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An economic comparison of high moisture feedstock biofuel production

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An economic comparison of high moisture feedstock biofuel production

by

Mitchell Amundson

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Program of Study Committee:
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NOMENCLATURE

AD	Anaerobic Digestion
BT2	Billion Ton Update
BTL	Biomass-to-Liquid
CSTR	Continuous Stirred-Tank Reactor
DOE	Department of Energy
DMT	Dry Matter Ton
DLUC	Direct Land Use Change
EPA	Environmental Protection Agency
ET	Evapotranspiration
FT	Fischer-Tropsch
GTL	Gas-to-Liquid
HTL	Hydrothermal Liquefaction
ILUC	Indirect Land Use Change
MM	Million
MPFR	Mixed Plug-Flow Reactor
MTG	Methanol-to-Gasoline
RFS	Renewable Fuel Standard
TPD	Tonne per Day
US	United States

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ABSTRACT

This study compares final fuel production costs of multiple biomass-to-liquid production facilities. Process economics are estimated for four different high moisture feedstocks, four different biomass supply chain pathways and three different conversion and upgrading technologies. Two biorefinery capacities are examined, small (200 tonne per day) and large (2000 tonne per day). Corn stover, corn silage giant miscanthus and sweet sorghum are the feedstocks considered for conversion via hydrothermal liquefaction (HTL) and anaerobic digestion (AD). Final product finishing is done by hydroprocessing of the HTL biocrude and either Fischer-Tropsch (FT) synthesis or methanol-to-gasoline (MTG) conversion of the AD biogas. Water footprints are estimated for blue, green and grey water consumption during the entire biofuel production process for each scenario.

In efforts to decrease the production costs, moisture and size reduction steps are omitted during the biomass supply chain stage. Multi-pass and single pass harvesting scenarios are considered along with wet and dry storage techniques. These steps lead to an estimated delivered feedstock cost ranging from \$63.84-\$86.19 per tonne; comparable with recent literature. Conversion and upgrading pathways were chosen based on ability to handle high moisture feedstock. Capital investments were estimated for each technology scenario and ranged from \$424-\$545 MM for the 2000 tpd biorefinery, within a degree of uncertainty; HTL resulted in the lowest estimated capital costs. Final fuel production costs ranged from \$2.00-\$6.55 per gallon for all feedstocks and all conversion pathways, with stover and sorghum resulting in the lowest. The total water footprints were estimated to range from 5.92-23.21 L_w/L_b and 5.58-14.89 L_w/L_b for the conservative and optimal blue water scenarios, respectively. The green and grey water footprints ranged from 232.30-2,568.27 L_w/L_b and 296-526 L, respectively.

CHAPTER I: INTRODUCTION

Why is Energy a Concern?

Climate change and sustainability have become large concerns of recent decades among governments, companies, international organizations and the general population. These concerns have stemmed from weather changes, including global temperature rise, ocean temperature rise and a tendency for more severe weather conditions [1]. The United Nations Framework Convention on Climate Change has defined climate change as: “a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variably observed over comparable time periods” [2]. Anthropogenic or human impacted climate change has been attributed to how humans have used the earth’s resources. According to Collins et al. [1], the atmosphere has held a relatively stable concentration of carbon dioxide, methane and nitrous oxides for roughly 10,000 years; in recent decades those concentration levels have increased at alarming rates. The accelerated increase in atmospheric concentration levels have been primarily blamed on greenhouse gas (GHG) emissions from fossil fuel production and consumption. Fossil fuels: coal, petroleum and natural gas, were formed by intense heat and pressure from being compacted by layers of earth for millions of years. Fossil fuels are comprised entirely of hydrogen and carbon, have relative high energy densities compared to other energy sources and are used heavily for transportation, heating, electricity generation and in the manufacturing of commodity products. The vast consumption of fossil fuels have left the environment in a state of diminishing health, requiring action to mitigate or reverse the negative effects of these resources.

The world's steady rise of derived energy consumption has led to rapidly diminishing reserves of these resources [2]. The human population is extinguishing the world's oil and coal deposits faster than the resources can be naturally reproduced. In 1956, Marion King Hubbert estimated that US oil production would peak in the 1970s and continually decline following a bell shaped curve [3]. This has proven to be the case, with the exception of a few events in recent history including technological advancements in shale oil production and hydraulic fracking and newly found, easily attainable oil reserves. The US has begun to look elsewhere to supply the nation with ample oil which has at times become dangerous and costly at times. The search for oil has often times resulted in dealing with regions of hostility toward Americans, which can result in variable supply and price of oil [4]. To become more energy independent and to better improve national security, the US needs become less dependent on petroleum and create a more diverse energy portfolio.

There are a wide variety of energy sources available for human production and consumption. Most commonly these sources are separated into two categories, the previously discussed non-renewable resources and renewable resources: sources that when consumed, could be replenished in a few decades. Renewable energy sources that have received attention as possible fossil fuel replacements have been solar, wind, hydro, geothermal and biomass. Biomass, organic material of recent biological origin [4], is possibly the leading candidate to "replace" petroleum as a dependent source of energy, due to the variety of biomass sources available and the diversity of derived products from biomass utilization. Biomass as a transportation fuel, biofuel, has gained much attention recently due to technological advancements that have drawn the economics closer to those of petroleum products and the ability to significantly aid in the mitigation of anthropogenic climate change [3].

Biofuel Production

Biomass is a worldwide abundant natural resource. In the US alone it is estimated that there is over one billion dry tons of biomass available for biorenewable energy utilization [5]. Many sources of biomass have been proven capable of conversion into useful fuel sources: agricultural and wood biomass and respective waste residues, energy crops and human and animal waste streams. Biomass utilization can include electricity and process heat production, commodity chemical production, soil nutrient replenishment and transportation fuel production (biofuel). The most common and historically mature production pathway is corn grain to ethanol although other pathways, such as sugarcane to ethanol, have been equally successful. However, these production pathways raise concerns related to food vs. fuel, direct land use change and indirect land use change [6]. Given these concerns, other methods of biofuel production have drawn interest as technologies improved and processes became more economically viable. Governmental energy policy has contributed to biofuel technology development as well with policies such as the Renewable Fuel Standard (RFS) mandate on biofuel blending with conventional transportation fuels. **Error! Reference source not found.** shows a schematic of the RFS biofuel volumetric mandate with associated greenhouse gas (GHG) reduction values from the RFS mandate update in 2007 [7]. **Error! Reference source not found.** shows a recently updated chart on the non-starch based biofuel production. The new rule out from the Environmental Protection Agency (EPA) increases the level of renewable fuel that is to be produced in the US, including a complex rule on conventional renewable fuel that sets the limit at less than 10% of the petroleum based fuel production [8]. In **Error! Reference source not found.** the conventional biofuel value is set to fill the volume remaining from the EPA set 2nd and 3rd generation biofuel production levels. The RFS categorizes biofuels into different GHG reduction groups based on the method in which the biofuel is produced [7]. Starch based ethanol, with a GHG reduction of 20%, is based on a biochemical conversion process using fermentation and distillation to convert corn grain into ethanol to be blended with gasoline. Cellulosic biofuels encompass biomass from a wide range of sources: perennial grasses, crop residues, forest materials, food and yard wastes and municipal solid wastes. The RFS describes cellulosic biofuels as including: the utilization of natural gas, biogas or biomass as process energy sources for conversion processes [7]. These processes may include thermochemical pyrolysis and gasification, biochemical fermentation, catalytic upgrading and any other process using biogas. Biomass based diesel has a GHG reduction of 50%, and the biodiesel is produced from esterification of a variety of oils: soy, non-food grade corn oil, algal oil and waste oils and greases. Advanced biofuel has a GHG reduction of 50% and is unique in that it includes ethanol production from sugarcane practiced in Brazil, liquefied petroleum gas from a variety of oils [7].

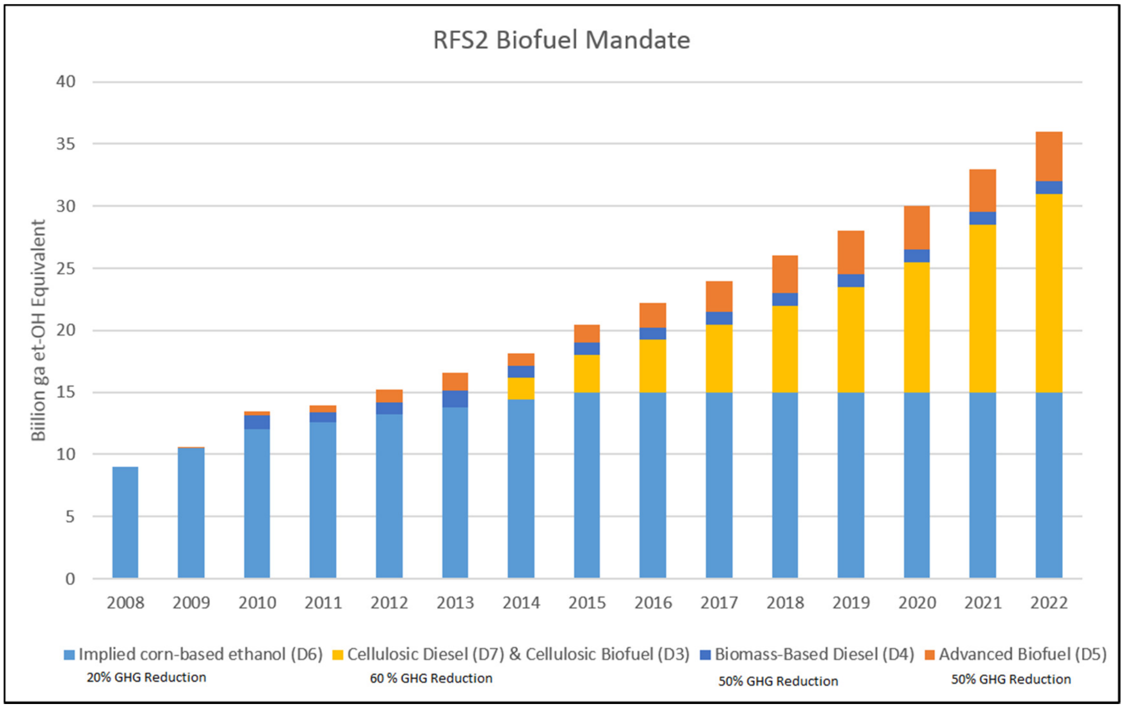


Figure 1: RFS2 biofuel mandate for years 2008 to 2022 (ga et-OH: gallons of ethanol; D6, D7, D3, D4 and D5 are all renewable identification numbers (RINs)) (adapted from [7])

Traditional biofuel production, known as the biochemical pathway; uses enzymes and microorganisms for the fermentation of starches and sugars to produce alcohols, most commonly ethanol. This process has been used for hundreds of years in the brewing of beer and is now being done on a commercial scale for producing gasoline additives to our transportation fuel supply [9]. Although biochemical conversion technologies are rather mature, thermochemical conversion technologies have been receiving increasing attention within the transportation and energy community. Thermochemical biomass conversion has received praise due to the products' close resemblance to fossil fuel resources: oil, natural gas and coal. Bio-oil and bio-crude from pyrolysis and hydrothermal liquefaction, respectively, resemble an oxygenated version of crude petroleum oil, although much more complex [10]. Syngas from gasification, once cleaned, is nearly identical to natural gas, and can behave in much of the same ways [11]. Biochar, a co-product of pyrolysis and hydrothermal liquefaction is composed mostly of carbon, and closely resembles coal. Many of these thermochemical co-products make up the short list to aid in efforts of anthropogenic climate change and carbon footprint reduction and mitigation.

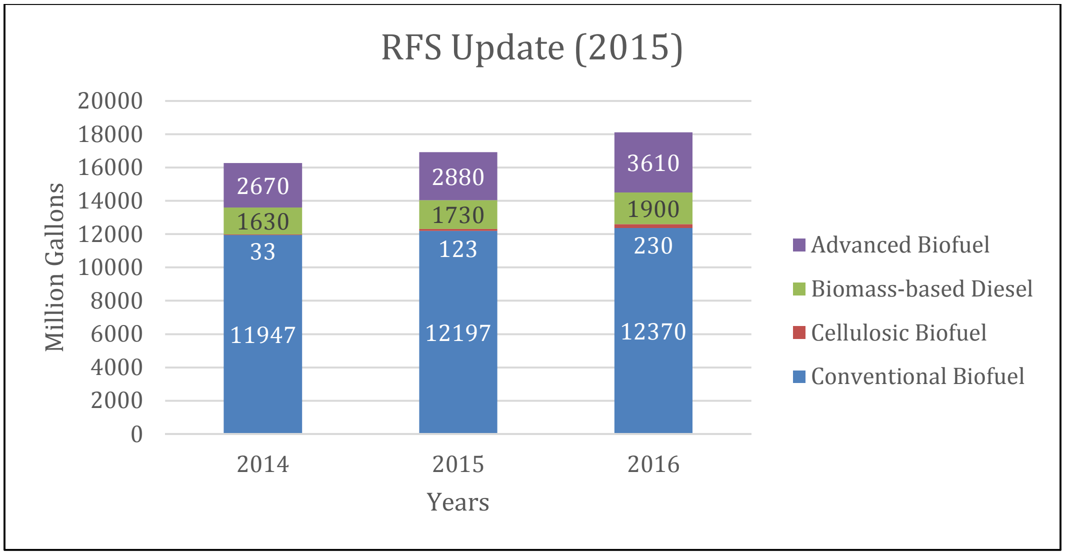


Figure 2: RFS 2015 mandate update [8]

Biofuels, especially those from thermochemical conversion methods, have not yet become reliable sources of consumption primarily due to economics. There are many complex steps for producing transportation fuels from biomass that account for the overall price of biofuel production. The multistep production process generally includes: biomass production, harvesting, transportation, preprocessing, conversion and upgrading. All of which can be divided into separate multistep processes that incur their own costs. To be competitive in the current transportation fuel markets, the overall maturity of the process technology must increase thus allowing production costs to decrease and opening the door for biobased product integration into the current infrastructure.

Thesis Overview

This study aims to provide a high level, preliminary economic analysis for a variety of pathways of high moisture biomass to transportation fuels. Four feedstocks are studied: corn stover, corn silage, giant miscanthus and sweet sorghum. The study analyzes small (200 tonne/day) and large (2000 tonne/day) biorefinery capacity scenarios beginning with the establishment and harvesting of each feedstock either from a multi-pass or single pass scenario. Biomass is then stored traditionally by bale in a dry environment or by an unconventional wet storage method. Trucks transport the biomass from farm to storage site and on to processing site. Preprocessing steps include all handling, grinding and conversion preparation needed before conversion occurs. In attempt to reduce energy consumption and costs, the biomass drying step is omitted from this process. Conversion methods have been strategically chosen for compatibility with wet feedstocks or moisture content of 20 wt% or greater. Thermochemical conversion method, hydrothermal liquefaction (HTL) and biochemical conversion method, anaerobic digestion (AD) have been selected for this study due to each method's ability to process high moisture feedstocks and the products that each method outputs. The conversion intermediates are then upgraded to final products through individualized upgrading techniques. HTL biocrude is upgraded via hydroprocessing to gasoline and diesel. AD biogas is upgraded via Fischer-Tropsch synthesis (FTS) yielding gasoline and diesel and via methanol-to-gasoline (MTG) yielding gasoline only. Capital and operating costs are calculated for each step of the process for each scenario from literature and scaling factors. Sensitivity analyses are done to find pessimistic, base and optimistic cost scenarios for fuel production cost. In addition to basic capital and operating costs, water accounting is performed in attempt to analyze the process in a more holistic approach. Blue, green and grey water are estimated based on water usage throughout the feedstock growing stage and biofuel production stage. Argonne National Lab's WATER, online water accounting tool, is used to aid in quantification of the water footprints of a variety of biofuel production scenarios.

Table 1: System Pathway Options (HTL: hydrothermal liquefaction, MTG: methanol-to-gasoline, FT: Fischer-Tropsch synthesis)

Capacity	Feedstock	Harvest	Storage	Conversion Technology
200	Corn Stover	Multiple Pass	Dry	HTL
2000	Corn Silage	Single Pass	Wet	MTG
	Giant Miscanthus			FT
	Sweet Sorghum			

CHAPTER II: LITERATURE REVIEW

Introduction

Biorenewable resource energy utilization has historically been the norm, peoples all over the world have used biomass as a primary energy source for thousands of years [4]. Since the discovery of coal and oil, biomass has drastically decreased in demand, quite noticeably among industrialized countries. Issues related to global climate change, energy security and national security have risen from the vast consumption of these resources. Energy security, anthropogenic climate change and resource sustainability have begun to gain interest as issues that need to be addressed from a variety of groups. Scientists, engineers, politicians and CEOs of many different groups are investing in energy utilization in one way or another. According to a Yale survey on global warming, 63% of Americans see global warming as an issue in the US. Out of a scientific population only 41% of scientists believe global warming to be an issue. 77% of people surveyed supported policy regulated funding of research for renewable energy sources and 74% support regulations of CO_2 as a pollutant [12]. There is growing interest and support from a variety of sources on the mitigation and reverse of climate change through renewable energy production and governmental policy implementation.

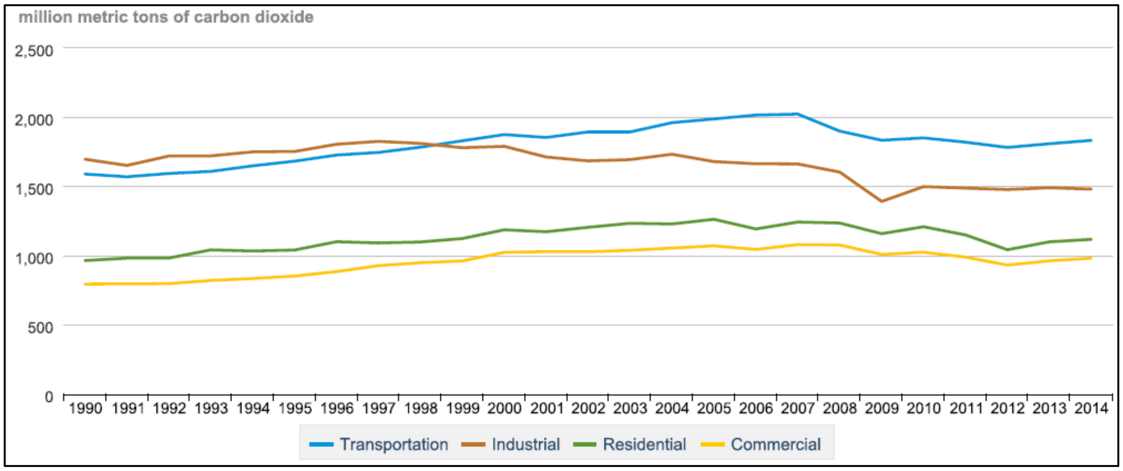


Figure 3: Energy consumption by sector from years 1990 to 2014 [13]

The transportation sector has the largest CO_2 emissions per energy consumption sector in the US. Figure 3 shows an Energy Information Agency (EIA) graph of each sector and their respective CO_2 emissions [13]. Figure 4 shows an EIA graph of the transportation sector dissected into CO_2 emissions by fuel consumption [13]. It can be seen from Figure 4 that gasoline and diesel are the main contributors to CO_2 emissions. Renewable fuel is a global opportunity to aid in the climate change mitigation process on a local level. Biofuel from a variety of biorenewable sources and through a variety of conversion pathways have been proven to benefit the environment [7].

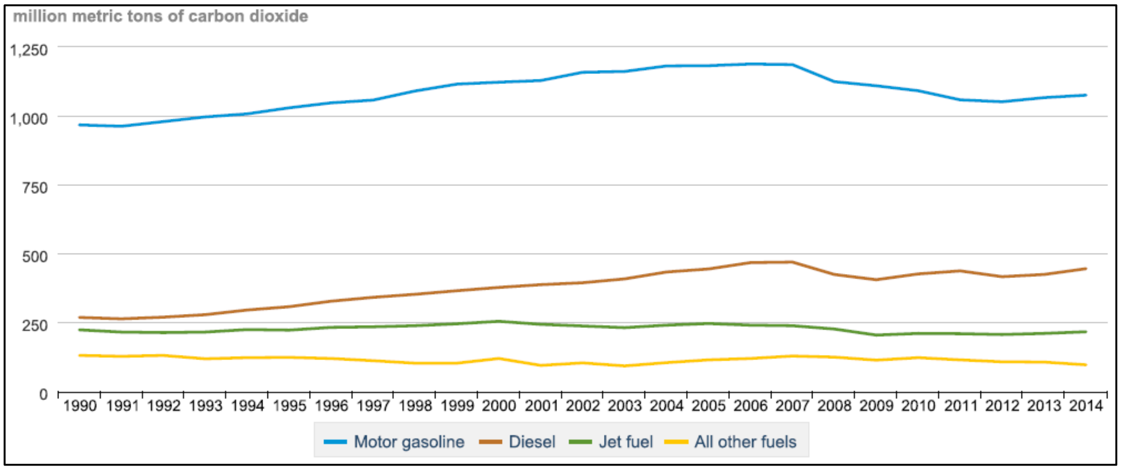


Figure 4: Transportation sector impact on CO_2 emissions from years 1990 to 2014 [13]

There are many studies that analyze the multistep process of biorenewable resource utilization. These studies include the supply chain process and logistics of harvesting, transporting and preparing the biomass to be converted into desired products via a variety of conversion and upgrading pathways. Table 2 summarizes applicable literature reviewed for these processes in a chronological order divided by stage, feedstock and technology. The following review of the literature will cover supply chain methods of preparing the biomass for bioenergy utilization, conversion of the biomass to intermediate products and upgrading techniques based on desired output.

Table 2: Literature review summary of a variety of feedstock and conversion and upgrading pathways

Agricultural Wastes	**Grasses**	**Multi-Biomass**
Supply Chain		
Sokhansanj, S (2002)	Hallam, A; Anderson, I (2001)	Ebadian, M et al. (2011)
Atchison, J; Hettenhaus, J (2004)	Kumar, A; Sokhansanj, S (2006)	
Shinners, K (2007)	Hess, J; Kenney, K (2009)	
Petrolia, D (2008)	Heaton,E; Taske, T (2010)	
Hess, J; Kenney, K (2009)	Amosson, S et al. (2010)	
Wu, M; Chiu, Y (2012)	Anex, R (2012)	
Shah, A (2013)	Hoque, M; Hart, C (2014)	
Argo, A et al. (2013)	Li, J; Li, S (2014)	
	Wu, M; Chiu, Y (2014)	
Technology Review	**Biofuel Production**	**Other**
Conversion/Upgrading		
Hamelinck, C; Faaij, A (2003)	Jones, S; Zhu, Y (2009)	Persson (2003)
Demirbas (2007)	Barta, Z; Reczey, K (2010)	Holm-Nielsen, J (2008)
Elliot (2007)	Swanson, R; ; Satirio, J (2010)	Baldwin, S; Lau, A (2009)
Braun, R; Weiland, P (2008)	Phillips, S; Tarud, J (2011)	Redman, G (2010)
Ward, A; Hobbs, P (2008)	Zhu, Y; Elliott, D (2013)	
Baldwin, S (2009)	Goellner (2013)	
Jorgensen, P (2009)	Zhu, Y; Biddy, M (2014)	
Akhtar, J; Amin, A S (2011)	Elliot, D; Biller, P (2014)	
Toor, S S; Rosendahl, L (2011)	Ou, L; Brown, R (2014)	
Hu, J; Yu, F (2012)	Boer, K; Bahri, P (2015)	

Biomass Supply Chain Logistics

Due to energy security, environmental, social and political reasons biomass is experiencing an increasing demand for utilization within the energy sector. It has been proven that biomass, if processed correctly, can provide replacements for all fossil fuel derived commodities [9], [14], [15]. The Billion Ton Update (BT2), completed by Oak Ridge National Lab (ORNL) in 2011 estimates that the US has the potential of providing 1 billion tons of biomass sustainably on an annual basis, enough biomass to theoretically displace approximately 30% of the current petroleum consumption [5]. A wide range of biomass types are available for utilization; the BT2 has identified availability of agricultural and wood wastes and energy crops. Other biomass sources such as algae and municipal solid wastes have shown feasibility of bioenergy utilization. This section will focus on the supply chain requirements of bioenergy utilization as it pertains primarily to biorenewable transportation fuels' technical and economic features.

Biomass logistical analysis is of great importance to the success of biofuel production; Sokhansanj and Turhollow have attributed feedstock costs to nearly one-third of the biofuel production costs [16]. This step of the production system has been studied for optimal performance for decades. In this study corn stover is harvested in two scenarios: 1) by means of a combination rake and shredder system followed by a round baling, 2) by means of separate shredding and raking operations followed by rectangular baling. Round bales were collected by a simple pull-type transporter with a telescopic loading arm, whereas the rectangular bales were collected by a self-propelled wagon with an automatic stacker. The final costs of simply the harvesting and collection equipment was \$21.60/tonne and \$23.60/tonne for the round baling and rectangular baling systems, respectively. The $2/tonne difference was attributed to the additional collection operations and increased capital cost of equipment.

Atchison and Hettenhaus [17] reported on a study in 2003 developing an innovative method for the corn stover supply chain. Here, corn stover has been termed the "largest underutilized crop in the US," where 250 million dry tons are produced annually. In this study collection, storage and transportation are addressed for optimization. Collection costs were summarized at a net profit back to the farmer of $22-$47/acre compared to $16-$22/acre, dependent on bushel yield, when single pass harvesting methods are used compared to multi-pass baled methods, respectively. Biomass is stored wet to increase the density, drastically decrease the storage area, increase the overall feedstock quality, decrease the overall losses of the process and to better fit the single pass harvest. This method has been proven to be viable for sugar cane bagasse but still requires demonstration and validation with corn stover. Rail transportation is proposed to decrease costs and to appeal to large processing facilities and single pass harvesting with elevated moisture contents. Although, for shorter distances and lower processing facilities, the truck is the more economic transportation method.

Shinners et al. [18] reinforces the efficiency improvements of wet corn stover harvest and storage from Atchison and Hettenhaus [17]. Wet harvest and storage resulted in less losses compared to dry harvesting and storage outdoors. Three scenarios were studied: 1) chopping, the stover was chopped, windrowed and dumped into trucks just hours after the grain was harvest, 2) wet bale collection, stover was shredded, raked and baled within an hour after grain harvesting, 3) dry bale collection, stover was allowed to sit in the field for four days, shredded, raked and baled. Leaving the stover to dry on the field for up to four days after harvesting the grain decreased ability to gather maximum tonnage, resulting in increased losses. Harvesting capacity was 26.2, 16.0 and 9.8 dry matter tonne (DMT) per hectare for stover that was chopped, baled wet and baled dry, respectively. Shinners concluded that harvesting wet stover directly after grain harvest resulted in greater harvesting rates, lower losses, higher quality biomass and a more efficient process.

A study by Petrolia [19] analyzes feedstock costs for a biomass to ethanol process. Corn stover yields, transportation distances, erosion constraints, machinery specifications, storage and densification costs are all factored into a final estimated feedstock cost. Each step of the collection process was quantified and monetary values were derived. Collection was done by two different multistep methods: 1) stover was chopped and windrowed behind the combine left to later be collected in large round bales, 2) stover was chopped and spread on the ground, a rake and shredder later came through the field to shred and rake the stover into a windrow that was be baled into large rectangular bales. Transportation was assumed to be semi-truck and costs were calculated to be $1.38 for biomass being transported a distance of 25 – 100 miles. Storage for each bale type is slightly different with round bales receiving a plastic wrap to protect from the elements and rectangular bales are not wrapped but are housed indoors. Petrolia estimates the costs for storage including the equipment, land and losses to be approximately $14 for rectangular bales and about half that for round bales. Overall feedstock costs ranged from $55/tonne to $95/tonne depending on harvesting method. After Monte Carlo simulation, 90% of feedstock costs were found to be between $68/tonne and $78/tonne.

According to the Department of Energy (DOE), for the biofuel industry to become a self-sustaining system the biomass supply logistics cannot exceed 25% of the total cost of biofuel production [20]. Hess et al. and Idaho National Lab (INL) have studied the biomass logistics of biofuel production for years and they have concluded that a “uniform-format” system would be required to process the vast amount of bulk solid biomass that would be required to displace nearly 30% of petroleum consumption as desired by the BT2 [5],[20]. The INL report proposes three different logistical methodologies: 1) Conventional Bale, which resembles the current technological practices, 2) Pioneer Uniform, which assumes the technology used in this model are near readily available for all logistics scenarios, 3) Advanced Uniform, which meets all cost requirements and supply targets but the technology is rather advanced and not currently commercially available. The overall vision of the “uniform-format” system is that many different types of biomass can be processed at appropriate depots near resource harvest location where it can then be moved on to a centralized conversion location to be upgraded and blended to final end-use specifications. This report considers both corn stover and switchgrass as biomass to be processed and delivered to the biorefinery, switchgrass will be discussed later in this section.

The Conventional Bale system is tasked to supply 800,000 tons per year (725,748 tonnes/yr) to the biorefinery. The model assumes 60,000 tons (54,431 tonnes) are lost due to operational efficiencies and a participation rate of 50% is used, resulting in a supply radius of nearly 46 miles. Stover harvest and collection includes the production and grain harvest, which incur no costs due to the assumption that they are accounted for within the grain industry, conditioning and windrowing, baling, collecting and roadsiding steps are all monetarily quantified and summed to $18.70/tonne. Losses of biomass during the harvest and collection process are quantified and included in a final harvest and collection feedstock cost or field gate cost, $23.82/tonne. Storage costs include bale handling, wrapping, losses (mechanical and biological) and any additional costs incurred to store the bales, $8.94/tonne. Truck and rail are options for transporting biomass, variations of truck and/or rail car can change the overall costs, but in general, the transportation costs follow a simple linear equation shown in Figure 4.The distance (miles) is slightly more complicated but relatively easy to obtain. The primary preprocessing biomass handling costs include: three biomass receiving steps and four preprocessing steps, grinding, dust collection and conveying. The preprocessing costs add up to $15.15/tonne, resulting in an overall biomass supply chain costs for the Conventional Bale scenarios are $61.26/tonne.

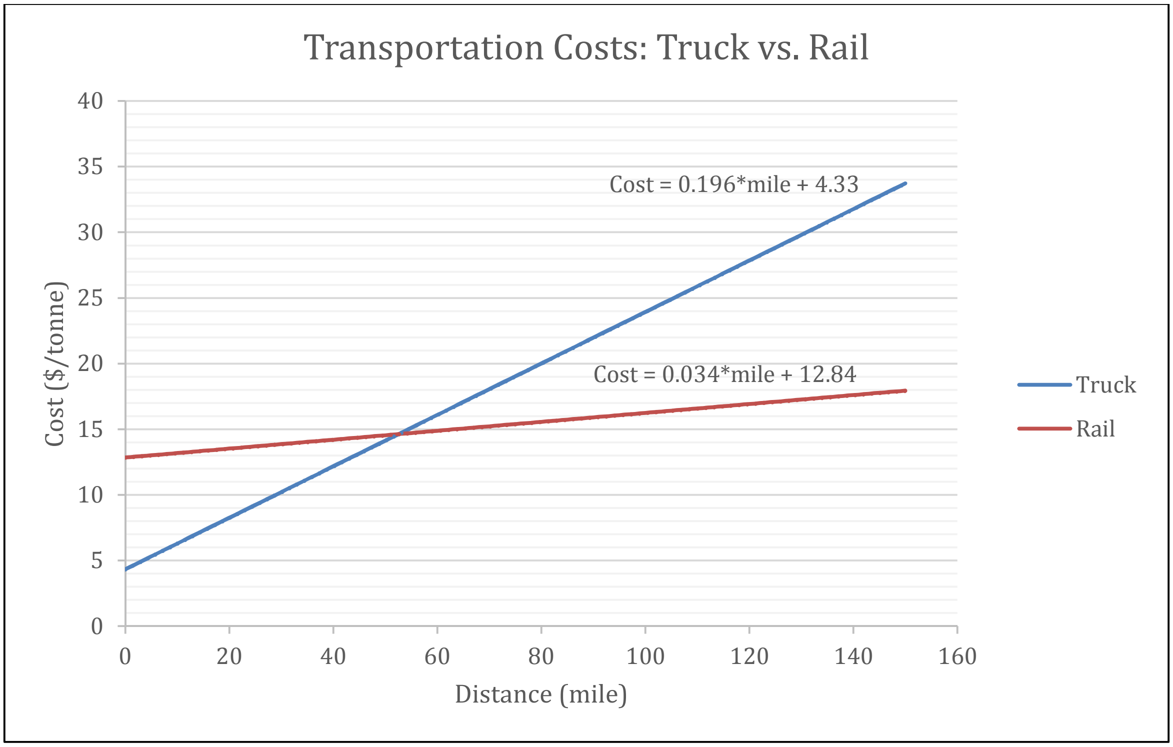


Figure 5: Transportation costs ($/tonne) of truck vs. rail as a function of distance in miles (Adapted from [16])

The Pioneer Uniform Format scenario has the same plant capacity, participation rate and supply radius. The harvest and collection process introduces single pass harvesting and a variation of bale type, round and rectangular. The single pass system slightly decreases the harvest and collection costs of rectangular bales to $22.27/tonne. This decrease is attributed to the increase in efficiency of the new equipment. Storage of the bales are done both on regular ground, as in the conventional case, and on an improved ground surface. This decreases the losses during storage, resulting in slight decrease of storage cost to $8.85/tonne. The report notes that although the improved storage surface decreases losses the, original surface would have had to incur losses of nearly 16% for this to be warranted. Transportation costs are essentially the same following the linear equation for each case. Preprocessing also followed the same steps but used more advanced and efficient handling equipment, resulting in a decrease in costs to $16.26/tonne. The overall Uniform Format feedstock costs are $60.73/tonne.

A study by Shah [21] analyzes the techno-economic analysis of corn stover supply chain to a Midwestern cellulosic biorefinery. Corn stover production requirements, supply chain operations and biomass preparations are considered for a 30 million gallon per year biorefinery. The plant gate price for the delivered stover is $122/tonne. Shah's methods are similar to those by Hess and INL, following a current technology multi-pass harvest and collection method for a near term solution eventually transitioning towards a single pass system. Shah has an elevated feedstock price, compared to Hess and INL, due to the inclusion of fuel, labor and nutrient replenishment costs in the model. Shah attributes nutrient replenishment costs to approximately 20% of the supply chain costs.

Argo et al. [22], similar to Hess et al. [20] and Shah [21], analyzed an ethanol biorefinery system by means of the uniform-format feedstock supply design. Although, Argo et al. took it a step further to account for environmental sustainability metrics in the analysis. Corn stover from Iowa and switchgrass from Georgia are analyzed for 500-10,000 tonne/day (tpd) biorefineries to find the optimal plant size for the advanced uniform-format feedstock supply system. Environmental sustainability parameters are modeled using a variety of tools: POLYSYS is used for feedstock production, Powersim System Dynamics Framework is used for the feedstock logistics, AspenPlus® is used for conversion, SimaPro is used for the life cycle analysis, and SWAT and SPARROW are used for soil water resource accounting. Plant gate feedstock costs ranged ~\$90- ~\$115/tonne for both conventional bale and advanced uniform format systems. On average, corn stover conventional bale system logistic costs accounted for 49% of the delivered feedstock cost and the other 51% was attributed to grower payments. Corresponding distances and biorefinery sizes of 15-30 miles and 500-2,000 tpd were analyzed, respectively, which accounted for approximately \$1 difference in logistics cost. Both corn stover and switchgrass were analyzed for the advanced uniform format system, where the costs delivered plant gate costs were generally, \$10-\$20/tonne higher compared to the conventional bale system. The advanced uniform format corn stover system resulted in the highest total feedstock cost with \$114.91/tonne for a plant capacity of 500-10,000 tpd, the switchgrass scenarios resulted in \$101.64/tonne and \$107.70/tonne for 500-5,000 tpd and 500-10,000 tpd, respectively.

For biofuel production systems to be sustainable water resources must be accounted for through the growing and conversion stages of the process. Water is required and accordingly appropriated for plant growth and the conversion process [22], [23]. The water needed from irrigation and process water for conversion are generally from surface and groundwater reserves and accordingly appropriated as blue water. The water that the plant uses from rainfall is appropriated as green water. Grey water is appropriated as the discharged water from fields contained fertilizer and polluted process water. Argo et al. [22] estimates each of the cases described above that blue water contributes for 4.3-7.3 gallons of water per gallon of ethanol (gal_w/gal_e) produced, green water contributes approximately 600-1,150 gal_w/gal_e produced and grey water contributes approximately 200-800 gal_w/gal_e produced. Water analysis shows that differing locations of production and conversion will affect the resources consumed.

Another water study done by Wu et al. [23] quantifies the water footprint impended on a county region in Iowa through the production of cellulosic ethanol. Similar to the Argo et al. [22]

study, water is appropriated based on the origin and how it is consumed in the process. Green water is quantified by regional precipitation data and blue and grey water are calculated based on various parameters including irrigation, irrigation losses, evapotranspiration (ET), nitrate loading and nitrate concentration. This study specialized in the ET verification and validation. ET was estimated by satellite imaging and verified by ground measurements. Grey water is dependent upon fertilizer application rates, crop rotation, crop yield, climate and land topography; thus can vary greatly in different regions around the country. Blue, green and grey water footprints are estimated based upon the above parameters. Blue water contributes 1.22-3.46 gal_w/gal_e, green water contributes 200.8-264.2 gal_w/gal_e and grey water contributes 11.6-417.7 gal_w/gal_e.

In addition to agricultural wastes, energy crops and herbaceous grasses are important resources for bioenergy utilization. Energy crops and grasses often experience higher yields than agricultural wastes. Hallam et al. [24] had analyzed the economics of producing perennial, annual and intercrop grasses. The study compared the production of switchgrass, alfalfa, reed canarygrass, big bluestem, sweet sorghum, forage sorghum and maize. The sorghums were intercropped with alfalfa and reed canarygrass. Intercropping was to maintain high yields from the sorghum crops while benefiting from good soil management from the alfalfa and switchgrass crops. Yields, tonnes per ha, were reported as follows: sweet sorghum (15.3-20.7), forage sorghum (14.6-16.7), switchgrass (8.3-15.3), big bluestem (6.4-12.4), reed canarygrass (5.5-10.3), and alfalfa (6.2-12.9). Production costs for switchgrass was $47.65/tonne, whereas the production costs for sweet and forage sorghum were $38.14/tonne and $41.81/tonne, respectively. The lower cost of production in the sorghum species was attributed to higher production yields.

Kumar and Sokhansanj [25] has recognized switchgrass as a leading crop in energy production due to relatively high yields and favorable economics of production. This study analyzes an integrated biomass supply and logistics model for the collection and transportation of switchgrass to a cellulosic biorefinery. Delivered feedstock costs ($/tonne) of a 1,814 tonne/day biorefinery for four scenarios were reported as follows: baled (44-47), loafed (37), chopped (40) and ensiled (48). An estimated $30-$36/tonne of farming costs for switchgrass are added to the delivered feedstock costs to obtain an accurate total feedstock production cost of switchgrass for cellulosic ethanol production.

Recent biomass utilization analysis expressed the need for a diversified biomass portfolio [5]. Hess et al. [20] has shown this to be an area of concern in recent INL reports on biomass logistics with scenarios for corn stover, switchgrass, and a variety of woods and wood residues. For herbaceous energy crops and grasses the supply chain system is very similar to that of agricultural residues as highlighted above. The total logistics cost are $48.82/tonne. The discrepancy in costs between switchgrass and stover has been attributed to the absence in grain handling step, increased bale density and decreased collection and storage losses.

Switchgrass, hay and alfalfa are energy crops that have shown value for bioenergy consumption, but other crops such as giant miscanthus and sweet sorghum have been gaining popularity in recent years. Heaton [26] claims that “miscanthus is the greatest biomass to date” as it is a “sterile hybrid and is unlikely to be invasive as it is unable to produce a seed.” European nations have used miscanthus for decades for combustion in power plants mainly due to its high yielding nature; southern Europe reports 4.53-9.98 tonnes/acre. In the US, yields have been demonstrated at 9.07-13.61 tonnes/acre. Miscanthus must be established vegetatively by planting live rhizomes. Heaton reports establishment as a high initial cost but it is reduced over time.

Harvesting miscanthus requires strategic planning for optimal biomass productivity. Harvesting must be done between maturity in the fall and regrowth in the spring but if harvested too early will harm subsequent plant growth and decrease overall fuel quality. Late harvest can reduce the yield by 30-50%. Optimal harvest time is late November or early December.

Hart et al. [27] builds off of Heaton's report to give a more in depth analysis for establishment of miscanthus. Miscanthus has proven ability to adapt to a variety of soil conditions but it is best suited for soil that ideal for corn production. Even with ideal soil types a costly and extensive establishment period is required. The year before the plant is established, termed pre-establishment, requires the planting of an herbicide tolerant crop, herbicide and field preparation operations such as brush mowing, disking and soil finishing, totaling $445 per acre. The following year, the establishment step requires additional field preparation work, fertilizer and rhizome planting. Additional fertilizer and nutrient application is recommended similar to corn. Rhizomes cost $0.09, with 7,000 to be planted with a 75% survival rate. No harvestable yield occurs in the first year, so harvesting cost is $0. The total cost of production in the establishment year is $1,132. Beginning year two, another herbicide application is recommended along with basic fertilizer application. Harvesting operations are mowing, windrowing, baling and moving to storage. Reduced yields are expected for the first year harvest. Total year two production costs are $275 per acre. Establishment is expected to be completed in year two, thus normal operations will commence in year three and continue for the life of the stand. Normal miscanthus production costs will include machinery, land rent, harvesting costs totaling $400 per acre.

A study by Wu et al. [28] summarizes the analysis of hydrologic model for the production of ethanol from miscanthus and switchgrass. This model estimates the blue, green and grey water, similar to the corn stover method described above. Multiple scenarios were analyzed for a variety of year and feedstock cost assumption comparisons. On average the green water footprint ranged from 1,091-1,170 liters of water per liter of ethanol (L_w/L_e). Grey water footprint depends on fertilizer application, soil quality and crop yield; the national average is estimated to range from 27-33 L_w/L_e. Since miscanthus and switchgrass do not consume irrigation water, blue water is solely allocated to biorefinery process water use. Miscanthus and switchgrass derived ethanol consumes 2.65-5.40 L_w/L_e. Wu et al. believes it is worthy to note that the implications placed on water resources from biofuel production can be significant. For a 50 million gallon per year biorefinery, 250 million gallons of ground water would be required for the process [28]. This much fresh ground water can have a significant impact on the local water supply and requires further investigation.

Another herbaceous grass grown in the Midwest is sweet sorghum. Sweet sorghum is a high yielding sugary grass from the vast sorghum family. Sweet sorghum closely resembles sugar cane and has been used for similar applications in the food industry as well as in the energy industry. A study by Amosson et al. [29] has identified sweet sorghum as a potential biofuel feedstock due to its high yields and easily fermentable sugars. This is an attractive crop for conventional ethanol production due to high sugar content and the ability to utilize the waste product, bagasse as a lignocellulosic feedstock. Amosson et al. estimates the cost of ethanol production from sweet sorghum in Texas that was only rain fed and sweet sorghum that was irrigated. The rain only scenario produced 475 gallons of ethanol per acre of biomass, both sugar and bagasse, with an estimated cost of $24.56 per wet tonne and a yield of 10.16 wet tonnes per acre. The irrigated scenario produced a total of 1150 gallons of ethanol per acre with an estimated cost of $22.30 per wet tonne and a yield of 26.1 wet tonnes per acre. Fertilizer and harvesting costs accounted for the largest components in each scenario, 30-34% and 25-28%, respectively. Irrigation only contributing to 12% of the final production cost for the respective scenario. It was concluded that all scenarios resulted in ethanol being produced for under $1/gallon.

Anex [30] studied the production costs of sweet sorghum in Iowa to compare with results others have compiled in warmer, dryer climates. Sorghum has had limited use in northern, cooler climates primarily due to the short harvest window and severe post-harvest requirements. Anex evaluated pre-harvest operational costs for scenarios that incorporated multiple different harvesters on owned and rented land. Fermentable carbohydrates were closely monitored throughout the process and it was determined that when harvesting technology included mobile sorghum juice extraction harvesting costs were 1.5-2.5 times greater than basic biomass harvesting scenarios. Anex concluded from this preliminary study that the fermentable carbohydrates for sweet sorghum harvesting are not attractively comparable to fermentable carbohydrate costs of corn grain. Thus, sweet sorghum is better utilized in other ways, possibly from the waste residue, bagasse.

Conversion and Upgrading

Raw biomass, in most cases is unsuitable for consumer use, thus requiring some sort of processing or conversion. Historically, biomass conversion has been done using a variety of techniques. Products of biomass conversion include: heat, cooking, electricity, transportation fuels and commodity chemicals. Conversion processes are strategically chosen to achieve desired products. Generically, conversion processes are divided into two categories: thermochemical and biochemical. Thermochemical conversion is a pathway that uses heat, pressure and catalysts to decompose the organic material for better consumer use. Biochemical conversion, for producing products that achieve similar goals, use enzymes and microorganisms as the means of conversion [31]. Both pathways have been employed for centuries, although not for the industrial purposes they are being asked of today. Today's application of thermochemical processing is being asked to convert biomass into heat and power through combustion; synthesis gases for heat, power, fuels and chemicals via gasification; and pyrolysis and hydrothermal liquefaction for transportation fuels, commodity chemicals and agricultural amendments. Few of the technologies listed above are commercially providing products or services to the public. However, biochemical processing of biomass has been demonstrated at a commercial scale in the late 20th Century. Biochemical conversion pathways primarily include hydrolysis, fermentation and anaerobic digestion. Products from these pathways include a variety of alcohols, gases and solids. Biochemical conversion of biomass has established itself as a viable option for commercial use and industrial availability, but due to several of thermochemical conversion's attractive attributes much research has gone into commercializing this pathway.

This study employs existing literature to characterize the conversion and upgrading steps. There are several review articles on thermochemical conversion [31], [9], [14], [15], hydrothermal liquefaction [32], [33], [34], [35], anaerobic digestion [36], [37], [38], Fischer-Tropsch synthesis [39], [40], [41] and methanol-to-gasoline [41],[42], [43] technologies. The review below will highlight the most relevant articles to this study.

A major disadvantage to thermochemical processing is the need for a dry feedstock. Hydrothermal liquefaction (HTL) makes use of all kinds of feedstocks, wet or dry, as it decomposes the biomass within a slurry of water at elevated temperatures and pressures. Compared to pyrolysis, the temperatures are slightly lower, in the 227-550 ºC range, with pressures generally 4-22 MPa [24], while still producing similar products. Akhtar et al. [32] provides optimal operating conditions for the production of HTL products based on a review of decomposition mechanisms that are assumed to be present in HTL. It is concluded that temperature is the most influential parameter affecting oil product yield, claiming that an optimal temperature range should be between 300-374 ºC. Temperatures above 350 ºC produce more gaseous product, thus inhibiting oil formation.

Traditional HTL systems were done on batch type systems [35], however continuous flow HTL systems have been studied for quite some time. Lawrence Berkley and the Albany Biomass Liquefaction Experimental Facility began work with continuous flow HTL systems in the 1970s-1980s [33]. Although, the idea of continuous flow HTL is not new, there have been many complications with scaling the process towards commercialization. In a study done recently, Elliot [33] aims to demonstrate the scaling process of this technology. Elliot highlights the advantages, disadvantages and difficulties that arise when pilot/demonstration scale is achieved. The conclusion from this work is that the technology shows great potential for commercialization with many feedstocks having been demonstrated but there are still challenges that need to be addressed for the technology to be market ready.

Recent literature focusses around algae or algae derivatives as the feedstock for HTL [44], [45], [46]. A study by Ou et al. [44] simulates a 2000 tonne/day (tpd) facility for processing defatted microalgae via HTL and hydroprocessing. It was concluded from the analysis that microalgae based HTL products were competitive with petroleum based products at an estimated $2.57/gallon. This is significant, as algae is high moisture feedstock and would require large amounts of preprocessing if to be converted by other thermochemical pathways.

A study by Zhu et al. [34] analyzes the economics of hydrothermal processing of woody biomass at a 2000 tpd facility as well. The facility was assumed to produce 42.9 million gallons of upgraded transportation fuel product for a cost of $4.44/gallon. At this cost, the process is not as competitive with petroleum transportation products. A secondary scenario was simulated based on improved technology, more efficient processing and using distributed processing facilities, and this scenario was capable of producing 69.9 million gallons for $2.42/gallon. This is significant because it shows the robustness of the conversion technology and the promising results that are derived from these analyses.

Anaerobic digestion (AD) is a biochemical conversion process that uses microorganisms in an oxygen free environment to break down organic material to produce a gaseous primary product. The gaseous product, termed biogas, is a valuable product with respect to the future of bioenergy. Biogas can replace fossil fuel sources in heating, chemical and power production and transportation fuel applications [47]. If cleaned properly to a primarily methane stream, the biogas can resemble natural gas and be integrated into the natural gas distribution grid [48]. Biogas resembling natural gas, composed almost entirely of methane (CH_4) can be a very valuable feedstock to a variety of commodity production processes.

AD is a rather complex process that can be divided into four main phases: hydrolysis, acidogenosis, acetogenosis and methanogenosis [47]. The hydrolysis step breaks down complex organic polymers to monomeric compounds easily used for sources of energy [48]. Acidogenosis, uses a host of microorganisms to ferment the monomeric organic compounds to low weight compounds (CO_2, H_2, and other organic acids) that are eventually turned into acetic acid through the acetogenosis step. The last step is methanogenosis, where the hydrogen and acetic acid is converted into CH_4, CO_2 and trace amounts of other compounds (H_2S, H_2) [37].

Digesters have been used around the world quite extensively, Redman [36] reports that over 8,000 are employed in Germany and approximately 30 million in China. These digester range in size and purpose, from small household digestion units for food waste to medium single farm livestock waste digesters to larger multi farm digester. Redman describes different scenarios in Europe where anaerobic digesters are used at different scales and for different purposes. A livestock farm with 220 head of cow supplies a digester with 13.2 m^3/day of manure, the residence time within the reactor is approximately 20 days and the gas product is then used to drive a turbine capable of producing 75 MWh_e per year. Two other scenarios are highlighted as central facilities with multiple farmers seen as the owners, operators and suppliers. These central plants range in plant rate from 420-547 m3/day and produce 4.8 -5.7 million m^3 per year. The biogas is either sold or used to run a turbine averaging 2037 kW electricity and 2600 kW thermal per day.

A study by Baldwin [37] reviews the technology of anaerobic digestion as well develops a calculator to aid in the economics of digester type and capacity. When designing a digester, it is important that the design is related to the material being digested and the desired output quality. In this study, a wide variety of feedstock yields (m^3/kg) are highlighted: livestock manure (25-55%), grass silage (56%) and corn silage (65%). Multiple digester types are examined but the continuous stirred tank reactor (CSTR) and the mixed plug-flow reactor

(MPFR) are chosen for further analysis and cases studies. Baldwin estimates the cost of each reactor configuration based on the electricity generation capacity of the biogas produced. Correlations are established based on data from experimental AD performance. Both the CSTR and the MPFR are chosen for further analysis with a feedstock mixture of cow manure and food waste. It was determined that the MPFR was the more economic choice where production costs are $0.09 per kWh.

Municipal solid waste (MSW) and livestock manure are used as feedstocks for anaerobic digestion in a study by Kieffer [48]. The biogas produced from this process is then used for upgrading to Fischer-Tropsch (FT) transportation liquids and/or used for electricity generation. Multiple integration scenarios are examine to affect the overall economics of the system. The base scenario is integrating 10% biogas based methane or renewable natural gas (RNG) into the upgrading and processing facilities, this resulted in negative net present values (NPV) for each scenario. Kieffer attributes the negative NPVs to the difficulty with scaling down from a traditional FT facility and the state of technology of the upgrading requirement process. For MSW AD the biogas selling price is $35/MMBTU at the 10% integration level but if that integration percentage is increased the cost could decrease to between $7 and $9 per MMBTU. It was determined via sensitivity analysis the NPV will rise drastically with the level of RNG integration into the plants and will decrease drastically with an increase in natural gas price.

Gaseous product upgrading to more usable consumer products has been proven for decades, dating back to World War II. FT synthesis is one of these technologies that converts synthesis gas (syngas), composed of carbon dioxide and hydrogen into a diverse range of hydrocarbon chemicals [48]. Raw syngas is often impure and requires cleaning and reforming before entering in the FT reactor for fuel synthesis. The raw syngas is purified to a primarily methane product (~97%) where it then goes through a reforming step via partial oxidation, steam methane reforming or autothermal reforming to convert the methane to the desired ratios of hydrogen and carbon monoxide. Catalytic conversion at varying operating conditions result in desired product formation.

A study by Swanson et al. [11] analyzes the gasification and FT synthesis of corn stover for transportation fuels and an electricity co-product. A 2000 tpd facility is analyzed for an n^{th} plant scenario study. Total capital investment is expected to range from \$500-\$650 MM with product values ranging from \$4-\$5/gallon. The capital investment is reported to be slightly higher than other similar studies. This has been attributed to conservative assumptions of the gasification conversion and FT synthesis current technology and feedstock costs of \$75/tonne. It is concluded that optimization of the FT synthesis will aid in decreasing capital costs and product values.

Goellner et al. [39] examines the economics of converting natural gas to liquids (GTL) via FT synthesis. This study builds off of recent technological demonstrations through GTL plants in operation in Qatar and South Africa. A 50,000 barrel/day (bbl/day) facility is modeled in this study to result in an \$86,000/bbl capital cost. FT synthesis comprised of 14%, upgrades and refinement comprised of 20% and operational costs comprised of 22% of the total capital costs. This estimated capital investment has been compared with current GTL facilities and Goellner concludes that this is a comparable and favorable analysis compared to other similar large facilities. Water used in the production process is analyzed and reported. This study assumes two sources of water are used: ground water and surface water. Ground water is fresh water from aquifers, surface water is publicly treated water. It is assumed that for both gasoline and diesel that each of these sources of water is responsible for 50% of the water required for the process. For every gallon of gasoline, 18 gallons of water are required. For ever gallon of diesel, 9.25 gallons of water are required.

Another upgrading technology utilized for GTL conversion is methanol-to-gasoline (MTG), first developed my Exxon Mobil. MTG converts syngas to methanol and ultimately to gasoline with a co-product of liquefied petroleum gas. A study is done by Jones et al. [43] for the gasification and gasoline production of wood chips via MTG. The product value ranges from $3-$4/gallon, suggesting that this technology would not be feasible unless oil prices are less than $100/barrel. Jones projects that capital costs can be decreased with advances in syngas clean up technology, as well as consolidated fuel synthesis steps.

A study done by Phillips et al. [42] on the gasification and MTG upgrading of wood chips analyzes the economics of a 2000 tpd facility. This process yields 60.74 gallons of gasoline per tonne of biomass and 10.25 gallons/tonne of liquefied petroleum gas. This plant costs $19 MM in capital resulting in a product value of $1.93/gallon gasoline and $1.53/gallon of liquefied petroleum gas. The feedstock cost at $55.89/tonne contributes the greatest to the minimum fuel selling price at $0.80. The reforming step is the second highest contributor at approximately $0.19. Water is used as a reactant, fluidizing agent and a cooling medium. Air cooled operations were utilized when applicable to decrease process water use. A majority of the water is used for cooling tower applications, two scenarios are estimated. A traditional cooling tower with water usage as the cooling medium requires 6.5 gallons of fresh water for every gallon of gasoline produced. A dry cooling tower, one that does not use water as the cooling medium, is analyzed for insight into an advanced technology that will cut back on the water use for the cooling tower or omit it altogether. For the scenario with the dry cooling tower only 2.5 gallons of fresh process water is required for every gallon of gasoline produced.

CHAPTER III: METHODS

System Design

This study describes the techno-economics of biofuel production from wet feedstock via HTL and AD conversion and subsequent upgrading through hydroprocessing, Fischer-Tropsch synthesis and methanol-to-gasoline. The scope of the analysis includes biomass cultivation, storage, transportation, conversion and upgrading. Harvest scenarios include both multi-pass and single pass. Storage scenarios include both dry and wet storage. Conversion scenarios include small-scale (200 tonne/day) and large scale (2000 tonne/day) conversion. In total, 96 pathways to biofuel production are compared. All scenarios generate gasoline and diesel range hydrocarbons representing near-final products. Figure 6 shows a process flow diagram of the entire system.

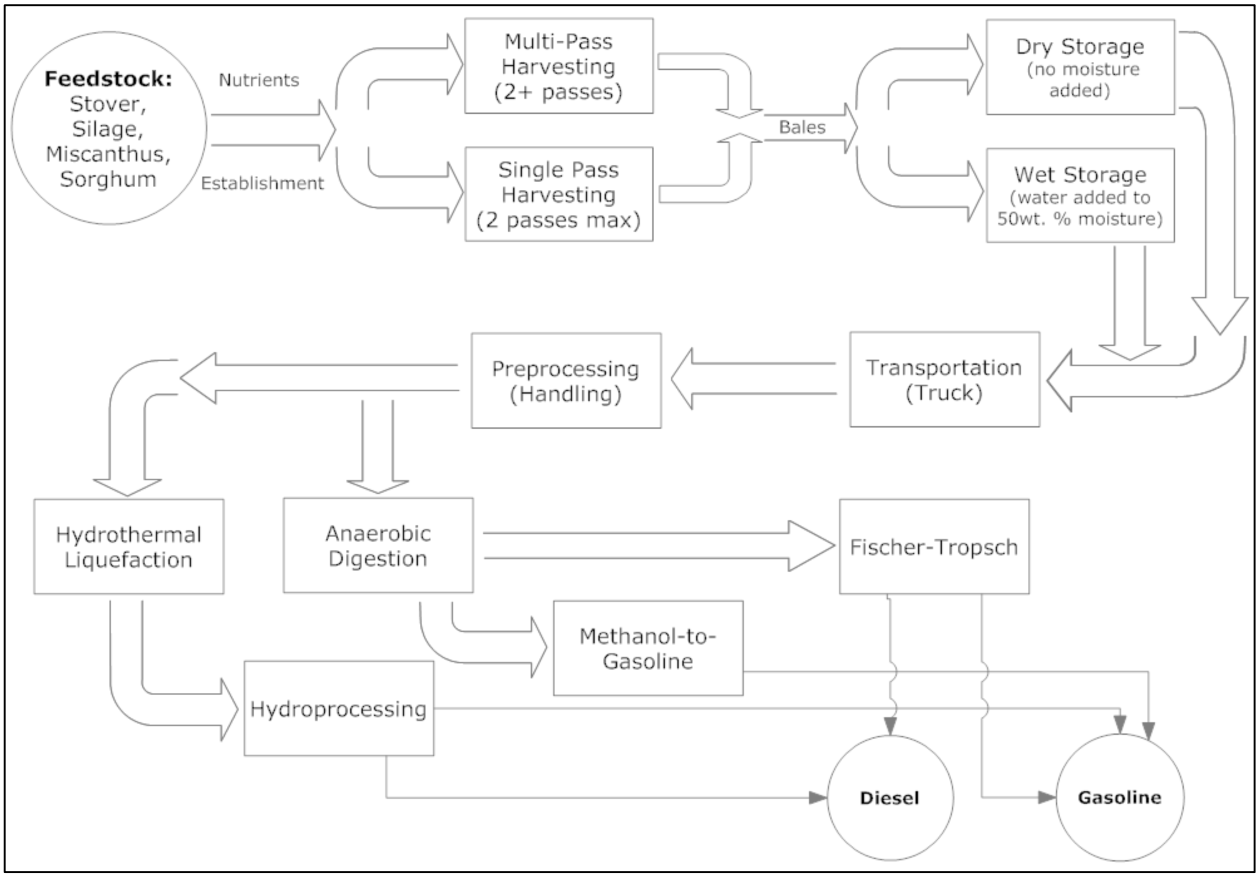


Figure 6: Overall system process flow diagram for converting high moisture feedstock into biofuels

Biomass Supply Chain Logistics

Feedstock

This study has chosen to utilize the abundance of agricultural wastes and energy crops within the Midwestern region by means of corn stover, corn silage, giant miscanthus and sweet sorghum. Corn stover and corn silage generally yields 3.1 tonnes per acre and 4.99 tonnes per acre and are valuable waste resources from the large corn grain growing market [49], [5], [50]. Giant miscanthus has been gaining increasing attention from the bioenergy community due to its high yields and low operational and maintenance costs after establishment [24]. Sweet sorghum is a versatile biofuel feedstock that has been demonstrated that both the primary crop, sugar content, as well as the waste stream, bagasse can be significant resources for bioenergy utilization [29]. Miscanthus and sorghum are not currently being produced on large quantities of Iowa land, but increasing knowledge of the crops has farmers, researchers and investors interested.

Pre-harvest costs can have a significant effect on the opportunity cost of rotating crops or planting new. Included in the pre-harvest costs are the establishment costs of new crops on the land. This model evaluates the establishment cost required to acclimate a crop to a new environment and increase the growing potential. It is assumed that the land is to be repurposed from corn to energy crops for the miscanthus and sorghum scenarios. An establishment estimator developed by researchers at Iowa State was used for estimating the establishment costs for each of the feedstocks, this can be seen in the APPENDIX [27], [51]. A negative cost (i.e. net profit) is seen for the establishment cost for corn stover due to a 3% increase in corn yield that has been reported from harvesting a percentage of the stover [52]. The cost to ensile the corn plant is assumed to take the place of the establishment costs for the corn silage scenario, an ensilage cost estimation tool can be seen in the APPENDIX [51]. Table 3 shows a summary of the basic needs of each feedstock including: assumed moisture content, yield, establishment costs and nutrient replenishment rates and costs.

Table 3: General feedstock information summary

Feedstock	Harvested Biomass (tonne/acre)	Moisture Content (wt. %)	Establishment Costs ($/tonne)	Nutrient Removal Rate (kg/tonne)		
				Nitrogen ($1.28/kg)	Phosphorus ($1.06/kg)	Potassium ($1.10/kg)
Stover	3.11	15	-1.43	7.7	2.5	12.5
Silage	4.99	50	21.34	7.7	2.5	12.5
Miscanthus	12.5	20	37.27	4.5	0.75	4
Sorghum	14.5	65	17.88	8	7	7

Cultivation

Delivered feedstock costs to the biorefinery is proving to be a vital factor in the sustainable production biofuels. The overall feedstock costs will include the pre-harvest costs shown in Table 3 as well as the costs of harvesting, storing, transporting and preprocessing the biomass before it arrives at the biorefinery for conversion and upgrading. A report by Idaho National Lab expresses the importance of the feedstock cost not exceeding $80/tonne for production to be sustainable [20]. This study follows this design consideration in attempt to provide sustainability to the biofuel production beginning with the supply chain process.

Harvest and collection methodology follows that described in literature from INL [20]. The harvesting and collection process is divided into two different scenarios; one is multiple pass harvest where the gain and residue are collected in separate passes through field, the other is a single pass harvest where the grain and biomass are collected simultaneously on the same passage through the field. Operationally, there is no difference in costs of the two scenarios, although, capital costs are much higher for the single pass method due to more advanced equipment required when collecting grain and biomass simultaneously. For energy crop harvest, where there is no grain to be harvested, the methodology follows the assumption that the grain collection step is omitted, thus grain harvesters are replaced by forage harvesters. Multi-pass perennial grass harvesting still requires multiple passes through the field to chop, windrow, bale and collect the biomass. Table 4 estimates the harvest and collection steps for each feedstock on a normalized per tonne basis.

Table 4: Situational feedstock harvest and collection summary in $/tonne

($/tonne)	**Stover**	**Silage**	**Miscanthus**	**Sorghum**
Condition	4.59	2.86	1.14	0.98
Baling	12.03	7.49	2.99	2.58
Collection	2.08	1.30	0.52	0.45
Losses	5.13	3.19	1.27	1.10
Total	23.82	14.83	5.92	5.10

Biorefineries prefer to have a 10-20 day supply of biomass stored on site [17], thus requires consideration of storage of biomass in conditions that mitigate mechanical or microbial losses. This study examines two types of storage techniques; 1) is dry storage by means of baling and stacking, following the INL report's methods [20], 2) is wet storage by means of a biomass slurry of 20 wt% solids content and piling the wet biomass upon itself, this scenarios follows the methodology of Hettenhaus [17]. For both scenarios land preparation is needed to minimize losses. Unique and individualized costs are incurred for each scenario as well. Dry storage costs include those of the loader, wrapper, any costs associated with storing the biomass like insurance, overhead, facility costs, etc. and all dry matter losses that occur during the storage process. Wet storage costs include the costs of the loader, facility costs, water, collection and any losses. A summary for dry and wet storage methods can be viewed in Table 5. Wet storage is considered for an increased efficiency of 98%, to that of dry storage of up to 95%. Wet storage losses are attributed to water soluble material. The storage area needed to store the same quantity of biomass is considerably less (1/10). Wet storage of biomass fits the single pass harvest scenario better than dry storage [17], [20].

Transporting raw biomass can be a complicated issue to find an optimal solution. Biomass in general has a relatively low energy density (15-17 MJ/kg) compared to coal (20-30 MJ/kg) and petroleum (40-50 MJ/kg); thus it can be rather costly and cumbersome to transport biomass long distances [53]. The cost to transport biomass from field to processing facility is a function of distance, weight, capacity, density, and route to facility. In this study, truck is used for transportation due to the biorefinery size, transport distance and economics; transportation cost is simplified to a linear equation from literature [20], [54]. Equations (1) and (2) show how the transportation costs are calculated.

$$Truck = 0.196 \times Distance + 4.33 \tag{1}$$

$$Distance = \frac{2}{3} \times \tau \times \sqrt{\frac{F}{Y \times f \times \pi}} \tag{2}$$

Where:

$\boldsymbol{\tau}$: ratio of actual distance traveled to that of a straight line distance to the plant, tortuosity

F: the tonnes of feedstock delivered annually to the plant

Y: annual yield of feedstock in tonnes/acre

$\boldsymbol{f}$: fraction of acreage around the plant devoted to biofuel feedstock production

Biomass, from the field, is often times not suitable for processing and conversion immediately upon arriving at the processing facility. Preprocessing steps are employed in many situations that format the biomass properly for specific conversion processes. Preprocessing steps include many handling steps including receiving, loading, queuing, moisture adaptation, size reduction and cleaning. For most thermochemical conversion processes, moisture content is recommended to be below 10 wt% and particle size is recommended to be in the range of 2-6 mm [11]. For biochemical conversion processes, moisture content is recommended to be below 20 wt% and the particle size is recommended to be in the range of 6-19 mm [11]. This study assumes no moisture adaptation or size reduction steps are taken during the preprocessing stage. These assumptions are made to omit the costly and energy intensive steps from the process simulation in attempt to positively affect the economics for biofuel production. Since both HTL and AD conversion pathways do not strictly follow these moisture recommendations for their respective category, these are possible assumptions. Table 5 shows the preprocessing step costs combined with storage costs associated with this model.

Table 5: Dry (no moisture added) and wet (moisture added) storage and handling costs in $/tonne

Dry	**$/tonne**	**Wet**	**$/tonne**
Loader	1.00	**Loader**	2.04
Wrapper	6.24	**Facility**	0.04
Facility	0.11	**Water**	0.06
Losses	1.59	**Collection**	2.08
Truck Receiving	0.41	**Truck Receiving**	0.41
Loader Receiving	0.93	**Loader Receiving**	0.93
Loader Operation	0.84	**Loader Operation**	0.84
Dust Collection	1.94	**Dust Collection**	1.94
Feed Conversion	0.84	**Feed Conversion**	0.84
Total	**13.89**		**4.22**

For biofuel production systems to be sustainable, water resources must be accounted for throughout the growing and conversion stages of the process. Water is accounted for based on literature [22], [23], [55] and validated based the online Argonne National Lab water assessment tool [56]. Water accounting is divided into three categories: blue, green and grey water. Blue water is ground and surface water used for irrigation and biorefinery process water. Green water is water that is from rainfall attributed to plant growth. Grey water is the virtual quantity needed to assimilate the nutrient and pollutant loading from the field water runoff to meet regional streams and rivers water standards. Climate data was used with national and regional crop and irrigation records are to estimate the spatial growing parameters to estimate water needs and uses. Feedstock production water appropriation is ultimately a complex problem with many factors needing to be accounted for, including: crop yield, crop land, percentage of irrigated land, temperature, precipitation, evapotranspiration rates, etc… This can be simplified to the water requirement from a specific crop is equal to net water gain from irrigation and rainfall minus the losses from the process attributed to field conveyance, withdrawal and evapotranspiration. Feedstock production grey water estimation incorporates fertilizer data and stream nitrate levels for each feedstock in each region [23]. A summary of the parameters needed to estimate water footprints from biofuel production is shown in Table 6.

Table 6: Feedstock production water footprint parameters (ET: evapotranspiration)

Feedstock	Water Required (mm)	Land Irrigated (%)	Precipitation (cm)	ET (mm/d)	Nitrogen Fertilizer Used (kg)
Corn	400-650	2.0 / 0.7	116.08	3.56	7.7
Miscanthus	500	2.0 / 0.7	116.08	3.56	4.5
Sorghum	300-380	2.0 / 0.7	116.08	3.56	8

Feedstock water requirements are best described as the depth of water needed to meet the water lost through evapotranspiration. The most reliable method of estimating the water requirement is through the PENMAN method. A simpler method has been provided in the Civil Engineer's Reference Book (CERB) (4th Edition) [55]. This method, shown in Equation (3), uses climate data, temperature and daytime hours to estimate the water requirement. Gross irrigation requirements, Equation (4), can be calculated from water requirement, effective rainfall and irrigation field application efficiency, provided in the CERB [55]. Irrigation losses through conveyance and application can be attributed to the difference of total irrigation requirements at the head of the system, Equation (5), and the gross irrigation requirements.

$$ET_o = (0.46 \times T_m + 8) \times k \times p \tag{3}$$

$$I_{gross} = (ET_o - R_e)/E_a \tag{4}$$

$$I_s = I_{gross}/(E_d \times E_f) \tag{5}$$

Where:

ET_o: water requirement (mm)

T_m: mean monthly temperature (°C)

k: crop monthly coefficient, varies based on maturity of crop

p: monthly percentage of annual daytime hours

I_{gross}: gross irrigation (mm)

R_e: effective precipitation (mm)

E_a: irrigation field application efficiency

E_d: distribution efficiency

E_f: field canal efficiency

Water is commonly measured in mm per m^2 per hr (mm m^{-2} h^{-1}), or simply the depth of water applied to a given area in one hour. Volumetric quantities are now attainable given that 1 mm of rainfall is equivalent to 1 L/m^2. Green water is attributed to the difference in water required for plant growth and gross irrigation water supplied to the plant. Blue water is the lost irrigation water due to conveyance, distribution and application. Although, due to adequate amounts of rainfall every year, very little land devoted to crop production is irrigated; Corn Belt (~2%) [57] and Iowa (0.7%) [23].

The grey water footprint is quantified by the amount of nitrogen applied to the field, as specified by the biomass requirements, the national standard set by the EPA for water to be in streams and rivers and the base concentration of nitrogen in streams and rivers for the region. The EPA standard was provided in literature [23] and the local stream nitrogen concentration level was found on an interactive model from the Iowa USGS [63].

Conversion and Upgrading

Raw biomass, in most cases is unsuitable for consumer use, thus requiring some sort of processing or conversion. Historically, biomass conversion has been done using a variety of techniques. Products of biomass conversion include: heat, cooking, electricity, transportation fuels and commodity chemicals. Conversion processes are strategically chosen to achieve desired products. Generically, conversion processes are divided into two categories: thermochemical and biochemical. Thermochemical conversion is a pathway that uses heat, pressure and catalysts to decompose the organic material for better consumer use. Biochemical conversion, for producing products that achieve similar goals, use enzymes and microorganisms as the means of conversion [31]. Biochemical conversion of biomass has established itself as a viable option for commercial use and industrial availability but due to several of thermochemical conversion's attractive product composition much research has gone into commercializing this pathway. There are two conversion technologies that are modeled in this analysis that have the ability to convert high moisture feedstocks: hydrothermal liquefaction and anaerobic digestion. There is limited reliable information available on HTL and AD yields for a variety of feedstock. This is due to significant differences in experimental conditions and feedstock characteristics reported in public studies.

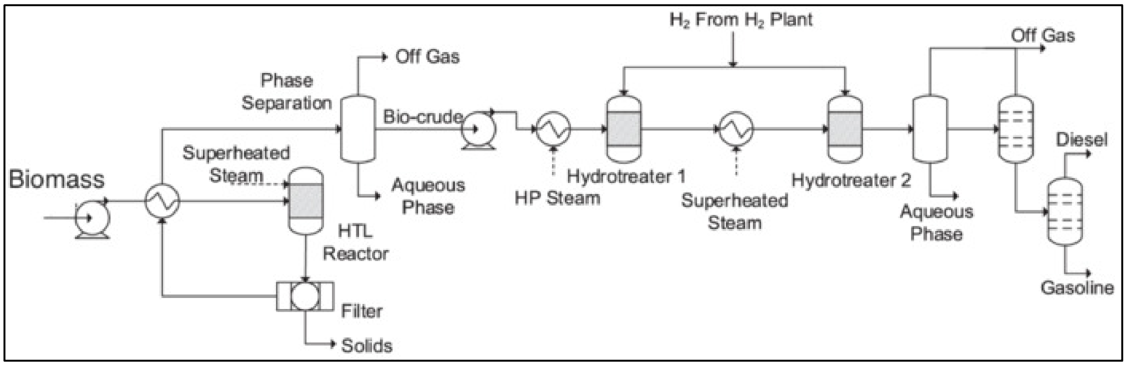


Figure 7: Biomass hydrothermal liquefaction (HTL) and hydroprocessing to gasoline and diesel [44]

This study follows the HTL and hydroprocessing system parameters, operating conditions and process assumptions of Ou et al. [44] and Akhtar et al. . The primary product, bio-crude, yields used for this study are 33-36 wt. % with hydroprocessing yields of 30.24% and 38.72% for gasoline and diesel, respectively. The hydroprocessing requires a two stage conditioning step for the upgrading g process as seen in Figure 7. Table 7 displays operating conditions for the HTL and hydroprocessing steps. Costs are calculated based on capital and operating expenditures. These include capital, feedstock costs, natural gas, electricity and utilities, catalyst and chemical usage and waste disposal, a summary of the 2000 tpd scenario capital and operating costs for HTL is shown in Table 9 and Table 10.

Table 7: HTL and Hydroprocessing Operating Parameters

COMPONENT	PARAMETER
CONVERSION TEMPERATURE	350 °C
CONVERSION PRESSURE	18 MPa
CONVERSION RESIDENCE TIME	30 min
BOILER WATER CONSUMPTION	323 tonne/day
COOLING WATER CONSUMPTION	730 tonne/day
BIO-CRUDE YEILD	0.33-0.36 wt.%

Anaerobic digestion is a biochemical process using microorganisms to convert organic material into a gaseous fuel intermediate. It has most commonly been used to process organic waste streams from food waste streams, livestock operations and wastewater treatment facilities [48]. Reactor configuration and operating conditions for this study are decided upon the AD economic calculator developed by Baldwin et al. [37]. Two reactor configurations were analyzed: a continuous stirred tank reactor (CSTR) and mixed plug-flow reactor (MPFR). Reactor sizing and capital investments are estimated based on AD methane yields and scaled estimates of both the AD process and the cleanup and upgrading required to improve the quality of the biogas to pipeline natural gas quality [58], [59]. AD methane yields are used from a Braun et al. [60] IEA report, in accordance with biogas composition [61] to calculate the power generating capacity to aid in sizing and cost estimate efforts. The MPFR configuration was determined to provide the best attributes for continuous operation, thus was chosen for further analysis. Table 8 shows the methane yield per feedstock and the capital cost for the reactors, it assumed that operating costs be 5% of capital costs.

Table 8: Anaerobic Digestion (AD) capital costs for continually stirred tank reactor (CSTR) and mixed plug-flow reactor (MPFR) based on methane yield from herbaceous feedstock [37], [60], [62]

	AD Methane Yield (m^3/tonne)	**MPFR**	
Corn Stover	250	**Capital Costs ($MM)**	
Corn Silage	250	117.8	
Miscanthus	198.5	**Operating Costs ($MM)**	**Normalized Op. Costs ($/tonne)**
Sorghum	333.5	5.89	8.96

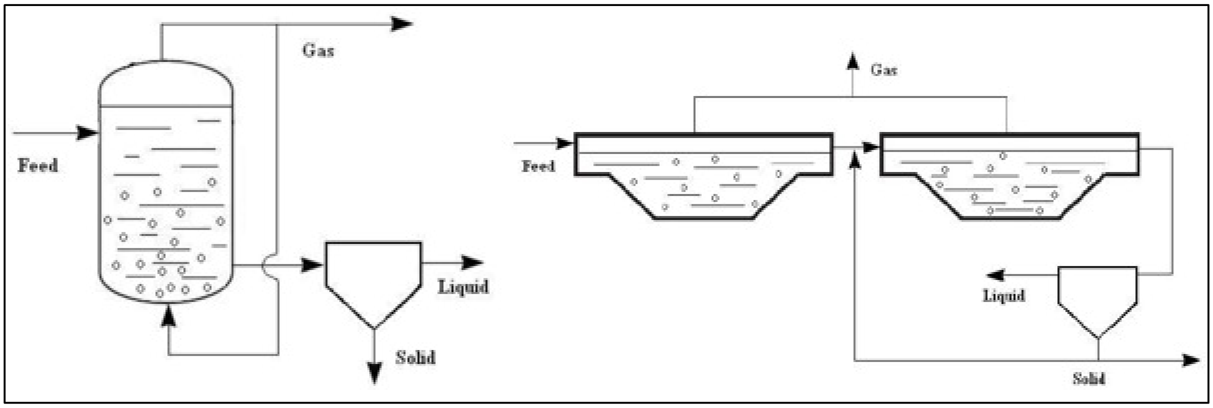


Figure 8: *Anaerobic Digestion (AD) reactors, continuous stirred tank reactor (CSTR), left, and mixed plug-flow reactor (MPFR), right* [37]

The biogas is then cleaned to +97% methane before entering the upgrading stage. Methanol-to-gasoline is one of the biogas upgrading scenario which utilizes a technique developed by Exxon Mobil in the 1970s [42]. This study follows the process considerations of a 2011 MTG report from the National Renewable Energy Lab (NREL) [42]. The MTG process converts syngas, biogas or methane to methanol via a methanol synthesis step, followed by a conditioning step that results in a mixture that is 96% methanol with the rest being CO_2 and H_2O. The crude methanol intermediate is then reacted over a zeolite catalyst for gasoline conversion where it is then sent for separation. The finished fuel products comprise of 82 wt. % gasoline, 10 wt. % liquefied petroleum gas and 8 wt. % fuel gas. The capital and operating costs estimated for this 2000 tpd scenario are shown in Table 9 and Table 10.

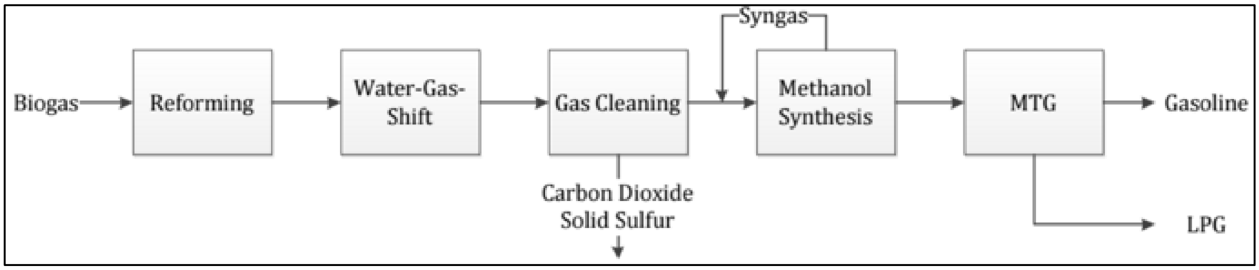


Figure 9: Methanol-to-gasoline (MTG) process flow diagram (LPG: liquefied petroleum gas)

Fischer-Tropsch synthesis is the other gas-to-liquid upgrading step used in this study for the upgrading of biogas to liquid transportation fuels. FT methodology follows the operations of a 2013 National Energy Technology Lab (NETL) report [39] that produces 50,000 bbl/day of biofuel from a natural gas feedstock. A FT process flow diagram is shown in Figure 10. FT efficiency is assumed to be 20.6% for cleaned biogas to gasoline and 54.6% for cleaned biogas to diesel. NETL estimates capital costs to be \$4.3 billion, which are then scaled to meet this study's operating conditions using Equation (5). Capital and operating cost estimates are summarized for the 2000 tonne/day scenario in Table 9 and Table 10.

$$C_{p,s} = C_{p,b}\left(\frac{S_s}{S_b}\right)^n \tag{5}$$

Where:

$\mathbf{C_{p,s}}$: predicted cost of specified equipment

$\mathbf{C_{p,b}}$: known cost of baseline equipment

$\mathbf{S_s}$: size of specified equipment

$\mathbf{S_b}$: baseline equipment capacity

n: scaling factor (0.7)

Table 9: Capital costs and normalized capital costs factors of hydrothermal liquefaction (HTL), anaerobic digestion (AD), methanol-to-gasoline (MTG) and Fischer-Tropsch (FT) technologies. ($MM: million dollars)

Technology	**Section**	**Capital Cost** ($MM)	**Normalized** Capital Cost ($/tonne)
HTL	Hydrothermal Liquefaction	209	318.11
HTL	Hydroprocessing	71	108.07
HTL	Product Refining	6	9.13
HTL	Hydrogen Generation	52	79.15
HTL	Steam Reformer	63	95.89
HTL	Auxilaries	23	35.01
HTL	**Total**	**424**	**645.36**
AD	**Total**	**117.8**	**179.25**
MTG	Steam Reformer	276.3	420.55
MTG	Acid Gas and Sulfur removal	12.1	18.42
MTG	Methanol Synthesis-compression	10.5	15.98
MTG	Methanol Conditioning/Degassing	4.8	7.31
MTG	Methanol-to-Gasoline Synthesis	21.6	32.88
MTG	Steam System and Power Generation	23.1	35.16
MTG	Cooling Water and Other Utilities	5.9	8.98
MTG	**Total**	**472.10**	**718.57**
FT	Steam Reformer	276.3	420.55
FT	Syngas Cleaning	29.3	44.60
FT	Fuel Synthesis	58.7	89.35
FT	Hydroprocessing	29.5	44.90
FT	Balance of Plant	27.2	41.40
FT	**Total**	**538.80**	**820.09**

Table 10: Operating costs and normalized operating costs factors of hydrothermal liquefaction (HTL), anaerobic digestion (AD), methanol-to-gasoline (MTG) and Fischer-Tropsch (FT) technologies. ($MM: million dollars)

Technology	Section	Operating Cost ($MM)	Normalized Capital Cost ($/tonne)
HTL	Capital	56.76	86.39
HTL	Natural Gas	6.32	9.62
HTL	Electricity	2.6	3.96
HTL	Boiling Water	0.08	0.12
HTL	Cooling Water	0.18	0.27
HTL	Catalysts and Chemicals	6.9	10.50
HTL	Waste Disposal	4.1	6.24
HTL	**Total**	**79.94**	**117.11**
AD	**Total**	**5.89**	**8.96**
MTG	Capital	58.3	95.08
MTG	Catalysts	0.34	0.52
MTG	Olivine	0.43	0.65
MTG	Other Raw Materials	1.37	2.09
MTG	Waste Disposal	0.51	0.78
MTG	Fixed Costs	12.23	18.61
MTG	**Total**	**79.89**	**121.60**
FT	Capital	66.5	102.51
FT	Operating Labor	27.57	41.96
FT	Maintenance Labor	5.35	8.14
FT	Admin and Support Labor	8.23	12.53
FT	Taxes and Insurance	6.86	10.44
FT	Maintenance Cost	12.18	18.54
FT	Water	0.62	0.94
FT	Chemicals	3.32	5.05
FT	Other	20.03	30.49
FT	Byproducts	-3.54	-5.39
FT	**Total**	**153.86**	**234.19**

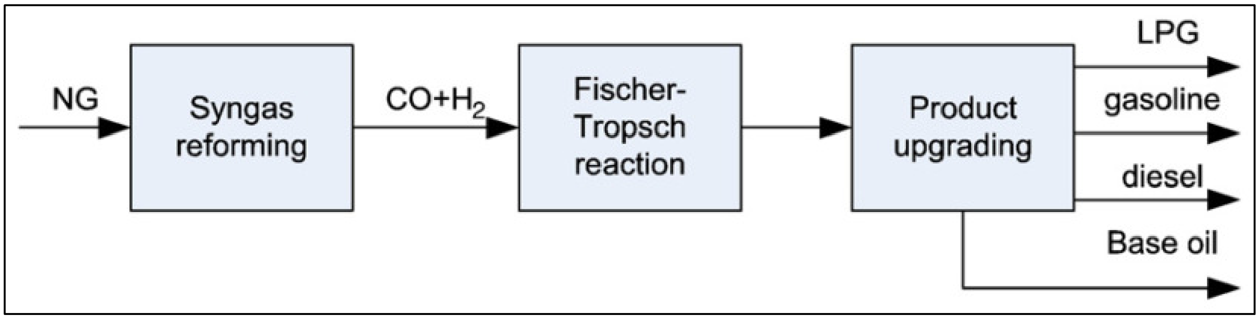


Figure 10: Fischer-Tropsch (FT) process flow diagram (LPG: liquefied petroleum gas)[63]

Water is an important resource to account for in the conversion and upgrading stages of biofuel production. Ou et al. [44], Zhu et al. [64], Goellner et al. [39] and Phillips et al. [42] all report water usage as operating parameters in their respective reports. A cellulosic ethanol study from corn stover by Wu et al. [23] is used for a base scenario to build off of. It estimates that 329 L of ethanol is produced from 1 tonne of corn stover. This results in a rate of 5.4 L of water consume for every liter of ethanol produced for a 2000 tpd biorefinery plant capacity. The same process was assumed for calculating the process water use for the three conversion and upgrading scenarios in this study. Table 11 summarizes biofuel rates used in the calculation. The volume of biofuel produced was calculated based on yields, biorefinery capacity and processing parameters described in the literature. These rates are used to calculate the process water used in conversion and upgrading, which is used in the accounting of the blue water footprint.

Table 11: Process water accounting parameters for cellulosic ethanol, hydrothermal liquefaction, methanol-to-gasoline and Fischer-Tropsch technologies based on herbaceous feedstock (L_b/tonne: liters of biofuel per tonne of biomass)

(L_b/tonne$_b$)	Corn Stover (Silage)	Miscanthus	Sorghum
Cellulosic Ethanol	329	362.8	300.1
Hydrothemal Liquefaction	338.1	225.1	291.9
Methanol-to-Gasoline	310.0	178.7	231.8
Fischer-Tropsch Synthesis	338.1	300.3	389.4

CHAPTER IV: RESULTS AND DISCUSSION

Results from this study include estimates of the final biofuel production costs for converting stover, silage, miscanthus and sorghum into gasoline and diesel via HTL, MTG and FT pathways. Two plant operating scenarios were analyzed, 200 tonne/day and 2000 tonne/day. Biofuel production costs range from \$2.04-\$6.39, with the small plant scenarios resulting in higher production cost trends on average. APPENDIX shows a summary of the costs for each feedstock, conversion and upgrading pathway and biorefinery capacity combination.

Feedstock costs range from \$63.84-\$86.19 per tonne for all feedstock and biorefinery capacity scenarios. The wide range in total feedstock cost is attributed primarily to drastic differences in feedstock yield and establishment needs and costs of the crops. Feedstock costs follow a distinct trend with corn stover exhibiting the lowest costs of all the feedstocks studied with \$63.84 being the lowest and 70.80 being highest. Although, corn stover has the lowest biomass yield, it results in the lowest overall feedstock costs due to establishment requirements. Collecting stover from the field post grain harvest has been proven to increase the overall crop yield slightly [52], resulting in a negative or net profit establishment cost assumption of \$1.43. Miscanthus results in the largest establishment costs based on the extensive three establishment period, where biomass is not harvested but costs are continuously incurred. Nutrient costs contribute a significant weight of the overall feedstock cost. The overall costs are in line with supply chain estimates from Shah [21] who also included nutrient costs in his analysis. Nutrient costs vary on the specific feedstock and contribute roughly \$25 for stover, silage and sorghum and only \$11 for miscanthus. Figure 11, Figure 12, Figure 13 and Figure 14 depict a breakdown of the feedstock cost for each biorefinery capacity and storage scenario.

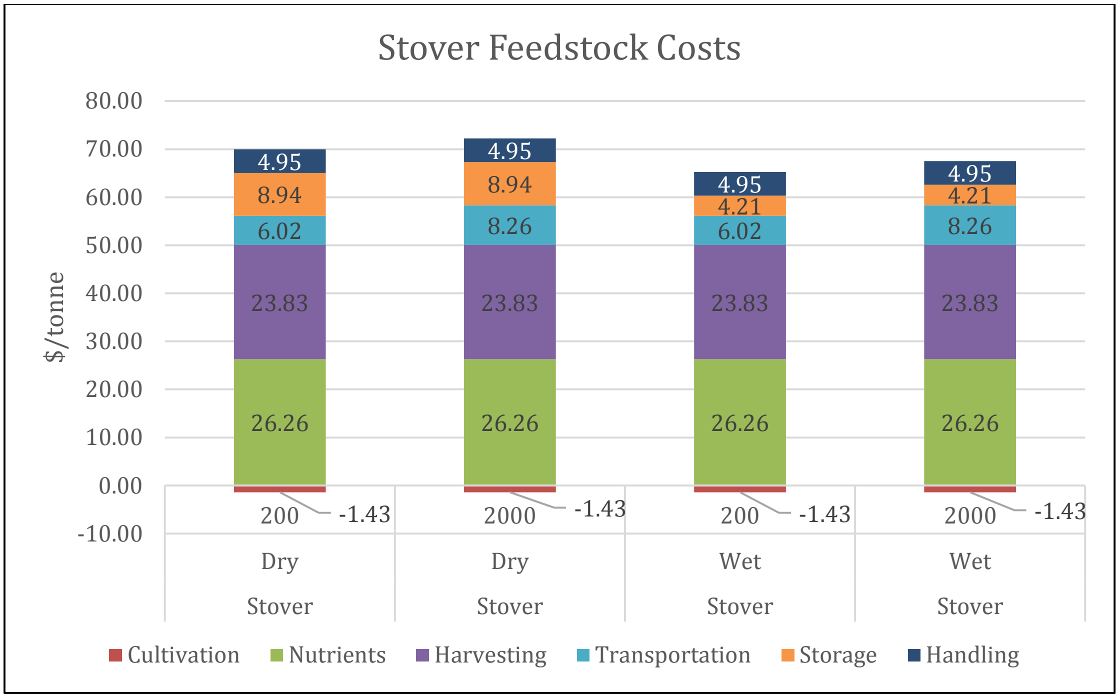


Figure 11: Stover feedstock cost break down ($/tonne) for 200 and 2000 tonne/day facilities

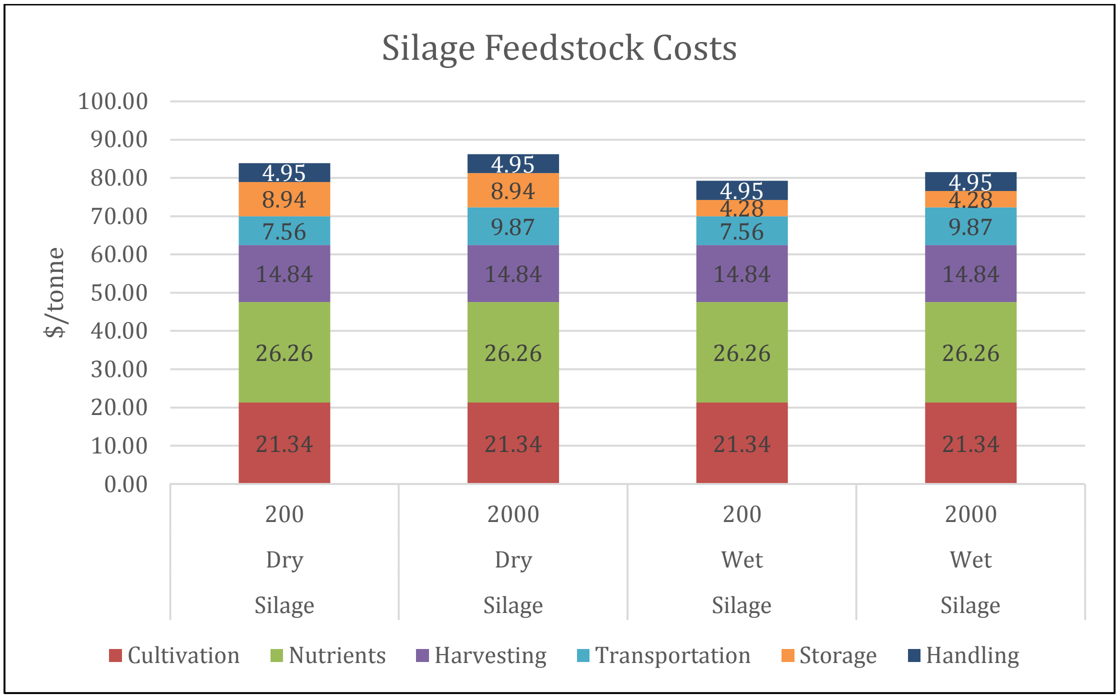


Figure 12: Silage feedstock cost break down ($/tonne) for 200 and 2000 tonne/day facilities

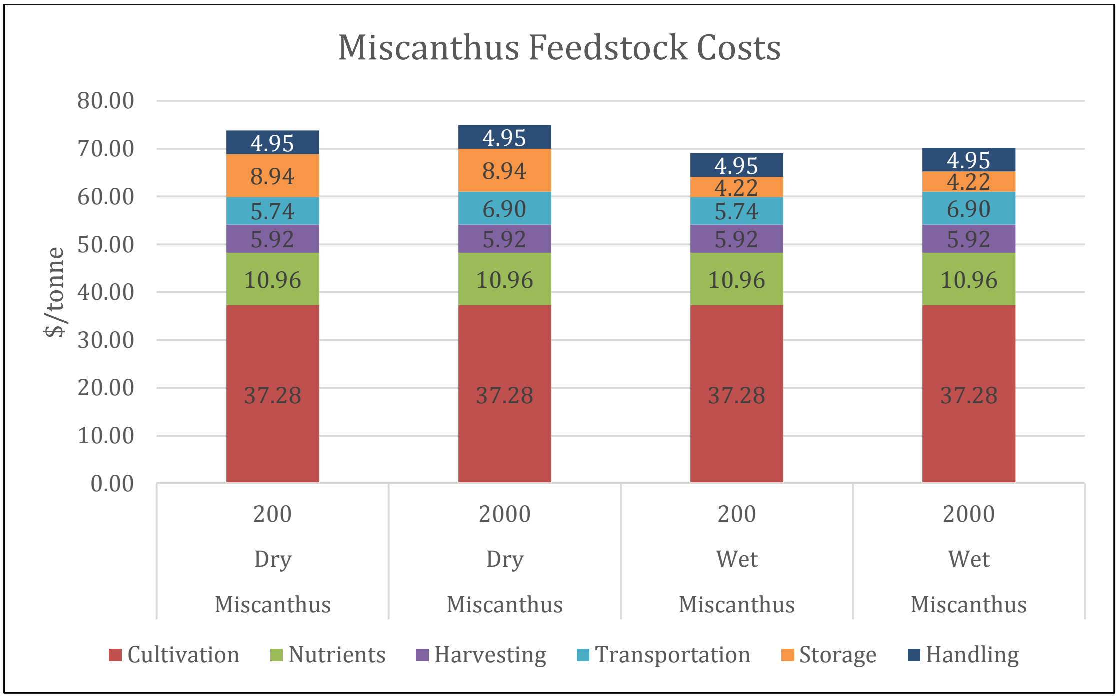


Figure 13: Miscanthus feedstock cost break down ($/tonne) for 200 and 2000 tonne/day facilities

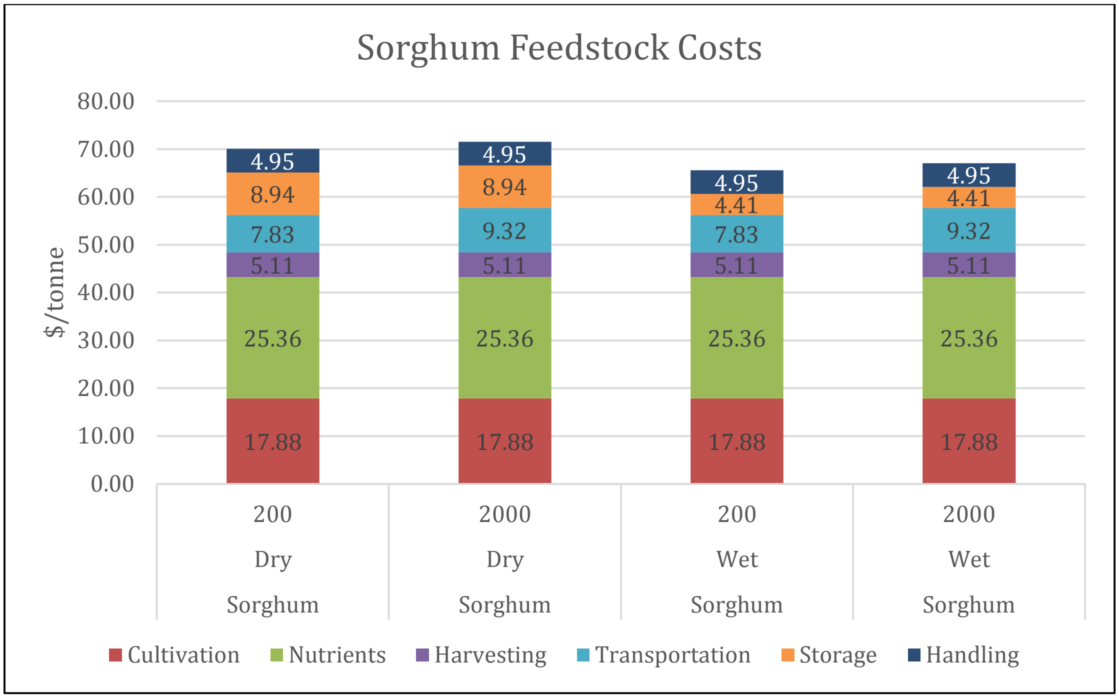


Figure 14: Sorghum feedstock cost break down ($/tonne) for 200 and 2000 tonne/day facilities

Biomass supply chain analysis quantifies handling steps from harvest and collection through delivery and preprocessing at the conversion and upgrading facility. Hess et al. [20] reports the biofuel production sustainability suggestion to keep supply chain costs less than \$80/tonne and the overall fuel production costs less than \$3/gallon. This analysis meets the feedstock cost goal in all pathways of the stover, miscanthus and sorghum feedstock scenarios and only three of the silage scenarios. Silage feedstock costs estimates do not meet the \$80/tonne goal in a majority of the scenarios due to the combination of high nutrient replenishment costs and relatively high costs to ensile the corn plant. Table 12 shows estimated feedstock costs of wet and dry storage for the 2000 tpd scenario. This analysis also attempts to meet the DOE goal of \$3/gal production costs of biofuel. To quantify this, operating costs are normalized on a gallon of biofuel basis. Half of the scenarios for the 2000 tpd biorefinery capacity case met the DOE goal, within reasonable uncertainty of ± 30%. Table 12, in addition to the feedstock costs for wet and dry storage conditions, shows the corresponding fuel production costs for the 2000 tpd case. Within reasonable uncertainty, HTL results in the lowest fuel production costs and FT results in the highest, on average. This follows a similar trend as shown in Table 10 with the normalized capital costs.

Table 12: Biomass supply chain feedstock costs and fuel production costs summary for 2000 tonnes per day (tpd)

2000 tpd	**Storage Scenario**	**Feedstock Cost (\$/tonne)**	**Fuel Production Costs (\$/gal)**		
			HTL	MTG	FT
Stover	Dry	70.80	2.03	3.21	3.94
	Wet	66.08	1.98	3.13	3.88
Silage	Dry	86.19	2.20	3.48	4.14
	Wet	81.53	2.15	3.40	4.08
Miscanthus	Dry	74.94	2.26	4.14	5.03
	Wet	70.23	2.20	4.04	4.95
Sorghum	Dry	71.56	2.04	2.42	2.96
	Wet	67.03	1.99	2.36	2.92

Operations for all three conversion and upgrading scenarios follow literature sources [44, 49, 51, 53] on the respective technology and are scaled to meet this study's operational parameters. Operating cost estimates follow a trend of increasing costs with HTL, MTG and FT, respectively. These estimates are to be used with understanding of an uncertainty of ± 30%. This is attributed to the number of processing steps, efficiencies at each step, unit costs of the process and feedstock and technology product yields. FT shows the highest yield with a max of up to 102.9 gallons of biofuel per tonne of biomass, HTL produces up to 89.3 gallons/tonne and MTG produces up to 79.3 gallons/tonne. In all cases, silage results in the largest costs to produce biofuel, closely followed by miscanthus, while stover and sorghum result in comparable costs for most scenarios. Capital costs dominate the composition of the operating cost breakdown. An operating cost summary is shown in Figure 15 for the 2000 tpd plant capacity.

Commercial scale conversion technologies incur high capital investments. For this analysis, capital costs are estimated based on literature [44], [37], [39], [42] and scaled to the facility capacity assumed for this study. A capital cost summary is shown in Figure 16 for the 2000 tpd plant capacity. The capital costs are reported within reasonable uncertainty of ± 30% from the base case estimates. Capital cost estimates are the lowest for the HTL and hydroprocessing pathway at almost $425 MM, with the majority of that being consumed by the liquefaction step itself at $209 MM. FT has the highest capital costs at approximately $540 MM. MTG's capital falls in between these two at approximately $475 MM. The major contributor to the FT and MTG capital cost estimates is the steam reformer. The steam reformer accounts for roughly 50% of the overall capital investment for both scenarios. GTL technologies generally operate on a much greater scale than this study assumes. The high percentage contribution of the steam reformers indicate challenges in scaling down these technologies.

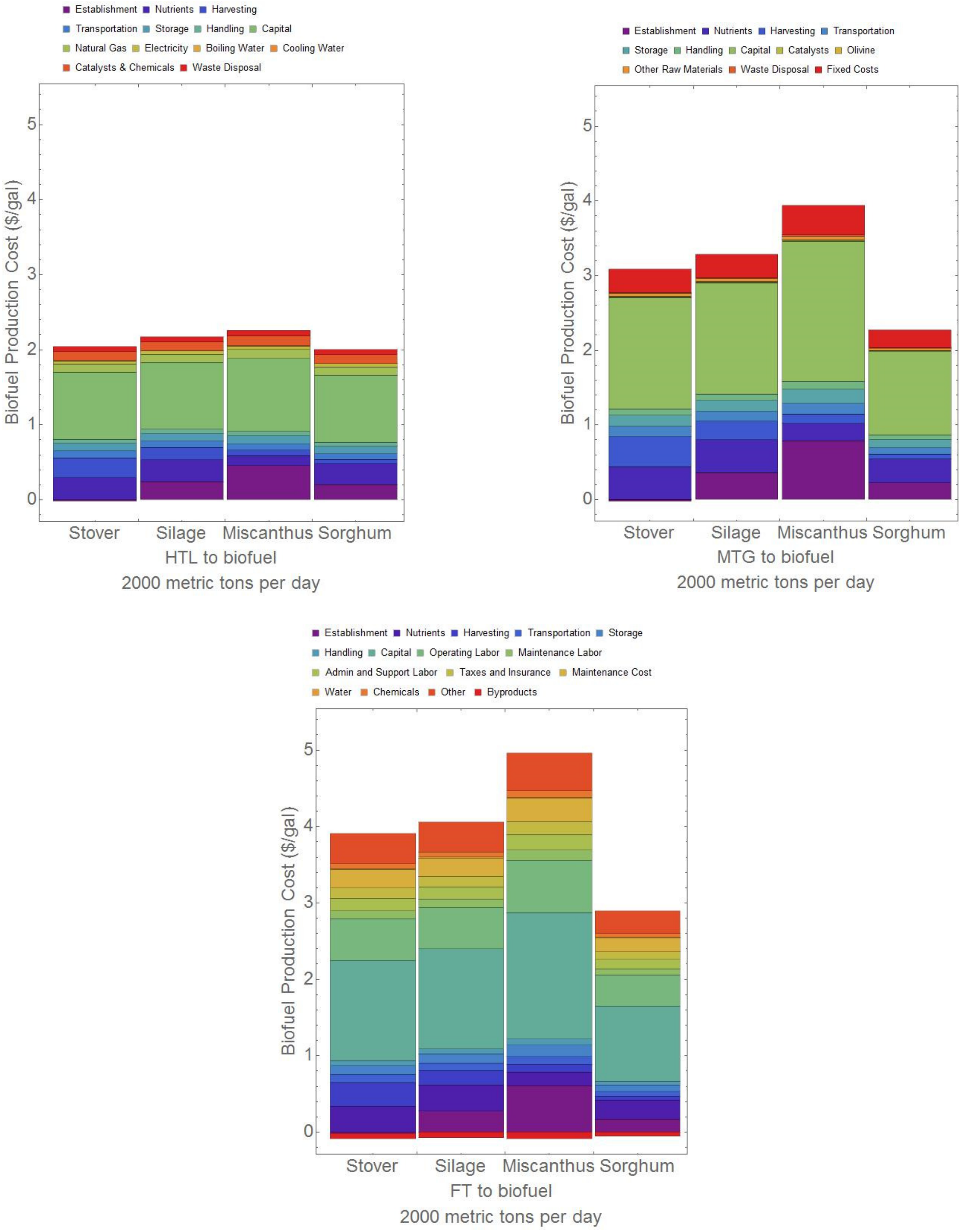


Figure 15: Biofuel production costs for hydrothermal liquefaction (HTL), Methanol-to-Gasoline (MTG) and Fischer-Tropsch Synthesis (FT) at 2000 tonnes per day

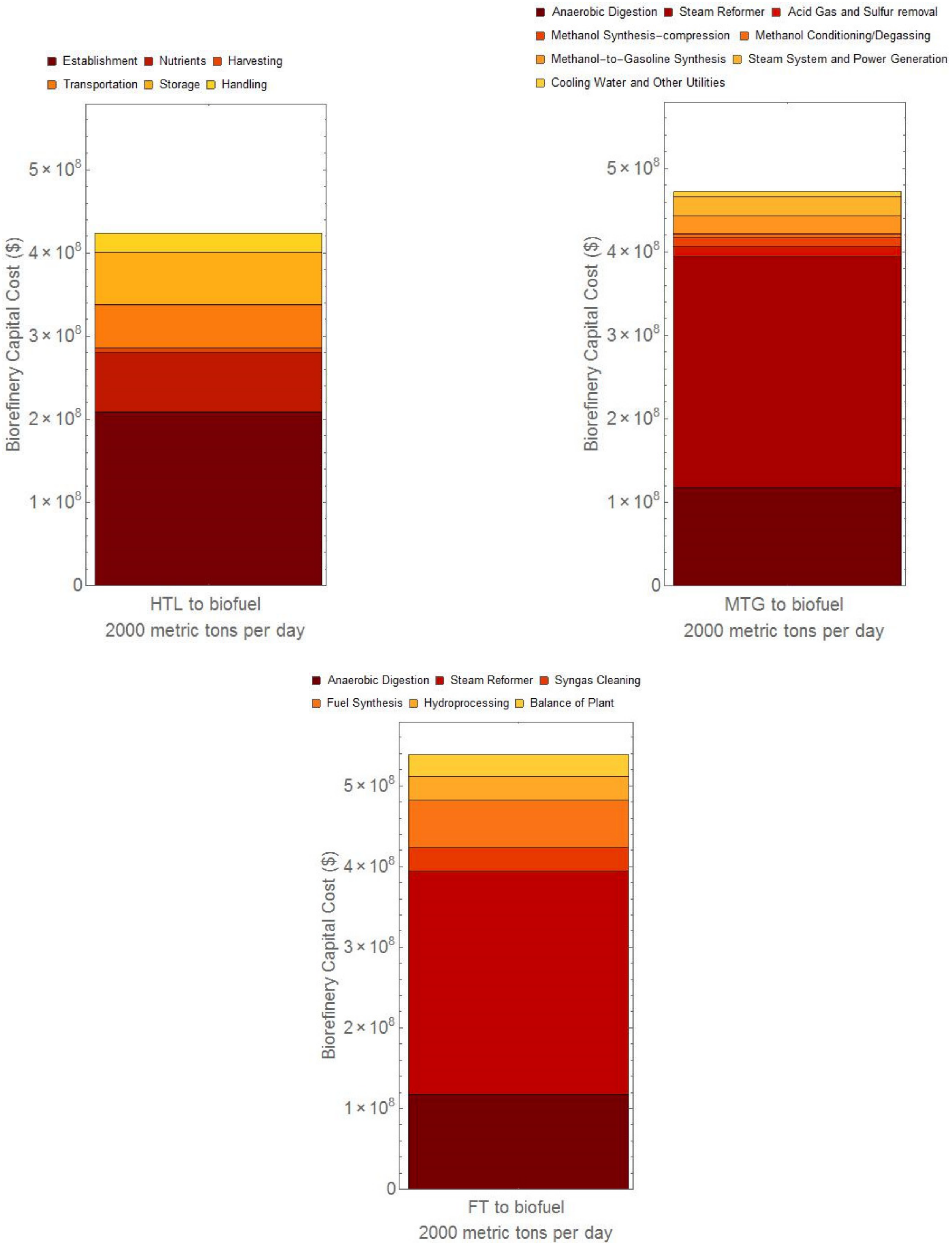


Figure 16: Biorefinery capital costs for hydrothermal liquefaction (HTL), methanol-to-gasoline (MTG) and Fischer-Tropsch (FT) synthesis at 2000 tonne/day

The need for small scale GTL facilities has been identified to make the economics of BTL technologies more feasible. Little research has been done and reported on small scale GTL technology. However, Velocys and GasTechno are two companies that have produced some promising small scale reactors to convert carbonaceous gas into useful liquid chemicals. Volocys is one of the leaders in micro-scale FT synthesis for GTL conversion. They provide combined steam-methane-reforming (SMR) and FT for small and medium scale GTL applications. The SMR operates without an oxygen plant, has a small footprint and a lower capital costs than competing reformers. The patented technology has claimed higher catalyst performance, higher syngas carbon monoxide conversion and lower reaction temperature and contact times than conventional FT technology [65]. The Velocys micro-scale FT technology was validated in a study by Nexant and Oxford Catalysts Group. GasTechno is another leader in the field, developing small scale MTG technology. The process developed by GasTechno converts methane directly to methanol via a patented direct homogeneous partial oxidation process. A study done by Nexant ChemSystems provides a comparison of the GasTechno technology against other commercial scale facilities at a 33 MMscfd (million standard cubic feet per day) or 246 MMgd (million gallons per day) [66]. The results of the study are shown in Figure 17, where it can be seen that the GasTechno plant (triangle data point) has a considerably lower normalized capital cost while still providing a high output of 330,000 MTPA (metric tonnes per year). The power trendlines are shown here to demonstrate that small scale GTL economics do not mesh with large scale GTL economics, indicating there must be an alternative scale that small scale GTL fits.

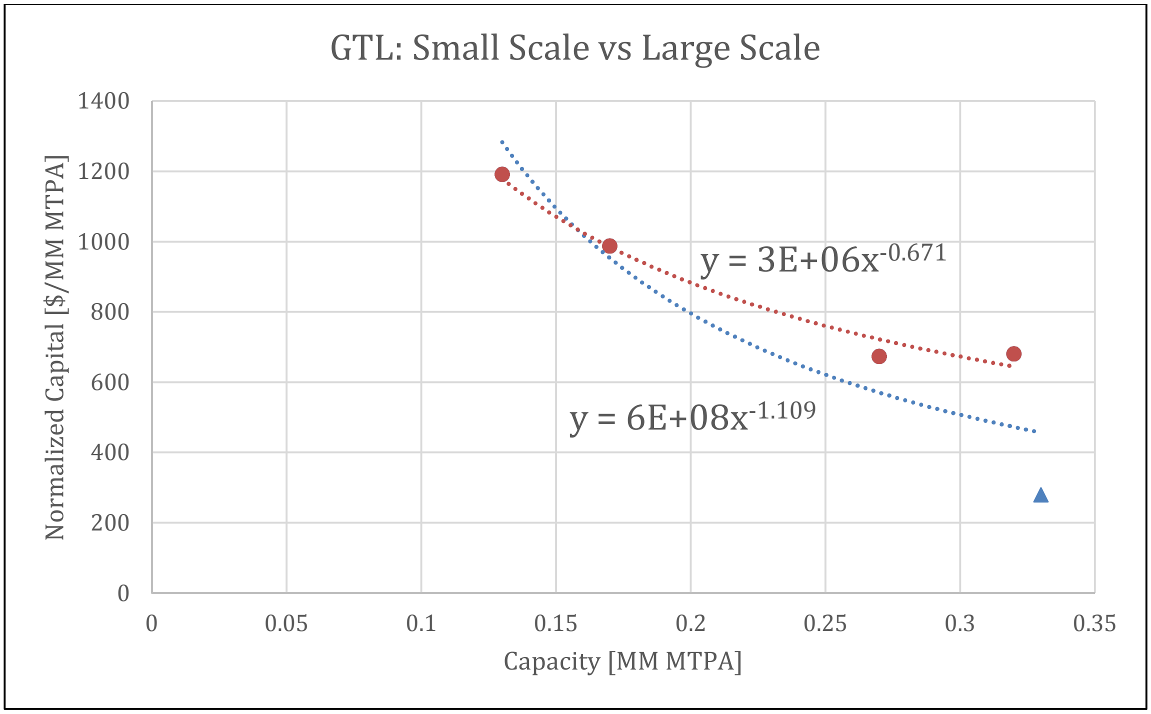


Figure 17: Normalized capital costs of small (triangle point) and large scale gas-to-liquid (GTL) production facilities with increasing plant capacity [64]. ($MM: million dollars, mmMTPA: million tonne per year)

Fuel production costs are estimated based on the capital and operating costs and the material balance of each stage of the production process. Process efficiencies are used throughout the biomass supply chain and the conversion and upgrading stages to estimate the volume of biofuel that is estimated to be produced in each scenario. To obtain fuel costs, the operating costs to produce the biofuel are divided by the volume of biofuel that is estimated to be produced on a yearly basis. The final fuel production costs ($/gal) are shown in Table 13, separated by technology, plant capacity and feedstock. The final fuel production costs follow similar understandings as operating and capital costs that values are within an uncertainty range of ± 30%. As discussed earlier, the smaller capacity plants incur higher fuel product costs compared to their respective counterpart. Sorghum and stover have comparable prices and comprise of the lowest product cost among the four feedstocks. Stover is among the lowest due to the establishment assumption and sorghum is among the lowest due to large crop yields.

Table 13: Overall fuel production costs of hydrothermal liquefaction (HTL), methanol-to-gasoline (MTG) and Fischer-Trophsch (FT) synthesis for stover, silage, miscanthus and sorghum conversion at 200 and 2000 tonne/day

$/gal	**Capacities**	**Stover**	**Silage**	**Miscanthus**	**Sorghum**
HTL	200 tonne/day	2.89	3.06	3.22	2.91
HTL	2000 tonne/day	2.03	2.20	2.26	2.04
MTG	200 tonne/day	4.81	5.08	6.17	3.63
MTG	2000 tonne/day	3.21	3.48	4.14	2.42
FT	200 tonne/day	5.33	5.21	6.39	3.77
FT	2000 tonne/day	3.94	4.14	5.03	2.96

Sensitivity analyses are important to give insight into situations where parameters may vary from the chosen estimation. For the base case of 2000 tpd, a sensitivity analysis was conducted on parameters that are thought to have a significant impact on the final fuel production cost. Reformer cost, capital cost, conversion yield and crop yield were chosen for the sensitivity analysis. It can be seen from Figure 18 that variation in the conversion yield estimates resulted in the greatest change in biofuel cost. In some scenarios, varying the conversion yield by ± 20% of the assumed yield resulted in a sway of fuel production costs by -16% to +25% from baseline estimates. Variation in capital cost seems to effect the fuel production costs the least. The impact of variation from the reformer costs on MTG was the greatest, resulting in a ±5% change in biofuel costs versus the ±3% change attributed to FT technologies. The impact of these parameters, though not as significant as variation in the conversion yield, is important to note even a slight variation in fuel production cost can be the difference between economically competitive and not.

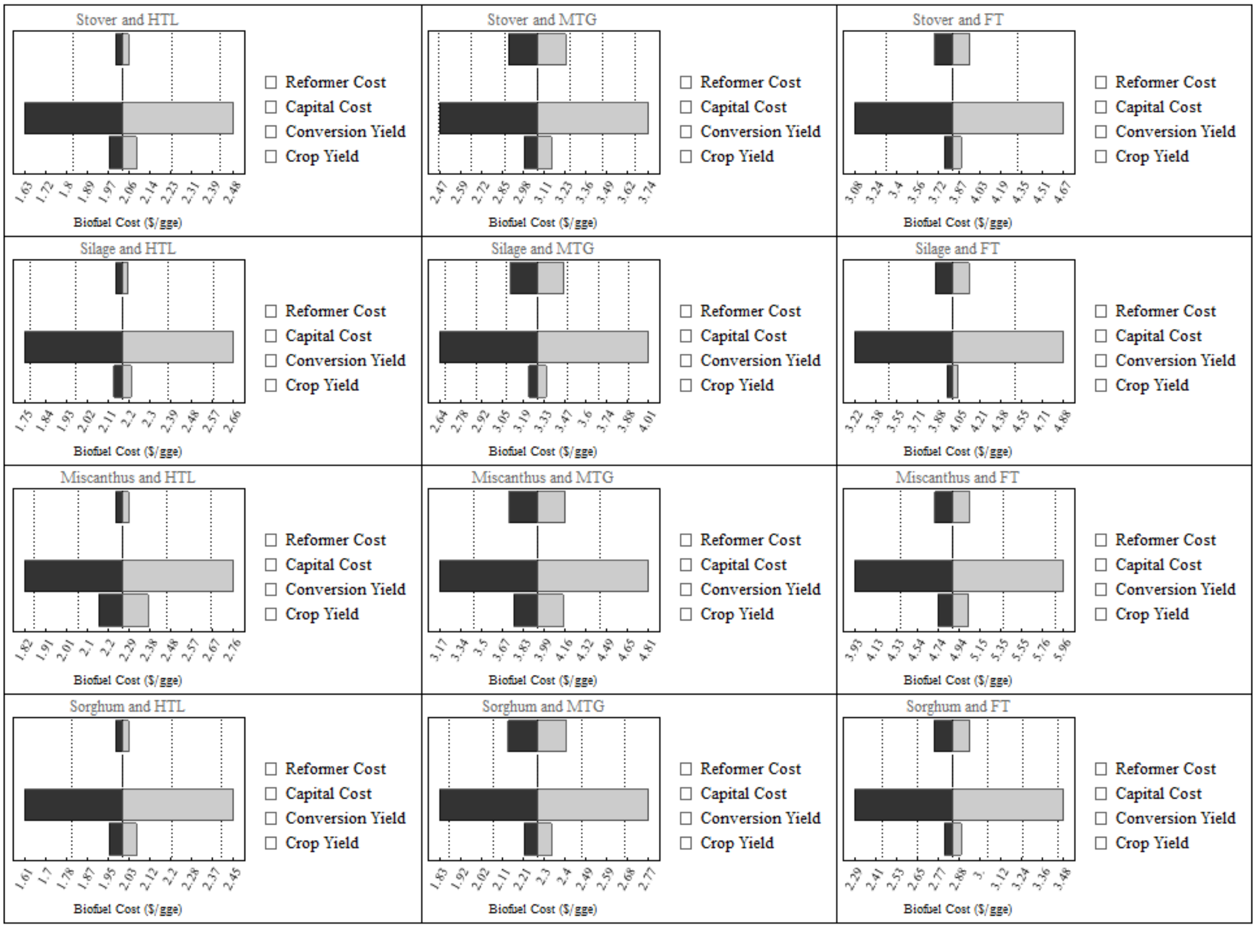


Figure 18: Biofuel production cost sensitivity analysis of hydrothermal liquefaction (HTL), methanol-to-gasoline (MTG) and Fischer-Tropsch (FT) synthesis for corn stover, corn silage, miscanthus and sorghum at 2000 tonne/day

Water is an essential factor for plant growth and thus is a vital factor for biofuel production. Whether it is through precipitation, irrigation or groundwater consumption, plants require water to grow. Water is also a major contributor in heating and cooling within the biorefinery. Due to an increasing concern about water availability and longevity around the world, water accounting has developed concern for consideration for energy production systems that consume large quantities of water. This study estimates the regional blue, green and grey water footprints for each feedstock and each conversion technology based on very limited data of the subject matter. Table 14 summarizes the blue and green water footprints developed for each scenario in this study.

Table 14: Water footprint results for ethanol (EtOH), hydrothermal liquefaction (HTL), methanol-to-gasoline (MTG) and Fischer-Tropsch (FT) for all feedstocks (2% irr = 2% of land is irrigated, 0.7% irr = 0.7% of land is irrigated)

Water Footprint		**Blue (L_w/L_b)**			**Green (L_w/L_b)**
		Feedstock (2% irr)	Feedstock (0.7% irr)	Process	
EtOH	Stover	11.36	3.97	5.40	1,757.04
	Miscanthus	2.28	0.80	5.40	381.95
	Sorghum	0.52	0.18	5.40	301.50
HTL	Stover	11.05	3.87	10.40	1,709.59
	Miscanthus	2.67	0.94	10.40	447.06
	Sorghum	0.47	0.16	10.40	267.56
MTG	Stover	16.60	5.81	6.50	2,568.27
	Miscanthus	4.64	1.62	6.50	775.37
	Sorghum	0.52	0.18	6.50	301.31
FT	Stover	12.80	4.48	10.41	1,980.10
	Miscanthus	3.57	1.25	10.41	597.80
	Sorghum	0.40	0.14	10.41	232.30

Ethanol (EtOH) is used as a baseline for this study to compare blue and green water contribution to the water footprint in all scenarios. Two blue water accounting methods were analyzed for feedstock prodcution, a 2% irrigation situation and a 0.7% irrigation situation. Wu et al. [57] reports that less than 2% of the farm land in the Corn Belt region uses irrigation to produce corn. Wu et al. [23] reports that from years 1970-2000 that irrigation practices have been used on less than 0.7% of farm land in Iowa. For both feedstock irrigation methods, corn stover resulted in the greatest blue water footprint, ranging from 5.81 (L_w/L_b) for the FT scenario to 16.60 (L_w/L_b) for the MTG scenario. The 2% irrigation feedstock blue water contribution relates to the high end of the range that is provided and used for reference in literature and the 0.7% relates to the low end of the reference range [23]. Miscanthus and sorghum result in much less feedstock blue water contribution due to a lower water requirement to grow the feedstock. This corresponds with literature, as miscanthus and sorghum are generally not irrigated crops. Process blue water accounts for the water required to produce a liter of biofuel at the biorefinery.

This water reported in literature generally accounts for boiler water makeup and cooling water makeup [64], [42], [39], while some report quantification of water that is aiding in conversions [39]. EtOH production is assumed to be 5.4 (L_w/L_b), based on literature [57]. The process water contribution to the blue water footprints are slightly higher for HTL, MTG and FT than the base EtOH case. Otherwise, the relatively higher process water parameters are to be expected for high moisture conversion and upgrading pathways. Green water footprint is estimated form regional precipitation records, effective rainfall consumption by the plant and water required for plant growth. The green water footprint presented here fits within reported ranges from Wu et al. [23], [28]. MTG and FT green water appropriation results in slightly higher consumption on average than EtOH and HTL. The grey water footprint values are calculated much differently than blue and green water footprints. The grey water accounts for the amount of water needed to assimilate nitrate leaching in field water runoff. It can be seen that sorghum has the greatest grey water footprint while miscanthus has the lowest. These calculations are highly correlated to the rate of nitrogen fertilizer applied.

Table 15: Grey water footprint (L_w) for each feedstock

Grey Water Footprint (L_w)		
Corn Stover	Miscanthus	Sorghum
506.4	295.9	526.1

CHAPTER V: CONCLUSIONS

This study provides a preliminary economic comparison of the biomass supply chain, conversion and upgrading steps of high moisture feedstock biofuel production. Two biorefinery capacity scenarios were considered for four high moisture feedstocks and a variety of pathways leading to renewable gasoline and diesel transportation fuels. The biomass supply chain consisted of two different harvesting scenarios and two different storage scenarios intended to decrease the feedstock costs. Hydrothemal liquefaction and anaerobic digestion were considered for conversion pathways. Final fuel product upgrading steps included the hydroprocessing of biocrude from HTL and Fischer-Tropsch synthesis and methanol-to-gasoline conversion of biogas from AD. Final fuel production costs ranged from $2.04-$6.39 per gallon.

The biomass supply chain has been deemed incredibly important to the biofuel production process as it can contribute significantly to the final fuel production cost. The biomass supply chain analysis quantifies handling steps from harvest and collection through delivery and preprocessing at the biorefinery. Feedstock costs range from $63.84/tonne to $86.19/tonne for all scenarios. The feedstock costs in this study fall within a range of feedstock costs from a variety of sources [19], [20], [21], [22]. This study met the DOE feedstock cost goal of $80/tonne for all pathways except for the majority of the silage feedstock scenarios. The high feedstock costs for silage were attributed to a combination of relatively high nutrient and replenishment costs and ensiling costs. Final fuel production costs met the $3/gal DOE goal in half of the scenarios analyzed.

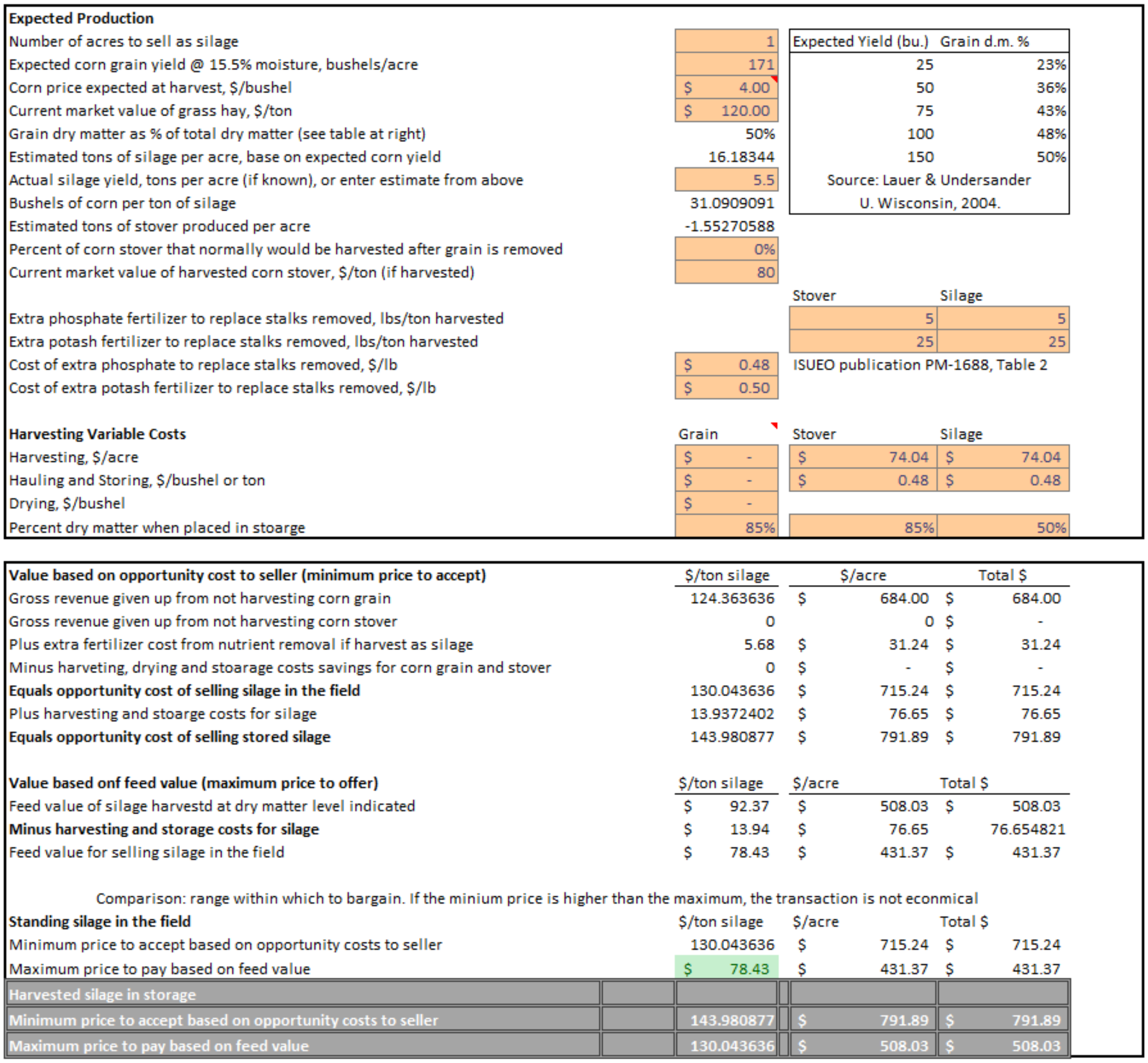
Conversion pathways were strategically chosen based on feedstock moisture content. Hydrothermal liquefaction and anaerobic digestion do not require extremely dry feedstock for conversion efficiency like other conversion pathways. Anaerobic digestion is generally not used for energy crop digestion for bioenergy purposes. With the limited data that was available, it can be concluded that herbaceous feedstock digestion can provide additional options when it comes to bioenergy utilization and waste management. HTL is increasing in popularity as the technology ages and operating processes are beginning to be better optimized. HTL exhibited the most promise as it can be estimated to produce nearly 90 million gallons of renewable gasoline and diesel per year, depending on feedstock. The high biofuel output also attributed to the lowest estimated fuel production cost per technology. Within reasonable uncertainty the production pathways analyzed in this study follow a trend of decreasing production costs from FT, MTG to HTL. These are assuming an uncertainty in calculated values of ± 30%, therefore the overall production costs may not be that different.

Fischer-Tropsch synthesis and methanol-to-gasoline conversion were chosen as upgrading technologies based on ability to process biogas and produce liquid transportation fuels. Both technologies generally operate on a large scale, up to 50,000 bbl/day [39], which poses a challenge when attempting to scale down to biomas-to-liquid range operating capacities. Some demonstrations of small scale FT and MTG technologies have been ongoing in recent years and have reported promising results. Additional research is needed to provide process data in steps to improve the economics of GTL and BTL operations on a small scale.

Water footprint analysis was undergone in this study to account for water contribution to the biofuel production process. Blue, green and grey water footprints were analyzed based on crop water requirements, nutrient and fertilizer application, irrigation, rainfall and associated losses. Two methods were used to estimate feedstock production blue water footprints for each feedstock. For the conservative case, blue water accounted for less than 1 L_w/L_b sorghum scenarios to greater than 10 L_w/L_b in all stover scenarios. The other method saw similar results on a smaller scale, <0.2 L_w/L_b to >5.5 L_w/L_b. Process water is considered ground or surface water used at the biorefinery in the process of producing biofuels. 5.4 L_w/L_b from a cellulosic ethanol plant was used as a reference case for the other technologies to be compared to. MTG resulted in the closest to the EtOH case at 6.50 L_w/L_b, where HTL and FT water use was roughly twice as much at 10.40 L_w/L_b and 10.41 L_w/L_b, respectively. Green water is essentially just the rainwater that the plant effectively uses for plant growth. In line with the feedstock water requirements stover resulted in the highest green water footprint, while sorghum was the lowest. Grey water footprints are based on the nutrient application of each feedstock. The grey water footprint for corn stover, miscanthus and sorghum was: 506.29 L, 295.95 L, and 526.13 L, respectively. These are in correlation with the nutrient application rates 7.7 kg/tonne, 4.5 kg/tonne and 8 kg/tonne, respectively. These values do not seem significant on a normalized basis but can ultimately be significant causing high stresses on local water resources when in some cases water resources are consumed at 23 times the rate that biofuel is produced. Wu et al. [28] reports that on a yearly basis a 50 million gallon producing cellulosic ethanol biorefinery would need 250 million gallons of water. This would be more significant for the technologies in this study. Wu et al. [57] claims that optimized thermochemical plants can decrease overall water footprints to below 5 L_w/L_b, thus there is room for additional research regarding water accounting and decreasing water consumption in biofuel production.

APPENDIX

A1 SILAGE PRICER

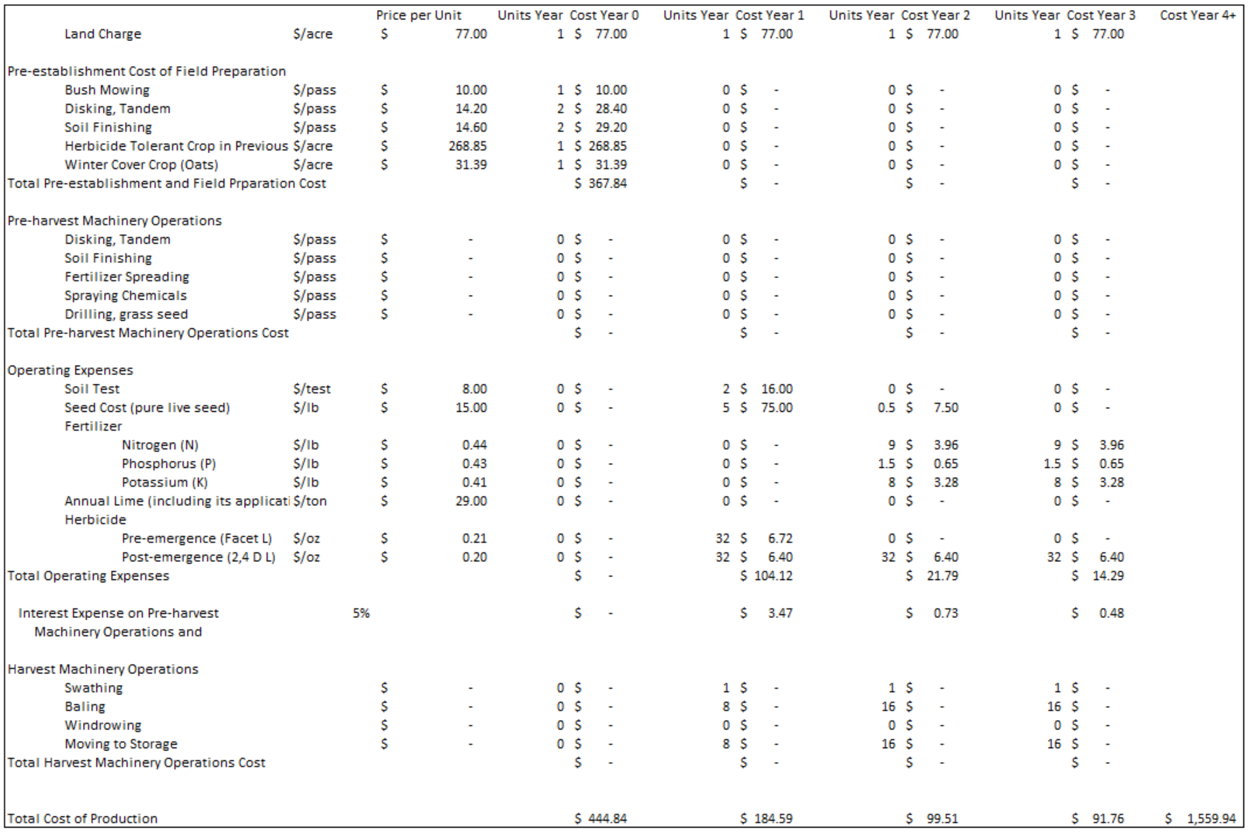


Expected Production			
Number of acres to sell as silage	1	Expected Yield (bu.)	Grain d.m. %
Expected corn grain yield @ 15.5% moisture, bushels/acre	171	25	23%
Corn price expected at harvest, $/bushel	$ 4.00	50	36%
Current market value of grass hay, $/ton	$ 120.00	75	43%
Grain dry matter as % of total dry matter (see table at right)	50%	100	48%
Estimated tons of silage per acre, base on expected corn yield	16.18344	150	50%
Actual silage yield, tons per acre (if known), or enter estimate from above	5.5	Source: Lauer & Undersander	
Bushels of corn per ton of silage	31.0909091	U. Wisconsin, 2004.	
Estimated tons of stover produced per acre	-1.55270588		
Percent of corn stover that normally would be harvested after grain is removed	0%		
Current market value of harvested corn stover, $/ton (if harvested)	80		
		Stover	Silage
Extra phosphate fertilizer to replace stalks removed, lbs/ton harvested		5	5
Extra potash fertilizer to replace stalks removed, lbs/ton harvested		25	25
Cost of extra phosphate to replace stalks removed, $/lb	$ 0.48	ISUEO publication PM-1688, Table 2	
Cost of extra potash fertilizer to replace stalks removed, $/lb	$ 0.50		
Harvesting Variable Costs	Grain	Stover	Silage
Harvesting, $/acre	$ -	$ 74.04	$ 74.04
Hauling and Storing, $/bushel or ton	$ -	$ 0.48	$ 0.48
Drying, $/bushel	$ -		
Percent dry matter when placed in stoarge	85%	85%	50%

Value based on opportunity cost to seller (minimum price to accept)	$/ton silage	$/acre	Total $
Gross revenue given up from not harvesting corn grain	124.363636	$ 684.00	$ 684.00
Gross revenue given up from not harvesting corn stover	0	0	$ -
Plus extra fertilizer cost from nutrient removal if harvest as silage	5.68	$ 31.24	$ 31.24
Minus harveting, drying and stoarage costs savings for corn grain and stover	0	$ -	$ -
Equals opportunity cost of selling silage in the field	130.043636	$ 715.24	$ 715.24
Plus harvesting and stoarge costs for silage	13.9372402	$ 76.65	$ 76.65
Equals opportunity cost of selling stored silage	143.980877	$ 791.89	$ 791.89
Value based onf feed value (maximum price to offer)	$/ton silage	$/acre	Total $
Feed value of silage harvestd at dry matter level indicated	$ 92.37	$ 508.03	$ 508.03
Minus harvesting and storage costs for silage	$ 13.94	$ 76.65	76.654821
Feed value for selling silage in the field	$ 78.43	$ 431.37	$ 431.37
Comparison: range within which to bargain. If the minium price is higher than the maximum, the transaction is not econmical			
Standing silage in the field	$/ton silage	$/acre	Total $
Minimum price to accept based on opportunity costs to seller	130.043636	$ 715.24	$ 715.24
Maximum price to pay based on feed value	$ 78.43	$ 431.37	$ 431.37
Harvested silage in storage			
Minimum price to accept based on opportunity costs to seller	143.980877	$ 791.89	$ 791.89
Maximum price to pay based on feed value	130.043636	$ 508.03	$ 508.03

Figure 19: *Tool to estimate the price of silage* [51]

A2 ESTABLISHMENT COST ESTIMATOR



		Price per Unit	Units Year	Cost Year 0	Units Year	Cost Year 1	Units Year	Cost Year 2	Units Year	Cost Year 3	Cost Year 4+
Land Charge	$/acre	$ 77.00	1	$ 77.00	1	$ 77.00	1	$ 77.00	1	$ 77.00	
Pre-establishment Cost of Field Preparation											
Bush Mowing	$/pass	$ 10.00	1	$ 10.00	0	$ -	0	$ -	0	$ -	
Disking, Tandem	$/pass	$ 14.20	2	$ 28.40	0	$ -	0	$ -	0	$ -	
Soil Finishing	$/pass	$ 14.60	2	$ 29.20	0	$ -	0	$ -	0	$ -	
Herbicide Tolerant Crop in Previous	$/acre	$ 268.85	1	$ 268.85	0	$ -	0	$ -	0	$ -	
Winter Cover Crop (Oats)	$/acre	$ 31.39	1	$ 31.39	0	$ -	0	$ -	0	$ -	
Total Pre-establishment and Field Prparation Cost				$ 367.84		$ -		$ -		$ -	
Pre-harvest Machinery Operations											
Disking, Tandem	$/pass	$ -	0	$ -	0	$ -	0	$ -	0	$ -	
Soil Finishing	$/pass	$ -	0	$ -	0	$ -	0	$ -	0	$ -	
Fertilizer Spreading	$/pass	$ -	0	$ -	0	$ -	0	$ -	0	$ -	
Spraying Chemicals	$/pass	$ -	0	$ -	0	$ -	0	$ -	0	$ -	
Drilling, grass seed	$/pass	$ -	0	$ -	0	$ -	0	$ -	0	$ -	
Total Pre-harvest Machinery Operations Cost				$ -		$ -		$ -		$ -	
Operating Expenses											
Soil Test	$/test	$ 8.00	0	$ -	2	$ 16.00	0	$ -	0	$ -	
Seed Cost (pure live seed)	$/lb	$ 15.00	0	$ -	5	$ 75.00	0.5	$ 7.50	0	$ -	
Fertilizer											
Nitrogen (N)	$/lb	$ 0.44	0	$ -	0	$ -	9	$ 3.96	9	$ 3.96	
Phosphorus (P)	$/lb	$ 0.43	0	$ -	0	$ -	1.5	$ 0.65	1.5	$ 0.65	
Potassium (K)	$/lb	$ 0.41	0	$ -	0	$ -	8	$ 3.28	8	$ 3.28	
Annual Lime (including its applicati	$/ton	$ 29.00	0	$ -	0	$ -	0	$ -	0	$ -	
Herbicide											
Pre-emergence (Facet L)	$/oz	$ 0.21	0	$ -	32	$ 6.72	0	$ -	0	$ -	
Post-emergence (2,4 D L)	$/oz	$ 0.20	0	$ -	32	$ 6.40	32	$ 6.40	32	$ 6.40	
Total Operating Expenses				$ -		$ 104.12		$ 21.79		$ 14.29	
Interest Expense on Pre-harvest Machinery Operations and		5%		$ -		$ 3.47		$ 0.73		$ 0.48	
Harvest Machinery Operations											
Swathing		$ -	0	$ -	1	$ -	1	$ -	1	$ -	
Baling		$ -	0	$ -	8	$ -	16	$ -	16	$ -	
Windrowing		$ -	0	$ -	0	$ -	0	$ -	0	$ -	
Moving to Storage		$ -	0	$ -	8	$ -	16	$ -	16	$ -	
Total Harvest Machinery Operations Cost				$ -		$ -		$ -		$ -	
Total Cost of Production				$ 444.84		$ 184.59		$ 99.51		$ 91.76	$ 1,559.94

Figure 20: *Tool to estimate the establishment costs for herbaceous grasses* [27]

A3 BIOMASS SUPPLY CHAIN LOGISTICS SUMMARY

($/tonne)	**Storage**	**Feed Capacity**	**Cultivation**	**Nutrients**	**Harvesting**	**Transportation**	**Storage**	**Handling**	**Total**
Stover	**Dry**	**200**	$ (1.43)	$ 26.26	$ 23.83	$ 6.02	$ 8.94	$ 4.95	$ 68.56
		2000	$ (1.43)	$ 26.26	$ 23.83	$ 8.26	$ 8.94	$ 4.95	$ 70.80
	Wet	**200**	$ (1.43)	$ 26.26	$ 23.83	$ 6.02	$ 4.21	$ 4.95	$ 63.84
		2000	$ (1.43)	$ 26.26	$ 23.83	$ 8.26	$ 4.21	$ 4.95	$ 66.08
Silage	**Dry**	**200**	$ 21.34	$ 26.26	$ 14.84	$ 7.56	$ 8.94	$ 4.95	$ 83.88
		2000	$ 21.34	$ 26.26	$ 14.84	$ 9.87	$ 8.94	$ 4.95	$ 86.19
	Wet	**200**	$ 21.34	$ 26.26	$ 14.84	$ 7.56	$ 4.28	$ 4.95	$ 79.23
		2000	$ 21.34	$ 26.26	$ 14.84	$ 9.87	$ 4.28	$ 4.95	$ 81.53
Miscanthus	**Dry**	**200**	$ 37.28	$ 10.96	$ 5.92	$ 5.74	$ 8.94	$ 4.95	$ 73.78
		2000	$ 37.28	$ 10.96	$ 5.92	$ 6.90	$ 8.94	$ 4.95	$ 74.94
	Wet	**200**	$ 37.28	$ 10.96	$ 5.92	$ 5.74	$ 4.22	$ 4.95	$ 69.06
		2000	$ 37.28	$ 10.96	$ 5.92	$ 6.90	$ 4.22	$ 4.95	$ 70.23
Sorghum	**Dry**	**200**	$ 17.88	$ 25.36	$ 5.11	$ 7.83	$ 8.94	$ 4.95	$ 70.07
		2000	$ 17.88	$ 25.36	$ 5.11	$ 9.32	$ 8.94	$ 4.95	$ 71.56
	Wet	**200**	$ 17.88	$ 25.36	$ 5.11	$ 7.83	$ 4.41	$ 4.95	$ 65.54
		2000	$ 17.88	$ 25.36	$ 5.11	$ 9.32	$ 4.41	$ 4.95	$ 67.03

A4 OVERALL PRODUCTION COSTS SUMMARY

		Stover							
Technology	Capacities	Feedstock Cost [dry storage] ($/tonne)	Feedstock Cost [wet storage] ($/tonne)	Operating Cost($MM)	Normalized Operating Cost ($/tonne)	Capital Cost ($MM)	Normalized Capital Cost($/tonne)	Gallons/tonne	Fuel Production Costs ($/gallon)
HTL	200 tonne/day	$ 68.56	$ 63.84	$ 12.46	$ 189.61	$ 84.60	$ 1,287.66	89.3	$ 2.89
HTL	2000 tonne/day	$ 70.80	$ 66.08	$ 72.49	$ 110.34	$ 424.00	$ 645.36	89.3	$ 2.03
MTG	200 tonne/day	$ 68.56	$ 63.84	$ 14.29	$ 217.46	$ 94.20	$ 1,433.73	59.5	$ 4.81
MTG	2000 tonne/day	$ 70.80	$ 66.08	$ 79.03	$ 120.29	$ 472.10	$ 718.57	59.5	$ 3.21
FT	200 tonne/day	$ 68.56	$ 63.84	$ 22.50	$ 342.54	$ 107.50	$ 1,636.30	77.1	$ 5.33
FT	2000 tonne/day	$ 70.80	$ 66.08	$ 153.01	$ 232.89	$ 538.80	$ 820.09	77.1	$ 3.94
		Silage							
		Feedstock Cost [dry storage] ($/tonne)	Feedstock Cost [wet storage] ($/tonne)	Operating ($MM)	Normalized Operating ($/tonne)	Capital ($MM)	Normalized Capital ($/tonne)	Gallons/tonne	Fuel Production Costs ($/gallon)
HTL	200 tonne/day	$ 83.88	$ 79.23	$ 12.46	$ 189.61	$ 84.60	$ 1,287.66	89.3	$ 3.06
HTL	2000 tonne/day	$ 86.19	$ 81.53	$ 72.49	$ 110.34	$ 424.00	$ 645.36	89.3	$ 2.20
MTG	200 tonne/day	$ 83.88	$ 79.23	$ 14.29	$ 217.46	$ 94.20	$ 1,433.73	59.3	$ 5.08
MTG	2000 tonne/day	$ 86.19	$ 81.53	$ 79.03	$ 120.29	$ 472.10	$ 718.57	59.3	$ 3.48
FT	200 tonne/day	$ 83.88	$ 79.23	$ 20.86	$ 317.54	$ 107.50	$ 1,636.30	77.1	$ 5.21
FT	2000 tonne/day	$ 86.19	$ 81.53	$ 153.01	$ 232.89	$ 538.80	$ 820.09	77.1	$ 4.14
		Miscanthus							
		Feedstock Cost [dry storage] ($/tonne)	Feedstock Cost [wet storage] ($/tonne)	Operating ($MM)	Normalized Operating ($/tonne)	Capital ($MM)	Normalized Capital ($/tonne)	Gallons/tonne	Fuel Production Costs ($/gallon)
HTL	200 tonne/day	$ 73.78	$ 69.06	$ 12.46	$ 189.61	$ 84.60	$ 1,287.66	81.9	$ 3.22
HTL	2000 tonne/day	$ 74.94	$ 70.23	$ 72.49	$ 110.34	$ 424.00	$ 645.36	81.9	$ 2.26
MTG	200 tonne/day	$ 73.78	$ 69.06	$ 14.29	$ 217.46	$ 94.20	$ 1,433.73	47.2	$ 6.17
MTG	2000 tonne/day	$ 74.94	$ 70.23	$ 79.03	$ 120.29	$ 472.10	$ 718.57	47.2	$ 4.14
FT	200 tonne/day	$ 73.78	$ 69.06	$ 20.86	$ 317.54	$ 107.50	$ 1,636.30	61.2	$ 6.39
FT	2000 tonne/day	$ 74.94	$ 70.23	$ 153.01	$ 232.89	$ 538.80	$ 820.09	61.2	$ 5.03
		Sorghum							
		Feedstock Cost [dry storage] ($/tonne)	Feedstock Cost [wet storage] ($/tonne)	Operating ($MM)	Normalized Operating ($/tonne)	Capital ($MM)	Normalized Capital ($/tonne)	Gallons/tonne	Fuel Production Costs ($/gallon)
HTL	200 tonne/day	$ 70.07	$ 65.54	$ 12.46	$ 189.61	$ 84.60	$ 1,287.66	89.3	$ 2.91
HTL	2000 tonne/day	$ 71.56	$ 67.03	$ 72.49	$ 110.34	$ 424.00	$ 645.36	89.3	$ 2.04
MTG	200 tonne/day	$ 70.07	$ 65.54	$ 14.29	$ 217.46	$ 94.20	$ 1,433.73	79.3	$ 3.63
MTG	2000 tonne/day	$ 71.56	$ 67.03	$ 79.03	$ 120.29	$ 472.10	$ 718.57	79.3	$ 2.42
FT	200 tonne/day	$ 70.07	$ 65.54	$ 20.86	$ 317.54	$ 107.50	$ 1,636.30	102.9	$ 3.77
FT	2000 tonne/day	$ 71.56	$ 67.03	$ 153.01	$ 232.89	$ 538.80	$ 820.09	102.9	$ 2.96

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