PRODUCTION OF SUSTAINABLE BUTANOL BIOFUEL FROM CELLULOSIC BIOMASS
A SOCIOTECHNICAL ANALYSIS OF U.S. BIOFUEL POLICY

A Thesis Prospectus
In STS 4500
Presented to
The Faculty of the
School of Engineering and Applied Science
University of Virginia
In Partial Fulfillment of the Requirements for the Degree
Bachelor of Science in Chemical Engineering

By
Olivia Wilkinson
October 27, 2023

Technical Team Members:
Isabella Powell
Rachel Rosner
Jason Thielen
Kevin London

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.

ADVISORS
MC Forelle, Department of Engineering and Society
Eric Anderson, Department of Chemical Engineering

Introduction

Despite only contributing to less than 5% of the world's population, the United States consumes up to 21% of the world's petroleum for transportation and other various uses (U.S Energy Information Administration , 2023). The transportation sector itself is dually responsible for 29% of the country's greenhouse gas emissions, making it a large target for improvement for the U.S. government and industry (US EPA, 2023). The U.S. has already invested in many different alternative energy sources, such as hybrid electric vehicles, fully electric cars, and even fuel cells. In the past two decades, there has also been a significant push towards the large-scale production and implementation of biofuels, which are renewable fuel sources produced from biomass feedstock (Markandya et al., 2018). The term biomass refers to renewable plant materials, spanning from edible food crops such as corn or sugar cane to agricultural, forestry, and municipal wastes (Gomez, Steele-King, and McQueen, 2008).

This process of converting biomass to biofuels presents an environmentally friendly alternative. It offsets the heavy reliance on CO_2 from finite fossil fuel reserves and creates a new mechanism for CO_2 absorption through the growing of new biomass (Woodward, 1999). Currently, biofuels such as ethanol are widely used as gasoline and diesel additives, but ethanol is limited in its energy content, low tolerance to water, and inability to blend with gasoline at a greater percentage (Szulczyk, 2010). This has inspired more advanced research into alternate biofuel compounds without these limitations, such as butanol.

In real-world context, biofuels were one of the U.S's first attempts at developing government-led solutions to the national energy security crisis that originally blossomed in the 1970s. Some may argue that these solutions set the original pace and tone for environmental governance on alternative energy sources (Bhatia et al., 2012; Holleman, 2012). However, with brand new policy comes reaction from stakeholders contributing to new developments in scientific, sociological, economic, and political biofuel research. Current critiques analyze how these novel biofuel policies and standards often neglect or discourage modern sociotechnical, environmental, and ecological problems (Holleman, 2012). Some of these problems include water supply, deforestation, a negative impact on biodiversity, and one of the most prominent issues: the food vs. fuel debate (Holleman, 2012). Other well-researched critiques investigate how biofuel policy development has also been guided by ambitious goals but supplemented with ineffective and insufficient policy instruments for successful implementation (Breetz, 2020).

Thus, if current biofuel policy, research, and implementation remains as it is now, the alternative energy source may bring more ecological and societal harm than good. The technical aspect of this project aims to improve the production of a newer, more energy-dense and engine-compatible biofuel, butanol, from a nonedible feedstock, corn stover, that will not compete with food and raise prices. The other half of the project aims to analyze the development of U.S. biofuel policy in the last two decades, and how its rhetoric, often over-idealistic mandates, and inevitable political influence translates to real-world execution. It will help improve understanding of what makes biofuel policy development environmentally effective and sociotechnically just, which is relevant for theoretical, real-world discharge of the team's technical work.

Technical Project

Emissions from internal combustion engines have driven the world's air pollution, a significant concern in the global warming phenomenon (Manzetti & Andersen, 2015). The pollution from these emissions is attributed to the extensive burning of fossil fuels, which are non-renewable fuels (US EPA, 2013). To help mitigate this problem, the United States federal government has implemented the addition of alcohol-based fuel additives to gasoline, which reduces the carbon emissions from internal combustion engines and partially replaces a finite fuel resource (i.e. petroleum) with a sustainable, renewable fuel source (US EPA*,* 2014). Ethanol is commonly added into gasoline for this purpose, as well as to better oxygenate the fuel. Research has shown that butanol, a longer chain alcohol, has a higher heating value, lower volatility, increased ignition performance, and higher energy density, making it a more promising fuel additive alternative (Trindade & Santos, 2017).

First generation feedstocks such as corn, sugarcane, oil palm, wheat, and soy are commonly used in ethanol production today (Tomei, J., & Helliwell, R, 2016). Like ethanol, butanol can be produced from this type of feedstock. Controversies arise concerning the use of these food crops for biofuel production because such use drives and increase in food prices, with some regions seeing food prices rise up to 83% in recent years (Tenenbaum, 2008). Second generation feedstocks are lignocellulosic agricultural residues such as corn stover. These byproducts have been presented as an innovative, low-cost way to repurpose waste into usable biofuel and prevent food price hikes (Bušić et al., 2018; Tomei & Helliwell, 2016). One impediment with this material is the requirement of advanced pretreatment technologies for successful fermentation since microorganisms cannot digest cellulose as easily as sugars and starches (Taha et al., 2016). This poses obstacles for large-scale commercialization; however, the team is optimistic in this regard due to recent research that has proposed cheaper, innovative pretreatment methods, such as the use of alkali as a hydrolyzing agent (Baral et al., 2016; Chen et al., 2021).

This project is intended to examine the production of biobutanol from a corn stover feedstock using an acetone-butanol-ethanol (ABE) fermentation process (Buehler, 2016). Fuel-additive grade butanol is the primary product, with byproducts of acetone and ethanol to be used as is most economically viable. Conversion of corn stover to butanol will be accomplished through pretreatment of the feedstock, followed by biological fermentation using the bacteria *Clostridium Acetobutylicum ATCC 824* (Buehler, 2016; Rao et al., 2016), and separation steps. The unit operations that will likely be used and designed in this process include reactors and washers for the pretreatment hydrolysis; a reactor for the fermentation reactions; and interconnected distillation columns to separate components and break aqueous ABE azeotropes (Pudjiastuti et al., 2021). A block flow diagram below depicts the general process to be designed by the team (Figure 1). Overall, this technical project aims to answer the following research question: How can the team simulate a technically optimized production process of butanol, a more energy dense, sustainable biofuel additive, from a cellulosic feedstock, corn stover, in an economically viable manner?

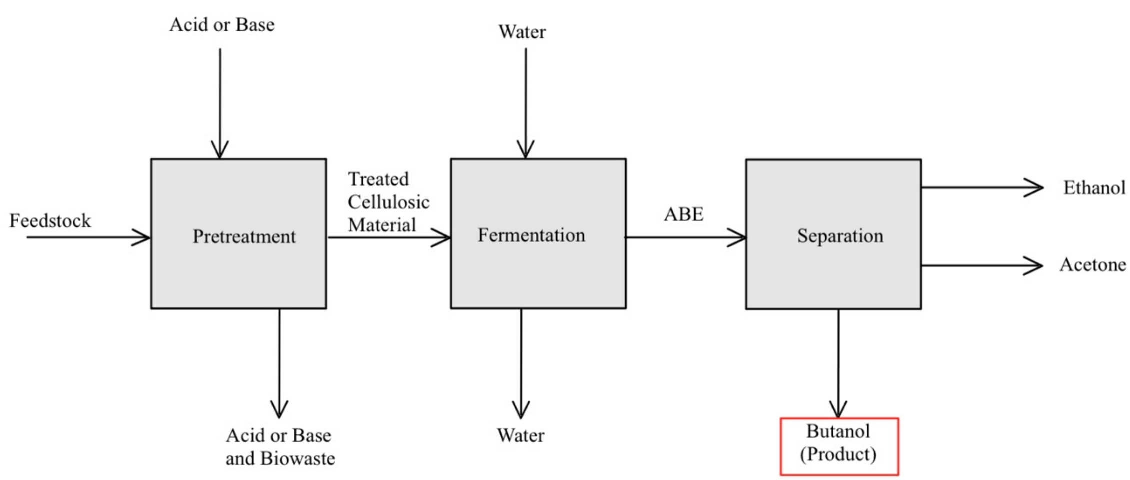

Figure 1. Butanol Production for ABE fermentation block flow diagram

The team will use Aspen Plus Simulation software to design a plant for the economical and sustainable production of butanol from ABE fermentation. This software allows the user to construct a process model and simulate its function using complex equations, mathematical computations, sensitivity analyses, and regressions. To begin construction, design data such as fermentation cell growth kinetics, methods of separation (e.g. azeotropic distillation, extraction, successive distillation columns), various feedstock viabilities, and economic analyses of the process, will be collected from peer-reviewed journal research and industrial data. Consultation with UVA Professor Ronald Unnerstall, who has 34 years of experience in the Oil and Gas industry and further experience writing BP's company directive for biofuel use in 2001, will also help direct the team's efforts in designing a process fit for an industrial scale application. This project will take place in the Fall 2023 and Spring 2024 semester as a part of the CHE 4474 and CHE 4476 senior design courses. The team will divide work based on preliminary research focus and relative familiarity of plant unit operation. They will complete the final design report in April of 2024.

STS Research Project

The U.S.'s biofuel policy in the last two decades has primarily focused on how the renewable fuel will be implemented wide scale. One of the most prominent biofuel governmental policies addressing these solutions has been the Renewable Fuel Standard (RFS) as authorized by the 2005 Energy Policy Act and expanded under the Energy Independence and Security Act of 2007 (US EPA, 2015). The RFS requires minimum production volumes of renewable fuel each year to reduce the U.S. heavy reliance on petroleum-based transportation fuel (US EPA, 2015). Specifically, it required the ascending production and use of biofuels from 4 billion gallons in 2006 all the way up to 36 billion gallons in 2022 (*The Renewable Fuel Standard (RFS): An Overview,* 2023). It also required 16 billion gallons of cellulosic biofuels by 2022, such as those from agricultural waste such as corn stover, despite these biofuels not yet being commercialized (Breetz, 2020). Since 2014—with little surprise—the U.S. has consistently not met this renewable fuel goal (*The Renewable Fuel Standard (RFS): An Overview,* 2023). Despite this failure, an updated RFS established in 2023 promotes up to an 8.2% increase by 2025 of current biofuel production volumes (*The Renewable Fuel Standard (RFS): An Overview,* 2023).

Some argue that these mandates, policies, and standards have crafted the entire U.S. biofuels industry, suggesting their influential nature (Lawrence, 2010). These lofty goals and incentives set forth by the national government have influenced wide-scale, severe ecological and social costs, such as extensive deforestation, a dramatic rise in food prices, and biodiversity harm to try and meet these unattainable goals (Holleman, 2012). This RFS has consistently and largely ignored the human-made societal and environmental issues associated with large-scale biofuel production by flaunting impressive mandates and goals theoretically designed to solve the country's energy crisis. These generalized mandates provide economic and political advantages to biofuel production by mobilizing several interest groups towards the cause, such as farmers, biofuel industry producers, environmentalists, and the larger energy security community (Lawrence, 2010). Yet, these biofuel mandates have proven to be rather blunt instruments that do not secure efficient, effective, sociotechnically just, and environmentally conscious methods of implementation (Lawrence, 2010; Breetz, 2020).

Tracing the political development of this Renewable Fuel Standard (from 2006-2023) through direct scrutiny of its rhetoric and content, as well as analysis of relevant Congressional hearings leading up to its development, will provide insight into relevant political stakeholder influence on the social, real-world execution of biofuels technology. Political science, sociological, and economic research journal analyses and critiques of biofuel policy will provide a pathway to monitor the policy's real-world impact and effectiveness. These works may also help develop a comprehensive suggestion for sociotechnical policy improvement and provide a model for this project's approach to policy analysis.

Pinch and Bjiker's (1984) STS framework for the social construction of technology (SCOT) may also be a useful tool in analyzing the relevant social groups responsible for the development of biofuel production technology. SCOT suggests that technological artifacts are not entirely objective and epistemological, but instead socially constructed by a complex web of actors that are key influencers in the trajectory of that technology (Pinch & Bjiker, 1984). As the U.S. government remains the pivotal stakeholder addressed in this project, using this framework may expansively offer answers into how biofuel production technology has been socially influenced by other groups, such as the petroleum industry, biomass feedstock growers, engine manufacturers, and environmentalists. This social influence perspective might help postulate the source of ecological, environmental, and social unjustness with biofuels, and it also might help track biofuel production technology success.

In conclusion, the STS, sociotechnical aspect of this project aims to answer the following research question: How has the political development of biofuel policy in the United States, specifically the Renewable Fuel Standard as part of the 2005 Energy Policy Act, influenced real world implementation of the alternative fuel source, related to its environmental, ecological, and social impacts documented by research experts?

Conclusion

The primary deliverable of the team's technical work will be an optimized process simulation in Aspen Plus of the production of biobutanol from corn stover. The individual STS research will supplement with an improved understanding of the effect of established U.S.

biofuel policy, specifically the Renewable Fuel Standard (RFS), on the sociotechnical, environmental, and political biofuel concerns of modern day viewed by research specialists.

Considering ethanol's limitations as a gasoline additive, the technical project aims to develop an advanced, more compatible butanol alternative for the energy and fuel industry to adopt. The simultaneous sociotechnical policy analysis may provide the U.S. government with a better STS perspective for future policy enactment to make biobutanol, the future of biofuels, a more effective alternative energy source. Through the biobutanol production simulation and the sociotechnical analysis of biofuel implementation, this project contributes to the alternative energy debates of today and deepens the understanding of one of the most powerful stakeholders, the U.S. government, in energy policy formation.

References:

Baral, N. R., Slutzky, L., Shah, A., Ezeji, T. C., Cornish, K., & Christy, A. (2016). Acetone-butanol-ethanol fermentation of corn stover: Current production methods, economic viability and commercial use. *FEMS Microbiology Letters*, *363*(6). https://doi.org/10.1093/femsle/fnw033

Bhatia, L., Johri, S., & Ahmad, R. (2012). An economic and ecological perspective of ethanol production from renewable agro waste: A review. *AMB Express*, *2*(1), 65. https://doi.org/10.1186/2191-0855-2-65

Breetz, H. L. (2020). Do big goals lead to bad policy? How policy feedback explains the failure and success of cellulosic biofuel in the United States. *Energy Research & Social Science*, *69*, 101755. https://doi.org/10.1016/j.erss.2020.101755

Buehler, E. A., & Mesbah, A. (2016). Kinetic Study of Acetone-Butanol-Ethanol Fermentation in Continuous Culture. *PloS one, 11*(8), e0158243. https://doi.org/10.1371/journal.pone.0158243

Bušić, A., Marđetko, N., Kundas, S., Morzak, G., Belskaya, H., Ivančić Šantek, M., Komes, D., Novak, S., & Šantek, B. (2018). Bioethanol production from renewable raw materials and its separation and purification: A Review. *Food Technology and Biotechnology*, 56(3). https://doi.org/10.17113/ftb.56.03.18.5546

Chen, X., Yuan, X., Chen, S., Yu, J., Zhai, R., Xu, Z., & Jin, M. (2021). Densifying lignocellulosic biomass with Alkaline Chemicals (DLC) pretreatment unlocks highly fermentable sugars for bioethanol production from Corn Stover. *Green Chemistry*, *23*(13), 4828–4839. https://doi.org/10.1039/d1gc01362a

Gomez, L. D., Steele-King, C. G., & McQueen-Mason, S. J. (2008). Sustainable liquid biofuels from biomass: The writing's on the walls. *New Phytologist*, *178*(3), 473–485. https://doi.org/10.1111/j.1469-8137.2008.02422.x

Holleman, H. (2012). Energy Policy and Environmental Possibilities: Biofuels and Key Protagonists of Ecological Change*. *Rural Sociology*, *77*(2), 280–307. https://doi.org/10.1111/j.1549-0831.2012.00080.x

Lawrence, R. Z. (2010). How Good Politics Results in Bad Policy: The Case of Biofuel Mandates. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.1724905

Manzetti, S., & Andersen, O. (2015). A review of emission products from Bioethanol and its blends with gasoline. background for new guidelines for emission control. *Fuel*, *140*, 293–301. https://doi.org/10.1016/j.fuel.2014.09.101

Markandya, A., Dhavala, K., & Palma, A. (2018). The role of flexible biofuel policies in meeting biofuel mandates. *AIMS ENERGY*, *6*(3), 530–550. https://doi.org/10.3934/energy.2018.3.530

Pinch, T. J., & Bijker, W. E. (1984). The Social Construction of Facts and Artefacts: or How the Sociology of Science and the Sociology of Technology might Benefit Each Other. *Social Studies of Science*, *14*(3), 399–441. https://doi.org/10.1177/030631284014003004

Pudjiastuti, L., Widjaja, L., Iskandar, K., Sahid, F., Nurkhamidah, S., Altway, A., Putra, A. (2021) Modeling and simulation of multicomponent acetone-butanol-ethanol distillation process in a sieve tray column, *Heliyon*, Volume 7, Issue 4, https://doi.org/10.1016/j.heliyon.2021.e06641.

Rao, A., Sathiavelu, A., & Mythili, S. (2016). Genetic Engineering In BioButanol Production And Tolerance. *Brazilian Archives of Biology and Technology*, *59*.

Szulczyk, K. R. (2010). Which is a better transportation fuel – butanol or ethanol? *International Journal of Energy and Environment*, *1*(3), 501–512.

Taha, M., Foda, M., Shahsavari, E., Aburto-Medina, A., Adetutu, E., & Ball, A. (2016). Commercial feasibility of lignocellulose biodegradation: Possibilities and challenges. *Current Opinion in Biotechnology*, *38*, 190–197. https://doi.org/10.1016/j.copbio.2016.02.012

Tenenbaum, D. J. (2008, June). *Food vs. Fuel: Diversion of Crops Could Cause More Hunger*. NCBI. Retrieved October 9, 2023, from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2430252/

The Renewable Fuel Standard (RFS): An Overview (Congressional Research Service Report R43325). (2023).

Tomei, J., & Helliwell, R. (2016). Food versus fuel? Going beyond biofuels. *Land Use Policy*, 56, 320–326. https://doi.org/10.1016/j.landusepol.2015.11.015

Trindade, W. R., & Santos, R. G. (2017). Review on the characteristics of butanol, its production and use as fuel in internal combustion engines. *Renewable and Sustainable Energy Reviews*, *69*, 642–651. https://doi.org/10.1016/j.rser.2016.11.213

U.S. Energy Information Administration. (2023, September 22). *Frequently Asked Questions (FAQs)—What countries are the top producers and consumers of oil?* EIA. Retrieved November 26, 2023, from https://www.eia.gov/tools/faqs/faq.php

US EPA. (2013, March 12). *The Sources and Solutions: Fossil Fuels* [Overviews and Factsheets]. https://www.epa.gov/nutrientpollution/sources-and-solutions-fossil-fuels

US EPA. (2014, April 17). *Economics of Biofuels* [Overviews and Factsheets]. https://www.epa.gov/environmental-economics/economics-biofuels

US EPA. (2015, August 4). *Overview for Renewable Fuel Standard* [Overviews and Factsheets]. https://www.epa.gov/renewable-fuel-standard-program/overview-renewable-fuel-standard

US EPA. (2023, May 11). *Carbon Pollution from Transportation* [Overviews and Factsheets]. EPA. https://www.epa.gov/transportation-air-pollution-and-climate-change/carbon-pollution-transportation

Woodward, S. (1999). *Biofuels: A Solution for Climate Change* (NREL/BR-580-24052; DOE/GO-10098-580). National Renewable Energy Laboratory, Golden, CO (US). https://www.osti.gov/biblio/14534.