The Environmental and Economic Sustainability of Cellulosic Ethanol

A Research Paper submitted to the Department of Engineering and Society

Presented to the Faculty of the School of Engineering and Applied Science
University of Virginia • Charlottesville, Virginia

In Partial Fulfillment of the Requirements for the Degree
Bachelor of Science, School of Engineering

Austin Scaglione
Spring, 2021

On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Signature ____ Date __________
Austin Scaglione

Approved ____ Date __________
Hannah Rogers, Department of Engineering and Society

Abstract

Cellulosic ethanol is currently one of the most promising alternatives to nonrenewable petroleum-based fuels like gasoline. Considering the increasingly apparent effects of climate change there is an increasing worry that the damage to the planet may soon become irreversible. Therefore, it is more important than ever for sustainable alternatives to be found that can eliminate the current dependency on fossil fuels and either stop the progression or reverse the effects of climate change. Additionally, the economic effects of large-scale production must also be considered when comparing different solutions. Its similarities to gasoline allow for the use of current infrastructure and combustion engines with minimal modification which are clear advantages when compared to electricity. In addition, cellulosic ethanol can be produced from any cellulosic material including corn stover, mixed paper, or wood chips making large scale production more sustainable than first generation ethanol which was produced from sugar or starch. However due to the small amount of cellulosic ethanol currently being produced it is necessary to analyze scientific research, case studies, and modeling simulations in order to accurately predict the impact of implementing cellulosic ethanol on a large scale. This paper studies the potential economic and environmental impact of cellulosic ethanol production in an effort to determine its viability as a replacement for fossil fuels.

The Environmental and Economic Sustainability of Cellulosic Ethanol

Introduction

Cellulosic ethanol is one of the most promising alternatives to the use of fossil fuels in transportation. In 2018 the transportation sector in the United States generated an astonishing 28 percent of the country's total Greenhouse Gas (GHG) emissions making it the largest contributing sector (U.S. EPA, 2020). Greenhouse Gas emissions are the leading cause of climate change which if not addressed is predicted to raise the average temperature within the U.S. by about 2.5°F by 2050. This temperature change is expected to cause coastal flooding, heat waves, forest fires, chronic drought, and more intense storms such as hurricanes depending on what region of the U.S. is being observed (Wuebbles, Fahey, and Hibbard, 2017). The rising threat posed by climate change along with the transience of remaining oil deposits has led to a push for the development of renewable and environmentally sustainable fuel in the U.S. As the leading producer of biofuel in the world the U.S. consumed over 1 million gallons of biofuel a day accounting for over 7 percent of total motor gasoline, distillate, and jet fuel consumption (U.S. EIA, 2020). Of the biofuel consumed ethanol was by far the largest contributor and is commonly used as an additive to gasoline around the country. However, there are multiple issues with current ethanol production that need to be addressed in order for it to be a viable alternative to fossil fuel. For example, corn-based ethanol barely recovers the energy used to create it and has less energy per gallon than gasoline. (Murphy, Hall, & Powers, 2011; U.S. DOE, n.d.). Also, ethanol may cause a net increase in emissions such as carbon dioxide due to land use change and because cornstarch and cane sugar are typically sold as food products their use may negatively affect food security (DeCicco, 2016; Tenenbaum, 2008). Over the past two decades the rapid development of enzyme technology has significantly improved the production of cellulosic ethanol and presented an alternative method of ethanol production with the potential to solve these existing issues and potentially offer a truly sustainable source of fuel.

An analysis of how cellulosic ethanol compares to other existing biofuels in terms of environmental and economic sustainability will reveal the potential it has a long-term replacement for petroleum-based fuels for use in the U.S. transportation sector. The concept of wicked problem framing is being applied to capture the various ways of defining sustainability and the unending and constantly changing nature of problems related to sustainability. To evaluate the viability of cellulosic ethanol, use for transportation in the U.S., the following question must be addressed: How does transitioning to cellulosic ethanol as a source of fuel for transportation in the U.S. increase long term economically and environmentally sustainability? This question will be explored throughout this paper by first analyzing the economic impacts of cellulosic ethanol production followed by an analysis of the environmental impacts. Finally, the paper will look at economic and environmental factors together to determine if cellulosic ethanol is a sustainable alternative for the U.S. transportation sector.

Framework and methods

This paper will use wicked problem framing to analyze the economic and environmental sustainability of cellulosic ethanol. Wicked problems are most commonly characterized as having difficulties in problem formulation, multiple but incompatible solutions, open-ended time frames, novelty (or uniqueness), and competing value systems or objectives (Seager, 2012, p.469). This framework will be used to highlight the difficulties with declaring a technology as sustainable and will help analyze cellulosic ethanol as a potential solution to the problem of sustainable transportation.

To research this problem this paper will utilize documentary research and case study analysis. Case studies of commercial cellulosic ethanol plants will be used to understand the direct impact of production and the improvements in production over time. In order to study the effects of growing or procuring cellulosic feedstock as well as the act of combusting the ethanol product will be studied using document research in order to predict the impact of large-scale production.

Economic Sustainability

Increases in biofuel production such as ethanol have increased the demand for crops like corn and sugar cane and critics fear that this will increase food prices. In the U.S. first generation ethanol is made primarily from starch in corn kernels. This is problematic because when large amount of corn is consumed to make ethanol it increases the price of foods such as breakfast cereal, corn flour, and corn sweetener which are made from corn (Albino, Bertrand and Bar-Yam, 2012). Also, the corn used to produce ethanol is often used to feed livestock and increasing its price can drive up the price of meat. Additionally, even if all of the corn produced in the U.S. is used in the production of ethanol it would only create approximately 38 billion gallons a year which would only replace 26% of the U.S.'s gasoline consumption (Hay, 2020). However, second generation ethanol also know as cellulosic ethanol is manufactured using cellulosic feedstocks including corn stover, switch grass, wood chips, or even waste paper. Cellulosic material accounts for 60 to 90 percent of the earth's biomass providing cellulosic ethanol with countless sources of feedstock and the potential to meet the demands of the U.S. transportation sector (Zarubin, 2014). The increased diversity allows for ethanol to be produced in large quantities while not over taxing a single resource to the point that prices would increase drastically and reduce competition with food crops. Some cellulosic ethanol can also be produced from waste products such as used paper and cardboard. Utilizing waste to manufacture ethanol significantly lowers the cost of raw materials and does not affect the prices of food or other consumer goods.

While cellulosic ethanol boasts a large and diverse source of available biomass converting cellulose to glucose comes at a price. In order to make ethanol from cellulosic biomass the cellulosic fibers must first be converted into glucose through a process called hydrolysis. After the glucose is produced it can then be fermented and distilled to produce ethanol. The conversion of cellulose to glucose is an expensive additional step in the process that is unnecessary when producing ethanol from starch or sugar. Hydrolysis of cellulose has been performed successfully with both acid and enzymes in order to produce ethanol at scale. The two different methods are incompatible with each other and therefore a choice must be made as to which is more sustainable. At first glance the German method, developed during WW2 which uses 40% hydrochloric acid to dissolve cellulose appears to be the most sustainable due to the ability to recycle the acid after each batch is converted (Miller, 2012). Unfortunately, the high acid concentration increases corrosion of materials and poses a significant health hazard to plant operators. Also recycling the acid requires the use of vacuum distillation which significantly raises the price of plant utilities making it less economic than it first appears.

Enzymes provide a less hazardous and energy intensive method for the hydrolysis of cellulose but they are expensive and not reusable. Simply purchasing premade enzymes from a third-party supplier is the most expensive method and cost 0.78 dollars per gallon of ethanol or roughly 28 percent of the total cost of production. To reduce this cost the enzymes can either be produced on site by a third party owned plant or the production can be fully integrated into the manufacturing process. Integrated enzyme production lowers the cost of enzymes to only 0.23

dollars per gallon or roughly 10 percent of the total manufacturing cost (Lane, 2017). Integrated production reduces the cost by eliminating the need to pay a third party and allowing for the enzymes to be produced using the same cellulosic biomass that the plant is converting into ethanol instead of more expensive glucose. Additionally, researchers are looking into ways to reuse enzymes for more than one batch cycle of hydrolysis. One method that is being pursued is the binding of enzymes to a substrate that can be retained within the reactor when the finished batch is removed. At South Dakota State University a scientist working with the enzyme company Novozymes has managed to successfully use the same enzymes for up to five cycles (SDSU, 2010). The research showed the enzyme activity to gradually decrease from 95 percent of the original in the second cycle to just 40 percent by the fifth cycle. Although mixing enzymes into the solution each batch remains the most economical method to convert cellulose into glucose, recycling enzymes is a potential way to significantly reduce the cost of ethanol production in the future.

In order to produce ethanol more economically side products created during the manufacturing process can be sold for additional revenue or used to reduce the operating cost of the plant. The main byproduct produced during the manufacturing process is lignin. Lignin is an organic molecule an is one of the components of plant cell walls along with cellulose. Before hydrolysis of cellulose occurs in a plant the lignin surrounding the cellulose fibers is ruptured to allow the enzymes or acid to produce glucose. In this process up to 30 percent of the biomass feed into the plant is unconverted lignin which can be separated as a side product (Folkedahl, n.d.). While it is possible to sell the lignin as an additional source of revenue it generally is more economic to use the lignin as a source of fuel to produce steam. Steam is used throughout the plant in heat exchangers such as the distillation column reboiler and by using the lignin as fuel less natural gas will need to be purchased to boil water. Also, by incorporating anerobic digestion into the waste water treatment waste biosolids like yeast and enzymes and unconverted biomass can be used to produce biogas and digestate. The biogas provides an additional fuel source for the plant and the digestate can be sold as a fertilizer. Finally, during fermentation, the yeast produce carbon dioxide gas when converting sugar into alcohol. Since the carbon dioxide being produced is relatively pure it can be captured and sold for use in carbonated drinks or the manufacturing of dry ice.

Government subsidies are an important factor to consider when determining the economics of cellulosic ethanol production. The market price for ethanol as of April 2021 is $2.01 per gallon (Trading Economics, n.d.). However, the production of cellulosic ethanol cost about $2.65 per gallon therefore at first glance cellulosic ethanol cost more money to produce than its worth (Osborn, 2007). Due to the high cost of production the government has introduced multiple subsidies to make cellulosic ethanol production profitable. For example the Second Generation Biofuel Producer Tax Credit is an incentive that rewards producers for each gallon of second generation biofuel that is sold and used by the purchaser in the purchaser's trade or business to produce a second generation biofuel mixture; sold and used by the purchaser as a fuel in a trade or business; sold at retail for use as a motor vehicle fuel; used by the producer in a trade or business to produce a second generation biofuel mixture; or used by the producer as a fuel in a trade or business (U.S Department of Energy, n.d.). Additionally, the Renewable Fuel Standards Program assigns renewable identification numbers (RINs) to each gallon of renewable fuel generated. After the renewable fuel is blended with non-renewable fuel the RINs are then purchased by refiners and importers of gasoline and diesel to fulfil government mandated obligations (EPA, n.d.). States like California have also introduced their own incentives such as the Low Carbon Fuel Standard (LCFS). The LCFS sets a standard for the lifetime carbon emissions of fuel throughout the supply chain and fuels generate credits in proportion to the reduction in lifetime carbon emissions the produce in comparison with the current set standard. These subsidies along with others allow for manufacturers of cellulosic ethanol to make a profit and encourage the development of new renewable fuel production facilities. Due to the reliance on government provided credits in order to make a profit the economic sustainability of ethanol can be debated. People or groups the highly value economic sustainability may oppose the use of cellulosic ethanol due to the dependency on subsidies increasing the cost society has to pay for its use. In contrast other groups may believe that the societal cost is outweighed by the benefits provided by the environmental benefits of cellulosic ethanol. These competing values must be analyzed carefully as the long-term implementation of a new fuel could have many different environmental impacts that could benefit or harm society as a whole.

Environmental Sustainability

Manufacturing cellulosic ethanol begins with growing or sourcing a sustainable source of cellulosic biomass. when considering large scale production, the largest environmental concern is the impact of significant land use change (LUC). LUC is the caused by the conversion of land into area to grow and harvest biomass needed to supply a cellulosic ethanol production plant. Recently in 2013 a group or researchers investigated the net effects of LUC for multiple cellulosic feedstocks in areas with different natural biomes across the united states (Dunn, Mueller, Kwon, & Wang; 2013). In this research different agro-ecological zones (AEZs) of the united states were investigated separately to determine the impact of the regional climate on LUC. The two regions focused on in the paper were the temperate arid region (AEZ 7) located in western U.S which includes states like Wyoming, Nevada, Colorado, Arizona, Utah, and Montana; and the temperate sub-humid region (AEZ 10) located primarily in the north eastern U.S which includes states like Iowa, Michigan, New York, Kansas, and Oklahoma. By analyzing the different regions, the researchers found that the net GHG emissions due to LUC were negative if grassland or cropland-pastures were transitioned to growing miscanthus or switchgrass. Additionally, when growing miscanthus it was even possible to has a net sequestration of carbon when transitioning from forested areas. in regards to the region, AEZ 10 was fount to sequester more carbon than AEZ 7 except when transitioning from foresee to miscanthus. The research concluded that the best method for preventing negative impacts due to LUC is to focus primarily on grasslands, cropland, and pastures and transition into high yield feedstocks such as miscanthus to maximize the amount of carbon sequestered.

While studies have shown that the impacts of LUC can be mitigated and even used to cause a net sequestering of carbon there are other sources of biomass that can be found without needing to change existing land use. For example, in the U.S over 90 million acres are reserved for corn production (Widmar, 2020). The leaves, stalks, and cobs that are left after harvesting are called corn stover and provide a large source of cellulosic biomass that is available without the need to transition the use of any existing land. In addition to corn stover research has show that wood waste, leaves, cardboard, and mixed paper are all potential feedstocks that due not require changes in land use. These feedstocks can even be sourced from municipal solid waste (MSW) where the biomass may even end up being landfilled or incinerated. Searching for existing sources of cellulosic material provide an additional method to reduce LUC and to even help improve the environment through the consumption of waste products.

After procuring a source of biomass the next step is to convert the cellulose into ethanol. This process requires the use of significant amounts of energy and often produces substantial emissions as fuels like natural gas are burnt to provide heat to the plant.

In order to fully analyze the net emissions of cellulosic ethanol many factors including fertilizer production, farming, ethanol production, transportation, and fuel combustion need to be considered. In a 2012 study by Argonne National Laboratory the total life cycle GHG emissions for five different ethanol pathways were calculated and compared to the life cycle emissions of gasoline (Wang 2012). The research shows that cellulosic ethanol when produced using corn stover, switchgrass, or miscanthus resulted in 77 to 115 percent reduction in GHG emissions compared to gasoline in contrast ethanol produces from corn starch and cane sugar only provided a reduction of 19 to 68 percent. For the cellulosic ethanol the largest source of emission came from the plant operation. However, the emissions due to farming, fertilizer production, and the nitrous oxide released by fertilizers accounted for 36 to 45 percent of the GHG emissions produced by the pathways using cellulosic feedstock. in order to reduce the net emissions further utilizing existing sources of biomass could reduce the GHG emission even further and make cellulosic ethanol more appealing to people and organization concerned about the environment. The emissions caused by production could also be reduced or even eliminated if the plant would use cleanly sourced electricity to provide heat to the necessary unit operations and captured the carbon dioxide produced by fermentation. While overall it is theoretically possible to make cellulosic ethanol has a negative production of GHG over its entire life cycle it would require significant investments in to clean energy production and government subsidies of the price of fuel would need to be increased.

Counterarguments

Cellulosic ethanol is just one of the multiple renewable fuel being tested for its ability to replace gasoline and diesel fuel. Different organizations have invested large sums of money into innovative technologies and often argue as to which alternative is the best replacement available. Electricity, biodiesel and hydrogen are some alternatives that are often compared to cellulosic ethanol. Of all the alternative solutions electricity is considered by many to be the best option for transportation due to its potential to reduce net greenhouse gas (GHG) emission to zero through the use of clean energy sources such as hydroelectric dams, geothermal energy, wind turbines, solar panels, and nuclear power plants and the high efficiency of electric motors. Also, electric vehicles are being developed by many large car manufactures such as Tesla and there increasing prevalence has led many to view electricity as the optimal solution to the current problems associated with fossil fuel supply and emissions. However electric vehicles have multiple downsides when compared to cellulosic ethanol. One of the biggest issues with electric vehicles is the lack of infrastructure. First in order to truly reach zero net emissions for transportation it is required to have 100 percent of the electricity used to charge car batteries be provided by clean sources of energy rather than coal or natural gas. Also, while people who own property may be able to have a charging station at home people who live in apartments or people traveling long distances will be dependent on the introduction of a network of charging stations that need to be built across the county. In contrast cellulosic ethanol is a liquid fuel and can be transported stored and distributed using the existing infostructure that has been built for gasoline and diesel fuel. Also, ethanol can be used in existing combustion engines with minor modifications to the fuel system and computers. This is a huge advantage for cellulosic ethanol because it significantly lowers the cost of implementation when compared to electric vehicles which are incompatible with all of the existing infrastructure. Another issue with electricity is its dependency on large heavy batteries. While batteries work well for cars and can provide a reasonable range, they are not practical for use in planes or boats due to the and weigh of the cells required to allow long continuous travel. Also, lithium-ion batteries burn at high temperatures and are incredibly difficult to extinguish making them a potential hazard in the case of an accident. Therefore, while many people believe that electric powered vehicle are the obvious solution the current state of infrastructure and lithium-ion technology show that research and development of cellulosic ethanol production should be continued for the foreseeable future.

Conclusion

Cellulosic ethanol is expensive to produce and economically it is currently unsustainable without government subsidies. However, since 2001 the cost of ethanol production has almost been halved (). The change in price is primarily due to continuing research into enzymes and better techniques to extract biproducts such as lignin. Therefore, it is likely that cellulosic ethanol will be economically profitable in the future as research continues and gas prices rise as the supply of gasoline decreases. Additionally, cellulosic ethanol produces significantly less GHG's than traditional gasoline which helps reduce the negative effects of climate change. Also, cellulosic ethanol can theoretically produce zero net emissions once clean energy replaces the use of fuels like natural gas for heating applications. It even has the potential to provide enough fuel to support the U.S. transportation sector due to the large quantities of cellulosic biomass in the world unlike corn-based ethanol which is limited by the amount of corn starch grown.

Overall cellulosic ethanol is currently economically sustainable with the inclusion of government subsidies and produces a profit but it causes a net increase in GHG over its life cycle due to production and farming which will continue to worsen the negative impacts of climate change and is unsustainable. However even electric vehicles currently produce a net increase in GHG's due to the continued use of coal and natural gas in power plants. Additionally, while electricity could in reduce net emissions to zero if the U.S. fully converts to clean energy cellulosic ethanol has the potential to produce a net decrease in GHG's due to the sequestering of carbon during the growth of biomass. in conclusion while cellulosic ethanol is economically sustainable it requires more research and infostructure in order to be considered environmentally sustainable.

References

DeCicco, J. M., Liu, D. Y., Heo, J., Krishnan, R., Kurthen, A., & Wang, L. (2016). Carbon balance effects of U.S. biofuel production and use. Climatic Change, 138(3), 667–680. https://doi.org/10.1007/s10584-016-1764-4

Dominic K. Albino, Karla Z. Bertrand, and Yaneer Bar-Yam, Food For Fuel: The price of ethanol, arXiv:1210.6080 (October 4, 2012)

Dunn, J. B., Mueller, S., Kwon, H. Y., & Wang, M. Q. (2013). Land-use change and greenhouse gas emissions from corn and cellulosic ethanol. *Biotechnology for biofuels*, *6*(1), 51. https://doi.org/10.1186/1754-6834-6-51

Environmental Protection Agency. (n.d.). *Renewable Identification Numbers (RINs) under the Renewable Fuel Standard Program*. EPA. https://www.epa.gov/renewable-fuel-standard-program/renewable-identification-numbers-rins-under-renewable-fuel-standard.

Folkedahl, B. (n.d.). *Cellulosic Ethanol: What to Do with the Lignin @BiomassMagazine*. Biomass Magazine. http://biomassmagazine.com/articles/2928/cellulosic-ethanol-what-to-do-with-the-lignin.

Hay, J. (2020, June 15). Bioenergy corn. Retrieved April 25, 2021, from https://cropwatch.unl.edu/bioenergy/corn#:~:text=Using%20a%20corn%20to%20ethanol,consumption%20(Energy%20Information%20Administration).

Lane, J. (2017, January 23). Process integrated enzyme production: the cost-efficient way to commercially viable 2G cellulosic ethanol. Biofuels Digest. https://www.biofuelsdigest.com/bdigest/2017/01/23/process-integrated-enzyme-production-the-cost-efficient-way-to-commercially-viable-2g-cellulosic-ethanol/.

Wang M. (2012, December 13). Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use. *Environ. Res. Lett.* **7** 045905

Miller, I. (2012, April 19). Ethanol by acid hydrolysis. Retrieved April 20, 2021, from http://my.rsc.org/blogs/84/659

Murphy, D. J., Hall, C. A. S., & Powers, B. (2011). New perspectives on the energy return on (energy) investment (EROI) of corn ethanol. Environment, Development and Sustainability, 13(1), 179–202. https://doi.org/10.1007/s10668-010-9255-7

Osborne, S. (2007, November). *Energy in 2020: Assessing the Economic Effects of Commercialization of Cellulosic Ethanol*. U.S. Department of Commerce. https://www.trade.gov/sites/default/files/2020-12/Energy%20in%202020_Assessing%20the%20Economic%20Effects%20of%20Commercialization%20of%20Cellulosic%20Ethanol.pdf.

Seager, T., Selinger, E., & Wick, A. (2012). Sustainable Engineering Science for Resolving Wicked Problems. *Journal of Agricultural and Environmental Ethics, 25*(1), 467-484. https://doi.org/10.1007/s/10806-011-9342-2

South Dakota State University. (2010, May 4). *Reusing Enzymes in the Ethanol Industry*. Farm Progress. https://www.farmprogress.com/energy/reusing-enzymes-ethanol-industry.

Tenenbaum D. J. (2008). Food vs. fuel: diversion of crops could cause more hunger. *Environmental health perspectives*, *116*(6), A254–A257.

Trading Economics. (n.d.). *Ethanol2005-2021 Data: 2022-2023 Forecast: Price: Quote: Chart: Historical*. Ethanol.

https://tradingeconomics.com/commodity/ethanol#:~:text=Ethanol%20is%20expected%20to%20trade,1.88%20in%2012%20months%20time.

U.S. Department of Energy. (n.d.). Energy Efficiency and Renewable Energy. Retrieved October 30, 2020, from https://afdc.energy.gov/fuels/ethanol_fuel_basics.html

U.S. Department of Energy. (n.d.). Second generation Biofuel Producer tax credit. Retrieved April 19, 2021, from https://afdc.energy.gov/laws/10515

U.S. Energy Information Administration. EIA projects U.S. biofuel production to slowly increase through 2050. Retrieved December 03, 2020, from https://www.eia.gov/todayinenergy/detail.php?id=43096

U.S. Environmental Protection Agency. (2020). Fast Facts U.S. Transportation Sector Greenhouse Gas Emissions 1990-2018. Retrieved December 03, 2020, from https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100ZK4P.pdf

Widmar, D. (2020, March 16). *95.0 million U.S. corn acres in 2020?* Successful Farming. https://www.agriculture.com/markets/analysis/950-million-us-corn-acres-in-2020.

Wuebbles, D., D. W. Fahey, and K. A. Hibbard (2017), How will climate change affect the United States in decades to come?, *Eos, 98,* https://doi.org/10.1029/2017EO086015

Zarubin, B. (2014, November 16). Cellulosic ethanol: Environmentally friendly, but costly. Retrieved April 20, 2021, from http://large.stanford.edu/courses/2014/ph240/zarubin1/