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Energy Systems and the Knowledge Problem: The Case of Biofuels

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Abstract:

Discussions of energy and global warming policy presume that the energy mix is a system that can be engineered in order to achieve desired environmental, economic and social goals. This paper argues that such a conception can be misleading and counter-productive. Drawing on FA Hayek's conception of the knowledge problem, and Vernon Smith's ideas on rationality in economics, this paper argues that it is more accurate to understand the energy mix as a spontaneously emergent order that is the product of human action, not human design. The complexity of energy systems, the subjectivist nature of the human actions determining the outcome of these systems, and the unknowability of technological innovation mean that attempts at designing the energy mix, mandating targets for specific energy sources, or subsidizing specific energy sources are misguided and can be counter-productive.

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I. CONTEXT

Recently, two global phenomena have sparked a rise in interest in biofuels. The first is the rise of oil prices to recent 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 (UNEP, 2009). 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 (Ammous, 2011) 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 (De Santi et al, 2008). 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]

1 United States Energy Information Administration website: EIA.gov.
2 Renewable Fuels Association website: EthanolRFA.org

The history of the development of the ethanol industry is the history of legislation supporting the ethanol industry. The International Institute for Sustainable Development (2013) 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 (2007) 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.

II. LIFECYCLE ANALYSIS

The policy goal that is most relevant for the purposes 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 (2007) 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." (Union of Concerned Scientists, 2007. P1)

On specific biofuels, the conventional wisdom and the majority opinion amongst the experts, public, and policy-makers 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 Analysis. Kammen et al (2007) 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 (2007) 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 (2007), 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.

a. American 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.[3] 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, Farrell et al (2006) 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.

3 See Pimentel (2003), Patzek (2004), Pimentel and Patzek (2005, 2005a), Pimentel, Patzek and Cicel (2007)

Among the lead researchers on the "opposite side" of this debate are Michael Wang, Hossein Shappouri and Norman Brinkman. Brinkman et al (2005) 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. Farrell et al (2006) 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 (2006) 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 (2006) and Farrell et al (2006), 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 (Wang, 2005). 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)." (Wang, 2005). 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 (2005) 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 Wang (2005) have also reached similar results, though their methodology and specifications varied. Finally, Marko Delucchi's LEM (2004, discussed below) 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.

b. <u>Biodiesel</u>

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 Delucchi (2006) illustrates. Crutzen et al (2007) account for the impact of N_2O 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.

4 Accessed on https://greet.es.anl.gov/main

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.

c. <u>Cellulosic Ethanol</u>

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 (2006, P1):

> "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 (2006, P1) 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 (2006) 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 (1999) 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 (2006), 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 (2005), 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 (2005) of GHG reductions, Larson (2005) arrives at the conclusion that cellulosic would offer significant reductions in gasoline consumption as well as GHG emissions. Delucchi's LEM (2004) 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 (2008), 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 (2005) similarly find increased emissions from the utilization of cellulosic ethanol.

d. 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 sugarcane ethanol, 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.

III. 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 (2004), regarded as the most comprehensive and systematic treatment of the topic, along with Kammen et al (2007). From this discussion this study then moves on to provide some theoretical background on these issues from economics and philosophy of science literature.

a. 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.

Pimintel & Patzek (2005) did not include co-products in their LCA's and found that ethanol is inefficient, Wang (2005) 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 (2007) 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 (2006) 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 (2004) 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 (2005) finds that there are six methods for allocating co-production credits. He lists these as:

1. 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.
2. The weight of co-products
3. The intrinsic energy content
4. How much of the total process energy their co-production is deemed to consume
5. The market value of co-products
6. 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 analysis. 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 (2006) 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, Wang (2008) 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."

b. ***Sources of variation within the LCA literature***

In their comprehensive review of LCA studies, Quirin et al (2004) 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_2O 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 (2004) and Kammen et al (2007), 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 (2004) identifies the major areas of uncertainty, disagreement and incompleteness in the existing literature as "treatment of lifecycle analyses 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) **<u>Policy:</u>** 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) **<u>production and consumption of energy and materials, and use of land</u>**: 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." (Kammen et al, 2007).

iii) **<u>Prices</u>**: 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

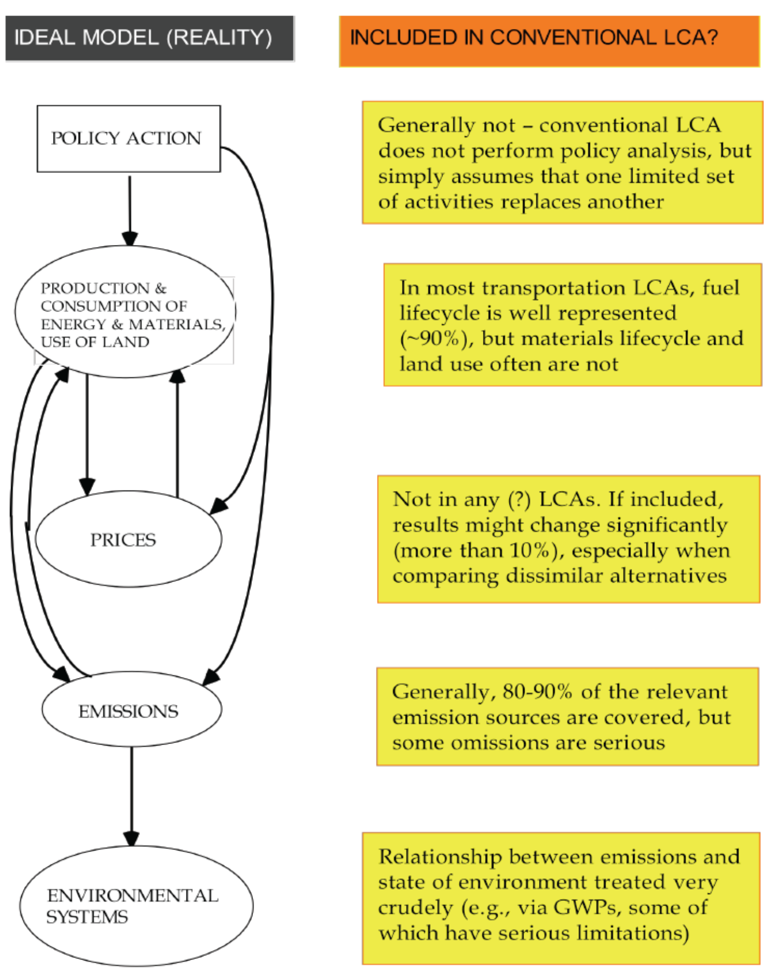

Figure 3. Ideal versus conventional LCA

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.

Delucchi summarizes the differences between his proposed model and the traditional approach in figure 1. After his extensive critique of old LCA's, and outlining of the traits of a better LCA, Delucchi (2004, p.18) concludes:

> *"lifecycle models must be designed to address clear and realistic questions. In the case of lifecycle analysis comparing the energy and environmental impacts of different transportation fuels and vehicles, the questions must be of the sort: "what would happen to [some measure of energy use or emissions] if somebody did X instead of Y," where – and here is the key – X and Y are specific and realistic alternative courses of actions. These alternative courses of actions ("actions," for short) may be related to public policies, or to private-sector market decisions, or to both. Then, the lifecycle model must be able to properly trace out all of the differences – political, economic, technological -- between the world with X and the world with Y. Identifying and representing all of the differences between two worlds is far more complex than simply representing the replacement of one narrowly defined set of engineering activities with another."*

IV. EXPLAINING THE PROBLEMS OF LIFE-CYCLE ANALYSIS

The previous sections illustrated the shortcomings of LCA's, and how such a large number of studies have failed to arrive at consensus on a seemingly simple question. This section draws on insights from economics and philosophy to explain why these studies fail to reach consensus. These insights are divided into five broad categories.

a. Complexity and Predictability:

The first problem LCA's encounter is that of irreducible complexity, which is hard to systemize and reduce for straightforward analysis. Under this broad heading we can list Quirin's points about the differing energy quantities that go into making fertilizers, the difference in crop yields, and the allocation of co-products as well as Larson's points about the inclusion of climate-active species, other emissions, co-products and soil-sequestration. This also includes Deluchchi's points about the consumption and production of energy and materials, land use change and other emissions. All these critiques have the same essence: LCA's analyze complex phenomena but and do not account for all the factors that matter in them.

Warren Weaver (1961) in his discussion of the evolution of scientific understanding of complex phenomena begins by defining complex phenomena and how science treats them. Weaver (1961, P57) argues that before the Twentieth Century, physical science's greatest advances and most momentous contributions to human welfare came from applying the scientific method to studying questions that involved only two (or only a few) variables. Relatively straightforward theories and experiments were sufficient to establish scientific rules which then became very important for human knowledge and society. Enormous gains from science and technology ensued from applying the scientific method to these laws and rules. Weaver then explains that the twentieth century presented an attempt to apply the methods of science studying a few variables to studying many more variables—studying complexity. He draws the distinction here between two types of complexity: disorganized complexity and organized complexity. Weaver (1961, p.58) defines disorganized complexity as:

> *"a problem in which the number of variables is very large, and one in which each of the many variables has a behavior which is individually erratic, and may be totally unknown. But in spite of this helter-skelter or unknown behavior of all the individual variables, the system as a whole possesses certain orderly and analyzable average properties."*

As examples of this type of complexity he cites a telephone exchange predicting the average frequency of calls, or an insurance company attempting to assess death rates. The key feature of disorganized complexity can be seen to be the lack of complex interrelations between the multiplicity of variables. Weaver argues that organized complexity is amenable to investigation by statistical and mathematical techniques. Because there are no complex interrelations between the variables, the totality of the variables can be assessed using statistical and mathematical techniques.

Organized complexity, on the other hand, is not amenable to easy analysis with mathematical and analytical techniques. The distinction, Weaver insists, is not in the number of factors or variables, but rather in the existence of complex interrelations between the multiplicity of factors. "They are all problems which involve dealing simultaneously with a sizable number of factors which are interrelated into an organic whole" (Weaver, 1961, p.58). These complex interrelations make trying to study the complex systems difficult because one cannot reduce the complexity away.

This distinction between "organized" and "disorganized" complexity is similar to the distinction between the concepts of *Extremistan* and *Mediocristan*, presented by Taleb in *The Black Swan*. Taleb defines *Mediocristan* problems as being scalable problems, where a large sample cannot be altered significantly by the introduction of a single observation, no matter how large or small it is relative to the others. These scalable problems are ones where the range of variation of the variables is not wide enough for one observation to skew the total results. Examples of distributions that are from *Mediocristan* include height, weight, calorie consumption, car accidents, mortality rates (Taleb, 2007, p.35).

Extremistan, on the other hand refers to situations where one extreme observation can disproportionately impact the aggregate or mean. In these distributions, the value of one observation can be so high or low compared to the rest that it could completely alter the final result. Taleb provides the example of the wealth of a group that includes Bill Gates. The mere introduction of Gates, even to a very large group of a thousand people, would completely change the metrics for the group, since Gates would account for 99.9% of the wealth of the entire group. Further examples include: book sales, number of references on Google, populations of cities, financial markets, and inflation rates (Taleb, 2007, p.35).

FAO Hayek (1967, p.3) illustrates this point by demonstrating the difference between physics and other fields of inquiry.

> *"More particularly, what we regard as the field of physics may well be the totality of phenomena where the number of significantly connected variables of different kinds is sufficiently small to enable us to study them as if they formed a closed system for which we can observe and control all the determining factors; and we may have been led to treat certain phenomena as lying outside physics precisely because this is not the case. If this were true it would certainly be paradoxical to try to force methods made possible by these special conditions on disciplines regarded as distinct because in their field these conditions do not prevail."*

For Hayek, it is the simplicity of the questions that physics tackles that makes these questions suitable for the methods of physics. Questions which do not exhibit this simplicity are, according to Hayek, unsuitable to be examined using the tools of physics. In agreement with, and elaboration on, Weaver, Hayek defines the complexity of systems to be dependent on "the minimum number of elements of which an instance of the pattern must consist in order to exhibit all the characteristic attributes of the class of pattern in question." (Hayek, 1967, p.25) As we move from simple physical inanimate systems that are amenable to investigation by physics' methods, we progressively witness increasing degrees of organized complexity, and increasing numbers of irreducible relationships that cannot be abstracted away in any attempt to study or manage the system.

Here, it is useful to turn to the more recent literature on Complexity Studies, which provides a useful insight into the issue of reductionism. Tamas Vicsek (2002, p.131) argues:

> *"Although it might sometimes not matter that details such as the motions of the billions of atoms dancing inside the sphere's material are ignored, in other cases reductionism may lead to incorrect conclusions. In complex systems, we accept that processes that occur simultaneously on different scales or levels are important, and the intricate behaviour of the whole system depends on its units in a nontrivial way. Here, the description of the entire system's behaviour requires a qualitatively new theory, because the laws that describe its behaviour are qualitatively different from those that govern its individual units."*

As these interrelations increase, the investigation of the systems then must be able to account for all of them in order to accurately study the system. One will need all the data that is relevant to the question to be included in the analysis. As we move towards investigating complex social and economic systems, we are faced with two main problems that make such studies difficult. The first problem is the lack of data. A lot of the important relations in complex systems do not have adequate data measuring them—though this could in some instances be remedied with better data collection, the real problem remains when one remembers that a lot of the data needed is simply unquantifiable and immeasurable. The second problem is the proliferation and unknowability of the real relations governing such complex phenomena. With many interrelated factors and variables, it can be impossible to determine what the actual relations between different variables are, and how they influence each other. Modeling these relations accurately is not possible unless one can know them precisely.

This understanding of complexity problems illuminates the disagreements in the LCA literature and why the results in them are so varied. In the quest to find the environmental effect of biofuels utilization, studies are unable to define all the factors that matter for biofuels production, or to specify all the interrelations that tie these factors together. Different studies choose to emphasize different factors and interrelations, and as a result different results emerge. None of these studies has come close to including *all* the factors and interrelations that matter, for such a task is impossible given the infinite number of transactions, agents, and knock-on effects involved. Further, the measurement of these factors and their interrelations continues to be dogged by uncertainty. In short, different studies arrive at starkly different results because they define different factors as being important, define their interrelations differently, and measured them differently.

Hayek identified the problems of LCA's in his analysis of the shortcomings of applying the methodology of science to social phenomena (Hayek, 1973, :

> *This brings me to the crucial issue. Unlike the position that exists in the physical sciences, in economics and other disciplines that deal with essentially complex phenomena, the aspects of the events to be accounted for about which we can get quantitative data are necessarily limited and may not include the important ones. While in the physical sciences it is generally assumed, probably with good reason, that any important factor which determines the observed events will itself be directly observable and measurable, in the study of such complex phenomena as the market, which depend on the actions of many individuals, all the circumstances which will determine the outcome of a process, for reasons which I shall explain later, will hardly ever be fully known or measurable. And while in the physical sciences the investigator will be able to measure what, on the basis of a prima facie theory, he thinks important, in the social sciences often that is treated as important which happens to be accessible to measurement. This is sometimes carried to the point where it is demanded that our theories must be formulated in such terms that they refer only to measurable magnitudes.*

b. Dynamic Economic Analysis and Prices

As discussed above, Deluchi's point about the need to take account of the effect of prices necessitates a comprehensive analysis of the dynamic economic impacts of different policies. Static and partial-equilibrium analysis will not suffice in a large complex system which includes significant knock-on effects to actions. As LCA authors agree, there is a need for LCA's to calculate the impacts of economic actions across the economy. An understanding of the dynamics of an economy is instructive to understanding this type of problem. To do so, we turn to an analysis of the coordinating mechanism of a market economy: the price mechanism.

The price mechanism is the naturally emergent way of coordinating exchange. The scarcity and abundance of different goods is reflected in their relative prices to one another. The price emerges to coordinate the production and consumption of all goods relative to one another. The price mechanism is the answer to the economic calculation problem faced by individuals and societies, as explained by the Austrian economists.

Ludwig von Mises states three main virtues for the price mechanism. Firstly, it allows for the valuation of all individuals taking part in trade is used for calculation. It allows people to compare the profitability of their methods of production to those of others. And thirdly, use of money prices allows values to be reduced to a common unit (Kirzner, 1988, p.12).

In *Economic Calculation in the Socialist Commonwealth*, Mises emphasizes the importance of private property rights to economic calculation. Mises states: "Who is to do the consuming and what is to be consumed by each is the crux of the problem of socialist distribution." (Mises, 1920, p.4) Dispersed calculation allows each individual to measure the factors relevant to them and make decisions based upon it. Centralized calculation, however, needs to take into account the totality of all relevant factors, and will naturally be unable to determine which of them matter to which individual. The problem is magnified when one considers decisions concerning higher order goods, or capital.

> *"Moreover, the mind of one man alone—be it ever so cunning, is too weak to grasp the importance of any single one among the countlessly many goods of a higher order. No single man can ever master all the possibilities of production, innumerable as they are, as to be in a position to make straightway evident judgments of value without the aid of some system of computation."* (Mises, 1920, p.12)

Only through monetary calculation carried out by individuals owning their own capital can production decisions be successful and a complex economic system function. It will be useful to refer to economic calculation carried out by individuals for the use of their private property as *situated calculation*, to differentiate it from centralized calculation. Mises adds:

> *"It is an illusion to imagine that in a socialist state calculation in natura can take the place of monetary calculation. Calculation in natura, in an economy without exchange, can embrace consumption goods only; it completely fails when it comes to dealing with goods of a higher order. And as soon as one gives up the conception of a freely established monetary price for goods of a higher order, rational production becomes completely impossible. Every step that takes us away from private ownership of the means of production and from the use of money also takes us away from rational economics."* (Mises, 1920, p.13)

While Mises in the 1920's emphasized the essential nature of situated calculation for the functioning of a market economy, Hayek in the 1930's moved on to discuss the importance of the price mechanism for coordinating dispersed knowledge that is not available to any central party. Hayek writes in *The Use of Knowledge in Society* (1945, p.520):

> *"The economic problem of society is thus not merely a problem of how to allocate "given" resources—if "given" is taken to mean given to a single mind which deliberately solves the problem set by these "data." It is rather a problem of how to secure the best use of resources known to any of the members of society, for ends whose relative importance only these individuals know. Or, to put it briefly, it is a problem of the utilization of knowledge which is not given to anyone in its totality."*

Prices are the way that signals and information about products and markets are communicated from an individual to another, and in the process, decentralized decision-making is coordinated among all the dispersed individuals and their dispersed knowledge. Kirzner, building on the work of Mises and Hayek, emphasizes another important role for prices in stimulating entrepreneurial discoveries, arguing that "prices emerge in an open-ended context in which entrepreneurs must grapple with true Knightian uncertainty" (Kirzner, 1988, p.15). This uncertainty is itself the stimulus for the discovery of new processes. Kirzner quote Lavoie that the entrepreneur "does not treat prices as parameters out of his control but, on the contrary, represents the very causal force that moves prices in coordinating directions." (Kirzner, 1988, p.15).

The central planner thus faces four intractable problems: He is not able to aggregate all the information from all the producers and consumers in order to find the 'correct' allocation. This problem is prohibitively complex. No central statistical board could accumulate all the correct information needed to make allocation decisions. The market for any product is very large and exhibits disorganized complexity. There are countless relations between different factors, variables and actors. These interrelations cannot be understood completely and laid out clearly from any central viewpoint. The complexity of this system makes central calculation very hard.

But beyond the complexity of the market or social order, the other problem is that the knowledge of each small pocket within the complex social order is dispersed, and situated with the actor in their respective locations within the complex structure. The knowledge of production and consumption conditions is very dispersed and cannot be accumulated by a single mind. Instead, every individual in the market possesses a small fragment of knowledge: that which is related to them. This is Hayek's knowledge problem.

Thirdly, and related to the dispersed knowledge problem, is the problem of the subjectivism of the preferences and decisions of individuals in the market system. Even if a central planner were to realize all the information needed to perform the calculations, the central planner cannot ascertain the subjective preferences of individuals who are all unique in their preferences of consumption and production. Fourthly, the central planner needs to also somehow internalize in their decision-making the entrepreneurial activities that have not yet been undertaken by others, and attempt to make calculations on what does not even exist.

The problem of calculation in a market, then, is one where the calculation cannot be performed centrally because of the dispersal of knowledge in a structure of disorganized complexity where individuals each ascertain a small part of knowledge pertaining to them, and because the preferences of an individual cannot possibly be communicated to a central planner completely. The striking insight from Hayek's work, however, is that there is never a need for this information to be centralized. Each individual knows their own preferences and subjective valuations, and using the guiding light of the price mechanism and what it tells him about his choices and their costs, he is able to arrive at the decisions he feels suit him the best, as evidenced by the prosperity of individuals living in prosperous free market economies. In due time, the position of Mises and Hayek on the socialist calculation debate would be borne out by real world events in the most accurate and tragic manner, with the complete economic collapse of all societies that employed economic systems based on centralized economic calculation.

A dynamic analysis of the economic impacts of an action, then, will need to internalize the different knowledge that different actors in a market have, and aggregate it into one large model of the market interaction. But this then will fall into the same intractable problem that faced the socialist economists of the interwar period. It was simply impossible for any central planner to devise calculations that accurately reflect and mirror the complexity of the price process. This is the problem that the more complex and sophisticated LCA studies encounter when attempting to quantify biofuels' impacts in a lifecycle analysis. Different studies will have different pieces of knowledge and information incorporated and will therefore yield different results from the dynamic analysis.[5]

c. ***Agent-based vs. Aggregate modeling***

The solution to the aforementioned calculation problem in a dynamic economy is achieved through the price system, which, in effect, disperses and decentralizes the calculation problem to the individuals who have the knowledge relevant to their decisions, as well as the knowledge of their own preferences. By decentralizing this calculation, every individual in the economy is responsible for a small part of the giant spontaneous order of calculation that emerges from free exchange. Economic calculation is carried out in the location where the market exchanges happen, by the agent who carries out the exchange. This situated calculation

5 This discussion of LCA's is parallel to the discussion of Dynamic Stochastic General Equilibrium models in macroeconomic analysis. For a treatment of this, see Leijonhufvud, 2008.

works because the knowledge and the preferences relevant for the calculation are present with the actor carrying it out, where it needs to be carried out.

It might be helpful here to think of the economy as an infinitely large matrix of simultaneous equations that are instantaneously and continuously solved through the market decisions of each person. Every individual decision is a single equation within the infinite matrix. Their local knowledge and their subjective preferences are combined with the price signal every time the individual makes a choice on the market. The 'solution' of this large matrix is the economic arrangement that emerges as a result of people's individual actions.

Aggregates-based modeling techniques like Dynamic Stochastic General Equilibrium modeling and Life-Cycle Analysis are attempts to abstract away from the real calculation that drives the market process—the individual situated calculation—by attempting to establish scientific relationships between the aggregate outcomes of these processes and attempting to measure their impacts. The problem that these methodologies invariably run into, and the reason they regularly produce erratic, divergent and inconsistent outcomes is that they fail to study the actual relationships governing the market process, and instead focus on constructed relationships that do not exist in the real world, but were instead constructed to yield the process to study and analysis by the economist or engineer.

This conclusion is also reflected in Delucchi's analysis of LCA's. Delucchi's argument on the need to structure LCA's as policy-specific questions introduces a methodological difference in the structuring of the analysis of biofuels. Delucchi is effectively saying that aggregates-based modeling is inadequate because it does not provide us with the answers we need, nor is it built on analyzing the correct constituting relations between different factors. Delucchi's proposed alternative of policy-specific basis for the models is a micro-based analysis that attempts to find the relevant and necessary outcomes as consequences of specific actions.

This clarifies another reason LCA's continue to produce inconsistent and contradictory results. By choosing to measure and analyze aggregates, these studies are constructing artificial relations between constructed aggregate factors that do not exist in the real world, and do not reflect on reality.

d. Modeling Technological Advance

In many Lifecycle analyses, large assumptions are made about the future course of technological advance in the production of a fuel.[6] Predictions are made about the likely course of efficiency increases in the

6 For examples of this, see Wang et al (2005), Delucchi (2004), Pimentel and Patzek (2005)

manufacturing processes of biofuels. This matter is an issue of dispute between different authors. The problem with such estimates is that they are built on the assumption that technological and technical advances are predictable and can be estimated.

Such presumptions are built on a rather mechanistic and linear model of technological advance, which presumes that advance is largely predictable and proceeds in an orderly manner. But a more nuanced understanding of the nature of scientific and technological advance would suggest that this predictability is not as well-placed. Nathan Rosenberg views technological and economic growth as the result of problem solving, technical inducement mechanisms, and learning-by-doing and not some over-arching long-term plan for scientific advances that spur technological advances, as the linear model suggests. He emphasizes the close relation between scientific advance and technological innovation, and how the relationship often runs both ways, and not from scientific knowledge to technology.

In his study of engineering and technological advance, Walter Vincenti looked in-depth at different engineering problems and came-up with the variation selection model for technological advance. By examining the process of landing gear development as it happened, Vincenti shows how the progression towards retractable airplane landing gear was far from an orderly linear logical process, but was rather a disorderly process of plenty of innovations being introduced, tried, tinkered with and eventually either discarded or utilized and built upon. While to the historian looking back, hindsight bias would portray the process as an orderly progression, discard any contrary evidence, and present it as though the right answer was known all along, and it was just a matter of finding the technical and specific ways in which to reach it. But that was not the reality of the process. Several inventions were experimented with, and the outcome was far from pre-ordained.

While the retractable gear, Vincenti (1994, p.21) argues, had a

> “technical imperative in light of the large, overall increase in speed that a combination of advances would eventually open up… Designers in the early 1930s, however, lived in a world of small, progressive speed increments coming from loosely related changes in various components of the vehicle… The community of designers was feeling its way into the future in a state of knowledge in which engineering assessment was, at best, problematic. The technical imperative of the retractable gear is knowledge after the fact. We see the outcome; designers at the time, by their own testimony, did not *fore*see it.”

Looking at their day-to-day problems, designers introduced a wide variety of different solutions to whose impact they were unforesighted. With time, trials and experimentation, it became apparent that retractable landing gear would be the most suitable technology and was then utilized.

This, according to Vicenti, conforms better with his variation-selection model than any linear model of technological advance. He quotes Donald Campbell's description of the model as one of "*blind variation and selective retention*"(Vincenti, 1994, p.21), and though he agrees with it, offers justification for using the term *unforesighted* rather than blind to describe the variation. They key is that innovators are not blind to the consequences of their innovations, "they *see* where they want to go and by what means they propose to get there. What they cannot do, if their idea is novel, is *foresee* with certainty whether it will work in the sense of meeting all the relevant requirements" (Vincenti, 1994, p.21-22)

Philip Scranton (2006), in his analysis of the development of the Jet Engine, is critical of the linear vision of the progression of scientific and technological advance. Scranton argues that "at the level of design, testing and building, science provided next to no guidance for resolving critical jet engine problems; instead Edisonian, cut-and-try engineering paved the route to eventual success" (Scranton, 2006, p.130). Scranton further describes the process as: "an extravagantly intense and passionate project – conflict-filled and failure-prone, non-linear, non-rational, in ways even non-cumulative, and, of course, secret" (Scranton, 2006, p.130).

Finally, we can draw on the work of Karl Popper to further elucidate this point. Popper famously remarked that to predict the wheel is to invent it (Giles, 2007). This illustrates precisely the unsolvable problem of knowledge prediction: if you know what you will know, then you already know it, and it is no longer a prediction. If you do not know it, then you cannot know that you will know it, or what it is.

Scientific discoveries, being discoveries, are discoveries of facts that were previously unknown. Discovering a fact is, by definition, the point at which it is discovered. This is why predicting a discovery is a logical impossibility. Once one predicts a discovery, then they have discovered it. This means that until they discovered it, they did not predict it. In knowledge, discovery and prediction are the same thing.

From these examples of actual scientific and technological advance, one can see the problem with the estimates of technological advance in the biofuels literature and another reason for the disparate results is apparent: the projections these studies use about future rates of advance in production cannot be considered robust and reliable projections—they are bound to result in errors in estimates.

Nowhere is this more pronounced than in the many analyses of the efficiency of cellulosic ethanol production. Once one considers the nature of the unknowability of future scientific advance, one realizes the problems inherent in attempting to assess the environmental friendliness of production techniques that have not been invented yet, and whose very inception in not certain. In fact, a review of the history of development of cellulosic ethanol would show why such analyses are misplaced by their very nature. As far back as 1980 one can find this statement in the USDA Yearbook of Agriculture (1980): "In 3 to 5 years, technology advances should occur that will allow the conversion of cellulosic materials, tree trimmings, old newspapers, crop residues, etc., to alcohol on an economic basis."

One of the co-authors of these lines, Otto Doering, also co-authored this about cellulosic ethanol in 2008 (Schnoor et al, 2008): “Currently, ethanol derived from corn kernels is the main biofuel in the United States, with ethanol from “cellulosic” plant sources (such as corn stalks and wheat straw, native grasses, and forest trimmings) expected to begin commercially within the next decade.”

Since the ‘energy crisis’ of the 1970’s, biofuels researchers have touted cellulosic ethanol as the technology that will make biofuels a viable significant contributor to the energy mix. The introduction of commercially produced cellulosic ethanol into the market has always been a few years away. The technological, technical and industrial advances have always been arriving “in 3-5 years” or “within the next decade”

This informs a skeptical assessment of all the aforementioned studies that discuss the potential of biofuels. There are still countless technical, technological and industrial challenges to the introduction of cellulosic ethanol. The predictions of scientific advance that will overcome these challenges are all built on a simplistic linear view of scientific advance. Based on the historical mismatch between the predictions of overcoming those challenges and the actual mismatches, one should be careful about using these estimates in efficiency studies.

This further helps explain the disparity of the results of different studies. When the scientific processes that are being modeled do not yet exist, it is to be expected that serious discrepancy would exist between different studies depending on their projections.

e. ***Constructivist View of Energy Systems***

Finally, perhaps the most general problem of the current approach to assessing energy sources and energy policy lies in the conception of the energy system as a product of rationalist human design rather than an emergent product of human action. Vernon Smith makes a distinction of two types of rationality:

constructivist rationality and ecological rationality. Smith defines *Constructivist Rationality* as the "deliberate use of reason to analyze and prescribe actions judged to be better than alternative feasible actions that might be chosen." *Ecological Rationality*, on the other hand, refers to "emergent order in the form of practices, norms, and involving institutional rules governing actions … created by human interaction but not by conscious human design" (Smith, 2007, p.2).

Constructivist rationality is what humans deliberately use when solving problems, choosing a course of action, designing machinery, inventing new technology, or trying to understand physical processes. It is what our brain learns to do through education. Constructivist rationality is what has produced the inventions, machines, devices and technological innovations that have improved our life. Ecological rationality, however, refers to order that exists without the direct reason of any individual designing it or implementing it, but is also not a natural system arising independently of human action. It emerges through countless individuals acting and *interacting* with each other. It is a product of "human action, not human design" as Adam Ferguson (1767 (1966), P122) put it. It is an order whose details cannot be forecast or expected beforehand. After it emerges, however, it is at times possible to apply constructivist rationality in order to understand its properties and its process of emergence.

Smith (2007, P38) maintains an evolutionary framework for understanding the emergence of ecologically rational systems:

> *"But in cultural and biological coevolution, order arises from mechanisms for generating variation to which is applied mechanisms for selection. Reason is good at providing variation, but it is far too narrowly limited and inflexible in its ability to comprehend and apply all the relevant facts in order to serve the process of selection, which is better left to ecological processes that implicitly weights more versus less important influences."*

Whereas constructivist rationality is what provides us with particular designs, it is an ecologically rational selection process, which is the result of the actions of various individuals that produces the ecologically rational system that employs some of these constructivist rationalist designs. Languages are a good example of ecological rationality; no single individual or planning committee sat down and devised a live language from scratch. Languages have evolved over time, through the actions and thoughts of an infinite number of individuals. The market system is another good example of ecological rationality: nobody has designed a market system in a modern market economy, outlining and ordaining the format for production and consumption of goods, their prices and their quantities. Instead, individuals *act* and in their action, shape the contours of the market system: they seek out their best interest, devise ideas for production and consumption, try to cooperate with one another, and a spontaneously emergent, ecologically rational system emerges as the outcome.

The energy markets of the United States of America or Europe never were designed by a central planner; they have always been the spontaneously emergent result of the actions of many individuals. Government policy has undoubtedly affected these actions immensely, but it has not directly drawn up the mix of the energy that is used. This is an important distinction that entails serious consequences for the policy-making associated with energy. The emergent aggregate phenomenon of the fuel mix is the product of many decisions carried out by many individuals and institutions. The attempt to plan these aggregates is fraught with difficulty because it methodologically fails to grapple with the micro foundations of the decisions that make this emergent outcome.

The example of the previous large attempt at planning energy illustrates this point. The US government's plan to design the energy system of America in the early 1980's was a drastic and comprehensive failure. People's choices and decisions were undoubtedly affected by the policies the government pursued, and the emergent order of the energy mix of America was certainly affected by the subsidies and regulations that the government implemented. But what emerged was drastically different from what the central planners had anticipated, designed or hoped for. Planners can make their plans and try to shape how order unfolds, but the actions of individuals are the one that ultimately determine the shape of the ecologically rational outcome.

Lee, Ball and Tabors (1990) have published a comprehensive overview of this episode of energy planning, detailing how the US Government sought to promote five main sources of energy in the aftermath of the "energy crisis" of the late 1970's. These energy sources were: Synfuels, photovoltaics, renewables, natural gas and nuclear energy. The following is a brief overview of the policy and fate of each of these:

1. Synfuels: The Synthetic Fuels Corporation was established to subsidize synthetic fuels, committing $17b, with the goal of producing 2 million barrels of synfuel per day by 1992. The program was scrapped after only $100m were spent. No commercial synfuel production has taken place.
2. Photovoltaics: PV joined a horse-race of competing for increasing efficiency, but, alas, it wasn't a competition for going on the market and succeeding commercially as much as it was a competition for federal funding. The government created the market and dictated prices, quantities and timeframes. Photovoltaics failed commercially. Lee et al conclude: "The major portion of this blunder was assuming that it was possible, in effect, to dictate the supply-demand relationship in advance and that by having the government establish the market through forced, prestated quantity

purchases, it would be possible to drive the price of the technology down." (Lee et al, 1990, P34) The second problem, for Lee et al, was the assumption that it was possible to predict the advancement of technology and the cost-curve for the future. (Lee et al, 1990, P78)

3. Renewables: Biofuels policies similar to the ones being used today were used back then. The one tangible result of these subsidies was massive wealth transfer to corn farmers and big agricultural companies.

4. Natural gas: The Fuel Use Act provision was put in place to dictate what were legitimate and illegitimate (legal and illegal) uses of natural gas, leading gas to become an energy source that was "too valuable to burn", according to Lee et al. The result was that this law hampered the development of natural gas as an energy source. Only when these interventions were repealed did natural gas become a more energy source.

5. Nuclear energy. Lee et al call nuclear energy policy in America "an outstanding example of what not to do following achievement of unquestionable scientific and technological leadership in a critical field." (Lee et al, 1990)

The end result of these programs was a resounding failure on all stated levels. This is not a result of the failure of these plans as much as it is the failure of the idea of making these plans. The important thing to learn from this lesson is not just a limited lesson about the viability of synfuels or any other energy source; it is rather that an emergent phenomenon like the energy mix cannot be designed willfully using constructivist rationalist methods.

V. IMPLICATIONS & CONCLUSION

The consequences of biofuels-promoting policies have been discussed in depth in another paper (Ammous, 2011), and will only be summarized here: a likely increase in deforestation and greenhouse gas emissions, increased fossil fuel consumption to produce expensive fuels, a rise in food prices, extinction of species from wild habitats destroyed to plant energy crops, damage to local ecosystems, and a large cost to taxpayers. This multititude of negative unintended consequences echoes (but to a lesser extent) the disastrous outcomes of centralized economic planning based on centralized economic calculation carried out by socialist economies in the twentieth century. By attempting to apply the tools of constructivist rationality to spontaneously emergent order shaped by human actions, and not human design, policy-makers in both situations have created real-world consequences unforeseeable with their calculation tools.

This paper illustrated the large disparities in the results of scientific studies on the efficiency of biofuels as a mechanism for reducing greenhouse gas emissions and fossil fuel consumption, concluding that there is no scientific consensus on these questions, in spite of hundreds of researchers and studies tackling the question over more than three decades. This lack of consensus can be explained by realizing that the question of biofuels suitability is not a technical scientific question that can be analyzed with the tools of the natural sciences to obtain certain answers. Rather, biofuels' suitability is a complex, social, dynamic question determined through real world experimentation, trial and error. The complex nature of fuel markets, the dynamic nature of markets and the dispersed knowledge they contain, as well as the indispensable role of the price mechanisms for achieving decentralized coordination of economic activity, imply that centralized theoretical calculation are not even wrong, they are inapplicable in this domain The uncertain nature of scientific advance, and the fact that energy systems are ecologically rational and not the result of constructivist rational design indicate invite us to rethink the rationale for making energy adoption a goal of government policy altogether. The costs of doing so, as illustrated in several cases over time, will likely exceed any benefits, and will result in unintended consequences. The unfortunate consequences of biofuels science and policy suggest that it is time to rethink the rational of using government policy to shape spontaneous outcomes of complex market and scientific processes.

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