI are unclear on the composition of gasoline GHG contribution that is used as a baseline reference, the difference between combustion of E0 and E10 has been acknowledged. "About 19.64 pounds (8.91 kg) of carbon dioxide (CO_2) are produced from burning a gallon of gasoline that does not contain ethanol. Most of the retail gasoline now sold in the United States contains about 10 percent fuel ethanol (or E10) by volume. Burning a gallon of E10 produces about 17.68 pounds (8.02 kg) of CO_2 that is emitted from the fossil fuel content. If the CO_2 emissions from ethanol combustion are considered, then about 18.95 pounds (8.60 kg) of CO_2 are produced when a gallon of E10 is combusted." (ICF, 2018b). This difference of 3.5% is close to the reduction of energy for an E10 blend and does not appear to take into account the carbon content of the fuel or any changes in that content due to blending strategies.

Han et al. (2015) presented the complexity of establishing a baseline greenhouse gas (GHG) metric for gasoline, noting varying crude oil weights and refinery configurations. They concluded that refineries dealing with low API gravity crude supply had an average CI (as CO_2) of 94.8 g/MJ, while refineries processing lighter crudes were at 93.1 g/MJ (higher heavy product yield) and 90.0g/MJ (lower heavy product yield). This refinery classification followed the findings of Elgowainy et al. (2014). Results were incorporated into the GREET model, discussed below. Typically, for US studies, a number such as 93 g/MJ (Scully et al., 2021; Wang et al., 2021) is used to describe gasoline for comparison of alternative fuels GHG performance. ICF (2018a) present a value of 98,000 g CO_2/MMBTU (92.9 g/MJ) for the year 2005, when gasoline would have had a low average ethanol content, with MTBE phase-out. Unnasch (2018) presents a value for petroleum gasoline of 96.82 g/MJ and compares it to the lower value of 93.08 g/MJ used by the EPA. California employs a value of 100.82 g/MJ, defined in state code, for California BOB (CARBOB). Improvements in refinery efficiency and use of renewable hydrogen at refineries would both reduce gasoline CI in the future.

Ethanol WTW CI

Although pure ethanol has an inherent chemical CI of 71 g/MJ, the carbon is deemed to be from a renewable resource and is not counted in a WTW analysis. However, the ethanol has an upstream footprint that constitutes its WTW CI. Based on the EPA (2010) assessment, and echoed in a report by Rosenfeld et al. (2018), there are 11 categories of contribution to GHG for the ethanol case, namely:

- Domestic farm inputs and fertilizer N2O
- Domestic land-use change
- Domestic rice methane
- Domestic livestock
- International livestock
- International land-use change

- International farm inputs and fertilizer N2O
- International rice methane
- Fuel and feedstock transport
- Fuel production
- Tailpipe

Not all WTW CI studies for ethanol CI follow this exact rubric, with some categories being combined, and others, such as by-product benefits, added separately. Sources of information also differ between studies, models and reports. This creates difficulty in comparing studies equitably and in assembling a CI total from partial contributions using multiple studies. Further, the efficiency of ethanol production has evolved rapidly, changing the CI value in consequence. Gallagher et al. (2015) observe that "[e]thanol made the transition from an energy sink, to a moderate net energy gain in the 1990s, and to a substantial net energy gain by 2008." It is therefore important to consider recent references in evaluating the GHG benefits of corn ethanol.

Early ethanol CI studies did not consider land use change (LUC) as part of the carbon impact. Direct LUC (DLUC) is associated with converting land to raise energy crops. Indirect LUC (ILUC) emissions occur elsewhere globally, due to the loss of prior production the land that is turned to energy crop production (Plevin et al. 2010). LUC components have the highest variation between prior studies, as shown by Scully et al. (2021). Plevin et al. (2010) confirmed the uncertainty, estimating that ILUC might vary from 10 to 340 g of CO_2/MJ of fuel energy at the time of that study. Some studies seek to address "food versus fuel" matters for corn-based ethanol production, and raise issues of its relationship to population growth, social impacts and "knock-on" effects on global climate change. Issues of this kind are difficult to separate, quantify and bound in an analysis, and they are not considered below beyond review of the ILUC value.

GREET Model

Researchers at the Argonne National Laboratory of the US Department of Energy were amongst the earliest workers to present WTW emissions for ethanol and have maintained continuity in this area to date (Wang et al., 1999). The "Greenhouse gases, Regulated Emissions, and Energy use in Technologies" (GREET) model has resulted from their efforts (Wang et al., 2007). GREET sub-models have also been used by other researchers seeking to evaluate overall WTW or specialized scenarios. Wang et al. (2021) report 43,800 GREET users globally in 2020. The Carbon Calculator for Land Use and Land Management Change from Biofuels Production (CCLUB) is a product of the GREET effort (Kwon et al., 2020). Rosenfeld et al. (2018), in a study for the US Department of Agriculture, used GREET to provide factors for energy use (including use of electricity) and emissions related to corn ethanol production. GREET has also served as the basis for CA-GREET, developed by the California Air Resources Board (Lee et al., 2021; CARB, 2021).

GREET has presented a steady decline in WTW CI for ethanol over time (Lee et al., 2021; Scully et al., 2021). Lee et al. (2021), in support of the GREET effort, reviewed changes in corn ethanol production over the period 2000 to 2019 and addressed the consequential reductions in ethanol WTW CI over that time. Not including LUC factors, the WTW ethanol CI fell from 58 to 51 g/MJ over 5 years and was predicted at 45 g/MJ for 2019. Major contributions to these numbers were farming, production, transportation and distribution, and combustion. The farming included the CI for fertilizer, fuels and electric energy used on the farm. Changes could be attributed to actual GHG reductions or to changes in data reported by primary sources. As examples the supplemental data provided by Lee et al. (2021) showed a 7% reduction in nitrogen use and a 15% reduction in lime use per bushel of corn over the 19 years of change. Data showed reductions of natural gas and LPG use but increases in electrical energy per bushel produced. However, net energy use decreased. A major contributor to reductions resulted from higher yields of corn, from 119 bushels/acre in 1990 to 168 in 2019. Broad benefits of higher precision placement of fertilizers and pesticides are well documented in agricultural literature.

In support of the steady CI reduction of GREET, Schimmelpfennig and Ebel (2011) report "significantly higher" yields for corn and soybean farms that adopted precision agriculture. Swath control serves to avoid application overlap for crops, saving on chemicals and fertilizers. Rosenfeld et al. (2018) have discussed increased efficiency in agricultural production, citing the fertilizer institute assertion that between 1980 and 2014 corn production doubled without appreciable increase in fertilizer use.

Lee et al. (2021) presented sources for their evaluation of ethanol production CI, covering 40% of national production, most of which employs dry milling of the corn. Ethanol production per bushel of corn rose by 6% between 2005 and 2019. At the same time energy demands were reduced from 9.0 to 6.9 MJ/liter of ethanol. They also addressed useful by-products, including animal feed (distillers' grains with solubles, DGS), oil, syrup and captured CO_2. These reduce the CI of the ethanol through crediting based on equivalent CI levels of the useful products. However, Wang et al. (2015) have addressed the difficulty of ascribing credit to ethanol and to corn-oil as fuel when the two are co-produced. Lee et al. (2021) identified a high variation in natural gas use at ethanol plants and suggested that this may represent a pathway for further CI reduction in the future. Wang et al. (2015) addressed the incorporation of corn stover as an efficient ethanol pathway in GREET.

A reduction over time in LUC CI estimates for ethanol was addressed by Lee et al. (2021). They reported that CCLUB was used to estimate a rate of 7.4 g/MJ that was used in GREET. Sources cited with dates after 2010 averaged a LUC CI of 12.3 g/MJ. The highest of these was due to CARB (2015), at 20 g/MJ, and the lowest was due to Elliott et al. (2014), at 6 g/MJ. Attaching the GREET value for LUC to the 2019 value without LUC yields a total of 52.4 g/MJ, substantially below the gasoline value.

Study of Scully et al. (2021)

Scully et al. (2021) examined literature from 1990 to 2020, reviewed prior models, noted changes over time, and determined representative values for the components of ethanol CI. They conducted interviews with experts to augment the review, and "calculated the total CI of corn ethanol by summing the central estimates for seven emission categories (LUC, farming, co-product credit, fuel production, fuel and feedstock transport, tailpipe, and denaturant), as well as the upper and lower bounds of the credible ranges." They presented LUC CI contribution, commencing with the high value of 104 g/MJ presented by Searchinger et al. (2008), and ending with values an order of magnitude lower for more recent studies and computations. Scully et al (2021) also considered the by-product benefits and noted that CI estimates after 2010 for the farming component are typically about 30 g/MJ and for ethanol production are about 13 g/MJ. These two values sum to a value close to the recent value of 45 g/MJ presented by Lee et al. (2021) for GREET. The CARB value (without LUC considered) of 58 g/MJ in 2015 is an exception among newer studies.

In reaching conclusions on the LUC component, Scully et al. (2021) expressed concern over models using satellite imagery that may misclassify land use and identified the Global Trade Analysis Project-Biofuels (GTAP-BIO) model as the "field-leading model" to use. They noted that GTAP-BIO is used in both the California low carbon fuel standard and by GREET. GTAP-BIO is sufficiently detailed to be executed for a variety of scenarios, and Scully et al. presented five analyses, considering land intensification as a land use factor, yielding values of -1.9 g/MJ (ICF, 2018): domestic, -2.3 (their own analysis): domestic, 8.0 (ICF, 2018): international, 1.3 (ICF, 2018): international and 8.7 (Taheripour, 2017): domestic. Ultimately, they concluded that total CI for ethanol could vary from 37.6 to 65.1 g/MJ, with a central value of 51.4 g/MJ, slightly below the 52.4 g/MJ value of GREET. A wide range in values is to be expected, noting uncertainty of input data and the varying processes and efficiencies in both the farming and industry components. Spawn-Lee et al. (2021) have reacted to the Scully et al. (2021) conclusions and are critical of the low LUC value that was presented, and the selection strategy used to reach that value.

Federal and California Estimates

Separate CI values have been adopted by the Environmental Protection Agency, The California Air Resources Board, and the US Department of Agriculture. The US Department of Energy is represented by the GREET model though Argonne National Laboratory.

A report for the US Department of Agriculture was prepared by ICF (Rosenfeld et al., 2018). The report acknowledged that GHG prediction "has been contentious since Searchinger et al. (2008) and Fargione et al. (2008) concluded that the emissions associated with its production and combustion exceeded the emissions associated with production and combustion of an energy equivalent quantity of gasoline." The ICF report acknowledged a 2010 EPA study that determined that international LUC was the highest CI contributor, with fuel production and farming as other major contributors. However, Rosenfeld et al. (2018) also stated that newer information is available since 2010 and used this information in the ICF analysis. For example, new data were available from the National Agricultural Statistics Service (NASS), and they also acknowledged advances in the GREET model. In particular, Rosenfeld et al. (2018) found that the international LUC projections were higher than the real outcomes since 2010. Three future scenarios with differing ethanol production volumes were considered, as well as a current estimate.

Rosenfeld et al. (2018) devoted a substantial part of their report to updating international and domestic LUC, using data from EIA and NASS, the GTAP-Bio and CCLUB models, and differences in LUC presented by

Taheripour et al. (2011) and Taheripour and Tyner (2013). They also cited Dunn et al. (2017) who argue that measurement and analytic techniques affect conclusions that are reached on conversions to cropland.

Some variability within the literature arises from the basis used to estimate CI components. For example, one may estimate the farming component from all current corn farming or use only projected near-term additional production associated with increased ethanol fuel use, which might be expected to embrace more or most efficient practices. The basis may also be confounded by considering population growth, changes in corn use other than for ethanol production, and per capita versus global assessments. For LUC, by-product assessment and related knock-on effects, a host of input variables including production location may vary. Further, LUC impacts may be both short-term and long-term. Lastly, some studies have looked to the future, where projected CI impact is more sanguine (Rosenfeld et al., 2018).

The EPA provide a range of CI for ethanol and a value of 98.2 g/MMBTU (93.1 g/MJ) for petroleum gasoline (EPA, 2021T). The values for ethanol were obtained from a 2010 study and support the renewable fuel standard (RFS) and clarify RFS pathways and pathway assessments (EPA, 2021P). Pathways depend upon feedstock, production process and fuel type. The ethanol CI for ethanol from corn with dry milling and natural gas energy source, the most common process, is presented as 73.8 g/MJ, 21% lower than for gasoline. The individual contributions are recognized as 18.4 g/MJ for agricultural activity and feedstock transportation, 28.4 for fuel production and transportation, and 26.35 for land use change.

When biomass is used for production energy, the CI drops to 67.4 g/MJ, while ethanol from wet milling with coal exceeds the value for petroleum gasoline, at 110.9 g/MJ. The EPA value of 73.8 g/MJ is substantially higher than other recently published values, primarily due to the high LUC component. Mueller (2016) petitioned the EPA to reduce its CI value applied to ethanol. Although the EPA projected 2022 WTW ethanol CI, that projection was part of their study in 2010 (Scully et al., 2021). Unnasch (2018) argued that reductions in GHG exceeded the projections from EPA, and that the EPA values represented minimum reductions "and were not intended to represent the weighted GHG reductions of all fuels produced under the program."

For the LCFS Reporting Tool and Credit Banking and Transfer System (LRT-CBTS), CARB (2021a) presents substitute pathways for certain transactions, with the CI for ethanol of 65.87 g/MJ for 2020 and 62.05 g/MJ for 2021. This should be compared with the CARB number for CARBOB (California BOB) of 100.82 g/MJ. For 2021, this implies a CI reduction of 38% for ethanol versus CARBOB. The reduction in CI between 2020 and 2021 is reflective of the improved farming techniques and recognition of by-products discussed above. CARB also presents specific pathways approved in 2019 and 2020 for corn ethanol produced by commercial entities. These values are influenced by production, transportation and by-product factors from descriptions provided and range from 59.0 to 77.8 g/MJ with a preponderance of values in the sixties (CARB, 2021b).

Summary of Prior Studies

General conclusions are that LUC emissions, and in particular ILUC emissions, are difficult to quantify, and that production increases may be associated with new land use, changed land use or more intensive farming. There is greater agreement amongst studies related to farming emissions and production emissions, both of which have seen reductions over time. Ethanol from different sources may have a different CI, and average and marginal CI values are expected to differ.

The GREET model has a long history of GHG prediction and has presented a downward trend in CI for corn-based ethanol over the last decade. GREET, which represents the DOE through ANL, currently finds an ethanol total CI of 52.4 g/MJ and uses a pure petroleum CI of 92.6 g/MJ. This represents a 43.4% reduction.

CARB presents a 62.05 g/MJ ethanol value for substitute pathways and a CARBOB value of 100.8 g/MJ, both values being higher than presented by GREET. There is likelihood that an E0 petroleum fuel would have a higher CI than a BOB due to increased aromatic content of a finished petroleum E0 to reach octane equivalency. However, since California limits aromatic content in fuel, this was not considered in calculating a 38% reduction based upon the CARB values.

The ICF report (ICF, 2018) for the US. Department of Agriculture presents a value of 56.7 g/MJ for ethanol, and a value of 92.9 g/MJ for "2005 gasoline," which would have contained higher aromatics and lower oxygenates than an E10 today (EPA, 2017). This represents a 39.7% reduction. The ICF report also projected a "business as usual" lower value for ethanol CI of 51.7 g/MJ for 2022. This represents a 44.3% reduction relative to the 2005 gasoline.

The EPA model is based on a 2010 effort that showed a 21% reduction. The literature widely describes improvements in ethanol CI over the last decade, and the EPA number was not employed for this reason.

The three current ethanol versus gasoline percentage reduction values from ICF, CARB and GREET for CI reduction for ethanol average to a reduction of 40.4%. If the gasoline and ethanol values for the three studies are averaged, the resulting percentage reduction is 40.2%. The ICF projection for 2022, if substituted, raises the averaged reduction to 41.9%. The 40.4% average reduction and the 43.4% reduction of GREET were both employed below for calculating ethanol GHG contributions.

Credit For Ethanol as an Octane Enhancer

This section of the report addresses the effectiveness of ethanol in reducing total fuel CI when blended with a gasoline BOB to form E10, E15 and higher ethanol blends. A blending carbon intensity (BCI) is proposed as a reference CI for ethanol, because ethanol displaces high CI species in the petroleum component. This benefit is in addition to the traditional WTT difference that averages 40.4% from three recent studies presented above, and 43.4% from GREET alone. Blending effects have been acknowledged previously in assigning a blending octane number (BON) to ethanol, and it is this BON that facilitates the BCI for ethanol in finished gasoline blends.

Most US gasoline is sold as a 10% blend of ethanol (by volume) with 90% BOB. The BOB is configured to produce a finished gasoline meeting specification after the ethanol is blended. Both petroleum components and ethanol blend in a way that change blend properties in a nonlinear fashion. One benefit is that ethanol offers a high BON, higher than that of the gasoline and higher than the octane number of pure ethanol (Anderson et al., 2010; Waquas et al., 2017). Stratiev et al. (2017) include both ethanol and reformate, containing a high proportion of aromatics, as octane enhancers and the blending data that they present suggest that a 1% change in ethanol would correspond to a change in aromatic level of about 0.8%. Historical data show that aromatic content declined as ethanol was blended into US gasoline, and a comparison of summer conventional gasoline compositions from 2000 and 2016 yield an aromatic reduction of about 0.8% for each percent addition of ethanol (EPA, 2017). An EPA study recently compared Tier 2 and Tier 3 certification test fuels. The Tier 2 fuel contained no ethanol, while the Tier 3 fuel contained 10.15% ethanol by volume. The Tier 3 fuel had 7.7% less aromatic content by volume than the Tier 2 fuel. This comparison suggests a reduction of 0.76% of aromatics for each percent of ethanol added. (EPA, 2018a).

Usually in comparative WTW studies, the CI for petroleum gasoline and ethanol are presented as two separate values, and ethanol blends are not addressed specifically. As an example, Unnasch (2018) computed national ethanol benefits solely in terms of displacement of petroleum gasoline, without blend effects. However, market fuels are not represented by a simple mixture of ethanol and finished petroleum (E0) gasoline. Generally, a dedicated BOB is used. Also, studies focus primarily on upstream activity, but changes in fuel composition also affect the CO_2 produced by the vehicle. This is due both to carbon content in the tank and to vehicle efficiency, necessitating a tank-to-wheels (TTW) understanding. TTW CO_2 reduction for ethanol blends may be examined from either a fuel-based perspective or a vehicle exhaust carbon inventory perspective.

Corn-derived ethanol provides a substantial reduction in GHG emissions when blended with a petroleum BOB. There are three mechanisms contributing to this reduction.

- First, as determined by the WTW review in this study, ethanol offers a CI reduction (such as 40.4% or 43.4%) relative to pure petroleum fuel on an energy basis and thereby reduces the CI of a blend by its own presence in the blend, because it displaces some of the petroleum component. This does not take into account that the petroleum component (BOB) may change in composition.
- Second, ethanol, as an octane enhancer, enables changes in the composition of the BOB relative to a purely petroleum E0 gasoline. Aromatic reduction is the most important change, but the balance of olefins, napthenes, paraffins and isoparaffins may also change as a result of blending practice. The result is that the ethanol addition enables a reduction in the energy specific CI of the petroleum component. This reduction, enabled by the high BON ethanol as the blending agent, may be credited to

the ethanol. This reduces the ethanol effective CI further, resulting in a lower value termed the BCI. Previously this mechanism has not been highlighted.

- Third, an ethanol blend fuel, with reduced volumetric energy content, may enhance the energy conversion efficiency of the vehicle engine. In other words, when comparing and E0 fuel to an ethanol blend, the increase in volumetric fuel use of the ethanol blend may be less than would be expected from the reduced volumetric energy content of the blend. This energy specific gain also may be assigned as a credit of CI to the ethanol, lowering BCI further.

In a prior TTW report by the authors, analysis of refining practice and blending of ethanol yielded Table 1, showing values of CI of ethanol and petroleum blends based on their chemical carbon content for various refining scenarios. From this table, recognizing the relative volumetric energy content of ethanol and the BOB, the chemical CI of the BOB may be calculated. In WTW terms, the E0 has a CI of 93 g/MJ, for E10 BOB CI is 92.1, for E15 BOB CI is 91.5 and for E20 BOB CI is 91.2. The BOB CI is reduced by about 0.9 g/MJ for each 10% of ethanol added. Each BOB is tailored to suit the ethanol blend level and produce required octane number for engine knock resistance.

All of the carbon in petroleum gasoline is assigned to its WTW CI. In all cases the petroleum component is deemed to have a WTW CI that is 19.5 g/MJ higher than the chemical content CI: this value is suggested from comparisons of WTW CI values with chemical CI content (akin to TTW content). This additional CI is associated with production, refining and transportation. Prior analysis by the authors has shown that the differences in refining footprint between the petroleum gasoline and each BOB are small.

	RON	Aromatics	Carbon	Energy	C Intensity	CO2 CI	CI Reduction
		vol%	wt%	MBTU/#	#C/MMBTU	g/mg Joule	% vs E0
E0	92.4	29.9	86.60	114.4	46.67	73.52	
E10 w BOB	93.0	21.7	82.34	109.9	46.01	72.48	-1.41%
E15 w BOB & Prod	93.3	17.9	80.14	107.4	45.63	71.89	-2.23%
E15 w BOB Demand	93.4	17.2	80.06	107.2	45.55	71.76	-2.40%
E15 Splash w E10 BOB	94.6	20.3	80.37	107.9	45.86	72.25	-1.74%
E20 w BOB & Prod	93.3	15.4	78.14	105.3	45.41	71.54	-2.70%
E20 w BOB Demand	93.4	14.0	77.98	105.0	45.25	71.29	-3.04%
E20 Splash w E10 BOB	96.0	19.2	78.49	106.0	45.76	72.09	-1.95%

Table 1: Compositions of petroleum gasoline and the blends of ethanol and BOB for various refinery and blending scenarios.

Consider a modeled comparison of an E0 petroleum fuel, with a WTT assigned value of 93 g/MJ, and an E10 blend. The ethanol in the E10 blend, with a 40.4% WTT reduction relative to the petroleum E0, has a CI of 55.5 g/MJ based on the average of three studies. The BOB in the E10 blend has a WTT CI of 92.1 g/MJ due to reduced aromatic content relative to the E0: this value is computed using Table 1 data and the 19.5 g/MJ addition.

The ethanol is 10% by volume, but ethanol contains less energy per unit volume than petroleum species. In this blend, the ethanol contributes 6.9% of the energy, and the petroleum BOB contributes 93.1% of the energy. In this way 6.9% of the energy is delivered by the lower CI component, at 55.5 g/MJ. However, the ethanol also contributes a high BON to the blend and enables the reduction of aromatic content in the BOB of 0.9 g/MJ relative to the E0 gasoline. The result is that for a mass of finished fuel that can deliver 1MJ of energy, the WTW petroleum component now contributes 85.75 g CO_2, and the ethanol contributes 3.83 g CO_2, for a total finished fuel CI of 89.57 g/MJ. This is 3.43 g/MJ lower than for E0 with CI of 93 g/MJ.

This reduction in total carbon content, of 3.43 g/MJ is attributable in part to the low WTW CI of the ethanol that replaced some petroleum fuel, and in part to aromatic reduction in the BOB. If the whole CI reduction is attributed to the ethanol as the enabling blending agent, then the WTW BCI of the ethanol is 43.36 g/MJ. Alternately, the reductions due to ethanol blending (2.59 g/MJ) and lower aromatic BOB (0.84 g/MJ) may be viewed and assigned separately.

$$1\ MJ\ x\ CI_{finished\ gasoline} = 0.069\ MJ\ x\ BCI_{ethanol} + 0.931\ MJ\ x\ CI_{E0}$$

so that

$$BCI_{ethanol} = \frac{1\ MJ\ x\ CI_{E10} - 0.931\ MJ\ x\ CI_{E0}}{0.069\ MJ}$$

$$= \frac{1\ MJ\ x\ 89.57\ \frac{g\ CO_2}{MJ} - 0.931\ MJ\ x\ 93\ \frac{g\ CO_2}{MJ}}{0.069\ MJ}$$

$$= 43.36\ \frac{g\ CO_2}{MJ}$$

The WTT BCI values for ethanol for E15 and E20 are given in Table 2. The BCI values reflect roundoff in the BOB predictions from the refinery model. The value for E20 is higher than the value for E10 because the ethanol elicits slightly less advantage from aromatic reduction with the reduced quantity of BOB in the blend. With increasing ethanol content, the WTT BCI for ethanol tends upwards toward the 55.5 g/MJ value for pure ethanol, while the CI of the blend tends downward to the 55.5g/MJ value for pure ethanol. From a GHG advantage, ethanol deployment in low to mid blend ratio offers high leverage, while use of pure ethanol offers the highest overall reduction.

Blend (1MJ)	Ethanol Energy (MJ)	Ethanol WTW CI (g/MJ)	Ethanol WTW CO2 (g)	Petroleum Energy (MJ)	Petroleum WTW CI (g/MJ)	Petroleum WTW CO2 (g)	Total WTW CO2 (g)	Ethanol BCI (g/MJ)
E0 w BOB	0	55.5	0.00	1	93	93	93.00	N/A
E10 w BOB & Prod	0.069	55.5	3.83	0.931	92.1	85.75	89.57	43.36
E15 w BOB & Prod	0.106	55.5	5.88	0.894	91.5	81.80	87.68	42.85
E20 w BOB & Prod	0.144	55.5	7.99	0.856	91.2	78.07	86.06	44.80

Table 2: BCI for ethanol in blends, and factors supporting the BCI calculation, using a pure ethanol CI of 55.5 g/MJ.

The BCI value is not fixed and the BCI concept may be applied to any upstream (WTW) CI prediction. Variations in specific CI values are commonplace, and CARB assigns CI individual values to commercial production facilities for ethanol. As one example, wet and dry milling are acknowledged as having different WTW CI values. Also, BCI may be based on different relative petroleum compositions. A BOB that had aromatic content closer to a comparative finished petroleum gasoline would imply a raised BCI value for the ethanol that is subsequently blended.

GREET is the most historied effort and widely used tool to address representative average ethanol CI. If the latest GREET values of 92.6 g/MJ for gasoline and 52.4 g/MJ for ethanol are used to evaluate ethanol blends, the predicted ethanol BCI is lower than portrayed in Table 2, as shown in Table 3.

Blend (1MJ)	Ethanol Energy (MJ)	Ethanol WTW CI (g/MJ)	Ethanol WTW CO2 (g)	Petroleum Energy (MJ)	Petroleum WTW CI (g/MJ)	Petroleum WTW CO2 (g)	Total WTW CO2 (g)	Ethanol BCI (g/MJ)
E0 w BOB	0	52.4	0.00	1	92.6	92.6	92.60	N/A
E10 w BOB & Prod	0.069	52.4	3.62	0.931	91.7	85.37	88.99	40.26
E15 w BOB & Prod	0.106	52.4	5.55	0.894	91.1	81.44	87.00	39.75
E20 w BOB & Prod	0.144	52.4	7.55	0.856	90.8	77.72	85.27	41.70

Table 3: BCI for ethanol in blends, and factors supporting the BCI calculation, using a pure ethanol CI of 52.4 g/MJ and a gasoline CI of 92.6 g/MJ, as provided by the GREET model.

Further reduction in ethanol CI is acknowledged if the efficiency of vehicles improves when they operate on fuels with reduced volumetric energy content. The EPA conducted a new study specifically to address CO_2 emissions and fuel economy changes associated with the current move from Tier 2 to Tier 3 certification fuel (EPA, 2018a). Tier 2 certification gasoline contained no ethanol while Tier 3 certification fuel is required to include 9.6% to 10% of ethanol by volume. In the comparative study, using a fleet of port fuel injected and direct injected technology vehicles, the Tier 2 fuel had a heat of combustion of 18,529 BTU/lb, and the Tier 3 fuel was 17,889 BTU, lb, 3.6% lower.

The Tier 3 fuel had a 1.3% lower in-tank chemical CI (based on energy content) than the Tier 2 fuel. Based on the study results the EPA proposed to adjust CO_2 data measured using oxygenated Tier 3 certification fuel to match Tier 2 fuel expectations "by multiplying by a factor of 1.0166 to produce the expected CO_2 performance had the vehicle been tested over the same test cycles while operating on Tier 2 fuel." This implies that on an energy equivalent basis, the E10 Tier 3 fuel yielded 1.66% less CO_2 in the tailpipe than for the Tier E0 fuel basis, or an additional 0.36% reduction due to vehicle efficiency. Although some uncertainty is implied in such testing (Sluder, 2019) and the true cause for efficiency change is not clear, if this vehicle efficiency improvement is also considered and assigned to ethanol as the agent, it would drive the ethanol BCI to below 40 g/MJ.

Conclusions

TTW and WTW CI analyses for gasoline differ in that a TTW analysis is concerned solely with the CO_2 emissions at the tailpipe whereas a WTW analysis seeks to identify a net global impact of the fuel production and use. WTW CI analyses for ethanol consider the carbon in the chemical makeup of the fuel to be from atmospheric fixation, and hence renewable. However, the CO_2 associated with the farming, processing and transportation is considered in its WTW CI. Also considered are CO_2 emissions associated with LUC. WTW CI for petroleum gasoline is assigned all of the carbon in the fuel, in addition to production and transportation impacts.

LUC estimates are the most difficult components to establish accurately, but recent studies have presented far lower LUC values than those from before 2010. Values from DOE (through the Argonne National Laboratory GREET model), CARB and the US Department of Agriculture study by ICF yield a 40.4% lower average CI for ethanol than for petroleum gasoline, and this percent reduction was adopted as a reasonable estimate in the present study. CARB used higher values of CI in g/MJ for both ethanol and petroleum gasoline that the other two studies but agreed reasonably on percentage reduction. The EPA reduction value was based on a study from 2010 and has not been revised recently. The GREET model presents a value for ethanol of 52.4 g/MJ (43.4% reduction): Scully et al. (2021) and the ICF report 2022 projection (Rosenfeld et al., 2018) present slightly lower values than GREET.

A benefit, neglected when pure ethanol CI is estimated, is that ethanol enables the reduction of aromatics in the petroleum mix with which it is blended. This is due to the high BON of ethanol. These aromatics have a high inherent chemical CI, so that ethanol displaces a component with a chemical CI approximately 10g/MJ higher than its own. If both an ethanol reduced WTW CI (e.g., 55.5 g/MJ) and the chemical CI reduction of the petroleum are assigned to the agency of the ethanol, the BCI of the ethanol for E10 and E15 are about 43 g/MJ, and the BCI for E20 is 45 g/MJ. Alternately, for E10, the ethanol blending CI reduction (2.59 g/MJ) and the enabled CI reduction from aromatics in the BOB (0.84 g/MJ) may be viewed as separate effects, but both may be ascribed to the presence of the ethanol. Using the GREET CI, BCI for E10 and E15 are estimated at about 40 g/MJ.

The difference in WTW CI between E0 and E15, including an ethanol versus aromatic tradeoff, is approximately 6%. CO_2 production associated with US light duty vehicle fuel consumption is of such a scale, that the difference between and E0 scenario and an E15 scenario is estimated to be about 85 million short (US) tons of WTW CO_2 annually. The EPA Tier 3 (E10) fuel versus Tier 2 (E0) fuel study results suggest additional benefits through increased vehicle energy efficiency when using the E10 fuel.

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