Lifecycle assessment of biofuel production

An overview

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Abstract

Can the mass utilization of biofuels help reduce greenhouse gas emissions and dependence on fossil fuels? Four particular types of biofuels have been the subject of extensive study in this regard: corn ethanol, sugar cane ethanol, cellulosic ethanol, and biodiesel. This paper overviews the evidence from the literature on Lifecycle Assessment studies pertaining to these four fuels and finds that no definitive answer to these questions exists in the literature. The example of biofuels co-products is used to illustrate the reason why no easy answer can be arrived at from these studies. The deeper sources of variation within the literature are identified as well as the requirements that would be needed to formulate an LCA which can provide conclusive and actionable answers.

Context

Recently, two global phenomena have sparked a rise in interest in biofuels. The first is the rise of oil prices to historical highs. The second is the rise of interest in — and awareness of — global warming. As these two concerns have grown recently, attention has turned towards finding alternative forms of energy to fossil fuels. At the forefront of this push to find clean energy are biofuels. Though certainly not a new fuel, biofuels have been attracting great attention recently and production has increased in several countries, most notably Brazil and the United States of America. This increased interest raises various questions about the usefulness and sustainability of biofuels, and whether pursuing them is a viable energy strategy in the long-term.

Together, Brazil and the USA produce around 80% of world ethanol production. Europe, however, is the world leader in production and consumption of biodiesel. Germany is the world’s largest producer, followed by France the United States and Italy. The recent large increases in the production and consumption of biofuels have been driven by strong interventionist policies by the US government and the European Union. The Brazilian experience with biofuels, however, has relied less on subsidies and direct government support.

A previous overview of EU policies supportive of biofuels concludes that the main drivers behind these policies are: reducing dependency on foreign oil, reducing greenhouse gas emissions, rural development and farm support, and promoting development in the third world. Yet in spite of the growing consumption of biofuels, the EU region did not meet the target of making biofuels reach 2% of total fuel consumption by 2005.

The main goals that US ethanol policy sought to accomplish over the years are: energy Independence, reducing greenhouse gas emissions, and rural development and farm support. It was only in the 1970’s, after the “energy
crisis” and growing environmental concern, that ethanol made its modern entry into the fuel mix of the American automobile. Since then, a large number of government subsidies, legislations, and mandates have raised the share of ethanol in all US transportation fuels from a negligible amount in 1980 to around 10% of total transportation fuel consumption in 2013\(^1\), in the process increasing ethanol production from only 175 million gallons in 1980 to 13.3 billion gallons in 2013.\(^2\)

The history of the development of the ethanol industry is the history of legislation supporting the ethanol industry. The International Institute for Sustainable Development\(^4\) attempts to quantify the total amount of subsidies spent on biofuels concluding that the European Union spent between EUR 5.5-6.9 billion in 2011 alone on subsidizing biofuels production. Another report by the International Institute for Sustainable Development\(^5\) finds that the United States has implemented more than 200 different subsidies for biofuels, and concludes that the sum of subsidies in 2006 was between $6.3-$7.7 billion.

**Lifecycle assessment**

The policy goal that is most relevant for the purpose of this paper is the goal of reducing greenhouse gas emissions to fight global warming. This has arguably become the major motivation of biofuels promotion in the US and EU. The policies enacted aim at greenhouse gas emissions reductions through promoting the increased use of biofuels. But this raises an important question: how can we know that the impact of more biofuels consumption will be a reduction in greenhouse gas emissions? Could it not be the case that increased biofuel consumption will lead to increased greenhouse gas emissions? This chapter considers this question from the perspective of the public debate before analyzing the scientific literature on the topic.

In an assessment widely echoed across American media, David Tillman and Jason Hill\(^6\) write in The Washington Post:

> Biofuels, if used properly, can help us balance our need for food, energy and a habitable and sustainable environment. To help this happen, though, we need a national biofuels policy that favors our best options. We must determine the carbon impacts of each method of making these fuels, then mandate fuel blending that achieves a prescribed greenhouse gas reduction. We have the knowledge and technology to start solving these problems.

The Union of Concerned Scientists—“an alliance of more than 250,000 citizens and scientists” that “is the leading science-based nonprofit working for a healthy environment and a safer world”—argues for a comprehensive accounting system for carbon emissions from biofuels “that measures global warming emissions over a transportation fuel’s entire life cycle.” Using this accurate accounting, the report then urges policies that are “performance-based policies that will reward low-carbon transportation fuels for their performance and help them compete against highly polluting fuels such as liquid coal”\(^7\).

On specific biofuels, the conventional wisdom and the majority opinion amongst the experts, public, and policymakers can be broadly characterized as follows: Sugarcane ethanol is far more efficient than corn ethanol. It produces far more energy than the energy invested in it. Corn ethanol is not a very desirable fuel, that cannot be relied on to replace substantial amounts of fossil fuels. There is disagreement within this view whether corn ethanol is harmful to the environment, not helpful to the environment, or currently helpful but unlikely to be helpful if its production is increased. But there is large agreement, even among corn interest groups, that corn
ethanol is unlikely to be the solution to the energy problems facing America.

Cellulosic ethanol is viewed as the most promising fuel that will be the sustainable fuel of the future. Even many critics of corn ethanol critics maintain that cellulosic ethanol will be far more efficient than corn ethanol, and will help in the achievement of many economic, political, social and environmental goals. Accordingly, even many critics of corn ethanol argue for subsidizing it as a way to set the scene for when cellulosic ethanol’s production commences. Finally, biodiesel continues to be a marginal topic in America (and as a share of biofuel production). It is, however, viewed as the most relevant fuel for Europe to reduce its consumption of fossil fuels and its emissions.

The underlying motivation of this debate is that scientists should determine which are the ‘good’ fuels to meet various environmental, economic, energy and social goals, and based on that, government should support, subsidize and promote these fuels.

The method most-widely utilized in the academic literature for the assessment of the efficiency of biofuels is Lifecycle Assessment. Kammen et al. define LCA’s as a “technique used to evaluate the energy and global warming impacts of biofuels” adding that it is “both a method and a framework to evaluate biofuels”.

The basic intuition of an LCA is that it looks at the entirety of the lifecycle of a fuel, and estimates the amount of energy and emissions that go into and out of this cycle, arriving at the conclusion of whether this fuel’s utilization relative to another fuel saves or increases energy; and whether it produces more or less emissions. Kammen et al. define the life cycle as comprising “all of the physical and economic processes involved directly or indirectly in the life of the product, from the recovery of raw materials used to make pieces of the product to recycling of the product at the end of its life.”

The techniques for carrying out LCA’s have changed a lot over the years, and the questions have grown in complexity and significance. Of the more recent and more complex studies, the two most common issues that LCA’s allow us to compare, according to Kammen et al., are:

1. What is the net change in the world energy supply from increasing biofuel use by a given date
2. How much of the GHG emissions in the world should we attribute to a unit of biofuel produced.

There is a large body of literature attempting to assess different aspects of different biofuels’ efficiency, energy intensity, environmental effects, and other factors such as social, political, employment, and international implications. This study focuses on three categories of biofuels: European and East Asian biodiesel, American corn ethanol and American cellulosic ethanol.

**Corn Ethanol**

The vast majority of LCA’s have been conducted to assess American corn ethanol. The results are very sporadic, as are the different types of methodologies used, with two predominant sharply opposed views. On the one side, many critics contend that corn ethanol is inefficient and an energy loser and that it will not contribute positively to any emissions reduction because it consumes more energy from fossil fuels than goes into producing it than the energy that it produces. The other side argues that the production of ethanol from corn is
efficient and can have significant beneficial environmental consequences.

Pimentel and Patzek have published a series of papers discussing ethanol production from corn and other materials. Their conclusions have continuously been negative and they have outlined a plethora of economic, energy-related and environmental factors against the production of ethanol. This paper will not provide an overview of these papers, but will concentrate on their last paper which used the most comprehensive Life-Cycle Analysis with the most recent and reliable data. It is also one of the most widely cited papers in academic circles in the mainstream media.

In a paper published in 2005, Pimentel and Patzek found that ethanol production using corn grain required 29% more fossil energy than that contained in the ethanol fuel produced. With switchgrass, the figure was 50% and with wood biomass the figure was 57%. However, many criticisms exist of these studies. As an LCA, this study included several factors that are usually not included in LCA studies. For example, the authors accounted for the food and transportation costs consumed by workers in the biofuels sector, as well as things like police protection. Further, criticized the paper for basing their calculations on outdated ethanol-producing technologies. As production has grown, newer and more efficient techniques are being utilized. Farrell et al. also critique Pimentel’s allocation of energy from bi-products of ethanol which can have several useful applications like cattle feed.

Among the lead researchers on the “opposite side” of this debate are Michael Wang, Hossein Shappouri and Norman Brinkman. published results that are contradictory to those of Pimentel and Patzek, finding that ethanol contained 1.35 times the energy that went into producing it, a very favorable ratio that they even claim is less than gasoline (which they claim contains 81% of the energy that goes into producing it.)

Hill et al. (2006) use a life-cycle analysis model to estimate that ethanol yields 25% more energy than the energy that goes into producing it. They also find that ethanol results in 12% less GHG emissions production than gasoline. find that ethanol from corn production is less petroleum intensive than gasoline, but that GHG emissions from corn ethanol production are similar to the use of gasoline. In other words, though ethanol may lessen dependence on foreign oil, a major American concern, it is unlikely to provide GHG emission reductions.

In another meta-analysis that normalized and standardized the analysis from 10 different papers, Hammerschlag found that the energy return on investment in ethanol is positive. Hammerschlag defines the Energy return on investment in ethanol ($r_E$) as the total product energy divided by the nonrenewable energy input into its manufacture. With a value of $r_E$ greater than 1 implying that ethanol production has captured at least some renewable and a value of $r_E$ greater than 0.76 indicating that ethanol consumes less nonrenewable energy in its manufacture than gasoline. The results imply that corn ethanol has a $0.84 < r_E < 1.65$.

Hammerschlag and Farrell et al., among many others, show that the main barrier for corn ethanol is that as it expands, it will have to move to less productive land, where its problems will multiply. This again raises the question of land use change from emissions, and none of the aforementioned studies assesses this satisfactorily.

In 2008, however, a new study by Searchinger et al. used a worldwide agricultural model to estimate emissions from land-use change, and found that “corn-based ethanol, instead of producing a 20% savings, nearly doubles greenhouse emissions over 30 years and increases greenhouse gases for 167 years.”

Finally, the widely-used Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET) model was developed in 1995 by the Argonne National Laboratory with support from the US Department of Energy. GREET is a very extensive and complex model, with “more than 85 transportation fuel pathways. Among them, four are fuel ethanol pathways (corn dry mill ethanol, corn wet mill ethanol, woody cellulosic ethanol, and herbaceous cellulosic ethanol).” GREET’s website states: “To fully evaluate energy and emission impacts of advanced vehicle technologies and new transportation fuels, the fuel cycle from wells to wheels and
the vehicle cycle through material recovery and vehicle disposal need to be considered.”[4]

Wang[12] states that GREET’s analysis “concludes that corn-based ethanol achieves energy and GHG emission reduction benefits, relative to gasoline. This is mainly because of 1) improved corn productivity in U.S. corn farms in the past 30 years; 2) reduced energy use in ethanol plants in the past 15 years; and 3) appropriately addressing of ethanol’s co-products.”

Previous GREET studies conducted by[12] have also reached similar results, though their methodology and specifications varied. Finally, Marko Delucchi’s LEM[13] finds that American corn ethanol emissions impact ranges between -25% to +20% compared to gasoline. Delucchi interprets these findings as suggesting that corn ethanol does not offer real gains in emissions and efficiency.

**Biodiesel**

Fewer LCA studies have been conducted on biodiesel than on ethanol. The disparity in results and methodologies is even larger than that amongst corn ethanol studies, and it makes comparing the results difficult. Hill et al. (2006) use a life-cycle analysis model to estimate that biodiesel yields 93% more energy than the energy that goes into producing it. They also find that biodiesel results in 41% less GHG emissions production than diesel. The GREET model, however, finds that biodiesel from Soy results in reduction in GHG emissions of 40% to 80%. Marko Delucchi’s LEM finds that biodiesel from soy emissions impact ranges between -20% to +50% compared to gasoline.

An important issue with the production of biodiesel is the impact that is caused by the application of Nitrogen compounds, mainly from fertilizers. This is a more serious issue with biodiesel crops than with ethanol crops, as[14] illustrates. Crutzen et al. (2007) account for the impact of N$_2$O and find that this can more than account for any carbon savings biodiesel might have had.

Reijneders and Huijbregts find that South Asian palm oil used as a biofuel will result in large emissions of CO2-equivalent emissions. They estimate that the “losses of biogenic carbon associated with ecosystems, emission of CO2 due to the use of fossil fuels and the anaerobic conversion of palm oil mill effluent currently correspond in South Asia with an emission of about 2.8-19.7 kg CO$_2$ equivalent per kg of palm oil. They attribute the large variability in their results to the wide range of plausible assumptions that one can utilize in the estimates of the calculation.

**Cellulosic Ethanol**

There currently is no commercial production of ethanol from cellulosic feedstocks. The technology for producing cellulosic ethanol is not yet commercially viable. This section presents an overview of the state of the art in research on cellulosic ethanol, and outline the expectation of cellulosic ethanol production.

According to the Department of Energy[15]:

> Cellulose-based ethanol is derived from the fibrous, generally inedible portions of plant matter (biomass) and offers a renewable, sustainable, and expandable resource to meet the growing
demand for transportation fuel. It can be used in today’s vehicles and distributed through the existing transportation-fuel infrastructure with only modest modifications. Additionally, the amount of carbon dioxide emitted to the atmosphere from producing and burning ethanol is far less than that released from gasoline.

The Department of Energy expresses what is the prevailing conventional wisdom on this topic: “Although most of the ethanol produced today is derived from corn grain, dramatic increases in the availability of ethanol are expected through increases in quantity and decreases in cost of ethanol from biomass. Corn-based ethanol is helping the new cellulosic ethanol industry by providing technology improvements, infrastructure, and demand. Both corn and cellulosic-based ethanol are likely to assist each other’s growth.” Former US Secretary of Energy Samuel Bodman has announced that it is the goal of the US government to displace 30% of gasoline consumption by 2030 with ethanol. Such a target would entail the production of 60 billion gallons of ethanol.

Writing in Science, Tilman et al. argue that low-input high-diversity grassland perennials “can provide more usable energy, greater greenhouse gas reductions, and less agrichemical pollution per hectare than can corn grain ethanol or soybean biodiesel.” They further calculate that low-input high-diversity biomass could produce the equivalent of “13% of global petroleum consumption for transportation and 19% of global electricity consumption. Without accounting for ecosystem CO2 sequestration, this could eliminate 15% of current global CO2 emissions.”

In a report for the Department of Energy and Department of Agriculture, Perlack et al. attempt to analyze whether the United States could produce enough biomass to meet the 30% target called for by Congress. The authors suggest that meeting this goal would require 1 billion tons of dry biomass feedstock each year, which they believe could be sustainably produced in the United States each year only from forestland and agricultural land. They insist that this is not a higher ceiling, but a scenario based on reasonable assumptions.

Girouard et al. carry out a study of short-rotation forestry willow and switchgrass. The study carries out simulations of planting, production and processing of these two crops under different scenarios and attempts to measure the environmental and energy balance of these production processes, as well. The study finds that both crops can yield net sequestration of carbon in the conditions in which they test them; they also find that willow is more efficient in carbon sequestering than switchgrass, and that it can produce more energy per unit of fossil fuel input (30:1 ratio for willow; 20:1 for switchgrass). They did find, however, that switchgrass is cheaper to grow than willow.

Farrel et al., in the same study cited above, using the Energy Resource Group Biofuels Analysis Meta-Model, also attempt an analysis of cellulosic ethanol efficiency. They begin with the disclaimer that the case they present is a “preliminary estimate of a rapidly evolving technology and is designed to highlight the dramatic reductions in GHG emissions that could be achieved” (p.507). They find that cellulosic ethanol is likely to generate significant reductions in GHG emissions, as well as large reductions in fossil fuel use. They find that every MJ of energy requires cellulosic uses 0.08 as much gasoline as would getting that same energy from gasoline. They also find that it produces around a tenth of the GHG emissions of gasoline.

Wang using the GREET model discussed above and finds that cellulosic ethanol reduces GHG emissions by 85% relative to gasoline. Using various estimates of switchgrass yields in 2025 and 2050 by Greene (2005) along with the estimates from Wang of GHG reductions, Larson arrives at the conclusion that cellulosic would offer significant reductions in gasoline consumption as well as GHG emissions. Delucchi’s LEM finds that cellulosic ethanol would cause reductions in greenhouse gas emissions by between 40% and 80%.

On the other hand, several studies find that cellulosic ethanol would not offer improved environmental
performance. Searchinger et al.\textsuperscript{18} after accounting for land use change impacts, find that biofuels from switchgrass, if grown on U.S. corn lands, increase emissions by 50%. Pimentel and Patzek\textsuperscript{19} similarly find increased emissions from the utilization of cellulosic ethanol.

**Conclusion**

The only solid conclusion from the current LCA literature is that there is no consensus on the answers to the questions of biofuel efficiency in corn ethanol, biodiesel or cellulosic ethanol. There is no conclusive evidence to suggest that these fuels, if utilized heavily, can reduce carbon emissions. For cellulosic, there is no solid evidence to even suggest that it might be produced commercially soon, if ever.

Biofuels policies were designed to increase biofuels use in order to reduce greenhouse gas emissions. However, since there is no solid evidence to suggest that increased biofuels use will actually meet these goals, serious doubt is cast on the efficacy of these policies and on the entire premise of using biofuels-promoting policies as tools in the fight against global warming and finding new energy sources.

The following chapter will discuss the methodological limitations of LCA’s in more detail and emphasize the nature of the ignorance of the efficiency of these fuels, and why their results cannot be viewed as scientifically determinate.

**Identifying the problems of life-cycle analysis**

Extensive debates surrounding the numerous variables, measurements, factors and technical specifications have been raised within the LCA literature discussed above and the wider literature. In order to illustrate the problems with these studies, I will select some of the most widely-cited review studies and mention their most significant explanations for the variations in the results. I conclude with the work of Delucchi\textsuperscript{13}, regarded as the most comprehensive and systematic treatment of the topic, along with Kammen et al.\textsuperscript{8}

**Co-products as an illustrative example of problems with LCA’s**

As a guide to understanding the problems of LCA’s, it is useful to begin by examining the complexity of debate surrounding one particular sticking point: allocation of biofuel co-product credit. Co-products are all products that emerge from the process of biofuels production other than the biofuel itself. These can have various useful applications, including cow-feed (corn ethanol co-products) and stationary energy (bagasse—sugarcane ethanol’s by-product). The treatment of co-products is by no means the biggest sticking point in LCA’s, nor is it the most methodologically intractable. It is, however, illustrative of the intractable problems facing LCA’s.

Pimentel & Patzek\textsuperscript{19} did not include co-products in their LCA’s and found that ethanol is inefficient, Wang\textsuperscript{12} included them and found that ethanol is efficient. Wang argued that since the co-products of ethanol production can be used as cow feed, one must then credit ethanol production with the carbon saved from the averted production of cowfeed. In turn, Pimentel & Patzek\textsuperscript{20} responded by pointing out that the quantities of cowfeed produced from ethanol exceed the quantities of cowfeed consumed in America, making it absurd to consider that they would “replace” any production processes.

More recently, Farrell et al.\textsuperscript{9} analyzed “six representative analyses of fuel ethanol” and argued in a widely cited Science paper that the studies that found negative net energy for biofuels “incorrectly ignored coproducts and
used some obsolete data.” Quirin et al. examine the issue and find that co-production credit ranges very widely within the literature, from 15% to 95% of emissions. This is reflected in the wide range of the results of these studies, which range from concluding that ethanol offers no emissions advantages compared to fossil fuels, to finding that it offers as much as a fourfold advantage.

In surveying the literature, Larson finds that there are six methods for allocating co-production credits. He lists these as:

- No allocation: Under this method, co-products are simply not counted as relevant in the LCA calculation, and their emissions and energy content is ignored. Larson cites Woods and Bauen as following this method.
- The weight of co-products
- The intrinsic energy content
- How much of the total process energy their co-production is deemed to consume
- The market value of co-products
- The energy displaced when the co-products substitute for products that would have been made by conventional routes and would have been used had the bio-based co-products not displaced them.

Larson provides evidence of how the results of an LCA would be skewed by adopting one of these methods versus the other. This raises the question of which is the correct way of calculating co-product credit. It cannot be (1) because these co-products can be made useful, can contain energy that can be used in the process and can be sold as cow-feed. Thus, an accurate measure of the energy or carbon balance of the process should take these into account. So a correct accounting for LCA’s must include co-product credit. But it cannot be (2), (3) or (4) either, because these assume that all co-products will be utilized and all their energy and carbon content will be useful. But since that is not the case, this is also incorrect accounting. (5) offers a more realistic estimate, since it will take into account what actually happens to the co-product on the market, but it is also insufficient, because it ignores that the market is dynamic and what happens with these co-products will itself affect the prices that they can fetch on the market. Further, accounting for the price alone will affect the financial calculation of the lifecycle, but not the calculation of energy and emissions. A more accurate accounting must include the effects that this production will have on other markets, other production processes and other commodities, calculating the changes in emissions and energy achieved there. Therefore, (6) comes closest to being the accurate way of assessing energy and emissions changes.
What (6) effectively measures, however, is the dynamic impact on the market of the production of ethanol and its co-products. Though it would be far easier to treat all inputs and outputs as lump sums of materials with well-defined prices, the reality is different. Consumption and production of new materials will affect their availability on the market and their prices, and influence other people’s choices of what to consume and use. These will all carry energy and emission implications.

In order to assess this accurately, we would need to integrate the LCA with a dynamic economic general equilibrium model that traces the impact of the production across the economy. This requires an accurate general equilibrium model of the economy, where all the co-products consumed are calculated, and all the displaced products they replace are accounted for, and the difference in emissions and carbon is calculated.

The rationale here is: if a correct accounting of the changes brought about by ethanol production is to be performed, this must account for all the changes that occur to energy consumption and all the changes to carbon emissions caused by this production. An LCA cannot just count the impact of the effects that are easily measured, it must include everything to be comprehensive. And in order to include everything, all impacts on all production and consumption of co-products must be accounted for. And for that, only a comprehensive economic model that measures the amount of co-products utilized, as well as what they are replacing, will suffice. No existing LCA study has been integrated with such an accurate and general economic model.

But the issue of co-products raises further questions about other aspects of the lifecycle assessment. What applies to co-products must apply to all inputs and outputs to the production of ethanol. When an ethanol plant consumes corn, this is corn that was taken away from food consumption and into ethanol production. This will have a ripple effect on corn markets: prices would rise, and this in turn will lead to other effects on production and consumption, each with its own impacts on the economy. These are referred to in the literature as ‘knock-on effects’. Some corn producers will increase their production, producers of other corn crops will shift to corn production, and marginal land will then be transformed to corn farms. All of these processes will consume energy and produce emissions. An accurate LCA must account for all of these effects. The same will hold true not just for all other inputs into the production process, from fertilizers to equipment to infrastructure. The implication here is clear: an LCA must be situated within a comprehensive general economic model in order to be able to assess emissions and energy effects.

This conclusion is affirmed in almost every LCA paper written. Even as scholars publish studies with precise estimates of biofuel energy and emissions efficiency, they nonetheless acknowledge the countervailing fact that their model is not comprehensive, and that only a comprehensive model could answer these questions.

Farrell et al.9 emphasize that in order for a study to be able to understand the effects of biofuel use “the entire lifecycle must be considered, including the manufacture of inputs (e.g. fertilizer), crop production, transportation of feedstock from farm to production facilities, and then biofuel production, distribution, and use.” Similarly, Wang22 also emphasizes the need to take account of all knock-on effects when modeling impacts, arguing: “Researchers must use general equilibrium models that take into account the supply and demand of agricultural commodities, land use patterns, and land availability (all at the global scale), among many other factors … At this time, it is not clear what land use changes could occur globally as a result of U.S. corn ethanol production.”

Sources of variation within the LCA literature

In their comprehensive review of LCA studies, Quirin et al.21 survey 800 studies, 63 of which they find to fit their criteria of detailed analyses, giving them 109 energy and CO2 balances of biofuels. They find widely
varying results in their survey. Quirin et al. attribute the variance in the findings to four main differences in assumptions. (1) The difference in data basis, such as different studies using widely varying estimates of the use of fertilizer, and the energy that goes into making the fertilizers. (2) The difference in crop yields, which vary by study and are location dependent. (3) The differences in process technology. (4) The assessment of co-products.

In his overview of LCA studies, Larson notes that one of the main “striking features” of these LCA studies is the wide range of results. Larson argues: “one may conclude that there can be a number of “right” answers to the questions of how much GHGs and fossil energy can be saved through use of biofuels. It would appear to be difficult to draw unequivocal conclusions regarding the precise quantitative energy and environmental benefits (or costs) of any particular biofuels pathway without detailed case-specific information and analysis.” He identifies four key factors for the uncertainties and differences in results between these studies: (1) The inclusion of climate-active species, (2) the analysis of N$_2$O emissions and other emissions, (3) allocation of co-product credits, and (4) soil carbon sequestration.

But the most systematic and comprehensive overview comes from Delucchi and Kammen, which built extensively on Delucchi’s work. Delucchi argues that “[t]oday, most LCAs of transportation and global climate are not appreciably different in general method from the analyses done in the early 1990s. And although different analysts have made different assumptions and used slightly different specific estimation methods, and as a result have come up with different answers, few have questioned the validity of the general method that has been handed down to them.” Delucchi identifies the major areas of uncertainty, disagreement and incompleteness in the existing literature as “treatment of lifecycle assessment within a dynamic economic-equilibrium framework; major issues concerning energy use and emission factors; and incorporation of the lifecycle of infrastructure and materials representation of changes in land use; treatment of market impacts of co-products; development of CO2 equivalency factors for all compounds; detailed representation of the nitrogen cycle and its impacts.”

Delucchi posits four main differences between the ideal model and the conventional LCA: prices; policies; the consumption of energy and materials and use of land; and the treatment of other emissions and the climate system. I will briefly discuss each of these issues, though the reader is referred to Delucchi’s work for a more thorough treatment.

i) Policy: Delucchi finds that most LCA’s do not look at policy decisions and analyze them, but instead seem to analyze two sets of activities defined as the “biofuels cycle” versus the “gasoline cycle” and evaluate their impacts. This is flawed because it is impossible to imagine that these two sets of activities can be replaced in a straightforward way that has no impact on anything else—rather, there will be far-reaching effects on prices, consumption and production worldwide. These effects will in turn have significantly different energy and environmental impacts, which cannot be ignored. The method of looking at fuel cycles does not take this into account and is therefore not reliable.

Delucchi argues that LCA’s should instead focus on analyzing the effect of specific policies pertaining to biofuels on emissions and costs. By framing the question that way, LCA studies can analyze specific policies, their impacts and their knock-on effects and compare them to alternative policy options and scenarios. This is a more relevant answer to real world concerns, where we do not face a choice between extreme stylized cases of two different energy cycles of different fuels, but rather, between changes at the margin of current patterns of consumption. Framing the question in this way allows the answer to be applicable to the situation at hand. It is also more useful for policy-makers, because they need to make practical choices between policy alternatives that can be directly assessed.

ii) Production and consumption of energy and materials, and use of land: Delucchi argues that “there remain serious concerns and oversimplifications” in the accounting of the energy use and material and
infrastructure part of LCA models. Perhaps even more significantly, the important question of land use changes is either ignored or treated very simplistically. The change in the use of land results in changes in emissions in several regards: changing the living matter on the land leads to a direct change in the carbon content, releasing/absorbing carbon into/from the atmosphere. Further changes in land use result in changes in many “physical parameters, such as albedo (reflectivity), evapotranspiration, and fluxes of sensible and latent heat”.

**iii) Prices:** Any environmental, food or energy changes will invariably affect prices in significant ways that will carry with them significant repercussions on consumption and production decisions of others. A move from using one fuel to another will inevitably cause price changes in both fuels and in its substitutes and compliments. When one fuel is substituted for another, we cannot assume that the quantities of production will be altered in precisely the same numbers. A drop in the consumption in one fuel will result in a drop in its price, which will in turn lead to an increase in its consumption in other places, and vice-versa. This is the point that was illustrated by the earlier discussion of co-products.

The traditional LCA model, by failing to account for this, becomes woefully lacking. Delucchi thus concludes that in order to be able to estimate a useful LCA, one must integrate the physical and lifecycle aspects of it with a dynamic general equilibrium model. Kammen *et al.* arrive at a similar conclusion on the effect of prices, concluding: “Ideally, one would use an economic model to determine the effect of coproducts on their markets and the extent to which co-products displace other production. No LCA has such an economic model built into it, although LEM does have a single parameter that is meant to account for these market-mediated impacts of co-products.”

**iv) Other emissions and the climate systems:** Delucchi raises the important point (ignored in most LCA’s) that the parameter of concern is not so much emissions of CO2, but the general effect emissions have on the climate system. This makes it important to look into GHG’s other than CO2 and assess their impact on the atmosphere, as well as looking into other sources of GHG’s. This also means that an LCA will need a comprehensive estimation of emission factors, which will quantify the impact of different gases on the atmosphere, as well as their impact on each other.

**Conclusion**

This paper provided an overview of the literature on Lifecycle Assessment of biofuels, attempting to summarize the environmental and economic impact of these fuels. The only conclusive answer obtained from that overview is that there are no conclusive answer to these questions, since the papers are not specified in a way that can give actionable and policy-relevant answers. An LCA study that is relevant to policy-makers would have to resort to agent-based modeling of specific policies and government actions, rather than aggregate modeling, and it would need to be integrated into an economic model that takes account of price effects. Further, such a study needs to go beyond the fixation on emission quantities and to focus instead on the environmental impact of the emissions. Finally, this study needs to take into account the energy and land changes involved in the manufacturing of materials and feedstocks. Another paper in this issue of the journal considers in detail the complexity of these requirements for a comprehensive and actionable LCA, and uses insight from complexity theory and economic theory to understand why biofuel LCAs fail to arrive at actionable conclusions.

**Footnotes**

1 United States Energy Information Administration website: EIA.gov.
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