Summer 2014

Field To Flight: A Techno-Economic Analysis of Stover to Aviation Biofuels Supply Chain

Amanda C. Bittner
Purdue University

Graduate School ETD Form 9
(Revised 01/14)

PURDUE UNIVERSITY
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By Amanda C. Bittner

Entitled Field to Flight: A Techno-Economic Analysis of Stover to Aviation Biofuels Supply Chain

For the degree of Master of Science

Is approved by the final examining committee:

Wallace E. Tyner

Farzad Taheripour

Michael R. Langemeier

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Approved by: Kenneth A. Foster 07/07/2014

Head of the Department Graduate Program Date

FIELD TO FLIGHT: A TECHNO-ECONOMIC ANALYSIS OF STOVER TO AVIATION BIOFUELS SUPPLY CHAIN

A Thesis

Submitted to the Faculty

of

Purdue University

by

Amanda C. Bittner

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science

August 2014

Purdue University

West Lafayette, Indiana

To Mom and Dad, without you I would not have gotten this far.

ACKNOWLEDGEMENTS

I would like to thank the Indiana and Iowa Corn Growers Association for funding this project.

This thesis would not have been possible without Dr. Tyner. I am extremely grateful you allowed me to be a part of this project and for the opportunity to work with you. Your continued support and guidance throughout this project was invaluable.

I would also like to thank my family and friends for their support during this time. I would not have been able to do this without you.

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ABSTRACT

Bittner, Amanda C. M.S., Purdue University, August 2014. Field to Flight: A Techno-economic Analysis of Stover to Aviation Biofuels Supply Chain. Major Professor: Wallace E. Tyner.

Greenhouse gas emissions have been a growing concern. The transportation sector contributes to one-third of GHG emissions in the United States from fossil fuel burning. The Renewable Fuel Standard set a requirement for 16 billion gallons (ethanol equivalent) of cellulosic biofuels to be used in the market. Aviation biofuels can help to meet both of these problems as well as improve U.S. energy security.

Investment in the biofuel industry carries a lot of risk. The biofuel industry is run by the private sector, but can be incentivized by government. Cellulosic biofuels carry even more risk than first generation biofuels, because conversion technology is more expensive. As a result, incentives are needed to reduce the risk for private investors. Government can implement policies to reduce the risk in investment in aviation biofuels. The issue is choosing which policy will provide the most reduction in risk, while providing a lowest cost to the government.

This analysis focuses on aviation biofuel production using fast pyrolysis from corn stover. Cost benefit analysis is used to calculate the net present value, internal rate of return, and benefit-cost ratio for a plant. We look at deterministic and stochastic cases. For the stochastic cases, this study uses @Risk, a Palisades Corporation software to determine the risk of investment in aviation biofuels. Uncertainty is added to fuel price and four technical variables: capital cost, final fuel yield, hydrogen cost, and feedstock cost. The fuel price can be steady or increasing at DOE projections.

We look at the impact of three policies: reverse auction, competitive capital subsidy, and carbon tax. For the reverse auction and capital subsidy, we used contract lengths of 5, 10, and 15 years to see the impact a longer contract could have on probability of loss.

All three policies reduced risk in investment of aviation biofuels. A reverse auction reduced risk of investment the most. As the contract length increased, the probability of loss and coefficient of variation in net present value were reduced substantially. When fuel price increased stochastically and a contract length of 15 years was used, probability of loss was reduced to 9.9 percent.

CHAPTER 1. INTRODUCTION

1.1 Importance of Aviation Biofuels

Biofuels came into existence to reduce oil imports, to reduce GHG emissions, and to increase farm income (Tyner 2008). A worldwide push for cleaner air to protect the environment and high oil prices led the way for increased awareness and production. The United States Environmental Protection Agency reports that the transportation sector is responsible for 32 percent of the total CO_2 emissions from combustion of fossil fuels. In 2012, it contributed to 27 percent of total US GHG emissions (U.S. Environmental Protection Agency). As a result, there has been a focus on producing biofuels for that sector as a way to reduce GHG emissions.

The transportation sector has many fuel sources. Figure 1.1 shows the energy consumption by fuel of the transportation sector. In 2011, jet fuel made up about 11 percent of the transportation sector's energy consumption. The U.S. Energy Information Administration predicts that by 2040, it will increase to 13 percent.

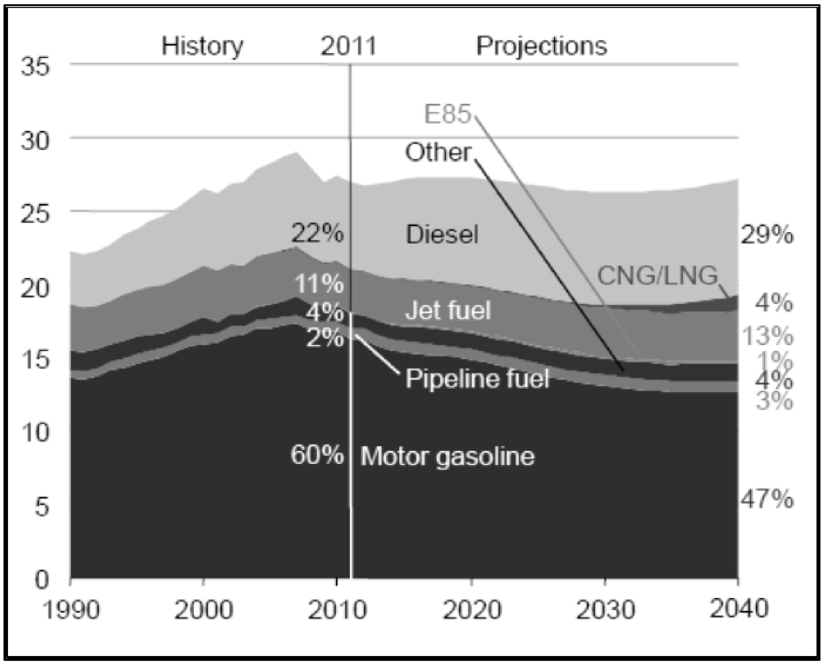

Figure 1.1 Transportation Energy Consumption by Fuel, 1990-2040 (quadrillion Btu) (source: (2013a))

The U.S. consumes over 20 billion gallons of aviation fuel each year. With a blending ratio of aviation biofuel to petroleum fuel of 50%, the potential for aviation biofuels is over 10 billion gallons. The U.S. Energy Information Administration expects consumption to grow each year (2013a). Currently, aviation is responsible for 2% of the world's manmade carbon dioxide emissions (2013b). This percentage is expected to grow as demand for air services increases (2013b).

Growth in aviation biofuels can have positive effects. Aviation biofuels allow for diversity in fuel supply as well as reduction in global carbon emissions. As a part of drop-in cellulosic biofuels, they have the potential to create jobs, generate economic growth, and drive innovation for clean technology (2013b). A sustainable future for aviation as well as improving U.S. energy security are also potential positive effects.

Biofuels used in vehicles have been around for many years, and became more pertinent to the public in 2007 with the implementation of the Renewable Fuel Standard (RFS) mandate. More recently, aviation biofuels have come to the forefront. There are other alternatives for ground transport such as ethanol, compressed natural gas and electric vehicles, but the only renewable alternative for aviation is biofuels (Tyner 2012).

1.1.1 Renewable Fuel Standards

The Renewable Fuel Standard consists of four categories: biodiesel, cellulosic advanced, other advanced, and conventional biofuels. Corn ethanol can only contribute to the conventional biofuels category. However, the RFS is a nested structure, so biodiesel, cellulosic advanced, and other advanced can contribute to the overall mandate as well as for their own category.

There are two main different types of biofuels, first-generation and second-generation. First-generation biofuels in the U.S. are mostly corn ethanol and oilseed and waste product biodiesel. Biodiesel and ethanol are not suitable for use in commercial aircraft. Aircraft engines do not use diesel, and ethanol energy density is too low for aviation. However, second-generation 'drop-in' biofuels are a good alternative to fossil fuels. Second-generation biofuels are mainly cellulosic biofuels. They require more advanced technology to extract the fuel compared to first-generation biofuels, and as a result cost more to produce.

Drop-in cellulosic biofuels are necessary to meet the requirements of the Renewable Fuel Standard. Ethanol has hit its blend wall at ten percent of gasoline consumption. Therefore, it is unlikely that much ethanol will be produced from cellulosic feedstocks. As a result, there is a need for other renewable products such as drop-in cellulosic biofuels to fulfill the cellulosic biofuels requirement.

Cellulosic biofuels volumes are expected to grow significantly, but will still fall short of the Energy Independence and Security Act of 2007 targets. Aviation biofuels fit into cellulosic drop-in fuels, which are fuels that are direct replacements for petroleum-based gasoline or distillate fuels (Administration 2013). Figure 1.2 shows the renewable fuel standard mandated by the 2007 EISA. The EISA of 2007, set a target level of 500 million gallons of cellulosic biofuels by 2012, 1 billion gallons by 2013, and 16 billion gallons by 2022 (Administration 2013), all ethanol equivalent. Overall, they set an RFS target of 35 billion gallons of ethanol-equivalent biofuels and 1 billion gallons of biomass-based diesel in 2022 (2013a). The U.S. Energy Information Administration predicts domestic consumption of drop-in cellulosic biofuels to grow from 0.3 billion gallons in 2011 to 9.0 billion gallons in 2040 (2013a). This growth is a result of rising oil prices and projected decreased production costs for biofuel technologies.

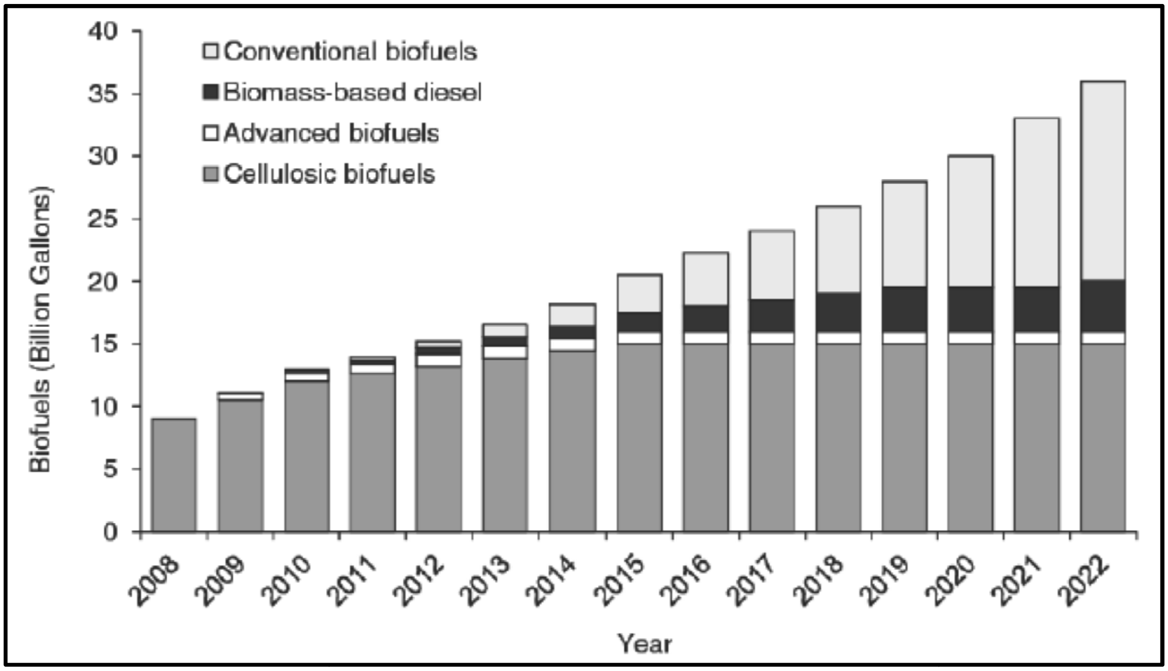

Figure 1.2 Renewable Fuel Volume Consumption Mandated by 2007 EISA, 2008-2022 (source: (National Research Council 2011))

1.2 Biofuel Industry

There are several different cellulosic biofuel pathways. Thermochemical pyrolysis, thermochemical gasification, biochemical direct fermentation, and biochemical fermentation with catalytic upgrading can be used (Voegele 2013). Brown et al.

concluded that fast pyrolysis with hydroprocessing is the most economically feasible (Brown et al. 2013b). This research examines the fast pyrolysis of corn stover to bio-oil.

Cellulosic feedstocks can come from dedicated energy crops such as miscanthus and switchgrass or from crop residues. First-generation biofuels, such as ethanol, are reliant upon crop sources which have an impact on food prices and induce land use change. Second generation biofuel feedstocks have less competition with food. However, dedicated energy crops like switchgrass do require land and thus can cause induced land use change. Dedicated crops tend to be more expensive than crop residues. According to the National Academy of Sciences report, alfalfa, switchgrass, and miscanthus all have willingness to accept prices exceeding corn stover. Corn stover's willingness to accept price is $92, which is less than alfalfa at $118, switchgrass in the Midwest at $133, and miscanthus in the Midwest at $115 (National Research Council 2011). For these reasons, this analysis is focused on the use of corn stover. Stover is a crop residue as opposed to a dedicated crop, and has little impact on food prices and land use change (Fiegel 2012). As a result, corn stover may be a viable source for use in producing renewable energy.

1.2.1 Policies to Stimulate Biofuels

The biofuel industry faces five major areas of uncertainty impeding investment: crude oil price, feedstock availability and cost, conversion technology yields and costs, environmental impacts, and government policy (Tyner 2012). Cellulosic biofuels require more expensive conversion technology, which results in higher costs. Higher costs means there is higher risk for private investors, so incentives may be needed to entice private investors to invest.

The biofuel industry can be incentivized by government, but is owned and operated by the private sector. There are a wide array of possible policies that could be used to stimulate biofuels production. In this research, we will focus on three policies, which differ in the extent to which they help reduce uncertainty for private sector investors. These are a reverse auction, competitive capital subsidy, and carbon tax.

One policy option which would help navigate uncertainties in investment is the reverse auction (Tyner 2012). In a reverse auction a prospective purchaser would request bids for a contract to supply aviation biofuels. The low bid (thus the name reverse auction) wins the bid.

A competitive capital subsidy is when potential plant builders compete for the subsidy from the government. The subsidy provides assistance to the private investor for a stipulated plant size and product type. The private investor that bids the lowest level for the subsidy wins the contract. A carbon tax is a tax on the CO_2 emissions. The difference in CO_2 emissions from fossil jet fuel and corn stover jet fuel is calculated. A tax in dollars per gallon is added to each year. All three policies reduce risk, but to what extent and what cost to the government?

1.3 Objectives

Aviation biofuels currently are expected to cost more than fossil jet fuels, at least in the near term. The objective of this research is to conduct a techno-economic analysis of stover to aviation biofuels pathway, and to determine the risk reduction/cost tradeoffs that allow the government to choose the policy most appealing to private sector investors and at a lowest government cost. The first step is to develop an economic model that details the costs for production of corn stover, transport to a plant, and conversion to aviation biofuel. Then, that model is used to estimate the uncertainty in reverse auction, competitive capital subsidy, and carbon tax. Comparing the outcomes for each policy in the context of expected plant economics will provide the government with a better understanding of the implications of the policies.

1.4 Organization

Chapter 2 provides a literature review of corn stover, fast pyrolysis, life-cycle analysis, policy options for implementation, as well as data drawn from relevant literature. Chapter 3 covers methods used in this analysis. To assess the processing model, data provided by Honeywell UOP will be used to develop a base case. An economic model will determine base case results, which will then be used to conduct a financial and uncertainty analysis on possible policy alternatives. The policy analysis will include a financial analysis.

Using the data and methods from Chapters 2 and 3, Chapter 4 presents the results of the analysis. Both a deterministic and a stochastic model will be used to present base case results and financial analysis results. The stochastic model will be used for the policy comparison cases. Lastly, Chapter 5 summarizes the key conclusions reached from the study as well as limitations and suggestions for further research.

CHAPTER 2. LITERATURE REVIEW

This literature review examines the corn stover to aviation biofuels pathway. It covers the issues related to corn stover harvest, storage, and transport to a processing plant. Concerns and costs related to soil nutrients and nutrient replacement, possible environmental impacts of stover removal are included. Pre-processing of stover for use in fast pyrolysis, as well as the process of fast pyrolysis and the storage of bio-oil will be described. Environmental impacts of aviation biofuel production will be assessed through life-cycle analysis. Possible policies for aviation biofuel implementation into the market will be explored.

2.1 Corn Stover

2.1.1 Benefits of Using Corn Stover for Aviation Biofuels

Using corn stover for aviation biofuels can help meet the target level of 16 billion gallons ethanol equivalent of cellulosic biofuels mandated by the RFS for 2022. Agricultural residues could account for around one-third of the total (Tyner 2010a). Corn stover has advantages over other biomass feedstocks. In comparison to switchgrass, hybrid poplar, and small-grain straw, corn stover yield is quite high. It also has the benefit of having corn as a high value co-product. (Shinners et al. 2007). There is an abundance of corn stover available for harvest throughout the United States. EPA estimates that 82 million dry tons of corn stover could be harvested in the Midwest alone in 2022 (National Research Council 2011).

Corn stover is a relatively inexpensive feedstock option. As stated in the introduction, corn stover has an estimated cost less than alfalfa, switchgrass, and miscanthus. Corn stover consists of the above ground, non-grain part of the corn plant (Vadas and Digman 2013). It is the part of the corn plant remaining in the field after harvesting the grain (2013b). Therefore, the only costs associated with corn stover are nutrient replacement, harvesting, storage, and transportation (Tyner 2010a). Corn stover is a lignocellulosic feedstock. Lignocellulosic feedstocks are composed of three parts: cellulose, hemicellulose, and lignin. Thermochemical conversion processes utilize all parts of the feedstock, including lignin (Tyner 2010a).

Corn stover supports rather than competes with human food production (MASBI). As an agricultural residue, corn stover does not require additional land, so therefore does not compete with food.

2.1.2 Harvest Process

Harvesting stover should be done without degrading soil, water, or air resources. Crop residues protect land from wind and water erosion, as well as supply an input of carbon and replenish plant nutrients (Karlen et al. 2011). Therefore, the removal of them must be done sustainably. Karlen et al. found that removal rates of 50% and 90% lead to gradual decline in total organic carbon (Karlen et al. 2011). The amount of stover that can be removed sustainably depends upon yield, tillage practice, and crop rotation (Zinkand 2012). A common rule of thumb can be used when determining the potential of corn stover: the mass of available stover will be about equal to the mass of grain harvested (Shinners and Binversie 2007). Blanco-Canqui found that only 25% of stover is available for removal (Blanco-Canqui and Lal 2009). Stover moisture averages about double the moisture of the grain. There are two portions of the corn stalk, upper and lower, in which nutrient concentrations differ. "The upper portion of the corn stalk provides a higher quality feedstock for both thermochemical and fermentation platforms (Johnson et al. 2010)." Harvesting stover at a height of about 40 cm would be best (Hoskinson et al. 2007) from the composition perspective.

Stover can be harvested dry or wet. Problems exist with both harvest methods. Field drying rate, harvest window, weather, and harvest efficiency must all be taken into consideration when choosing a harvest process (Vadas and Digman 2013). Generally, stover is harvested dry, which is at 20-25% moisture. This requires cutting and shredding, windrowing, baling, and hauling of bales. The harvesting efficiency is only about 30% due to inefficiencies from the shredder and baler (Shinners et al. 2007). Dry stover can also contain large quantities of foreign matter collected by the baler (Caldecott). Wet stover harvest (>45% moisture) uses a combine followed by a shredder. A forage harvester then gathers the stover. Harvesting wet stover, eliminates the drying period between grain and stover harvest and increases the harvest window (Shinners and Binversie 2007). The harvesting efficiency is greater for wet stover compared to dry stover due to less time for decomposition to occur.

Timing of harvest and the harvest window are very important. There is only a 40-day window to collect residue (Caldecott). Delayed collection can diminish the quantity of stover that remains to be collected (Pordesimo et al. 2005). Action must be taken quickly to harvest it. However, for dry stover harvest, the time after grain harvest for stover to reach ideal moisture can take a few days to weeks (Shinners et al. 2007). This leaves time for weather to heavily influence the quality of the stover. As time between grain and stover harvest increases, yield and harvesting efficiency decrease (Shinners et al. 2007).

A possible solution to harvest problems is the Cornrower system. It is an attachment that fits on a New Holland 99C corn head. Dirt accumulation is nearly nonexistent, and labor and fuel are eliminated to windrow stover. Fuel use and labor costs are reduced. Smaller particles are created, which allow bales to be denser. Increased density results in reduction in time, fuel, and storage space with hauling and storing stover (Straeter 2011, Zinkand 2012).

2.1.3 Corn Stover Storage

Stover can be stored in many different ways and for various periods of time. It can be stored wet or dry. For wet storage, it is ensiled. For dry storage, it can be baled into round or square bales. There is also the option to store bales outdoors or indoors. Bales have three preparation methods: twine, net wrap, or plastic wrap. Net wrap is the cheapest option (Tyner 2010a). Vadas et al. determined that outdoor, wrapped bales was the least-cost storage option due to zero cost for structures or stone pads (Vadas and Digman 2013). Thompson and Tyner concluded that net-wrapped bales stored outside on a stone bed under a tarp was the best option (Thompson and Tyner 2014).

Dry matter loss occurs during storage. The length of time stover is in storage and the type of baling chosen affect the amount of dry matter loss (Brechbill, Tyner, and Ileleji 2011). Moisture level affects the storage success rate. At a certain level of moisture, there is no storage structure that can successfully conserve stover. As the moisture level increases, more problems arise, and successful conservation of stover decreases or becomes unattainable. Successful stover conservation has low DM losses, minimal compositional changes, and low mold growth. Shinners found that only stover stored in covered aerobic piles when stover moisture was less than 25% or stover stored anaerobically met the criteria (Shinners et al. 2010).

2.1.4 Transportation to Plant

Transportation from the farm to the plant can happen four ways: by road, by railway, by waterway, or by pipelines. Trucks have been proven to be the most realistic form of transportation. Road transportation has flexibility, low fixed costs, and higher variable costs. It is the preferred transportation. A 53-foot flatbed trailer can haul about 26 large round bales (Fiegel 2012).

2.1.5 Concerns of Stover Harvest

2.1.5.1 Soil Nutrient Loss

Removal of stover can have adverse effects on the soil depending on the removal rate. Studies have found both positives and negatives associated with stover removal. For no-till continuous corn, stover removal may be beneficial. Removing stover can lead to faster spring soil warm-up. Karlen et al. found that for producers with high yields, where residue management may be a problem, moderate stover harvest is beneficial. It may decrease fuel use and save energy by reducing tillage (Karlen et al. 2011). Harvesting corn stover may also increase grain yield (Karlen et al. 2014). Karlen et al. 2014 found that in about 50% of the sites tested, removing stover at moderate and high rates increased the grain yield. Johnson et al. 2014 found that 6 Mg residue ha^{-1} yr^{-1} rate was needed to sustain SOC levels (Johnson et al. 2014). However, most studies have found that stover removal has negative impacts on the soil. Stover removal results in a decrease in nutrients. The three main nutrients impacted from stover removal are nitrogen (N), phosphorus (P), and potassium (K), as well as micronutrients. Setiyono et al. found for every 1000kg of stover removed per hectare, 8.11 N g/kg, 0.52 P g/kg, and 21.82 K g/kg was removed (Setiyono et al. 2010). Johnson et al. found that as the cutting height of stover is lowered, the amount of C removed from the field increases (Johnson et al. 2010).

Nutrients that are lost due to stover removal may need to be replaced. There is ongoing debate over how much nutrients, if any, need to be replaced. Jeffrey Volenec, an Agronomy Professor at Purdue University believes that mass balance suggests you would need to replace the nutrients, which are lost (Volenec 2013).

Nutrient replacement is vital to obtaining good crop yields. In particular, nitrogen replacement is important since it is a large driver of yield. As a result, the assumption is generally made that little or no nitrogen carries over from year-to-year due to its influence on yields (Volenec 2013). Therefore, farmers generally apply a full application of nitrogen to ensure good yields. However, a full application is not always necessary depending on the crop rotation used.

The type of crop rotation used has an impact on nutrient replacement. Volenec suggests that replacement rates vary depending on the crop grown in the field the previous year (Volenec 2013). The two main crop rotations used are corn-corn and corn-soybean. For a corn-corn rotation, corn planted the previous year does not transfer a sufficient amount of nitrogen back into the soil for a good yielding corn crop this year. As a result, a full application of nitrogen each year is necessary. This is not the case for a corn-soybean rotation. Depending on the field conditions, only a partial application of nitrogen may be necessary to ensure good corn yields. Therefore, farmers may apply less nitrogen (Volenec 2013). Fiegel calculated the total nutrient replacement of corn stover removed excluding nitrogen replacement for both crop rotations per ton to be $12.73 (Fiegel 2012). However, the total nutrient replacement cost of corn stover removed for a continuous corn rotation may be higher due to nitrogen application. Therefore, the total nutrient replacement cost of corn stover for a continuous corn rotation may be closer to that calculated by Thompson and Tyner, which includes nitrogen, at $19.07 (Thompson and Tyner 2014).

There are solutions to lessening effects of stover removal on the soil. Two possible solutions are decreasing tillage and adding cover crops. By adding cover crops, the soil organic carbon is increased (Pratt 2012). Bonner et al. (2014) found that using cover crops and no-till management can increase the sustainable stover supply. By using no-till, winter cover crops, and vegetative barriers, more stover can be harvested without exceeding soil erosion values or depleting SOC ((Bonner et al. 2014)). As a result of these practices, nutrient cycling, TOC content, and productivity can be improved (Karlen et al. 2011).

2.1.5.2 Transportation

Transportation of stover from the farm to the plant is costly. One cause of inefficiency is low bale density (Karlen et al. 2011). The issue is that although the truck beds reach volume capacity, they do not reach mass capacity. The law states that the maximum gross weight of the truck and biomass can be 36,000 kg (Miao et al. 2012). However, current gross weight does not come close to reaching that maximum. Densification and size reduction of stover can be crucial to improving delivery efficiency (Miao et al. 2012). Increasing bale density will result in fewer trips having to be made to the plant and will reduce the transportation cost of stover. Road transportation must also take into consideration infrastructure limitations, traffic congestion, and environmental impacts. Multiple trips from the farm to the plant can cause wear and tear on the roads. The best indicator of road infrastructure impact is vehicle trip miles for each plant (Tyner 2010b). Tyner and Rismiller conclude that a 50 million gallon per year cellulosic plant will have 55,182 truckloads of biomass delivered each year.

2.1.6 Total Cost of Stover

Fiegel conducted a study in which she calculated the total cost of stover for a corn-soybean rotation and a corn-corn rotation. The total cost of stover was broken down into harvest, storage, loading and unloading, and transportation. Harvest cost accounted for fuel, labor, equipment, net wrap, and nutrient replacement costs. The storage cost was calculated assuming stover was stored outside on a rock bed under a tarp for up to a year. Loading and unloading focused on time it took to put the bales on the truck. Transportation occurred from the farm to the plant. All costs were the same except for total harvest cost as shown below in Table 2.1. The harvest cost for a corn-corn rotation results in needing one less tillage pass which achieves a cost reduction of $13.28 per ton (Fiegel 2012). Farm gate cost is also included which accounts for total harvest cost and storage cost.

Table 2.1 Costs found by Fiegel ($/ton at 15% moisture) (source: (Fiegel 2012))

Description	**Corn-Soybean Rotation**	**Corn-Corn Rotation**
Harvest Cost		
Fuel Cost	$3.59	$3.59
Labor Cost	$3.08	$3.08
Equipment Cost	$6.54	$6.54
Net Wrap Cost	$5.60	$5.60
Nutrient Replacement Cost	$12.73	$12.73
Total Harvest Cost	$31.54	$18.25($31.54-$13.28)
Storage Cost	$16.10	$16.10
Farm Gate Cost	$47.64	$34.35
Loading and Unloading Cost	$6.22	$6.22
Transport Cost	$20.18	$20.18
Total Cost	$74.03	$60.75

2.2 Fast Pyrolysis

Four processes are available for converting biomass to energy forms: thermal, biological, mechanical, and physical. Thermal conversion gives multiple products in short reaction times with a quality product. There are three main thermal processes as shown below in Figure 2.1 (pyrolysis, Fisher Tropsch gasification, and combustion). However, pyrolysis appears to be quite attractive due to its versatility, improved efficiency, and environmental acceptability (Bridgwater 2012).

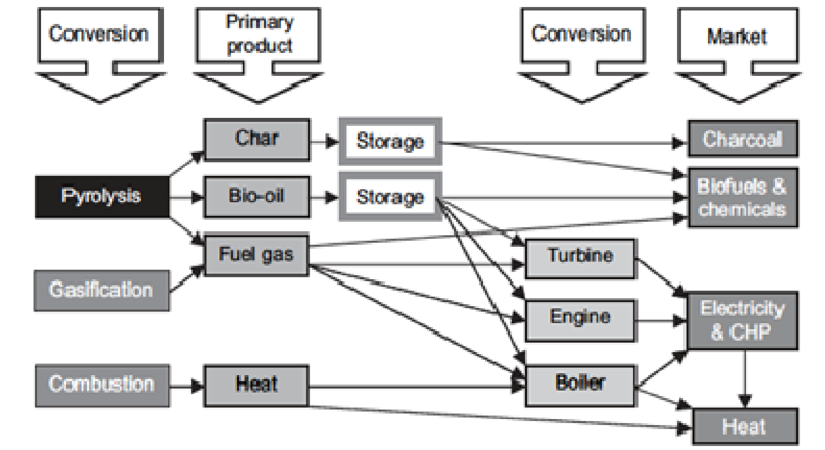

Figure 2.1 Products from Thermal Biomass Conversion and Available Markets (source: (Bridgwater 2012))

There are four types of pyrolysis: fast, intermediate, slow, and gasification, which can produce liquid, char, and gas (Jones 2009). Each mode of pyrolysis is capable of producing different yields of the three products. The process that appears to be most attractive is fast pyrolysis (Brown et al. 2013b). It is preferred to the other options because it produces a higher yield of liquid (Jones 2009). Production of liquid is advantageous, because it allows for easier storage and transport compared to char and gas. Fast pyrolysis for production of liquids has developed considerably since its first introduction in the 1970s. Over the years, it has become a potentially viable route to renewable liquid fuels (Bridgwater 2000).

Pyrolysis is also preferred in comparison to other conversion processes due to its lower cost. Anex et al. (2010) compared the costs of three conversion platforms: pyrolysis, gasification, and biochemical. The conversion technologies were chosen based on commercial feasibility in the near future, facility feasibility using current agricultural feedstocks, and final product compatibility with current fuel infrastructure. The product range for all three conversion processes was \$2.00-\$5.50 per gallon of gasoline equivalent. Pyrolysis had the lowest product range of \$2.00-\$3.00/gge. Biochemical had the highest with a product value range of \$5.00-

$5.50/gge. Overall, pyrolysis had the lowest product value and total capital investment (Anex et al. 2010).

2.2.1 Pre-processing

Before biomass can be processed into bio-oil, there are three pretreatment steps that must be taken to ensure an efficient process. The first step is removal of ash content present in the biomass. As discussed in the previous section of the literature review, corn stover harvest picks up a certain amount of ash. The presence of ash in stover can cause fouling and plugging of equipment (Wright et al. 2010). Minerals cause thermal decomposition reactions that are necessary to produce quality bio-oil (Wright et al. 2010). Washing stover with water can reduce the alkali content present to ensure a quality bio-oil is produced. Washing stover before chopping and grinding it minimizes the moisture that can be absorbed by the product (Aden 2002). Therefore, washing should be done first in the pretreatment steps.

The second step necessary for an efficient process and better yields is drying. The moisture content of delivered stover varies for different biomasses, harvest conditions, and storage. In order for biorefineries to want to purchase corn stover, it must contain <36% moisture (Thompson 2011). More moisture in the feed leads to lower process yields. For a good pyrolysis yield, the recommended moisture is less than 7% (Wright et al. 2010). As a result, washing of the stover must be followed by drying. Drying of stover is essential to obtaining good yields. The maximum optimal moisture content of the feed at the pyrolyzer is 10% (Palma 2011). Any moisture that is present in the feedstock when it begins pyrolysis will vaporize, but will re-condense with the bio-oil product. Even if the feedstock contained zero percent moisture, the bio-oil would still contain 12-15 wt% water (Ringer 2006). Therefore, it is important that moisture content is low. This means that stover drying will be part of the conversion process (Brown et al. 2013b).

Chopping and grinding of the feedstock is an important part of pretreatment. The particle size is reduced to 10 mm and then 3 mm. By shrinking the size of the particle, the risk of decreasing yields and increasing heat requirements are reduced (Wright et al. 2010). Other studies found that the biomass must be ground to a size less than 3 mm for the optimum temperature to be reached during pyrolysis (Bridgwater 2012). Since pyrolysis occurs with two second residence times, the particle must be heated thoroughly in a short time. Reducing the size of the particle allows for more uniform heating. It also helps with the physical transition from pyrolysis when char develops at the surface of the particle. Char slows down the transfer of heat throughout the entire particle, so smaller particles are better (Ringer 2006).

2.2.2 Process Description

Once the feedstock is dried, chopped, and ground, it is then ready for pyrolysis. Pyrolysis converts biomass into bioenergy through heat in the absence of oxygen (Palma 2011). It is a thermal process that is characterized by temperatures around 500^{o}C, rapid heat transfer, and low residence times (Wright et al. 2010). A temperature of 500^{o}C maximizes the yield, while a residence time of less than 2 seconds minimizes secondary reactions. The yield of liquid that results is based on biomass type, temperature, hot vapor residence time, char separation, and biomass ash content (Bridgwater 2012).

The reactor is the main part of pyrolysis. There are many different reactors available for use. Some reactors available are bubbling fluidized bed pyrolyzers, circulating fluidized bed pyrolyzers, rotating plate pyrolysis, rotating cone pyrolysis, ablative pyrolysis, and hydropyrolysis (Bridgwater 2012, Sadaka). The most popular reactors are the fluid beds and circulating fluid beds due to their simple construction and operation (Bridgwater 2012). Most of the studies examine the bubbling fluidized bed pyrolyzer in Figure 2.2. They are desirable due to their good temperature control and efficient heat transfer (Bridgwater 2012). They also have large heat storage capacity. The small particle enters a sand medium in a zero-oxygen environment. While there, it is quickly heated and decomposes into char, gas, vapors and aerosols

(Sadaka). The char is separated in cyclones with it making up about 15 wt% of the product. Some of the char is used to provide heat during combustion, while the rest is exported (Bridgwater 2012). A study by Lee et al. found that biochar from pyrolysis is suitable for improvement of soil and as a carbon sequestration agent (Lee 2010). The gas, vapors, and aerosols get cooled in the quench cooler. This must occur quickly or the compounds will further crack (Ringer 2006). Then the condensed bio-oil is collected and stored. The non-condensable gas goes through the electrostatic precipitator where it is recycled or used as fuel for heat (Sadaka).

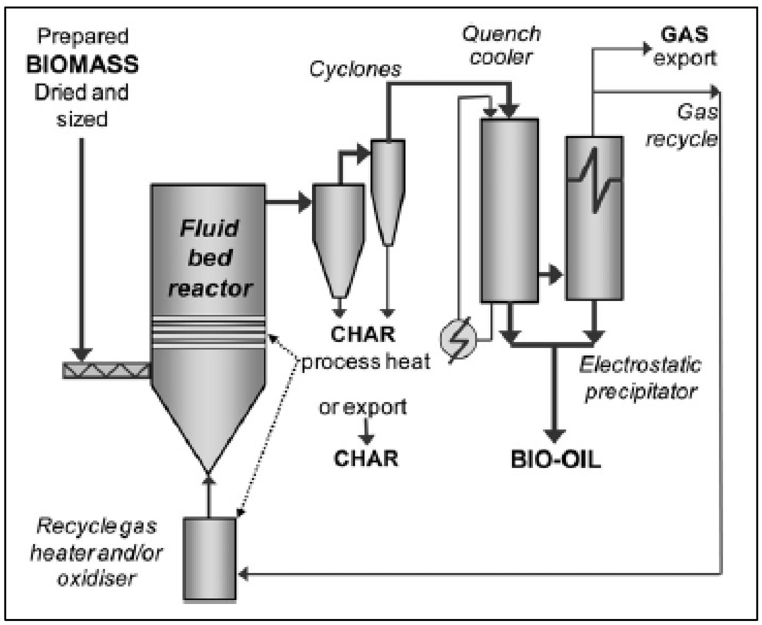

Figure 2.2 Bubbling Fluid Bed Reactor with Electrostatic Precipitator
(source: (Bridgwater 2012))

2.2.3 Storage of Bio-oil

Bio-oil is made up of oxygenated hydrocarbons and water (Bridgwater 2012). It generally contains anywhere from 12 to about 25% water (Ringer 2006) (Jones 2009). It is the liquid condensate of the vapors after they leave the quench cooler. It is dark-brown and has a high density and viscosity. Bio-oil has a high oxygen content, which results in a lower heating value. It is also acidic, making it unstable and corrosive (Sadaka). Once collected, bio-oil is stored. The storage capacity is large enough to store up to four weeks of liquid product. The reason for storage is in case there is delay in getting the product to market (Bridgwater 2012).

Although bio-oil has many benefits, there are problems associated with the long-term storage of it. Over time, bio-oil can increase in viscosity (Sadaka). The reason this occurs is because the production of bio-oils from fast pyrolysis is a thermodynamically non-equilibrium process (Ringer 2006). Oxygenated compounds in the bio-oil attempt to achieve equilibrium through chemical reactions in storage. The chemical reactions result in a higher viscosity.

2.2.4 Upgrading of Bio-oil

Bio-oil is corrosive and highly oxygenated which make it difficult to store, transport, and refine (Brown et al. 2013b). Therefore, upgrading of bio-oil is necessary to stabilize it. It can be upgraded physically, chemically, or catalytically. Physical upgrading uses filtration and a solvent. Filtration produces a higher quality bio-oil, and a solvent reduces the viscosity (Bridgwater 2012). Catalytic upgrading requires full deoxygenation of bio-oil. One form of catalytic upgrading is hydroprocessing shown in Figure 2.3. Hydroprocessing involves hydrotreating and hydrocracking. Hydrotreating removes the sulfur and nitrogen, which reduce bio-oil's viscosity and corrosiveness (Brown et al. 2013a). Hydrocracking follows hydrotreating, and reacts with the hydrotreated bio-oil. The goal of hydrocracking is to completely deoxygenate the bio-oil, so it can be blended with gasoline and diesel fuels (Brown et al. 2013b).

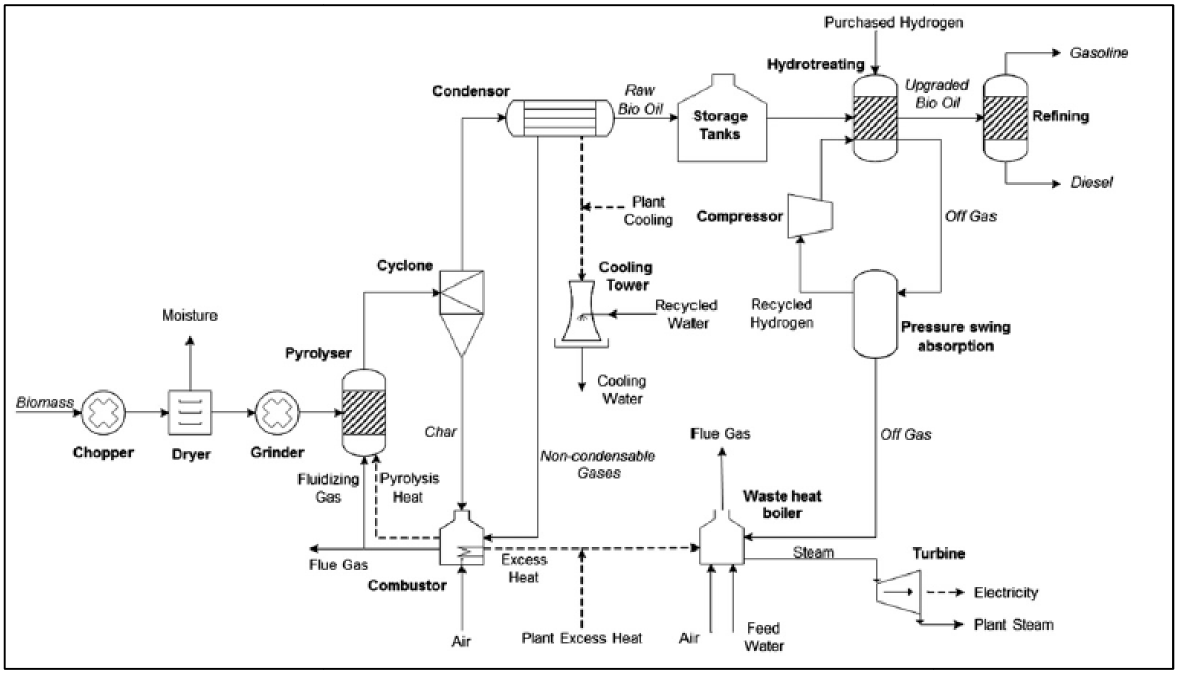

Figure 2.3 Fast Pyrolysis and Hydroprocessing System (source: (Brown et al. 2013a))

Upgrading requires a certain amount of hydrogen. Plants can either choose to produce it or purchase it. Producing hydrogen diverts a portion of the plant's bio-oil produced to generate hydrogen. Wright et al. (2010) examined the production of naptha and diesel range stock fuel from fast pyrolysis of corn stover and upgrading of the bio-oil. The study explored the cost of upgrading bio-oil to transportation fuel. Naptha and diesel range products can be produced at a competitive cost of $3.09-$2.11/gal (Wright et al. 2010). For hydrogen production, the fuel product value estimate was $3.09 per gallon of gasoline equivalent. For the hydrogen purchasing scenario, the fuel product value estimate was $2.11 per gallon of gasoline equivalent. Results showed that fuel could be produced cheaper by hydrogen purchasing than hydrogen production. Brown et al. (2013b) updated the study. Three changes were employed: construction of a boiler and turbogenerator unit, more expensive hydroprocessing unit, and a lower bio-oil yield. This resulted in a change in the minimum fuel selling price to $2.57/gal as shown below in Table 2.3 (Brown et al. 2013b). Therefore, fast pyrolysis and hydroprocessing are still estimated to be competitive with petroleum-based transportation fuels, but not as competitive as the in the previous study. Table 2.2 shows the assumptions that Brown used to find the minimum fuel selling price.

Table 2.2 Assumptions Brown used in his studies (Source: (Brown et al. 2013b))

Assumptions	**2010 ISU Study**	**2013 Study**
Facility size (MTPD)	2000	2000
Facility fuel output (MGY)	58.2	57.4
Equity (%)	100	50
Bond yield (%)	N/A	7.5
TPI (million $)	200	429
Hydrogen Source	Merchant	Merchant
Hydrogen cost ($/kg)	1.33	1.33
Electricity price ($/kWh)	0.054	0.054
IRR (%)	10	10
Feedstock Cost ($/MT)	83	83

Table 2.3 Transportation fuel MFSPs from Brown (Source: (Brown et al. 2013b))

Analysis	**2010 ISU Study**	**2013 Study**
Transportation fuel MFSP ($/gal)	2.11	2.57

2.2.5 Envergent Technologies

Envergent technologies was founded in October 2008. It is a joint venture by UOP, a Honeywell Company, and Ensyn. UOP is a leading process technology licensor. Ensyn has experience with commercial fast pyrolysis, and are the developers of rapid thermal processing (RTP). Together, the two companies provide pyrolysis oil technology for fuel oil substitution (Streff 2009). The technology used is rapid thermal processing (RTP).

2.2.5.1 Rapid Thermal Processing

Rapid thermal processing is a fast thermal conversion process using fast pyrolysis (Envergent Technology 2013). It is sustainable, cost-effective, and almost carbon-neutral. In comparison to combustion, it delivers more useable energy, and the energy has the ability to be stored on site. In comparison to gasification, it requires lower temperatures and pressure, making it less energy intensive. The process can handle a variety of feedstocks for conversion into char, gas, and bio-oil (Envergent Technology 2010).

2.2.5.1.1 Pyrolysis

The pyrolysis process used for rapid thermal processing has similarities and differences to the generic pyrolysis described above. As stated previously, the process rapidly heats biomass in the absence of oxygen. As pictured in Figure 2.4 below, the dried small biomass particles make contact with the circulating hot sand in the reactor (Envergent Technology 2013). The process can be done at temperatures between 400 and 950^{o}C (Goyal, Seal, and Saxena 2008). For generic pyrolysis, yield is maximized at 500^{o}C, whereas for RTP pyrolysis, the temperature which optimizes liquid yield is less than 600^{o}C (Graham 1994). Similar to the generic pyrolysis, pyrolytic vapor is rapidly quenched to produce liquid fuel, which is then preserved through cooling. The liquid yield varies from 55-80% depending on the biomass feedstock used (Envergent Technology 2010).

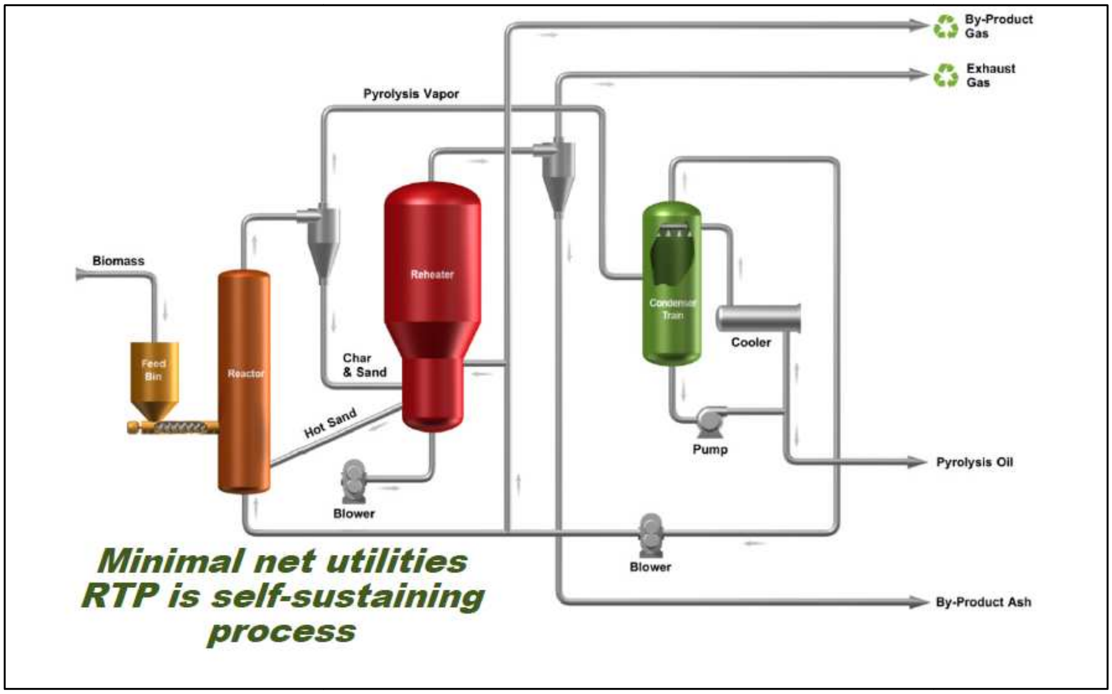

Figure 2.4 Rapid Thermal Processing Flow Diagram (source: (Streff 2009))

Rapid thermal processing green fuel is expected to reduce carbon emissions up to 90%. The price of RTP green fuel is largely dependent on the cost of the biomass feedstock. However, at a cost of $110 per tonne of biomass, RTP green fuel is still expected to be cost competitive with heavy fuel oil (Envergent Technology 2013).

2.2.5.1.2 Hydrotreating

Similar to hydroprocessing described previously, after RTP green fuel is produced, it is upgraded to transportation fuel by hydrotreating. In order to upgrade RTP green fuels, oxygen molecules must be removed and acidity and viscosity must be reduced (Streff 2009). The RTP green fuel goes through a two stage hydrodeoxygenation. The resulting liquid is a pH neutral fuel (Streff 2012).

2.3 Life-Cycle Analysis

Life-cycle analysis is key to understanding and improving biofuel production. It assesses the environmental impacts of a product from beginning to end. For the case of aviation biofuels, it estimates the benefits of using aviation biofuels to reduce Greenhouse Gas (GHG) emissions relative to conventional jet fuel (CJF) (Han et al. 2013). With air traffic expected to grow in the future, so will GHG emissions and the importance of life-cycle analysis.

A well-to-wake analysis (WTWa) accounts for energy and emissions from all stages in development and use of an aviation fuel. This includes feedstock recovery and transportation, fuel production and transportation, and fuel consumption during aircraft operation (Han et al. 2013). Han et al. uses the Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET) model to examine the well-to-wake analysis. By using GREET, WTWa results can be estimated for energy use and GHG emissions for various types and classes of aircraft (Elgowainy et al. 2012).

2.3.1 Greenhouse Gas Emissions

There is variability in life-cycle analysis GHG emissions. Feedstock source, fuel conversion technology, allocation or displacement credit methodology applied co-products, and different alternative bio-jet pathways affect the reduction in life-cycle GHG emissions (Elgowainy et al. 2012).

Feedstock source can have a large impact on reduction of life-cycle GHG emissions. Different crop residues and dedicated energy crops have various effects on land use change and GHG emissions. Estimating land use change is difficult, however an important part of life-cycle analysis. There are two types of land use change, direct and indirect. Much of the previous literature discusses land use change in terms of direct and indirect land use change. However, the definitions of these terms have never been precise and have varied a bit from one analyst to another. For example, some consider direct land use change essentially to be that which occurs in the country where the biofuel is produced, while indirect occurs outside the country.

Others define direct land use change (dLUC) to be when change occurs within the production boundary of a feedstock (e.g. forest converted to agricultural land) (Bailis 2010). Indirect land use change (iLUC) is an implied change, outside the production boundary of a feedstock (Shonnard, Williams, and Kalnes 2010). Taheripour and Tyner use the term induced land use change which includes both direct and indirect. Their GTAP model of land use change estimates the land use change induced by increased biofuels production, and it can occur anywhere in the world.

There are several studies which looked at effects of land use change from dedicated energy crops and crop residues. Dedicated energy crops such as switchgrass require large amounts of land, and contribute to iLUC emissions (Taheripour and Tyner 2013). Bailis and Baka conducted a study to replace conventional jet fuel with synthetic paraffinic kerosene (SPK) from Jatropha, a dedicated energy crop. The life cycle emissions they use for jet fuel is 88.1 kg CO2e/GJ. With no dLUC, there are emissions of 40 kg CO_2e per GJ of fuel product, a 55 percent reduction relative to conventional jet fuel. However, for Jatropha planted on former agricultural land, there is a net GHG reduction of 91 percent relative to CFJ under low yields, 83 percent under medium yields, and 81 percent under high yields. They also found that converting pasture to Jatropha may result in a net loss of carbon. Jatropha planted on shrublands results in a net GHG increase of 193 percent if yields are low, and 14 percent if yields are high (Bailis 2010). Another study by Shonnard et al. (2010) looked at camelina-derived jet fuel. They found GHG life cycle emissions of 22.4 gCO_2 equiv/MJ fuel, which is a reduction relative to petroleum jet fuel of 75 percent. However, impacts of land use change were not included in the analysis (Shonnard, Williams, and Kalnes 2010). Stratton et al. (2010) state that avoiding land use change which results in positive GHG emissions is key (Stratton, Wong, and Hileman 2010). On the other hand, converting crop residues to biofuels has no significant iLUC emissions (Taheripour and Tyner 2013). Taheripour and Tyner (2013) concluded that converting corn stover to biofuel barely affects land use. Corn stover is a co-product, which requires little land use change. As a result, crop residues such as corn stover do not result in positive GHG emissions. In fact, a study by Jin et al. (2014) found that corn stover removal decreased soil CO_2 and N_2O emissions (Jin et al. 2014).

Alternative aviation biofuels can reduce life-cycle GHG emissions relative to petroleum jet fuel. Currently, biojet is blended with petrojet at a 50%-50% blend. This is due to a lack of aromatic compounds in biojet, which are needed to meet fuel property and performance requirements for use in airplanes (Agusdinata et al. 2011). Elgowainy et al. (2012) looks at three alternative aviation biofuels: Fischer-Tropsch from natural gas, coal, and biomass, bio-jet fuel from fast pyrolysis of cellulosic biomass, and bio-jet from vegetable and algal oils. These three pathways can be grouped into two fuels: synthetic paraffinic kerosene (SPK) and synthetic kerosene aromatic (SKA). FT and HEFA jet fuels are composed of paraffins and are grouped under SPK, while pyrolysis jet fuels are composed of aromatic compounds and grouped under SKA (Elgowainy et al. 2012). The three pathways reduce GHG emissions by 55-85% relative to petroleum jet fuel, without considering land use change. Jet fuel production via pyrolysis of corn stover resulted in a reduction of well-to-wake analysis GHG emissions by 55 percent. Hydroprocessing of soybean or algal oil reduced WTWa GHG emissions by 70 percent (Elgowainy et al. 2012). Han et al. (2013) also concluded that all three pathways result in reduced GHG emissions relative to petroleum jet with the range being from 41-89 percent; 41-63 percent with hydroprocessed jet fuel, 68-76 percent with pyrolysis jet fuel, and 89 percent with Fischer-Tropsch jet fuel from corn stover (Han et al. 2013).

Pyrolysis jet fuel GHG emission reductions relative to petroleum jet vary depending on allocation of co-products. The percentage of reduction in GHG emissions depends upon biochar allocation. When biochar was combusted for power generation, WTWa GHG emissions were reduced 68 percent relative to petroleum jet. When biochar was used in soil amendment for carbon sequestration, WTWa GHG emissions were reduced 76 percent relative to petroleum jet (Han et al. 2013). Elgowainy et al. (2012) also found that the amount and source of hydrogen can have an impact on GHG emissions. When hydrogen was produced from NCG and char, liquid fuel yield was high, but the reduction in GHG emissions only 45 percent. When hydrogen was produced internally via pyrolysis oil and char was sequestered in soil applications, liquid fuel yield was reduced, but there were large reductions in GHG emissions, at 103 percent (Elgowainy et al. 2012). Hsu (2012) concluded that GHG emissions could be reduced more if electricity and hydrogen used in the process are produced from biomass. This holds true as long as fuel yield does not fall to offset the GHG savings (Hsu 2012).

Since our process uses corn stover as its feedstock, there will be no GHG emissions associated with land use change. Thus, we will take the range of direct life cycle emissions for fast pyrolysis produced by others to form the basis for our GHG assessment of the process.

2.4 Policy Options

2.4.1 Reverse Auction

There are two types of auctions: traditional (or forward) and reverse. The most common type of auction is the traditional. In a traditional auction, buyers bid on the product being put up for auction by the seller. The highest bidder wins the product, and the lowest unique bidder is among the losers. However, this is not the case for reverse auctions. In a reverse auction, the lowest unique bidder wins, while all the higher bidders lose (Gaggero 2010). In a reverse auction, the buyer initiates the sale. The buyer controls the market since multiple sellers are offering the same product for sale. The seller's decrease their price for the product until a market price is achieved. For an auction, this price is a reduced price, because the seller can see the price level needed to get the sale (Smeltzer and Carr 2003). However, most of the time reverse auctions are sealed bids. Therefore, the bidders submit their price, and the lowest bid wins.

In order for a reverse auction to be successful, certain conditions must be fulfilled. The four conditions required are the product or service specifications must be clear and comprehensive, the purchase must be large enough to provide incentive for the supplier to participate, the appropriate supply market conditions must exist, and the appropriate infrastructure must exist. If a reverse auction is successful then reduced purchase prices, lower administrative costs, and improved inventory should occur (Smeltzer and Carr 2003).

Reverse auctions used for government policy are always sealed bids. The buyers put up a good or service and the bidders place bids on it. Looking specifically at the aviation biofuel industry, the buyers would put up a long-term contract, and the private investors would place bids on it. The bidding variable is price per gallon of fuel. The private investor with the lowest bid wins.

The government incurs a cost with a reverse auction. The production level is fixed regardless of the oil price. Therefore, the government may win or lose depending on oil price. No matter what oil price, the government must pay the contracted price per gallon of fuel. Low oil prices and higher aviation biofuel prices results in binding of the contract. Binding simply means that the contract causes aviation biofuels consumption to be greater than it otherwise would be (Gaffigan 2010). This is similar to what occurs with ethanol production. The binding standard imposes an implicit tax on gas consumption which consumers pay (Tyner and Taheripour 2008). Similarly for aviation biofuels, the contract imposes an implicit tax on consumption when biofuel prices are higher than fossil prices, which the government must pay. An implicit tax is simply the effect of taxes on the price of an asset (Weisbach 1999). It acts as an implicit subsidy to the producer. At high oil prices and low aviation biofuel prices, binding is unlikely and an implicit tax does not occur. In fact, in this case there is an implicit tax on the biofuel producer since the buyer is getting the product at less than market value.

2.4.2 Competitive Capital Subsidy

A competitive capital subsidy is similar to a reverse auction. Governments use capital subsidies to lower capital costs for public interest. The private investors compete for a capital subsidy from the government. Similar to the reverse auction, the lowest bidder gets the subsidy. However, the bid variable is different. The amount or percent of capital subsidy is bid on instead of the price per gallon. One advantage is that the government cost is all up front. However, subsidization usually results in economic loss (Baldwin 1986).

2.4.2.1 Defense Production Act

The Defense Production Act (DPA) is an example of a competitive capital subsidy. The act came about due to an urgent need for military manpower, supplies, and equipment for the Korean War. It "ensures the availability of the nation's industrial resources to meet the national security needs of the United States" (Else 2009). Through the DPA, the domestic industry must give priority to national security production. The President can also offer incentives within the domestic market to enhance production and supplies when necessary (Brown 2013). Capital subsidies are meant to allow companies to compete in markets and achieve gain.

When created in 1950, the act had seven titles. However, over the years, only Titles I, III, and VII remain in effect (Else 2009). Title I is priority performance authority. It allows the federal government to have timely availability of materials, equipment, and services needed for national defense, as well as gives government first priority over those materials, equipment, and services through contracts. The president can also allocate and prioritize contracts to maximize domestic energy supplies. Title III helps ensure an adequate supply of materials and goods. This title helps stimulate private investment in production resources. Under the section for purchases and purchase commitments, purchases provide direct subsidy to companies. The direct subsidies help establish production capacity (Buffler 2010). Title VII contains several distinct authorities (Brown 2013).

2.4.3 Carbon Tax

A carbon tax is a kind of Pigouvian tax. That is, it is a means of putting a price of a non-market externality, in this case, GHG emissions. Pigou believed that the tax rate should be equal to social marginal damages from an additional unit of emissions (Metcalf 2009). Those who face the tax internalize their cost. They set their emissions level at a point where their cost is equal to the marginal benefit from not emitting. The optimal tax rate is where marginal cost of abatement equals marginal damages of emissions. Marginal abatement costs are the amount emissions can decrease if an additional dollar were spent on it (Metcalf 2009). Metcalf and Weisbach (2009) state that calculating the optimal tax rate is complex. Therefore, there are a wide range of optimal tax rates which exist in literature.

Carbon taxes have advantages and disadvantages. One advantage of a carbon tax is that it makes the price explicit (Metcalf 2008). As a result, it provides an incentive for emitters of carbon dioxide emissions to reduce their emissions. A carbon tax can reduce energy use, improve energy efficiency, and promote development for renewable energy (Lin and Li 2011). Metcalf found that in the short and long run, a carbon tax reduces emissions (Metcalf 2008). Similarly, Lin and Li (2011) looked at the effect of a carbon tax on per capita CO_2 emissions for 5 European countries. They found a negative impact on growth of per capita CO_2 emissions in all countries. However, it was only significant in Finland (Lin and Li 2011). Although there are advantages to a carbon tax, there are also some concerns. It can slow down economic growth, decrease social welfare, and lead to carbon leakage (Lin and Li 2011). Carbon leakage is when companies look to shift their business to countries that do not have a carbon tax (Metcalf 2009).

A carbon tax can be designed to encourage change in consumer behavior or to raise revenues for carbon mitigation programs (Sumner 2009). Three issues associated with a carbon tax in a developed country are the optimal tax base, issues with the rate, and trade (Metcalf 2009). The tax can be collected upstream or downstream. Both types of taxes reach consumers, but there is a difference in how it reaches them. The tax is imposed to minimize collection and monitoring costs, while ensuring maximum coverage (Metcalf 2009). Taxing upstream means that you are taxing at the earliest point in the production process. Producers see the tax first when it is imposed upstream and then pass it on to consumers, while taxing downstream goes directly to consumers. One argument for taxing downstream is that it is more visible to consumers, so it will have a larger effect. However, taxing upstream results in a lower cost per unit of tax due to economies of scale (Metcalf 2009). By imposing a tax upstream, the tax is embedded in the price and passed on to consumers (Metcalf 2009). The tax can also be introduced one of three ways: slow ramp-up, grandfathering existing emissions, or cold-turkey. The preferred approach is cold-turkey, or without any transition (Metcalf 2009).

Trade with a carbon tax can result in an origin base system being used or a border tax adjustment (Metcalf 2009). If two countries who wish to trade have a carbon price, then an origin base system is preferred. An origin based system is one without border tax adjustments. If they do not, then a border tax adjustment must be used. A border tax adjustment system provides a rebate for taxes paid when a good is exported and imposes a tax when a good is imported (Metcalf 2009). Some benefits to it are it cannot be avoided by producers altering location, and it reduces the incentive for countries to be renegades. A problem with the border tax adjustment is how to determine the carbon content of goods that are exported or imported. Determining the carbon content of a product can be a problem.

A carbon tax on aviation can contain even more issues. Domestic flights are straightforward, however international flights are complicated. An option would be to tax fuel at the refinery, but the issue is you do not know which will be used for domestic or international flights (Metcalf 2009).

The social cost of carbon “allows agencies to incorporate social benefits of reducing carbon dioxide emissions into cost-benefit analyses” (Interagency Working Group 2013). It is an estimate of monetized damages due to increased carbon emissions in a year. The Interagency Working Group on Social Cost of Carbon of the United States Government conducted an update of their 2010 interagency technical support document. Their revised social cost of carbon estimates were higher than their 2010 document. The integrated assessment models (IAMs) were updated using three models, three discount rates, and five scenarios resulting in 45 separate distributions for global social cost of carbon. The three discount rates used were 2.5%, 3%, and 5%. The averages of annual social cost of carbon using the three discount rates were reported, as well as a higher-than-expected 95th percentile at a 3%

discount rate. For 2020, the SCC estimates reported were $12, $43, $65, and $129. For 2014 at the 3% discount rate, the social cost of carbon is $37 per metric ton of CO_2 (Interagency Working Group 2013). In our analysis, we will use this rate of $37/MT, and we will simply apply that rate to the carbon content of fossil jet fuel and corn stover jet fuel to get a differential for the biomass based fuel.

2.5 Conclusion

Aviation biofuels production using corn stover has the potential to play a large role in meeting the RFS cellulosic biofuels requirement. Risks in investment serve as a road block to commercial take off. Government intervention through policy implementation can serve as a way to reduce the uncertainty. In this section, the relevant literature on corn stover, pyrolysis, and the three policy options has been covered. The relevant data on corn stover and pyrolysis has also been covered from previous literature. The next chapter presents the methodology to be used to conduct the techno-economic analysis. Policy analysis will estimate the extent to which each policy alternative reduces uncertainty for private sector investors and the cost to the government of using that policy approach.

CHAPTER 3. METHODS

This chapter contains three main sections: the financial model, risk analysis, and policy analysis. The first section provides an overview of a Discounted Cash Flow Analysis, and breaks down the base case. The base case is first done using assumptions followed by many engineers. This analysis is based on the Iowa State University techno-economic analyses done by Wright et al. (2010) and Brown et al. (2013). The assumptions are then changed in the second base case to follow reality in the marketplace more closely. The second section details technical, system, and fuel price uncertainty used to determine risk in investment. The last section explains how to approach the reverse auction and carbon tax in our analysis.

3.1 Financial Model

3.1.1 Methodology

Discounted cash flow analysis is used to find the value of a project in order to assess whether it will be successful or not. It has two steps, cost analysis and discounted cash flow analysis, which lead to calculating a minimum fuel selling price (MFSP). It is useful for comparing projects of different size (Towler 2013). A discounted cash flow rate or return (DCFROR) is the interest rate at which the net present value (NPV) equals zero. It measures the maximum rate a project can pay and still break even by the end of the project life (Sinnott 2005). A lot of engineers use this analysis to assess whether or not plants should be built.

Many current studies conducting techno-economic analyses use NREL's approach as well as Peters and Timmerhaus installation factors. NREL's approach calculates the total project investment, variable operating costs, and fixed operating costs. Once these costs are obtained, NREL conducts a discounted cash flow analysis using a lot of parameters based off of the work done by Short et al. (1995) (Aden 2002).

3.1.1.1 Cost Analysis

Before the discounted cash flow rate of return (DCFROR) can be calculated, a cost analysis must be done. A cost analysis includes calculating the total project investment, variable operating costs, and fixed operating costs. The first step to calculating the total project investment is calculating the installation cost. There are two ways in which the installation cost can be found. The first approach is to study everything needed to install all the equipment necessary to make the plant operational. This approach is generally taken when the process is close to construction. When the process is a little further away, a factor approach is used (Aden 2002). A common engineering text used for installation factors is Peters and Timmerhaus (Brown et al. 2013b) (Aden 2002). The installation factors are applied to the equipment costs to yield the installed cost. Aden et al. (2002) states that the standard textbook factors method was developed for the chemical and petroleum industry, and that a better methodology may be to use that of Delta-T (Aden 2002). Once the installed equipment cost is found, it must be indexed to the project year. Next, indirect costs, project contingency, and working capital expenditure must be calculated. Fixed capital investment is the sum of installed costs, indirect costs, and project contingency. Lastly, total project investment can be found by adding working capital expenditure, fixed capital investment, and land. Variable operating costs include raw materials, waste handling charges, and by-product credits (Aden 2002). They are incurred only when the process is operating. On the other hand, fixed operating costs are incurred regardless of if the plant is running at full capacity or not. Fixed operating costs include labor as well as other overhead items. The general overhead factor is 60 percent of total salaries. It includes safety, general engineering, general plant maintenance, payroll overhead, plant security, janitorial services, phone, light, head, and plant communications (Aden 2002). Annual maintenance materials and insurance and taxes are also part of fixed operating costs. Annual maintenance materials are 2 percent of total installed equipment cost, while insurance and taxes are 1.5 percent of total installed cost. Although these are commonly used all over the U.S., Aden et al. 2002 does state that their estimates represent Midwest U.S. locations. All salaries must be indexed to the project year using the Bureau of Labor Statistics (Aden 2002).

3.1.1.2 Discount Cash Flow Analysis

In order to find a non-risk adjusted breakeven fuel price (NRABFP), a discounted cash flow analysis must be done. The non-risk adjusted breakeven fuel price is the price of fuel which makes NPV equal to zero at the discounted cash flow rate of return. Related literature refers to this fuel price as the minimum fuel selling price. However, we will use the term non-adjusted breakeven fuel price stated above since it is a breakeven price. The NRABFP will have a percentage chance of loss, so no one will invest at that price. A discounted cash flow analysis requires a specified discount rate, depreciation method, income tax rate, plant life, and construction start-up period to find the NRABFP (Aden 2002). Aden et al. 2002 bases the discount rate, depreciation amount, and income tax rate off of the work of Short et al. The discount rate serves as a measure of time value. It accounts for the risk in investment (Short 1995). A discount rate of 10% is specified in Aden et al. 2002. Short et al. states that, “In absence of statistical data on discount rates used by industrial, transportation, and commercial investors for investments with risks similar to those of conservation and renewable energy investments, it is recommended that a real after-tax discount rate of 10% be used within the Office of Energy Efficiency and Renewable Energy for these sectors.” Short et al. recommends the Modified Accelerated Cost Recovery System (MACRS) for depreciation (Aden 2002). It allows for two declining balance (DB) methods of depreciation. For property with a recovery period of less than 10 years, 200% DB method is used. Property with a recovery period greater than 10 years, 150% DB method is used (Short 1995). It also allows for a straight line depreciation method. For a project with a recovery period less than 10 years, it is depreciated at 200% DB until the annual depreciation values for DB become less than straight line. A faster depreciation is preferred since a dollar earned today is greater than a dollar earned tomorrow (Short 1995). For income tax rate, Aden et al. 2002 uses a rate of 39 percent. This is due to the recommendation that for energy efficiency analyses where investor-specific data is unavailable, the highest tax bracket is used (Short 1995). The highest federal tax bracket is for large corporations who face the tax rate used in Aden et al. (2002). The income tax is averaged over the plant life (Aden 2002). During construction there is no income, and large amounts of money are being spent. The construction time is based on work done by Perry and Green. For small projects, construction time is less than 18 months. Large projects can have a construction time of up to 42 months (Perry 1997). Aden et al. 2002 uses a construction time of 2.5 years. Perry and Green also indicate that for a moderately complex plant, the start-up should be a quarter of the construction time. As a result, Aden et al. 2002 uses a start-up time of 6 months during which 50 percent of production is reached with 75 percent of variable expenses and 100 percent fixed expenses. During the first 6 months 8 percent of capital is spent. In the next 12 months, 61 percent of capital is spent. In the last 12 months of construction time, the remaining 31 percent is spent (Aden 2002).

3.1.2 Base Case

For the base case we look at two different types of analysis: engineering and economic. The engineering analysis uses a discount cash flow analysis, while the economic uses a cost-benefit analysis. The base year for all data is 2011.

3.1.2.1 Engineering

The data used in this analysis comes mainly from the Iowa State University studies by Wright et al. 2010 and Brown et al. 2013. We recreated their analysis using a discounted cash flow rate of return analysis in order to be certain that our data used in the economic analysis was accurate.

Brown et al. 2013 follows the analysis used by most engineers stated in the methodology section above. Chemcad software as well as Aspen Energy Analyzer was used to design the model. The capital cost data used was from KiOR for its 454 MTPD facility in Columbus, MS (Brown et al. 2013b). Brown et al. 2013 also used a 2011 basis year. In order to recreate the work of Brown et al. 2013, we first calculated the total project investment using the installation factors shown in Table 3.1, which Brown et al. (2013) obtained from Peters and Timmerhaus. The total project investment is the sum of fixed capital investment, working capital, and land. All of the costs are a percentage of total purchased equipment cost. Total purchased equipment cost is the sum of the equipment needed to make the plant operational. Brown et al. 2013 did not provide the data on the equipment costs used from KiOR, so we used a different method to find the total purchased equipment cost. We plugged the equations and installation factors for each parameter into an excel spreadsheet and used the goal seek add-in to find the total purchased equipment cost when the total project investment is equal to $429,000,000.

Table 3.1 Methodology for Capital Cost Estimation

Parameter	Abbrev.	Assumption	Source
Total Purchase Equipment Cost	TPEC	100%	Brown et al. 2013
Purchased Equipment Installation	PEI	39%	Brown et al. 2013
Instrumentation and Controls		26%	Brown et al. 2013
Piping		10%	Brown et al. 2013
Electrical Systems		31%	Brown et al. 2013
Buildings (including services)		29%	Brown et al. 2013
Yard Improvements		12%	Brown et al. 2013
Service Facilities		55%	Brown et al. 2013
Total Installed Cost	TIC	TPEC*InF (3.02)	Brown et al. 2013
Installation Factor	InF	3.02	Brown et al. 2013
Indirect Cost		0.89*TPEC	Brown et al. 2013
Engineering		32%	Brown et al. 2013
Construction		34%	Brown et al. 2013
Legal and Contractors Feeds		23%	Brown et al. 2013
Total Direct and Indirect Costs	TDIC	TIC+IC	Brown et al. 2013
Contingency	Con	20% of TDIC	Brown et al. 2013
Fixed Capital Investment	FCI	TDIC+Con	Brown et al. 2013
Working Capital	WC	15% of FCI	Brown et al. 2013
Land Use	Land	6%	Brown et al. 2013
Total Project Investment	TPI	FCI+WC+Land	Brown et al. 2013

(source: (Brown et al. 2013b))

Table 3.2 Economic Assumptions

Parameter	Input Value	Units	Source
Real Discount Rate	10%	%	Brown et al. 2013
Nominal Interest Rate	7.50%	%	Brown et al. 2013
10 Year Depreciation	200%	%	Wright et al. 2010
Plant Depreciation Life	7	Years	Wright et al. 2010
Equity	50%	%	Brown et al. 2013
Financing	50%	%	Brown et al. 2013
Loan Term	10	Years	Brown et al. 2013
Project Life	23	Years	Brown et al. 2013
Construction Time	3	Years	Wright et al. 2010
% Spent in Year 1	8%	%	Wright et al. 2010
% Spent in Year 2	60%	%	Wright et al. 2010
% Spent in Year 3	32%	%	Wright et al. 2010
Income Tax Rate	35%	%	Wright et al. 2010

(source: (Brown et al. 2013b, Wright et al. 2010))

Table 3.3 Technical Assumptions

Parameter	Input Value	Units	Source
Total Purchased Equipment Cost	78,631,915	$/year	Calculated
Total Installed Cost	237,468,382	$/year	Calculated
Total Indirect Costs	69,982,404	$/year	Calculated
Project Contingency	61,490,157	$/year	Calculated
Working Capital Expenditure	55,341,142	$/year	Calculated
Total Fixed Capital Investment	368,940,944	$/year	Calculated
Land	4,717,915	$/year	Calculated
Total Capital Investment (with Land)	429,000,000	$/year	Brown et al. 2013
Facility Capacity	2,000	MT/day	Brown et al. 2013
Max Annual Feedstock Use	658,460	MT/year	Calculated
Bio-oil Yield	63%	Mg/Mg biomass	Brown et al. 2013
Fuel Yield	42%	Mg/Mg bio-oil	Wright et al. 2010
Gas Conversion Rate	21%	Mg/Mg bio-oil	Wright et al. 2010
Diesel conversion Rate	21%	Mg/Mg bio-oil	Wright et al. 2010
Gallon to Litre Conversion	0.264	gal/L	Staffell 2011
Naphtha Fuel Density	0.745	kg/L	Staffell 2011
Diesel Fuel Density	0.847	kg/L	Staffell 2011
Metric tonne to kilogram	1,000	kg/MT	Supple 2007
Plant Online Time	329.23	Days/year	Brown et al. 2013
Startup Period	0.75	Years	Wright et al. 2010
Startup Production Rate	50%	%	Wright et al. 2010
Startup Variable Expense	75%	%	Wright et al. 2010
General Overhead	60%	% of TS	Wright et al. 2010
Annual Maintenance	2%	% of FCI	Wright et al. 2010
Insurance & Taxes	1.50%	% of FCI	Wright et al. 2010
Total Fixed Operating Costs	15,744,489	$/year	Calculated
Feedstock Cost	83	$/MT	Brown et al. 2013
Electricity Price	0.054	$/kWh	Brown et al. 2013
Electricity Use	11,490	kW/hr	Brown et al. 2013
Electricity Generation	223,000,000	kWh/year	Brown et al. 2013
Catalyst Cost	1,770,000	$/year	Wright et al. 2010
Hydrogen Price	1.33	$/kg	Brown et al. 2013
Hydrogen Use	2,041	kg/hr	Wright et al. 2010
Fuel Sale Price	3	$/GGE	Brown et al. 2013

(source:(Brown et al. 2013b, Wright et al. 2010, Staffell 2011, Supple 2007))

Total variable operating costs include the feedstock cost, catalyst replacement cost, hydrogen cost, electricity cost, and electricity sales. The total variable operating costs were calculated using Equations 3.1 through 3.5 shown below. The parameter values used to calculate the costs are shown in Table 3.3

$$Feedstock\ Use\ \left(\frac{Mg}{year}\right) = Plant\ Capacity\ \left(\frac{MT}{day}\right) * Online\ Time\ \left(\frac{days}{year}\right)$$

Equation 3.1

$$Feedstock\ Cost\ \left(\frac{\$}{year}\right) = Feedstock\ Use \left(\frac{Mg}{year}\right) * Price\ of\ Feedstock\ \left(\frac{\$}{Mg}\right)$$

Equation 3.2

$$Hydrogen\ Cost\ \left(\frac{\$}{year}\right) = Hydrogen\ Use\ (kwh) * 24 \left(\frac{hours}{day}\right) * Online\ Time\ \left(\frac{days}{year}\right) * Hydrogen\ Price\ \left(\frac{\$}{kwh}\right)$$

Equation 3.3

$$Electricity\ Cost \left(\frac{\$}{year}\right) = Electricity\ Price \left(\frac{\$}{kwh}\right) * Electricity\ Use\ \left(\frac{kwh}{day}\right) * 24 \left(\frac{hours}{day}\right) * Online\ Time\ (\frac{days}{year})$$

Equation 3.4

$$Electricity\ Sales\ \left(\frac{\$}{year}\right) = Electricity\ price\ \left(\frac{\$}{kwh}\right) * Electricity\ Produced\ \left(\frac{kwh}{year}\right)$$

Equation 3.5

Total fixed operating costs include total salaries and total general costs. The data used to calculate total salaries was obtained from Wright et al. 2010, and is shown in more detail in the appendix. General costs include overhead costs, maintenance costs, and insurance and taxes. The assumptions for these are listed under Table 3.3.

Total fuel production was calculated using Equation 3.6 below. Using the assumptions listed in Table 3.3, we found a facility fuel output of 58.0 MGY. Brown et al. 2013 found a facility fuel output of 57.4 MGY. In the 2010 ISU study, Wright et al. found a facility fuel output of 58.2 MGY. Therefore, we can be confident that our technical parameters in Table 3.3 are functioning similarly to Brown et al. 2013 assumptions.

$$Fuel\ Production\ \left(\frac{gallons}{year}\right) = \left(Feedstock\ Use\ \left(\frac{Mg}{year}\right) * Bio-oil\ \ Yield\ (\%)\right) * \left(Fuel\ Conversion\ Rate\ (\%) * \left(\frac{1}{Fuel\ Density\left(\frac{litre}{kg}\right)}\right) * Conversion\ \left(\frac{kg}{MT}\right) * Conversion\ \left(\frac{gallons}{litre}\right)\right)$$

Equation 3.6

In order to recreate the discounted cash flow spreadsheet and obtain a non-risk adjusted breakeven fuel price (NRABFP), we used economic, technical, and financing assumptions. The economic assumptions are listed in Table 3.2. Some of the important assumptions are a 10% discount rate, a 200% DB method with a life of 7 years, a 35% income tax rate, a project life of 23 years, and a construction time of 3 years. There is also 50% equity and 50% debt financing. The technical assumptions used in the spreadsheet are listed in Table 3.3. Some of the calculations in the spreadsheet are detailed above in Equations 3.1 through 3.6. Fuel sales were also used in the spreadsheet, and is provided below in Equation 3.7.

$$Fuel\ Sales\ \left(\frac{\$}{year}\right) = Annual\ Fuel\ Production\ \left(\frac{gallons}{year}\right) * Fuel\ Selling\ Price\ \left(\frac{\$}{gallon}\right)$$

Equation 3.7

Financing and tax assumptions also affect the results of the analysis. Brown et al. 2013 and Wright et al. 2010 do not provide detail of the assumptions used. We assume that their assumptions are similar to work done by Humbird et al. 2011 and Aden et al. 2002. There are five financing and tax assumptions listed in the table below. Humbird et al. 2011 assume that land is paid with equity. They also assume that interest on the loan is paid during construction time, and loan and interest are not included when you compute taxes (Humbird 2011). Aden et al. 2002 assume that income tax is averaged over the plant life. Lastly, Brown et al. 2013 does not specify an inflation rate.

Table 3.4 Financing and Tax Assumptions for Engineering Analysis

Assumption	Source
(1) Land is paid with equity	Humbird et al. 2011
(2) Interest on the loan is paid during construction	Humbird et al. 2011
(3) Income tax is averaged over plant life (i.e. tax benefits or losses carry over)	Aden et al. 2002
(4) Loan and interest are not included when taxes are computed	Humbird et al. 2011
(5) Inflation rate is zero	Brown et al. 2013

(source: (Humbird 2011, Aden 2002, Brown et al. 2013b)

The non-risk adjusted breakeven fuel price is the fuel price that makes the net present value equal to zero. When the net present value is zero, present value benefits are equal to present value costs. Using the assumptions listed in the Tables 3.1, 3.2, and 3.3, we found a minimum fuel selling price of $2.47. The goal seek add-in in Excel was used to calculate the fuel price when net present value is set to zero. Brown et al. (2013) found a fuel price of $2.57 when the internal rate of return is 10%. Therefore, we can be confident that our assumptions and results are an accurate recreation of Brown et al. (2013). The next section uses assumptions that follow a more realistic representation of the marketplace.

3.1.2.2 Economic

Cost-benefit analysis involves conducting an economic analysis and a financial analysis. The financial analysis accounts for financing and taxes, while the economic does not. We present both analyses in nominal terms using Excel. As stated previously, using a discounted cash flow analysis yielded an NRABFP of $2.47 per gallon. However, some costs are in real terms while others are in nominal terms. In order to calculate a more accurate NRABFP, the costs must all be in the same terms.

There are a few differences between an engineering and economic analysis. A comparison between the financing and tax assumptions is presented below in Table 3.5. We assumed that land is included in calculating the total capital investment. Total capital investment is then split evenly between debt and equity. Another difference is that interest is capitalized (added to the total cost) during construction. Taxes are also handled differently. Instead of carrying over, tax benefits or losses occur in the year they occur. In computing taxable income, loan interest is subtracted from cash flow. Lastly, we used an inflation rate of 2.5%. Costs and revenues can be expressed as current (nominal) or constant (real) dollars. However, actual cash flows in the marketplace are current dollars (Short 1995). As a result, we use an inflation rate to present our costs and returns in current dollars.

Table 3.5 Comparison of Engineering and Economic Financing and Tax Assumptions

Engineering	Economic
(1) Land is paid with equity	(1) Land is included in capital investment and the cost is split between financing and equity
(2) Interest on the loan is paid during construction	(2) Interest is compounded annually during construction
(3) Income tax is averaged over plant life (i.e. tax benefits or losses carry over)	(3) Tax benefits or losses occur in the year they occur
(4) Loan and interest are not included when taxes are computed	(4) Loan interest is deducted from taxes
(5) Inflation rate is zero	(5) Inflation rate is 2.5%

As stated previously, using the engineering assumptions we found a fuel price of $2.47 when the internal rate of return was 10%. A comparison of the breakeven fuel prices using engineering and economic assumptions is provided below in Table 3.6. For this comparison we use Brown's tax rate of 35%. Engineering assumptions with an inflation rate of 2.5% results in a lower fuel price of $2.43.

The fuel price which sets net present value equal to zero with a 35% tax rate and 0% inflation when the internal rate of return is 10% is $2.62. This is substantially higher than the fuel price found using a discounted cash flow analysis. Using the authors' assumptions leads to higher breakeven fuel prices. Using an inflation rate of 0% leads to a fuel price of $2.62. Adding inflation results in a decrease in the fuel price to $2.58. Overall, we can see that changes in the financing and tax assumptions have an impact on the breakeven fuel price.

Table 3.6 Comparison of Breakeven Fuel Prices with a 10% IRR Using Different Assumptions and a 35% Tax Rate ($/gallon)

	Author Assumptions	Engineering (Brown) Assumptions
0% Inflation Rate	2.62	2.47
2.5% Inflation Rate	2.58	2.43

The United States currently uses a statutory corporate income tax rate of 39.1%. This includes a federal tax rate of 35% plus an average of state tax rates. Globally, the U.S. has the highest marginal corporate income tax rate followed by Japan with 37% (Pomerleau 2014). However, although this is the rate that is set by the law, corporations rarely pay that tax rate. U.S. corporations take advantage of subsidies, shelters, and special breaks (Kocieniewski 2011). David Kocieniewski from The New York Times stated that U.S. companies pay about a 25% income tax rate. The Organization for Economic Cooperation and Development (OECD) countries have an average income tax rate of 25% (Pomerleau 2014). The U.S. pays only a little more than that average (Kocieniewski 2011). Kocieniewski (2011) also states that taxes vary by industry. American retailers face on average about a 31% income tax rate, while manufacturers face about a 26% income tax rate, and mining only faces a 6% income tax rate. In his article, Kocieniewski also states that Honeywell International paid about 22% income tax rate, which accounted for the United States, abroad, and a large pension contribution. Before accounting for the pension contribution, they only paid a 15% income tax rate. United Technologies, a competitor, reported an average income tax of 24% (Kocieniewski 2011). The Government Accountability Office (GAO) found that large U.S. corporations pay an average federal tax rate of 12.6%. Adding foreign, state, and local taxes puts the total rate at 16.9% (O'Toole 2013). Using OECD and Bureau of Economic Analysis (BEA) data from 2001-2008, Philip Dittmer found that corporations paid an average effective tax rate of 24.1%. PricewaterhouseCoopers found an average effective tax rate of 27.7% for the United States from 2006-2009, while American Enterprise Institute found a tax rate of 29.0% (Dittmer 2011). Overall, most U.S. corporations pay lower tax rates than what is set by the law. The tax rate we use for our analysis is 16.9%, which is the average tax rate of 12.6% found by the GAO plus foreign, state, and local taxes.

The two tables below show comparisons of the non-risk adjusted breakeven fuel price at a 10% internal rate of return with two tax rates, two inflation rates, and two sets of assumptions. They introduce the tax rate found in the paragraph above. Table 3.7 shows a comparison of NRABFP's using Brown's parameter values and assumptions, while Table 3.8 uses Brown's parameter values and the authors' assumptions. In Table 3.7, using Brown's tax rate of 35% and 0% inflation, the breakeven fuel price is $2.47 as stated previously. Using the authors' tax rate of 16.9% results in lower breakeven fuel prices. A tax rate of 16.9% and an inflation rate of 2.5% result in a breakeven fuel price of $2.37. When inflation is decreased to 0% there is an increase in fuel price to $2.41. Overall, we can see that when inflation is introduced it decreases the breakeven fuel price. This makes sense since inflation reduces the real cost of finance and taxes, which causes the fuel breakeven price to fall. Lowering the tax rate from 35% to 16.9% also has a visible impact, reducing the breakeven fuel price by 6 cents.

Table 3.7 Comparison of Non-risk Adjusted Breakeven Fuel Prices at 10% IRR with New and Old Tax Rates using Brown Parameter Values and Brown Assumptions ($/gallon)

Brown Parameter Values & Brown Assumptions		
	16.9% Tax Rate	35% Tax Rate
0% Inflation Rate	2.41	2.47
2.5% Inflation Rate	2.37	2.43

Table 3.8 Comparison of Non-risk Adjusted Breakeven Fuel Prices at 10% IRR with New and Old Tax Rates using Brown Parameter Values and Author Assumptions ($/gallon)

Brown Parameter Values & Author Assumptions		
	16.9% Tax Rate	35% Tax Rate
0% Inflation Rate	2.56	2.62
2.5% Inflation Rate	2.51	2.58

Table 3.8 has comparatively higher breakeven fuel prices than Table 3.7. Using the authors' assumptions, a tax rate of 16.9%, and an inflation rate of 2.5% results in a breakeven fuel price of $2.51. The breakeven fuel price increases to $2.56 when inflation is reduced to zero. Similar to Table 3.7, Brown's tax rate of 35% increases the fuel prices as seen earlier. In comparison to Table 3.7, we see that there is a difference in breakeven fuel prices using Brown's assumptions versus the author's assumptions of about 15 cents.

3.2 Risk Analysis

3.2.1 Uncertainty

3.2.1.1 Technical Uncertainty

There are five variables which have large impacts on the non-risk adjusted breakeven fuel price. Feedstock cost, hydrogen cost, and capital cost make up a large percentage of the cost share as shown below in Table 3.9. Feedstock cost accounts for the largest percentage with 34.4%. Capital cost is second with 30.3% of the cost. Hydrogen cost is third, but still makes up 21.0% of the cost. A change in cost for any three of these variables has a large impact on the minimum fuel selling price. The bio-oil yield and fuel yield also impact the non-adjusted breakeven fuel price. Bio-oil yield and fuel yield directly impact the overall fuel output. As a result, a change in fuel output has a substantial impact on the non-adjusted breakeven fuel price.

Table 3.9 Cost shares for key variables

Item	NPV cost ($)	Cost share (%)
Capital cost (with working capital)	$303,129,655	30.3%
Feedstock	$344,499,049	34.4%
Hydrogen	$209,663,508	21.0%
Other operating cost	$142,824,530	14.3%
Total	$1,000,116,742	100.0%

(source: (Petter and Tyner 2014))

3.2.1.1.1 Feedstock Cost

Feedstock cost can vary substantially due to a number of factors. The two main factors affecting feedstock cost are location and time of year (Tyner 2010a). Crop rotation used can also have a large impact. Nutrient replacement cost is dependent upon the crop rotation used. As stated in the literature review, a corn-corn rotation may have a higher nutrient replacement cost than a corn-soybean rotation. However, a corn-corn rotation may result in a reduction in tillage, which allows for a cost savings. The facility size, harvest system, and storage type may also contribute to variation in the cost of stover (Perlack 2003, Vadas and Digman 2013). Most older studies price stover at a lower cost than more recent studies. In literature from 1998 to 2003, Brechbill and Tyner (2008) found the total cost for corn stover per dry ton to range from a low of $19.70 to a high of $51.60 or $22.06-$57.79/MT (Brechbill 2008). More recent studies tend to calculate a total cost for corn stover above $60 per metric ton as shown below in Table 3.10 (Thompson and Tyner 2014, Fiegel 2012). A more recent study by Thompson and Tyner (2014) calculates a stover cost range of $82.19-$100.57/MT. Fiegel conducts a similar study, but excludes nitrogen as part of nutrient replacement cost. As a result, she finds a range in stover cost of $68.06-$82.94/MT, which is lower than Thompson and Tyner. Looking at Table 3.10, the 2013 dollars column ($/MT) cost lows seem to hover around $60-70/MT, while the highs seem to hover around $100/MT. Based on this data from the literature, we will assume a distribution of stover cost with a min, mode, and max of $55/MT, $83/MT, and $100/MT.

Table 3.10 Total Corn Stover Cost

Source	Range (Units in paper)	Range ($/MT)	2013 dollars
Thompson and Tyner (2014)	$82.19-100.57/MT	82.19-100.57	82.60-101.07
Fiegel (2012)	$60.77-74.05/ST	68.06-82.94	68.36-83.31
Brechbill et al. (2011)	$63.00-75.00/MT	63.00-75.00	66.51-79.17
Sokhansanj and Turhollow (2004)	$60.15/MT	60.15	82.73
Aden et al. (2002)	$62.00/MT	62.00	95.06

*MT: metric tonne
*ST: short ton
*Conversion Rate $/MT: 1 short ton = 1.12 metric tonne
*Conversion Rate 2013 dollars: (2013 dollars/Source data year dollars)*Range($/MT)

(source: (Thompson and Tyner 2014, Fiegel 2012, Brechbill, Tyner, and Ileleji 2011, Sokhansanj 2004, Aden 2002))

3.2.1.1.2 Final Fuel Yield

Final fuel yield for gasoline and diesel is obtained in two steps. The first step is conversion of the biomass to bio-oil, and the second step is conversion of bio-oil to fuel. Both steps have had a variety of conversion rates reported in the literature. The final fuel yield is the product of bio-oil yield and fuel yield.

Bio-oil yield has a direct impact on the fuel yield. The higher the bio-oil yield, the better the fuel yield since the fuel yield is a percentage of the bio-oil yield. Reaction times have an effect on the quality and quantity of bio-oil produced. Quicker reaction times favor higher quality bio-oil as well as higher yields (Wright et al. 2010). Yields above 70% and below 55% are not uncommon depending on the feedstock and the type of reactor used (Brown et al. 2013b). Wright et al.(2010) and Brown et al. (2013) both use a min, mode, and max bio-oil yield of 55%, 63%, and 70% of biomass on a weight basis. Brown et al. (2013) bases his yields off of the work done by Mullen et al. (2010). Mullen (2010) finds an actual recovery of 58% bio-oil from corn stover by fast pyrolysis using a fluidized bed reactor. To correct for a percentage of the biomass being left in the system he uses an optimization model, which results in a bio-oil yield of 61.7% (Mullen et al. 2010). The type of reactor used can have an impact on the bio-oil yield. Fluidized bed reactors generally result in higher yields than other reactors (Jahirul et al. 2012, Sadaka). Jahirul et al. (2012) finds a range of 50-75% bio-oil yield for fast pyrolysis. Ash content can also impact bio-oil yields (Sadaka). High contents of ash can have a negative effect on bio-oil yields. Reported yields are summarized in Table 3.11.

Table 3.11 Corn Stover Bio-oil Yield (% biomass)

Source	Min	Mode	Max
Wright et al. (2010)	55	63	70
Brown et al. (2013)	49	63	70
Mullen et al. (2010)	58.2		61.7
Bridgwater (2012)	55		75
Sadaka and Boateng		60	
Meier et al. (2013)	55		75
Zhang et al. (2013)		65	
Jahirul et al. (2012)	50		75
Jones and Male (2012)	60		65
Jones et al. (2009)	59.9		66

(source: (Wright et al. 2010, Brown et al. 2013b, Mullen et al. 2010, Bridgwater 2012, Sadaka , Meier et al. 2013, Zhang et al. 2013, Jahirul et al. 2012, Jones 2012, Jones 2009))

Fuel yield has a large impact on the non-risk adjusted breakeven fuel price. Wright et al. (2010) found that as the fuel yield increases, the minimum fuel selling price or as we refer to it, the NRABFP decreases. Some factors that can affect fuel yield are the performance of the pyrolysis reactor, liquid bio-oil collection, storage, and bio-oil yield. A reduction in reactor performance, reduced liquid bio-oil collection, losses during storage, and a low bio-oil yield can all reduce the fuel yield (Wright et al. 2010). Wright (2010) and Brown (2013) both report a similar mode of fuel yield at 42 wt% bio-oil.

However, their minimum and maximum yields differ. Brown et al. (2013) bases his range off of the work of Elliot et al. (2009). Elliot et al. (2009) finds a range of 31-61% fuel yield from corn stover.

Table 3.12 Fuel Yield (% bio-oil)

Source	Min	Mode	Max
Wright et al. (2010)	37	42	47
Brown et al. (2013)	32	41	61
Elliot et al. (2009)	31		61
Jones et al. (2009)	38		44

(source: (Wright et al. 2010, Brown et al. 2013b, Elliott et al. 2009, Jones 2009))

Total fuel yield is the product of the percentage of bio-oil and the percentage of fuel. The literature for bio-oil yield ranges from 49-75% biomass as shown in Table 3.11, while the fuel yield ranges from 31-61% bio-oil as shown in Table 3.12. A recent study by Thilakaratne et al. (2014) using woody biomass and mild catalytic pyrolysis with hydrogen production found a fuel yield of 58.6 gallons per MT of dry biomass for their pessimistic (base) case. They use a yield for the oil phase of 24.2 wt% biomass and a hydroprocessing conversion of 73.4 wt% feed. This results in an overall conversion rate of 17.7% (Thilakaratne et al. 2014). Gasoline makes up 39.9 gallons per MT, and diesel accounts for 18.7 gallons. Thilakaratne et al. (2014) also look at an optimistic case. The yield for the oil phase increases to 30 wt%, which causes an increase in the overall conversion rate to 22%. The fuel yield is around 73.2 gallons per MT. Brown's overall conversion rate is 26.5%, which is higher than Thilakaratne's optimistic case. Table 3.13 provides a comparison of the fuel yields from different Brown papers. Wright et al. (2010) finds a fuel yield of 35.4 MGY or 53.8 gal/MT when hydrogen is produced, and 58.2 MGY or 88.4 gal/MT when hydrogen is purchased. Fuel yields differ depending on if the hydrogen is produced or purchased. Plants that produce hydrogen have a higher output, because a portion of bio-oil is not being used for the production of hydrogen. We will be looking at a plant that purchases hydrogen. The ratio of gasoline to diesel also affects total fuel output. Brown et al. (2013) and Wright et al. (2010) also use a 50-50 split for fuel yield between gasoline and diesel, while Thilakaratne et al. uses 66-33 split. Diesel is denser than gasoline, so less is produced. For bio-oil yield, the min, mode, and max from the literature are 49%, 61.7%, and 75%. For fuel yield, the min, mode, and max from the literature are 31%, 37%, and 44%. Table 3.14 shows the total fuel yields using these ranges. Rather than using the extremes for our distribution, we will use the second row in Table 3.14, which results in a min, mode, and max total fuel yields of 18.1%, 22.8%, and 27.8%.

Table 3.13 Total Fuel Yield Comparison from Brown papers

Source	Bio-oil Yield	Fuel Yield	Total Fuel Yield	Gal/US Ton	Gal/MT
Wright et al. (2010)	63%	42%	26.5%	97.50	88.45
Brown et al. (2013)	63%	42%	26.5%	96.09	87.17
Thilakaratne et al. (2014)	24.2%	73.4%	17.8%	64.60	58.60

*Total Fuel Yield = Bio-oil Yield * Fuel Yield

(source: (Wright et al. 2010, Brown et al. 2013b, Thilakaratne et al. 2014))

Table 3.14 Total Fuel Yield's from Literature Ranges for Bio-oil and Fuel Yield

Fuel Yield	Bio-oil Yield		
	Min = 49%	Mode = 61.7%	Max = 75%
Min = 31%	15.2%	19.1%	23.3%
Mode = 37%	18.1%	22.8%	27.8%
Max = 44%	21.6%	27.1%	33.0%

(source: Calculated)

3.2.1.1.3 Hydrogen Cost

Hydrogen cost contributes significantly to operating costs. The two least expensive feedstocks for hydrogen production are coal and natural gas (2012). The United States Department of Energy conducted a multi-year technical plan for the production of hydrogen. They looked at distributed natural gas H2A cost distributions. H2A is an analysis group who develop frameworks needed to analyze hydrogen technologies (2006). Using the H2A model, the U.S. Department of Energy found a levelized production cost for hydrogen of $2.00/kg in 2011, which is shown in Table 3.15. The dispensed cost, which includes compression, storage, and dispensing was $4.50/kg in 2011 (2012, Brown et al. 2013b). Estimating for 2015, they found a production cost for hydrogen of $2.10/kg and a dispensed cost of $3.80/kg. However, we assume that plants will use the hydrogen right away, so there is little need for hydrogen storage. NREL's study focused on production of hydrogen from reforming of natural gas. They found a range for hydrogen total cost for 2005 of $2.75-$3.50/kg using the H2A model. The Producer Price Index for Industrial Commodities allows us to adjust the range to 2011 dollars (Bureau of Labor Statistics 2013). After adjusting to 2011 dollars, we obtain a range of $3.47-$4.42/kg. A recent study by Zhang et al. use a hydrogen cost of $3.33/kg, which is based on averages from the U.S. Energy Information Administration Annual Energy Outlook. Wright et al. (2010) and Brown et al. (2013) both use a much lower hydrogen cost of $1.50/kg and $1.33/kg. Looking at Table 3.15, the hydrogen cost in the min column hovers around $2.00-2.50/kg. The hydrogen cost in the max column hovers around $4.00-4.50/kg. The hydrogen costs that make up the min, mode, and max are $2.25/kg, $3.25/kg, and $4.25/kg.

Table 3.15 Hydrogen Cost ($/kg)

Source	Min	Mode	Max
Wright et al. (2010)	0.98	1.50	1.96
Brown et al. (2013)		1.33	
Zhang et al. (2013)	2.33	3.33	4.33
NREL (2006)	3.47		4.42
Technical Plan (2012)	2.00		4.50

(source: (Wright et al. 2010, Brown et al. 2013b, Zhang et al. 2013, 2006, 2012)

3.2.1.1.4 Capital Cost

Large variations in estimated capital costs for fast pyrolysis plants exist. Cleveland (1984) states that history has shown we underestimate capital costs of new energy process plants by more than 100 percent (Cleveland 1984). Another study found that process plant projects generally have underestimated capital costs (Merrow 1983). Merrow looked at more than 40 Rand process plants spanning 20 years, and there was a consistent underestimation. He found that cost estimates which were made before engineering was well advanced were poor estimates. We will be looking at an n^{th} plant, which is the cost of a plant built at some point in the future after some engineering experience has been gained. Merrow (1983) also found that even when little or no new technology was introduced, plants may still have poor estimates. One possibility for why cost estimates are poor whether new technology is introduced or not is because cost estimations for capital projects is complex (Merrow 1983). Therefore, we want to use capital cost that accounts for underestimation. Brown et al. (2013) calculates a total project investment of $429 million, and uses a distribution of $288-$463 million for total project investment as shown in Table 3.16. Therefore, his distribution only accounts for an 8 percent underestimation. In the study preceding Brown, Wright et al. (2010) calculates a capital cost of $200 million, and uses a distribution of $83-$247 million. This accounts for about a 24 percent underestimation in his distribution. Cleveland (1984) and Merrow (1983) show through history that plant capital cost is commonly underestimated. In order to account for this underestimation, we will use a distribution for capital cost of $365 million, $429 million, and $600 million (min, mode, max). This accounts for a 15 percent overestimation and a 40 percent underestimation in capital costs.

Table 3.16 Capital Cost (million $)

Source	Min	Mode	Max
Wright et al. (2010)	83	165	247
Brown et al. (2013)	288	429	463

(source: (Wright et al. 2010, Brown et al. 2013b))

3.2.1.1.5 Summary

The use of the new parameter values specified above will help us to calculate a more accurate breakeven fuel price. The mean values were calculated from the new parameter value ranges and are shown in Table 3.17.

Table 3.17 List of New Parameter Values

Parameter	Min	Mode	Max	Mean
Feedstock Cost ($/MT)	55	83	110	82.83
Final Fuel Yield (% biomass)	18.1	22.8	27.8	22.85
Hydrogen Cost ($/kg)	2.25	3.25	4.25	3.25
Capital Cost ($ million)	365	429	600	446.83

Table 3.18 Comparison of New and Old Parameters

Parameter	Author	Brown
Feedstock Cost ($/MT)	82.83	83
Final Fuel Yield (% biomass)	22.85	26.5
Hydrogen Cost ($/kg)	3.25	1.33
Capital Cost ($ million)	446.83	429
Tax Rate (%)	16.9%	35%
Inflation Rate (%)	2.5%	0%

Using the mean of the new parameter values, we can calculate a new non-risk adjusted breakeven fuel price. All of the new parameters shown in Table 3.18 under Author are used including the four mean values, the tax rate of 16.9%, and inflation rate of 2.5%. The breakeven fuel price is substantially higher than the breakeven fuel prices with the old parameter values in Table 3.7 and 3.8. With all of the new parameters the fuel price is $3.58 per gallon.

The increase in prices is due primarily to the increase in hydrogen cost and decrease in final fuel yield from the old parameter values. A comparison of the new and old parameter values is provided in Table 3.18. Brown uses a hydrogen cost of $1.33, which is not in our range of values for hydrogen in Table 3.17. Current literature showed a higher cost range for hydrogen with our mean being $3.25/kg. This is almost a $2.00 difference between the old and new parameter values, which has a large impact on the breakeven fuel price. The final fuel yield also decreases from the old parameter values. Brown et al. 2013 found that fuel yield was the most important parameter. We also see those findings.

Figure 3.1 provides a breakdown by major cost category of the breakeven fuel price. The breakdown of breakeven fuel price is provided for 4 different cases: (1) using all of Brown's assumptions, (2) the author's assumptions and Brown's conversion rate, and (3) all of the author's assumptions with conversion rate impact separated out, and (4) all of the author's assumptions with the new conversion rate incorporated . The sum of all the parameters in each bar is the breakeven fuel price. The breakeven fuel price using Brown's assumptions was $2.47 per gallon and is represented by the stacked bar on the left. The breakeven fuel price using the author's assumptions was $3.58 and is represented by the two stacked bars on the right. Each parameter was added individually to see the impact it has on the breakeven fuel price. Using Brown's conversion rate and the new parameters versus the old parameters had a substantial impact on the breakeven fuel price. Each parameter had a larger impact on the price under the author's assumptions. The capital cost accounted for $0.97 using Brown's assumptions. Increasing the capital cost by about $18 million, increases the capital cost share to $1.05 using the author's assumptions and Brown's conversion rate. Feedstock and other operating cost shares increase a little bit from Brown's assumptions to the author's assumptions. The largest difference in breakeven fuel prices between the two sets of assumptions is hydrogen cost. As shown in Figure 3.1, hydrogen cost accounts for $0.90 of the breakeven fuel price.

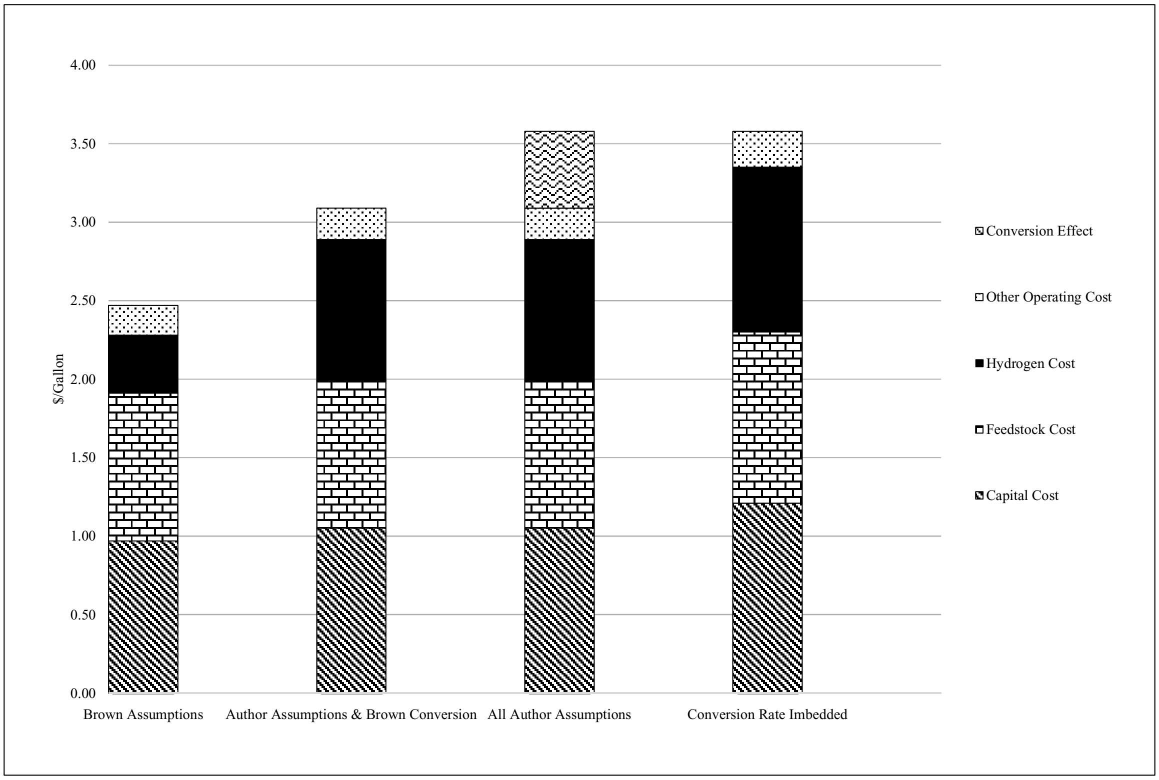

Figure 3.1 Breakdown of Impact each Parameter has on Non-risk Adjusted Breakeven Fuel Prices ($/gallon)

There is also a decrease in the final fuel yield from Brown's assumptions to the author's assumptions from 26.5% biomass to 22.85% biomass. This results in a decrease of annual production from 58.0 million gallons to 50.1 million gallons. Figure 3.1 shows the change in breakeven price due to a change in annual fuel production from the second stacked bar to the third one. We calculated the change in final fuel yield as dollars per gallon. Decreasing the fuel yield to 50.1 million gallons from the author's assumptions & Brown conversion to all of the authors assumptions results in an increase in price by $0.49 per gallon and vice versa. We also created a fourth stacked bar, where the conversion rate is imbedded in the four parameters. This demonstrates how much impact a change in final fuel yield can have on the breakeven fuel price.

We also calculated the NPV cost and cost share percentage for the new key cost parameters in Table 3.19. The key parameters are capital cost, feedstock, hydrogen, and other operating costs. Capital cost, feedstock, and hydrogen contribute to more than 90% of the cost share. Capital cost makes up the largest percentage of cost at around 34%. Feedstock and hydrogen are the second and third largest with cost shares of 30.4% and 29.2%. Other operating costs contribute to less than 7% of the cost. The cost values and cost shares for the key parameters presented below are the same as what is shown above in Figure 3.1 in the fourth stacked bar on the right.

Table 3.19 Cost Shares and Levels for the Key Parameters

Parameter	NPV Cost ($)	Cost Share (%)
Capital Cost	$310,234,132	33.8%
Feedstock	$278,661,106	30.4%
Hydrogen	$267,805,540	29.2%
Other Operating Costs	$60,066,395	6.6%
Total	$916,767,172	100.0%

The cost shares and levels calculated above are relatively close to the ones shown previously in Table 3.9. Capital cost has the largest cost share instead of feedstock due to an increase of about $17 million in its mean value. Hydrogen also makes up a larger cost share than shown in Table 3.9. Although the cost shares and levels are similar, the cost per gallon differs from the two studies. Petter and Tyner 2014 calculate a breakeven fuel price of $2.62 per gallon. Our cost is substantially higher due to the decrease in production and increase in hydrogen cost. Petter and Tyner use a production similar to Brown et al. 2013, while we use one that is about 8 million gallons per year less.

3.2.1.2 Fuel Price Uncertainty

In the 2013 annual energy outlook, the U.S. Energy Information Administration (EIA) projects jet fuel prices from 2011 to 2040 in real terms in 2010 dollars per gallon (2013a). The base year we use is 2011. Adjusting them to 2011 dollars, the 2011 jet fuel price is $3.14 with projections increasing to $4.31 by 2040. The annual growth is expected to be 1.1 percent.

We use two jet fuel price projections to capture uncertainty on the expected return on investment. The two jet fuel price projections used are (1) a stochastic fuel price with no trend and (2) a stochastic fuel price that increases over time at a rate of the EIA jet fuel price projections stated above. We use an initial fuel price of $3.03, which is an average of the wholesale/resale price for jet fuel and diesel by refiners. The price is in real terms.

There are two main types of stochastic processes used for forecasting oil prices: Brownian motion and mean reversion. Brownian motion is not stationary and the price follows a random walk with a drift, while mean reversion is stationary and reverts to a trend line that increases or decreases (Pindyck 1999). There is much debate among researchers over which process is better.

There are advantages and disadvantages to using both Brownian motion and mean reversion. Geometric Brownian motion can over or underestimate values, and has more risk involved (Pindyck 1999). There are a few advantages to using GBM as opposed to mean reversion. One advantage is that it allows for combined effect of uncertainty. The GBM accounts for a worst scenario for investors (Postali and Picchetti 2006). Another advantage is that is has high price variability. Mean reversion has a lower level of uncertainty than GBM. This is due to mean reverting process prices fluctuating around the long-run equilibrium. Mean reversion is a little more realistic.

The key factor in determining which process to use is the speed of mean reversion. Researchers agree that if mean reversion is fast, then a mean reversion process is preferred. On the other hand, if mean reversion is slow, then Brownian motion is not a bad option for forecasting oil prices (Pindyck 1999, Postali and Picchetti 2006). Pindyck 1999 looked at the long-run evolution of energy prices. He looked at oil prices from

1870 to 2000. The prices were deflated to 1967 dollars using Wholesale Price Index for 1870 through 1970 and Producer Price Index for 1970 through 2000. The natural logarithm of oil prices were taken. From 1900 to 1970, Pindyck found that prices stayed close to the average, which suggests mean-reverting. The log real price mean reverted to a trend line. However, the mean reversion took up to a decade to occur, which is very slow (Pindyck 1999). Pindyck concludes that his figures suggest there is a slow rate of mean reversion. As a result, the geometric Brownian motion process is not bad. He states that GBM is unlikely to cause large errors in the optimal investment rule. Postali and Picchetti 2006 also state that prices are not instantaneous. There is a lag in price on the demand and supply side (Postali and Picchetti 2006). The trend in oil prices is evaluated using a unit root test (Pindyck 1999, Postali and Picchetti 2006). Postali and Picchetti 2006 found that a larger sample size is needed to reject the null hypothesis. The null hypothesis was $\rho - 1 = 0$, where ρ is the asymptotic variance. The data generating process equation was $P_t = \rho P_{t-1} + \varepsilon_t$, where ε_t is the stochastic term and the variance must be $\rho<1$. The variance was given by $\sigma^2(\rho) = (1-\rho^2)/T$, where T was the number of years. It was only possible to reject unit root when the length of time was more than a century. This suggests that the speed of mean reversion is very slow. As a result, geometric Brownian motion is a good process for forecasting oil prices (Pindyck 1999, Postali and Picchetti 2006).

Geometric Brownian motion is a little simpler than mean reversion, requiring one less variable. The equation for GBM is below

$$dP = \alpha P dt + \sigma P dz$$

Equation 3.8

where P is the oil price, α is the expected growing rate, t is time, σ is the instantaneous standard deviation, and Z is the Wiener process. The returns from taking the log of dP have normal distributions, and is expressed mathematically as $dlnP \sim N(\alpha dt, \sigma dt)$. The expected growing rate as well as the instantaneous standard deviation are constant (Postali and Picchetti 2006).

The process we use is a geometric Brownian motion (GBM). In order to calculate the projected prices for our project we use a similar equation. The equation used to calculate our projected prices is

$$P_t = P_{t-1} * e^r + \varepsilon$$

Equation 3.9

where P_t is the price at time t, P_{t-1} is the price in the previous year, r is the expected growth rate, and ε is the random component. We used the steps listed below to find the stochastic increasing price.

1) Collected wholesale/resale jet fuel prices for the past 20 years from 1993 to 2013 (Energy Information Administration 2014)
2) Prices were adjusted to 2011 dollars using the Consumer Price Index (Bureau of Labor Statistics 2014)
3) The change in price from year to year from 1993 to 2013, standard deviation of changes in prices from 1993 to 2013, and expected annual growth rate from DOE projections were calculated.

The random component was a normal distribution with a mean of zero and a standard deviation of about 0.46. Standard deviation was calculated using the differences in jet fuel wholesale/resale prices by refiners from year to year.

We ran a check to make sure Brownian motion was okay to use for our analysis. We took the projected price in year 2034, the last year of the project, from Brownian motion with a drift jet fuel prices and made it an output in @Risk. We ran the simulation, and found that the output was normal. The skewness was near 0 and kurtosis was near 3 as they should be for a normal distribution.

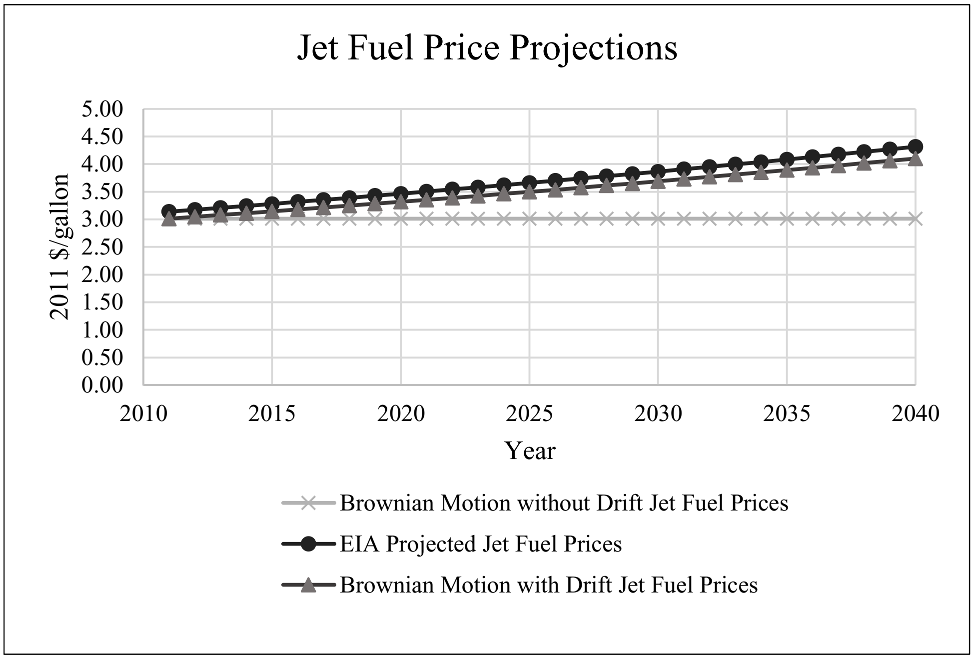

Figure 3.2 Comparison of Jet Fuel Price Projections

Figure 3.2 shows a comparison of the different jet fuel price projections. All of the prices are in real terms. The Brownian motion with a drift jet fuel prices follow the EIA projected jet fuel prices closely. EIA projected jet fuel prices are slightly higher than the projected prices from Brownian motion.

We regressed diesel and jet fuel wholesale prices from 2004 to 2013. The regression showed an R square of 99.8%, which shows high correlation between the prices. In order to find diesel projected prices based on jet fuel projected prices we used the intercept and slope of the regression. Using the intercept and slope we found equation 3.10 below for diesel price.

$$Diesel\ Price_t = -0.014 + 1.015 * Jet\ Fuel\ Price_t$$

Equation 3.10

We assume that 50% of the fuel produced is jet fuel and 50% is diesel. By taking the average price of jet fuel and diesel each year, we get a combined price.

3.3 Policy Analysis

3.3.1 Reverse Auction

As stated in the literature review, a reverse auction is when bidders bid on a contract to produce a product, and the lowest unique bidder wins. The bid variable in our case is price per gallon of fuel. The government puts up a long-term contract for a certain quantity of fuel to be produced, and the private investor with the lowest bid price per gallon of fuel wins. Once the winner is chosen, they enter a contract with the government. The production level is fixed at the amount that is stated in the contract, and the government must pay the price per gallon bid that won. The government can win or lose depending on the price of oil and aviation biofuels. If low oil prices occur in the market and the contract price for aviation biofuels is high, then the government loses. The government faces an implicit tax. On the other hand, if oil prices are high and the contract price of aviation biofuels is low, then the government wins. Biofuel producers would face an implicit tax since the buyer is purchasing the product at less than market value. The average difference in the contract price and market price equals government cost.

We will approach a reverse auction by doing sensitivity on two main factors. The first is length of the contract. We will evaluate contract lengths of 5, 10, and 15 years. All biofuel not sold under contract is assumed to be sold at the uncertain market price. The second sensitivity is on how we determine the bid value. In the first case, we assume private investors are risk neutral. The standard breakeven fuel price is one with about a 50% probability of losing money. However, a risk neutral bidder might bid this value. More likely, bidders would be risk averse, and their lowest price bids may all be higher than they would be otherwise. For example, we assume that the winning bid would be the price at which the probability of a loss is no more than 25%.

There are many variants of reverse auctions. There can be minimum or maximum prices (called collars), and prices can have inflators included. For example, we will consider a case in which the initial bid value goes up at the rate of the DOE reference price case for aviation biofuel.

3.3.2 Carbon Tax

A carbon tax is a Pigouvian tax that puts a price on negative externalities. In this case the negative externality associated with aviation fuel is greenhouse gas emissions. The way we approach a carbon tax is to apply it to the carbon content of the fuel. Fossil jet fuel and corn stover jet fuel have different carbon contents. We will use the social cost of carbon calculated by the Interagency Working Group. The social cost of carbon allows us to include a social benefit in the cost-benefit analysis. The social benefit is the benefit from reducing carbon dioxide emissions. We will apply the 2014 social cost of carbon found by the Interagency Working Group with a 3% average discount rate of $37 per metric ton of CO_2 to both the carbon content of fossil jet fuel and corn stover jet fuel. This will allow us to get a differential for the corn stover based fuel.

CHAPTER 4. RESULTS

Chapter 4 presents the results of five cases: deterministic, stochastic, reverse auction, capital subsidy, and carbon tax. For the deterministic case, results are shown with the fuel price of $3.03/gallon calculated above in the fuel price uncertainty section, as well as the breakeven fuel price. Results for the stochastic case are shown when there is no drift in fuel price and when there is one. For a reverse auction and capital subsidy, results are reported for contract lengths of 5, 10, and 15 years. Our results focus on the financial analysis, although both the financial and economic results are reported.

4.1 System Economics

4.1.1 Deterministic

4.1.1.1 Base Case Results

The base case is deterministic with all of the variables fixed at mean values over the life of the project. Feedstock cost, final fuel yield, hydrogen cost, and capital cost are fixed at their mean values stated in Table 3.17 in the previous chapter. Fuel price is fixed at $3.03/gallon. This is the average of the wholesale/resale price for jet fuel and diesel by refiners. Three discounted measures of project worth are calculated: net present value (NPV), internal rate of return (IRR), and benefit-cost ratio (B/C). The economic analysis is before financing and taxes, while the financial analysis is after financing and taxes. We report the results with all of the variables fixed as stated above, and then find the breakeven fuel price for the financial analysis.

The results with all variables fixed and a fuel price of \$3.03/gallon are reported in Table 4.1. All three discounted measures of project worth have different criterions for accepting a project. A project is accepted when the net present value is greater than zero. For the internal rate of return, the IRR must be greater than the discount rate. Benefit-cost ratio is the ratio of discounted benefits to discounted costs. A project is accepted when the B/C is greater than one. In Table 4.1, both NPV's using a fuel price of \$3.03 are negative. The internal rate of return for both analyses is less than the real discount rate of 10%. The last discounted measure of project worth, B/C, also fails the criterion for acceptance of the project. This demonstrates the reality that without government intervention, investors would not be likely to find the plants attractive.

Table 4.1 Case 1 Results: Deterministic Results with Fuel Price of \$3.03/gallon

	NPV	IRR (real)	B/C
Economic	(\$194,251,397)	3.0%	0.52
Financial	(\$140,250,724)	2.2%	0.37

We found the breakeven fuel price with all of the variables fixed. The breakeven fuel price is the price at which a plant is neither running at a loss nor profit. We found the breakeven fuel price for the financial analysis instead of the economic since it is more realistic, accounting for financing and taxes. Using the goal seek tool in excel, we found the fuel price which sets NPV equal to zero. The breakeven fuel price was \$3.58/gallon. This is the same value reported in the previous chapter. At a breakeven fuel price of \$3.58/gallon, the financial NPV was zero, the IRR was 10%, and the B/C was equal to one as shown in Table 4.2.

Table 4.2 Case 1 Results: Deterministic Results with Breakeven Fuel Price of $3.58/gallon

	NPV	IRR (real)	B/C
Economic	($25,477,962)	9.2%	0.94
Financial	$0	10.0%	1.00

The NPV, IRR, and B/C are all better in the financial then in the economic analysis. This may not always be the case, although most of the time it holds true throughout our results. Economic analysis gives a public perspective, while financial analysis gives a private perspective. The results are not the same between the analyses due to three differences: (1) treatment of taxes and subsidies, (2) economic values versus private, and (3) interest on capital. The financial analysis results may be better for two reasons. One reason is if the nominal interest rate is less than the real discount rate, the project return increases. The IRR of a project is equal to the debt ratio times the IRR on debt plus the equity ratio times the IRR on equity. Therefore, as the equity ratio decreases, the return on investment increases. The second reason is financing benefits may exceed tax payments. If tax payments are greater than the benefits from financing, then the economic NPV may be better than the financial.

4.1.2 Stochastic

Stochasticity shows uncertainty in the results. The Palisade Corporation software @Risk was used to determine the risk of investment in aviation biofuels for the stochastic cases. Monte Carlo analysis is used to predict the uncertainty in NPV. By using a pert distribution for the four technical variables stated in section 3.2.1.1, uncertainty is incorporated into the spreadsheet. We assume perfect correlation for the technical variables. That is, once a random draw is taken for any of the uncertain technical variables, it holds throughout all the years of the investment (for that iteration). In other words, perfect correlation means the values are perfectly correlated through time. As a result, the values for the technical variables do not change from year to year. There is also no correlation among our four technical variables. They are assumed to be independent of each other. The stochastic case was run with both of the jet fuel price projections stated in the fuel price uncertainty section. The initial fuel price for each projection was $3.03/gallon. A breakeven fuel price was found for each projection. Results were reported for both prices. The mean, standard deviation, and probability of loss are reported in the tables for both economic and financial analysis.

4.1.2.1 Stochastic with No Trend in Fuel Price

The results in Table 4.3 were found using a steady stochastic fuel price of $3.03/gallon. The mean, standard deviation, and probability of loss are reported for the NPV, IRR, and B/C. The mean NPV's are negative, with the financial analysis being less negative than the economic analysis. Figure 4.1 shows a probability density graph for the financial NPV. The values on the horizontal axis are in billions ($). There is a 90% probability the NPV lies between -$653 million and $392 million. This is quite a large distribution. In Table 4.3, the standard deviation and probability of loss are less in the financial analysis than in the economic. This is seen throughout all of the results. Standard deviation is reduced due to taxes being included. The inclusion of taxes reduces gains and losses. The standard deviation is a result of the input distributions from the uncertain variables. There is a reduction of almost $65 million from the economic to the financial analysis. Probability of loss also decreases over 2 percent from 69.9 percent to 67.5 percent for the NPV.

There can be errors in IRR when stochastic simulations are run. Table 4.3 has IRR's for both the economic and financial analysis which contain errors. As a result the IRR will be inconsistent with the NPV and B/C. Errors occur in @Risk when it cannot return a result for the calculation. This is commonly due to all or most flows being positive or negative for any given iteration. These results for IRR are seen consistently throughout our stochastic results.

Table 4.3 Case 2 Results: Stochastic Results with Steady Stochastic Fuel Price of $3.03/gallon

	Economic			Financial		
	NPV	IRR (nominal)	B/C	NPV	IRR (nominal)	B/C
Mean	($194,063,200)	10.7%	0.52	($140,094,000)	11.9%	0.38
Standard Deviation	$379,790,200	9.2%	0.94	$315,364,000	11.0%	1.41
Probability of Loss	69.9%			67.5%		

*Note: (1)Nominal Discount Rate Used for NPV was 12.75% (2)IRR calculation had errors in the stochastic calculation

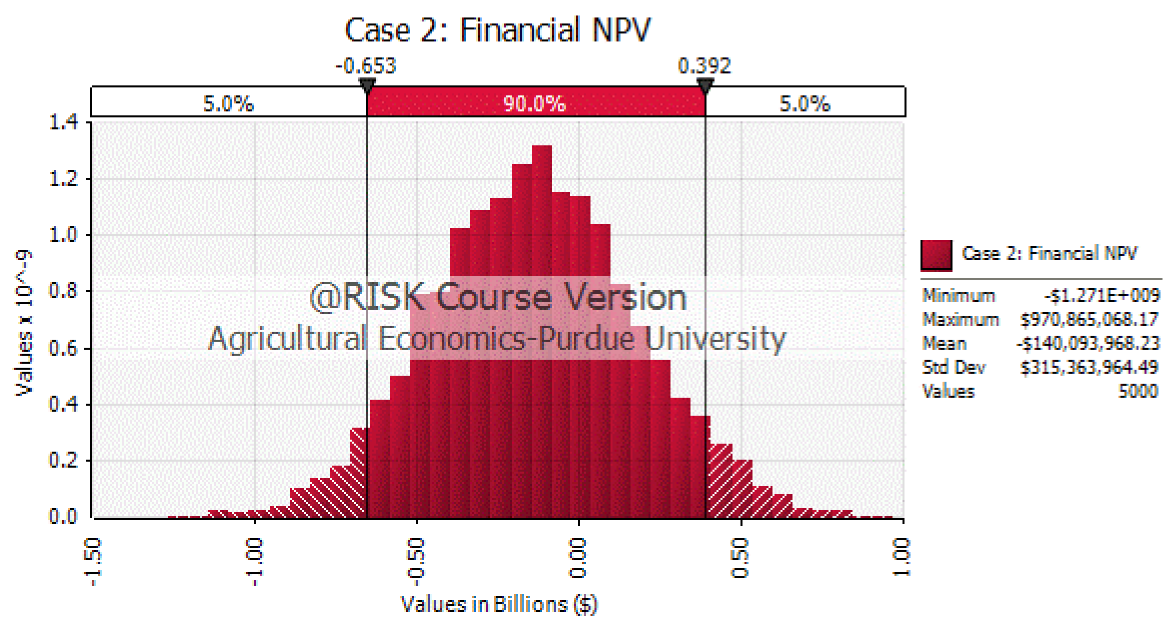

Figure 4.1 Case 2: Financial NPV with a Steady Stochastic Fuel Price of $3.03/gallon

We found the breakeven fuel price for when there is no trend in the fuel price. For a steady stochastic fuel price, the breakeven fuel price was $3.58/gallon. This is over a fifty cent increase from the fuel price used initially. Increasing the fuel price, increases the mean NPV for both economic and financial. The mean NPV is positive for the financial analysis in Table 4.4. Standard deviation remains relatively the same due to input distributions remaining the same. The biggest difference between Tables 4.3 and 4.4 is the probability of loss. With a fuel price of $3.03/gallon, the probability of loss for NPV hovers around 70 percent, while with a fuel price of $3.58/gallon it hovers around 50 percent.

Table 4.4 Case 2 Results: Stochastic Results with Steady Stochastic Fuel Price of $3.58/gallon

	Economic			Financial		
	NPV	IRR (nominal)	B/C	NPV	IRR (nominal)	B/C
Mean	($25,273,960)	14.0%	0.94	$169,872	16.1%	1.01
Standard Deviation	$381,332,200	9.3%	0.95	$316,645,900	11.3%	1.42
Probability of Loss	53.1%			50.2%		

*Note: (1)Nominal Discount Rate Used for NPV was 12.75% (2)IRR calculation had errors in the stochastic calculation

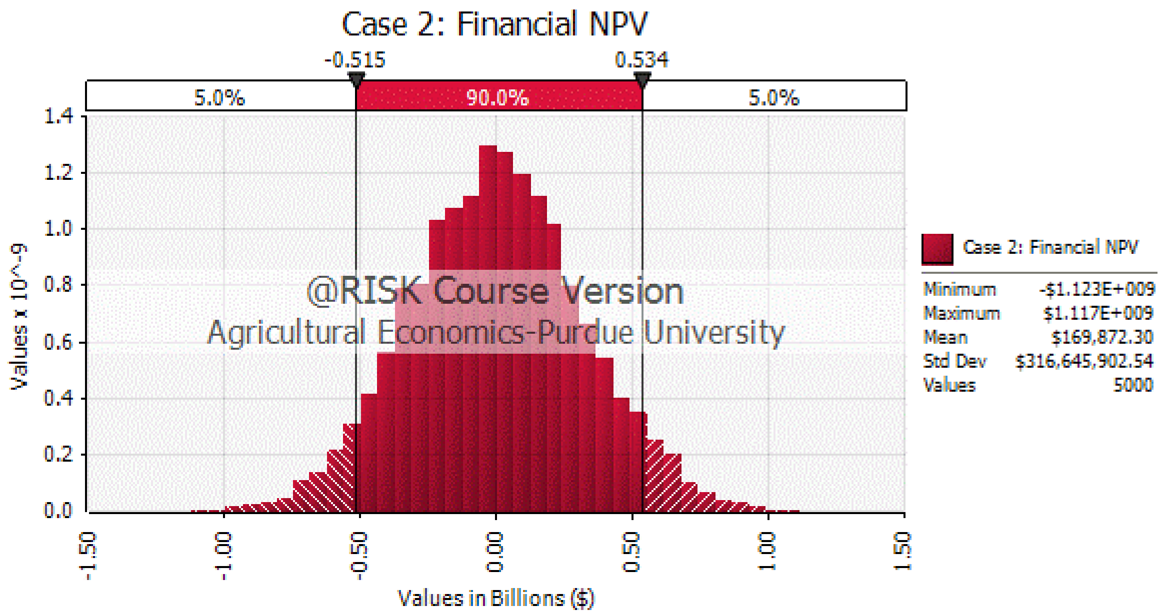

Figure 4.2 Case 2: Financial NPV with a Steady Stochastic Fuel Price of $3.58/gallon

An increase in the fuel price makes the financial NPV range less negative, but larger. There is a 90 percent probability the NPV lies between -$515 million and $534 million. This is a shift of about $100 million to the right from Figure 4.1.

In comparison to work done by Petter and Tyner 2014, we see larger NPV ranges, larger standard deviations, and higher probabilities of loss. Petter and Tyner 2014 used three uncertain variables: hydrogen price, feedstock price, and fuel yield (bio-oil yield). We introduce capital cost as an uncertain variable. There are differences in fuel yield. Our fuel yield is much lower, accounting for a total fuel yield calculation versus one focused on bio-oil yield. The tax rate used is also lower than in their report. These factors contribute to the differences in results. As a result, we see higher probabilities of loss than were seen in their paper. Higher breakeven fuel prices compensate for a little bit of the increase in uncertainty. Petter and Tyner 2014 saw around a 40 percent probability of loss for the financial mean NPV when fuel price was stochastic and steady, which is about 10 percent less than ours.

Overall, there is a lot of risk for an investment in this case. When a fuel price of $3.03/gallon is used, the probability of loss is 70 percent. Private investors would be discouraged from making an investment. When the breakeven is found, the probability of loss is reduced, however, it is still 50 percent.

4.1.2.2 Stochastic with Increasing Fuel Price

For this case, the stochastic fuel price is increasing at a rate derived from DOE projections. The initial fuel price was $3.03/gallon, increasing to a price of $3.83/gallon in the last year of the plant life. The mean NPV's in Table 4.5 are still negative. However, they are less negative then the case where a steady fuel price of $3.03/gallon was used in Table 4.3. Standard deviation is larger when the fuel price is increasing then when it was steady. It is also less in the financial analysis than in the economic. In comparison to Table 4.3, the probability of loss decreases substantially. An initial fuel price of $3.03 results in a probability of loss of 56.6 percent for the financial analysis. There is a decrease of about 10 percent from using a steady stochastic fuel price of $3.03/gallon versus one that increases over the plant life. In Figure 4.3, there is also a shift to the right in the range for the financial NPV, which is the same as what was seen in the steady fuel price case. There is a 90 percent probability the financial NPV falls between -$603 million and $518 million.

Table 4.5 Case 3 Results: Stochastic Results with Increasing Stochastic Fuel Price Initially at $3.03/gallon

	Economic			Financial		
	NPV	IRR (nominal)	B/C	NPV	IRR (nominal)	B/C
Mean	($90,267,960)	12.6%	0.78	($53,840,140)	14.1%	0.77
Standard Deviation	$406,901,900	9.2%	1.01	$337,908,200	11.1%	1.52
Probability of Loss	59.1%			56.6%		

*Note: (1)Nominal Discount Rate Used for NPV was 12.75% (2)IRR calculation had errors in the stochastic calculation

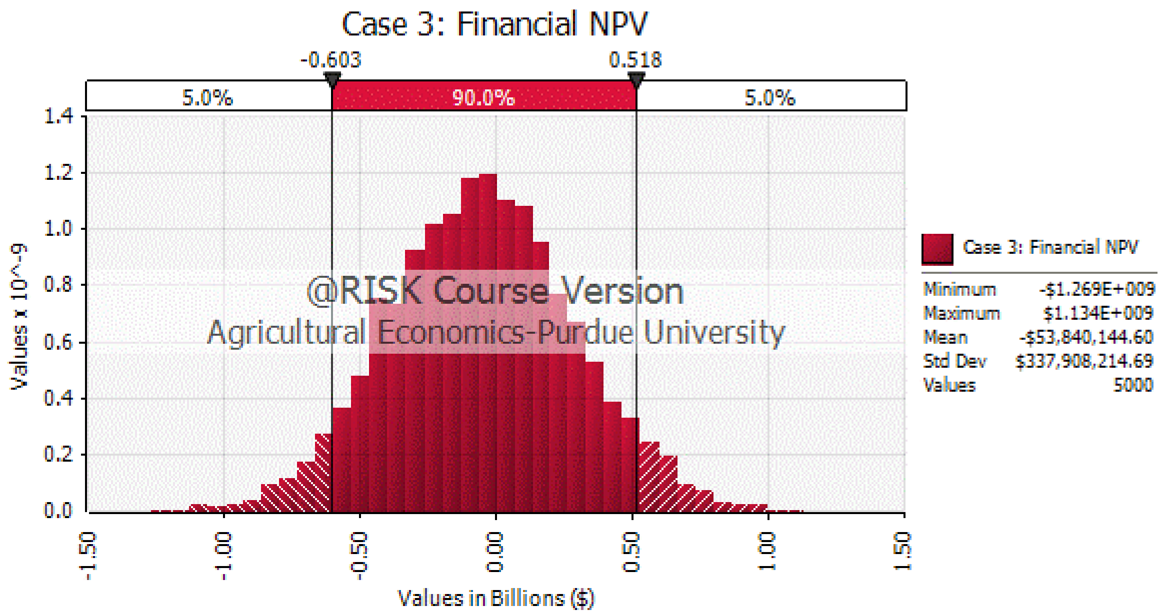

Figure 4.3 Case 3: Financial NPV with Increasing Stochastic Fuel Price Initially at $3.03/gallon

These results are different from the results Petter and Tyner found with an increasing stochastic fuel price. With an initial fuel price of $2.68/gallon increasing to $3.41/gallon, both mean NPV's were positive at around $80 million. Our mean NPV's in Table 4.5 were both negative. Standard deviation was about four times larger in our results than theirs. Their results also saw lower probabilities of loss, 14.5% probability of loss for the financial NPV. Although our probabilities of loss decreased from the steady stochastic price to the increasing stochastic price, they did not decrease that much. This is largely due to the higher fuel price.

The initial breakeven fuel price for the financial case when fuel price is increasing stochastically is $3.22/gallon. The fuel price increases over the plant life to a price of $4.07/gallon. In comparison to using an initial fuel price of $3.03/gallon, the mean and standard deviation of the NPV for both analyses remain about the same. Probability of loss decreases. For the NPV, there is about a 6 percent decrease in probability of loss from Table 4.5. The probability of losses in Table 4.6 are relatively similar to the ones in

Table 4.4, where fuel price was the breakeven fuel price when prices were steady, because they both are reporting results for the breakeven fuel price.

Table 4.6 Case 3 Results: Stochastic Results with Increasing Stochastic Fuel Price Initially at $3.22/gallon

	Economic			Financial		
	NPV	IRR (nominal)	B/C	NPV	IRR (nominal)	B/C
Mean	($25,266,780)	13.9%	0.94	175,837	15.7%	1.01
Standard Deviation	$407,485,100	9.2%	1.01	338,393,000	11.2%	1.52
Probability of Loss	52.7%			50.2%		

*Note: (1)Nominal Discount Rate Used for NPV was 12.75% (2)IRR calculation had errors in the stochastic calculation

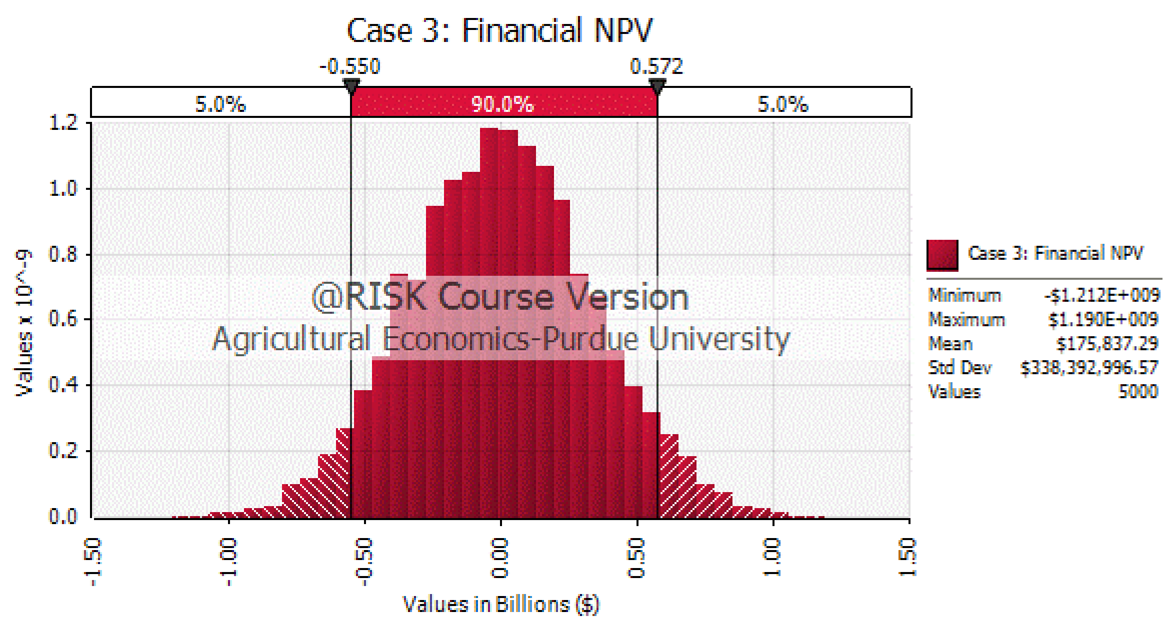

Figure 4.4 Case 3: Financial NPV with Increasing Stochastic Fuel Price Initially at $3.22/gallon

Introducing uncertainty into the spreadsheet allows us to determine the risk involved in investment. Without any policies, we see the results shown in Tables 4.3-4.6. When breakeven fuel price is found for both cases, the probability of loss is reduced to 50.2 percent. This is still a large probability of loss. As a result, some policy intervention may be needed to reduce the probability of loss.

4.2 Policy Analysis

4.2.1 Reverse Auction

A variety of cases were conducted for a reverse auction. The four main cases are (1) a stochastic fuel price with no trend where producers bid a breakeven fuel price with 50% probability of loss, (2) a stochastic fuel price with no trend where producers bid a breakeven fuel price with 25% probability of loss, (3) a stochastic fuel price that increases over time where producers bid a breakeven fuel price with 50% probability of loss, and (4) a stochastic fuel price that increases over time where producers bid a breakeven fuel price with 25% probability of loss. Within these four cases, four contract lengths are analyzed. The contract length builds from zero to fifteen years. Currently, the Navy has contracts for five years. We wanted to evaluate the impacts longer contract lengths can have on the probability of loss. The contract quantity used was 42 million gallons per year. We made our annual fuel production of about 50 million gallons an output in @Risk. At 0 percent probability of loss, the lowest quantity was around 42 million gallons per year, so that is what we made our contract quantity. Once again we focus on the financial analysis since it is more realistic than the economic. We also calculated the cost to government for each of the four cases and each contract length.

For the reverse auction, we created two columns in our spreadsheet. One column was the market price, and the other was the reverse auction price. When the contract was in effect, the reverse auction price was used, and when it was not, the market price was used. We made the fuel sales into an IF statement. If the plant year was less than or equal to the contract length, the statement returns the contract quantity times the reverse auction price plus annual production minus the contract quantity times the market price. For all other years, fuel sales is just annual production times the market price.

4.2.1.1 Stochastic without Drift in Fuel Price

4.2.1.1.1 Producers Bid Breakeven Fuel Price with 50% Probability of Loss

The first case is a reverse auction with a stochastic fuel price with no trend where producers bid a breakeven fuel price with 50 percent probability of loss. Both the market price and the reverse auction price are steady over the plant life. The market fuel price is \$3.03/gallon, and the reverse auction fuel price is \$3.58/gallon. For this case, the fuel price of \$3.58/gallon is the breakeven fuel price for a steady price case when there is no contract. Note that the 0 contract years case reverts to the previous case with no contract since the previous price regime is always in force. Therefore, when the contract length is 0 years, the fuel price reverts to the market price of \$3.03/gallon. As a result, we see negative NPV's since the market price is not large enough to compensate for the costs. The market fuel price has stochasticity in it for all cases, while the reverse auction fuel price does not.

Table 4.7 Case 4-1 Economic Results: Reverse Auction Results with Stochastic Fuel Price with No Trend and Producers Bid Breakeven with 50% Probability of Loss

Economic					
Length of Contract	Min	Max	Mean	Standard Deviation	Probability of Loss
0	(\$1,564,155,000)	\$1,141,450,000	(\$194,063,200)	\$379,790,200	69.9%
5	(\$1,144,703,000)	\$964,687,600	(\$134,184,100)	\$299,152,400	67.2%
10	(\$796,660,900)	\$675,631,400	(\$93,332,900)	\$210,488,500	68.0%
15	(\$573,817,500)	\$494,160,100	(\$67,969,270)	\$143,462,600	69.8%

Table 4.8 Case 4-1 Financial Results: Reverse Auction Results with Stochastic Fuel Price with No Trend and Producers Bid Breakeven with 50% Probability of Loss

Financial					
Length of Contract	Min	Max	Mean	Standard Deviation	Probability of Loss
0	($1,271,222,000)	$970,865,100	($140,094,000)	$315,364,000	67.5%
5	($922,656,600)	$823,975,700	($90,334,470)	$248,301,400	64.4%
10	($636,738,800)	$583,769,900	($56,387,110)	$174,502,400	63.3%
15	($451,555,800)	$431,806,900	($35,309,930)	$118,609,400	63.5%

For all of the reverse auction cases we reported the mean, standard deviation, and probability of loss for the NPV. For the cases where producers bid with a 50% probability of loss we also reported the minimum and maximum. Tables 4.7 and 4.8 report the economic and financial results for a steady fuel price case when producers bid with 50% probability of loss. In both tables the mean NPV increases, becomes less negative, as the contract length increases. For the financial analysis, mean NPV decreases from $140 million to $35 million. The standard deviation also decreases as the contract length increases. It decreases at a larger rate than the mean NPV, decreasing by almost $200 million from no contract to a 15 year contract. For all reverse auction cases, we expect to see an increase in mean NPV and a decrease in standard deviation. We would also expect that as the contract length increases, the probability of loss decreases, however, that is not what we see in either of the tables. When producers bid a breakeven fuel price with 50% probability of loss, the NPV hovers around zero when the contract length is fifteen years. The minimum, maximum, and mean slowly converge to zero as the contract length increases. Since the NPV hovers around zero, the probability of loss also hovers. As a result, we do not see the decrease in probability we originally expected to see.

Figures 4.5-4.8 below show the financial NPV for the different contract lengths. For no contract, Figure 4.5, we see the minimum NPV is greater than negative $1 billion, while the maximum is just shy of positive $1 billion. When there is no contract and bidders bid with a 50 percent probability of loss, the NPV range is extremely large. In Figure 4.8, when contract length is 15 years, the NPV range decreases by more than half.

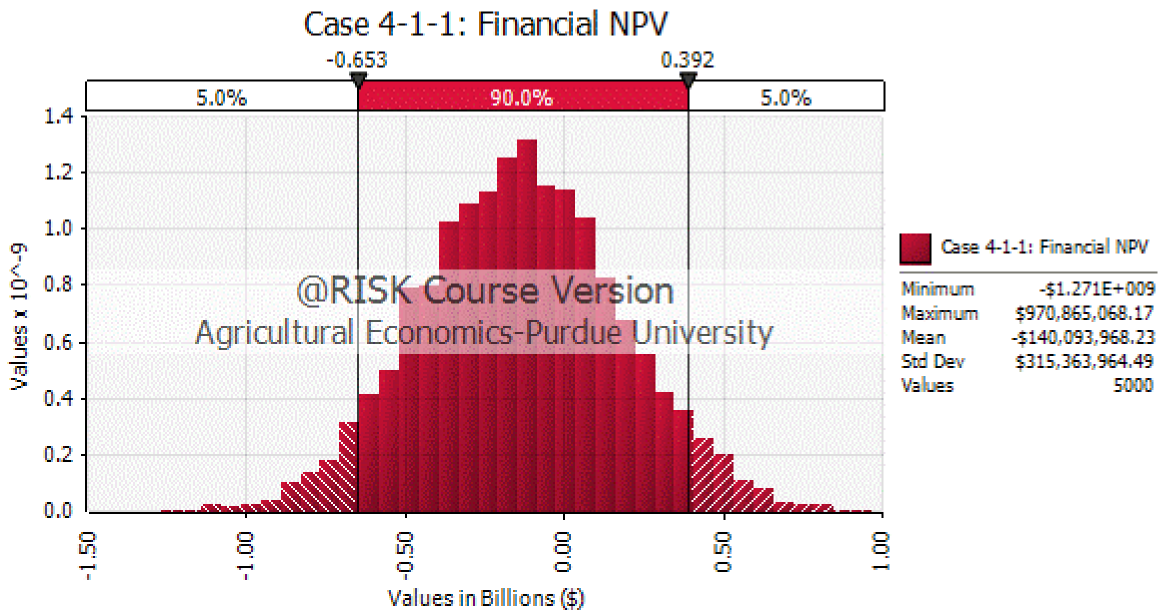

Figure 4.5 Case 4-1-1: Financial NPV with Steady Stochastic Fuel Price when Producers Bid 50% Probability of Loss and Contract Length = 0 years

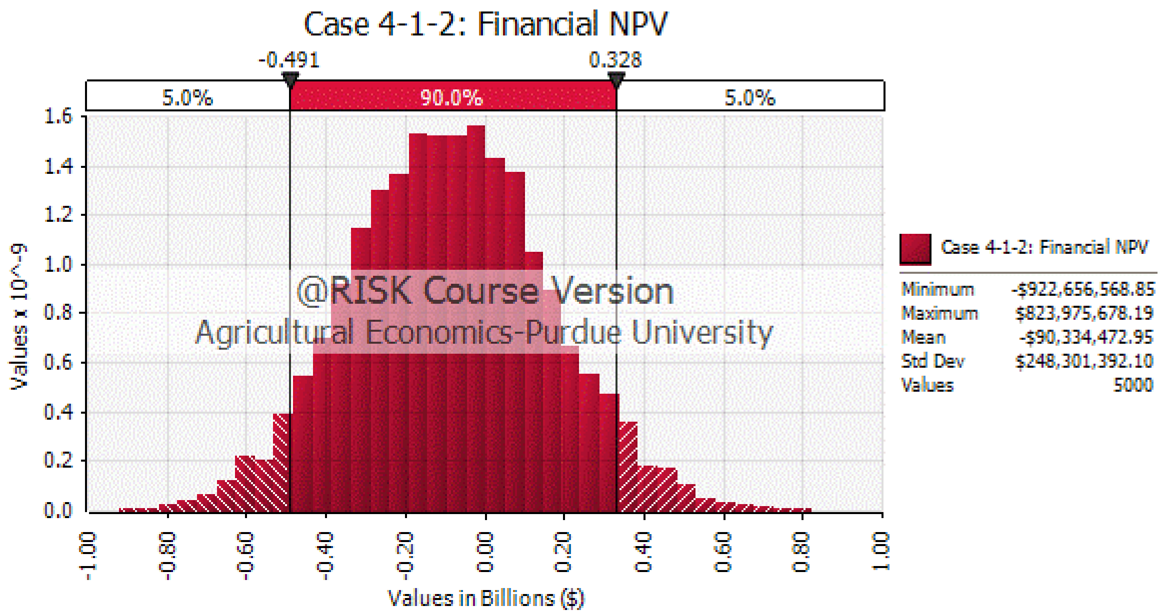

Figure 4.6 Case 4-1-2: Financial NPV with Steady Stochastic Fuel Price when Producers Bid 50% Probability of Loss and Contract Length = 5 years

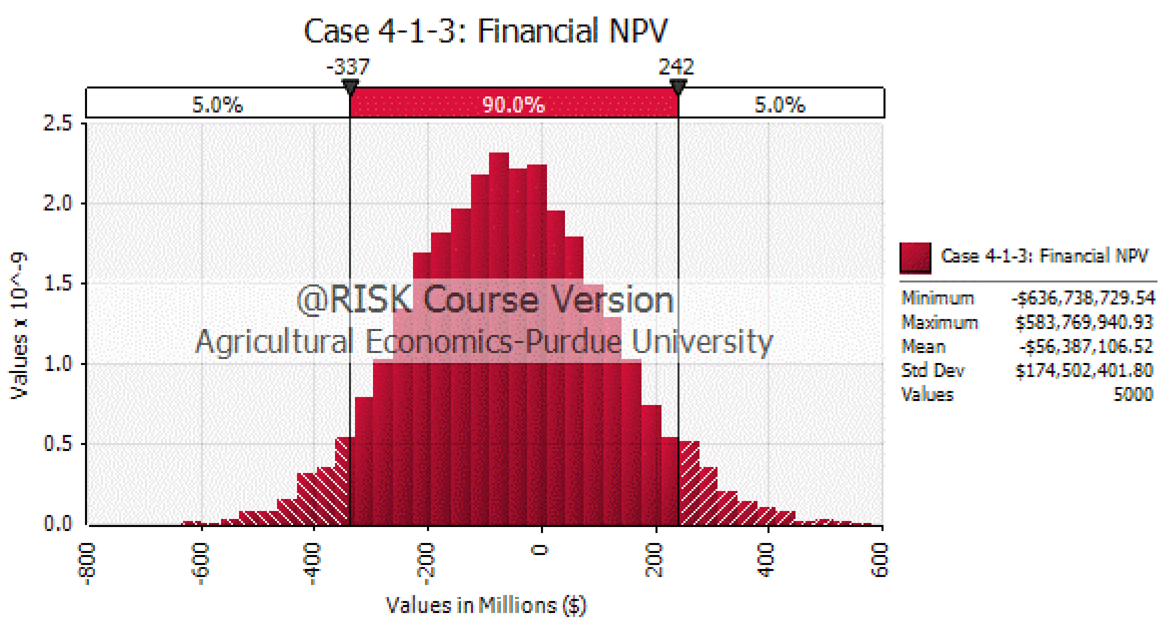

Figure 4.7 Case 4-1-3: Financial NPV with Steady Stochastic Fuel Price when Producers Bid 50% Probability of Loss and Contract Length = 10 years

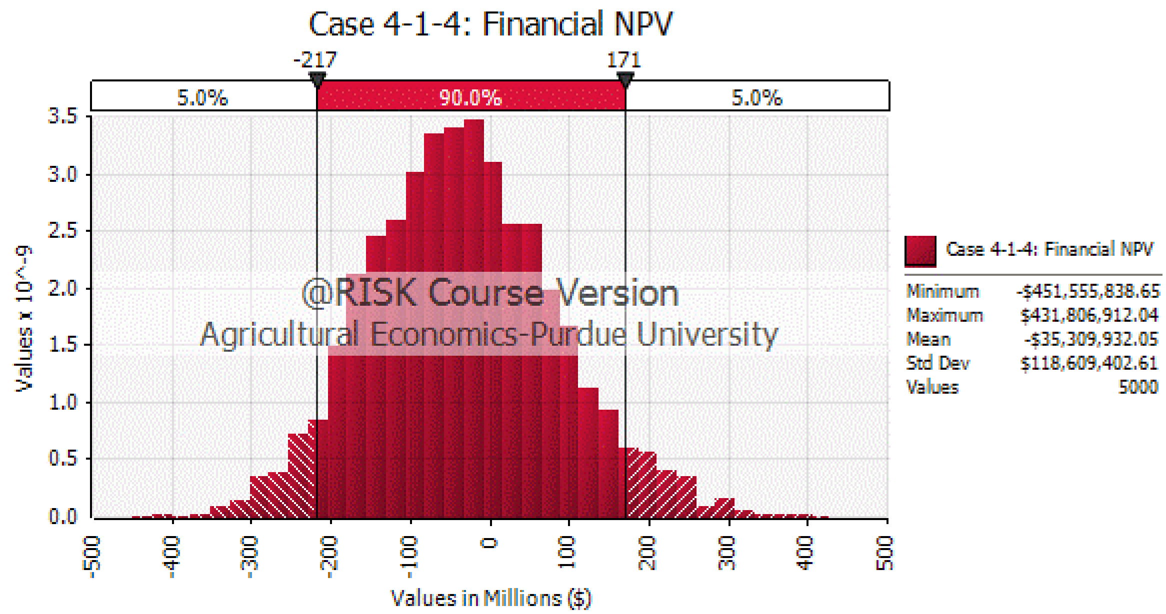

Figure 4.8 Case 4-1-4: Financial NPV with Steady Stochastic Fuel Price when Producers Bid 50% Probability of Loss and Contract Length = 15 years

These results were not completely what we expected to find. When the producers bid with a 50 percent probability of loss, the fuel price is too low to have an overall impact on the probability of loss for the NPV. As a result, we see the probability of loss hover around 60 to 70 percent for the economic and financial analysis. These results differ from Petter and Tyner 2014 because our case is, in general, much less profitable than their case.

4.2.1.1.2 Producers Bid Fuel Price with 25% Probability of Loss

The second case is a reverse auction with a stochastic fuel price with no trend where producers bid a breakeven fuel price with 25 percent probability of loss. The market fuel price is the same as in case 4-1 at $3.03/gallon, while the reverse auction fuel price is different. The reverse auction fuel price is the breakeven fuel price when producers bid with a 25 percent probability of loss when there is no contract. For this case, the fuel price is $4.45/gallon. This is over 80 cents higher than the fuel breakeven price for case 4-1.

Table 4.9 Case 4-2 Results: Reverse Auction Results with Stochastic Fuel Price with No Trend and Producers Bid Breakeven with 25% Probability of Loss

	Economic			Financial		
Length of Contract	Mean	Standard Deviation	Probability of Loss	Mean	Standard Deviation	Probability of Loss
0	($194,063,200)	$379,790,200	69.9%	($140,094,000)	$315,364,000	67.5%
5	($39,474,480)	$299,152,400	55.3%	($11,630,760)	$248,301,400	51.9%
10	$65,995,180	$210,488,500	38.5%	$76,014,520	$174,502,400	33.7%
15	$131,481,800	$143,462,600	18.5%	$130,433,900	$118,609,400	13.3%

Tables 4.9 reports the economic and financial results for a steady fuel price case when producers bid with 25 percent probability of loss. The mean NPV increases, becoming positive when the contract length increases to 10 years, which it did not do when producers bid with a 50 percent probability of loss. When producers bid with a higher probability of loss, the mean NPV remained negative for all contract lengths. Standard deviation decreases as the contract length increases, same as in case 4-1. Lastly, the probability of loss decreases as the contract length increases. This is what we expected to happen. When producers are more risk neutral, we see the NPV hovers around zero. However, when producers are more risk averse, we see that the NPV mean surpasses zero and becomes positive. As a result, we see a decrease in probability of loss. For the financial analysis, probability of loss is 67.5 percent with no contract, and decreases to 13.3 percent with a fifteen year contract. This is over a 50 percent decrease in probability of loss, which is substantial. Figures 4.9-4.12 below show the financial NPV for the different contract lengths.

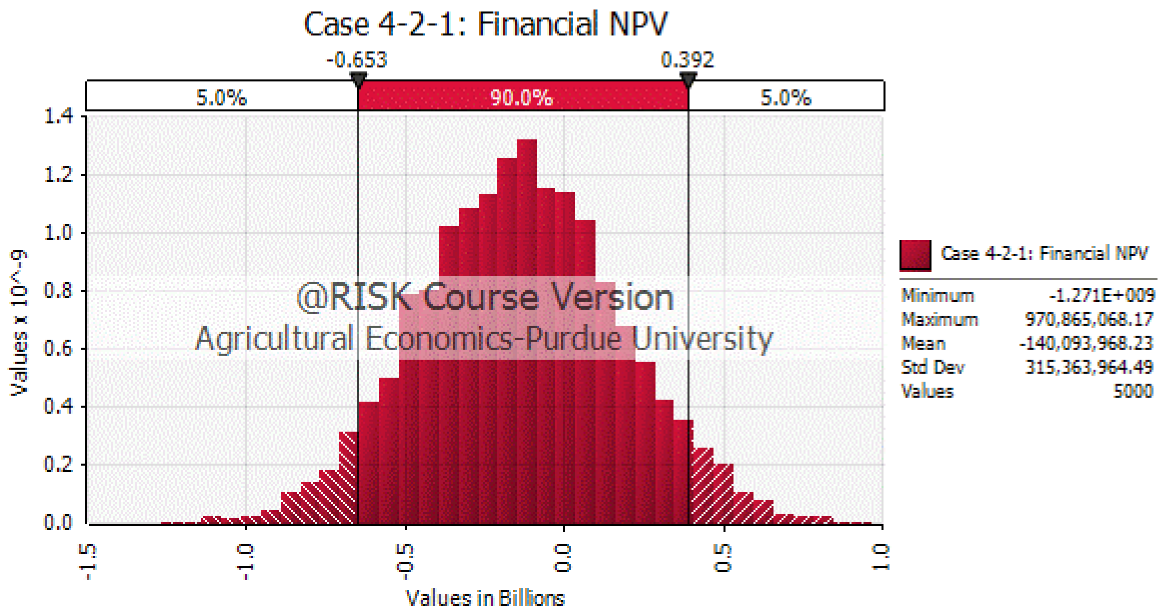

Figure 4.9 Case 4-2-1: Financial NPV with Steady Stochastic Fuel Price when Producers Bid 25% Probability of Loss and Contract Length = 0 years

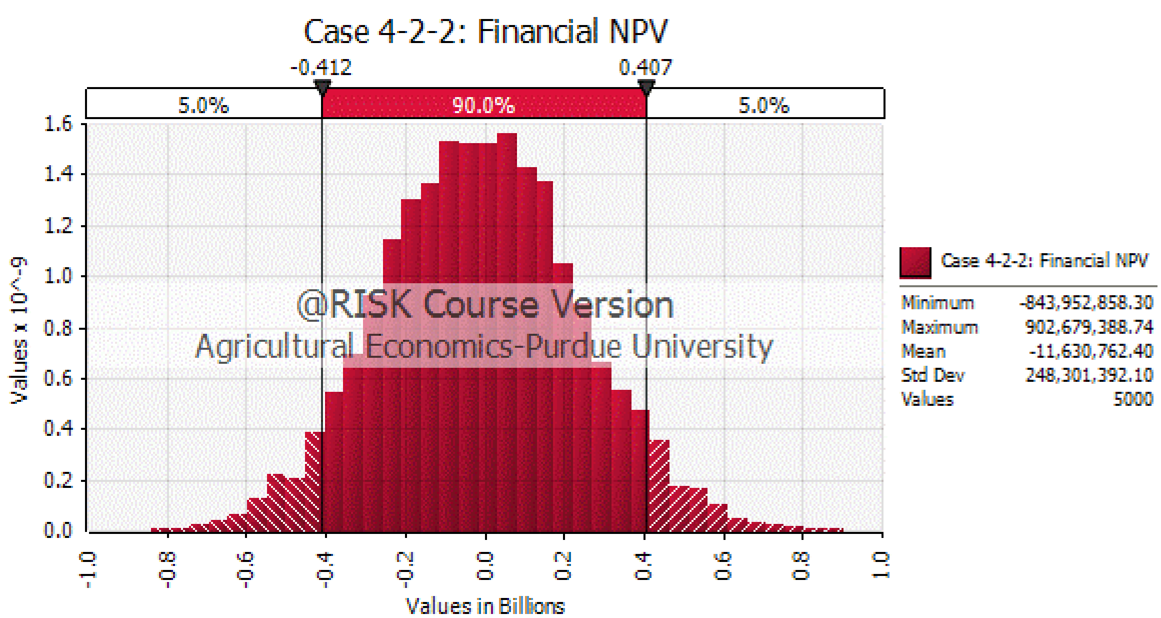

Figure 4.10 Case 4-2-2: Financial NPV with Steady Stochastic Fuel Price when Producers Bid 25% Probability of Loss and Contract Length = 5 years

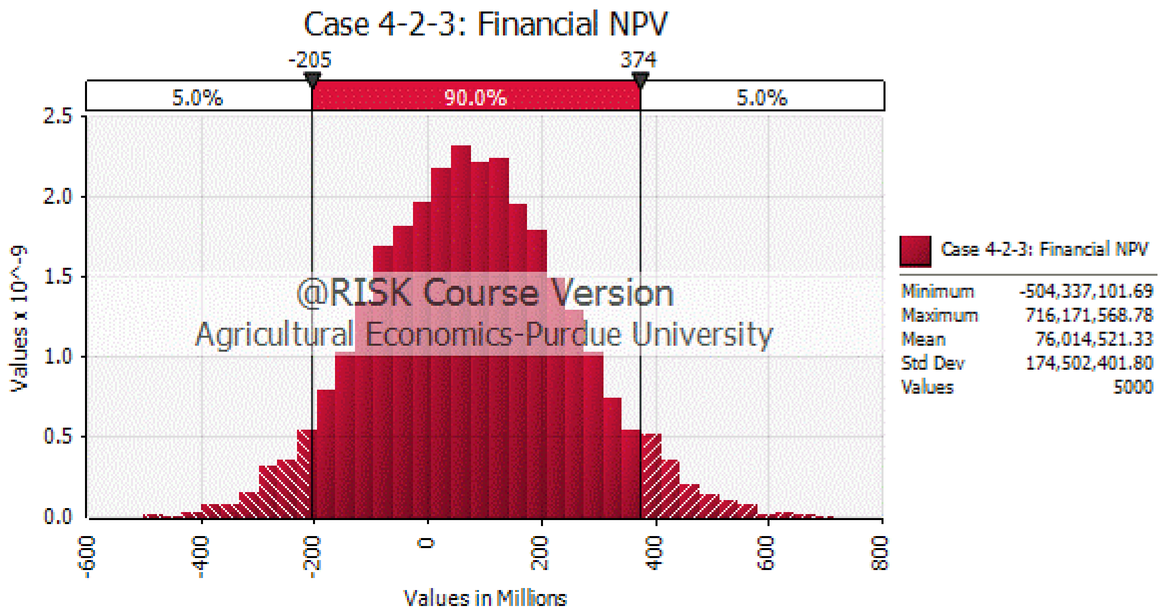

Figure 4.11 Case 4-2-3: Financial NPV with Steady Stochastic Fuel Price when Producers Bid 25% Probability of Loss and Contract Length = 10 years

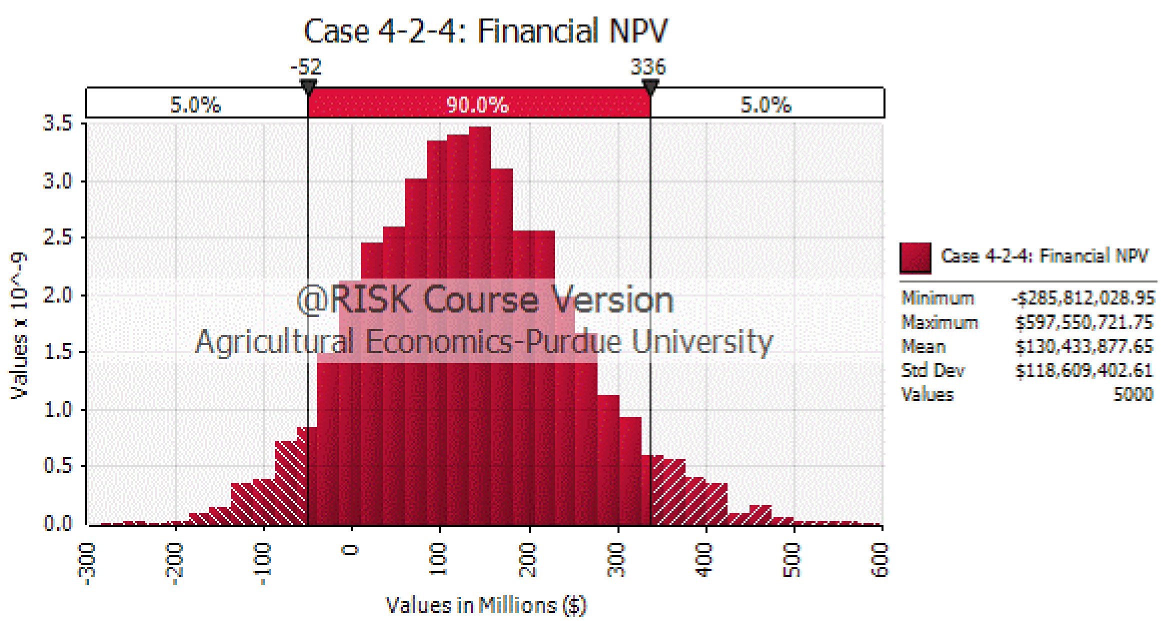

Figure 4.12 Case 4-2-4: Financial NPV with Steady Stochastic Fuel Price when Producers Bid 25% Probability of Loss and Contract Length = 15 years

Petter and Tyner 2014 run a stochastic case with three uncertain variables and an uncertain fuel price, which is one outcome of a reverse auction. Using a breakeven fuel price of $2.68/gallon, they find a probability of loss for the financial NPV of 13.2 percent. In their case, $2.68 is the reverse auction price. There is no contract specified for this case. As a result, it does not depict a real reverse auction. Our reverse auction shows the impact of contract length when fuel price is stochastically steady. We also take into account producers bidding with different probabilities of loss. It is unrealistic to believe that all producers would bid with the same probability of loss. Therefore our results are more realistic.

4.2.1.2 Stochastic with Drift in Fuel Price

4.2.1.2.1 Producers Bid Breakeven Fuel Price with 50% Probability of Loss

The third case is a reverse auction with an increasing stochastic fuel price where producers bid a breakeven fuel price with 50 percent probability of loss. The market price and reverse auction price increase over the plant life. The initial market fuel price is $3.03/gallon and increases to $3.83/gallon. The initial reverse auction fuel price is $3.22/gallon and increases to $4.07/gallon.

Table 4.10 Case 5-1 Economic Results: Reverse Auction Results with Stochastic Increasing Fuel Price and Producers Bid Breakeven with 50% Probability of Loss

Economic					
Length of Contract	Min	Max	Mean	Standard Deviation	Probability of Loss
0	($1,561,904,000)	$1,337,260,000	($90,267,960)	$406,901,900	59.1%
5	($1,169,604,000)	$1,118,032,000	($68,553,700)	$323,090,200	58.3%
10	($812,138,300)	$787,943,000	($53,033,880)	$228,625,000	59.7%
15	($574,310,700)	$572,174,300	($42,921,620)	$154,958,800	62.7%

Table 4.11 Case 5-1 Financial Results: Reverse Auction Results with Stochastic Increasing Fuel Price and Producers Bid Breakeven with 50% Probability of Loss

Financial					
Length of Contract	Min	Max	Mean	Standard Deviation	Probability of Loss
0	($1,269,351,000)	$1,133,584,000	($53,840,140)	$337,908,200	56.6%
5	($943,350,000)	$951,404,600	($35,795,590)	$268,213,700	55.5%
10	($646,295,600)	$677,100,900	($22,898,620)	$189,605,000	55.6%
15	($451,965,700)	$496,636,700	($14,495,340)	$128,206,500	56.0%

Tables 4.10 and 4.11 report the economic and financial analyses for an increasing stochastic fuel price case when producers bid with 50% probability of loss. Once again we see the same thing occur as in case 4-1. In both tables the mean NPV increases as the contract length increases, but stays negative. The standard deviation decreases as the contract length increases. The probability of loss does not decrease as the contract length increases. Instead of hovering around 70 percent as in case 4-1, it hovers around 56 percent. Compared to case 4-1, the mean NPV is less negative, increasing to negative $14 million when contract length is 15 years. Standard deviation is also larger by about $20 million. The maximum financial NPV's are also larger. Figures 4.5-4.8 below show the financial NPV for the different contract lengths. When there is no contract, the maximum is higher by about $160 million. In Figure 4.13, the maximum NPV is $1.13 billion as opposed to $970 million in case 4-1.

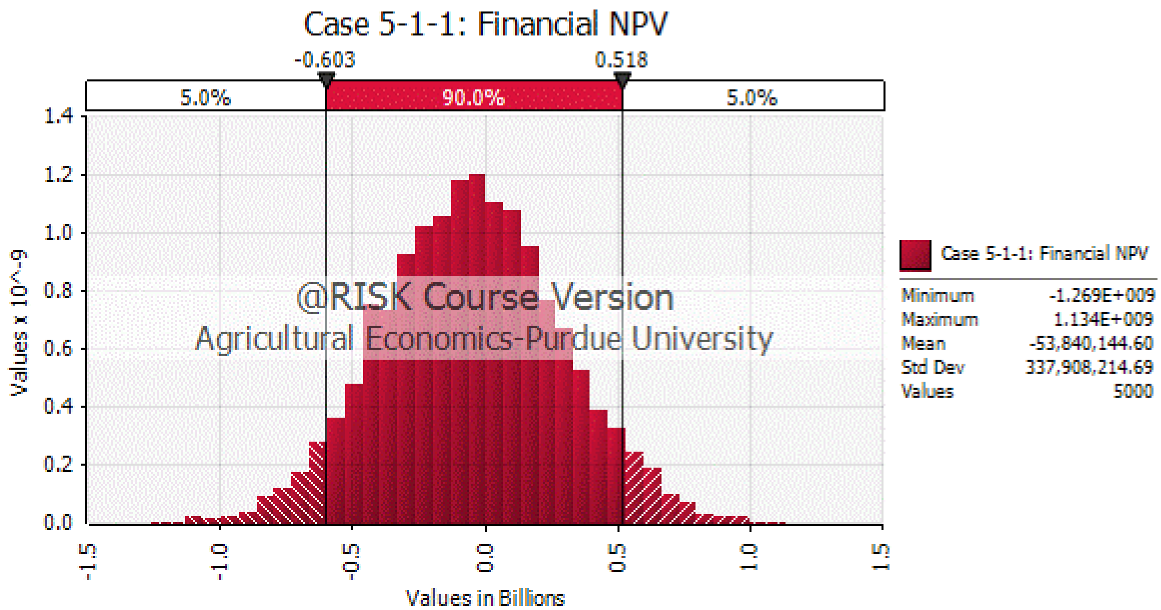

Figure 4.13 Case 5-1-1: Financial NPV with Increasing Stochastic Fuel Price when Producers Bid 50% Probability of Loss and Contract Length = 0 years

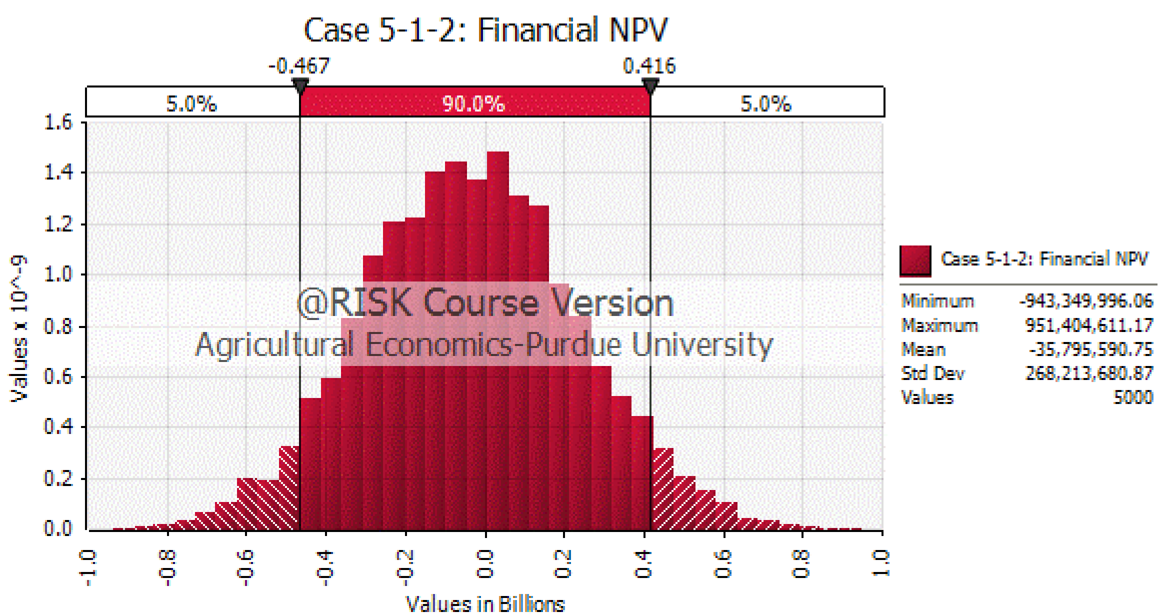

Figure 4.14 Case 5-1-2: Financial NPV with Steady Stochastic Fuel Price when Producers Bid 50% Probability of Loss and Contract Length = 5 years

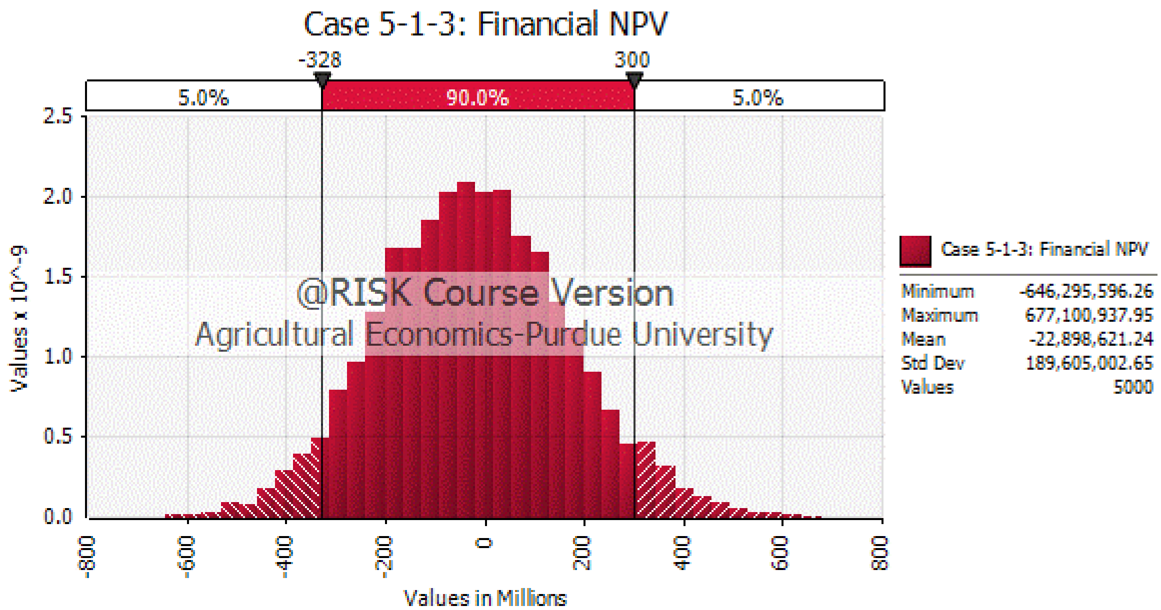

Figure 4.15 Case 5-1-3: Financial NPV with Steady Stochastic Fuel Price when Producers Bid 50% Probability of Loss and Contract Length = 10 years

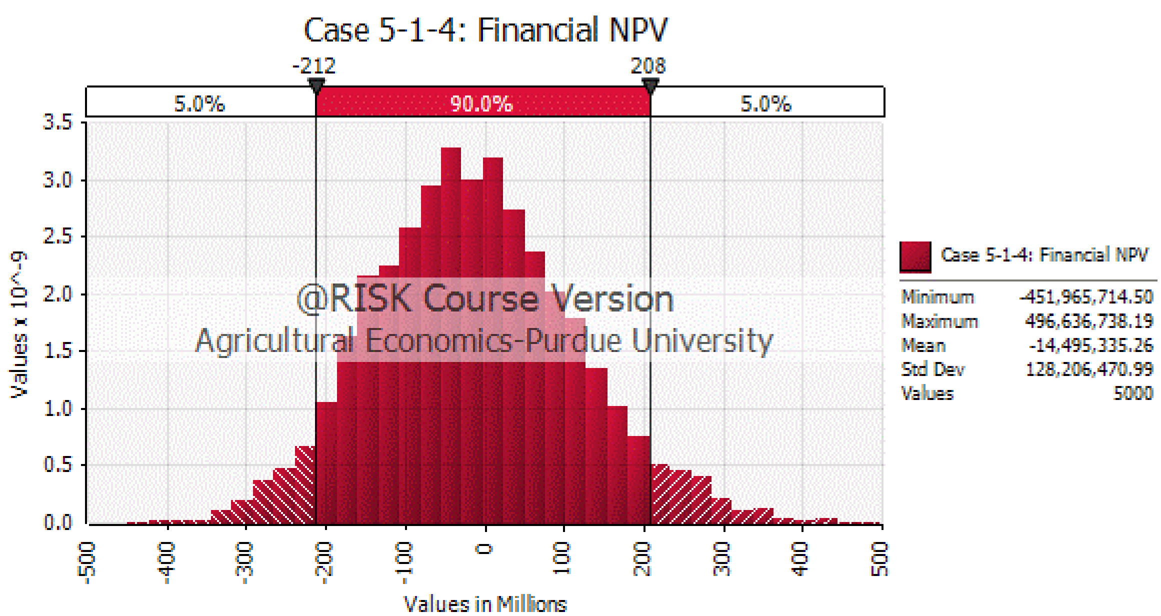

Figure 4.16 Case 5-1-4: Financial NPV with Steady Stochastic Fuel Price when Producers Bid 50% Probability of Loss and Contract Length = 15 years

Changing the price from steady to increasing has impact on the results. Going from case 4-1 to case 5-1, Tables 4.8 and 4.11, there are four changes. First, the range in NPV increases. The minimum remains about the same, but the maximum increases. This is due to the fuel prices increasing to $3.83/gallon for the market and $4.07 for a reverse auction. The mean NPV's decrease and standard deviation increases slightly. Lastly, the probability of loss decreases. There is over a 7 percent decrease for all contract lengths. This is a result of fuel price increasing over the plant life.

4.2.1.2.2 Producers Bid Fuel Price with 25% Probability of Loss

The last case is a reverse auction with an increasing stochastic fuel price where producers bid a breakeven fuel price with 25 percent probability of loss. The market fuel price is the same as in case 5-1 at $3.03/gallon. The reverse auction fuel price is different since the producers bid with a lower probability of loss. The reverse auction price is the breakeven price, while the market fuel price is not. When producers bid with a 25 percent probability of loss when there is no contract, the breakeven fuel price is $4.05/gallon. The fuel price increases to $5.11/gallon in the last year of the plant life. In comparison to case 5-1, the breakeven fuel price is $0.83 higher.

Table 4.12 Case 5-2 Results: Reverse Auction Results with Increasing Stochastic Fuel Price and Producers Bid Breakeven with 25% Probability of Loss

	Economic			Financial		
Length of Contract	Mean	Standard Deviation	Probability of Loss	Mean	Standard Deviation	Probability of Loss
0	($90,267,960)	$406,901,900	59.1%	($53,840,140)	$337,908,200	56.6%
5	$26,707,720	$323,090,200	47.1%	$43,366,650	$268,213,700	43.9%
10	$110,623,700	$228,625,000	32.2%	$113,100,800	$189,605,000	28.2%
15	$165,511,300	$154,958,800	14.0%	$158,712,400	$128,206,500	9.9%

Table 4.12 reports the economic and financial results for an increasing stochastic fuel price case when producers bid with 25 percent probability of loss. The results are similar to case 4-2. The mean NPV increases as the contract length increases. However, instead of becoming positive when the contract length increases to 10 years, it becomes positive when the contract length is 5 years. Standard deviation decreases by $200 million from no contract to a contract of fifteen years. The probability of loss decreases as the contract length increases, which is what we expect. It decreases to a lower probability of loss than case 4-2. When there is no contract, the probability of loss is 56.6 percent. This is the same probability of loss seen in Table 4.5. It decreases to less than 10 percent with a 15 year contract. Figures 4.17-4.20 below show the financial NPV for the different contract lengths.

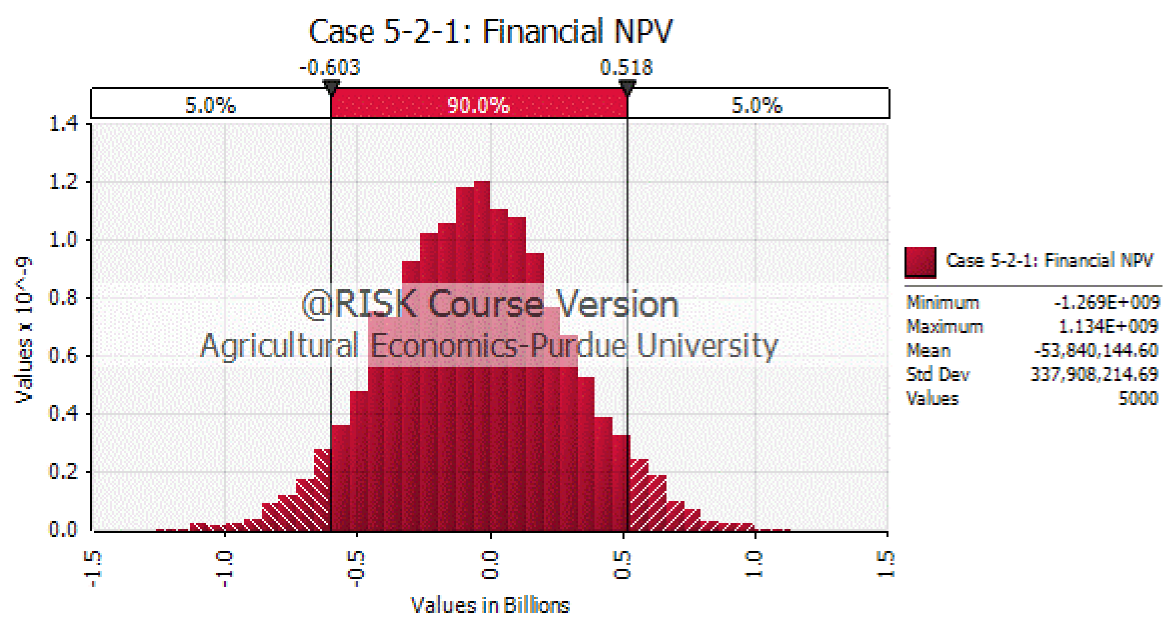

Figure 4.17 Case 5-2-1: Financial NPV with Increasing Stochastic Fuel Price when Producers Bid 25% Probability of Loss and Contract Length = 0 years

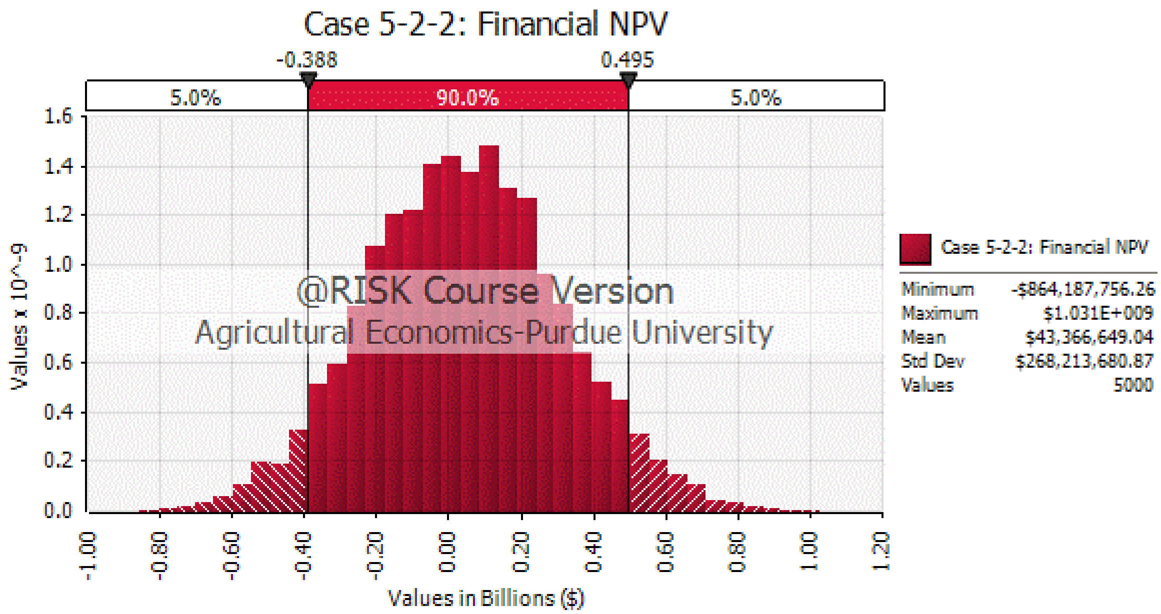

Figure 4.18 Case 5-2-2: Financial NPV with Increasing Stochastic Fuel Price when Producers Bid 25% Probability of Loss and Contract Length = 5 years

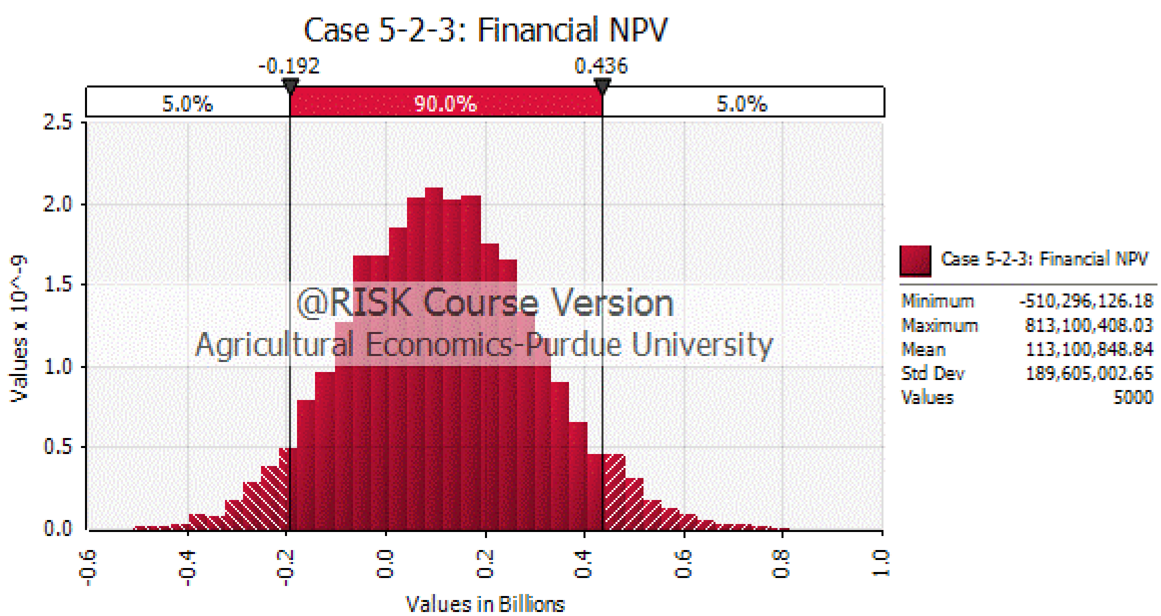

Figure 4.19 Case 5-2-3: Financial NPV with Increasing Stochastic Fuel Price when Producers Bid 25% Probability of Loss and Contract Length = 10 years

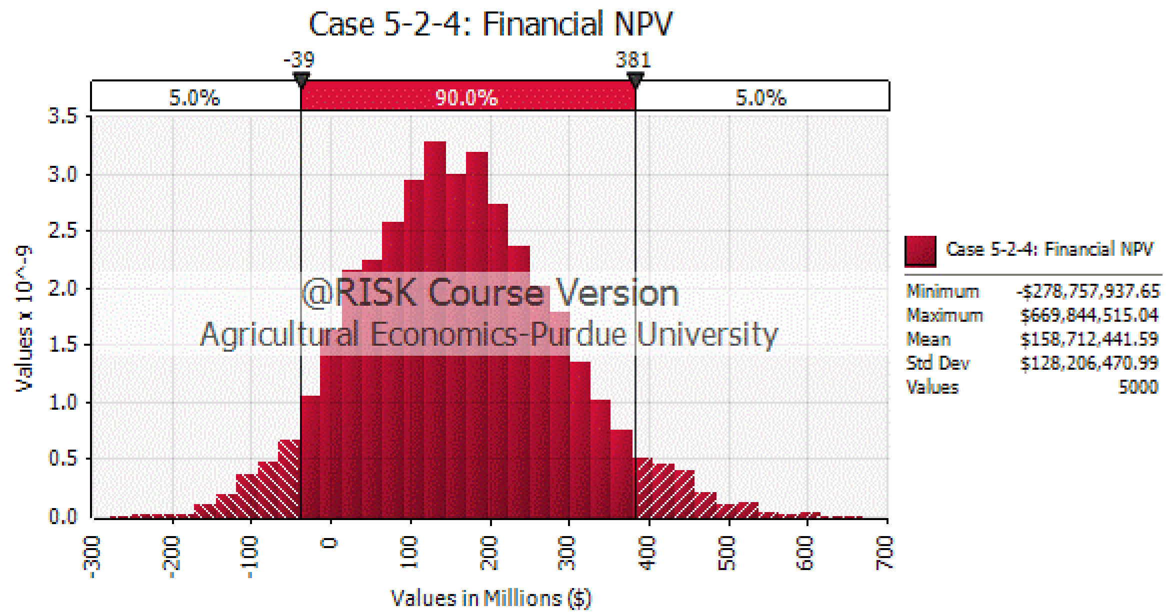

Figure 4.20 Case 5-2-4: Financial NPV with Increasing Stochastic Fuel Price when Producers Bid 25% Probability of Loss and Contract Length = 15 years

Petter and Tyner (2014) run a stochastic case for a reverse auction with increasing fuel price and a forward contract of 45 million gallons per year. The contract length is 18 years, or for project years 5-23. We use shorter contract lengths to evaluate the contracts which are actually being used today. Our contract quantity is also lower. This is due to the fact that we use a lower final fuel yield in our analysis. Our annual production is around 50 million gallons per year instead of 58.6 million gallons per year. Petter and Tyner (2014) find a probability of loss for the financial NPV of 0.04 percent. For a contract length of 15 years we find a probability of loss for financial NPV of 9.9 percent. Our results are more realistic of what is going on in the market. We also have uncertainty in capital cost which increases the probability of loss.

Overall we see that when producers bid with a 50% probability of loss, the NPV probability of loss hovers around a percentage above 50%. This is due to the NPV hovering around zero. When producers bid with a 25% probability of loss, the NPV probability of loss decreases as the contract length increases. There is also a difference in mean NPV's. With a 50 percent probability of loss for both fuel prices, mean NPV is negative for all contract lengths. At a 25 percent probability of loss, mean NPV becomes positive. This is a result of the larger fuel prices bid when producers have a lower probability of loss. Overall, we also see that when the fuel price is stochastically increasing versus being steady, there are lower probabilities of loss.

4.2.1.3 Cost to Government

A reverse auction can create a cost to government. As stated previously, the government can win or lose depending on the market price of oil and aviation biofuels. The cost to government is calculated as the reverse auction fuel price minus the market fuel price multiplied by the contract quantity for the contract length. For all other years that the contract is not in effect, the cost to government is zero. Using this formula, we find costs to government listed below in Table 4.13 for the four reverse auction cases and the three different contract lengths.

Table 4.13 Cost to Government for the Four Reverse Auction Cases

Length of Contract	Case 4-1	Case 4-2	Case 5-1	Case 5-2
5	$41,772,260	$107,848,380	$15,145,746	$81,606,827
10	$70,272,610	$181,431,103	$25,972,960	$140,152,041
15	$87,969,086	$227,120,185	$33,028,923	$178,446,436
5	9%	24%	3%	18%
10	16%	41%	6%	31%
15	20%	51%	7%	40%

The cost to government varies depending on what probability of loss producers bid. The cases where producers bid with a 50 percent probability of loss, cases 4-1 and 5-1, have a much lower cost to government. This is due to the fact that when producers bid with a higher probability of loss, the initial reverse auction fuel price is lower. Case 5-1 has the lowest cost to government. The cost to government ranges from as low as $15 million in case 5-1 to as high as $227 million in case 4-2. These calculations are used to analyze a capital subsidy policy in the next section.

We also included what percentage the capital subsidy makes up of capital costs in Table 4.13. For some of the cases the capital subsidy accounts for a large percentage of capital costs. Specifically, for case 4-2, when the contract length is 15 years, the capital subsidy makes up over 50 percent of the capital cost.

4.2.2 Capital Subsidy

Capital subsidy is another policy which can be used to encourage investment in aviation biofuels. We want to compare the reverse auction to a capital subsidy, so the costs to government calculated for the various reverse auction cases in Table 4.13 are the capital subsidies. When there is no contract, there is no cost to government. We report the results for a 5, 10, and 15 year contract. Capital subsidy is not stochastic for any of the cases. As a result, it is subtracted from the draw on capital cost. Because the breakeven fuel price is higher than the market price in the reverse auction cases, the cost to government can be large.

4.2.2.1 Stochastic without Drift in Fuel Price

4.2.2.1.1 Producers Bid Breakeven Fuel Price with 50% Probability of Loss

The capital subsidy results in Table 4.14 are from using the costs to government for case 4-1. These results are different than the reverse auction results. The mean NPV is negative for all cases and increases as the contract length increases. However, they are actually more negative than with a reverse auction. For the financial case with a 15 year contract, the mean NPV is -$65 million with a 58.4 percent probability of loss. Probability of loss is 63.0 percent for financial with a 5 year contract and decreases to 58.4 percent with a 15 year contract. For the reverse auction case, probability of loss hovered around 70 percent. For capital subsidy we actually see the probability of loss decrease slightly as the contract length increases, but the standard deviation remains quite large.

Table 4.14 Case 6-1 Results: Competitive Capital Subsidy with Stochastically Steady Fuel Price of $3.03/gallon Using Case 4-1 Costs to Government

	Economic			Financial		
Length of Contract	Mean	Standard Deviation	Probability of Loss	Mean	Standard Deviation	Probability of Loss
5	($148,780,400)	$379,790,200	65.5%	($104,443,400)	$315,364,000	63.0%
10	($117,884,400)	$379,790,200	62.4%	($80,119,150)	$315,364,000	60.5%
15	($98,700,300)	$379,790,200	60.6%	($65,015,720)	$315,364,000	58.4%

4.2.2.1.2 Producers Bid Fuel Price with 25% Probability of Loss

When producers bid with a lower probability of loss the fuel price is higher. As a result, the cost to government is higher. The costs to government for case 4-2 were used to find the results reported in Table 4.15. The costs to government were more than double what they were for case 4-1; therefore, there is an even larger impact. The mean NPV's are positive for contract lengths of 10 and 15 years, increasing to $53 million for the financial analysis when there is a 15 year contract. The probability of loss decreases to 43.2 percent with a 15 year contract. All probability of losses for case 6-2 are less than those for case 6-1, but still high. This is due to the fact that the capital subsidies are more than double what they are for case 6-1. For case 6-2, the capital subsidies range from

$107 million to $227 million, as opposed to $41 million to $87 million. When producers bid with a 25 percent probability of loss, there is a larger impact on the NPV probability of loss, but they remain high and variance is very large.

Table 4.15 Case 6-2 Results: Competitive Capital Subsidy with Stochastically Steady Fuel Price of $3.03/gallon Using Case 4-2 Costs to Government

	Economic			Financial		
Length of Contract	Mean	Standard Deviation	Probability of Loss	Mean	Standard Deviation	Probability of Loss
5	($77,149,950)	$379,790,200	58.2%	($48,049,320)	$315,364,000	56.4%
10	$2,618,153	$379,790,200	49.7%	$14,751,390	$315,364,000	48.3%
15	$52,147,870	$379,790,200	44.6%	$53,745,700	$315,364,000	43.2%

4.2.2.2 Stochastic with Drift in Fuel Price

4.2.2.2.1 Producers Bid Breakeven Fuel Price with 50% Probability of Loss

This case has the lowest costs to government and therefore the lowest capital subsidies. When fuel price is stochastically increasing with a 50 percent probability of loss, the capital subsidies range from $15 million to $33 million. The subsidies for this case are less than half of what the capital subsidies were when fuel price was stochastically steady with a 50 percent probability of loss. The results using the costs to government for case 5-1 are reported in Table 4.16. Due to the capital subsidies being smaller for this case, the impact is not as large. Financial analysis mean NPV's are negative for all contract lengths. Probability of loss decreases as the contract length decreases. However, it does not decrease at a rapid rate. This rate is similar to the one seen with a steady fuel price when producers bid with a 50 percent probability of loss in case 6-1. It decreases to 53.4 percent with a 15 year contract. This is 5 percent lower than in case 6-1. Probability of loss decreases only 1.7 percent for the economic analysis and 1.8 percent for the financial analysis as the contract length increases. The variances are huge.

Table 4.16 Case 6-3 Results: Competitive Capital Subsidy with Stochastically Increasing Initial Fuel Price of $3.03/gallon Using Case 5-1 Costs to Government

	Economic			Financial		
Length of Contract	Mean	Standard Deviation	Probability of Loss	Mean	Standard Deviation	Probability of Loss
5	($73,849,980)	$406,901,900	57.5%	($40,914,510)	$337,908,200	55.2%
10	($62,112,620)	$406,901,900	56.4%	($31,673,790)	$337,908,200	54.0%
15	($54,463,540)	$406,901,900	55.8%	($25,651,730)	$337,908,200	53.4%

The impact of the capital subsidy is driven by the actual amount of the capital subsidy. Whether the fuel price is steady or increasing also has an impact. Case 4-2 had the highest capital subsidies. As a result, the impact on probability of loss was greater. Capital subsidy decreased to 43.2 percent as opposed to 58.4 and 53.4 in cases 6-1 and 6-3. The mean NPV's were also greater than in cases 6-1 and 6-3. However, the variance, which is driven mainly by the stochastic aviation fuel price, remains very high.

4.2.2.2.2 Producers Bid Fuel Price with 25% Probability of Loss

A capital subsidy when fuel price is increasing stochastically with a 25 percent probability of loss has the largest impact on probability of loss. The impact is largest because the probability of loss that producers bid is lower as well as the fuel price is increasing. In stochastic cases 2 and 3, we saw the probability of loss was lower when fuel prices were increasing stochastically. We see this same trend in the capital subsidy results. Table 4.17 shows the results for the three contract lengths. Mean NPV's are positive for all contract lengths in the financial analysis. For the economic analysis, mean NPV's are positive for contract lengths of 10 and 15 years, but not for 5 years. For the financial analysis, mean NPV increases to $98 million. When the contract length is 5 years, probability of loss is 48.4 percent for the financial analysis. It decreases to 38.7 percent when the length of contract is increased to 15 years. This case has the lowest probabilities of loss out of all capital subsidy cases.

Table 4.17 Case 6-4 Results: Competitive Capital Subsidy with Stochastically Increasing Initial Fuel Price of $3.03/gallon Using Case 5-2 Costs to Government

	Economic			Financial		
Length of Contract	Mean	Standard Deviation	Probability of Loss	Mean	Standard Deviation	Probability of Loss
5	($1,802,161)	$406,901,900	50.2%	$15,808,100	$337,908,200	48.4%
10	$61,664,380	$406,901,900	44.0%	$65,774,740	$337,908,200	42.4%
15	$103,177,800	$406,901,900	40.2%	$98,457,890	$337,908,200	38.7%

Previously, we saw that the financial results were always better than the economic results. However, this does not hold for this case when the contract length is 15 years. In this case, the financial benefits do not exceed tax payments. As a result, economic analysis is better than the financial.

Cost to government is driven by the fuel price. When the fuel price for the reverse auction is higher than the market price, the government incurs a cost. For all cases, our reverse auction fuel price exceeded our market fuel price. As a results, there was a cost to government. As the gap between the reverse auction price and the market fuel price increases, the cost to government increases. Petter and Tyner 2014 ran a capital subsidy case in their paper. They had a relatively lower fuel price, but saw similar results. In our analysis, the high breakeven fuel price did not seem to have a large impact on the results for a capital subsidy. As a result, we do not see large decreases in the probability of loss when a capital subsidy is introduced.

4.2.2.3 Comparison of Reverse Auction to Capital Subsidy

Reverse auction and capital subsidy have different effects. In order to see how the effects of a reverse auction and capital subsidy differ, we did a comparison of all four cases. We focused on the financial results for each policy, reporting the mean, standard deviation, and probability of loss for NPV for contract lengths of 5, 10, and 15 years.

The comparison of capital subsidy and reverse auction policy cases reveals quite a bit about the way the two policies function. In effect, the capital subsidy shifts the mean NPV to the right by the amount of the subsidy. However, it has no effect on the variance of NPV. The reverse auction also shifts the NPV to the right somewhat, but at the same time has a very large impact on variance, with standard deviation of NPV being much smaller in all cases. Thus, it is clear that the reverse auction is much more effective in reducing risk for private sector investors than is the capital subsidy. That is true despite the fact that probability of a loss is a bit lower for capital subsidy for the 15 year case. When the variances are as high as we see here, the probability of loss is not as good an indicator as the coefficient of variation (standard deviation/mean), and that is lower for all reverse auction cases.

Table 4.18 Comparison of Reverse Auction and Capital Subsidy Financial Analysis Results When Fuel Price is Stochastically Steady and Producers Bid with 50% Probability of Loss

	Reverse Auction Financial				Capital Subsidy Financial			
Length of Contract	Mean	Standard Deviation	CV	Probability of Loss	Mean	Standard Deviation	CV	Probability of Loss
5	($90,334,470)	$248,301,400	(2.7)	64.4%	($104,443,400)	$315,364,000	(3.0)	63.0%
10	($56,387,110)	$174,502,400	(3.1)	63.3%	($80,119,150)	$315,364,000	(3.9)	60.5%
15	($35,309,930)	$118,609,400	(3.4)	63.5%	($65,015,720)	$315,364,000	(4.9)	58.4%

When producers bid with a 25 percent probability of loss, mean NPV's increase to positive values and probability of losses decrease as the contract length increases in Table 4.19. However, the difference between mean NPV values for the policies is larger than in Table 4.18. For a contract length of 5 years, the difference is over $30 million increasing to about $80 million when the contract length is 15 years. When contract length is 5 years, the probability of loss for the reverse auction is 51.9 percent. For a capital subsidy, the probability of loss is 56.4 percent, which is actually higher than the reverse auction by 4.5 percent. Probability of loss decreases to 13.3 percent when the contract length increases to 15 years for the reverse auction. For a capital subsidy, the probability of loss only decreases to 43.2 percent when there is a 15 year contract. In all cases except the 5 year case the coefficient of variation is much lower for the reverse auction cases.

Table 4.19 Comparison of Reverse Auction and Capital Subsidy Financial Analysis Results When Fuel Price is Stochastically Steady and Producers Bid with 25% Probability of Loss

	Reverse Auction Financial				Capital Subsidy Financial			
Length of Contract	Mean	Standard Deviation	CV	Probability of Loss	Mean	Standard Deviation	CV	Probability of Loss
5	($11,630,760)	$248,301,400	(21.3)	51.9%	($48,049,320)	$315,364,000	(6.6)	56.4%
10	$76,014,520	$174,502,400	2.3	33.7%	$14,751,390	$315,364,000	21.4	48.3%
15	$130,433,900	$118,609,400	0.9	13.3%	$53,745,700	$315,364,000	5.9	43.2%

The effects on the results for both policies are both larger than in Table 4.19 because under assumption of producer bids at 25% probability of loss, more of the variance is reduced and the mean is shifted further to the right. When producers bid with a lower probability of loss, the reverse auction price increases, which causes mean NPV's to surpass zero and probability of loss to decrease. The increased reverse auction price also increases the costs to government, causing the capital subsidies to be larger. Although both policies reduce probability of loss, the reverse auction reduced probability of loss to a lower value. When contract length is 15 years, the probability of loss for reverse auction is almost 30 percent lower than for capital subsidy.

In comparison to Table 4.18, the reverse auction and capital subsidy cases are more similar when fuel price is stochastically increasing. The difference in mean NPV values is slightly less. For mean NPV, the difference between the policies is $5 million when contract length is 5 years, increasing to only $11 million when contract length is 15 years. The mean NPV is negative for all contract lengths. Probability of loss is similar for all cases under both policies, but coefficient of variation is lower for the reverse auction cases.

Table 4.20 Comparison of Reverse Auction and Capital Subsidy Financial Analysis Results When Fuel Price is Stochastically Increasing and Producers Bid with 50% Probability of Loss

	Reverse Auction Financial				Capital Subsidy Financial			
Length of Contract	Mean	Standard Deviation	CV	Probability of Loss	Mean	Standard Deviation	CV	Probability of Loss
5	($35,795,590)	$268,213,700	(7.5)	55.5%	($40,914,510)	$337,908,200	(8.3)	55.2%
10	($22,898,620)	$189,605,000	(8.3)	55.6%	($31,673,790)	$337,908,200	(10.7)	54.0%
15	($14,495,340)	$128,206,500	(8.8)	56.0%	($25,651,730)	$337,908,200	(13.2)	53.4%

When fuel price is stochastically increasing and producers bid with 25 percent probability of loss, we see the results in Table 4.21. The results are relatively similar to those in Table 4.19. The impact when fuel price is increasing versus steady is seen in both policies. The mean NPV’s for a reverse auction are higher than in Table 4.19. Probability of loss is also lower than in Table 4.19. For the capital subsidy, a change in the fuel price to increasing, also affects the mean NPV and probability of loss, but capital subsidy loss probability losses remain relatively constant, while the decline with longer contracts under reverse auction. All mean NPV’s are higher than those in Table 4.19. The coefficients of variation are lower in all instances for the reverse auction case.

Table 4.21 Comparison of Reverse Auction and Capital Subsidy Financial Analysis Results When Fuel Price is Stochastically Increasing and Producers Bid with 25% Probability of Loss

	Reverse Auction Financial				Capital Subsidy Financial			
Length of Contract	Mean	Standard Deviation	CV	Probability of Loss	Mean	Standard Deviation	CV	Probability of Loss
5	$43,366,650	$268,213,700	6.2	43.9%	$15,808,100	$337,908,200	21.4	48.4%
10	$113,100,800	$189,605,000	1.7	28.2%	$65,774,740	$337,908,200	5.1	42.4%
15	$158,712,400	$128,206,500	0.8	9.9%	$98,457,890	$337,908,200	3.4	38.7%

Using a reverse auction versus a capital subsidy results in higher mean NPV's for all contract lengths. When producers bid with a lower probability of loss, lower probability of losses are also seen. This trend is seen in Tables 4.18-4.21. When fuel price is increasing and producers bid with a 25 percent probability of loss, both policies see decreases in probability of loss as the contract length increases. However, the probability of loss is lower for a reverse auction. The coefficient of variation is a better indicator of risk in these cases, and it is always lower for the reverse auction.

4.2.3 Carbon Tax

Carbon tax puts a price on negative externalities. We wanted to see what sort of impact a carbon tax could have on the probability of loss. We calculated a carbon tax in dollars per gallon and incorporated it into our spreadsheet. Fossil jet fuel CO_2 emissions reported by the North Carolina Division of Air Quality was 9.57 kg CO_2/gallon (North Carolina Division of Air Quality 2009). We used a 60 percent reduction in CO_2 emissions from fossil jet fuel for stover jet fuel CO_2 emissions. This is the average of what was reported in the life-cycle analysis section. The difference is CO_2 emissions was found and then multiplied by the carbon tax of $37/MT CO_2 provided by the Interagency Working Group 2013. This yielded a carbon tax of $0.14/gallon. The carbon tax was multiplied by annual production and added to fuel sales. We ran a deterministic and a stochastic case for the carbon tax.

4.2.3.1 Deterministic

The deterministic results for the carbon tax case are similar to case 1. All the technical variables are fixed at mean values. The only difference is a carbon tax of $0.14/gallon is included in fuel sales. We ran the results with the average fuel price of $3.03/gallon and with the breakeven fuel price. With the carbon tax the effective fuel price becomes $3.17. Table 4.22 reports the results from using a fuel price of $3.03/gallon plus the carbon tax.

Table 4.22 Case 7 Results: Deterministic Case with Fuel Price of $3.03/gallon

	NPV	IRR (real)	B/C
Economic	($150,674,966)	4.8%	0.63
Financial	($104,038,710)	4.4%	0.54

The results for the deterministic carbon tax case are slightly better than the results in Table 4.1. The NPV's for the economic and financial analysis are slightly less negative. The internal rate of return is also a little better for both analyses. This is due to the extra revenue generated by the carbon tax. However, using a fuel price of $3.03/gallon plus the carbon tax, none of the criterion for acceptance of a project for the three discounted measures of project worth are met. As a results, investors would most likely not want to invest when fuel price is steady at $3.03/gallon.

We also found the breakeven fuel price for the deterministic case of a carbon tax. The results for the breakeven are reported below in Table 4.23. They are the exact same as the results in Table 4.2. The only difference is the breakeven fuel price was $3.44/gallon. This is exactly fourteen cents less than the breakeven fuel price without a carbon tax reported in case 1 of $3.58/gallon. At a steady stochastic fuel price of $3.44/gallon, the plant would be running at neither a loss nor a gain. For the financial, the IRR is 10% and the B/C is 1.

Table 4.23 Case 7 Results: Deterministic Case with Breakeven Fuel Price of $3.44/gallon

	NPV	IRR (real)	B/C
Economic	($25,477,962)	9.2%	0.94
Financial	$0	10.0%	1.00

4.2.3.2 Stochastic

The stochastic case was run with a fuel price with no trend and one that is increasing at DOE projections. Comparatively, the results we found were similar to case 2. A carbon tax adds the set amount of $0.14 to the fuel price each year. In the deterministic results, we saw a decrease in the breakeven fuel price from case 1. Now we will add uncertainty to that case, as well as one where fuel price is increasing.

4.2.3.2.1 Steady Fuel Price

A stochastic case with a carbon tax gives slightly better results than one without a carbon tax. The results for a stochastic case where the technical variables are uncertain and an uncertain fuel price with no trend of $3.03/gallon is used are shown below in Table 4.24. In comparison to Table 4.3, case 2 results when there is a steady stochastic fuel price of $3.03/gallon, the mean NPV's are less negative by about $40 million. The probability of loss decreased by about 4.5 percent for the financial analysis, from 67.5 percent to 63 percent. There also is almost a 3 percent decrease from the economic to the financial analysis in Table 4.24. The increase in mean NPV and decrease in probability of loss are due to the additional revenue gained through the carbon tax. For our plant with an annual production of about 50 million gallons per year, the carbon tax generates an additional $7 million annually. Although there is an increase in fuel sales, it does not seem to have a large impact on the probability of loss. The mean benefit-cost ratios are both still less than one, although they have increased from those in Table 4.3.

Table 4.24 Case 7-1 Results: Stochastic Case with Fuel Price with No Trend of $3.03/gallon

	Economic			Financial		
	NPV	IRR (nominal)	B/C	NPV	IRR (nominal)	B/C
Mean	($150,486,800)	11.6%	0.63	($103,882,000)	12.9%	0.54
Standard Deviation	$380,165,700	9.2%	0.94	$315,676,100	11.1%	1.42
Probability of Loss	65.7%			63.0%		

*Note: (1)Nominal Discount Rate Used for NPV was 12.75% (2)IRR calculation had errors in the stochastic calculation

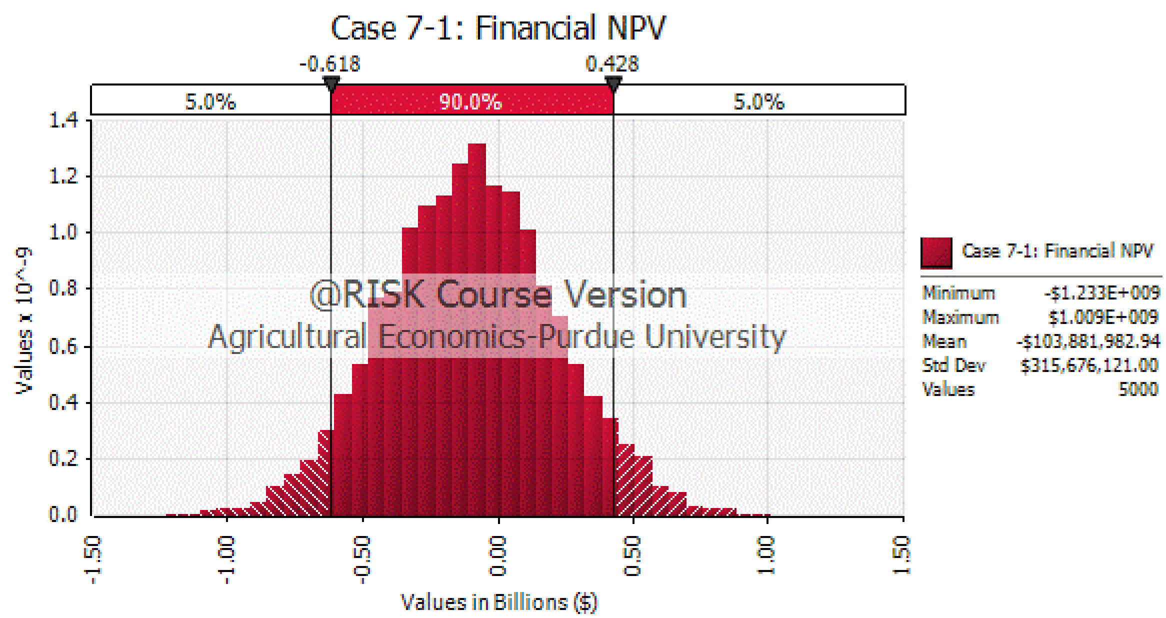

Figure 4.21 Case 7-1: Financial NPV with a Steady Stochastic Fuel Price of $3.03/gallon

The results from the breakeven fuel price with no trend are the same as those in Table 4.4. The breakeven fuel price with no trend is $3.44/gallon with a carbon tax as opposed to $3.58/gallon without one. We get the same results, but with a lower breakeven fuel price in Table 4.25.

Table 4.25 Case 7-1 Results: Stochastic Case with Breakeven Fuel Price with No Trend of $3.44/gallon

	Economic			Financial		
	NPV	IRR (nominal)	B/C	NPV	IRR (nominal)	B/C
Mean	($25,273,960)	14.0%	0.94	$169,872	16.1%	1.01
Standard Deviation	$381,332,200	9.3%	0.95	$316,645,900	11.3%	1.42
Probability of Loss	53.1%			50.2%		

*Note: (1)Nominal Discount Rate Used for NPV was 12.75% (2)IRR calculation had errors in the stochastic calculation

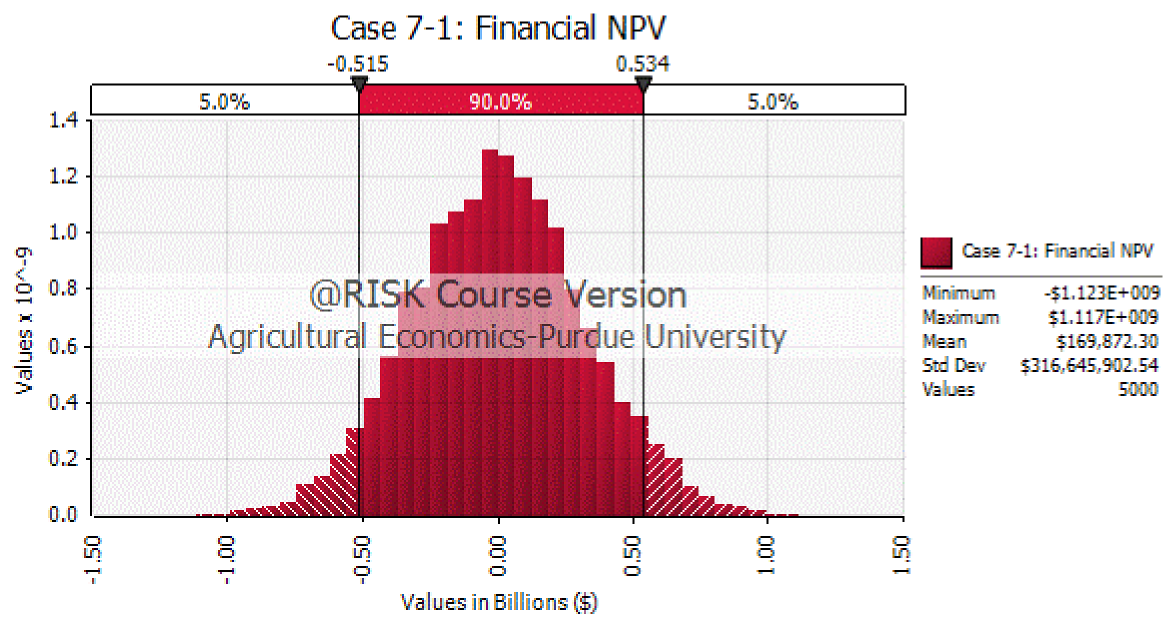

Figure 4.22 Case 7-1: Financial NPV with a Steady Stochastic Fuel Price of $3.44/gallon

When fuel prices are stochastically increasing, a carbon tax does not have much effect on the results. As stated previously, the mean NPV's become less negative, B/C increases, and probability of loss decreases. However, the carbon tax only influences them slightly. Therefore, it may not be the most useful policy.

4.2.3.2.2 Increasing Fuel Price

Similar results are seen for a stochastic case with an increasing fuel price as were for a stochastic fuel price with no trend. In comparison to Table 4.5, the mean NPV for the economic and financial analysis increases, becomes less negative, by about $40 million. For the financial analysis, the IRR also increases by about one percent. There is a 4.2 percent decrease in probability of loss for financial. This is slightly smaller than the decrease in probability of loss seen for the case were fuel price has no trend. Benefit-cost ratios increased by about 0.10 from the results in Table 4.5. There is also an increase in the financial mean B/C by almost 0.40 from Table 4.24, where there is no trend in the fuel price. Overall, we see that using a fuel price which increases over time, increases NPV, increases B/C, and decreases probability of loss.

Table 4.26 Case 7-2 Results: Stochastic Case with Increasing Fuel Price of $3.03/gallon

	Economic			Financial		
	NPV	IRR (nominal)	B/C	NPV	IRR (nominal)	B/C
Mean	($46,691,560)	13.5%	0.89	($17,628,160)	15.1%	0.93
Standard Deviation	$407,289,300	9.3%	1.01	$338,230,200	11.2%	1.52
Probability of Loss	55.0%			52.4%		

*Note: (1)Nominal Discount Rate Used for NPV was 12.75% (2)IRR calculation had errors in the stochastic calculation

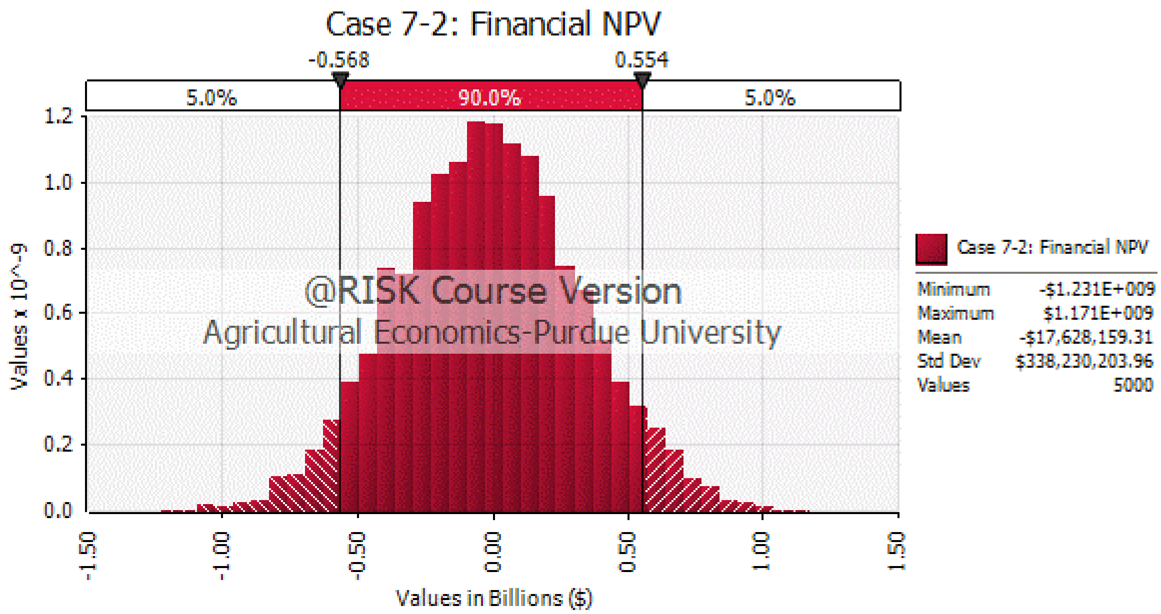

Figure 4.23 Case 7-2: Financial NPV with an Increasing Stochastic Fuel Price of $3.03/gallon

The results for the breakeven are the same as those in Table 4.6 for a stochastic case with an increasing fuel price of $3.22/gallon. With a carbon tax, there is a decrease in the initial breakeven fuel price from $3.22/gallon to $3.09/gallon. This is a decrease of $0.13/gallon, which is one cent less than the decrease in the breakeven fuel price from a stochastic steady fuel price. At a breakeven fuel price of $3.09/gallon, there is a 50.2 percent probability of loss for NPV in Table 4.27. This fuel price is only 6 cents higher than the average fuel price calculated in fuel price uncertainty section. However, including the carbon tax, increases the fuel price to $3.23, which is the same price as what was found without a carbon tax.

Table 4.27 Case 7-2 Results: Stochastic Case with Increasing Breakeven Fuel Price of $3.09/gallon

	Economic			Financial		
	NPV	IRR (nominal)	B/C	NPV	IRR (nominal)	B/C
Mean	($25,266,780)	13.9%	0.94	175,837	15.7%	1.01
Standard Deviation	$407,485,100	9.3%	1.01	338,393,000	11.2%	1.52
Probability of Loss	52.7%			50.2%		

*Note: (1)Nominal Discount Rate Used for NPV was 12.75% (2)IRR calculation had errors in the stochastic calculation

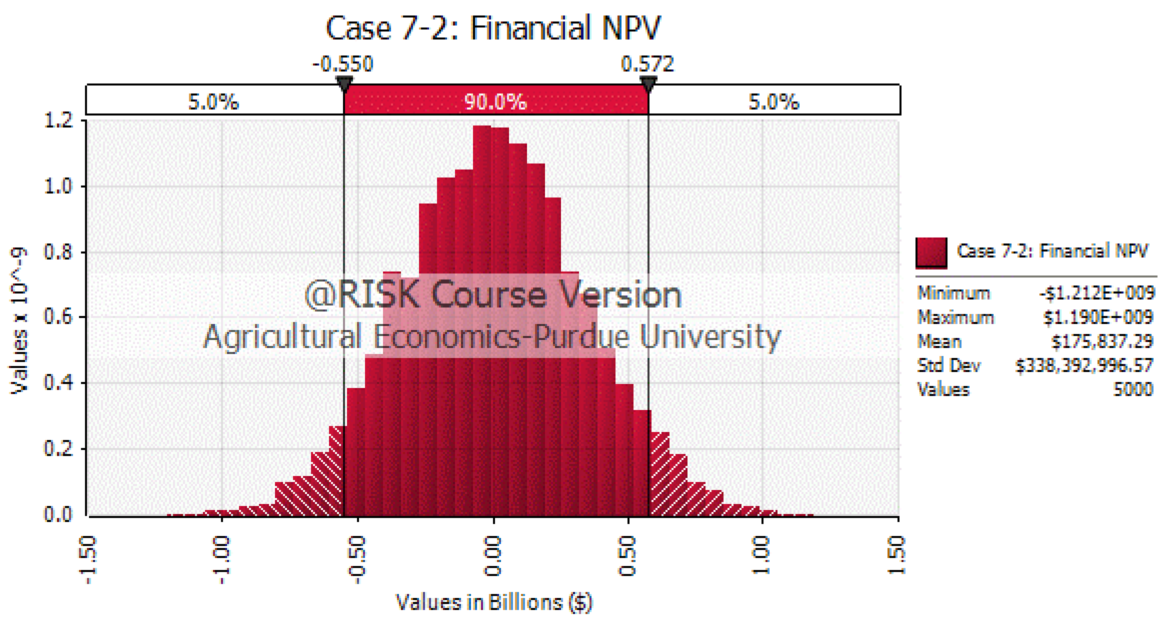

Figure 4.24 Case 7-2: Financial NPV with an Increasing Breakeven Fuel Price of $3.09/gallon

The carbon tax did not have a large impact on the NPV probability of loss. In comparison to a reverse auction, the carbon tax did less to reduce the probability of loss in the NPV, IRR, and B/C. In comparison to cases 1, 2, and 3, the carbon tax had a slight impact on the NPV, IRR, B/C, and probability of loss. It generates an additional $7 million annually, which helps positively influence the results. Although it has a positive impact when fuel price is stochastically steady and increasing, the impact is small. Clearly, the carbon tax is not large enough to significantly impact the results.

CHAPTER 5. CONCLUSIONS

5.1 Summary of Findings

The aviation biofuel industry at present presents a high risk for private investors. There is uncertainty prevalent in fuel price, feedstock availability and cost, process yields and costs, environmental impact, and government policy. Our analysis looks at the production of aviation biofuel from corn stover using the fast pyrolysis process. Currently, the risk is high for private investors. One way to reduce this risk is through government intervention.

Government intervention can be done in the form of a wide range of policies. We look at three policies in our results: reverse auction, capital subsidy, and carbon tax. Three additional cases are evaluated: a deterministic case, a stochastic case where fuel price is steady, and a stochastic case where fuel price is increasing.

For the deterministic case, with a fuel price of $3.03, NPV is negative, IRR is less than the discount rate, and B/C is less than one. Therefore, a private investor would not want to invest. The breakeven fuel price calculated was $3.58/gallon.

For the stochastic cases, we look at two fuel prices: (1) fuel price is steady and (2) fuel price increases at DOE projections. The fuel price is $3.03/gallon, increasing to $3.83/gallon for the increasing case. Using the fuel price of $3.03/gallon, probability of loss is lower in the case when fuel price is increasing at DOE projections. When fuel price is steady, probability of loss for the financial analysis is 67.5 percent. The probability of loss for when it is increasing is 56.6 percent. The breakeven fuel price is $3.58/gallon for the steady fuel price case, and $3.22/gallon for the increasing fuel price case. Breakeven fuel price is the price at which NPV is zero.

At this price, the plant is running neither at a loss or gain. The probability of loss when this occurs is 50.2 percent for the financial analysis.

All three government policies reduced risk in investment. However, some reduced risk more than others. The reverse auction and capital subsidy reduce the probability of loss more than the carbon tax. For the carbon tax, when fuel price is stochastically steady, there is a 4.5 percent decrease for the financial compared with case 2. When the fuel price is increasing, there is a 4.2 percent decrease. This is substantially smaller than the decrease for reverse auction and capital subsidy due to the carbon tax not being large enough to have a large impact.

Reverse auction and capital subsidy were analyzed using both fuel prices. For each fuel price two probabilities of loss were used for bids from producers: 50% and 25%. When producers bid with 25% versus 50% probability of loss, the probability of loss decreased to a lower value for both fuel prices and both policies. We looked at four contract lengths: 0, 5, 10, and 15 years. For the reverse auction, the probability of loss hovered around a percentage when producers bid with a 50 percent probability of loss for both fuel prices and the contract length increased. When producers bid with 25 percent probability of loss, the probability of loss for the NPV decreased as the contract length increased. With a steady price, the probability of loss was 67.5 percent with no contract, decreasing to 13.3 percent with a 15 year contract. When fuel price was increasing, the probability of loss with a 15 year contract was even lower at 9.9 percent. For the comparison of reverse auction, the coefficient of variation may be a better risk indicator than probability of loss. In our analysis, the coefficient of variation was always lower for the reverse auction compared with the capital subsidy. The probability of loss shows much less difference. When price was increasing and producers bid 25 percent probability of loss, the probability of loss was 43.9 percent with a 5 year contract, decreasing to 9.9 percent with a 15 year contract under reverse auction. This was substantially lower than the probability of loss for a capital subsidy at 48.4 percent and 38.7 percent.

The three factors which contributed to lower probabilities of loss were (1) a stochastic fuel price increasing at DOE projections, (2) when producers bid with a 25 percent probability of loss, and (3) longer contract lengths. Reverse auction and capital subsidy both had large impact on probability of loss, but the coefficient of variation for this analysis is more revealing on risk reduction differences between the two policies. Coefficient of variation is the standard deviation divided by the mean. Because the variances were high, probability of loss is not as good of a measure of risk. The coefficient of variation was lower for reverse auction than for the capital subsidy in most cases.

The reverse auction reduced risk the most and at the lowest cost to the government. In a reverse auction, the purchaser requests bids for a contract to supply aviation biofuels. The lowest bid wins the contract. Implementation of this policy likely would be done by the government. The government would put up a contract for a certain quantity of aviation biofuels to be produced each year for a certain contract length. The plant builders would place bids on the government's contract. This bidding process is a means of effectively creating a competitively based subsidy for aviation biofuels. That is why it turns out to be more efficient. However, there may be difficulties in securing adequate competition for new processes such as pyrolysis based aviation biofuels. Reverse auctions have worked well for known technologies, but they may not function as well for new and unproven technologies.

5.2 Future Research

Our analysis looks at three policies: reverse auction, capital subsidy, and a carbon tax. These are not the only policies which could reduce risk for private investors. We could also conduct analysis on other policies such as a loan guarantee and RIN credits. In the current political environment, the Renewable Fuel Standard itself also is uncertain. Future research also could examine the implications of elimination or changes in the RFS.

We look at uncertainty in four technical variables as well as the fuel price. The analysis could also be done to include system uncertainty. System uncertainty relates to the possibility that the whole plant may not function as planned (e.g., Kior), or the market may take a serious turn downward. By adding the probability of the plant succeeding or going bankrupt, it would give even more realistic results.

Lastly, we chose to look at aviation biofuels using fast pyrolysis from corn stover. Other conversion processes as well as feedstocks can be analyzed. However, we chose fast pyrolysis and corn stover based on our literature review. Our research was also focused on the United States. It could be expanded to look at other countries.

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APPENDIX

APPENDIX

Employment Costs

Position	**Number**	**Employment Tim**	**Annual Salary**	**Annual Expense**
Plant Manager	1	100%	$ 80,000	$ 80,000
Plant Engineer	1	92%	$ 65,000	$ 59,560
Maintenance Supervisor	1	100%	$ 60,000	$ 60,000
Lab Manager	1	100%	$ 50,000	$ 50,000
Shift Supervisor	5	92%	$ 37,000	$ 169,518
Lab Technician	2	92%	$ 25,000	$ 45,816
Maintenance Technician	8	92%	$ 28,000	$ 205,254
Shift Operators	20	92%	$ 25,000	$ 458,156
Yard Employees	32	92%	$ 20,000	$ 586,440
General Manager	0	100%	$ 100,000	$ -
Clerks & Secretaries	3	92%	$ 20,000	$ 54,979
Total Salaries	74			**$ 1,769,723**

Figure A 1 Total Salaries Spreadsheet