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Techno-Economic Feasibility of Distributed Torrefaction Systems Using Corn Stover Feedstock

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TECHNO-ECONOMIC FEASIBILITY OF DISTRIBUTED TORREFACTION SYSTEMS USING CORN STOVER FEEDSTOCK

BY

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TORREFACTION SYSTEMS USING CORN STOVER FEEDSTOCK

This thesis is approved as creditable and independent investigation by a candidate for the Master of Science in Mechanical Engineering degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

TECHNO-ECONOMIC FEASIBILITY OF DISTRIBUTED

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This study investigated the economic feasibility of distributed torrefaction biorefining systems using corn stover feedstock to generate value-added products. Distributed torrefaction systems have the potential to operate on private agricultural enterprises as well as community-scale processing facilities, similar in scale to local grain elevators. Distributed systems will thus, reduce the need for large capital investments for dedicated commercial biorefining facilities and decrease logistical concerns for harvesting and marketing the torrefied corn stover products. In this study, a techno-economic model was developed to analyze the economics of harvesting techniques, logistics, processing requirements, and end product utilization. Results were determined using baseline and sensitivity analyses to determine the effects of varied parameters on the performance of the torrefaction system and the value added products. This study indicated that distributed torrefaction could be economically viable under an array of cases of variable harvest, processing rates, and system sizes. Overall, appealing profits, payback periods, and return on investments were shown to occur.

1 Introduction to Study

1.1 General Introduction

A majority of the United States (U.S.) energy consumption comes from fossil fuel resources (e.g., coal, natural gas, and petroleum). In 2014 the United States produced nearly 4,093 billion kilowatt-hours of electricity, of which 67% was derived from fossil fuels [1]. Within the remaining 33%, 7% of power was produced using renewables and 1.7% was generated using biomass [1]. Fossil fuel resources emit higher concentration of $C0_2$ when compared to bio-based fuels, which absorb $C0_2$ during their growth cycle, making renewable energy an attractive option to meet emission requirements for power generation facilities and other energy intensive industries. In 2015, the Environmental Protection Agency (EPA) put into policy the Clean Power Plan (CPP), which requires reduction of carbon emissions on a statewide basis [2]. In order to meet the requirements put forth by the EPA, which requires that carbon pollution be reduced by 870 million tons by 2030 – 32% below 2005 levels [2] – renewable biomass resources can be used to decrease fossil fuel emissions. Although fossil fuel energy has increased in recent years, there has also been an increase in the renewable energy sector. Renewable energy consumption has increased by nearly 34% since 1980 [3] and accounted for 9.6% of all fuel energy consumed in 2014 [4], as illustrated by Figure 1.

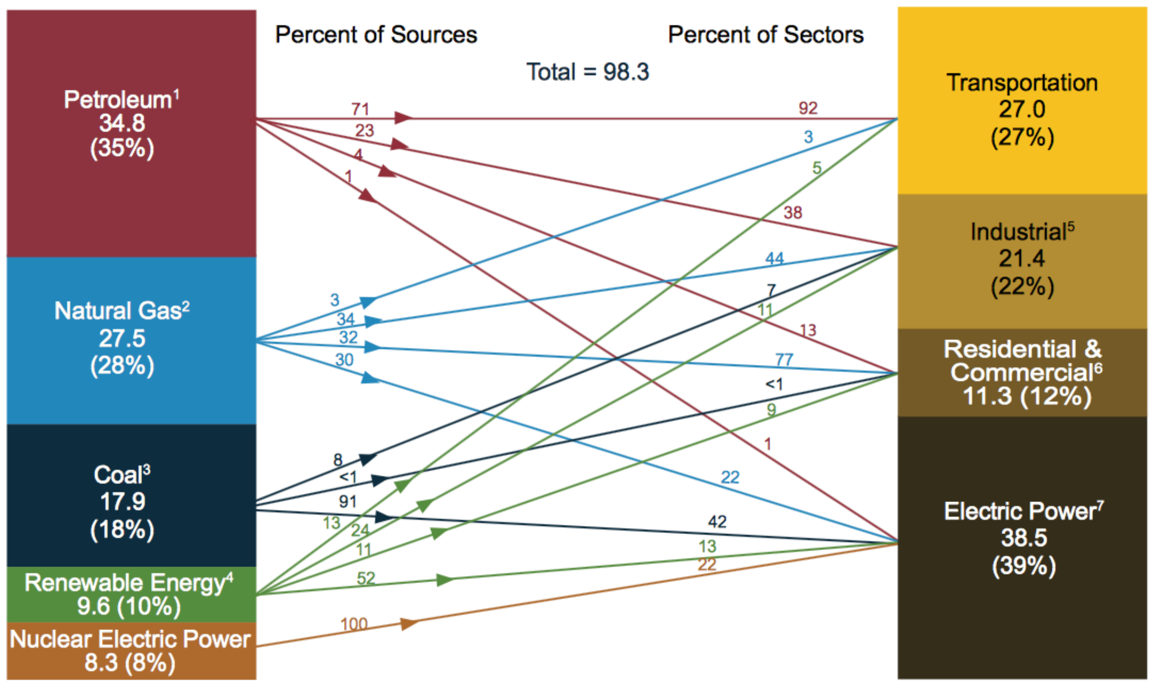


Figure 1: Primary energy consumption by source in the U.S., 2014 [4]

As governmental regulations aim to reduce the reliance on fossil fuel resources, renewable fuel mandates have been developed to subsidize the development of bio-based fuel sources and products. Renewable energy production and consumption is expected to continue increasing, partly in response to the Energy Independence and Security Act of 2007 (EISA 2007) and Renewable Fuel Standard (RFS), which calls for the production of 36 billion gallons per year of biofuels by the year 2022 [5]. Within the RFS, it is stated that 14 billion gallons per year (BGY) of advanced biofuels are to be derived from non-conventional biofuels (e.g., corn starch-based ethanol). Since federal support for ethanol production has declined, including the expiration of non-cellulosic biofuel subsidies in 2011 [6], alternative biomass based energy sources have shown to be sustainable options to meet governmental regulations and energy requirements. At the current date, nonliquid biomass energy has been primarily focused on the heat generation and biomass densification industries [7], such has wood pelletizing for home heating, although new technologies have emerged to replace petroleum based products [8].

Biomass is an important energy source as it accounts for a majority of renewable energy within the U.S. According to the 2011 Billion-Ton Study Update, biomass renewable energy accounted for 4.6% of the energy usage within the United States, where other renewable energies accounted for 4.8% of the national total [9]. Biomass is also in great abundance within the United States; the National Renewable Energy Laboratory (NREL) determined an estimated amount of 423 million tons of biomass resources are available, with the largest portion of the biomass being agricultural residue [10]. Given its abundance, biomass has potential to be a major market for sustainable energy options in the future.

Agricultural residue is comprised of both plant based (crop residue) and animal based (methane gas, manure) material. The largest contributor of agricultural residue is crop residue, where corn stover residue makes up approximately 70% of agricultural residue based upon the annual harvestable tonnage available [9]. Corn stover is the non-grain portion of the corn plant that consists of the stalks, cobs, leaves, and husks. Corn stover is typically a byproduct of corn kernel harvesting although it accounts for approximately 50% of the mass of the corn plant. There are approximately 56 pounds of shelled corn kernels per bushel of corn and, due to corn stover accounting for nearly half of the plant mass, the amount of corn stover equates to nearly the same weight of stover per bushel

[11]. This indicates that a significant amount of crop residue is left in field during the harvesting process, allowing for potential of post-harvest stover collection.

While biomass offers a renewable alternative to energy use, there are concerns associated with its use. Examples of concerns that arise with biomass, specifically corn stover residue, are the low bulk density of the material, its high moisture content, the potential for material degradation, and lower energy content per unit volume. These characteristics are notable when compared to fossil fuel resources like coal and petroleum, both of which have high mass density, energy content, and have resistance to degradation. These issues make the economics for logistics, storage, and processing difficult to be feasible in addition to being highly energy intensive.

Improving the physical and chemical properties of the material are important to increase the usability of biomass as an energy source. Baling corn stover into round or square bale configurations has shown to increase the overall density from approximately 3 lbm/ft^3 [12] to 5-10 lbm/ft^3 [7] depending on bale type. This densification method aids in decreasing the space required to transport the material, lessening logistical concerns. Corn stover can also be compacted into pellets or briquettes, significantly increasing the mass density to approximately 37-44 lbm/ft^3 [13] and further enabling the logistics and applications of corn stover.

In addition to logistical improvements, both physical (density and resistance to degradation) and chemical (energy) properties of biomass have been shown to improve during the torrefaction process [14, 15]. Torrefaction, a thermochemical reaction that occurs at approximately 200 to 300°C, is a process that is used to upgrade biomass into value-added products or fuel. The effects of torrefaction result in increased energy density, improved hydrophobicity, and enhance the ability for further densification through pelletizing methods [16, 17].

Previous research has been completed on torrefaction of biomass, and to some degree corn stover biomass [18, 19]. While many research objectives focused on temperature and reaction time of the biomass material itself [20, 21], others have focused on the potential applications for torrefied biomass [22-25]. Although torrefaction of biomass can produce value added material and chemical characteristics, scale-up technologies present a challenge for large-scale torrefaction facilities. Some of the issues for scaling from pilot scale to commercial scale include reactor design, uneven heat distribution, and decreasing conversion and energy efficiencies [26]. These issues have prevented biomass torrefaction from gaining a large presence in the energy market, although some pilot-to-commercial scale facilities have become operational with successful processing and upgrading results.

1.2 Research Objectives

This study hypothesizes that a distributed torrefaction biorefining system could be economically viable, have a favorable payback period, and be an innovative solution to the utilization of readily available biomass resources. Unlike commercial scale applications, the capital investment of the demonstration-scale distributed system could be significantly less, creating a pathway to a novel production market.

The objective of this study is to determine the feasibility of distributed biorefining systems for stand-alone use on private agricultural operations, small commercial facilities (e.g., grain elevator facility), or for implementation in a side-by-side process at a dedicated biorefining site. A techno-economic model was developed to analyze system feasibility by looking at the effects of feedstock availability, harvesting techniques and logistics, processing system requirements, and end product utilization. Results of the analyses were quantified with respect to input costs required to generate torrefied products, potential profit of processed products, the payback period of the torrefaction biorefining system, as well as the energy consumption and recovery.

1.3 Thesis Organization

This thesis is divided into five chapters that cover the background, development, and the results of the study completed at South Dakota State University. The first chapter contains a general background on the topic of bioenergy, reasoning for pursuing the study of the topic, and general outline of the thesis material. Chapter 2 provides a detailed review of literature pertaining to the history of bioenergy, biomass resources and their availability, thermochemical conversion technologies, as well as supplemental information on biorefining and other previous studies completed on biomass energy related topics. Chapter 3 discusses the development of the techno-economic model for this study, including assumptions, reasoning of selected values, and explanation of the process used in determining the outputs. Chapter 4 is comprised of the results of the economic analysis; this contains the baseline case developed and a multi-factored sensitivity analysis. The final chapter includes a summary of the work completed and recommendations for future work on the topic.

2 Review of Literature

2.1 Historical Overview of Bioenergy Applications

Bioenergy is not a new technology; humans have used various forms of biomass and biomaterials as fuel well before recorded history. The earliest forms of bioenergy commonly used wood as a fuel source, a source that is still used for heating applications today.

The most commonly noted bioenergy fuel in recent history, ethanol, predated the use of petroleum based fuels before they were discovered in 1859 [27]. As the availability of whale oils, a widely used fuel for lamps and some heating applications, diminished during the mid-1800s, the use of ethanol as a fuel substitute began to increase. During the early 1900s biofuels became increasingly popular, as petroleum refining was not meeting demand within the United States. As the exploration and production of cheaper petroleum derived products increased, biofuel production decreased, primarily within the ethanol sector. This was the case until 1917 when World War I began, which called for the rationing of petroleum products, ultimately driving production of biofuels to increase. Trends similar to this have continued in the 20th and 21st centuries, usually occurring during major political events, such as World War II, the Arab Oil Embargo of 1974, the 1979 energy crisis, as well as the introduction of renewable fuel mandates in the early 2000's [28].

In addition to the increase in biofuel production during these time periods, a revitalization of biomass energy applications was also apparent. Biomass gasification technologies were present in the mid-1800s, where it was primarily used for lighting, industrial fuel, and for some home cooking applications. Additionally, gasified biomass was also used in the development of synthetic chemicals; this was similar to a process that converted coal to synthetic fuel developed in Germany [29]. During World War I and II, gasification of coal and biomass were used within European countries when petroleum supplies became limited. Small-scale gasification units were built and attached to numerous vehicle types, ranging from cars to busses and even being used for ships and trains.

Within the United States during 1973 and 1974, the Organization of Petroleum Exporting Countries (OPEC) declared an oil embargo against the U.S. and other industrialized nations. The result of the embargo and decreased petroleum availability drove prices from $3 per barrel to as high as $12 per barrel [30] in the United States. This issue continued in 1979 during the oil crisis, in which non-OPEC nations reduced their dependence on OPEC based oil when prices increased to nearly $40 per barrel [31]. As a result of increasing oil prices, governmental initiated research programs were developed to explore alternatives to petroleum-based fuels. For example, biomass energy use, particularly wood fuels, rose from 0.3 quadrillion Btus in 1972 to nearly 1.0 quadrillion Btus by 1984 in an attempt to reduce fossil fuel resources [32]. Since the late 1970s biofuel and bioenergy production has continued to increase in order to reduce the dependence on foreign energy. This movement has largely been in part to governmental mandates, such as the Alternative Motor Fuels Act of 1988, the Clean Air Act of 1990, the Energy Policy

Act of 2005, the Renewable Fuel Standard (RFS) of 2005, and more recently, the Energy Independence and Security Act (EISA) of 2007.

Based upon the events of the past 150 years, it can be seen that although fossil fuel resources own a majority of the energy market, in times of political unrest or low energy supply, countries and governments typically revert to bioenergy technologies to stabilize the energy market. Additionally, as interest in renewable technology continues to increase, bioenergy has become more than just alternative to fossil fuels; it has become a staple in energy efficient and cost effective processes.

2.2 Current State of Bioenergy

Bioenergy has been used in many applications throughout history, many of which are still common practice. Some of these technologies, such as fermentation to create alcohols or combustion in order to produce heat, have been scaled up to large facilities to meet demands for bioenergy. Over time, advances in technology have increased the spectrum for biomass and bioenergy production, particularly in the advanced biofuel category where biomasses, such as grasses and crop residue, can now be converted into more readily useable fuels.

2.2.1 Biochemical

Bioenergy produced through means of biochemical processes have become increasingly popular within the renewable fuel market. The most used biochemical conversion type, fermentation, is currently used on a large scale to produce ethanol fuel. As of 2015, there were approximately 195 conventional ethanol facilities operating in the U.S. [33] producing nearly 14.4 billion gallons of ethanol fuel [34]. Cellulosic ethanol, derived from grasses and crop residue, has also increased in production due to the RFS, which mandates production of 14 billion gallons per year of advanced biofuels [5]. Despite the RFS mandate, the EPA ultimately reduced the requirement to 6 million gallons, and as of May 2014, it was further reduced to 0.81 million gallons [35]. This has been largely in part due to the inability to upscale cellulosic ethanol and other advanced biofuel easily; a challenge that has severely hindered the funding and building of advanced facilities.

2.2.2 Thermochemical

The use of thermochemical conversion for energy applications is very diverse as it encompasses pyrolysis, gasification, and torrefaction processes. Pyrolysis is used extensively within the chemical industry in order to upgrade and produce chemical products. Examples of common solid products are charcoal, activated carbon, and bio-char. Common liquid product applications include transforming medium-weight hydrocarbon fuels from oil into lighter products, such as gasoline, as well as converting solid biomass into liquid bio-oils. At the current date, pyrolysis use in the heat and power industry is the only form of biomass pyrolysis that has reached commercial scale. In this case of biomass solid to liquid conversion, the bio-oils produced are used in either a combustion or gasification process to produce heat and power. Additional biomass pyrolysis applications use the bio-oil product in fractionation process of extraction, fermentation, and hydrogenation to produce fuels, refinery feedstocks, oxygenates, organic acids, and other value added products [36].

Gasification is also used and has more energy-based applications due to the gaseous product being more controllable than solid fuel. Gasification is commonly implemented using coal or biomass as a feedstock to generate syngas for use as a fuel, and depending on the feedstock, the fuel produced can be considered a renewable energy application [37]. One of the most commonly known applications of gasification is within the integrated gasification combined cycle (IGCC) power plant. In this application the gasification of coal, biomass, or waste material is performed where the produced syngas is cleaned and used as fuel within a gas turbine. Here, the combustion exhaust gases and waste gasification heat pass through a heat recovery steam generator (HRSG) and produce steam for additional turbine operation. This process can be used to produce both heat and power, making it an attractive application for energy and power applications. This technology is of special interest for carbon capture and clean coal applications. While this process has merit, the initial capital investment for building IGCC power plants is costly [38] and the gasification process difficult, which has hindered the more rapid implementation of IGCC power plants.

Currently implemented torrefaction processes are typically used for upgrading products as a pre-processing technique. In some instances of biomass torrefaction, which often times uses wood as a feedstock, the primary interest of the torrefaction process is to increase the characteristics of the biomass, such as heating value, grindability, bulk energy density, or the hydrophobic nature [39]. While torrefaction is not currently a commercialized technology within the energy industry [24], it does have potential to be a factor in power generation facilities. An example of torrefaction product applications is in coal-fired power plants, where the torrefied product can be co-fired with coal to introduce a renewable energy product to a pre-existing fossil fuel process [40]. Although this application does have value, further development in the availability, processing, and post-processing must be done before torrefaction can expand to a widespread market. However, demonstration scale torrefaction facilities have been built [41] where woody-biomass is converted into a torrefied and pelletized product. These products have also been co-fired in existing coal-fired power plants, demonstrating similar heating efficiency while reducing carbon emissions.

2.2.3 Power and Heat Generation

The use of biomass for heat generation is an age-old concept that has been used throughout history. Recently, the use of biomass heat and power generation has become increasingly more popular due to the potential for CO_2-neutral energy applications [42]. At the current date, there are approximately 227 biomass power plant facilities within the U.S. that generate nearly 7,500 MW_e [43]. While these power plants generate power using biomass, the diversity of feedstock is large, including municipal solid waste, wood waste, corn stover residue, and other grass-based biomass to name a few.

Combined heat and power (CHP), or cogeneration, is a common bioenergy use that is also currently implemented. Biomass CHP is typical in the wood, pulp, and paper-milling industries where waste wood, sawdust, and other woody materials are used to generate steam and electricity for supporting the facility processes itself. A study completed in 2012 by the EIA states that nearly 57.6 Terawatt-hours (TWh) of CHP power was produced using renewable feedstocks, with approximately 35% of the power generated by non-wood biomass [44]. Operations of CHP are typically smaller in scale when compared to dedicated power generation facilities, such as a biomass or coal fired power plant [45], and are often used in industries that require the use of power and steam for processing materials.

2.2.4 Dedicated and Secondary Energy Crops

The argument of "food versus fuel" has been an increasing topic in recent years. Whether general interest or mandates have increased biofuel production, the allocation of some cropland has shifted from producing foodstuffs to biomass for bioenergy applications. The most noted scenario related to this issue is the amount of corn dedicated to ethanol production in recent years. According to the United States Department of Agriculture (USDA), approximately 38% of total corn use in the U.S. was allocated towards ethanol production in the 2014/2015 market year (September 2014 through August 2015) [46]. Alternatives to usage of food crops as bioenergy feedstocks have increased interest in dedicated energy crops, which are non-food crops used solely for bioenergy applications. In many cases these crops grow on land not suitable for conventional food crops, although they may take away from food-based cropland in some cases. A secondary option is the use of second-generation biofuel feedstocks, which includes agricultural residues, waste wood, and grasses [47]. Utilization of these byproduct feedstocks allows bioenergy production without taking away from crops allocated for food production.

2.2.5 Scaling Biomass Energy

While there are numerous bioenergy technologies at the current date, scaling from laboratory to commercial sized processes have presented challenges. Unlike traditional chemical processing industries (CPI) the biofuel processing industry (BPI) has seen limited commercial scale applications, leaving little available data to provide rapid scale-up. Another issue with BPI scale-up is the heterogeneity in biomass, which changes significantly between feedstocks. As a result, BPI scaling factors are typically smaller when compared to CPI [48], and in some cases up to an order of magnitude less than CPI (scaling comparisons shown in Table 1) when the feedstock processing rate is considered.

Table 1: Comparison of CPI and BPI scaling factors [48]

Scaling Factor (Processing Capacity)	Traditional CPI Processes Gas-Liquids	BPI Processes Dry Solids
Lab/Bench	0.001 - 0.1 (1-10 mL/min)	0.01 - 0.1 (1-10 g/hr)
Pilot	1 (1 - 5 L/hr)	1 (1 - 5 kg/hr)
Demonstration	100-1,000 (5-100 bbl/day)	10-100 (1 - 5 m.t./hr)
Commercial	10,000-30,000 (30,000-100,000 bbl/day)	1,000 - 5,000 (200 - 1,000+ m.t./hr)

Issues that arise in BPI scaling include the accumulation of material within the processing system, difficulty in supplying uniform feedstock, and the energy intensive requirements to pre-process and convert biomass. These BPI issues cause decreased process efficiency and may lead to difficulties in maintaining energy positive conversions, leading to sustainability and economic concerns. Another major issue surrounding biomass scaling is the logistical challenge of transporting low-density feedstocks [49]. Whereas solid and liquid fossil fuels are typically dense, raw biomass has a relatively low bulk density, leading to transportation and storage concerns. Currently, roadway transport is the major route for transporting biomass, whereas coal and petroleum products rely on rail transport and pipeline transmission.

2.3 Biomass Energy Resources

Biomass is an important energy source as it accounts for a majority of renewable energy within the United States. According to the 2011 Billion-Ton Study Update, biomass renewable energy accounted for 4.6% of the energy usage within the United States, where other renewable energies accounted for 4.8% of the national total [9]. Biomass is also in great abundance within the United States. The National Renewable Energy Laboratory (NREL) determined an estimated amount of 423 million tons of biomass resources are available [10], where the largest potential source of biomass being agricultural residue [50].

2.3.1 Agricultural Residue – Corn Stover

Agricultural residue can be divided into two main categories; animal based and plant based. While animal waste (manure) can be used as a source of methane gas or combusted, plant-based residue – specifically crop residue – can be used in for multiple purposes ranging from direct biomass combustion to a feedstock for value added upgrading. The largest contributor to the crop residue supply is corn stover residue. Corn stover is the non-grain portion of the corn plant that consists of the stalks, cobs, leaves, and husks, accounting for 70% of agricultural residue of the annual harvestable tonnage available [9]. Corn stover is a byproduct of corn kernel harvesting even though it accounts for approximately 50% of the mass of the corn plant. Being that there is approximately 56 pounds (lbm) of shelled corn kernels per bushel of corn produce, it can be determined that the corn stover residue equates to nearly the same weight on a per bushel basis [11].

Corn stover is a byproduct of the corn harvesting process and is typically applied back onto the cropland where it was grown and either left on the surface or tilled into the soil. In both cases, the chopped corn stover acts as a combatant against soil erosion and aids in returning essential nutrients back into the soil itself; an essential step in the growth cycle for future crops. Stover decomposition delivers significant amounts of phosphorus (P) and potassium (K) back into the soil, which are essential for plant growth. However, it has been shown that sustainable stover removal has advantages to the soil as well, primarily in Northern corn producing regions where the colder climate causes slower decomposition of the plant material [51]. In Northern regions the addition of crop residue to the surface and subsurface also increases the insulating effect on the ground, whereas the removal of excess residue allows the soil to increase in temperature earlier within the growing year. In this case the partial removal of corn stover can allow for earlier planting and the option of planting longer maturity corn crops. In an effort to determine the effects of corn stover removal from fields on future crop yields, the University of Missouri conducted research by comparing multiple methods of corn stover removal and nutrient addition, including row cleaning, nitrogen applications, stalk chopping, and removal by baling half of the on-surface residue [52]. Results of the research, displayed in Figure 2, show that baling and removing the stover residue proved more effective in increasing the grain yield versus other management practices in no-till, corn-corn crop rotations. Although additional effort is associated with baling and removing stover residue, increased yields have the potential to mitigate or eliminate the implemented residue management cost.

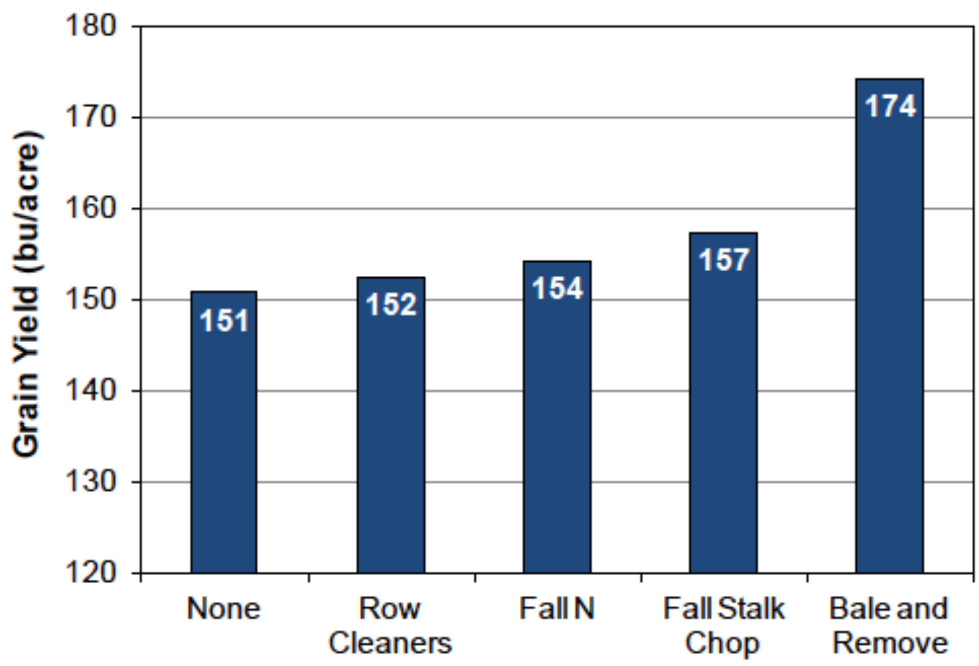


Figure 2: Grain yield as a result of stover management practices on continuous corn crop rotation [52]

While the removal of corn stover from fields has shown to have attractive outcomes in terms of future corn crop yields, removal of the corn stover does reduce the amount of nutrients that are returned to the soil through plant decomposition. This can lead to additional costs in nutrient addition that may need to occur in order to adequately supply future crops with nutrients. Being that there is no definitive amount of residue that could (or should) be removed during agricultural management practices, recommendations for the amount of residue removal are based on an array of factors that could affect soil quality and longevity. The primary factors to take into account include the slope of the field for potential runoff, soil composition, typical weather conditions based on the specific region, and agricultural management (harvest, planting, fertilization, etc.) practices. Table 2 shows a range of values for the amount of stover recommended to remain in field to protect soil against wind and water erosion, based upon specific harvesting and planting techniques. Based upon research conducted, it can be seen that there are significant increases in stover availability for corn-corn rotations. It can be approximated that the amount of stover to remain in field varies between 2.3 tons per acre (tons/ac) for corn-corn rotation and upwards of 5.2 tons/ac for corn-soybean rotations [53].

Table 2: Stover retention to prevent erosion and support soil nutrification [7, 51, 53]

Retention Amount ($tons_{wet}$/ac)	Crop Rotation	Field Management Technique	Ref.
3.4	Corn-Corn	Plow	[53]
2.3	Corn-Corn	No-Till	[53]
5.6	Corn-Soybean	Plow	[53]
3.5	Corn-Soybean	No-Till	[53]
2.3	Corn-Corn	No-Till	[51]
3.5	Corn-Soybean	No-Till	[51]
4.8	Corn-Soybean	Plow	[7]
2.2	Corn-Corn	Plow	[7]

Average Retention Metric	No-Till Retention ($tons_{wet}$/ac)	Plow Retention ($tons_{wet}$/ac)
Corn-Corn	2.3	2.8
Corn-Soybean	3.5	5.2

2.3.2 Harvesting Techniques

Since corn stover is a byproduct of the corn harvesting process, a majority of it is left on the ground or chopped by the corn head. Upon harvest, corn stover typically contains twice the moisture content (MC) as the corn kernel itself, where corn is often harvested between 15 – 30% MC. Typical moisture contents of the corn stover, based on approximately 15% MC of the corn kernel itself at harvest, are 19% MC, 24% MC, and 33% MC for the cobs, husks, and stalks/leaves, respectively [54]. Additionally, in cases where corn moisture is higher, such as that of being near 23% MC during typical harvesting periods, the stover moisture content is significantly higher than 30% MC. This high moisture content can lead to a multitude of issues, making high moisture stover unsuitable for most harvesting practices [55, 56]. High moisture content requires the aid of field drying to achieve suitable short-term storage moisture content. Although highly wet raw stover is less favorable for long-term storage, it does have uses as silage or bedding for feedlot operations.

The process to gather the stover crop can take as many as four operations depending on the type of harvest technique. While cob collection can be done directly from the combining process, this only allows for collection of approximately 15% of the corn residue [7]. A common process is baling the stover residue (stalks, cobs, leaves, and husks), which can be broken into two main processes – multi-pass and single-pass – both having varying degrees of options. Multi-pass baling is common among farming practices whereas single-pass baling is a newer harvesting development and is not as commonly practiced. Baling operations typically consist of raking the stover (this operation can also be foregone if less stover collection is desired), baling into large square (0.6 $tons_{wet}$/bale) or round bales (0.75 $tons_{wet}$/bale), collecting the baled stover, and transporting to a storage or processing site.

Multi-pass baling begins with disengaging the combine residue spreader so that the stalks, cobs, leaves, and husks are dispensed directly behind the combine rather than spread over a vast area. Depending on the desired amount of collection the stover can be raked or left as is for baling. By raking the stover approximately 50% of the stover can be removed, whereas the non-raking option allows for 25-30% stover removal [7]. Raking involves passing over the crop residue and forming a windrow, similar to that of hay baling, which is then collected by either a round or square baler. During non-raking, a baler is passed of the loose stover residue and collected by similar means.

Single-pass baling involves a large square or round baling system used in conjunction with the combine during the harvest process. This option eliminates dispensing the stover residue to the ground as well as ranking, decreasing the likelihood of rocks, dirt, and other foreign material from entering the bale [57]. Depending on the moisture content of the corn stover, baling of this type may require further air-drying of the bales post-harvest.

There are benefits for selecting either round or large square bales, although collection and transport remains similar for both multi and single-pass baling. Round baling equipment cost is generally lower than that of square baling equipment, though square bales are easier to handle due to their uniform shape. The logistics of the stover crop involves transporting the stover bales to storage or a processing site as well as stacking the product. The uniform size and shape of square bales has another advantage; the bales stack in a denser manner, requiring less space than that of round bales. This holds true for both transport and storage of square bales, which can make it a more efficient option.

2.4 Bioenergy Conversion

In order to utilize biomass, forms of chemical conversion technologies can be used to change the properties of the biomass and produce liquid, solid, and gaseous products. The three foremost types of chemical conversion technologies for biomass include biochemical, physicochemical, and thermochemical conversion processes. A diagram showing the three primary pathways is shown in Figure 3. Currently, biochemical (fermentation and anaerobic digestion) and physicochemical (esterification) conversions are the most implemented in liquid biofuel production of ethanol and biodiesel, respectively. In order to generate gaseous and solid energy products from biomass, the use of thermochemical conversion can be used, such as in the case of creating a bio-based charcoal. Whereas physicochemical and biochemical processes require the use of catalysts or microbes to induce reactions, thermochemical conversion relies on the addition of heat. Thermochemical conversions have multiple pathways; pyrolysis, gasification and combustion are the bases for the process, although sub-processes within this, such as torrefaction, are also common.

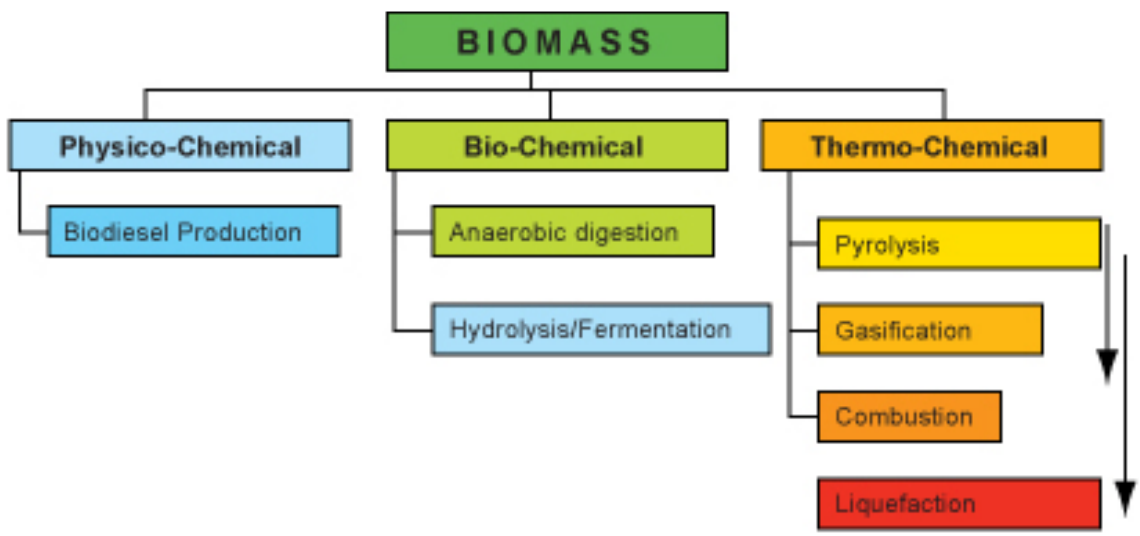


Figure 3: Typical biomass conversion pathways [58]

2.4.1 Thermochemical Processes

Conversion of biomass by the means of thermochemical conversion can be useful to upgrade solid materials, generate heat and power, as well as produce syngas. Thermochemical reactions can occur at temperatures ranging from 572°F to 1832°F that can produce an array of chemical conversions pathways. Depending on the temperature and oxygen availability in the environment, there are different processes that occur. The most notable of these processes are combustion, gasification, pyrolysis, and torrefaction; each which can be used to convert solid biomass feedstock [59]. Each has specific uses, such as heat generation, upgrading of materials, or capturing off-gasses.

2.4.2 Combustion

Combustion is one of the simplest methods to convert biomass into a useable energy (heat or electricity) with byproducts of charred ash. This method is a widely used thermochemical process, where biomass accounts for nearly 11% of fuels used for combustion [60]. Combustion is an exothermic reaction that results in a notable amount of heat generation that continues as long as material is available and at high enough temperatures [59]. For the process to occur, energy is required in the form of heat to initiate the combustion of the material, which then proceeds to combust using the energy from the material itself. This process can be done in a batch process, such as a wood stove [61], or in a continuous cycle similar to that of a boiler or steam generator application.

Combustion is a popular thermochemical pathway as it is the most simple and it can be implemented on a diverse array of biomass feedstocks. One stipulation for using combustion to convert biomass to heat energy is the moisture content of the feedstock. Moisture levels within the biomass must typically be lower than 60% moisture on a wet basis [59, 61] or a reduction in material temperature could occur, ultimately decreasing in combustion efficiency and preventing continuous combustion [61, 62]. Biomass first begins losing moisture during the drying stage of combustion, which occurs around 212°F [63].

Applications of biomass combustion range from traditional uses (e.g., wood burning for home heating or cooking) to industrial applications, such as steam generation in the Rankine cycle for electrical generation [60]. Additionally, CHP applications also utilize biomass as a heating fuel, with excess steam from the turbine generation stages used to provide steam heat for facility heating or process equipment.

2.4.3 Gasification

Gasification is another thermochemical process that can be used to process raw biomass into a usable product by undergoing the processes of dehydration, pyrolysis, combustion, and gasification. The primary product of the gasification process is syngas, or a synthetic gas comprised of mostly hydrogen compounds (H and H_2), carbon monoxide (CO), carbon dioxide (CO_2), and other carbon compounds (C_2^+) [64]. For this thermochemical process to occur, temperatures need to reach levels near 1,292°F to 1,832°F [65, 66] in a limited or oxygen free environment to prevent combustion of the biomass.

Gasification applications can be performed to produce syngas products from a variety of feedstocks, including coal, biomass, and other waste-based sources. The use of gasification has often been employed in integrated gasification combined cycle (IGCC) power plants, where the syngas produced is used as fuel for a gas turbine. By utilizing biomass as a feedstock for gasification in IGCC applications, similar efficiencies as a coal fired power plants can be reached while maintaining the use of renewable energy sources.

As in the case of many bioprocessing technologies, there are drawbacks associated to using biomass in gasification. The most notable of these is the production of a tar-like substance as a byproduct, which may cause issues in the gasification process by inhibiting or blocking flow. Additionally, the net-energy usage of the gasification process has also been called into play as an issue, stating that more energy is consumed than is produced during the gasification process.

2.4.4 Pyrolysis

Pyrolysis is a thermochemical reaction where organic and inorganic materials are thermally decomposed at high temperatures in an inert environment to produce liquid, solid, and gaseous products that can be used as a drop-in fuel or upgraded for further applications. The pyrolysis process can be divided into three categories comprised of slow (conventional), fast, and flash pyrolysis. These categories are determined by temperature and the heating rate of each process.

Slow pyrolysis takes place at lower temperatures with temperatures ranging from approximately 662°F up to 932°F, whereas fast pyrolysis occurs at higher temperatures from 662°F to 1202°F. Flash pyrolysis is similar to that of fast, although temperatures are much higher (1430°F to 1880°F). Additionally, slow pyrolysis occurs at rates of 32°F/s to 33.8°F/s, where fast and flash pyrolysis take place during rates of 50°F/s to 212°F/s or higher [67]. During the process, raw materials are thermo-chemically converted into solids, non-condensable gases, and condensable gaseous products (which can later be condensed into bio-oil). As in the case of thermochemical processes, changing the heating rate (°F/s), residence time (s), or other federate parameters can yield different amounts of solid, liquid and gaseous products [68].

The pyrolysis process is more energy intensive and less efficient when compared to other thermochemical processes; however, the products from the process can be upgraded or used more easily than those of other processes (e.g., upgrading pyrolysis bio-oil compared to gasification syngas). The primary product of the pyrolysis process is a liquid bio-oil, which can be more advantageous than gas as it takes less post-processing to make storable or usable, while having an energy density much greater than gas. Often times, the oxygen content of the bio-oil is higher than that of a typical hydrocarbon fuel. In order to upgrade the bio-oil, processes such as hydrodeoxygenation (HDO), or hydrotreating, can be implemented [69]. This upgrading treatment process introduces hydrogen (H) to the bio-oil through thermal heating and mechanical mixing at temperatures near 572°F, which chemically alters the bio-oil to improve the energy content of the fuel.

2.4.5 Torrefaction

Torrefaction is a subcategory of thermochemical processing, as it is a form of mild pyrolysis with heating rates of approximately 122°F/s. The process is similar to other thermochemical processing as it takes place in an oxygen-deprived reaction but it occurs at much lower temperatures (392°F to 572°F) when compared to other pyrolysis processes. The greatest difference between torrefaction and other thermochemical processes is the purpose for which it is being employed [70] – torrefaction targets maximum yields of solid products with gaseous products as a secondary product. In addition to trying to maximize solid product yield, torrefaction also aims at maximizing the energy content of the solid product by using low temperature reactions to remove low energy content volatiles from the feedstock. The torrefied solid product shows significant mass and energy densification when compared to the raw feedstock, making it an attractive option for uses in power generation, CHP and other bio-based applications.

2.5 Overview of Torrefaction Process

Torrefaction is a thermochemical process that can be used to convert raw feedstock, either organic or inorganic, into a solid product that has both increased mass and energy density characteristics. These chemical changes in energy and physical changes in mass are attributed to the thermal degradation of the biomass as temperatures increase during the reaction process. The densification of energy and mass occurs in the absence of oxygen and can be done on either a dry or wet basis [71, 72], although increased moisture content of the biomass requires a more energy intensive process in order to remove moisture from the feedstock. Moisture removal and thermal degradation of the biomass occurs as unbound moisture and volatiles are evaporated, in addition to bound moisture being removed during the drying process. The moisture and volatile removal results in biopolymers (cellulose, hemicellulose, and lignin) being partially decomposed [73] and leaving a dry, hydrophobic, solid material as an end product.

While the basis of the torrefaction process is relatively simplistic, there are many factors that can affect the degree of conversion that occurs during the process. One of the foremost factors affecting the outcome of the torrefied product is the temperature and heating rate at which process occurs. As with pyrolysis, gasification, and other forms of thermochemical conversion, the heating rate (approximately 122°F/s for torrefaction) and temperature range can affect the amount solid, gaseous, and liquid (condensable gases) that is produced during the reaction. In the case of torrefaction, it is important to maximize the amount of solid product, ideally with little to no liquid product being formed during the reaction. While there has been research conducted on torrefaction of corn stover [74, 75] a majority of research has been conducted on woody biomass [24, 76-78] and other biomass feedstocks [21, 79-81]. In many of these research cases the temperature of the torrefaction range was an important factor. A summary of researchers, feedstocks and proposed temperature ranges used for the torrefaction of various biomass resources can be seen in Table 3, with typical torrefaction temperatures extending from 392°F to 572°F.

Table 3: Torrefaction temperature ranges from various researchers and feedstock applications

Researcher	Feedstock Type	Temperature Range	Ref.
Arias et al. (2008)	Woody Biomass	428-572^{o}F	[78]
Chen and Kuo (2010)	Bamboo, Willow Coconut Shell, Wood	437-572^{o}F	[79]
Prins (2005)	Woody Biomass		[82]
Zwart et al. (2006)	n/a - Biomass (Generic)		[83]
Pimchuai et al. (2010)	n/a - Agricultural Residue	446-572^{o}F	[21]
Prins et al. (2006)	Woody Biomass		[77]
Bergman et al. (2005)	Woody Biomass	392-572^{o}F	[24]
Tumuluru et al. (2011)	n/a - Generic		[84]
Rouset et al. (2011)	Bamboo		[80]
Sadaka and Negi (2009)	Wheat and Straws		[81]

During the initial stages of the of the torrefaction process, heat is required to begin removal of bound moisture within the material. The drying process demands the greatest input as it takes a large energy input to remove the bound moisture within the stover [85]. It has been shown that the thermal behavior during the torrefaction process shifts from being endothermic at lower temperatures to more exothermic with increasing temperatures [86]. This occurrence can be attributed to the pyrolysis effects of cellulose, which is endothermic in nature, and the degradation of hemicellulose and lignin, which is exothermic [87]. This transition from endothermic to exothermic reactions decreases the energy required to process the biomass feedstock and also creates potential for additional energy savings through heat recovery and pre-heating measures.

Another important aspect of torrefying biomass is the size of the feedstock particles. By grinding, milling or pre-processing the biomass into fine particles the overall surface area is increased, ultimately increasing the heat transfer characteristics of the feedstock particle. Additionally, by pre-processing the biomass a more uniform feedstock particle can be created, increasing the potential for uniform torrefaction throughout the process. Some issues do arise by pre-processing the non-torrefied biomass due to the soft, non-brittle characteristics of raw feedstock, which increases the required input energy [70].

2.5.1 Torrefaction Processing Stages

The torrefaction process can be done on both continuous and batch scales, and while the continuity of the process may change, the stages in which the biomass is converted is similar. The primary stages that a feedstock will experience during the process can be broken down into heating, drying, transformation of the material on either a chemical or physical basis (torrefaction degradation and densification) and cooling of the product. Temperatures, heating rates, and residence time within each stage control the degree in which the torrefaction occurs. A simplified diagram showing the basis of the torrefaction process is shown in Figure 4.

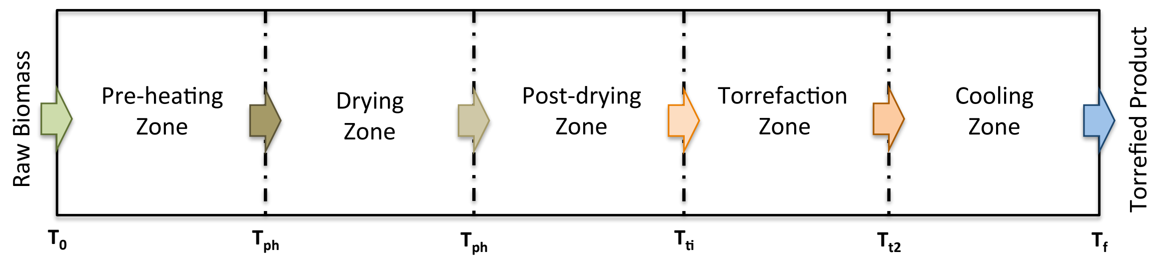


Figure 4: Simplified torrefaction process heating and cooling stages (modified from Gerometta 2014 [74])

The first stage of the process involves material preparation, which includes chopping, milling, or grinding the biomass into smaller fragments for processing. Once completed, the feedstock is then submitted to a series of drying stages including a pre-heater, a dryer, and a post-dryer. Throughout these stages, the biomass feedstock is raised from ambient temperatures to 212°F (T_{ph}) in the pre-heater to initiate moisture evaporation, held at 212°F through the drying zone and ultimately reaching upwards of 392°F (T_{t1}) in the post-drying zone, where physically bound moisture is removed. Once this temperature is reached torrefaction begins and heat is added to the feedstock until temperatures reach near 572°F (T_{t2}). At this point in the process, condensable vapors are either captured or used for fuel elsewhere (if applicable) and non-condensable vapors (volatiles) are removed or used for heating in other energy intensive process stages (e.g., used as fuel supplementation in the drying stage). Once torrefied, the solid product is cooled from its maximum temperature (T_{t2} to a temperature suitable for post-processing (T_f)). During this stage, waste heat from the cooling process can be recovered and used within the preheating stage to reduce energy (fuel) input to the system.

2.5.2 Process Energy

Energy input is required in the form of heat to adequately convert the raw feedstock to a charred final product. Pre-heating is the first stage and is the least energy intensive of the heating processes. Here, the temperature increases sensibly at a steady rate of less than 122°F/s from ambient (T_0) conditions up to approximately 212°F (T_{ph}). In this stage the unbound moisture begins the removal from the biomass while at the same time the temperature of the raw biomass is increased without initiating the effect of drying. Moisture removal during this stage primarily occurs in the constant-rate period of drying where water is entirely unbound and acts as though no solids were present. The energy (heat) required to elevate the biomass temperature and remove unbound moisture is modeled in Equation 1.

$$Q_{ph} = \frac{m_s C_{pw}(212 - T_0)}{h_{uph}} \quad \text{[Eq. 1]}$$

Where: Q_{ph} = Energy required for pre-heating the biomass (Btu)

m_s = Mass of the raw biomass as received (lbm_{wet} basis)

C_{pw} = Specific heat of raw biomass (Btu/lbm-°F)

T_0 = Initial temperature of the as received biomass (°F)

h_{uph} = Heat utilization factor in pre-heating process

Drying is the most energy intensive step as moisture bound within the biomass is removed at this point, making high moisture biomass drying highly energy intensive [85]. Throughout this stage the temperature is held constant at 212°F (T_{ph}) or higher depending on the resultant temperature from the pre-heating stage. Throughout this stage the temperature of the biomass does not see a significant increase, although the latent heating load increases throughout the falling-rate period of drying. The total energy (heat) required during the drying stage is shown in Equation 2.

$$Q_d = \frac{LM_f m_s}{h_{ud}} \qquad \text{[Eq. 2]}$$

Where: Q_d = Energy required for drying of the biomass (Btu)

L = Latent heat of vaporization of water at 212°F (Btu/lbm)

M_f = Moisture fraction of raw stover

m_s = Mass of the raw biomass as received (lbm)

h_{ud} = Heat utilization factor in dryer

Post-drying is the final drying stage in which the biomass is heated until it reaches the minimum torrefaction temperature of 392°F (T_{pd}) [85]. Under this temperature, trace amounts of decomposition occur [24] and the moisture physically bound by the stover is removed through sensible heating. It is because of this that the energy requirement for this drying stage is minimal as well [85]. Upon the end of the drying stage, the biomass moisture content is nearly zero, having both unbound and bound moisture removed by this point in the process. The energy (heat) required for this processing stage is modeled by Equation 3.

$$Q_{pd} = \frac{m_s(1-M_f)C_{pd}(T_{t1}-212)}{h_{upd}} \quad \text{[Eq. 3]}$$

Where: Q_{pd} = Energy required to increase biomass to torrefaction temperature (Btu)

m_s = Mass of the raw biomass as received (lbm)

M_f = Moisture fraction of raw stover

C_{pd} = Specific heat of dried biomass (Btu/lbm-°F)

T_{t1} = Minimum torrefaction temperature (°F)

h_{upd} = Heat utilization in post-drying process

The most important stage in the process is the torrefaction stage where a majority of the material degradation occurs. This stage occurs once the dried stover reaches the torrefaction temperature (T_{t1}) of 392°F. The energy that is required during this process is dependent on whether the stover is endothermic or exothermic, shown as X_t, which is positive for endothermic and negative for exothermic reactions [85] and determines the amount of heat absorbed during the torrefaction process. Once temperature elevates to approximately 482°F, the torrefied material becomes exothermic and begins releasing heat as the stover breaks down [82], significantly reducing the required energy input for this process stage. During this stage the residence time and temperature are critical in determining the degree of torrefaction that occurs. Final torrefaction temperatures (T_{t2}) during this process reach approximately 572°F. The residence time during this process is measured from the point where the temperature of the biomass reaches 392°F, with any degradation occurring below this temperature assumed to be negligible compared to complete torrefaction [85]. In addition to torrefaction occurring during this stage, both condensable and non-condensable (volatile) vapors are emitted from the degradation of the biomass feedstock. These flue gases can then be recovered for further use in either drying, post-drying, or within the torrefaction stage to alleviate total energy consumption throughout the process. The energy needed for this portion of the torrefaction process is shown in Equation 4.

$$Q_t = H_L + m_s(1 - M_f)X_t \qquad \text{[Eq. 4]}$$

Where: Q_t = Energy required for torrefaction process (Btu)
H_L = Heat loss to the environment (Btu)
m_s = Mass of the raw biomass as received (lbm)
M_f = Moisture fraction of raw biomass
X_t = Heat absorbed/emitted during torrefaction process depending on endothermic/exothermic reactions (Btu/lbm)

Although the cooling process does not require energy input, heat recovery from this stage can be utilized to exchange heat back into the drying stages. Heat recovery is most effective at this point in the process as the torrefied biomass enters the cooling stage at the peak torrefaction temperature near 572°F. This allows for increased sensible heating during the heat recovery process as the torrefied biomass temperature is heavily reduced to post-processing temperatures (T_f). When employed, this heat recovery operation can alleviate the energy input of the pre-heating and drying processes. As a result, this generates a more efficient system, resulting in energy savings as well as creating a more sustainable process. To determine the amount of energy that can be exchanged from the cooling zone to the heating zones, Equation 5 can be used.

$$Q_c = m_s(1 - M_f)MY_{db}C_{pt}(T_{t2} - T_f) \qquad \text{[Eq. 5]}$$

Where: Q_c = Energy available for heat recovery (Btu)

m_s = Mass of the raw biomass as received (lbm)

M_f = Moisture fraction of raw biomass

MY_{db} = Mass yield of torrefied biomass on a dry basis

C_{pt} = Specific heat of torrefied biomass (Btu/lbm-°F)

T_{t2} = Peak temperature as biomass leaves torrefaction stage (°F)

T_f = Temperature of biomass once cooled to post-processing temperature (°F)

2.5.3 Degree of Torrefaction: Mass & Energy

Depending on the temperatures used within the torrefaction range, the degree of torrefaction varies between light, medium, and severe for approximate temperature ranges of 392-464°F, 464-500°F, and 500-572°F, respectively [70]. Consequently, the mass yield can be significantly changed by the degree of torrefaction. Previous research has shown that mass yields can vary from less than 70% up to 90% depending on the temperatures used [20, 45, 74]. Similar to that of mass, energy yields have also been shown to decrease as the degree of torrefaction increases, with yields as high as 95% falling to 80% or lower [20, 45, 74]. This trend results in the most torrefied feedstock having the greatest increase in energy density when compared to the raw feedstock energy density. However, it has been shown that increased degradation of the biomass feedstock during higher degrees of torrefaction may be unsuitable for energy applications [79].

2.6 Corn Stover Market Considerations

The uses for corn stover residue are growing in interest and application as the need to meet governmental mandates, increase renewable options, and farm using more sustainable agricultural practices becomes more prevalent. Corn stover can be harvested or grazed for livestock feeding, refined in processes to create solid and liquid biofuels, as well as converted into value added bio-products. Although corn stover is widely available, there are currently few applications for it other than that of agricultural use. Progress has been made to use corn stover as feedstock for cellulosic ethanol [88, 89] but many challenges have risen with this process, and therefore, the market for cellulosic corn stover ethanol has yet to expand. Other uses of corn stover been developed, such as building material and fuel pellets, but as with other corn stover applications the use has yet to become widespread.

2.6.1 Agricultural Applications

Corn stover residue has existing presence within the agricultural market while remaining a secondary crop. The main uses of corn stover are non-energy related; typical uses are for soil nutrition and erosion control. The most common non-energy use for corn stover is in the agricultural industry as a means of forage, silage in feedlot production, and as bedding for livestock. As a feed source, stover can be used in conjunction with hay and dried distiller grains (DDGs) as a supplement for an affordable feedstock [90]. As a feed supplement, corn stover can replace 1.2 to 1.3 tons of hay per year for cattle weighing between 1,200 and 1,400 pounds [90]. In the years from 2012 to 2014, the total number of cattle in the United

States, including feedlot and range grazing, was estimated to be between 87 and 97 million head with feedlot specific cattle estimated between 12 and 14 million head [91]. Corn production for these years was shown to yield between 10.8 to 14.2 billion bushels of corn, providing upwards of 302 to 397 million tons of corn stover [92]. In the extreme case that each cow consumed the maximum amount of corn stover at 1.3 tons of stover per cow, stover consumption for feedlot supply would require approximately to 32% of the total available stover within the country. However, since feedlot cattle make up a smaller portion of the total cattle amount, the actual consumption amount decreases significantly. Cattle consuming feed directly, either in a feedlot or dairy setting, account for approximately 15% of the total, which ultimately reduces the total corn stover consumption down to nearly 5% of the total available amount. This shows that while corn stover use for livestock feed does reduce the available amount, a significant amount of corn stover remains available for energy industry applications.

2.6.2 Cellulosic Biofuels

Cellulosic ethanol is a recently developing energy market for corn stover. Cellulosic ethanol differs from conventional ethanol as it can be developed from a variety of biomass feedstocks rather than being limited to corn or sugars. Ethanol facilities of this nature require large quantities of biomass feedstock delivered by over highway trucking or railway transportation to continuously run the conversion process. In recent years, DuPont, POET-DSM, and Abengoa Energy have each constructed cellulosic ethanol plants in Nevada, IA, Emmetsburg, IA, and Hugoton, KS, respectively. The biomass and stover consumption of each facility, displayed in Table 4, is shown to vary depending on the facility. Additionally, each plant can operate on a variety of feedstocks, although corn stover residue is the most prominent at each of these facilities. Each facility requires more than 285,000 tons of stover or biomass per year to run at full nameplate production rate [88, 89]. The total consumption of corn stover for cellulosic ethanol conversion is approximately 1 million tons per year, which equates to less than 1% of the total stover crop available when compared to the total available amount from studies conducted by NREL [10].

Table 4: Cellulosic ethanol facilities currently in operation within the United States [88, 89]

Facility Title	Facility Location	Operating Capacity (tons/year)	Purchase Radius (miles)	Ref.
DuPont - Nevada Site Cellulosic Ethanol Facility	Nevada, IA	375,000	30	[88]
POET-DSM Project Liberty	Emmetsburg, IA	285,000	45	[89]
Abengoa Energy - Hugoton Cellulosic Ethanol Facility	Hugoton, KS	300,000	50	[88]

2.6.3 Biomaterial Products

An emerging topic of interest about biomass is in biomaterial applications, such as the biomass material construction industry. Biomass has been studied in the past for use in building products, with the most notable being that of wood. In recent years, corn stover has also become a material of interest for use in solid building and insulating materials [93, 94]. As a building material corn stover can be manufactured as particleboard or oriented strand board (OSB) for use in structural applications, flooring, roofing, and sheathing applications. Biomass can also be blown in as a loose insulation, offering a renewable option to insulation typically made of fiberglass or plastic-based material.

2.6.4 Solid Biomass Energy Fuels

Pelletized stover is an emerging market for corn stover byproduct in the energy industry and is already common for fuel woods like sawdust and woodchips [95]. Dried corn stover has a HHV of approximately 7,560 Btu/lbm, which is near that of wood (8,570 Btu/lbm) [96]. Pelletizing offers increased benefits when compared to raw stover, as it is significantly denser than raw, loose corn stover. Pelletized corn stover can also be used in auger systems, hopper bottom semi-truck trailers, and stored in silos without machinery modifications [7]. An upcoming and popular use for pelletized stover is use within coal-fired power plants as a heating fuel source. This is one option that has gained interest recently due to emission regulations, and since corn stover is a renewable product, there is a sense of "carbon neutrality" when using it as a fuel source. Another option for pelletized stover fuel is in residential pellet stover heating applications, where the pelletized corn stover can be sold in commercial retail venues as more traditional wood pellets.

2.7 Summary of Literature Review

Biomass energy applications have shown to gain and lose interest throughout history, deepening on the availability of fossil fuel sources. However, by investing in biomass conversion technologies for the future, a market can be further established to make the volatile market of the past a more consistent pathway for biomass energy.

Corn stover is a promising pathway for bioenergy applications and can be used to convert an abundant biomass resource into a value upgraded fuel or material. Corn stover itself is an appealing resource for a variety of reasons, including:

i. Being the most abundant of crop residues
ii. Its widespread availability throughout the Central and Eastern regions of the U.S.
iii. An energy content (HHV) similar to that of wood
iv. The ability to alleviate emissions in power plant facilities through co-firing and primary combustion

Conversion of corn stover through means of torrefaction is also a favorable upgrading pathway due to the high solid mass yield potential and the relatively low temperatures in which the process occurs. The clean and simple process is also important for the widespread implementation of corn stover torrefaction; high complexity processes and issues of biorefining have shown to make scale-up technology increasingly difficult. By implementing cost-effective processing techniques, the scale-up of corn stover torrefaction could have the ability to generate clean, efficient, and profitable bioenergy solutions.

3 Techno-Economic Modeling Approach

3.1 Introduction

In order to quantify outcomes for utilizing corn stover as a feedstock for torrefaction on a distributed basis, a techno-economic model was developed using Microsoft Excel. The primary basis of the model was to analyze the feasibility of the torrefaction system in regards to payback period by looking at the profitability of the value added torrefied stover product and the necessary input cost considerations required for a system of this type. Prominent factors built into the model included harvesting consideration and techniques, logistical information for transporting the corn stover feedstock, the requirements for the torrefaction processing system, energy for heating the feedstock to the required temperatures, heat and torrgas energy recovery, and lastly, end product utilization. An overall process-flow diagram of the model can be seen in Figure 5.

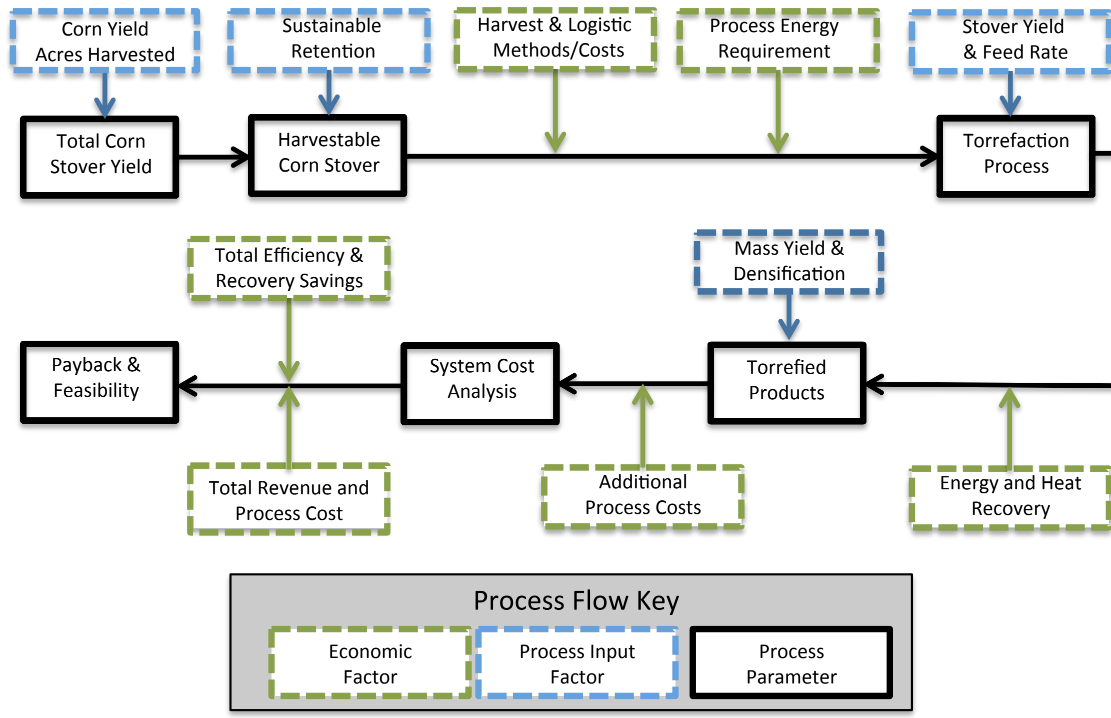


Figure 5: Process-flow diagram of techno-economic model with unit steps (black), process input parameters (blue), and economic factors (green) shown

3.2 Availability of Corn Stover Feedstock

While corn stover is an abundant resource, making up nearly 70% of the available harvestable tonnage [9], there are considerations that should be taken into account before the commercial-scale harvesting of corn stover residue. The availability of corn stover residue is directly related to the yield of field corn and accounts for nearly 50% of the mass of the corn plant. This relationship leads to a greater availability of corn stover feedstock in areas where the greater corn yields occur. Establishing an estimate for corn yields is the first step in determining the potential for stover harvest, which can vary based on a multitude of factors.

3.2.1 Corn Crop Yields

To determine an estimate of corn yields, and ultimately the stover yield, historical data based on information from the United States Department of Agriculture (USDA) and the National Agricultural Statistics Service (NASS) was collected. Estimated corn production, displayed in Figure 6, is shown to be the greatest in the upper Midwest states and the Western Great Lakes region, with some counties producing more than 20 million bushels of corn. It can also be seen that there is little to no production in the western mountain states and that some significant production is present in the eastern and southeastern United States.

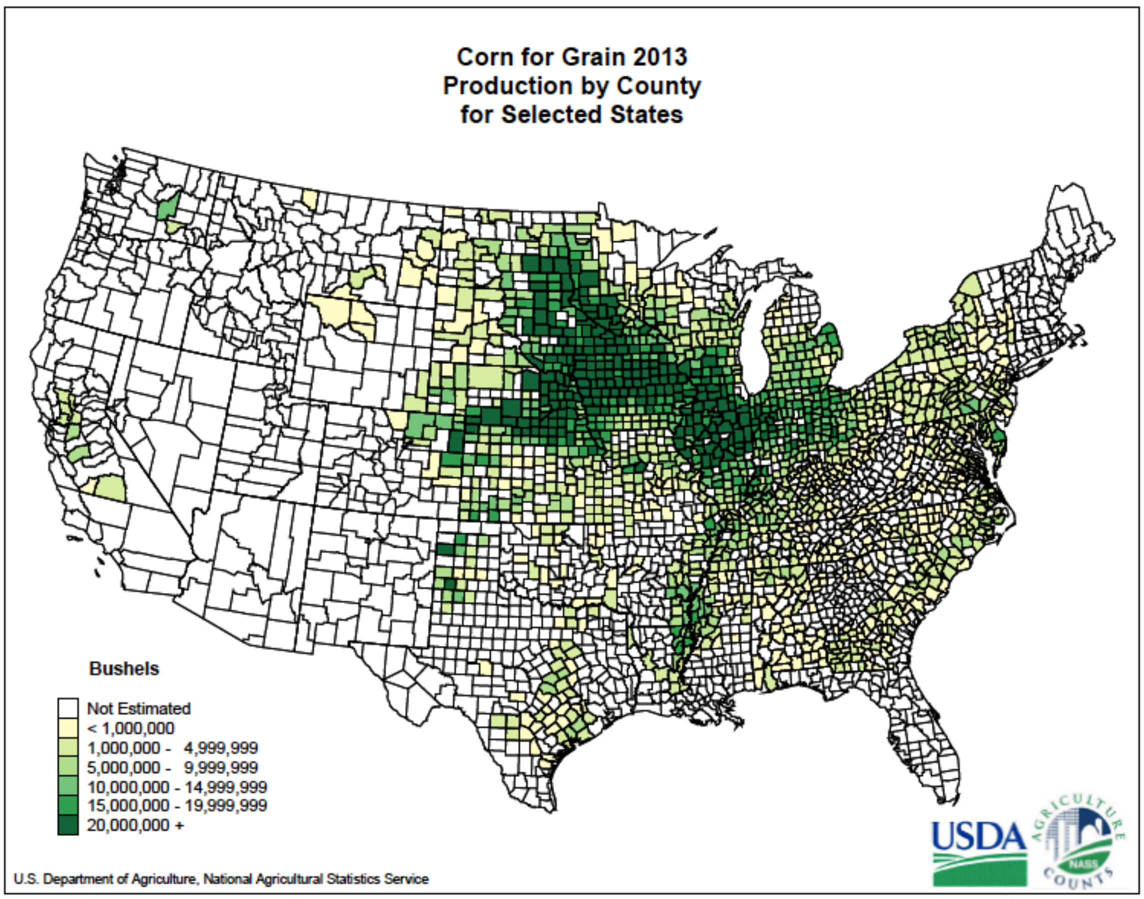


Figure 6: USDA estimated corn product ion (bushels) by county for the 2013 harvest season [92]

The greatest corn yields occur in the regions of Southern Minnesota and Wisconsin, Eastern South Dakota and Nebraska, Iowa, Northern Missouri, Illinois, and portions of Indiana, Michigan, Kansas, as well as Ohio. Although these locations tend to yield the greatest amount of corn, there can be significant variations in year-to-year yields as well as from region to region, primarily due to growing degree days, weather effects, local soil conditions, and the seasonal planting date of the corn crop itself. The highest corn producing states were evaluated to determine the maximum, minimum, and average corn yields by state, based on 15-year average corn yield data from the USDA and NASS. Average corn yields on a by-state basis are shown in Table 5 and display the maximum corn yields each state produced, Table 6 shows the minimum yields by state, and the average yields for each state are shown in Table 7.

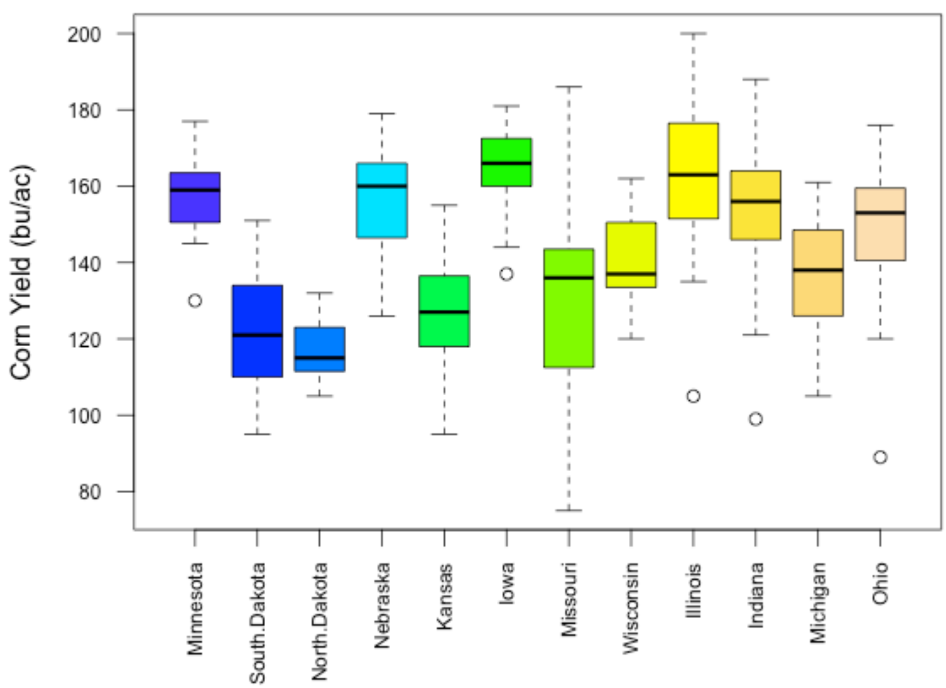


Figure 7: Boxplot representation of average corn yields (bu/ac) on a by state basis, based on 15-year average corn yields from NASS [97]

Table 5: Maximum corn yield (bu/ac) by state, based on 15-year average corn yields from NASS [97]

State	Yield (bu/ac)	State	Yield (bu/ac)
Illinois	200	Ohio	176
Indiana	188	Wisconsin	162
Missouri	186	Michigan	161
Iowa	181	Kansas	155
Nebraska	179	South Dakota	151
Minnesota	177	North Dakota	132
Maximum Average (bu/ac)		171	

Table 6: Minimum corn yield (bu/ac) by state, based on 15-year average corn yields from NASS [97]

State	Yield (bu/ac)	State	Yield (bu/ac)
Iowa	137	Illinois	105
Minnesota	130	Indiana	99
Nebraska	126	South Dakota	95
Wisconsin	120	Kansas	95
Michigan	105	Ohio	89
North Dakota	105	Missouri	75
Minimum Average (bu/ac)		107	

Table 7: Average corn yields (bu/ac) by state, based on 15-year average corn yields from NASS [97]

State	Yield bu/ac)	State	Yield (bu/ac)
Iowa	165	Wisconsin	141
Illinois	161	Michigan	137
Minnesota	158	Missouri	131
Nebraska	156	Kansas	128
Indiana	153	South Dakota	122
Ohio	148	North Dakota	116
Overall Average (bu/ac)		143	

The overall maximum and minimum averages were determined to be 171 bushels per acre (bu/ac) and 107 bu/ac, respectively. The lowest average yield was found to be 116 bu/ac in North Dakota and the highest average yield was 165 bu/ac in Iowa. An overall average based on the entirety of the 12-state and 15-year data was determined and verified by the means of a statistical "t-test" which indicated that the overall yield average was 143 ± 3.4 bu/ac, given a 95% confidence interval.

3.2.2 Corn Stover Availability

Since corn stover production has direct correlation to the amount of corn yielded by the land, the amount of stover produced can be determined from the corn yield values. Stover yields range from approximately 3.0 to 4.5 wet tons per ac (ton_{wet}/ac) on fields averaging 100 to 150 bushels of corn per acre [98], or 0.03 $tons_{wet}$/bu. This value is also confirmed for comparison as there is approximately 56 pounds of stover per bushel of corn [11], which equates to approximately 0.029 $tons_{wet}$/bu. Based upon this direct correlation of stover-to-corn weight, values for potential corn stover yields can be calculated based on corn yield from the NASS and are shown in Table 8.

Table 8: Average stover yield by state based upon state average corn yields from NASS 15-year average [97]

State	Stover Yield ($tons_{wet}$/ac)	State	Stover Yield ($tons_{wet}$/ac)
Iowa	4.9	Wisconsin	4.2
Illinois	4.8	Michigan	4.1
Minnesota	4.7	Missouri	3.9
Nebraska	4.7	Kansas	3.8
Indiana	4.6	South Dakota	3.7
Ohio	4.5	North Dakota	3.5
Average Stover Yield ($tons_{wet}$/ac)		4.3	

3.3 Sustainable Agricultural Management Practices

While it is shown in section 3.2.2 that an average of 4.3 $tons_{wet}$/ac of corn stover could be available, the amount that can be sustainably removed from the field decreases the actual harvestable amount. A portion of the stover should be left within the field to ensure sustainable agricultural practices that aid in protecting and reintroducing nutrients to the soil. The amount of stover recommended to remain in field, as determined from the values within Table 2, can be used to develop a sustainable harvest quota. The projected amount of harvestable stover, shown in Table 9, combines the average available stover per acre with the sustainable crop cover recommendations of Table 2 in a variety of harvesting and tilling practices.

Table 9: Harvestable stover on a percent basis based on crop rotation and harvest technique for a 4.3 ton/ac stover yield [7, 51, 53]

Retention Amount ($tons_{wet}$/ac)	Ref.	Crop Rotation	Field Management Technique	Harvestable Amount*
3.4	[53]	Corn-Corn	Plow	21%
2.3	[53]	Corn-Corn	No-Till	47%
5.6	[53]	Corn-Soybean	Plow	**
3.5	[53]	Corn-Soybean	No-Till	19%
2.3	[51]	Corn-Corn	No-Till	47%
3.5	[51]	Corn-Soybean	No-Till	19%
4.8	[7]	Corn-Soybean	Plow	**
2.2	[7]	Corn-Corn	Plow	50%

* Percentages based on available stover yield of 4.3 $tons_{wet}$/ac from Table 8 and yield data from NASS corn yield data in Table 7
** Indicates no stover would be available based on average stover production of 4.3 $tons_{wet}$/ac and respective retention amount ($tons_{wet}$/ac)

Given the harvestable stover on percentage basis, it can be seen that no-till, corn-corn operations allow for greater amount of harvestable stover when compared to other techniques; whereas plowing and corn-soybean operations require greater stover retention for sustainability reasons. These values are not exact as there are limiting factors to the percentage of stover that can be removed from a parcel of land. One other major consideration that must be taken into account when removing stover is the water-based erosion that occurs due to ground slope. These environmental constraints must be evaluated based upon specific field topography and geological conditions. If the slope of a field is large, removal of stover can increase the likelihood of soil erosion, which would ultimately remove nutrient-rich soil. Suggested corns stover removal amounts by Milhollin, et al. (2007) are shown in Table 10, along with potential harvest options and their respective stover removal amounts

Table 10: Stover removal with respect to slope of cropland [7]

Field Slope	Potential Stover Removal Amount	Harvest Method	Removal Amount Given Harvest Method
> 5%	0%	None	0%
2 - 5%	< 25%	Cobb Collection Direct Baling	15% 25 - 30%
< 2%	< 50%	Rake & Bale	50%

It can be seen that that the maximum recommended amount for stover harvest is near 50%, based upon the recommended amount of retention for either nutrient return (Table 9) or soil erosion prevention (Table 10). It should be noted that, in most cases, the amount of stover retention/stover removal would be directly related to the specific cropland, given the multi-factored agricultural aspects of crop rotation, harvest technique, and environmental effects. Example values of harvestable stover amounts are shown in Table 11, ranging from 10% to 50% collection that encompasses the recommended ranges of nutrient consideration and slope from Table 9 and Table 10, respectively.

Table 11: Example of potential harvestable stover ($tons_{wet}$/ac) given corn yield (bu/ac) and stover yield ($tons_{wet}$/ac) based on removal amount (percent basis) to encompass recommended soil nutrient and erosion retention

Corn Yield	Stover Yield	Harvestable Stover ($tons_{wet}$/ac)				
(bu/ac)	($tons_{wet}$/ac)	10%	20%	30%	40%	50%
100	3.0	0.3	0.6	0.9	1.2	1.5
125	3.8	0.4	0.8	1.1	1.5	1.9
150	4.5	0.5	0.9	1.4	1.8	2.3
175	5.3	0.5	1.1	1.6	2.1	2.6
200	6.0	0.6	1.2	1.8	2.4	3.0
225	6.8	0.7	1.4	2.0	2.7	3.4
250	7.5	0.8	1.5	2.3	3.0	3.8
275	8.3	0.8	1.7	2.5	3.3	4.1
300	9.0	0.9	1.8	2.7	3.6	4.5

3.4 Harvesting Methods and Considerations

Collection of stover is an important step in preparing the feedstock for the torrefaction process. While the harvesting process can be completed in as many as four operations, performing this step in the most efficient and cost effective manner can significantly affect the overall operational cost of the process. The harvesting procedure can be completed by either in-house harvesting (stover collection is completed by the producer) or by custom harvesting (stover collection is contracted out by producer). Baling of the corn stover is the most effective means to prepare for transportation and pre-processing as the densification into either round or square bales can increase the corn stover bulk density from approximately 3 lbm/ft^3 [12] to as high at 5-10 lbm/ ft^3 [7]. The baling process can be completed by numerous methods (previously discussed in section 2.3.2 Harvesting Techniques) although typical multi-pass round or square baling is the most effective and common. Square baling offers advantages over round baling, especially for biofuel related operations, due to easier handling and logistics of the square shaped bale. While square bales weigh less than round (large square bales are near 0.6 $tons_{wet}$/bale and round bales near 0.75 $tons_{wet}$/bale) they do have similar harvesting costs on a per ton basis. A summary of harvesting costs on both harvesting type and baling type bases are shown in Table 12, where it can be seen that in-house square baling is shown to be the most cost effective process.

Table 12: Harvesting methods and costs for corn stover based upon various researchers [57, 99, 100]

Researcher	Ref.	Harvest Method	Bale Type	Harvesting Cost ($/ton)
Brechbill, S., and W.E. Tyner	[99]	---	---	$34.92
Edwards, W., A. Hohanns, and A. Chamra, and Edwards, W.	[57, 100]	In-house	Round	$17.94
		In-house	Square	$17.03
		Custom	Round	$29.02
		Custom	Square	$30.17

3.5 Logistical Methods and Considerations

Logistics of transporting corn stover is another major consideration that must be taken into account after the stover has been baled into either round or square bales. Logistical costs are dependent on two primary factors including the amount of stover that must be handled as well as the total weight of the stover crop. While the amount of stover and total weight that must be transported is reliant on the amount of collected stover, the weight of the individual transport loads changes, specifically between large square and round bales due to the volume density of the bale. As with harvest, logistics can also be completed by either in-house or custom means. Costs associated with stover transportation, including round baling, square baling, in-house, and custom harvesting options are shown in Table 13. Unlike stover harvest with square baling being the most cost-effective method, round baling is shown to be the lowest cost option for stover transportation for both in-house and custom harvesting situations, based upon a per ton-mile basis.

Table 13: Logistical methods and costs for stover transport based upon various researchers and modified to a per ton basis [57, 99, 100]

Researcher	Ref.	Logistical Method	Bale Type	Logistics Cost ($/ton-mile)
Brechbill, S., and W.E. Tyner	[99]	---	---	$0.31
Edwards, W., A. Hohanns, and A. Chamra, and Edwards, W.	[57, 100]	In-house	Round	$0.32
		In-house	Square	$0.42
		Custom	Round	$0.32
		Custom	Square	$0.42

3.6 Torrefaction Biorefining System

The torrefaction system modeled for this study was defined as a simplified system, which covered the stages of drying, torrefying, and cooling the corn stover feedstock. In order to determine the energy requirements for the model, the energy equations, from Section 2.5.2 Process Energy, are applied in conjunction with the unit operations of the torrefaction system. The energy intensive processes of the torrefaction system were also investigated for potential heat and torrgas energy recovery, which were used to increase the efficiency of the system and improve the economic process.

3.6.1 Process Overview

The torrefaction process was divided into five major zones for use in the economic model, including pre-heating, drying, post-drying, torrefaction, and cooling. The torrefaction processing system was considered to be that of a continuous process, with a constant feed rate (tons/hr, lbm/hr) to occur throughout the duration of the biorefining. The raw stover feedstock, at approximately 30%

MC, was assumed to be pre-processed (e.g., chopped, ground, milled, etc.) making the feedstock smaller and more uniform in size. This pre-processing step, occurring prior to entering the heating stages, would increase the ability to process the feedstock more efficiently when compared to the non-uniform stalks, cobs, leaves and husks of the raw corn stover. Additionally, pre-processing would increase the heat transfer of the feedstock and aid in producing a more uniform, torrefied product. Beyond the pre-processing step, the feedstock would be induced to heating and drying through various stages, as discussed in Section 2.5.1 Torrefaction Processing Stages. Upon completion of the torrefaction process, the energy dense product would then be post-processed in a final step where the torrefied stover could be compressed into pellets for residential use, compressed into briquettes for use in industrial applications, or other various packaging for commercial use. For the techno-economic model development, both the pre-processing and post-processing steps were analyzed solely as an economic factor (i.e., the process itself was not analyzed in terms of energy use, ability to grind the raw biomass, compressibility of the end-product, or the design of related equipment).

3.6.2 System Energy Requirements

The energy requirements stated in Section 2.5.2 Process Energy explains the potential amount of thermal energy that must be supplied in order to make the system operational. The equations, which encompass the energy necessary for pre-heating, drying, post-drying, and torrefaction each depend on factors including the temperature, federate of the feedstock, as well as thermodynamic feedstock properties. The primary equations used are listed in Equation 1 through Equation 5, showing the steps required through the processes of pre-heating, drying, post-drying, torrefaction, and cooling, respectively.

$$Q_{ph} = \frac{m_s C_{pw}(212 - T_0)}{h_{uph}} \quad \text{[Eq. 1]}$$

$$Q_d = \frac{L M_f m_s}{h_{ud}} \quad \text{[Eq. 2]}$$

$$Q_{pd} = \frac{m_s \left(1 - M_f\right) C_{pd}(T_{t1} - 212)}{h_{upd}} \quad \text{[Eq. 3]}$$

$$Q_t = H_L + m_s \left(1 - M_f\right) X_t \quad \text{[Eq. 4]}$$

3.6.3 Heat Recovery

In addition to the energy required for the torrefaction process, heat recovery was also taken into account within the model to determine potential savings, based upon energy efficient implementations that could be possible within a commercialized system. Potential heat recovery, as shown by Equation 5, models the potential heat that could be recovered through the means of a heat exchanging system as the torrefied product is decreased to a post-processing temperature.

$$Q_c = m_s \left(1 - M_f\right) M Y_{db} C_{pt} (T_{t2} - T_f) \quad \text{[Eq. 5]}$$

The heat recovered from the cooling stage could have potential use within early stages of the torrefaction process, such as pre-heating, where the temperature of the feedstock would be significantly lower than the recovery fluid. It should be noted that for this process, the heat exchanger effectiveness must also be taken into effect. Due to no specific design constraints specified by this study, heat exchanger effectiveness was stated as an artificial value of 0.6 for use within the model.

3.6.4 Torrgas Energy Recovery

Torrgas energy recovery was also taken into consideration to model the potentially recoverable torrgas produced during the torrefaction stage. For modeling purposes, it was assumed that the torrgas recovered would be used within earlier stages of the process to alleviate required fuel consumption. The energy content of the torrgas vapor stream was determined based on the mass and energy yields of previous research, which indicated that typical mass yields ranged from less than 70% to near 90% and energy yields near 80-95% for various biomass feedstocks [20, 45, 74]. Previous research, specifically on corn stover torrefaction, has shown mass and energy yields of approximately 65-85% and 80-85%, respectively [74]. It should be noted that the mass losses due to torrefaction do not include mass losses due to moisture removal in preceding heating and drying stages. For use within the model, it was assumed that torrefaction mass yields would be 75%, whereas energy yields would be 85%. These values accounted for potentially lower values due to higher degrees of torrefaction temperatures, resulting in decreased mass yields in the torrefied stover product. Raw, unprocessed corn stover has shown to yield a HHV of 5,290 Btu/lbm, and when dried, an increased HHV near 7,560 Btu/lbm [96]. Previous research has shown that torrefaction of corn stover further increases the HHV to approximately 8,468 Btu/lbm [74], significantly greater than that of unprocessed or dried corn stover. Based upon the known characteristics of dried and torrefied corn stover, along with the known mass and energy yields, the potential HHV of torrgas can be approximated, assuming no losses, through the unit operation of the torrefaction stage (Figure 8).

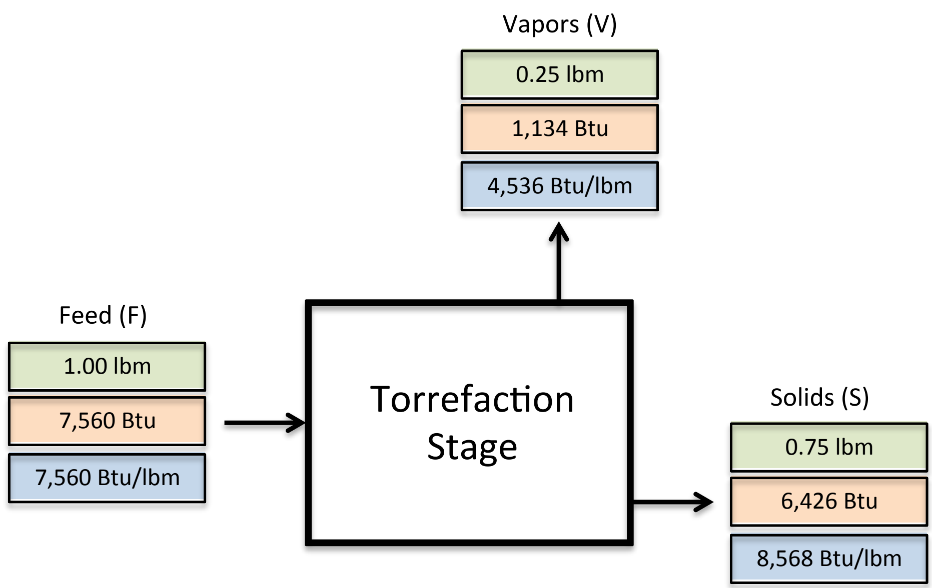


Figure 8: Unit operation of torrefaction stage with vapor (V) and solid (S) products on mass (lbm) and energy (Btu) bases, given the pre-dried corn stover feed (F) with mass yields of 75% and energy yields of 85% through torrefaction stage. Note: losses (e.g., heat, mass, energy) are not accounted for within this approximation

In the specific case of 75% mass and 85% energy yields, the approximated torrgas HHV (using Equation 6 and 7) is 4,536 Btu/lbm or approximately 269 Btu/ft^3, based upon biomass syngas densities near 0.06 lbm/ft^3 [101] and no losses within the stage itself. While the energy content of the torrgas exhibits a lower HHV (Btu/lbm or Btu/ft^3 basis) when compared to other gas-fuel types (Table 14), it does have value for upstream energy applications, such as direct use within the torrefaction system to alleviate fuel usage. In addition to direct use, previous research has been conducted where the torrgas is cleaned and stored for later use in heat and power generation processes such as IGCC, CHP, and combustion turbines and engines. [102, 103].

Table 14: Comparison of torrgas to selected gaseous fuel type

Gas Type	HHV (Btu/lbm)	HHV (Btu/ft^3)	Gas Density (lbm/ft^3)	Ref.
Torrgas (stover)	4,536[1]	269[2]	0.0593	[101]
Syngas (coal)	---	250-400	---	[104]
Natural gas	20,488	1,080	0.0527[2]	[105]
Propane	21,597	2,538[2]	0.1175	[105]

Note: Values marked with [1] were calculated using the Figure 8 unit operation results and values marked [2] are theoretically calculated based upon HHV (Btu/lbm or Btu/ft^3) and density (lbm/ft^3) of the gas based upon reference values

$$m_F x_F = m_V x_V + m_S x_S \qquad \text{[Eq. 6]}$$

Where: m_F = mass of feed (lbm)

m_V = mass of vapor stream (lbm)

m_S = mass of solid product (lbm)

x_F = mass of feed

x_V = mass yield of vapor stream

x_S = mass yield of solid product

$$E_F y_F = E_V y_V + E_S y_S \qquad \text{[Eq. 7]}$$

Where: E_F = energy of feed (Btu)

E_V = energy of vapor stream (Btu)

E_S = energy of solid product (Btu)

y_F = energy of feed

y_V = energy yield of vapor stream

y_S = energy yield of solid product

3.7 System Economics

The economics of the torrefaction system were determined based upon capital investment, the annual operation and maintenance (O&M) costs, the revenue generated by the torrefied product, and the payback period of the system itself. It was determined that associated costs and revenues would remain equal throughout the model, meaning that during the payback period analysis no increases in maintenance or operating costs would occur.

3.7.1 Capital Investment

The capital cost (CC) of the torrefaction processing system was selected based upon the throughput-processing rate (PR) of the system itself. A base value was determined for the baseline throughput system, which would increase during scale-up. Due to the torrefaction system not being commercially available, existing reference costs were not available and were based upon existing biomass processing and drying systems (e.g., corn and grain dryers).

3.7.2 Harvest and Logistics

Harvesting and logistic costs were determined based upon previous research discussed in sections 3.3 Sustainable Agricultural Management and 3.4 Harvesting Harvesting costs (C_h) accounted for the amount of corn stover harvested (HS) as well as the cost based on bale type and harvesting technique (BC). Logistical costs (C_l) were also determined based upon the amount of corn stover harvested (HS), the distance traveled (DT), as well as the bale type and logistic technique (LC).

Equations 8 and 9 model the costs associated with harvesting and transporting the corn stover feedstock from field to storage or processing site.

$$C_h = (HS)\times(BC) \quad \text{[Eq. 8]}$$

Where: C_h = cost of corn stover harvest ($\$_{USD}$)

HS = amount of harvested corn stover ($tons_{wet}$)

BC = cost of bale harvesting ($\$_{USD}/ton_{wet}$)

$$C_l = (HS)\times(DT)\times(LC) \quad \text{[Eq. 9]}$$

Where: C_l = cost of corn stover logistics ($\$_{USD}$)

HS = amount of harvested corn stover ($tons_{wet}$)

DT = distance traveled (mile)

LC = cost of harvest logistics ($\$_{USD}/ton_{wet}$-mile)

3.7.3 Operating and Maintenance

Operating and Maintenance (O&M) costs incorporated a variety of metrics and were based upon operator time (hours), electrical energy consumption (kWh), fuel requirement (gal or Btu), and annual preventative maintenance costs ($) on an annual basis. The cost to control and operate the torrefaction equipment was based upon time (hours) and operator pay rate ($/hour). Operating hours were determined by the required time to process the entire harvested corn stover crop, which was based upon the processing rate (PR) and total amount of corn stover feedstock (HS) harvested. The total cost of operators (C_{op}) is modeled in Equation 10.

$$C_{op} = \left(\frac{1}{PR}\right)\times(HS)\times(RP)\times(N_{op}) \quad \text{[Eq. 10]}$$

Where: C_{op} = cost to employ equipment operator ($\$_{USD}$)

PR = time to process corn stover feedstock ($tons_{wet}$ /hr)

HS = amount of harvested corn stover ($tons_{wet}$)

RP = rate of pay for individual operator ($\$_{USD}$/hr)

N_{op} = number of operators

Operating costs, in terms of required electrical energy, were determined based upon the needs of the processing system, which would require electrical energy to drive motors (e.g., milling, conveying, pelletizing, etc.) as well as process instrumentation and electrical equipment (e.g., control system, valve operation, safety equipment, etc.). Equation 11 models the cost of electrical power (C_{ep}) for use in operating the torrefaction system.

$$C_{ep} = (EP)\times\left(\frac{1}{PR}\right)\times(HS)\times(EC) \qquad \text{[Eq. 11]}$$

Where: C_{ep} = cost of electrical power ($\$_{USD}$)

EP = electrical power required by system (kW)

PR = time to process feedstock ($tons_{wet}$ /hr)

HS = amount of feedstock ($tons_{wet}$)

EC = electrical power cost ($\$_{USD}$/kWh)

The torrefaction system requires fuel energy, such as propane (LP), to operate burners and generate the required heat to process the feedstock (3.6.2 System Energy Requirements). The process energy needed (PE), shown in Equations 1-4, can be potentially alleviated through torrgas energy recovery (ER) and heat recovery (HR) practices. Equation 12 models the cost of fuel required to generate thermal energy (C_{th}) for the torrefaction process.

$$C_{th} = (PE - ER - HR)\times\left(\frac{1}{LP}\right)\times(PC) \qquad \text{[Eq. 12]}$$

Where: C_{th} = cost of thermal energy ($\$_{USD}$)

PE = process energy required (Btu)

ER = torrgas energy recovery (Btu)

HR = heat recovery (Btu)

LP = propane energy (Btu/gal)

PC = propane cost ($/gal)

Due to the mechanical nature of the torrefaction system, the gaseous and solid products generated, as well as the composition of material being process, it was determined that preventative maintenance would need to be implemented in order to operate the system safely and efficiently. It was determined that a percentage of the capital cost should be allocated towards annual maintenance (MP) for continues use of the system. Equation 13 models the cost of preventative maintenance (C_{pm}) for the torrefaction system.

$$C_{pm} = (CC)\times(MP) \qquad \text{[Eq. 13]}$$

Where: C_{pm} = cost of preventative maintenance ($\$_{USD}$)

CC = capital investment of equipment ($\$_{USD}$)

MP = preventative maintenance percent of capital cost

3.7.4 Torrefied Product Market Value

Torrefied corn stover exhibits many value added characteristics, including higher energy content, hydrophobic qualities, and the ability to be compressed denser than raw corn stover. The enhanced value added nature of the torrefied and pelletized product allows for corn stover to be more competitive within the energy sector, based upon logistics, usability with existing infrastructure, and the energy value of the product. A comparison of solid fuel products, shown in Table 15, shows how corn stover compares to other commonly used solid fuel sources. This comparison shows that pelletized and torrefied corn stover is competitive in terms of energy content and bulk density to selected biomass and fossil product fuels.

Table 15: Comparison of torrefied corn stover pellet HHV (Btu/lbm) and bulk density (lbm/ft³) to selected solid fuel types

Fuel Type	HHV (Btu/lbm)	Bulk Density (lbm/ft^3)	Ref.
Raw corn stover	5,290	3 (loose) 5-10 (baled)	[7, 96]
Dried corn stover	7,560	---	[96]
Torrefied corn stover (pelletized)	8,500	37-44	[13, 74]
Wood pellets	8,570	40	[96, 106]
Subbituminous coal (PRB)	8,300-9,500	42-57	[107]
Lignite coal (NDL)	6,300-8,300	40-54	

Torrefied corn stover has a HHV of approximately 8,500 Btu/lbm and is very similar to the HHV of wood, which is 8,570 Btu/lbm [96]. Wood is often dried and pelletized, making it highly effective for use in residential heating applications. This same process can also be done to torrefied corn stover that has a similar energy content as wood in a very dense envelope of 37-44 lbm/ft^3 [13]. Wood pellets retail in a commercial settings for approximately $180-$250 per ton [108], but can also be purchased individually in 40 pound bags.

Pelletized and torrefied corn stover is also comparable to that of some coal types, both in terms of its HHV and bulk density. The most similar types of coal include Powder River Basin (PRB) subbituminous coal and North Dakota lignite

(NDL), which have HHVs of approximately 8,300-9,500 Btu/lbm and 6,300-8,300 Btu/lbm, respectively [107]. This similarity aids in making it possible for torrefied corn stover pellets to emerge within the power generation market as a co-firing fuel in existing facilities or as a stand-alone fuel for biomass power generation facilities. Market values reported by the EIA for 2014 shown PRB and NDL coal valued at $14-$18 per ton [109]. These values are those typically seen in large industrial power generation facilities, although other prices may arise based upon the end-user sector.

Since torrefied corn stover pellets have similar attributes to that of wood pellets and some coal types, torrefied corn stover pellets could be sold in the same market for a similar price as wood. However, due to the large market value differential of wood pellets and coal ($180-$250 per ton for wood pellets and $14-$18 per ton for coal), it is more profitable to value corn stover based upon wood pellet prices for residential heating use. Within the power generation market the cost of torrefied corn stover could be substantially more than that of coal, primarily due to bio-based fuels having less emissions and potential for carbon neutral emissions. Equation 14 models the potential revenue available (R_{tp}) based upon the market value of the torrefied corn stover pellets.

$$R_{tp} = (TP)\times(MV) \qquad \text{[Eq. 14]}$$

Where: R_{tp} = revenue of torrefied pellets ($\$_{USD}$)

TP = amount of torrefied product ($tons_{dry}$)

MV = market value of torrefied pellets ($\$_{USD}/ton_{dry}$)

3.7.5 System Feasibility

The feasibility of the torrefaction system was based upon three primary metrics; the total annual profit generated ($/year), the payback period of the investment (years), and the return on investment. Total system profit (on an annual basis) was determined by accounting for the associated costs of harvesting and logistics, O&M, and the market value of the torrefied corn stover product. Equation 15 models the potential profit (P_{tp}) generated by the marketing of the torrefied pellet product, with all associated costs accounted for. The payback period of the torrefaction system is calculated using Equation 16 and the return on investment (ROI) by Equation 17; each use the torrefied pellet profit (P_{tp}) given on an annual basis and the capital equipment cost (CC) on a one-time basis.

$$P_{tp} = (R_{tp}) - (C_h) - (C_l) - (C_{op}) - (C_{ep}) - (C_{th}) - (C_{pm}) \qquad \text{[Eq. 15]}$$

Where:
P_{tp} = profit of torrefied pellets ($\$_{USD}$)
R_{tp} = revenue of torrefied pellets ($\$_{USD}$)
C_h = cost of corn stover harvest ($\$_{USD}$)
C_l = cost of corn stover logistics ($\$_{USD}$)
C_{op} = cost to employ equipment operator ($\$_{USD}$)
C_{ep} = cost of electrical power ($\$_{USD}$)
C_{th} = cost of thermal energy ($\$_{USD}$)
C_{pm} = cost of preventative maintenance ($\$_{USD}$)

$$PP = \frac{CC}{P_{tp}} \qquad \text{[Eq. 16]}$$

Where:
PP = system payback period (years)
CC = capital investment of equipment ($\$_{USD}$)
P_{tp} = profit of torrefied pellets ($\$_{USD}$/year)

$$ROI = \frac{P_{tp}}{CC+AC} \quad \text{[Eq. 17]}$$

Where: ROI = return on investment (percentage)

P_{tp} = profit of torrefied pellets ($\$_{USD}$/year)

CC = capital investment of equipment ($\$_{USD}$)

AC = sum of annual costs ($\$_{USD}$)

4 Economic Analysis of Distributed Torrefaction

4.1 Introduction

The overall viability of implementing distributed torrefaction systems is heavily reliant the system feasibility –specifically the system payback period and return on investment. As discussed in Chapter 3, a multitude of factors affect the system, including stover feedstock collection, material processing, and the market value of the torrefied stover product. These factors are further investigated using the techno-economic model within the following sections and focus on the following topic studies:

- A baseline case using average and typical values to act as a benchmark for comparison.
- A sensitivity analysis to determine operating performance for individual input variations.

4.2 Baseline Case Analysis

Values selected for use within the baseline case are based upon previous research (see Chapter 3 for in-depth discussion of potential value ranges) in order to develop a basis for comparison and benchmarking subsequent analyses. In the baseline case the values selected for use were the average, typical, and most likely to occur (i.e., values that fell within the ranges set forth by previous research for crop production, harvestable stover, etc.). Values used within the baseline analysis are shown in Table 16. Parameter values used within the model were based upon previous research or current-date values; however, it should be noted that several values were determined based upon comparison to existing mechanical systems or processes due to torrefaction systems not being commercialized at the time this thesis was written.

Table 16: Parameters set for baseline analysis

Parameter	Value	Unit	Reasoning	Ref.
Corn Yield	150	bu/ac	Based upon NASS data	[92]
Harvest Area	1,000	ac	Baseline assumption	---
Harvest Rotation	Corn-Corn	---	Allows for greater harvest	[7, 51, 53]
Harvest Type	In-house	---	More cost effective	[57, 100]
Baling Type	Square	---	Logistics and handling	[57]
Transport	20	miles	Baseline assumption	---
Harvest Amount	40	%	Sustainable and attainable	[7, 51, 53]
Capital Cost	200,000	$	Baseline assumption	---
Processing Rate	5.0	tph	Demonstration scale	[26]
Motor Power	200	hp	Baseline assumption	---
Operators	2	---	Baseline assumption	---
Fuel Cost	2.00	$/gal	Current propane price	[110]
Electric Cost	0.12	$/kWh	Current electric price	[111]
Product Value	120	$/ton	Near wood pellet value	[108]

Based upon the parameters set forth for the baseline (Table 16), the following process parameters and results (Table 17) in terms of material, energy, and products were attained. The results show that required process energy (Btu), modeled by Equations 1-4 and taking into account the processing rate (tph), heating rate (Btu/hr), and time (hr) set forth by the input parameters, follow the theoretical steps of drying being the most energy intensive operation at 1,191 MMBtu. Heat and torrgas energy recovery, modeled by Equation 5 and the mass-energy balances of Equations 6-7, is shown to alleviate nearly 70% of the required process energy, given a heat recovery effectiveness of 0.5 and a torrgas energy recovery effectiveness of 0.6. Total fuel requirements (Btu), less all energy and heat recovery, were shown to be 457 MMBtu, which would require approximately 5,000 gallons of propane fuel to meet the heating requirements of the system. End products, based on a 75% mass yield and 85% energy yield, equated to approximately 913.5 $tons_{dry}$ and 15,471.0 MMBtu of energy. It should be noted that the final product of 913.5 $tons_{dry}$ is 75% of the dried biomass that entered into the torrefaction stage and does not include the mass loss due to moisture removal in the drying stages. In total, 52.5% of the initial 1,740 $tons_{wet}$ was retained.

Table 17: Baseline process operation parameters, requirements, and end products

Process Operation	Value	Unit
Feedstock Processing		
Processing Rate	5	tph
Feed	1,740	$tons_{wet}$
Total Time	348.0	hours
Process Energy		
Pre-Heating	214.2	MMBtu
Drying	1,191.4	MMBtu
Post-Drying	32.8	MMBtu
Torrefaction	41.4	MMBtu
Heat and Energy Recovery		
Heat Recovery	27.7	MMBtu
Torrgas Energy Recovery	994.5	MMBtu
Energy Savings	69.1%	---
Fuel Requirements		
Total Energy	457.5	MMBtu
Propane	5,000	gal
End Product		
Solid Product	913.5	$tons_{dry}$
Product Energy Content	15,471.0	MMBtu

4.2.1 Annual Baseline

Results of the of the annual baseline analysis indicated that the distributed torrefaction system would cost approximately $79,587 to operate while generating nearly 913 $tons_{dry}$ of torrefied product – a value of nearly $109,620. An approximate annual profit of $34,701 was possible, generating a potential payback period of 5.8 years and an annual ROI of 46%. The annual economic summary (Table 18) and cost distribution (Figure 9) show all associated costs for preparing and processing the stover feedstock on a yearly basis, not including capital costs. Annual results show that stover harvest and transport were the most costly portions of the overall process, accounting for 59.1% of the overall costs. The torrefaction system O&M made up the remaining costs at 40.8% of the total. Given that the analysis was based upon a single operating year, it can be determined that actual collection and preparing the raw corn stover crop for feedstock was the most costly operation. Additionally, due to the single year period, it was impractical to evaluate the capital costs within the annual baseline analysis, as it would make up 72.7% of the costs.

Table 18: Baseline case annual economic summary

Economic Metric	Value	Unit
Costs		
Capital Equipment Cost	$200,000	$
Stover Harvest	$29,632	$
Stover Logistics	$14,616	$
Equipment Operator	$10,440	$
Electrical Energy	$6,231	$
Thermal Energy	$10,000	$
Preventative Maintenance	$4,000	$
Total Costs for Operation	*$74,919*	$/year
Revenue		
Annual Product Revenue	$109,620	$/year
Profit		
Annual Operating Profit	$34,701	$/year
System Feasibility		
System Payback	5.8	years
Annual ROI	46.3%	---

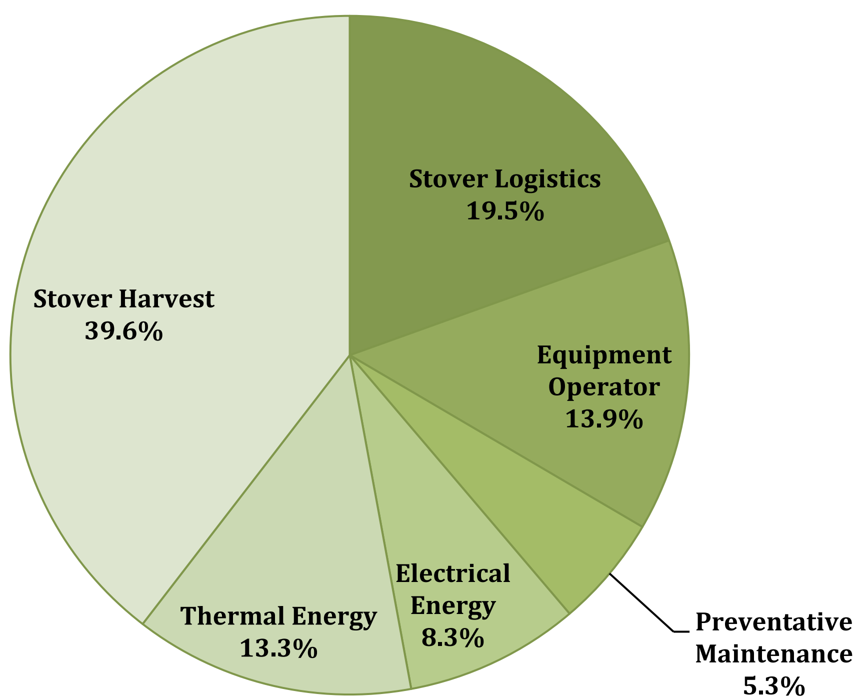


Figure 9: Annual baseline cost distribution excluding capital cost

4.2.2 10-Year Baseline

In order to determine how the capital cost affects the lifecycle of the system, the baseline results were extended to a 10-year period operation – this makes it possible to determine what effect equipment costs have on total profit. The cumulative cash flow for the projected 10-year operating period and 5.8-year payback period is shown in Figure 10, while Table 19 and Figure 11 show overall cost distributions that include capital equipment costs. It was determined that a potential ROI of 15% was possible over the 10-year operation period, which included capital and annual costs. The results of this analysis showed harvesting and logistics accounted for 46.6% of the total costs over a 10-year period. Costs associated with O&M were 32.3% and the remaining capital equipment costs accounted for 21.1% – a 70.9% decrease from the single year period. This shows that over longer periods of time, capital costs make up a significantly lower portion of the costs associated with operating the distributed torrefaction system.

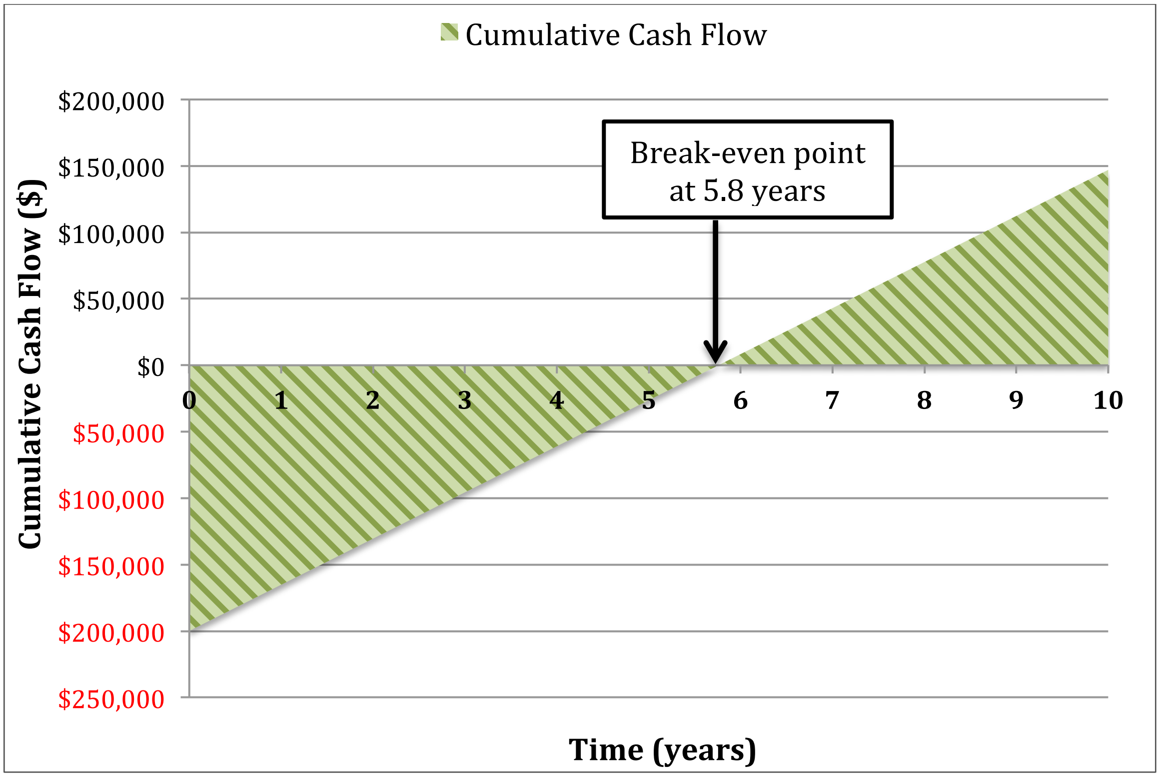


Figure 10: Cumulative cash flow 10-year operating period.

Table 19: Baseline case 10-year operation economic summary

Economic Metric	Value	Unit
Costs		
Capital Equipment Cost	$200,000	$
Stover Harvest	$296,322	$
Stover Logistics	$146,160	$
Equipment Operator	$104,400	$
Electrical Energy	$62,306	$
Thermal Energy	$100,004	$
Preventative Maintenance	$40,000	$
10-Year System Cost	*$949,192*	$/10-years
10-Year Revenue		
Revenue	$1,096,200	$/10-years
10-Year Profit		
Profit	$147,008	$/10-years
System Feasibility		
System Payback	5.8	years
10-Year ROI	15.5%	---

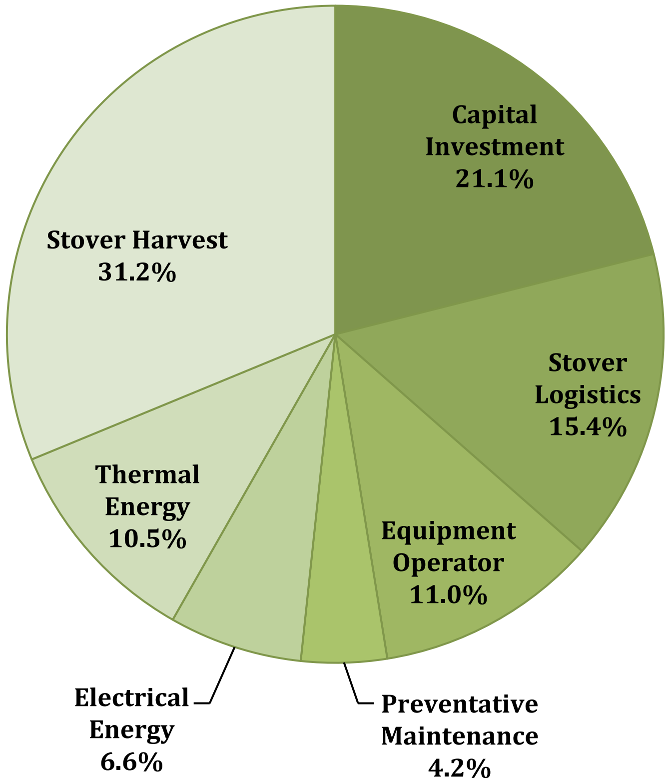


Figure 11: 10-year baseline cost distribution including capital cost

4.2.3 Baseline Analysis Summary

Outcomes showed that it was feasible to operate the distributed torrefaction system given the set parameters of the baseline analysis. Results indicated that it was possible to attain a payback period of 5.8 years under continuing annual operation of the baseline parameters. The conversion process of the system was shown to be economical in terms of energy costs, which made up 21.6% of the total annual operating costs (8.3% electric energy and 13.3 % thermal energy). However, it was indicated that significant costs were attributed to the harvesting and logistical operations (59.1% of annual costs). This was shown to be the case on both an annual and 10-year period basis.

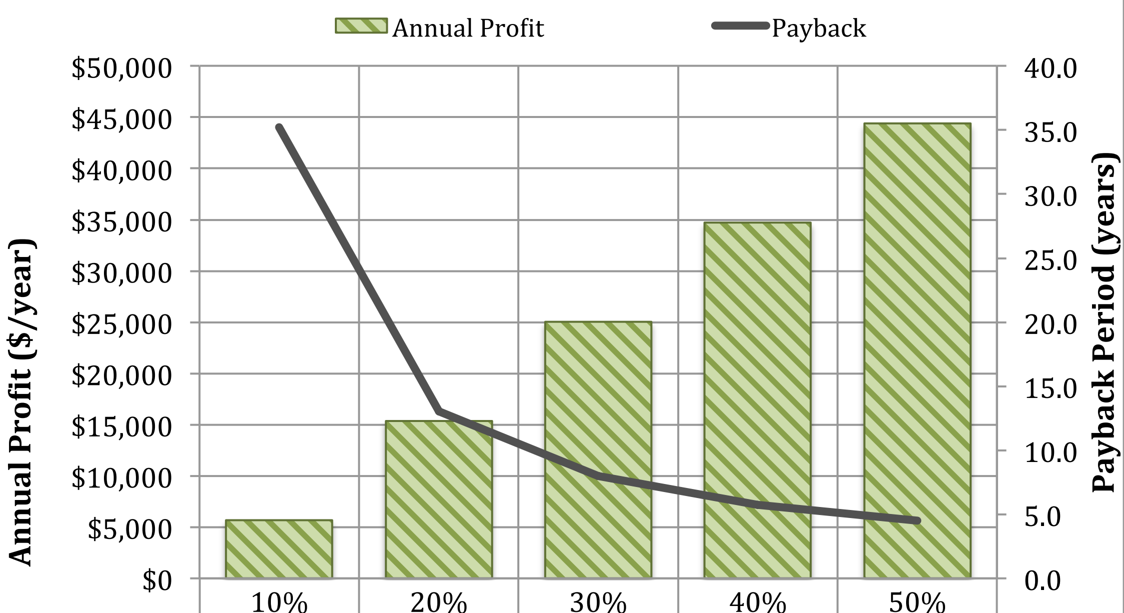
4.3 Sensitivity Analysis

The operation of the torrefaction system model is highly dependent on the variable input parameters used, which increases the potential for multiple outcomes by varying one or more parameters. The purpose of the sensitivity analysis was to determine the effects that certain parameters had on the overall model, and ultimately the theoretical viability of the distributed torrefaction system. The following sections explain in detail the factors that were varied and the outcomes of the respective variations.

4.3.1 Corn Stover Collection

The time-related performance of the torrefaction system is highly dependent on two primary factors; the processing rate of the system (tph) and the total amount of feedstock ($tons_{wet}$). In many cases it is not possible to harvest the maximum amount of corn stover available (see Section 3.4 Harvesting Methods and Considerations) or the amount may vary from year to year, depending on the corn crop yield. In order to determine operating conditions and system viability with variable stover collection, the baseline case parameters were applied in conjunction with variable corn stover collection amounts ranging from 10% up to 50% (Figure 12).

Profits were shown to have a linear relationship for the analysis, increasing approximately $9,675 per additional 10% of stover collected. However, the payback period did not follow the same linearity. This was attributed to the additional amount of stover collected that increased the total amount of feedstock to be processed. Given the fixed processing rate of 5 tph, the overall amount of time increased, ultimately increasing costs related to operating, electrical energy consumption, and the amount of fuel required. Overall, the system was shown to be feasible at stover collection amounts as low as 30%, yielding an 8.0-year payback period. Results also indicated that the law of diminishing returns applied directly to this case analysis, where the payback period decreased rapidly at low collection amounts and in small increments as stover harvest increased (e.g., decrease in payback period from 10% to 20% stover harvest was 22.2 years and from 30% to 40% it was only 2.3 years).



	10%	20%	30%	40%	50%
Annual Profit	$5,675	$15,350	$25,026	$34,701	$44,376
Payback	35.2	13.0	8.0	5.8	4.5

Amount of Stover Crop Harvested

Figure 12: Profit and payback period based on harvest amount variation from 10% to 50% under baseline parameters

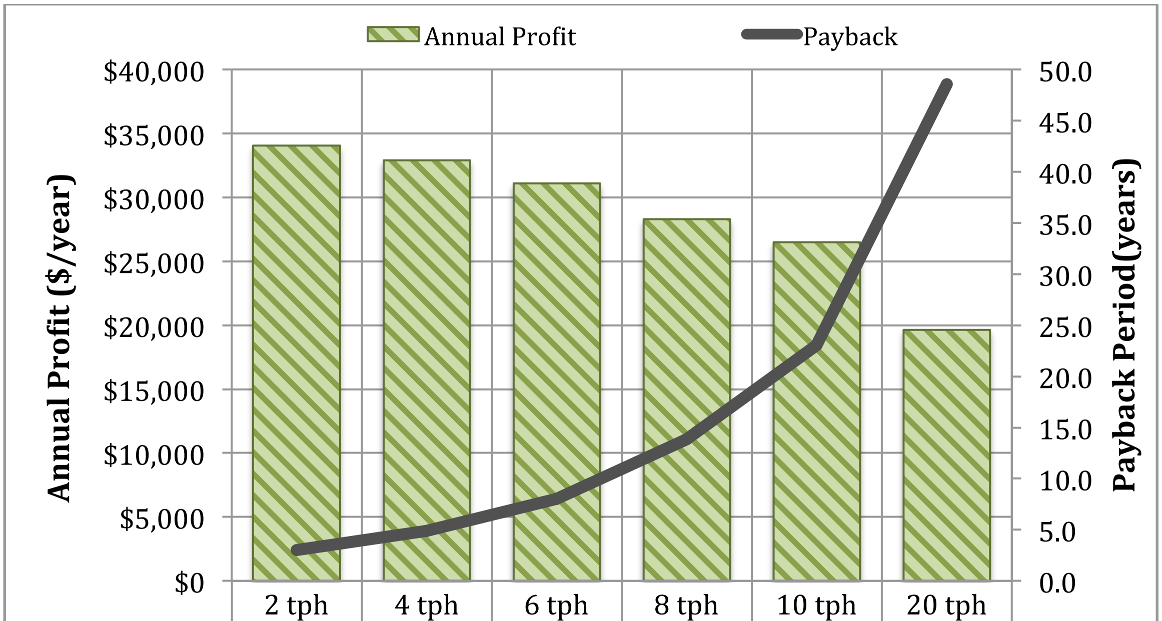
4.3.2 Scaling and Processing Rate

The processing rate can greatly affect the overall performance of the torrefaction system as the processing rate determines the time it takes to torrefy the feedstock supply. Varying the processing rate shows direct correlation to changes in electrical energy consumption (kWh), the required heating rate (Btu/hr) (total heat requirement is maintained), as well as operator time and cost. For this analysis the baseline parameters were used and the processing rate (tph), motor sizes (hp), number of operators, and capital costs ($) were varied using scaling factors. The scaling factors selected (Table 20) were based on BPI scaling and available data on related equipment (e.g., blower motors, pumps, and boilers). The processing rate was varied from 2 to 20 tph in order to show the effect of the scaling factor of 10, with processing rates of 4, 6, 8, and 10 tph used to show intermediate rates applicable to the baseline analysis.

Table 20: Scaling factors used in processing rate analysis

Factor	Scaling Factor	Reference System
Processing Rate (tph)	10	BPI scaling [48]
Motors (hp)	5	Corn dryer blow motors Centrifugal pump motors
Process Operators (#)	8	Assumption
Capital Cost ($)	8	Corn dryers, industrial electric motors Centrifugal pumps, gas-fired boiler systems

The variation of processing rate showed significant effects on the overall profitability of the system, as well as the potential payback period. It can be seen by Figure 13 that profit decreased linearly as the processing rate increased, which was attributed to the increased costs associated to additional motors and operators. However, the payback period was shown to increase in a non-linear trend as the processing rate increased, a result of the capital cost increasing as processing rates increased. The greatest profit and lowest payback period was shown to occur at a 2 tph processing rate – this rate had the lowest capital costs and required the least amount of motor horsepower and operators. Following the trend throughout the processing rate increase, it was shown that the lowest profit and longest payback period occurred at 20 tph. The payback period was shown to increase more rapidly as the processing rate increased. Given the fixed amount of feedstock in the analysis (1,740 $tons_{wet}$ of corn stover), increasing the size of the torrefaction biorefining system was shown to be a non-profitable investment. However, if the amount of feedstock were to increase significantly it would be viable to implement a higher processing rate torrefaction system. Additionally, if the time allowed for processing was of concern a faster processing rate system could be an option although it would not be as profitable.



	2 tph	4 tph	6 tph	8 tph	10 tph	20 tph
Annual Profit	$34,043	$32,891	$31,091	$28,278	$26,494	$19,627
Payback	3.0	4.9	8.0	13.8	23.0	48.6

Figure 13: Profit and payback period based on processing rate variation from 2-20 tph at 40% corn stover harvest

4.3.3 Torrgas Energy Recovery and Storage

Recovering torrgas from the torrefaction stage for use within the heating and drying stages is both an efficient and economical option for operating a distributed torrefaction system. It was shown in the baseline analysis that implementing torrgas energy recovery, along with waste heat recovery, approximately 69.1% of the total energy required by the system could be alleviated. While this option decreases the required fuel input, storing the torrgas for future use in other applications is also an option. Exploration of this pathway was based upon the baseline parameters but implementing no gas recovery – this ultimately decreased the amount of energy savings within the system and increased the fuel required to provide process heating. A comparison of the baseline case (torrgas recovery) and the storage analysis (torrgas storage) is shown in Table 21. It should be noted that additional costs of storage equipment (e.g., pressure vessels, rotating equipment, chiller units, etc.) were not included within the analysis, as the purpose was to exhibit the effects of additional fuel requirements on annual profit and the payback period of the system.

Table 21: Comparison of system fuel requirements and feasibility between torrgas recovery and storage with baseline parameters

Energy Accounting	Torrgas Recovery	Torrgas Storage	Unit
Energy Use/Savings			
Process Energy Required	1,480	1,480	MMBtu
Heat Recovery	27.7	27.7	MMBtu
Torrgas Energy Recovery	994.5	0	MMBtu
Torrgas Recovered	3,697.1	0	Mcf
Net Energy	457.5	1,452.0	MMBtu
Energy Savings	69.1%	1.9%	---
Propane Requirement	5,000	15,869	gal
(Natural Gas Equivalent)	(457.5)	(1451.9)	Mcf
System Feasibility			
Annual Operating Profit	$34,701	$12,964	$
System Payback	5.8	15.4	years
Annual ROI	46.3%	13.4%	---

A direct result from eliminating torrgas recovery was an increase in the purchased fuel required to process the corn stover feedstock – an increase of approximately 994 MMBtu or the equivalent of 10,869 gallons of propane. The significant increase in propane usage accounted for an additional $21,737 in costs, which ultimately reduced the profit while making the payback period increase from 5.8 years up to 15.4 years. Although the operating costs increase by storing torrgas, the potential downstream applications (e.g., gas turbine or combustion engine fuel, renewable fuel supplementation) of the cleaned torrgas extend the markets of the torrefaction products.

Currently, there is one coal-to-syngas facility in operation within the United States, which produces syngas for natural gas supplementation and chemical applications. This coal-derived syngas product has a HHV of 975 Btu/ft^3 and is sold at an average retail value of $3.84/MMBtu [112]. Torrgas exhibits an approximate HHV of 269 Btu/ft^3 (4,536 Btu/lbm, see section 3.6.4 Torrgas Energy Recovery for value determination) – a HHV that is 28% of coal syngas (970 Btu/ft^3) and 25% of natural gas (1,080 Btu/ft^3). A comparison of gas fuels on energy and cost bases is shown in Table 22. Given the typical market prices of coal syngas at $3.84/MMBtu and natural gas at $2.00/MMBtu, an assumed value of $3.84/MMBtu was set for the stover-derived torrgas product. As a result, the market value of the torrgas only equates to $3,819 – a substantially lower value than the nearly $20,000 of propane alleviated when directly using the torrgas within the torrefaction system itself. It can be determined from this analysis that torrgas storage proves to be a less economically viable pathway, given the current low natural gas prices.

Table 22: Comparison of torrgas to other fuels on equivalent energy and cost bases

Gas Type	Energy Content (Btu/ft^3)	Market Value ($/MMBtu)	Energy/Cost (Btu/$)
Torrgas (stover)	269	$3.84	260,417
Syngas (coal)	975	$3.84	260,417
Natural Gas	1,080	$2.00	500,000
Propane	2,538 [91,500 But/gal]	$21.86 [$2.00/gal]	45,750

4.3.4 Summary of Sensitivity Analysis

Completion of the sensitivity analysis yielded multiple outcomes to further analyze the feasibility of the distributed torrefaction system. One key parameter was varied in each case, including the amount of harvested or collected stover, the processing rate of the system, and the recovery of the torrgas. The following outcomes were determined:

1. Increasing stover harvest supplies a greater amount of feedstock to be converted into value added products (increased profit). However, under a constant processing rate (tph) the added feedstock supply increases the overall processing time, fuel requirements, and electrical consumption. As a result, the payback period significantly decreases beyond 20% collection and shows that collection beyond 40% yields little additional benefits due to diminishing returns.
2. Increasing the processing rate was shown to be non-profitable given the fixed amount of 1,740 $tons_{wet}$ of corn stover feedstock. Scaling factors were shown to make the lower-rate processing system less economically feasible, although the higher-rate processing could be beneficial if a greater amount of feedstock was present, such as in a commercial biorefining site.
3. Consumption of torrgas as a fuel supplement within the torrefaction process was shown to be more profitable and economically viable when compared to storing the gas for future uses. Savings due to propane alleviation far outweighed the profits generated by selling the torrgas, given the assumed value of $3.84/MMBtu based on coal syngas. In addition to this, additional processing and transportation costs were not included, which would incur additional costs for storing the torrgas product. However, if an alternative value-added option existed (e.g., use of torrgas for specialty chemicals) then torrgas storage may prove to be a lucrative option.

5 Conclusion and Future Applications

5.1 Conclusion

The research performed for this thesis investigated the economic feasibility of implementing a distributed torrefaction system. This study assessed the techno-economic aspects of a harvest to market scenario for corn stover that would produce value added products, which included torrefied biomass and torrgas. The model was evaluated on the assumption that it would be operated and owned by an agricultural enterprise, meaning the analysis encompassed the collection, transport, processing, and marketing of the torrefied corn stover product.

Outcomes of the techno-economic model showed that both harvesting and operating parameters affect the feasibility of implementing a farm-scale torrefaction system. Harvesting considerations of the corn stover feedstock were shown to be highly influential in sustainable stover collection and governed the feedstock availability. The torrefaction process itself was shown to produce valuable solid products that could be pelletized and sold as a coal substitute, a co-firing agent, or as a residential pellet stove fuel. Torrgas products were shown to be an effective source for fuel alleviation within the process and the implementation of heat and torrgas energy recovery proved to make substantial impacts on the required process energy.

The baseline analysis showed that the distributed system could produce value added products while maintaining a payback period of less than 6 years at an annual ROI of 46%. Extending the baseline analysis to a 10-year operation showed that overall profitability, when maintained, would generate a 15% ROI with annual operating and capital costs were taken into account. Implementation of heat and torrgas energy recovery was shown to decrease the fuel required for process energy by nearly 70%, substantially decreasing the required fuel costs.

A sensitivity analysis was used to show that specific changes in key parameters would affect the overall performance of the system in terms of profitability and payback period. Variable harvest was shown to be influential on the profitability and payback period, although as the harvest amount increased, diminishing returns were prevalent. Processing rates, in addition to scaling factors, were shown to make higher-rate processing less feasible than lower-rate processing systems given a fixed amount of feedstock. Payback periods were shown to increase non-linearly as the processing rate increased due to the scaling factors for motor size, number of operators, and the capital cost. Torrgas recovery was shown to be a highly valuable implementation in the system when compared to capturing and storing the torrgas for later uses. The low prices of natural gas and the higher production cost of torrgas made recovering the torrgas a more beneficial pathway.

Upon reviewing literature, researching existing thermochemical pathways, and analyzing the results of the techno-economic model, it was concluded that distributed torrefaction using corn stover feedstock offers an innovative and feasible pathway to utilizing a commonly discarded biomass resource.

5.2 Future Work

The results of this study provided an in-depth look into the technical and economic aspects of distributed torrefaction based upon experimental and theoretical values. In order to further validate the results of this study, the following recommendations are presented:

- Investigate more complex process-simulation models to take into account chemical reactions, mechanical processes, and equipment sizing for design considerations of a full-scale system.
- Expand the existing techno-economic model to analyze scaling processes and compare a demonstration scale distributed torrefaction system to a multi-system biorefining site (multiple demonstration scale systems in a side-by-side process) and a dedicated biorefining facility (single system on a large commercial scale).
- Explore additional uses for the torrefied products to make use of the energy dense solids and torrgas.
- Analyze a demonstration-scale torrefaction system to validate the techno-economic results.

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