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Case Study

Full carbon accounting: the case of ethanol

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Abstract

Transport needs to be decarbonised, but the lack of a comprehensive carbon accounting framework prevents policy consensus. Policies are moving towards inclusion of indirect effects, but not yet in a comprehensive manner. The engine efficiency improvements of higher octane levels should be included in LCAs. Ethanol is both a fuel and a chemical. A framework of full carbon accounting is suggested. Illustrative calculations are presented for European ethanol. Results show that European ethanol is better than oil. Indirect land use change impacts appear entirely offset by fuel economy improvements. The ethanol portion in E10 (10% ethanol blended in petrol) may have less than one-third the climate footprint of petrol. Furthermore, ethanol in E20, expected in the next decade, may be carbon neutral, if appropriate High Octane Fuels regulations and policies are enacted.

Keywords: Carbon accounting, Bioethanol, High octane fuel, Bioenergy sustainability, E20, LCA, Ethanol, Biofuel, Engine efficiency improvement, Climate change, Carbon footprint, Greenhouse gas saving, Transport policy.

Introduction

The need for climate change mitigation is emphasized by the 2015 Paris Climate Agreement, which also recognises the need to accelerate the reduction of global greenhouse gas (GHG) emissions. Transport GHG emissions have increasingly been in the spotlight globally. Road transport alone contributes one-fifth of total EU and US GHG emissions. Transport is the major sector where GHG emissions have decreased the least, if at all, in the past two decades, underscoring the need to focus on practical solutions. There is no panacea in transport, and so a variety of measures (including electrification, modal shift, emissions standards and low carbon fuels) are needed to control GHG emissions. Biofuels were suggested as a way to reduce the carbon intensity of transport fuels.

Concerns have been raised about the sustainability of biofuels, and bioenergy production in general. Bioenergy is the form of renewable energy used most in the EU. The climate change mitigation credentials of bioenergy production, including bioethanol, or ethanol, have been questioned. It is increasingly apparent that without clarity on the GHG profile of various bioenergy sources, policy-makers struggle to agree on coherent transport decarbonisation policies both in the EU and the US. In the following the focus is on the EU, with relevance to the US also.

To foster transport fuel decarbonisation, the following two policy documents of the EU are of highest relevance; i. The Renewable Energy Directive (RED), which mandates Member States to achieve at least 10% renewable energy in transport by 2020, and ii. The Fuel Quality Directive (FQD), which requires fuel suppliers to reduce the GHG intensity of their fuels by a minimum of 6% from 2010 to 2020[1,2]. The RED and the FQD, the key policy documents of the EU to incentivise bioenergy use in transport (although neither actually requires that any biofuels be used), have however become politically contentious. Given concerns over biofuel sustainability, in particular competition with food production and indirect land use change (iLUC) effects, the EU has second thoughts on how to implement the directives.

The past few years could perhaps be described as tumultuous and indecisive. As an important step, the EU in 2015, in the so called iLUC Directive, lowered its expectation for the amount of renewable energy in transport by 2020. Accordingly, revisions were made to the RED by implementing a 7% “cap” on the contribution of biofuels from conventional feed stocks to achieving the transport target of 10% renewable energy, and iLUC was included for reporting purposes. The future of both directives beyond 2020 is unknown.

Policymakers now, for the most part, view biofuels as intractably contentious. Policy debates since the RED entered into force in 2009 have unsettled industry, and as a result investments have been far short of expectations. Limited practicable alternatives to ethanol exist in the near or medium term for transport decarbonisation, and the existing vehicle fleet in particular. As a result, decision-makers need more clarity on the climate benefits of various forms of bioenergy in order to formulate policies capable of interesting investors. It seems that without a clear direction on the biofuel files, EU decarbonisation policies may not deliver as expected.

Our aim with this paper is to contribute to policy developments primarily in the EU, but given similar debates in the US, some implications may apply to US policy-making, too. We believe that by providing a comprehensive framework of carbon accounting and illustrative calculations based on the latest real world data and modelling findings, some clarity can be inserted in policy discussions with regard to the true climate impacts of bioenergy, and ethanol in particular.

There are calls in the EU bioenergy and transport decarbonisation debate for policies to embrace, and for analyses to prioritize, full carbon accounting. Given that the original RED and FQD did not consider indirect land use change impacts; this call is frequently made in the context of efforts to include iLUC into policy. However the concept of full carbon accounting should not be limited to indirect land use change. Under a system with full carbon accounting, all positive and negative direct and indirect impacts of bioenergy (and fossil fuels) would be booked.

The concepts of "fossil fuel comparators", "indirect land use change" and "High Octane Fuels" are each simultaneously important to evaluating the role of ethanol, a primary form of bioenergy in decarbonising the EU transport sector. For comprehensive or full carbon accounting, all of these need to be taken into consideration. Crucially, current life-cycle assessments (LCA) in their Tank-to-Wheel cycles do not yet include the implications of higher octane fuels (HOF). An emerging field of studying the potential benefits of moving towards HOF has relevance to Well-to-Wheel LCA calculations.

Ethanol is different from other forms of bioenergy in that it is both a fuel and a chemical. As a fuel, it is a proven alternative to oil. Yet, ethanol as a chemical functions as an octane booster, and more efficient spark ignition engines are not practicable without higher octane fuels. As an octane booster ethanol is promising in its combination of relatively low price and low risk to human health and the environment.

A critical element of the paper is based around this second property of ethanol; a High Octane Fuel, contributing to engine efficiency improvement. Higher-octane is the cure for “knocking”, the inability of fuel combustion to match the timing needed by a spark ignition engine. Ethanol has a higher octane level (RON 109) than average petrol, so it can be used as an octane-booster. When ethanol is blended in fuel, the resulting higher octane fuel mix is combusted more efficiently gaining energy. HOF give rise to engine efficiency improvements[3,4].

There are two basic pathways to explain how HOF contributes to fuel economy (Table-1). The first pathway describes how existing vehicles can make use of higher-octane fuels, while the second pathway encompasses various degrees of optimisation of future engines. Efficiency gains for legacy vehicles can be realised[3]. It can be with and without recalibration. A recalibration of the engine and controls is technically feasible (requiring automaker testing for each vehicle model and individual implementation on each vehicle – likely through dealerships). Recalibration would bring efficiency gains. The authors claim that a lesser gain would be realized on most, if not all, vehicles without a calibration change. Given that modern engines incorporate knock sensors and spark control, the base spark advance map could take advantage of a favourable working condition; fuels with increased octane.

In contrast, system optimisation of engines would result in a full realisation of the fuel efficiency potential. The primary mechanism is through increasing the geometric compression ratio of the engine. The compression ratio is the predominant design factor that would be adjusted in future engines in response to the availability of HOF. A higher compression ratio enables engine downsizing, leading to further efficiency improvements.

Table-1: Pathways of High Octane Fuels contribution to Fuel Economy.

Existing vehicles not optimised for the higher-octane fuel		Full system optimisation of future engines	
Base spark calibration adjusts to better circumstances (HOF)	Recalibration of engines: Update (or “reflash”) engine calibrations on existing vehicles	Increasing engine compression ratio made possible by HOF	Downsizing of engines

A framework for full carbon accounting

In the following, a framework for full carbon accounting is laid down, and basic assumptions behind an illustrative calculation for ethanol produced in Europe are discussed. Two timeframes are discussed: i. 2020, which is assumed to correspond to an adoption of E10 (10% ethanol blended in petrol) as a standard fuel in most EU countries, ii. 2030 (or 2025 in most optimistic case), by which time E20 (20% ethanol blended in petrol) may become the standard fuel in Europe. The second timeframe aims to provide inputs to policy discussions on EU transport decarbonisation policies beyond 2020 (i.e. post-2020 policies looking to 2030).

Fossil fuel comparator

Under the EU regulatory framework enshrined in annexes to the RED and the FQD, biofuels are primarily described by their percentage GHG savings. A biofuel follows a prescribed methodology to calculate its carbon intensity in grams per mega joule of carbon dioxide equivalent ($gCO_2e\ MJ^{-1}$), and then that number is divided by 83.8, which is known as the fossil fuel comparator. Going forward, unless the result shows as least 50% GHG savings, that biofuel is not eligible for regulatory compliance (from 2017).

It is often implicitly assumed that the RED fossil fuel comparator of 83.8 gMJ^{-1} is a static number. The fossil fuel comparator, as defined in both the RED and the FQD, is however a dynamic figure, meant to reflect the emissions of actual sources of oil and midstream processing.

To illustrate the problem of ambiguities of quantification, the fossil fuel comparator methodology under the RED/FQD calculates the GHG savings of EU biofuels as if they displace average fossil fuels, not marginal fossil fuels. Calculating the average GHG intensity of fossil fuels used in the EU policy documents results in numbers ranging from 83.8 $gCO_2e\ MJ^{-1}$ to 95.1 $gCO_2e\ MJ^{-1}$. However, calculations of the GHG intensity of the marginal fossil fuels displaced by EU biofuels yields a range of 83.8 $g\ MJ^{-1}$ to 140 $g\ MJ^{-1}$[5]. Disaggregated data exist on the climate impacts of various sources of oil to allow for a consequential approach calculation of fossil fuel comparator, and the authors calculated a marginal fossil fuel comparator to be 115 $gCO_2e\ MJ^{-1}$. Largely in line with the above, the European Commission recently commissioned a study on the actual GHG emissions for fossil fuels[6]. In their effort to collect lifecycle actual GHG emissions data, the authors find that petrol's GHG emissions figure is above 90 $gCO_2e\ MJ^{-1}$ and that for unconventional oil it is between 110 and 120 $gCO_2e\ MJ^{-1}$. Furthermore, the study suggests that the value of the fossil fuel comparator is too low and it should actually be 95 $gCO_2e\ MJ^{-1}$.

In order to be conservative, the updated FQD baseline for petrol of 93.3 $gCO_2e\ MJ^{-1}$ is used in our illustrative calculation for 2020. There is limited literature on the future evolution of carbon intensity of oil. Various factors are at play determining upstream, midstream and downstream emissions[7]. As regards average refinery emissions projects a 4% decrease by 2020, and 6-9% decrease by 2030, but note that midstream emissions comprise about one tenth of the total[6]. The authors assume the future mix of crudes imported to the EU to have low impact on the quality of crude. We believe this assumption can be debated; however discussion of this topic falls outside the scope of our paper. In total, there is virtually no change projected by the authors, and therefore in our calculations unchanged carbon intensity is assumed for 2020 and 2030.

Direct GHG emissions

Due to innovations, the carbon intensity of EU ethanol production has been decreasing, and based on industry data average EU ethanol in 2015 had 64% direct GHG savings (RED methodology), which equates to a direct GHG intensity of 30g MJ^{-1}. This compares to 51% in 2010. It is reasonable to assume that technological improvements will continue to be gradually implemented, and therefore so called "direct" GHG emissions will continue to decrease. Direct emissions include GHG emissions from cultivation of feed stocks (such as corn, wheat or sugar beet), whether energy inputs are fossil or renewable, processing of feed stocks and delivery of product. Process emissions have been in the decline with utilisation of co-products such as DDGS, an animal feed, or increasing efficiency of the plants as a whole. Some EU ethanol plants already run on renewable sources of heat and electricity, and the greening of the electricity grids, especially in Western Europe, will be reflected in higher GHG savings of ethanol produced in that region. Additional co-products, such as corn oil, were identified and extraction has become industry standard. Furthermore, CO_2, a by-product of ethanol production has begun to be utilised (i.e. fizzy drinks, industrial applications).

There is no reason to believe that such technological improvements should not continue in the future. In addition to future innovations, a path to higher direct GHG savings can also be based on more widespread adoption of existing best technologies (e.g. CO_2 utilisation becoming standard and energy is sourced from renewable sources). Moreover, cultivation emissions may also see some improvements. Sustainable intensification of crop production (producing more output with less use of input) contributing to closing the "yield gap" may increase the productivity of land; hence contribute to reducing unit GHG emissions of feedstock production[8].

An average ethanol plant in the EU is expected to have significantly lower direct GHG emissions in 2030 than today. Some models (i.e. EU transport white paper based on Primes and Sultan modelling) assume a direct GHG saving of 75% for ethanol in 2030, albeit assuming an increasing share of advanced biofuels[9,10]. In our illustrative calculations a perhaps conservative figure of 29 and 25$gCO_2e\ MJ^{-1}$ is assumed for average EU ethanol in 2020 and 2030, respectively (65% and 70% GHG saving by RED methodology, respectively).

Indirect land use change impact (iLUC)

iLUC occurs when additional demand for a crop (or any feedstock in fact) diverts some quantum of supply to a new use. The "missing supply" may be produced some place else, possibly leading to land use change. Note that there are several market responses to meet the additional demand, including increasing the productivity of land. When land use change happens however, GHG emissions will follow. This impact is often expressed by iLUC factors.

When assessing the sustainability of bioenergy in line with the RED and FQD targets, it is important to consider iLUC emissions. With the 2015 "iLUC Directive", iLUC factors will likely be used to show EU wide GHG savings of bioenergy[11]. iLUC factors are calculated based upon the land use displacement impact resulting from the price impacts on a feedstock of increasing bioenergy use from a volume of X in year A to a volume of Y in year B. For purposes of the current EU biofuels debate, year A is 2008 and year B is 2020, and so the actual impact on prices and land use resulting from volume increase from X to Y can only be known in the future. iLUC cannot be measured, only modelled. A recent modelling, or as commonly referred to the "Globiom report", is the latest attempt to model iLUC impacts of various bioenergy feedstocks[12]. The report aims to model the impact of the demand shock triggered specifically by the EU's biofuel policy. The Globiom report is expected to supersede in EU policies the iLUC figures calculated by the IFPRI study[13].

In the absence of aggregated figures for ethanol in the Globiom model, we calculated iLUC impact for average European ethanol based on feedstock level iLUC values provided, and shares updated by latest industry data. The report uses two scenarios, with and without foregone sequestration, an assumption on land abandonment and corresponding natural vegetation reversion functioning as a carbon sink. The authors acknowledge that this assumption "can be debated, as the extent to which the effect occurs in reality is not well documented". We believe that it is more plausible that cropland area will not decrease and partly revert into grassland or forest in the EU, even in the absence of a demand shock from bioenergy. EU policies generally are aimed at preventing loss of farmland. However, in order to be conservative, iLUC of 14 $gCO_2e\ MJ^{-1}$ is used for ethanol in our illustrative calculations, instead of the 8$gCO_2e\ MJ^{-1}$ without the effect of foregone sequestration included (Supplementary material for calculation of iLUC).

Making assumptions about the future evolution of iLUC figures goes beyond the scope of our paper, hence, in the absence of any other relevant modelling results, the same iLUC figure is applied in our calculation for both the 2020 and 2030 timeframe. This may be a conservative assumption as in Globiom, the iLUC factors are calculated based upon predicted volume increases in ethanol that appear to be beyond plausible 2020 rates of growth in the market. Globiom iLUC results are based on the assumption that EU biofuels policy was to create an extra 5 billion litres supply of several different types of ethanol by 2020. However, given the lower than expected growth in ethanol consumption and the fact that there is no type of ethanol whose growth in supply approaches 5 billion liters, actual iLUC impact may turn out to be overestimated.

Note that in a methodological sense, due to the 20 years amortisation period applied in Globiom, a significant part of ethanol produced in 2030 will have already become iLUC-free. Ethanol production capacity in 2010 will have its iLUC impact amortised, hence will have an iLUC factor of zero. Incorporating this however would go beyond the scope of our paper, therefore not taken into consideration.

Engine efficiency improvement (High Octane Fuels and fuel economy)

A recent paper shows that recalibration of engines would result in fuel efficiency gains ranging from approximately 0.6% to 4.4% when switching to higher octane fuels[3]. In their test, the octane number of the fuel was increased from 91 to 97 (RON), a change roughly matching the difference between E0 and E10, or E10 and E20. The authors estimate that for moving from 91 to 96RON (E20 case in the US), the total increase in efficiency is 4.0% without additional downsizing and 4.4% with additional downsizing of the assumed turbocharged engine.

The European Commission in 2014 commissioned a study to review literature on E20/25 technical developments[14]. The resulting meta-analysis finds that fuel consumption when using E20/25 should rise by approximately 8% to reflect the fact that ethanol has a lower energy density than petrol. Yet, studies show an increased consumption of about 3%, which reflects increased engine efficiency due to blending of ethanol into fuel. This approximately 5% improvement is attributed to the effect of HOF (E20/25). Although the effect appears to be non-linear, lower levels of blending of ethanol also brings fuel economy improvements. Drawing conclusions from the literature, the authors find that for E5/10, theoretical fuel consumption due to energy density of ethanol is 1.8% (102.9-101.1) higher than real fuel consumption (Table-2).

Table-2: Fuel economy improvements due to different levels of ethanol blending, based on a meta-analysis[14].

Fuel	E0	E5/10	E20/25
Theoretical fuel consumption	100%	102.9%	107.7%
Real fuel consumption	100%	101.0%	103.1%
Fuel economy improvement	0%	1.8%	4.6%

Note that the paper finds higher values for effects of HOF than the meta-analysis[3,14]. In the interest of being conservative, our illustrative calculation for E10 uses the findings of the meta-analysis, and thus a fuel economy improvement of 1.8% is assumed. It is reasonable to assume however that the introduction of E20 will be based on a fuel standardisation process where potential benefits of HOF are considered, and minimum octane is specified, therefore enabling engine designers and manufacturers to make full use of the potential. It is assumed that the introduction of E20 would enable engine downsizing (i.e. system optimisation). Accordingly, in line with the paper, for moving from E10 to E20, a total efficiency gain of 4.4% is assumed in our calculations[3].

The engine efficiency improvement of E10 ethanol blends is calculated to result in a potential energy equivalence gain of 0.56 MJ per liter of ethanol, corresponding to a GHG saving of 25$gCO_2e\ MJ^{-1}$. Currently, most ethanol in the EU is used for E5 and E10 fuel blends, while it is used for E10 and E15 in the US. As both the EU and US move towards E20, the engine efficiency improvement benefits of ethanol blending are expected to result in larger savings. Accordingly, a 1.85 MJl^{-1} potential energy gain is estimated by E20 as a result of 6.2% (1.8% plus 4.4% for E10 and E20, respectively) improvement in fuel economy, corresponding to 41 $gCO_2e\ MJ^{-1}$ potentially avoided in the 2030 timeframe (Table-3 and Supplementary material for further details). Admittedly, it is an optimistic scenario, based on the assumption that regulators will maximise the climate benefits when setting the standards for E20, therefore the result illustrates the scale of the potential. If octane will not be increased in line with what would follow from ethanol blending, some of the efficiency gain will be lost, and GHG avoided will be lower.

Table-3: Potential engine efficiency effect.

Fuel (ethanol blend)	Efficiency gain	Energy gain	Petrol replaced by ethanol	GHG avoided
	%	MJl^{-1}	MJ MJ^{-1}	gCO_2e MJ^{-1}
E10	101.8%	0.56	1.26	-25
E20	106.2%	1.85	1.44	-41

It is important to note that some of the fuel economy benefits of E10 is not realised as octane is not increased with ethanol blended. In the absence of regulation to require fuel suppliers to maintain octane level of the petrol blend stock when ethanol is blended, consumers are deprived of realising the full extent of engine efficiency improvement benefits. Another way to look at it is that octane level of petrol blend stock is often lowered by fuel suppliers prior to blending ethanol.

A 0.5% thermal efficiency benefit per 10%v ethanol is shown by, and this effect is irrespective of octane[15]. This thermal efficiency benefit of ethanol as a biochemical translates into a 7 gCO_2e MJ^{-1} fuel economy gain (see Supplementary material), and since the effect is irrespective of share blended, this serves as a floor to potential fuel economy gains of both E10 and E20. Therefore, E10 is calculated to bring fuel economy benefits in the range of 7 to 25 gCO_2e MJ^{-1}, and E20 in the range of 7 to 41 gCO_2e MJ^{-1}.

LCA methodological issues

Choice of methods (attributional or consequential LCA) and their underlying assumptions as well as changes in the magnitude of sensitive parameters (such as soil N_2O emissions, allocation of co-product credit or land use change) may substantially change results. These are salient in the differences between EU (RED) and US (Renewable Fuel Standard and Californian Low Carbon Fuel Standard) LCA methodologies[16]. Problems arise when attempting to mix attributional and consequential LCA methodologies.

Adding iLUC factors calculated by a partial consequential methodology on to the GHG intensity figures calculated by the RED methodology, a partial attributional LCA, may be problematic. To the best of our knowledge, there is no modelling that takes into account all the elements we described in the context of a full carbon accounting. Effect of HOF is not yet incorporated in models.

There is a growing abundance of data however on all the elements, and therefore we believe that an illustrative calculation is possible. Given the methodological differences in modelling each element, results may not be aggregated however. While it may not be methodologically sound to include iLUC factors in GHG accounting based on the RED approach, the policy direction shows signs of moving that way (2015 ILUC Directive). If a recent paper is right, arguing that scientific robustness of inclusion of iLUC into carbon footprint calculations is not sufficient for political and corporate decision making, than policies are better to focus on proactive mitigation[17].

The author notes that iLUC factors come with high uncertainty. However it appears that most recent European modelling results for ethanol tend to converge showing early signs of the maturing of iLUC models[12,13]. Accordingly, our aim here is only to show that partial fixes to RED methodology, as is on the table of current EU policy-making, fail to account for a comprehensive picture. In our illustrative calculation the scope of the methodology based in RED is further expanded to include HOF.

There is also uncertainty regarding the engine efficiency improvement effect of HOF, and hence ethanol, albeit seemingly on a lower level of magnitude than with iLUC. There is a growing literature confirming the existence of the effect, and that literature, seeing the respective confidence intervals of the values, appears more robust than the literature surrounding iLUC quantification. It is difficult to estimate the size of the effect though, given the fact that comparable fuels do not exist on the market where the difference is only in ethanol and/or octane. When fuel suppliers blend ethanol, other components of the blend stock are also changed.

In particular, refiners may use lower octanepetroleum-derived blend stock to be combined with ethanol (since ethanol improves octane). The effect is sufficiently robust though to allow for inclusion in carbon accountings. And the effect also points to a regulatory fix in the EU context, namely to disallow fuel suppliers from using ethanol to bring petrol onto the market that otherwise would fall below minimum legal standards.

Table-4 summarises the expected directions of changes in all the elements of a full carbon accounting framework. Also, assumptions of current and future values are provided in the lower lines.

Illustrative calculations based on full carbon accounting

Based on the full carbon accounting framework outlined here, illustrative calculations are made for European produced ethanol. The calculations are by no means precise, as uncertainties are relatively high, both with regard to methodology and data as well as future policy directions impacting the extent of making use of the emission savings potential offered by HOF. Nevertheless we believe that some illustrative calculations are useful as inputs to policy discussions. Furthermore, once data becomes more robust, and methodological uncertainties are reduced, the calculations based on the framework can be updated.

Table-4: Expected direction of changes in values behind full carbon accounting of ethanol.

Full carbon accounting of ethanol	2015	2020	2030
Ethanol blending in EU	E5	E10	E20
Fossil fuel comparator ($gCO_2e\ MJ^{-1}$)	93.3	≈ 93.3	≈ 93.3
Direct emissions ($gCO_2e\ MJ^{-1}$)	30	↓ 25-29	↓↓ 21-25
iLUC ($gCO_2e\ MJ^{-1}$)	14	≈ 14	? 14
Engine efficiency improvement (%)	1.8	≈ 1.8	↑↑ 4.4
Expected total improvement		↑	↑↑

Our calculations illustrate the potential benefits expressed in terms of carbon intensity to be realised with E20 in 2030. It is important to note that results for 2030 are illustrative. On the one hand data inputted are selected on a conservative basis. When there was a choice conservative figures (or unfavourable to ethanol) were selected, such as with values for fossil fuel comparators, and iLUC factors where i. foregone sequestration assumption was not excluded, ii. amortisation implications were not considered and iii. there is a chance that ethanol consumption in the EU will be lower than assumed.

On the other hand policy assumptions made on E20 are optimistic. It is a reasonable assumption that regulation, when specifying E20, will be capable to maximise benefits of HOF, yet there is a risk that regulation will be suboptimal. Our aim was to illustrate the potential benefits for decision-makers to be maximised.

Indeed, the fuel economy benefits of E10 have not been realised due to the fact that regulations did not require fuel suppliers (refiners) to maintain the octane level of petrol blend stock, and therefore a large part of the benefit has been lost to consumers (and the climate).

Using the latest available data, European produced ethanol (E10) may save about 60-80% GHGs compared to 93.3 $gCO_2e\ MJ^{-1}$ of petrol (updated fossil fuel comparator). E20 shows higher saving potential.

Indirect land use change impacts appear to be more than offset by fuel economy improvements, provided that regulation concerning E20 takes advantage of high octane. Upper boundary values in Table-5 correspond to fuel standardisation taking advantage of HOF.

Table-5: Calculation of GHG emissions of ethanol produced in Europe based on Full carbon accounting approach[11,18].

Full carbon accounting approach	E10	E20
	$gCO_2e\ MJ^{-1}$	$gCO_2e\ MJ^{-1}$
Direct Emissions	29	25
iLUC	14	14
Engine efficiency improvement	-(7-25)	-(7-41)
Total GHG saving	60-80%	65-100%

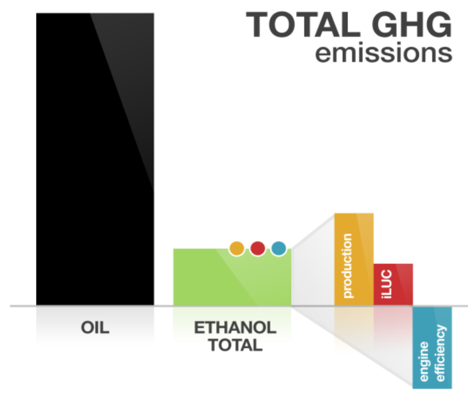

Figure-1: Key elements of GHG emissions of ethanol produced in Europe based on Full carbon accounting approach.

Discussion

Currently, the RED and the FQD provide an EU-level sustainability framework for biofuels, and the ILUC Directive is an attempt to consider iLUC. The European Commission in 2016 has begun to review the sustainability of all bioenergy sources and final uses for the period after 2020. The transport decarbonisation policy of the EU is expected in 2017. In its transport decarbonisation and bioenergy sustainability policies the EU appears to move towards a carbon intensity approach with inclusion of iLUC factors. Although the aim may be a right step towards more comprehensive carbon accounting, the regime is incomplete without inclusion of all direct and indirect impacts. Our full carbon accounting framework may be a useful input into the processes for devising a post-2020 policy framework.

Although our analysis focuses on the EU, the framework outlined may also be useful in US policy debates. Methodologies are somewhat different, the US model is rather a consequential LCA, but it should not preclude US policies from moving towards a more comprehensive LCA. Clearly, models, such as the California Air Resources Board (CARB) does not yet include the biochemical properties of ethanol. Yet discussion has already begun on High Octane Fuels in the US, and so we see no reason why engine efficiency improvement effects will not be considered by US carbon accounting models and related policies.

HOF are increasingly in the spotlight. Some authors argue that there are social and economic benefits to be gained from a switch to higher octane fuels[4]. By quantifying the economic and environmental benefits of designing U.S. light-duty vehicles (LDVs) to attain higher fuel economy by utilizing higher octane (98 RON) gasoline, the authors estimate the annual direct economic benefit to be \$0.4–6.4 billion in 2040, and the annual net societal benefit including the social cost of carbon to be \$1.7–8.8 billion in 2040. Furthermore, net CO_2 emissions are reduced by 19–35 Mt y^{-1} in 2040 (2.5–4.7% of total direct LDV CO2 emissions).

Given the GHG mitigating potential in HOF, it is important to recognise the role of HOF in carbon accounting, and transport and bioenergy policies. Appropriate policies are needed. It is suggested that promotion of HOF is validated as beneficial, and the role of ethanol and other octane boosters is re-assessed.

In essence, ethanol contributes to GHG emission reduction both as a renewable fuel and as an octane enhancing chemical. While the first is widely acknowledged, the latter effect is yet to be recognised in methodologies and policies.

HOF are generally seen by car makers (OEMs) as a positive means to optimise the combustion process in engines. In contrast, refiners may be disinterested in increasing octane given associated costs due to infrastructure needs. We suggest regulators should seek to maximise social benefits of the octane boost offered by ethanol to deliver lower tailpipe emissions and better fuel economy. Technical specification for E20 fuel is to be decided accordingly, along with protection grades, the fuel infrastructure in place and pump labelling matters.

It is important to note that the primary gasoline specifications in both the EU and the US do not provide minimum requirements for octane after ethanol blending. Therefore when blending ethanol, a higher octane fuel, to petrol blendstocks, refiners are now able to produce a blendstock with octane ratings lower than gasoline produced prior to the use of ethanol as a blending agent. Refiners (fuel suppliers) are allowed to use lower octane petrol blendstocks as the higher octane of ethanol will compensate for this decrease in octane, and as a result, final RON is not decreased.

In this way, regulation allows for fuel suppliers in both the EU and the US to weaken the effectiveness of biofuel policies, substituting potential large climate change mitigation gains for society with relatively small private profits.

In other words, the current ethanol blending practices deprive consumers and society of the full realisation of fuel efficiency improvements in the existing vehicle fleet. If octane of the final fuel was increased in line with ethanol blending, consumers could reap more of the benefits of HOF. Accordingly, fuel standardisation policies and regulations need to ensure that octane levels of final fuels rise in line with the increasing rate of ethanol blending, otherwise some of the potential climate change mitigation and other benefits will be lost.

Realising the benefits would require coordination among car makers, refiners and regulators. The next opportunity in both the EU and the US will be E20 fuel standards. If regulators obligate refiners to increase octane in line with what would follow from ethanol blending, society and the climate would gain. It is suggested that minimum octane (RON) levels in the standard for the finished fuel is increased to the equivalent of the desired ethanol blend plus the current petrol blendstock. The extent of which the potential benefit is realised depends on the ambition of the upcoming regulations. Our calculation has provided for an illustration of the potential.

Conclusion

Recent debates in the EU suggest that partial fixes to carbon accounting may lead to suboptimal policy-making processes. Shortcomings of the RED have been in the focus (i.e. iLUC); policy solutions however have so far offered only partial fixes. We argue for a full carbon accounting, which takes into account all climate change related aspects, and therefore leads to a comprehensive account. To that end, carbon accounting should include not just iLUC, which was not incorporated in original carbon accounting models in the EU, but also realistic fossil fuel comparators. Furthermore, there is an emerging acknowledgement of a phenomenon, labelled as the engine efficiency improvement of ethanol blending, which has also been left out of the picture. Therefore, we believe that for a comprehensive carbon accounting, all of these need to be incorporated.

Our illustrative calculation finds that inclusion of iLUC impacts worsens the climate profile of ethanol, yet once the fossil fuel emissions used as baseline better reflect reality, and the fuel economy improvement of ethanol blending is incorporated, the total change appears to be positive for ethanol. Accordingly, our illustrative estimation of total GHG emissions based on full carbon accounting finds that ethanol is better than fossil fuels.

A full carbon accounting of ethanol appears to show that ethanol is a promising tool to decarbonize the EU transport sector both in the period up to 2020, when decarbonisation options are in short supply, and until 2030, when EU transport policies are yet to be designed and agreed on. Importantly, ethanol's contribution is expected to increase over time as technological innovations are gradually implemented, and fuel policies are expected to make increasing use of the engine efficiency improvement potential; both contributing to reducing marginal GHG emissions. By 2030, when E20 may be a standard fuel, European ethanol's carbon intensity calculated based on full carbon accounting framework may be reduced to zero, corresponding to being carbon neutral in the sense of total GHG emissions.

Supporting Information[18]

iLUC calculations: In the absence of industry data available at the time, Globiom had to rely on estimates by USDA Foreign Agriculture Service (2014). In the meantime, ePURE has collected feedstock specific data on European ethanol production, which made it possible to update iLUC calculations of Globiom with the latest data and come up with a European average for ethanol. Importantly, this is not self-reported data, but the result of a process in which ePURE hired a forensic accounting firm to independently collect and audit (including on site audits at ethanol production facilities) data, a first in the history of biofuel data as far as we are aware. Our calculation uses European industry data on 2010-2015, representing about 90% of ethanol produced in Europe.

Table-S1 shows that corn dominated the cumulative growth in feedstocks use between 2010 and 2015 for European ethanol production, amounting to 98% of the increase. Multiplied by conversion yields (figures taken from the Globiom), shows that corn represents 95% of accumulated growth in energy terms. The vast majority of the demand shock triggering iLUC hence comes from the production of corn ethanol. This overwhelming share explains why iLUC for average European ethanol is found to be very close to iLUC factor of corn ethanol calculated by Globiom. Note that the category "other" includes feedstocks such as barley, rice straw or energy crops, but since no further information was available on its composition, no ILUC values could be assigned, and therefore was excluded from the calculation. Given its low share (under 5% of cumulative growth) it does not have a salient impact on results.

When cumulative growth is multiplied by Globiom iLUC factors iLUC impact is calculated. With foregone sequestration assumed to be 1.6 $mtCO_2e$, and without this assumption 0.95 $mtCO_2e$ land use change impact is calculated from producing feedstocks for ethanol produced in Europe. Divided by accumulated growth arrives at an estimated average iLUC factor for European ethanol. In the assessed period 14 gCO_2e/MJ iLUC is calculated for average ethanol produced in Europe. Without applying the assumption on foregone sequestration iLUC of average European ethanol drops to 8 gCO_2e/MJ (Tables S2 and S3).

Table-S1: Feedstock mix of European ethanol (thousand Metric tonnes / Sugar equivalent MT).

Feedstock	2010	2011	2012	2013	2014	2015	2010-2015 cumulative growth
Corn	2 273	3 505	4 479	4 824	5 268	5 212	11 924
Wheat	4 576	4 618	3 880	4 067	5 397	5 068	150
Sugar beet	1 580	1 317	1 769	1 784	1 792	1 898	661
Others	1 272	1 092	981	1 090	1 312	1 337	-548
Total	9 700	10 533	11 109	11 765	13 768	13 514	12 187

Source: ePURE data.

Table-S2: Calculation of total iLUC emissions.

Feedstock	Yields	2010-2015 cumulative growth	Globiom iLUC factor (With foregone sequestration)	Globiom iLUC factor (Without foregone sequestration)	iLUC (With foregone sequestration)	iLUC (Without foregone sequestration)
	GJ/Ton	PJ	gCO_2e/MJ	gCO_2e/MJ	tCO_2e	tCO_2e
Corn	8.72	103974	14	8	1455630	831789
Wheat	7.68	1151	34	22	39150	25333
Sugars	13.31	8805	15	11	132078	96857
Total		113 930			1 626 859	953 979

Table-S3: Average iLUC emissions of European ethanol (gCO_2e/MJ).

iLUC factor	With foregone sequestration	Without foregone sequestration
European ethanol	14.3	8.4

Engine efficiency gains calculation: Avoided GHG emissions by engine efficiency improvement of ethanol blending is calculated based on a meta-analysis in Geringer et al.[14] and figures provided by Leone et al.[3] on fuel economy gains. For E10 a fuel economy gain of 1.8% is assumed, while for E20, considering full system optimisation of vehicles, an additional 4.4% is assumed.

Using 32 MJ/l as the low heating value (LHV) for petrol and 21.1 MJ/l for ethanol, LHV of both blends are calculated resulting in 30.91 MJ/l for E10 and 29.82 MJ/l for E20. These figures are multiplied by the efficiency gain to work out the LHV in both fuel blends after efficiency improvement took place. Therefore the LHV of E10 is calculated as 31.47 MJ/l, while 31.67 MJ/l for E20. Subtracting the original LHV from these figures we arrive at the energy gain; 0.56 MJ/l and 1.85 MJ/l for E10 and E20, respectively. In order to put these values into perspective, LVH of ethanol in the blends are needed to be calculated. LHV of ethanol in the blend is simply calculated by multiplying LHV of ethanol by the share in blend, i.e. by 10% for E10, and 20% for E20, resulting in 2.11 MJ/l and 4.22 MJ/l, respectively. Finally, petrol replaced by the fuel economy gain needs to be calculated. This step is done by adding an energy gain to ethanol LHV in fuel blend, and the sum is divided by ethanol LHV in fuel blend. As a result of engine efficiency improvement 1.26 MJ petrol is calculated to be replaced by each MJ of ethanol in E10, and 1.44 MJ by each MJ of ethanol in E20 (Table-S4).

As a final step avoided GHG emissions are calculated. For this the updated fossil fuel baseline of 93.3 gCO_2e/MJ for petrol value is used. The petrol carbon intensity figure is multiplied by petrol replaced, and this value is deduced from petrol's carbon intensity to result in avoided GHG emissions by ethanol blended. The following function is used:

Avoided GHG emissions by fuel economy gain = carbon intensity of petrol * (1 – petrol replaced by ethanol)

Through engine efficiency improvements, E10 is calculated to potentially avoid 25 gCO_2e/MJ, while E20 to avoid 41 gCO2e/MJ emissions.

As for a lower bound estimate, the same methodology described above is used, with engine efficiency improvement figures of 1.8% for E10, and 6.2% for E20 replaced by a 0.5% thermal efficiency benefit per 10%v ethanol (based on Jung et al., 2013) (Table-S5).

Table-S4: Calculation of potential engine efficiency effect.

Fuel (ethanol blend)	LHV of blend	efficiency gain	LHV in fuel blend after efficiency improvement	energy gain	ethanol LHV in fuel blend	petrol replaced by ethanol	GHG avoided
	MJ/l	%	MJ/l	MJ/l	MJ/l	MJ/MJ	gCO_2e/MJ
E10	30.91	101.8%	31.47	0.56	2.11	1.26	-25
E20	29.82	106.2%	31.67	1.85	4.22	1.44	-41

Table-S5: Calculation of lower bound engine efficiency improvement effect.

Fuel (ethanol blend)	LHV of blend	efficiency gain (lower bound)	LHV in fuel blend after efficiency improvement	energy gain	ethanol LHV in fuel blend	petrol replaced by ethanol	GHG avoided (lower bound)
	MJ/l	%	MJ/l	MJ/l	MJ/l	MJ/MJ	gCO_2e/MJ
E10	30.91	100.5%	31.06	0.15	2.11	1.07	-7
E20	29.82	101.0%	30.12	0.30	4.22	1.07	-7

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