Environmental and Energy Consequences of Using Corn Ethanol as a Biofuel

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A Thesis presented to the Graduate Faculty
of the University of Virginia in Candidacy for the Degree of
Master of Arts

Department of Environmental Sciences
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August 2016

ABSTRACT

Corn ethanol is viewed by many supporters as a sustainable fuel that can replace gasoline, reduce greenhouse gas emissions relative to fossil fuels, and increase energy security. Unfortunately, these claims are not supported by production practices. Corn ethanol is more expensive than gasoline. Its production and use results in higher carbon emissions than gasoline and causes additional environmental concerns such as eutrophication, soil erosion, land use change, and air and water pollution. The net energy from ethanol—be it positive or negative—almost certainly provides less than the minimum surplus required to support our present industrial society. Separately, high cost, negative environmental impacts, and insufficient energy return, could each prevent corn ethanol from being a sustainable fuel; taken together, corn ethanol certainly should not be blended with gasoline. Nonetheless, under the current renewable fuels standard, corn ethanol is a required additive and its use will continue for the foreseeable future.

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LIST OF ABBREVIATIONS

BTU	British Thermal Unit
CBO	Congressional Budget Office
CHP	Combined Heat and Power
DDG	Dry Distiller's Grains
E0	Fuel: 100% gasoline, containing no ethanol
E10	Fuel mixture: 10% Ethanol / 90% gasoline
EPA	Environmental Protection Agency
EROI	Energy Return on Investment
gal	gallons
Gb	Giga-barrels
GHG	Greenhouse gas
HPDDG	High Protein Distillers Dried Grain
L	Liters
MJ	Mega Joule
MTBE	Methyl Tertiary Butyl Ether
NOx	Nitrogen oxides
U.S.	United States
USDA	United States Department of Agriculture
WDG	Wet Distiller's Grains

ACKNOWLEDGEMENTS

I would like to thank the U.S. Department of Defense for providing me the opportunity and funding to pursue a Master's in Environmental Science.

I would to thank my wife Valerie for her support during my long hours of school work and during the drafting of this thesis. She has always been willing to listen to my ideas and has been a crutch for me to lean on whenever I needed a little help. Thank you my love!

I would like to thank my boys: Gavin, Cullen, and Kai. They drive me crazy, make me work harder than I ever thought possible, and bring me more joy and more love than I could possibly deserve.

I would like to thank my advisor, Stephen Macko for helping me join the MA program and his considerable guidance through the process.

I would like to thank my committee members, Deborah Lawrence and Ann Adams, for reviewing my work and providing valuable feedback.

I want to thank all the professors and graduate students whose classes or lectures I had the pleasure of attending this year: Deborah Lawrence, Jonathan Cannon, Stephen Macko, Heather Sullivan, Todd Scanlon, Bob Davis, John Porter, Amy Ferguson, Patricia Wiberg, Marie Lise Delgard, Howie Epstein, Matthew Oreska, Carleton Ray, Jerry McCormick-Ray, Matt Reidenbach, Michael Pace, Hank Shugart, David Smith, Bob Swap, Manuel Lerdau, Karen McGlathery, Itiya Aneece. You have impacted my life on so many levels. I can't tell you how much I appreciate the opportunity to spend time with you.

I want to thank Will Tomanek, Cindy Allen, Laurie Hammond, and Rachel Short for answering all my questions and helping me whenever I needed it.

Also, a big thanks to everyone else in the Environmental Science Department, especially the Graduate Students. You all have an incredible amount of energy, ambition, and heart. You made my year at Virginia an absolute pleasure. Keep caring about the world and creating the change that we need!

1. Introduction

Concerns over climate change, energy security, and energy availability in general have led to growing interest in alternatives to fossil fuels. One alternative is biofuels, such as corn-based ethanol. Many governments and scientists support biofuels claiming they provide energy security, environmental benefits, foreign exchange savings, and socioeconomic advantages. Strong proponents suggest that biofuels can satisfy the energy requirements of the United States (U.S.) and the world. Detractors site numerous drawbacks—including net energy balance and environmental impacts—to the production and use of biofuels.

The net energy return of biofuels has been shown to be negative by several highly-respected scientists (Pimentel and Patzek 2005, Murphy and Hall 2011). Even if not negative, the net energy return from biofuels may not provide the minimum energy surplus required to support our current society (Hall *et al.* 2014). In particular, many studies have raised concerns about the energy return on corn ethanol, one of the most widely produced and used biofuels.

Claimed environmental benefits of corn ethanol have also been questioned. Supporters view it as a sustainable energy source that will reduce our dependence on oil and reduce carbon emissions (Glozer 2011). Critics claim the opposite, i.e. that ethanol production does not provide greenhouse gas (GHG) reductions and is therefore not an effective fuel. Some studies have concluded that fuel ethanol use results in increased carbon emissions due to land use change and fossil fuel use during production (Stashwick 2010). Other environmental concerns with corn ethanol include fertilizer use, eutrophication of surface waters, and air and water pollution (Niven 2005).

Clearly, the use of corn ethanol as a fuel is controversial. Its use has been attacked and supported based on cost, environmental impacts, and the net energy produced (also known as Energy

Return on Investment (EROI)). In all these respects, there are large differences between data and calculations presented by supporters and critics of corn ethanol. As such, evaluating corn ethanol as a biofuel requires a clear understanding of each of these issues. Many authors have addressed the corn ethanol debate; although, consensus within the scientific community is still lacking. Evaluating the financial cost is complicated by subsidies and competing resources (e.g., land use, food). Environmental impacts have been addressed by the government (U.S. EPA 2011, CBO 2009) and scientists (e.g., Gomiero *et al.* 2010, Pimentel *et al.* 2008, Niven 2005); however, stated benefits and impacts vary with viewpoint. The net energy balance of corn ethanol is probably the most contested. Hall *et al.* (2014) postulated that data quality and co-production allocation cause most of the differences in calculated Energy Return on Investment (EROI). In each of these areas, the range of assumptions used by various researches make comparisons and conclusions challenging.

Fuel ethanol use and its associated cost to taxpayers has increased substantially over the past several years; 35% of all corn grown in the United States is being used to produce ethanol (US EPA 2011). Current U.S. policy requires the use of ethanol as an additive in domestic gasoline (Glozer 2011). The Congressional Budget Office estimates that increased use of ethanol accounted for about 10 percent to 15 percent of the rise in food prices between 2007 and 2008, resulting in an estimated $600 million to $900 million increase in federal spending on child nutrition programs alone (CBO 2009). This is in addition to the roughly $3 billion in annual ethanol tax credits. These costs are typically justified by ethanol supporters who claim that ethanol is reducing and replacing the use of fossil fuels.

The use of ethanol may also come at a substantial environmental cost in terms of net GHG emissions and other environmental impacts (U.S. EPA 2011). While the chief argument that enticed Congress to enact a 2007 ethanol mandate was a promise of reduced GHG emissions (Glozer 2011), ethanol is not providing this expected benefit. The U.S. EPA (2011) reported an estimate of the environmental impacts of corn ethanol based on current understanding of biofuel production and use, including input gained through consultation with the U.S. Departments of Agriculture and Energy. The findings stated that for corn ethanol, “the extent of negative [environmental] impacts to date are limited in magnitude and are primarily associated with the intensification of corn production” (U.S. EPA 2011). Current and potential future impacts of biofuel production include land-use conversion, degradation in water quality driven by use of fertilizer and other chemicals, increased water use as corn production expands, decreased soil quality from erosion and decreasing organic matter due to high corn stover—the above ground parts of the corn plant except the grain—removal rates, increased air pollution in some areas (for some pollutants), and depletion of ecosystem health through, for example, eutrophication of surrounding (Kim and Dale 2005). The EPA finds that future environmental impacts may be positive or negative depending on the choice of energy feedstock, land-use change, cultivation, and conservation practices (U.S. EPA 2011). The agency projects that in 2022 an average natural gas-powered ethanol plant realize carbon-emission savings of 21% relative to gasoline (based on entire fuel cycle), but these savings are not being realized today, and might not be achieved in the future (Stashwick 2010). Although studies such as that conducted by Quirin *et al.* (2004) show net reduction in GHG emissions when corn ethanol is used as a fuel, more recent studies have found that land-use changes required for corn cultivation can lead to increased carbon emissions (Glozer 2011, Gomiero *et al.* 2010).

The debate over energy produced, and the potential contribution of corn ethanol, is probably more controversial than its environmental impacts. All forms of economic production—including energy and food generation—require the use of energy (Hall *et al.* 2011, Elsayed *et al.* 2003). For the past century, cheap and seemingly-limitless fossil fuels have supported economic growth that was unparalleled in human history. The enabling factor was the energy return on investment (EROI) of fossil fuels that provided energy to expand the economy and develop technologies other than food and direct energy production (e.g., economic growth). With the availability of cheap fossil-based energy declining—either because of declining fossil fuel resources or the climate-costs related to their use—scientists have been seeking replacements. However, not all sources provide the same return on energy, and a society must generate an energy surplus to allow for division of labor, creation of specialists, and the growth of cities. It must generate a substantially greater surplus to support wide-spread wealth, art, culture and other social amenities (Hall *et al.* 2011, King 2015). Fossil fuels have enabled humans to populate—and impact—all corners of the planet. The societal need for excess energy suggests that any new energy technology must provide a minimum energy surplus. The value of any biofuel critically depends on its energy balance (Elsayed *et al.* 2003), and when our energy supply falls below a minimum energy surplus—or minimum EROI—society will become unsustainable. The potential role of corn ethanol for future energy supply, and its ability to avoid the energy cliff is one central focus of this thesis.

Complicating the scientific debate is the interest of policy makers and investors who view ethanol as an energy source that will expand the country's energy options to help alleviate future rising energy prices, reduce GHG emissions, and provide jobs and tax revenue to farmers (Gomiero *et al.* 2010, Shapouri *et al.* 2003). The combined desires to increase farm income and to reduce reliance on imported oil have led to broad support for ethanol by the U.S. government. At present, the Renewable Fuels Standard requires petroleum refiners and importers to blend 15 billion gallons of ethanol annually in gasoline while receiving a tax credit of 45¢ per gallon of ethanol so blended (Glozer 2011).

Certainly, the commitment of the government to ethanol is supported by the corn and ethanol industries, which both benefit directly. However, the assertion that ethanol helps energy security critically depends on the net energy provided by corn ethanol. If, as critics state, the non-renewable energy required to grow and convert corn into ethanol is greater than the energy available from the ethanol fuel, then corn ethanol provides no energy security and, rather, serves only as a farm subsidy (Glozer 2011). Regardless, current EPA gasoline regulations state that ethanol is the only octaneenhancing gasoline blend that refiners and importers can use to increase the octane rating of unleaded gasoline (Glozer 2011). As such, irrespective of its net energy balance, its environmental impacts, its cost, or its overall impact of food supplies, corn ethanol will continue to be used as an automobile fuel for some time.

Based on the energy demands of society and the need for environmentally clean energy sources, corn ethanol is almost certainly not a viable and sustainable fuel. The following sections examine the ethanol debate as it stands today. First, the ethanol production process is discussed, as it sets the stage for understanding factors that influence ethanol's environmental impacts and its energy balance. Then, the use of corn ethanol as a fuel and its impacts on the environment are considered. Finally, the importance of EROI for liquid fuels and corn ethanol are analyzed, with attention to the numerous studies that have attempted to quantify EROI for corn ethanol.

2. Ethanol Production Process

The conversion of corn into ethanol is a well-known and established technology with conventional ethanol produced from the fermentation of corn starch. According to the U.S. EPA (2011) two production process methods are currently in use:

- *Dry milling—in which the corn kernel is first ground into a meal, usually without separating out the various component parts of the grain. The meal is then slurried with water and cooked at high temperature to form a mash, which then undergoes fermentation. This is the more common process.*
- *Wet milling—in which the kernels are steeped in water containing sulfur dioxide to separate out the germ, fiber, and gluten (fractionation). From this initial separation, co-products such as corn meal, corn gluten meal, and corn gluten feed are recovered. The remaining mash contains the water-soluble starch, which undergoes further processing for biofuel.*

Both processes involve the conversion of corn starch into glucose through an enzyme-catalyzed hydrolysis reaction. The glucose is fermented by yeast into ethanol. The mash is then distilled to collect a mixture of roughly 95% ethanol / 5% water, which is dehydrated (often using molecular sieves, but can be done via an azeotropic distillation) to provide 99.5% ethanol. Pimentel (2008) reports that yield is about 2.5 gallons of ethanol per bushel (56 pounds) of corn, but yield numbers have been rising as ethanol plants become more efficient. The amount of corn required to produce an equivalent amount of ethanol reportedly fell by 5.3% from 2001 to 2008 (U.S. EPA 2011, Wang *et al.* 2007). Such an improvement should translate into a more energy-efficient conversion and higher net energy value for ethanol.

Traditionally, wet milling plants are much larger than dry milling plants. Wang *et al.* (2007) report that several wet milling ethanol plants in the U.S. have an annual production capacity of about 150 million gallons while capacity of typical dry milling plants has generally been on the order of 50 million gallons. All recent and planned corn ethanol plants are dry milling plants and some will have annual capacity of 100 million gallons.

There are some variations in the ethanol production processes, but many process steps are common among all plants (Figure 1). Energy (e.g., planting, harvesting) and materials (e.g., chemicals) are input to the corn field. Harvested corn is cleaned, ground and slurried with water and enzymes, followed by cooking of the slurry to liquefy the starch (liquefaction). After liquefaction, the mash is cooled, and another enzyme is added to convert the liquefied starch into fermentable sugars. Yeast is added to ferment the sugars to ethanol and carbon dioxide, followed by distillation and dehydration with molecular sieves.

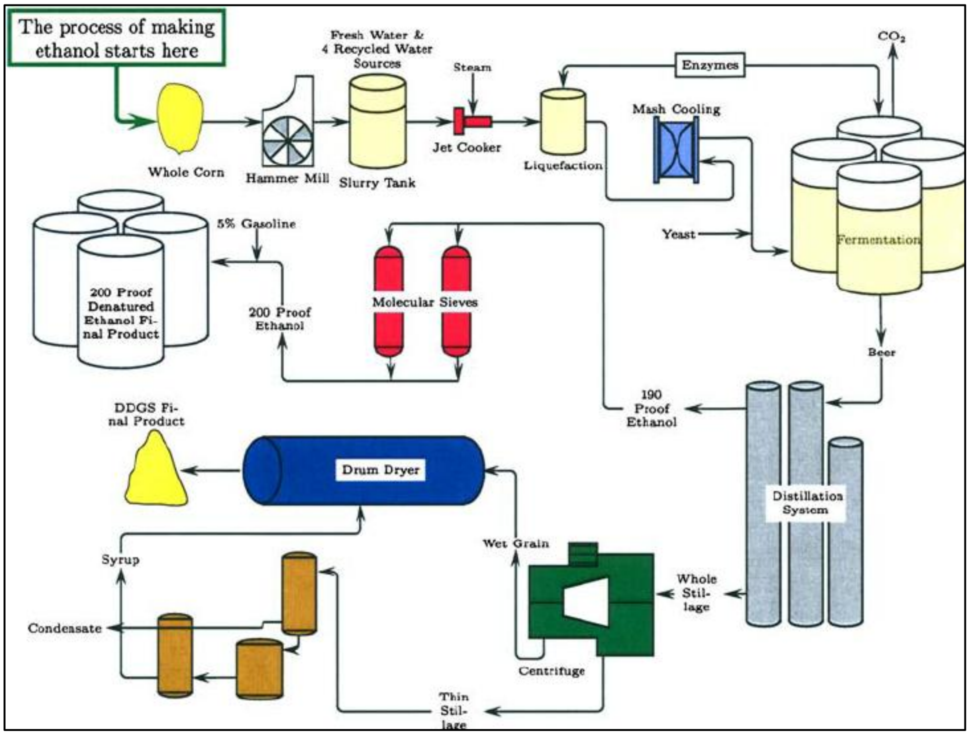

Figure 1: Typical Ethanol Process (Patzek, 2006)

In addition to ethanol, a typical plant also processes the non-fermentable nutrients (protein, fat, and fiber) left over after the distillation and dehydration process. If dried these compounds are called dried distillers grain (DDG), otherwise these are classified as wet distillers grains (WDG). DDG and WDG are generally used as animal feed. The DDG has a longer shelf life than WDG and can be shipped more economically. The ratio of WDG and DDG production from a dry mill ethanol plant depends on local market conditions with a shift towards WDG if livestock operations are located nearby. Depending on the configuration, modern ethanol plants can produce many other co-products including high protein distillers dried grain (HPDDG), bran cake, corn oil, corn gluten feed, bran energy feedstock, zein protein for bio-plastics, and fertilizer products (Mueller and Copenhaver 2009).

After corn feedstock, fuel costs are the largest expense in ethanol plants (Wang *et al.* 2007). The type of fuel used to power ethanol plants and the heat/steam management within each facility is of critical importance for the calculation of both net energy production and GHG emissions. Emissions of GHGs from inefficient plants using coal, for example, are much greater than emissions from a highly-efficient facility powered with natural gas or corn stover.

2.1 Power Options for Ethanol Facilities

A range of power options / configurations have been suggested for corn ethanol plants, and the choice of these directly effects the energy and GHG balance of a particular facility. Wang *et al.* (2007) detailed several options that greatly impact the energy balance including power from natural gas, coal, or biomass (e.g., DDG, corn stover, wood), inclusion of combined heat and power (CHP) systems, and production of WDG rather than DDG. A CHP system produces both steam and electricity for plant operation thereby reducing the amount of electricity that must be provided by other energy sources. Using less expensive energy sources (e.g., coal) reduces plant cost, but increases GHG production. Implementing CHP systems reduces overall power requirements and GHG production, but raises operating cost. Producing WDG rather than DDG reduces drying costs and power but is only possible when the ethanol facility is situated near a livestock facility. The choices appropriate for one facility may not be appropriate for another, depending on what is being optimized e.g., cost, power, GHG emissions (Wang *et al.* 2007).

2.2 Corn Yield

Corn yield—or amount harvested per given area—is an important factor for evaluating corn production. Further, since corn yield is directly related to land requirements, fertilizer and chemical use, and energy inputs, many authors treat it as an important aspect in calculating the net energy balance of corn ethanol. U.S. corn yield has increased since the 1915 (Figure 2). Although the trend is important with a roughly 700% increase over 100 years, it also captures the yearly fluctuation in yield that is likely due to climatic variations and economic conditions. Additionally, yield varies with geographic location which can be an important aspect of overall energy efficiency. Some portion of the increased yield could be attributed to increased chemical or machinery use or from intensive agricultural management practices, any of which could lead to adverse environmental consequences (Chum et al 2013).

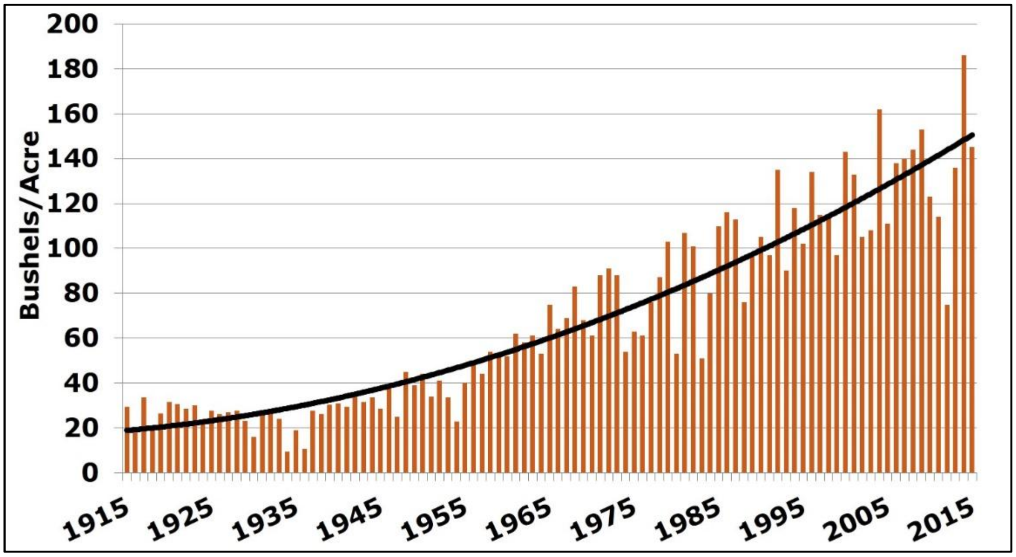

Figure 2: U.S. Corn Yield since 1915 (University of Missouri 2016)

2.3 Production Rates

U.S. ethanol production increased from less than 0.18 billion gallons per year in 1980 to approximately 14.7 billion gallons in 2015, making the U.S. the world's largest ethanol producer. Of the estimated 209 U.S. ethanol plants, nearly 95% use a dry milling process to produce 89% of total production in 2011; the remaining ethanol was produced using the wet milling process (Chum *et al.* 2013). Production has increased dramatically since 1980 (Figure 3). According the U.S. EPA (2011), most corn ethanol facilities are located in the major corn-producing states: Iowa (with the largest production capacity and the greatest number of plants) followed by Nebraska, Minnesota, Indiana, and Illinois. Production location is important as it is linked directly to energy requirements though water use for irrigation and co-products produced by each facility.

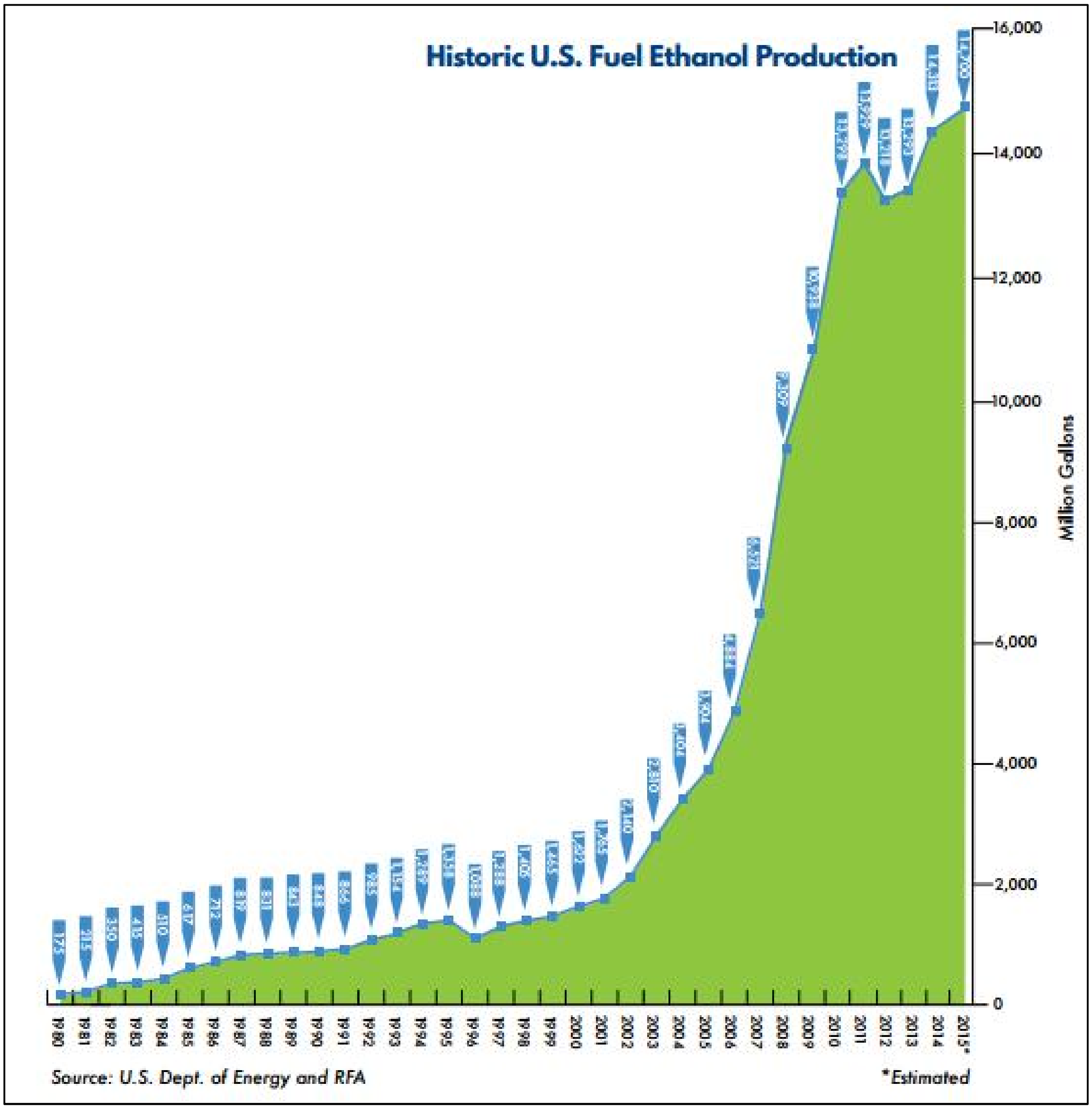

Figure 3: Annual U.S. Fuel Ethanol Production 1980 to 2015 (Renewables Fuels Association 2016).

2.4 Energy Required for Ethanol Production

The energy required to produce ethanol from corn includes both the energy involved in growing corn (planting to harvesting) and the energy required to convert corn to ethanol. The U.S. Department of Agriculture (USDA) report that corn producers use most energy products (gasoline, diesel, natural gas, liquid petroleum gas, and electricity) directly in planting, harvesting, and drying their crop, but acknowledge that energy used for the production and application of fertilizers is also significant (Gallagher *et al.* 2016). All corn-related energy costs have declined appreciably over the past two decades with nitrogen-use falling roughly 20% and direct energy use falling by about 50%. These improvements were achieved through use of modern farming equipment—including GPS guided equipment—and genetically enhanced corn, which increases yield and reduces energy requirements per acre (Mueller and Copenhaver 2009). Taken together, these efficiency gains result in about a 30% reduction in energy required to produce a bushel of corn. According to the USDA, energy requirements were about 65,000 BTU per bushel in the mid-1990s and had fallen to about 38,000 BTU per bushel by 2010. The rate of improvements has declined since the mid-2000s, but energy efficiency is still rising (Gallagher *et al.* 2016).

Producing ethanol from corn requires power in the form of electricity and steam. The specific amounts of each depend on the plant configuration (as discussed above) including the power source, the use of CHP, and the co-products produced. For typical plants, electricity is purchased from the grid or produced on site, and steam is produced on site using natural gas. Today, most plants use fossil fuel-based power sources, but many plants are investigating the use of biomass or other renewable energy sources in order to reduce their carbon footprint. A survey conducted by the U.S. EPA found that ethanol plants required about 28% less thermal energy and 32% less electricity in 2008 compared to 2001 (U.S. EPA 2011). A separate study found that in 2006 natural gas powered ethanol plants required roughly 32,000-34,000 BTU (thermal energy) and 0.75 kWh (electricity) per gallon with 100% DDG drying; by 2009 a similar plant would have required 29,000 BTU and 0.69 kWh per gallon (Mueller and Copenhaver 2009). Such process improvements are consistent with the growth of the ethanol industry and the increased scale of many newer ethanol plants. As production rates increase, energy requirements to produce ethanol have fallen (Figure 4) (Chum *et al.* 2013). While this trend cannot continue indefinitely (i.e., energy required will not fall to zero), the graph shows that economies of scale are typical for the ethanol industry.

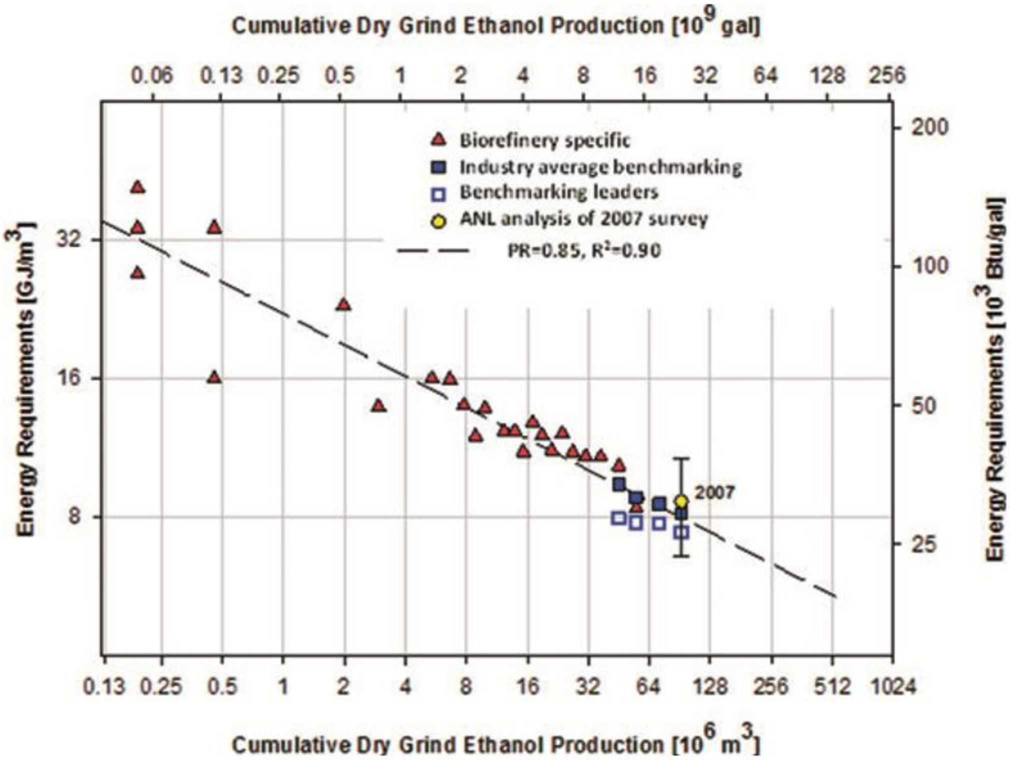

Figure 4: Process energy requirement learning curve (logarithmic scale) for dry mill corn ethanol production (Chum *et al.* 2013).

Ethanol facilities using CHP systems are able to generate electricity and thermal energy—typically steam—from the same fuel source in a single integrated system. Historically, CHP systems are powered by fossil fuels such as coal, but today more are being powered by natural gas and biomass. The value of a CHP systems comes from improved efficiency because heat generated is used for productive work (e.g., drying, distillation) rather than vented to the atmosphere as is the case in most electricity generating plants. Further, because CHP systems are located on-site, there is little transmission loss for either the electric or thermal power being generated. Overall energy efficiency can be much higher in a CHP facility—sized for a specific plant—compared to on-site thermal generation and grid-purchased electricity (Mueller and Copenhaver 2009).

Few ethanol facilities have incorporated the use of biomass power—either as part of a CHP system or simply for steam generation. The primary advantage of employing biomass power is reduced GHG emissions through the use of a renewable fuel (e.g., corn stover, wood) rather than fossil fuels; lower operating cost is also possible. Nonetheless, many plant operators prefer the convenience of natural gas power since it is easily controlled for on-demand power generation. Thus, there is both an operational efficiency cost for plants to adopt biomass power and a higher initial financial cost since a biomass system is more complex and expensive to install than a natural gas boiler (Gallagher *et al.* 2016).

2.5 Co-products

Co-products are any marketable item produced during the ethanol production process. Co-products are an important aspect of corn ethanol production and are critical for considering corn as a food and energy crop. The primary co-product of ethanol production is dried distillers grains (DDG), the high-protein feed product that remains after low-value starch is removed to make fuel (Griend 2009). The primary co-product, DDG, has a nutritional value (for livestock) equivalent to 50% of raw corn. In addition to DDG, other co-products are produced in varying amounts by some ethanol facilities. These include food grade corn oil, corn gluten, and bran cake; gluten and bran cake can, like DDG, be used as animal feed. Alternatively, bran cake can be used to power a solid fuel boiler to produce thermal heating for plant operation, reducing fossil fuel requirements (Mueller and Copenhaver 2009). Thus, co-products are important not only economically for ethanol production facilities, which benefit financially, but also for the consideration of net energy balance.

The treatment of so-called 'co-product credits' when calculating net energy return and EROI is, perhaps, the most controversial and debated aspect of corn ethanol net energy balance. Many supporters argue that co-products must be counted separately from the corn ethanol process and, thus, a portion of the energy used for producing corn and processing it must be assigned to the co-products instead of the ethanol itself (Gallagher *et al.* 2016, Griend 2009, Kim and Dale 2005). Others suggest that co-products are obtained at the expense of, for instance, the return of nutrients to the soil. Thus, the use of co-products for food reduces soil nutrients and will not be sustainable over many crop cycles (Murphy *et al.* 2011). It is also argued that the value of the co-products can, at most, be valued as equal to an alternative livestock feed product (e.g., soybeans) which in many cases require lower energy to grow and process than DDG (Pimentel and Patzek 2005).

Also important in the energy balance discussion is the specific type of co-products produced. Specifically in relation to distillers grains, with some facilities are able to produce wet distillers grains (WDG) rather than DDG. From a process standpoint, WDG are much less energy intensive as they do not require drying; however, from a product standpoint DDG has a longer shelf-life and can be distributed more broadly. Each plant may decide to produce WDG and/or DDG based on the selling price of these products compared with the cost of drying operations. Additionally, only facilities in certain locations have the option of producing WDG, as they must be located near a livestock facility (buyer) due to the short shelf-life. Because of their ability to produce and sell WDG, some facilities—particularly those in Iowa—have a lower energy use and better net energy return than the average corn ethanol plant (Gallagher *et al.* 2016).

Related to the co-product discussion is the concern with using DDG as an animal feed in general. With the rise in ethanol production and the prices of corn and soybeans, DDG has become an increasingly important feed component for confined livestock. According to the U.S. EPA (2011) roughly one-third of the corn processed into ethanol is converted into DDG; this will translate to the production of about 45 million tons of DDG in 2015. Because DDG is higher in both nitrogen and phosphorus content compared to corn, livestock fed on DDG diets produce waste with higher nutrient levels. While this manure can be used as a fertilizer directly, it can still lead to eutrophication of surface waters (U.S. EPA 2011).

2.6 Corn Stover

Corn stover refers to all of the above ground parts of the corn plant except the grain (Kim and Dale 2005). During harvest, the mass of corn stover is roughly equal to the mass of grain. Currently, the vast majority of corn stover (~90%) is left on the field in the U.S.; however, its use for cellulosic ethanol production or as biomass fuel for ethanol plants has been studied (Kim and Dale 2005). The use of corn stover—either for ethanol or fuel—has benefits and issues. Its use as a fuel can lower the overall GHG emissions for ethanol production by reducing the required fossil fuels. Alternatively, leaving corn stover on the fields helps reduce soil erosion and allows important nutrients (e.g., carbon, nitrogen) to be retained in the soil. The energy required to return nutrients to the soil—through use of fertilizer—after the removal of corn stover is not easily estimated. At this time it is not clear if ethanol plants will widely adopt use of corn stover for biomass fuel or use it to produce ethanol, but as concerns of the GHG balance of corn ethanol continues, its use could increase. As of 2010, no ethanol facilities produced cellulosic ethanol from corn stover (EPA 2011)

3. Ethanol as Fuel

The use of ethanol as a fuel has a long history, but the relatively recent rise in corn ethanol production—specifically as a gasoline additive—took shape with the first federal tax subsidy for ethanol in the 1970s and tariff protection by 1980 (Glozer 2011). At the time, the ethanol lobby was pushing its increased fuel-use based on the promise of energy security, and ethanol enjoyed support by environmental groups who cited lower vehicle carbon monoxide emissions when it was added to gasoline. Later, with growing concern over climate change and the use of fossil fuels, many environmental groups continued to support the use of ethanol as a gasoline replacement when it was mandated by the renewable fuels standard (Glozer 2011).

Under the first Bush administration, mandates to use oxygenated fuels (e.g., methyl tertiary butyl ether (MTBE), ethanol) in gasoline were authorized. However, after MTBE was identified as a significant contaminant in ground water, ethanol became the preferred oxygen source for U.S. gasoline supplies. Since that time, ethanol production in the U.S. has sharply increased (Figure 5) (Glozer 2011, Wang *et al.* 2007). Even then, however, there were concerns about the environmental and energy impacts of using corn ethanol as a fuel (Pimentel *et al.* 2008, Pimentel 2003).

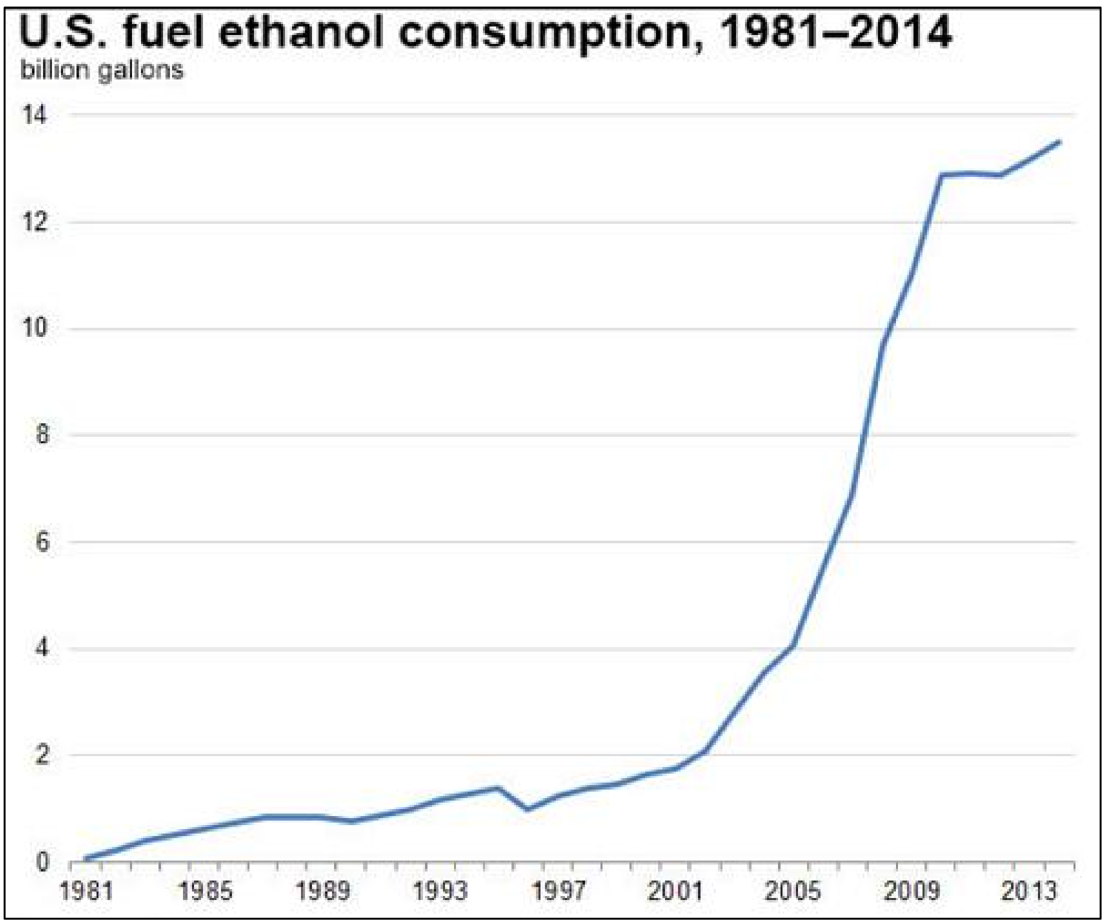

Figure 5: U.S. fuel ethanol consumption. (U.S. EIA 2015)

Today, many people still view corn ethanol as a sustainable transportation fuel and a means to reduce U.S. dependence on fossil fuels. Much of the public also sees ethanol as environmentally positive, reducing GHG emissions without any negative impacts. However, the full environmental impacts and its contributions to global energy supplies are likely not well understood by the general public or most policy makers. Depending on the specific growing region and plant operations, cumulative fossil energy demand for producing ethanol might, at times, only be marginally lower or even higher than that of fossil fuel. An ethanol life cycle analysis conducted by von Blottnitz and Curran (2007) reported that impacts on acidification and human ecological toxicity were usually unfavorable. Concerns over food prices and food supplies have caused many to question the use of any food crop for energy production (Glozer 2011). In terms of scale, even if the entire 341 billion kg of corn produced in the U.S. was devoted to ethanol production, it could only replace roughly 7% of total U.S. oil consumption (Pimentel *et al.* 2008), meaning that at best, corn ethanol only offers a partial solution for energy security.

In this section, significant concerns related to the use of corn ethanol as a fuel are addressed. After considering the renewable fuels standard and the energy available from ethanol, social and environmental issues related to the manufacture and use of corn ethanol are discussed. The question of net energy return for corn ethanol will be discussed in detail in section 4.

3.1 Renewable Fuel Standard

The Energy Independence and Security Act of 2007 amended the Renewable Fuel Standard to include categories of renewable fuels that must be used in transportation fuel. Included in this was the requirement for conventional biofuel (i.e., corn ethanol), the production and use of which was to increase to 15 billion gallons per year by 2015 (U.S. EPA 2011). This requirement is in addition to the tax credit of 45 cents per gallon of ethanol blended into gasoline which has been in place since the early

1980s (Glozer 2011). Baring changes to the law, ethanol will remain artificially inexpensive and its use will remain at current levels, regardless of environmental impacts.

3.2 Energy Content of Ethanol

On a volumetric basis, ethanol contains less energy than gasoline. Burning a liter of gasoline releases 36.1 MJ of energy while burning a liter of ethanol releases 23.6 MJ of energy (Hammerschlag 2006). This simple relationship means that a 90% gasoline / 10% ethanol blend contains less energy than an equivalent volume of 100% gasoline, by roughly 4.5%. When used widely, as it is now, this serves to reduce the fuel efficiency (miles per gallon) of the entire U.S. automobile fleet. Thus, about 4.5% more fuel must be used by every vehicle, and about 4.5% more fuel must be delivered to gasoline stations throughout the country. The impacts of increased distribution costs and lower fuel economy have not been widely addressed in energy balance calculations.

3.3 Environmental & Social Issues

Despite the rapid expansion in its use, whether corn ethanol provides energy and carbon benefits remains unclear (Yang 2013, Pimentel and Patzek 2005). Certainly, any sustainable energy source must both provide energy and have a neutral or positive impact on the environment. This is required to avoid trading one set of problems for another, which can occur when all impacts are not considered. Thus, ecological advantages should outweigh any disadvantages to the environment and/or human health. A number of studies have been conducted considering energy and carbon benefits of corn ethanol and many have concluded that ethanol has benefits for carbon emissions and fossil fuel conservation (von Blottnitz and Curran 2007, Hill *et al.* 2006; Kim and Dale, 2005; Wang *et al.* 2007). However, a full accounting of the effects of corn ethanol suggest that its use comes with significant environmental costs.

An increasing number of scientific assessments point towards a broad range of environmental impacts, such as eutrophication, smog formation, acidification, and water and land use (Yang 2013). Pimentel *et al.* (2008) highlight the following significant issues with corn ethanol associated with corn production, ethanol production, and ethanol use:

1) Corn production causes more soil erosion than any other crop grown.
2) Corn production uses more nitrogen fertilizer than any other crop grown (~155 kg / ha.).
3) Corn production uses more insecticides than any other crop grown (~ 0.45 kg/ha.).
4) Corn production uses more herbicides than any other crop grown (~6.4 kg/ha.).
5) More than 1,700 gallons (on average) of water are required to produce 1 gallon of corn ethanol.
6) After accounting for land use change and fossil fuel requirements, ethanol production releases more carbon dioxide to the environment than would have been released from fossil fuel use alone.
7) Like gasoline, use of ethanol as a fuel releases pollutants such as peroxyacetyl nitrate, acetaldhyde, alkylates, and nitrous oxide.

Each of these environmental concerns as well as societal concerns over food supply and cost are addressed in more detail in the following sections.

3.3.1 Carbon and Greenhouse Gas Emissions

One of the primary drivers in the U.S. adoption of a renewable fuel standard—which currently includes ethanol mandates—was the promise of reduced carbon emissions. Many advocates claim that ethanol reduces GHG emissions by 20% to 50% compared to gasoline (Hofstrand 2009). However, these claims were not tested before implementing U.S. policy; rather, it may be that policy makers simply assumed ethanol would prove environmentally superior to gasoline (Glozer 2011). The promised benefits included global reductions of GHG emissions and local air quality improvements. Nonetheless, drafters of the renewable fuel standard may have also harbored some concern regarding the carbon benefits since the standard also includes mandates for future corn ethanol plants to achieve 20%

reductions in carbon relative to gasoline. Unfortunately for the environment, all ethanol facilities either operating or planned at the time of the standard were exempt from this mandate (Glozer 2011, McMahon and Witting 2011).

Contrary to the widely accepted belief that corn ethanol reduces carbon emissions, scientific analysis—including analysis from the Environmental Protection Agency—reports that GHG emissions from corn ethanol are higher than those of gasoline (McMahon and Witting 2011, Stashwick 2010). The non-scientific theory was simple…plants uptake carbon dioxide during photosynthesis and release it when ethanol is burned for fuel. The carbon cycle for biofuels (Figure 6) could indicate that all carbon released from combustion is returned to biomass through photosynthesis. However, the balance of carbon released by fossil fuel use, manufacture of agricultural chemicals, and land use changes are not fully evident in the figure. These factors can, and in many cases will, push the overall carbon balance negative.

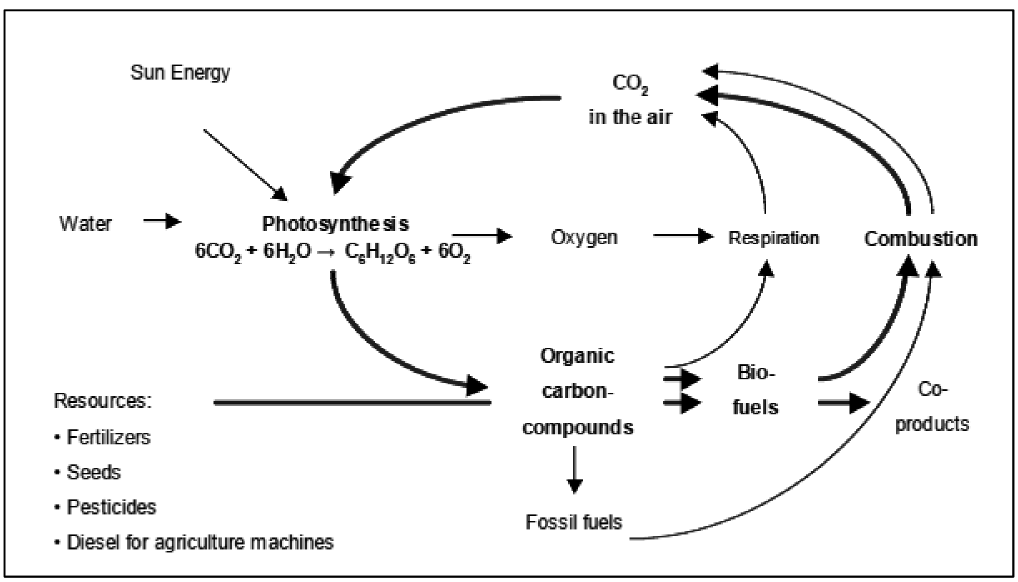

Figure 6: Carbon cycle of biofuels. Although carbon generation by fossil fuels is indicated, the magnitude of its contribution may not be fully captured. (Quirin *et al.* 2004)

Based on the expectation that emission mandates will eventually change how ethanol plants operate, EPA projections conclude that corn ethanol will have less GHG emissions in the future. Today, facilities producing ethanol release—on average—roughly 36 percent more GHGs than gasoline (Figure 7) (McMahon and Witting 2011, U.S. EPA 2011). Alternative studies suggest that corn ethanol could offer some carbon benefits (Hill *et al.* 2006; Kim and Dale 2005; Wang *et al.* 2007), but all of these results are projections for the future and not reflective of emissions today. Further, the impact of land use change resulting in soil carbon emissions, may be the most significant factor keeping ethanol from being carbon neutral (Yang 2013).

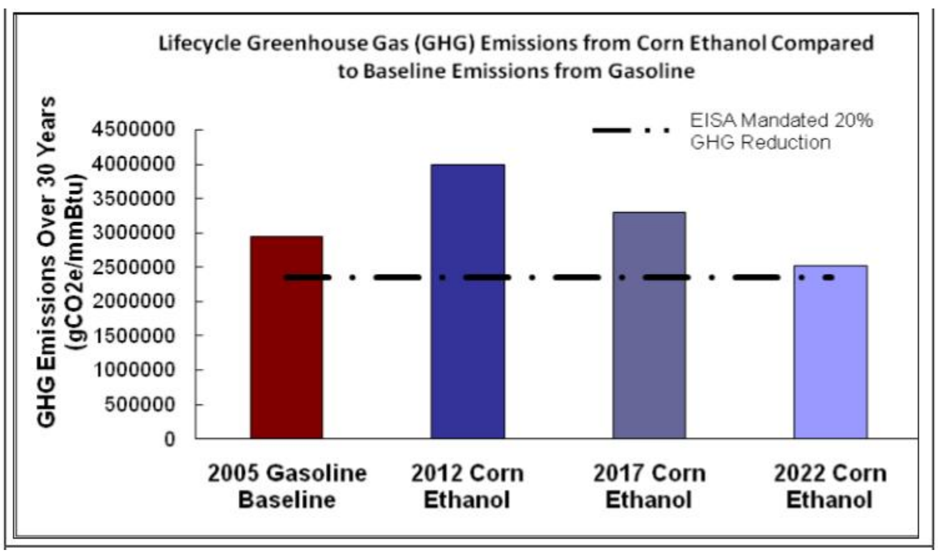

Figure 7: Greenhouse Gas (GHG) emissions in grams of carbon dioxide equivalents per million British Thermal Units (gCO2e/mmBTU) for gasoline in 2005 and projected for corn ethanol in 2012, 2017, and 2022. This indicates that in 2012, GHG emissions for corn ethanol are greater than emissions from gasoline, and that even in 2022, the mandated 20% GHG reduction for corn ethanol may not be achieved. (**McMahon and Witting 2011**)

Gomiero *et al.* (2010) estimated that the conversion of rainforests, peatlands, savannas, or grasslands to produce biofuels may cause the release of 17–420 times more CO_2 than any annual GHG reductions achieved by replacing fossil fuels with biofuels. They report that use of corn ethanol will nearly double GHG emissions over the next 30 years. Plevin *et al.* (2010) modeled the GHG emissions from indirect land-use change related to the expanded use of corn ethanol. Their results suggest that GHG emissions ranged from small—but not negligible—to several times greater than the life cycle emissions of gasoline. Such land-use changes lead to carbon release both through the removal of existing biomass—assumed to be converted to carbon dioxide—and the increased respiration that occurs in the disturbed soils.

Several changes in production could help reduce GHG emissions during ethanol production. Generally, these relate to corn growing and ethanol production, but some are simply dependent on geographic location. The use of no-till planting—also known as conservation tillage or zero tillage; a method of growing crops without disturbing the soil through tillage—can reduce soil respiration and erosion, thereby reducing carbon emissions due to land use change (Gomiero *et al.* 2010). Changes to new power systems could also improve the carbon balance. Such changes include the use of CHP systems, preferably with biomass as a fuel source. Ideally, a CHP system could eliminate direct fossil fuel use by ethanol plants (Chum *et al.* 2013).

3.3.2 Water

Agricultural production depends on water. Likewise, the production of fossil fuels also requires water. Any consideration of water use for corn ethanol production must include a comparison to the water required to produce these fuels. Production of one liter (L) of gasoline requires between 2.1 L of water (conventional petroleum crude) and almost 14 L (fuel from tar sands) (Fingerman *et al.* 2010). Water is used extensively in biofuel production (Figure 8). The amount of water required to produce a liter of corn ethanol is much greater than for fossil fuels due to its irrigation and production requirements. Although water is still readily available in most of the U.S., population growth and dietary changes are projected to drive a 70–90% increase in demand for water worldwide in the next 50 years

(Fingerman *et al.* 2010). Further, water is being used for irrigation in some agricultural areas at rates 10 times faster than aquifers are being replenished (Pimentel and Patzek 2005, Pimentel 2003), suggesting that rates of water use are not sustainable. The increasing water demands and decreasing supply means that expanding water use for energy production may soon compete with its use for food production.

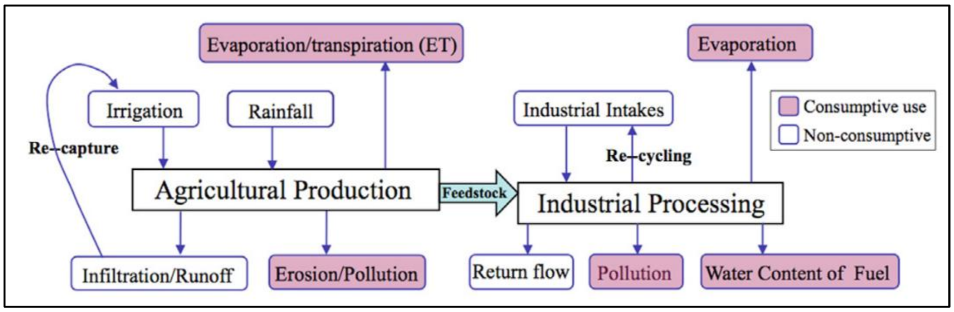

Figure 8: Schematic of water uses in the biofuel life cycle. Flows of water both into and out of the bioenergy production system are represented (Fingerman *et al.* 2010)

Processing corn into ethanol requires at least 15 L of water per liter of ethanol—primarily for steam generation and cooling (Pimentel *et al.* 2008); however, the bulk of water use for corn ethanol production is for growing corn. Examinations of water-use for growing corn usually separate irrigated corn from non-irrigated corn. Clearly, a healthy crop requires a certain amount of water. Further, any water—be it rainwater or irrigation water—not used for corn would be available for other uses. While rain fed crops do not require certain energy inputs for pumping and distributing water to the crops, the amount of water dedicated to crops and unavailable for other uses must be roughly equivalent.

Quantifying water-use is much easier for irrigated vice non-irrigated crops since the amount of water pumped is known directly while the amount of rainwater falling over cropland can only be estimated. Also, water-use—based on irrigation—varies tremendously with geographic location. According to the U.S. EPA (2011), less than 1 percent of the more than 14 million corn acres in Iowa were irrigated. In contrast, approximately 60 percent of Nebraska's 9.5 million acres of corn was irrigated in the same year. In 2008 a national average of 1 acre-foot (325,851 gallons) of water was used on an acre of irrigated corn. In Iowa and Illinois, the rate of corn irrigation was half the average, while in Nebraska the rate was 0.8 feet (260,680 gallons) per irrigated acre. Approximately 5 billion gallons of irrigation water could be used in a single season in places like Iowa and Illinois versus 300 billion gallons in Nebraska in 2011 (U.S. EPA 2011). A USDA survey reported irrigation water-use was about 1200 L/Mg of corn in Iowa compared to 141,000 L/Mg in Nebraska in 2008 (Chum *et al.* 2013). The difference relates to the amount and timing of rain, which varies significantly with both location and year. Similarly, Fingerman *et al.* (2010) reported the amount of water required to produce ethanol from biomass in California ranged from 500 L to 3500 L of water per liter of ethanol.

3.3.3 Land Use

A greater amount of land is used for biofuels—primarily corn ethanol—than any other energy source despite providing less than 5% of the total U.S. energy. Under current law, incentives for biofuel production will result in at least 206,000 km^2 of new land for biofuel production by 2030 (Gomiero *et al.* 2010). By one estimate, producing ethanol to replace 10% of U.S. gasoline would require 22 million ha., about 10 times greater than the 2.2 million ha. used for corn ethanol production in 2002 (Pimentel 2003). The concern with land use relates both to aforementioned carbon emissions from land-use change and to the competition for food production.

Gomiero *et al.* (2010) has claimed that agricultural soil, when properly managed, can be an important carbon sink. For this to be the case, however, requires proper land-use such as reducing chemical inputs and practicing no-till farming. Additionally, they report that returning residues to the soil rather than removing them can convert many soils from carbon ‘‘sources’’ to carbon ‘‘sinks’’. This is important with regards to the use of corn stover as an energy source—claimed as another way to reduce carbon emissions—and demonstrates the complexity of conducting a life cycle analysis of corn ethanol.

3.3.4 Fertilizer

Fertilizer-use for corn is larger (per acre) than for any other biofuel crop. A survey by the U.S. EPA (2011) covering 19 states found that 138 pounds per acre of nitrogen fertilizer were used on corn crops in 2005. A separate study found that an average of 55 pounds per acre of phosphorus were applied to corn crops in Iowa. Using EPA assumptions of 154 bushels per acre and 2.7 gallons of ethanol per bushel, they report 0.33 pounds of nitrogen and 0.13 pounds of phosphorus applied per gallon of ethanol produced. Beyond the environmental impact of fertilizer production, its use for corn production increases the carbon emissions for ethanol production and also potentially results in eutrophication of surface waters (including the Gulf of Mexico). Nitrogen run-off from corn fields can range from 24% to 36% of the amount applied, with higher percentages during years with high rainfall. Further, when corn stover is removed, percentages of nutrient run-off may increase (U.S. EPA 2011).

3.3.5 Pollution

Air and water pollution are a concern with any chemical-based energy source, and it may be unrealistic to assume a liquid fuel will have no associated pollution. Thus, the pollution caused by corn ethanol production should be compared with pollution caused by production of the fossil fuel it is replacing. Nonetheless, comparing potential for, and impacts of, events such as nutrient run-off from corn fields against major oil spills is not possible; the events are too disparate. Fortunately, it is possible to quantify known pollution effects and also the differences between the use of 100% gasoline (E0) and 90% gasoline / 10% ethanol (E10). However, a clear determination of which is better depends on what pollutants one considers most important.

Pimentel (2003) examined air and water pollution associated with ethanol production facilities. He highlights that roughly 12 L of wastewater are generated for each liter of ethanol. The environmental and financial costs associated with treating this water are often not captured in considerations of ethanol production. He also notes that that EPA has, in the past, threated to shutdown ethanol producers due to high air-pollutant emissions (Pimentel and Patzek 2005). Yang (2013) reported that ethanol generates potentially larger freshwater toxicity than gasoline due to pesticide use, specifically from atrazine, acetochlor, chlorpyrifos, and cyfluthrin. He also reports that corn ethanol may result in greater non-cancer impacts on human health than gasoline alone, while gasoline likely presents a greater cancer risk to human health.

Niven (2005) studied the pollution impact of E10 and found that it may result in higher photochemical smog, will result in higher soil and groundwater contamination, and offers minimal advantages for GHG emissions compared with E0. Simplistically, ethanol introduces oxygen to a fuel mixture and thereby improves combustion efficiency. However, Niven (2005) suggests that the process is much more complex. He reports that E10 results in lower tailpipe emissions of total hydrocarbons and carbon monoxide than gasoline, it also causes a substantial increase in emissions of acetaldehyde (a probable carcinogen and precursor to respiratory irritant peroxylacetate nitrate), with levels increasing by about 100–200% and in some cases by up to 700%. E10 has also been found to have higher emissions of nitrogen oxides (NOx). Overall, E10 likely produces lower total hydrocarbon, carbon monoxide, benzene, and particulate tailpipe emissions than E0, but substantially higher acetaldehyde and ethanol emissions, and higher NOx, methanol, and ethylene emissions.

3.3.6 Food Supply

There is significant debate regarding the use of food crops and arable land for the production of energy. Supporters in the U.S. cite low food prices and claim that the use of food crops for fuel will help preserve farmers and farmland for future use. Critics cite the worldwide food shortages to claim that using food for fuel is wasteful and shortsighted (Pimentel *et al.* 2008). Clearly, this issue is complex. Food shortages typically result from distribution, transportation, and financial reasons rather than total worldwide food availability, and claiming that food grown in the U.S. would necessarily find its way to malnourished populations does not capture the complexity of the situation. Conversely, claims that farmers require an ethanol market to sustain farms appears to be self-serving for those who gain financially from ethanol production. There seems to be no clear determination as to whether using crops for energy is good or bad (Quirin *et al.* 2004).

Nevertheless, it is true that using any food crops—including corn—for energy production raises food prices; this predominantly impacts low-income individuals. By some estimates, using corn for ethanol increases the price of U.S. beef, chicken, pork, eggs, breads, cereals, and milk by 10% to 30% (equivalent to billions of dollars) (Pimentel *et al.* 2008). Further, when considered in total, green plants in the U.S. collect an estimated 32 quads (1 quad = 1015 BTU) of solar energy per year. The U.S. currently uses roughly 100 quads annually. Thus, even if all biomass is converted (at 100% efficiency) to fuel, it would still only replace about one third of the current U.S. energy requirements (Pimentel *et al.* 2008).

3.3.7 Economics / Subsidies

Compared with gasoline, ethanol—produced by corn or other biomass—is not economical, and its use must be supported by subsides. Direct federal subsidies for ethanol in the U.S. approach one billion dollars each year. Most other countries, including Brazil, also subsidize ethanol production. In the late 1990s, consumers in Brazil paid an estimated $2 billion dollars per year in overpriced gasoline to subsidize sugarcane ethanol production (Niven 2005). Pimentel and Patzek (2005) estimated that combining production costs and tax subsidies results in an ethanol cost of $1.24 / L. When accounting for the lower energy capacity compared to gasoline, the cost for equivalent energy from ethanol is $1.88 / L ($7.12 / gallon). All drivers and taxpayers are impacted by this high fuel cost, but as it is spread across the U.S. population, the impact often goes unnoticed.

Certainly, fuel cost is important since it impacts the cost of all goods and the overall economy. Nonetheless, many would argue that higher fuel cost is a small price to pay to reduce the use of fossil fuels. There is some merit to this argument—at least for environmentalists—but it may not apply to ethanol if its use does not reduce fossil fuels consupmtion. Actual fossil fuel reduction depends on the net energy balance of corn ethanol, which is addressed in the next section.

4. Energy Return on Investment

Energy Return on Investment (EROI) is important for all energy sources as it impacts how economies and societies function. Simply defined, EROI is the ratio of energy obtained from a process relative to the energy input required. Most authors present it as a ratio (e.g., 3:1) or as just the first number (e.g., 3). An EROI of 1 (i.e., 1:1 or 1) means that the process under consideration provided the same amount of energy as the amount of energy input to the process. An EROI of 5 means that the process returned 5 times as much energy as the energy input to the process. EROI can be expressed by the simple equation (Murphy *et al.* 2011):

$$EROI = \frac{Energy_{Out}}{Energy_{In}}$$

In addition to EROI, two related concepts are also important to consider for energy calculation: net energy and gross energy. Net energy is the energy gained from an activity beyond that which is needed to maintain that activity. Net energy can be considered the energy surplus or energy profit; thus, it is the energy that is delivered to society by an energy generation or extraction process. Gross energy is the total amount of energy input to an energy extraction process required to provide a certain net energy. Thus, gross energy is always higher than net energy (Murphy *et al.* 2011).

As will be discussed in more detail below, these concepts are useful for understanding the importance of an energy sources' EROI. By these definitions, it is mathematically and logically impossible for fuels with an EROI of less than one to deliver any net energy. Recent studies of EROI have focused on three area: (1) how much gross energy must be extracted to deliver one unit of net energy to society, (2) the Net Energy Cliff, and (3) the minimum EROI for fuels to sustain current society (Murphy *et al.* 2011). Each of these concepts is relevant to a discussion of corn ethanol and will be addressed in detail.

Economic growth requires a society to generate increasing surplus energy. Over the past several hundred years, economic growth has been powered by fossil fuels. These fuels have high EROI values ranging from 10 to (at times) over 100. Such high EROI values are possible because much of the energy contained in the fuels was collected and stored over millions of years, but is being released over decades. Thus, energy inputs are limited to recovery (e.g., drilling, pumping), conversion (e.g., changing crude oil to gasoline), and transportation. All these process are energy intensive, but the main work of collecting the energy was completed long ago and is not part of energy balance calculations. Alternative energy sources generally have lower EROI values, and so, the depletion of fossil fuels could be coupled with the reduction of economic growth (Hook and Tang 2013).

Most non-fossil sources of energy require a greater energy input in order to recovery surplus energy for society. Additionally, renewable energy (with the exception of biomass) requires upfront energy investment to provide future energy returns. Unlike fossil fuels that required continuous energy investment but provide immediate energy return, most renewable energy options introduce a significant delay between energy investment and return (Sgouridis and Csala 2014). For instance, use of hydroelectric power requires building a dam and manufacturing, installing, and operating turbines. Harnessing solar or wind energy requires building and installing equipment (i.e., photovoltaic collectors, wind turbines); the EROI of these systems depends mainly on the initial energy input and their effective operating life. Biomass-based liquid fuels—such as corn ethanol—are more similar to fossil fuels since the energy generated is available as the fuel is produced; only the delay for biomass growth is required (Hook and Tang 2013).

The inevitable depletion of fossil fuels and rising expense of their recovery, has been coupled with proposals for maintaining current industrialized society using a portfolio of renewable energy sources. Such a transition in energy sources, even if able to replace the net energy currently available to society, will require changes in how energy is produced, stored, and used. Additionally, several studies have predicted economic and social consequences when EROI drops below a minimum value (Hook and Tang 2013, Murphy *et al.* 2011, Hall *et al.* 2014). If these predictions prove accurate, addressing energy availability will become increasingly important over the next several decades.

4.1 Impact for society

At the turn of the 21st century, the balance between available energy sources and the ability to recover these resources made possible the cheapest food and energy the world has ever known (King 2015). In the U.S., the rapid expansion of natural gas fracking is continuing this trend, at times driving the cost of energy to new depths. An analysis by Murphy and Hall (2011) suggests that about 50% of the changes in economic growth over the past 40 years can be explained by the changes in oil consumption, enabled by both increasing oil supply and low oil prices. They report that changes in oil consumption led to changes in economic growth, and that economic growth is enabled/constrained by available energy. GDP closely tracks energy consumption—and oil consumption in particular (Figure 9) (Tverberg 2015). As we near (or pass) the time of peak oil, the supply of high EROI oil will plateau and eventually decline (Murphy and Hall 2011).

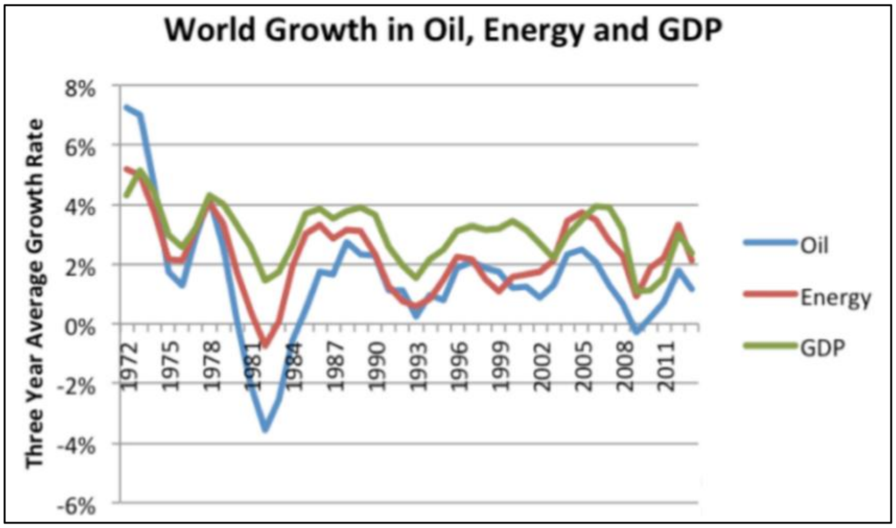

Figure 9: Growth rates in oil use, energy, and gross domestic product (GDP) from 1972 to 2014 (Tverberg 2015).

The current EROI for fossil fuels ranges from roughly 80 for coal to 11-20 (depending on the source) for oil and gasoline. On a global average, for every barrel of oil invested in seeking and producing more oil, roughly 20 barrels are delivered to society (Hall *et al.* 2009). At this return, oil provides sufficient energy surplus to support an expanding human population along with its advanced industrial society. It also provides for the large agricultural yields that deliver food to this growing population and enables the bulk of society to be employed in professions not related to the energy industry. However, as we exploit more and more of the earth's limited fossil fuel supply, the cost of recovery and processing the fuels will necessarily, eventually increase, thereby decreasing the EROI. Not surprisingly, there has been a clear trend of decreasing EROI for oil over the last two decades. EROI for global oil extraction declined from 36 in the 1990s to 18 in 2008 (Murphy and Hall 2011). This decline probably resulted from the increased use of enhanced recovery techniques (e.g., nitrogen injection, fracking) at existing sites and the more frequent exploitation of oil sources that require more energy to recover (e.g., deep sea locations).

As EROI declines, more expended energy is required to generate surplus energy for society. The impact of this change can be best illustrated by considering two example societies that were proposed by Murphy and Hall (2011). Society A has an energy source that can be extracted at an EROI of 18 (representing oil today). Society B has an energy source that can be extracted at an EROI of 1.2 (representing of an alternative fuel such as corn ethanol). Consider a situation in which both societies require 100 units of surplus (net) energy (Figure 10).

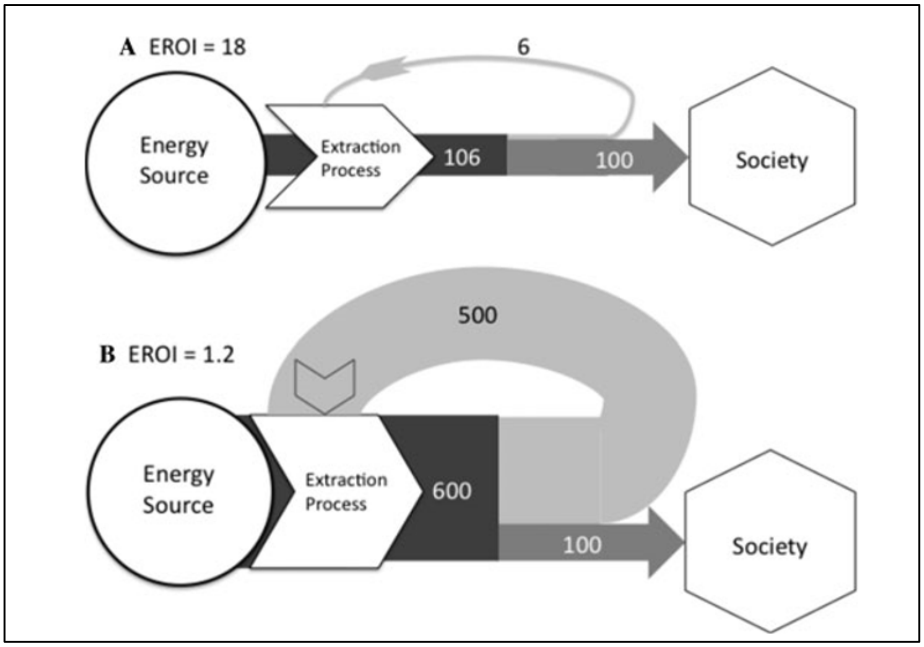

Figure 10: The flow of energy from the point of extraction to society accounting for the energy cost of extraction. Assuming that 100 units are delivered to each society, and the energy source is extracted at an EROI of 18 for Society A and 1.2 for Society B (Murphy and Hall 2011).

Owing to the different EROI of the fuel sources, the amount of gross energy that must be generated to provide 100 units of net energy is vastly different for the two societies. To supply society with 100 units of net energy using an extraction process that has an EROI of 18, Society A requires 106 units of gross energy (Figure 10A) (Murphy and Hall 2011). Thus, just six units are necessary to maintain the investments associated with energy extraction. To deliver the same amount of net energy from a process with an EROI of 1.2, Society B requires 600 units of gross energy (Figure 10B). At an EROI of 1.2, much more energy (500 units) is required to support the balance of society than is provided to society

(Murphy and Hall 2011). This relationship between % energy delivered by a fuel as a function of EROI is known as the Net Energy Cliff (Figure 11).

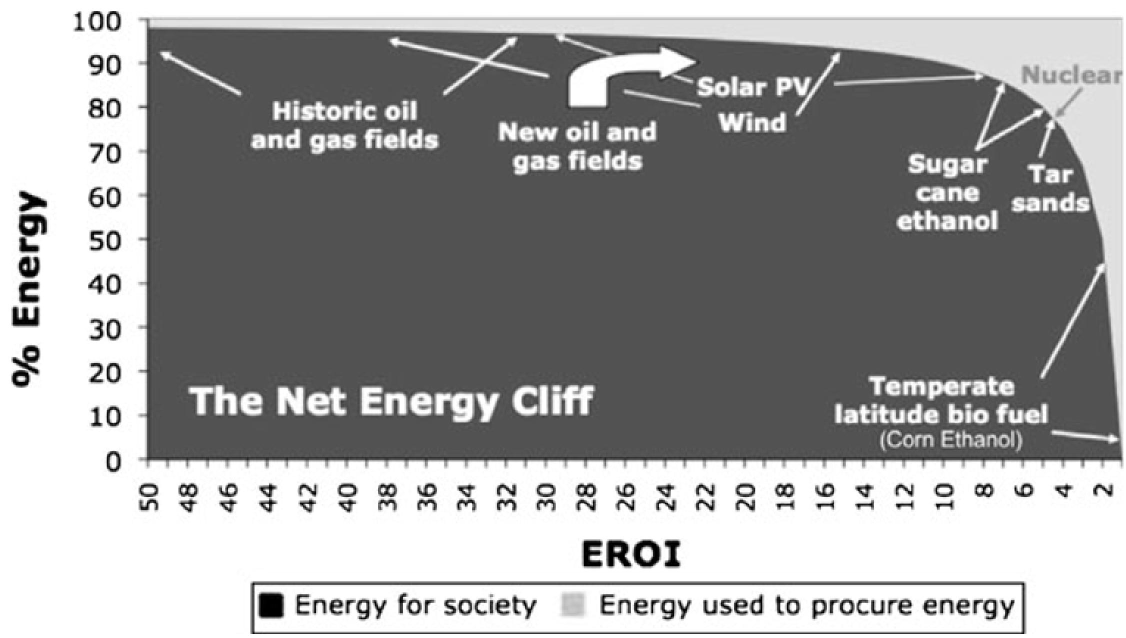

Figure 11: The Net Energy Cliff, showing how, as EROI approaches 1, the percent of energy delivered to society as net energy drops rapidly (Murphy *et al.* 2011).

An alternative examination by Murphy and Hall (2011) considers world oil resources under a situation of declining EROI. They begin with the assumption that the current EROI for oil production is 18, so that of the 30.8 gigabarrels (Gb) of oil produced in 2008, 29.1 Gb were delivered to society as net oil. Further, they assume the world has roughly 925 Gb of oil remaining. If the rate of consumption and the EROI for production remain constant, then the world has 30 years of conventional oil remaining (925 Gb divided by 30.8 Gb per year). Consider now, the impact of reducing the EROI by one half (EROI = 9). Gross energy would increase to 34.6 Gb and leave only 27 years (925/34.6) of oil supply. Further, if EROI was reduced to 3, gross energy demand would increase to 46.2 Gb per year, and reduce the remaining supply of conventional oil to 20 years. As EROI approaches 1, the length of time the oil supply will last approaches zero (Murphy and Hall 2011, Deng and Tynan 2011).

The impact of decreasing EROI can also be considered from a financial perspective, as was done by Hall *et al.* (2009). Using 2008 oil prices as a reference point, they assume that the real price of oil—relative to other goods and services—increased to $140 a barrel while the total size of the U.S. economy remained roughly constant. In this scenario, some components of the economy would necessarily be diverted to pay for the more expensive oil. At this price point, about one fifth of the U.S. economy (17 billion barrels per year at $140 per barrel = $2.38 trillion; compared to 2008 U.S. GDP of $12 trillion) would be required to support the remaining four fifths. As the price increases further to $250 per barrel, about one third of all economic activity would be required for oil. If oil reaches $750 a barrel, the entire economy ($12 trillion) would be required to purchase the energy required to run the economy—resulting in no net output. Although devoting the entire economy to oil is not a realistic scenario, this simple calculation demonstrates how sensitive the economy is to energy cost. Since cost and EROI are linked, economic output is also closely linked to the EROI of our primary energy sources. (Hall *et al.* 2009)

The above analyses demonstrate that shifting our primary energy supply to a low EROI fuel will also necessitate shifting enormous resources to energy production. EROI values for several common energy sources today vary widely (Figure 12). Certainly, the EROI of oil and coal are high enough to support current society, as they are doing this today. Since an EROI of 20 supports the needs of society and an EROI of 1—which provides no net energy—is unsustainable, there is probably a minimum EROI (between 1 and 20) below which a fuel no longer will support modern society. Consideration of a minimum EROI is important—especially in relation to the EROI of corn ethanol—as it provides an indication of the viability of any potential replacement for fossil fuels.

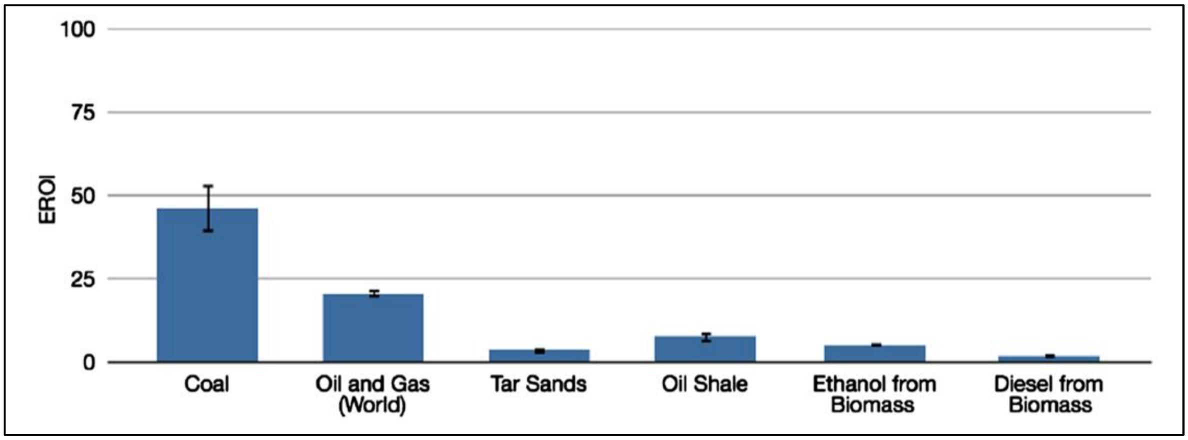

Figure 12: Mean EROI (with error bars) for select primary fuel sources (Hall *et al.* 2014).

4.2 Minimum EROI for liquid fuels

There is no consensus in the literature for the minimum EROI a fuel must have to be energetically and economically sustainable. Mathematically, any EROI below 1 cannot be sustainable since acquiring the fuel requires more energy than the fuel provides. However, as the EROI of a fuel falls towards 1, the gross energy and finances required to support production of the fuel increase rapidly as demonstrated by the Net Energy Cliff. As such there should be an EROI below which a primary fuel cannot sustain society. Both philosophically and practically, a minimum EROI must exist, but since it is a theoretical construct—especially given that society uses a combination of energy sources—its value depends on ones' perspective.

Hall *et al.* (2009) conducted an analysis to assess the minimum EROI that a society must attain from its energy exploitation to support continued economic activity and social function. They assume that for any organism or system to survive or grow it must gain substantially more energy than it uses in obtaining that energy. Also, energy is required to obtain, deliver, and use any fuel for any application. While theoretically it could be possible to use a large quantity of fuel with an EROI of 1.1 to provide surplus energy to society, this is likely impractical. Rather, Hall *et al.* (2009) include the cost of obtaining and transporting the fuel in the overall EROI calculation; this reduces the effective EROI. They found that using this approach approximately triples the EROI required to use a fuel for primary energy. Their calculation suggests that rather than a minimum EROI of 1 (i.e., the limit below which no net energy is provided), the effective minimum EROI should be 3.

Their analysis applies the following logic. Considering a fuel with an average EROI of 10, Hall *et al.* (2009) estimate that roughly 40% of the available energy is used in the refining, conversion and delivery chain—resulting in an EROI of about 6 at the point of use. They further postulate that energy services (e.g., transport in a car) are desired, not energy itself (e.g., gasoline) thereby necessitating an infrastructure to support energy investments. When the associated energy costs are included, it results in a lower effective EROI. After the energy costs for refinement and blending, transport, and infrastructure are included, they calculate an effective EROI of 3. Based on their assumptions and calculations, roughly twice as much oil is used to deliver the service than is used in the final-demand machine (i.e., automobile). They also consider a minimum EROI for ethanol using similar assumptions regarding corn conversion, delivery chain, and infrastructure requirements. Consistent with their general conclusions, a detailed analysis found that an EROI of at least 3 is required to avoid the need to subsidize its production with fossil fuels. In a related analysis, Inman (2013) reported a minimum EROI for liquid fuels of 5-9 (Figure 13), but did not support his claims with any discussion.

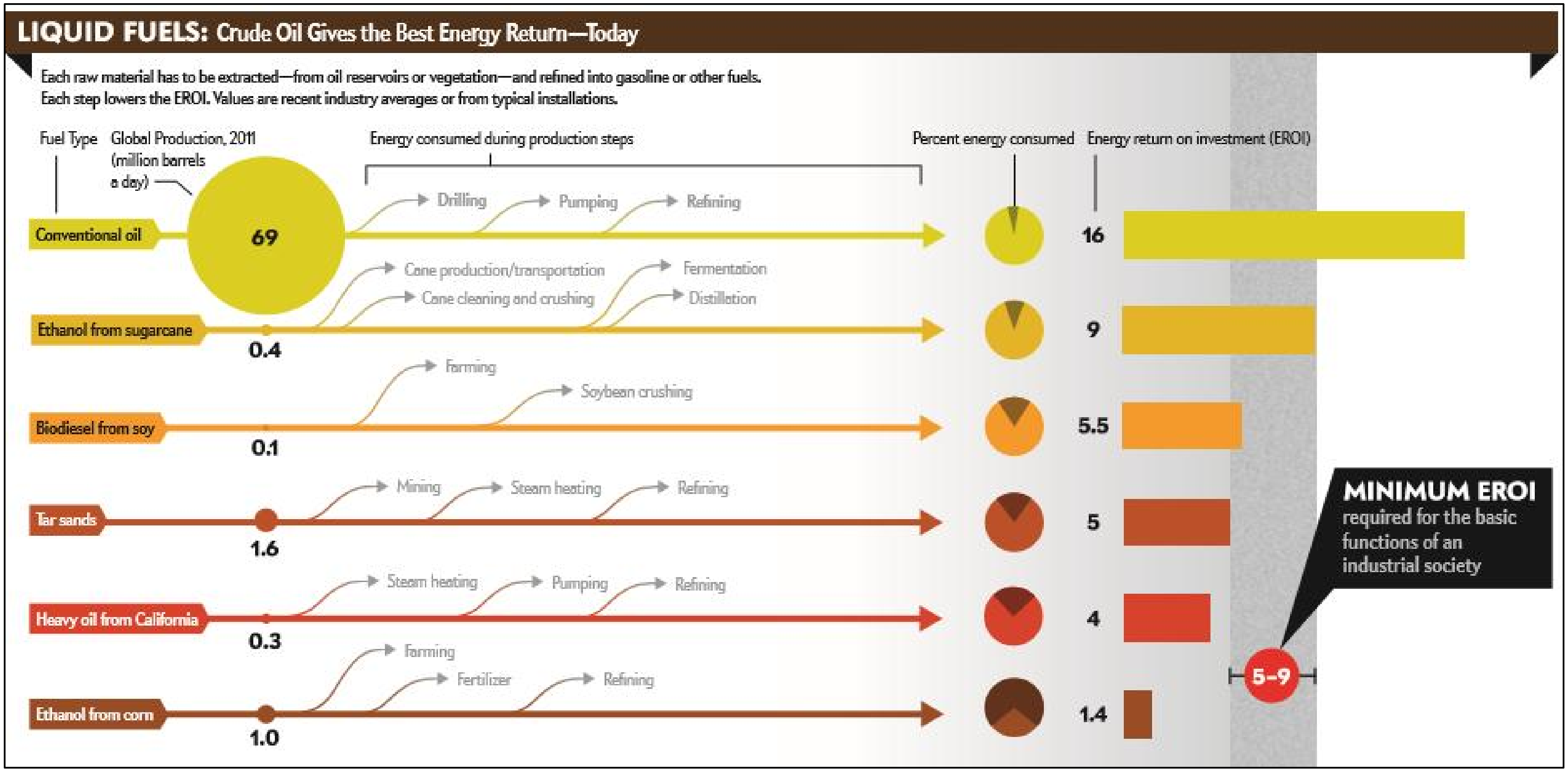

Figure 13: Global production rates and EROI for several liquid fuel sources (Inman 2013). Minimum EROI to support an industrial society is estimated at 5-9, suggesting that fuels including corn ethanol cannot support current energy demands of society.

Hall *et al.* (2009) conclude that any fuel with an EROI less than the current mean for society (~10) may in fact be subsidized by the general petroleum economy. For instance, fuels such as corn-based ethanol that have marginally positive EROI (<2) require subsidizes of about two times more than the energy value of the fuel itself. Thus, any debate regarding the EROI of corn ethanol should be focused not on whether it is greater than 1, but on whether it is above a minimum EROI of ~3 or above the average fuel EROI of ~10. Additionally, the minimum EROI calculated by Hall *et al.* (2009) is just that, a minimum to support a sustainable society. Using fuels at the minimum EROI may not provide surplus energy for such things as art, medicine, and education. Because of this, EROI is likely to become an extremely important issue in defining our future economy and quality of life (Hall *et al.* 2009).

4.3 Ethanol EROI

Much of the discussion regarding the use of corn ethanol as a gasoline additive has focused on its EROI or the net energy produced after corn and ethanol production. Many studies of corn ethanol—especially those that do not consider environmental impacts—simply state that if the energy returned is greater than the energy invested, then the fuel should be produced (Hall *et al.* 2009). The bulk of these studies do not consider the concept of a minimum EROI for a sustainable fuel, and, beyond addressing net energy, do not consider if ethanol is sustainable. Calculation of EROI requires comparing inputs and outputs (Figure 14)

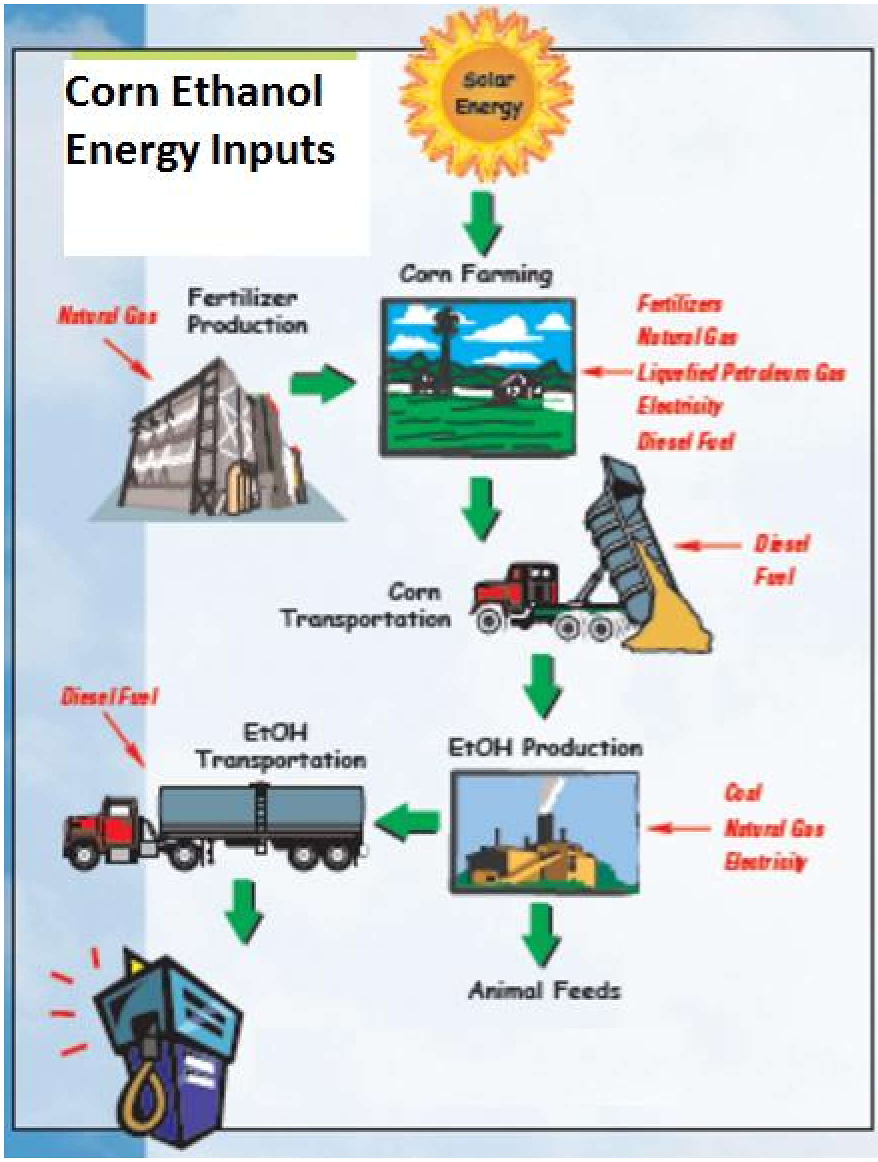

Figure 14: Energy inputs to the production of corn ethanol (Mexico Energy Forum, 2012)

Published EROI values for ethanol over the past fifteen years range from 0.82 (Pimentel and Patzek 2005) to 2.3 (Gallagher *et al.* 2016). The large difference in values does not simply reflect improvements in energy efficiency, but rather, fundamentally different approaches to accounting for energy outputs (e.g., coproduct credits) and energy inputs (i.e. whether or not to include the energy required to compensate for environmental impacts in the future) (Murphy and Hall 2010). For corn ethanol—and most fuels in general—future environmental issues are poorly understood and rarely quantified; as such, many published EROI values are probably higher (i.e., more favorable) than they would be if all impacts were tallied (Hall *et al.* 2009).

One of the main objectives of this analysis is to determine if ethanol is sustainable based on its net energy return. Certainly, with an EROI below unity, the fuel is not sustainable. Alternatively, an EROI of 2.3 begins to approach the estimated minimum EROI for a sustainable fuel. The full range of EROI values for corn ethanol that have been published by creditable researchers and government agencies are probably reasonable, based on the assumptions made for each study. The critical question then becomes, what assumptions regarding energy inputs and energy outputs should be included (i.e., what are the appropriate boundary conditions for the calculation). Because the calculated values of EROI are near unity, the assumptions one makes and their approach to energy inputs and outputs can tip the EROI of corn ethanol from below unity to above 2. Understanding which approach provides the correct EROI is impossible since the validity of each is subjective, depending on perspective and weight placed on various factors. However, understanding how EROI is calculated for corn ethanol and what factors affect the range of values is a start.

4.3.1 Comparison of Studies

A comparison of EROI studies should begin with how and why the corn ethanol debate developed. Almost certainly the debate evolved from disagreements between the ethanol lobby—with a vested interest in promoting the use of corn ethanol—and two panel studies published by the U.S. Department of Energy in the early 1980s. The findings indicated that the conversion of corn into ethanol was energy negative. The response to these studies—by supporters of corn ethanol—initiated the debate over what energy inputs and outputs should be used for net energy calculations (Pimentel and Patzek 2005).

Determining which inputs and outputs to consider in an EROI analysis depends entirely on the designation of the system boundary. Definition of the boundary sets the inputs (energy/mass units that enter the system) and an outputs (energy/mass units that exit the system) (Murphy *et al.* 2011). All studies considered include direct energy and estimates of system efficiency. Thus, all the nonrenewable energy required to grow corn and to process it into ethanol are tallied and compared with the energy value of the process outputs (i.e., ethanol and co-products). Most studies include only these primary energy inputs since secondary inputs, such as energy used to manufacture the materials used in the construction of ethanol facilities, farm vehicles, irrigation equipment, and transportation vehicles, and co-product credits are extremely difficult to quantify (Hall *et al.* 2011, Shapouri *et al.* 2003). Although there may not exist a single acceptable system boundary, comparative studies must use the same boundaries if they are to provide useful results (Hall *et al.* 2011).

Comparing studies of corn ethanol energy return is not straightforward because data sources and assumptions vary widely. Primary values used in several studies for corn yield, fertilizer application rate, energy to produce fertilizer, corn ethanol conversion rate, energy for corn ethanol conversion, and co-product credits are detailed in Table 1. Whereas some of these values (e.g., corn yield) are roughly the same for all studies, others, such as energy to produce fertilizer vary greatly.

Table 1: Energy inputs from select corn ethanol studies (Shapouri *et al.* 2003).

Energy input estimates from selected corn ethanol studies.

Study (year)	Corn Yield (t/ha)	Nitrogen Fertilizer Application Rate (kg/ha)	Nitrogen Fertilizer Production (MJ/kg)	Corn Ethanol Conversion Rate (L/kg)	Ethanol Conversion Process (MJ/L)	Total Energy Use[a] (MJ/L)	Coproducts Energy Credits[a] (MJ/L)	Net Energy Value[a] (MJ/L)
Pimentel (1991)	6.90	152	17.97	0.373	20.54	36.52 (LHV)	5.99	–9.34
Pimentel (2001)	7.97	145	16.05	0.373	20.94	36.53 (LHV)	5.99	–9.35
Keeney and DeLuca (1992)	7.47	151	18.16	0.381	13.51	25.42 (LHV)	2.25	–2.35
Marland and Turhollow (1990)	7.47	142	14.90	0.373	13.97	20.61 (HHV)	2.27	5.06
Lorenz and Morris (1995)	7.53	138	13.21	0.380	15.04	22.6 (HHV)	7.69	8.53
Ho (1989)	5.65	NR	NR	NR	15.89	25.09 (LHV)	2.93	–1.11
Wang et al. (1999)	7.84	147	10.09	0.380	11.39	19.08 (LHV)	4.17	6.27
AAFC (1999)	7.28	140	NR	0.401	14.05	19.01 (HHV)	3.92	8.31
Shapouri et al. (1995)	7.65	125	10.06	0.377	14.85	23.09 (HHV)	4.2	4.31
This study (2002)	7.84	145	8.80	0.396	14.43	21.53 (HHV)	4.01	5.88

[a] The midpoint or average is used when studies report a range of values.

One reason why the net energy values vary so widely is data availability. Obtaining current and accurate estimates of fertilizer and energy use can be challenging as these are typically obtained through surveys of farmers and ethanol producers. As both of these groups may be included to provide data that suggests the industry is profitable, survey results could be skewed. Further, survey locations and timing can also affect results since fertilizer and irrigation requirements, corn yield, energy costs and type, and co-product production varies from year-to-year and from location-to-location.

An alternative accounting for energy-use was conducted by Hammerschlag (2006). Hammerschlag breaks out the energy used for each step in the process (Table 2) and includes the EROI (listed as rE in Table 2) from each study considered. The outlier in Table 2 is the Pimentel and Patzek (2005) study which calculates an EROI below unity. Hammerschlag attributes this to a series of conservative assumptions regarding energy required at each step, including the amount of fertilizer required.

Hall, Dale, and Pimentel (2011) considered the different EROI results published by two of the authors in Kim and Dale (2005) and Pimentel and Patzek (2005). The different approach used in these two papers resulted in very different EROI values of 1.62 to 1.73 from Kim and Dale (2005) and 0.82 from Pimentel and Patzek (2005). The estimates of the total energy used to generate a liter of ethanol differ because of the inclusion (or not) of different costs. Pimentel and Patzek include more categories of inputs and estimate the total energy input to generating a liter of ethanol as 28.1 MJ; Kim and Dale and others estimate ~16.7 MJ, which is 59% of the value of Pimentel and Patzek. However, the principal reason for the large difference between the EROIs derived from these two papers was the difference in the allocation approaches for co-products. Kim and Dale used a “system expansion” approach to estimate that only 74% of the total energy costs should be allocated to generating the ethanol and the remainder to the primary co-product, DDG. Their system expansion approach assigned the energy “cost” of producing soy bean meal—the major commodity with which DDG competes in the market—to

DDG. This allocation accounted for about a half of the difference between the EROI of the Pimentel and Patzek (2005) and the Kim and Dale (2005) papers. Another roughly one third of the difference was due to differences in estimates of the energy intensity of the inputs (i.e., supply chain issues), and about 15% was due to the greater inclusivity of costs by Pimentel and Patzek (Hall *et al.* 2011).

Table 2: Results of select corn ethanol studies (Hammerschlag 2006)

Results of Corn Ethanol Studies, Grouped by Common Process Steps and Normalized to HHV (Sums May Not Match Totals Due to Rounding Error)

	Marland & Turhollow 1991	Lorenz & Morris 1995	Graboski 2002	Shapouri et al. 2002	Pimentel & Patzek 2005	Kim & Dale 2005
milling technology:	wet	mixed	mixed	dry	dry	dry
	all values in MJ per liter ethanol unless otherwise noted					
	fuel and electricity					
agriculture						
fuel	2.0	0.7	2.2	2.7	2.0	0.8
electricity	0.2	2.0	0.5	0.6	0.5	0.1
feedstock transport		0.4	0.5	0.6	1.5	0.5
industrial process						
fuel	10.5	10.9	11.8	10.0	11.7	12.5
electricity	3.5	3.2	2.9	3.6	5.3	2.2
ethanol distribution			0.4	0.4		0.6
total fuel and electricity	16.1	17.1	18.4	17.9	21.0	16.8
	upstream energy					
agriculture						
fertilizer	4.2	3.6	2.6	2.3	4.7	2.0
biocides	0.3	0.3	0.2	0.4	1.3	0.4
other		0.9	0.3	0.1	3.1	0.1
other nonagriculture					0.1	
total upstream energy	4.5	4.9	3.2	2.8	9.2	2.5
	calculation of r_E					
gross energy input	20.6	22.0	21.6	20.7	30.1	19.3
coproduct energy input	(2.3)	(7.7)	(4.5)	(3.7)	(2.0)	(4.8)
net energy input	18.3	14.3	17.1	17.1	28.1	14.5
allocation factor (%)	89%	65%	79%	82%	93%	75%
r_E (unitless)	**1.29**	**1.65**	**1.38**	**1.38**	**0.84**	**1.62**
	reference data					
upstream fuel included?	yes	no	yes	yes	yes	yes
electricity heat rate	3.0	2.4	3.0	2.7	3.3	3.2–3.4
corn yield (Mg/ha)	7.5	7.5	8.8	7.7	8.7	9.0
ethanol yield (L/kg)	0.37	0.38	0.39	0.39	0.37	0.39
oil reduction (%)			94%	84%		
projected r_E (unitless)	1.67	2.51	1.40			1.91

The results of Hall, Dale, and Pimentel (2011) are important in that they highlight both the inherent value of EROI calculations and the sensitivity of the calculation to the assumed system boundary. As production efficiency and overall energy costs fall, the energy balance of corn ethanol will become more favorable; however, whether the use of corn ethanol as a fuel is sustainable may depend on the value one places on co-products.

The most recent study of corn ethanol EROI was published by the Department of Agriculture. This 2015 Energy Balance for the Corn-Ethanol Industry placed a strong emphasis on both efficiency gains and co-product credits (Gallagher *et al.* 2016). Compared to an earlier USDA study (Shapouri *et. al* 2010), the report found moderate gains in corn production, procurement, and ethanol distribution leading to a survey-based EROI of 2.3, which includes a significant co-product credit. Gallagher *et al.* (2016) report there are additional prospects for improvement through management of power and drying costs and increased marketing of WDG rather than DDG. They also find that use of biomass power instead of natural gas could improve variable energy expenditures. Gallagher et al. (2016) report all energy inputs of 50,172 BTU/gal compared with the resulting available energy in ethanol of 76,300 BTU/gal. This results in an EROI of 1.5 without accounting for co-product credits. In calculating the co-product credit, they account for the fact that only the starch fraction of the corn plant is used for ethanol; this is the same “system expansion” approach used by Kim and Dale (2005). After accounting for heat and electricity used to produce dry co-products, they report an EROI of 2.3. This is one of the highest EROI values published in the past 15 years. While it may reflect the most recent and best information, it may also be an outlier that is not consistent with other published results.

4.3.2 Reason for Differences

Broadly, the choice of boundary limits for an EROI calculation will impact the results. This is more evident with regards to the application of a co-product credit, which represents a boundary of the output energy. Other differences relate to consideration of corn yield and location, which can be critical to process energy inputs. Other differences, such as source and age of data will certainly affect results. Below, the importance of co-product credits, yield, and location are addressed.

4.3.2.1 Co-product Credit

The energy costs of producing corn ethanol can be partially offset by allocating the energy used to various products and co-products. The primary co-products considered for most net energy calculations is DDG from dry milling operations and corn oil, corn gluten meal, and corn gluten feed from wet milling operations. As most current ethanol plants are dry milling operations, DDG is the primary co-product today. Generally, the energy value of these coproducts is based on their replacement value. Thus, if corn meal is considered comparable to soybean meal and corn oil is comparable to soybean oil, then the energy used to make those products can be substituted in the corn ethanol calculation (Shapouri *et al.* 2003).

Kim and Dale (2005) assume that about 33% of corn feedstock can be recovered as DDG with 27% protein content. This DDG is suitable for feeding cattle that are ruminants, but has only limited value for feeding hogs and chickens. Complicating this co-product credit is that DDG is used as a substitute for soybean meal that contains 49% protein, which is required in lower amounts as livestock feed. Also, as much less fertilizer is required, soybean production for livestock feed requires less energy per weight than corn production. However, considerable energy is required to remove oil from soybeans and produce soybean meal as animal feed. In practice 1 pound of soybean protein provides the equivalent nutrient value of 1.6 pounds of DDG. Kim and Dale (2005) allocate a co-product credit of 26%; conversely, Pimentel and Patzek (2005) only apply a 7% credit. Hall *et al.* (2011) and Murphy *et al.* (2011) both report that EROI calculations are very sensitive to the co-product credit.

An alternative method of treating co-products considers the corn itself. Shapouri *et al.* (2010) report that only 66% of the corn plant (starch fraction) is used for ethanol production. Thus, the energy required to grow the remaining 34% can be disregarded. In this approach, the total energy to grow corn is calculated and then discounted by 34% for the energy calculation. This approach suggests that other parts of the corn plant could be considered as equal products with the starch portion of the corn plant. At one extreme, this could include a discount for corn stover which is roughly 50% of the total mass of corn plant in a field. This is analogous to not counting the energy used to grow the peel or wood (which could be used as fuel) when considering an orange grove. The result of this approach is that the calculated EROI is much higher than might be the case otherwise. Since the co-product credit is, in many cases, sufficient to tip an EROI calculation from below unity to above unity, the method in which it is applied is important (Murphy *et al.* 2011).

4.3.2.2 Corn Yield

Real energy requirements to produce ethanol have been falling over the past several decades. Several authors have suggested that increasing corn yield is one reason for the drop in energy requirements (Gallagher *et al.* 2016, Shapouri *et al.* 2003). Murphy *et al.* (2011) investigated the impact of possible higher yields on the EROI of corn ethanol for various scenarios using yield levels that were up to three times greater than the average yield in 2005. Although corn yields are not expected to increase by a factor of three, this provided a theoretically upper bound. For their analysis, they assumed only that yield increased; they did not increase fertilizer application rates, as might be necessary to achieve higher yields. They found that increasing yield even far beyond the highest levels in 2005 had a small impact on the EROI of corn ethanol suggesting that yield is not a significant factor for corn ethanol EROI (Figure 14).

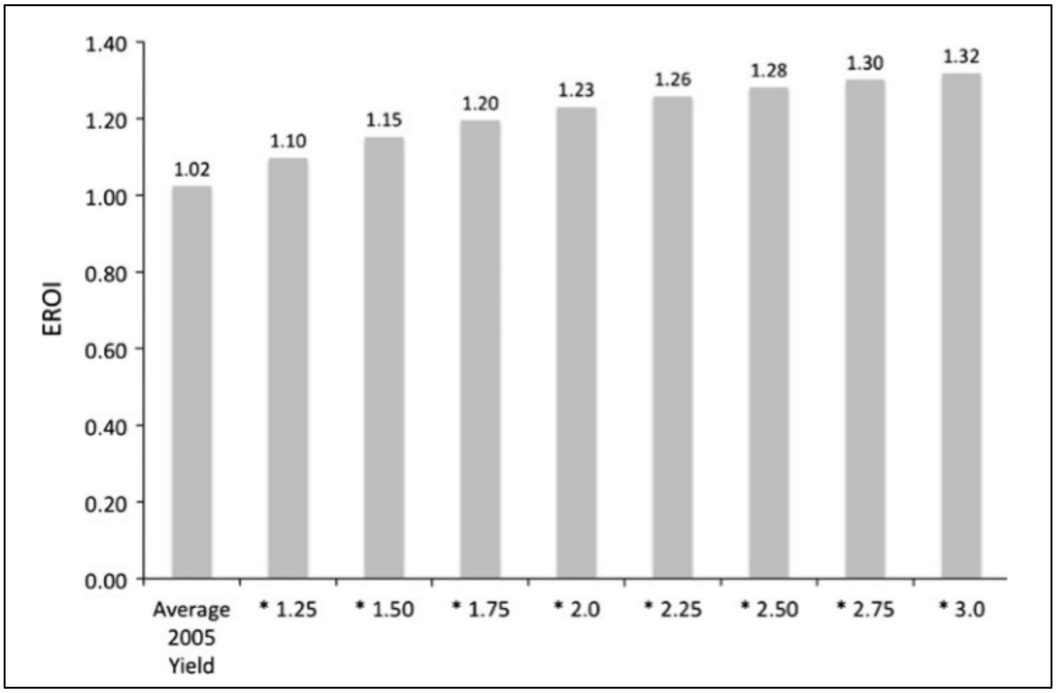

Figure 15: EROI as a function of corn crop yield. Tripling the yield results in a roughly 30% increase in the EROI of corn ethanol (Murphy *et al.* 2011).

4.3.3.3 Location

There is wide variation in energy balance across refinery configurations. Refineries such as those in west Iowa, near corn supplies, livestock operations, transport infrastructure, and final markets have the best energy balance (Gallagher *et al.* 2016). The climatic conditions in Iowa are clearly at the ''center of corn's gradient space'' (Murphy *et al.* 2011) and, at least until recent years, most of the corn grown for ethanol production was in Iowa. Correspondingly, Murphy *et al.* (2011) report that the EROI of the corn ethanol process is higher in Iowa than other corn growing states. This is expected, since more ideal growing conditions should require less external inputs. For example, the percentage of irrigated corn acres in Iowa is much lower than the percentage in Nebraska (U.S. EPA 2011, Shapouri *et al.* 2003).

These findings suggest that when calculating or reporting energy costs, it is critical to know the source of the data. Additionally, as the use of corn ethanol expands, corn will increasingly be grown in less ideal locations. This will almost certainly raise the average energy cost associated with ethanol production.

5. Conclusion

Fueled by claims of improved energy security and positive environmental impacts, corn ethanol has become the highest volume renewable transportation fuel in the United States. Its use has garnered strong support from policy makes, farmers, ethanol producers, and—at least initially—some environmental groups. Many view its use as a path to reducing fossil fuel consumption and reducing GHG emissions, while supporting U.S. farmers and farm land. For many supporters and much of the public, ethanol-use requirements under the renewable fuels standards demonstrate the governments' recognition of climate change and the need to take action. Unfortunately, many of the claimed benefits of corn ethanol are not supported by scientific evidence.

The production and use of corn ethanol results in significant environmental impacts. Most critically, carbon emissions from ethanol production and use are, at present, larger than those from gasoline. Further, land use impacts including carbon emissions, soil erosion, and eutrophication are important issues related to growing corn. Use of ethanol as a fuel, produces lower total hydrocarbon, carbon monoxide, benzene, and particulate tailpipe emissions than gasoline alone, but also substantially higher acetaldehyde and ethanol emissions, and higher NOx, methanol, and ethylene emissions. Water use associated with ethanol production can average 1700 L / L; far above the ~10 L / L required for gasoline. The overall environmental impacts of ethanol, while different from those of gasoline, were not any less detrimental.

The highly-debated net energy return of ethanol has been reported in the range of 0.82 to 2.3. The range of values reflects the improving efficiency of ethanol production, variations in energy data, and differences in the treatment of co-product credits. Even the most optimistic EROI values indicate that corn ethanol cannot provide the minimum energy surplus required to support our present industrial society.

Corn ethanol is not, and will probably not become, a cheap and sustainable fuel. Its production and use has too many associated environmental concerns, and its net energy is too low to meet societal needs. Hopefully, society will soon reevaluate the benefits of corn ethanol and realize that ethanol cannot solve our energy problems. Ideally, this will occur before large-scale adoption of biofuels causes further deterioration of the global environmental and social situation.

While the EROI of primary energy sources continues to fall, energy will become increasingly expensive. As this happens, it will be incumbent on society to identify suitable energy sources to support a sustainable way of life. The sooner we recognize that biofuels such as corn ethanol do not represent a prime energy source, the sooner we can reallocate the roughly $10 billion per year used to subsidize biofuels towards research into sustainable, renewable energy technologies (Pimentel *et al.* 2008).

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