4-19-2022

Comparison of Bio-mass to Bio-oil Reactor Systems: Direct Conversion vs. Companion Coal Gasification

Luci Evans
Western Michigan University, lucievans@gmail.com

Letter of Transmittal

Western Michigan University
College of Engineering and Applied Sciences
Department of Chemical and Paper Engineering

April 25th, 2022

Dr. James Springstead
Associate Professor and Graduate Advisor
4601 Campus Drive
A-222 Floyd Hall
Kalamazoo, MI 49008-5462

Dear Dr. Springstead:

The following report regarding bio-oil has been completed and sent. The object of this report was to assess and analyze two different processes to produce bio-oil. This project initially started on February 4th, 2022 and was finished on April 5th, 2022.

We hereby submit a report on the direct conversion of biomass to bio-oil production as well as a companion conversion of coal gasification into a combined system. A comparison of the two processes has been evaluated for further economic analysis. This project has been prepared as part of the CHEG 4870 Senior Design course. Some objectives of this project include research of the economic feasibility of the biomass and bio-oil industry, obtain a market survey, design two process flow diagrams, calculate the material and energy balances as appropriate, develop cash flow tables and economic indicators for complete summarization, determine the operating costs, profits, and raw material pricing, and conduct a complete comparison of the two processes to obtain an optimal design. The two process flow diagrams were designed using Aspen Plus V11 simulator and the total capital investment was given here as well. Every other part was calculated by hand and scaled to a plant size. In this report we compare the direct conversion of biomass to bio-oil using fast pyrolysis to a combined process with the side reaction of using coal gasification as a part of the fast pyrolysis system. In the end, we have concluded about which system would work best economically.

The total expense for Direct Pyrolysis is $76,976,025.4 with a total income of $2,741,412,259. Additionally, the Direct Pyrolysis had a net present value (NPV) of $356,837,586, and a IRR value of 23.5%. The return on investment (ROI) for this process was 23.6% with a payback period of 0.04 years (2.09 weeks).

For the Combined Process, the expense is $101 million with a total income of $274,203,532.4. Additionally, the coal gasification process has a net present value (NPV) of $ 292.5 MM, and an Internal Rate of Return (IRR) value of 8.89%. The return on investment (ROI) for this process was 8.9% with a payback period of 0.11 years (5.7 weeks).

Sincerely,

Dominic T. Chirillo, Luci C. Evans, Mika J. Greening, and Aaron T. Kischnick

Executive Summary

The purpose of this project was to define, design, and optimize the economic feasibility of the production of bio-oil from a direct conversion of biomass to bio-oil using fast pyrolysis and a secondary side reaction of the production of a syngas from coal gasification. In the end, a combined process of these two was created to show the new strengths and more efficient options to produce a desired product within a budget. The main objectives of this project were to research the economic feasibility of the biomass and bio-oil industry, obtain a market survey, design two process flow diagrams showing the two different processes, calculate the material and energy balances for both processes, develop cash flow tables and economic indicators to show the economic analyses for complete summarization, determine operating costs as well as profits and raw material pricing, and conduct a comparison of the two processes in order to obtain and produce an optimal design. Also specified in this report is an incremental investment option, which is an alternative design. The potential for both processes—Direct Pyrolysis and Combined process—to be implemented in an already existing plant negating real estate costs is this alternate scenario. This project is known as a defender-challenger, to see which process is more efficient and more economically feasible. It can be said that using the Coal Gasification process combined with the Direct Pyrolysis was more viable and useful in this case.

To begin this project, the research process was started by reviewing the AIChE National Student Design Competition of 2013 given to the team as a reference of some initial conditions. During this review, process description, and stream identifications were made clear. A further review would have to be made including research into the fast pyrolysis process, coal gasification process, and overall combining the two together. Operating conditions such as temperature and pressure of each process were also assessed during this research time. The goal then became to use this information and to start a basic design of each process, while taking the market survey and economics into account. The resulting process flow diagrams and basic costing information were designed and estimated using Aspen Plus V11 simulator from similar published processes. After the processes were done and material and energy balances were calculated, a complete economic analysis was made and with related conclusions drawn.

The economic analysis for this project includes some important factors such as the bio-oil produced as a final product, the amount of feed rate into each system, installation and equipment costs, expenses, and profitability. The income for the Combined Process has two factors; bio-oil produced, and syngas produced coming in at $274 million/year. The installation and equipment costing for the Direct Pyrolysis is estimated at $5,755,309, while for the side reaction of Coal Gasification is estimated at $5,933,165 with a combined total of $11.7 million. The total expense cost for the overall Combined Process was $101 million. Based on these estimations, the total profit for a plant running this Combined Process design would be $173 million. Also, this process had an IRR of 9.2%, MAR at 0.4, payback period of 0.108 years, and an NPV of 275.2 million. As a result, the combined process of direct conversion using fast pyrolysis and a side reaction of coal gasification proved to be more efficient given the reduced cost of heat and profit margin.

Comparison of Bio-mass to Bio-oils Reactor Systems: Direct Conversion vs. Companion Coal Gasification

For
James R. Springstead, PhD
Western Michigan University
Department of Chemical and Paper Engineering

From
Dominic T. Chirillo, Luci C. Evans, Mika J. Greening, and Aaron T. Kischnick
Department of Chemical and Paper Engineering
Spring of 2022

Table of Contents

List of Figures

List of Tables

1. Introduction

1.1 Environmental History and Project Goal

Since the Industrial Revolution, fossil fuels have been used as the primary fuel source around the world. It is fact within the scientific community that humanity's reliance on fossil fuels for an extended period has increased the global temperature of the world at a historically unprecedented rate. Previously, the Earth experienced only one other known period of warming similar in scale to that which is currently taking place. This abrupt warming period is known as the Paleocene-Eocene Thermal Maximum (PETM) and took place 55 million years ago. During this time, the globe warmed 4°C-8°C over a period of 1,000-10,000 years causing mass extinction of ocean organisms and changes in the global geographic ecosystems where plant life could survive. Currently, because of increased Greenhouse Gases (GHGs) in the atmosphere, this level of warming is projected to take place in a fraction of that time.

This sudden exponential increase in GHGs present in today's atmosphere has contributed to an increase in the global temperature of the Earth as a direct result of the Greenhouse Effect. GHGs are classified as gases that absorb and emit thermal infrared radiation with the most prevalent current GHGs in the atmosphere being the following: carbon dioxide, methane, nitrous oxide, ozone, and water vapor. When any amount of these gases are present in the atmosphere, they absorb heat which is naturally emitted by the Earth's surface and re-emit that heat back into the atmosphere. This is the process known as the Greenhouse Effect. Figure 1 below shows a pictorial representation of that process.

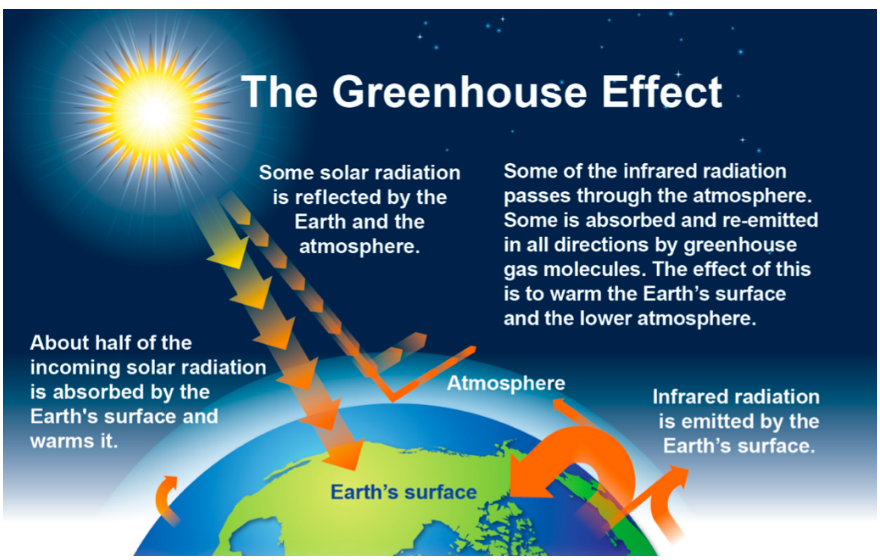


Figure 1: The Greenhouse Effect

The Greenhouse Effect on average makes the Earth's atmosphere about 60°F warmer than it would otherwise be in the absence of GHGs. As this is the case, many GHGs naturally occur in the atmosphere, but the concentration of these gases has been increasing at a surprising rate as a direct result of human activity and the continued burning of fossil fuels. On top of the increase in naturally present GHGs in the atmosphere, human activity has also resulted in new, human-made GHGs including the following: chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and fuller hexafluoride (SF6). The increase in natural and human-made GHGs results in an increased greenhouse effect causing the overall global temperature to rise.

Figure 2 below shows a representation of potential futures for the Earth. It includes the observed temperature changes since 1900 and includes three different projections of possibilities for the global temperature increase based on what humans chose to do or not do to mitigate climate change and global warming. If nothing is changed and business as usual continues, the "Higher Scenario" in red known as RCP8.5 is the projected future. This climate change model predicts that the global temperature will increase by 2.4°C-4.7°C by 2100 relative to the 1986-2015 average. If the "Even Lower Scenario" is followed, the global temperature is projected to increase 0.2°C-1.5°C relative to the 1986-2015 average. This climate model is referred to as RCP2.6 and is the current best-case scenario in fighting climate change.

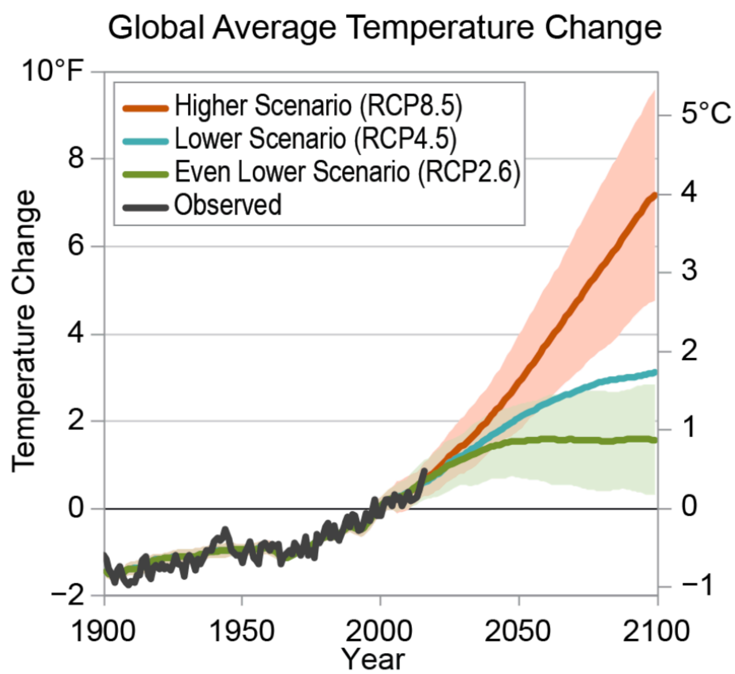


Figure 2: Observes and Projected Changes in Global Temperature

Currently, the mistakes made in the past cannot be undone. At this point, it is necessary to produce viable, economically sound replacements for one of the major causes of global warming and climate change—the continued burning of fossil fuels and elevated levels of carbon emissions. There have been some changes made to what is currently legal at an industry level, but more work must be done to preserve the planet as a habitable place for humans. The goal of this project is to potentially produce a possible fossil fuel replacement which is better for the environment and can help to mitigate the effects of climate change and global warming.

1.2 Project Description

With the growing strain on the global environmental crisis, the demand for a renewable replacement fuel source has skyrocketed. Many processes have been researched in the hopes of producing a viable replacement fuel for the current standard—fossil fuels. Several different types of energy sources are under investigation to determine usefulness and longevity including solar power, wind power, geothermal power, nuclear power, and bio-mass driven alternatives. This project focuses on specifically the bio-mass driven alternatives for a renewable fuel source.

There are two main types of reaction processes which can be used to produce a fuel from bio-mass. The first process is known as pyrolysis. This process takes place in the absence of oxygen and uses the mechanism of thermal decomposition to breakdown the molecules of the bio-mass with a product of bio-oil. This bio-oil can be further upgraded into other more specific products which can be used in different specific situations. There are two types of pyrolysis reactions—fast and slow. This project centers on the use of fast pyrolysis to produce the bio-oil as the main product of both systems. In fast pyrolysis, high temperatures typically around 500°C are used with low retention times to perform the thermal decomposition of the bio-mass as mentioned previously.

The second main type of process which can be used is gasification. This process also takes place at very high temperatures (typically between 600°C-1,000°C) and includes oxygen in the reaction. This means that thermal decomposition is not the reaction mechanism in this case. Instead, a typical combustion reaction takes place. In the case of bio-mass gasification, the main resulting product would be synthesis gas or syngas which could be further refined into different fuel sources. This process is not studied in this project. Instead, coal gasification is studied as a secondary side process. The goal of this is to determine if this combined process of Direct Pyrolysis and Coal Gasification would be a more cost effective option rather than promoting the Direct Pyrolysis process as a stand-alone. The intention is to use the Coal Gasification side-process as an extra heat source in the Direct Pyrolysis conversion to mitigate costs incurred in that process individually.

1.3 Market Survey

To provide a precise cost estimate for this project, a market survey must be generated. The scope of this project will include raw materials such as the cost of coal prices, fuel prices, crude oil, and corn stover.

1.4.1 Coal Pricing History and Analysis

There are four main ranks of coal including lignite, subbituminous, bituminous, and anthracite. This depends on the amount of carbon contains and the amount of heat energy that can be produced. A rule of thumb is that prices are higher for coal that contains higher heat content. The lowest rank of coal is lignite due to having the lowest energy content. Listed below are the price and coal amounts of the four different coal types listed in Table 1.

Table 1: Price of Coal Types and Carbon Amounts

Coal	Price ($USD/ST)	Carbon Amount (%)
Bituminous	50.05	45-86
Subbituminous	14.43	35-45
Lignite	22.16	25-35
Anthracite	96.68	86-97

Table 1 shows that anthracite has the highest price of $96.68 per short ton in 2022 which makes sense since it has one of the highest carbon amounts of approximately 86-97%. The lowest price of coal is the subbituminous priced at $14.43 per short ton, with a carbon amount of 35-45%. All price and carbon amounts were provided by the EIA government website. Figure 3 below displays a visual representation of the average cost of coal transportation within the last decade.

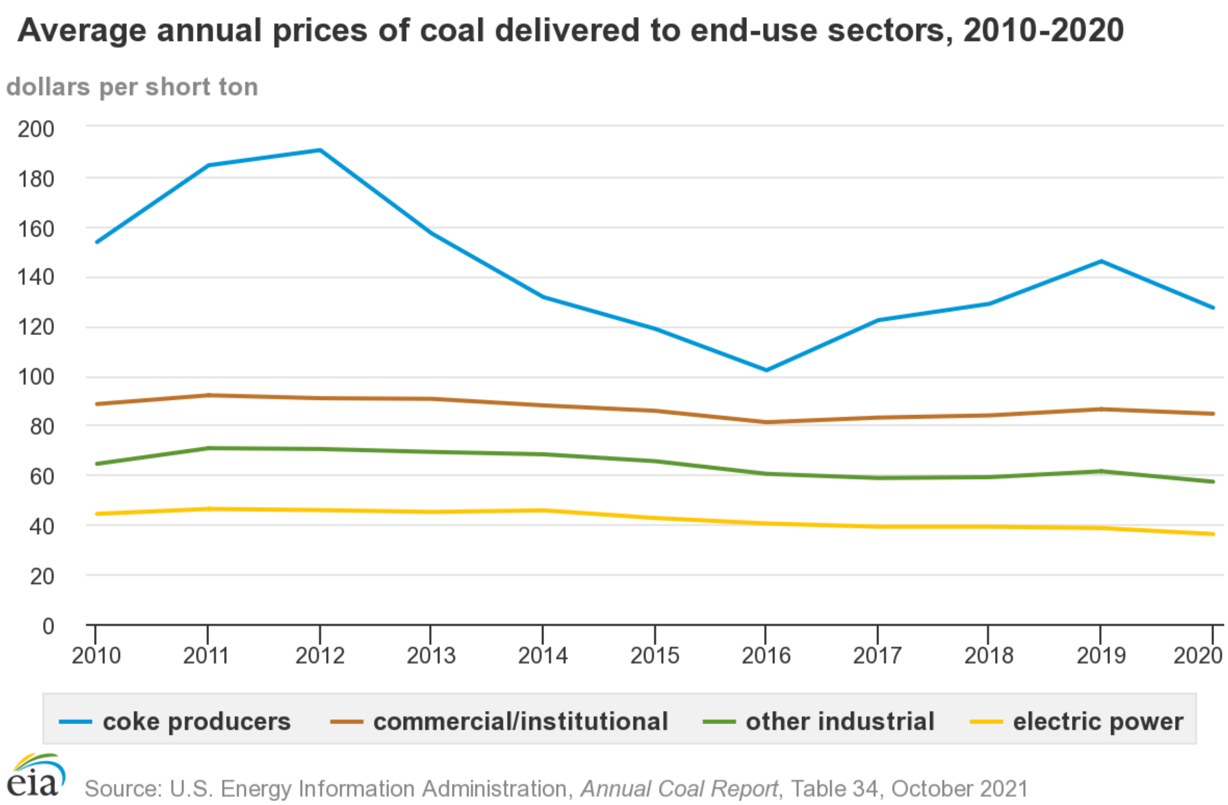


Figure 3: Average Annual Prices of Coal Transportation from 2010-2020

Figure 3 shows the cost of transportation of coal within the last decade. The cost of transporting coal adds an additional cost to the final price. The main transportation methods include train, barge, truck, or a combination of these. Regardless of the method of transportation, they all use diesel fuels which significantly affects the cost of transportation. The national average sales price of coal at coal mines, excluding anthracite, was $28.88 per short ton, with an average price for coal delivered to the electric power sector of $36.14 per short ton. The difference in average transportation cost was $7.26 per short ton which could be a potential savings amount in the future. Figure 4 presents a visual representation of gas prices from 2014 to 2017.

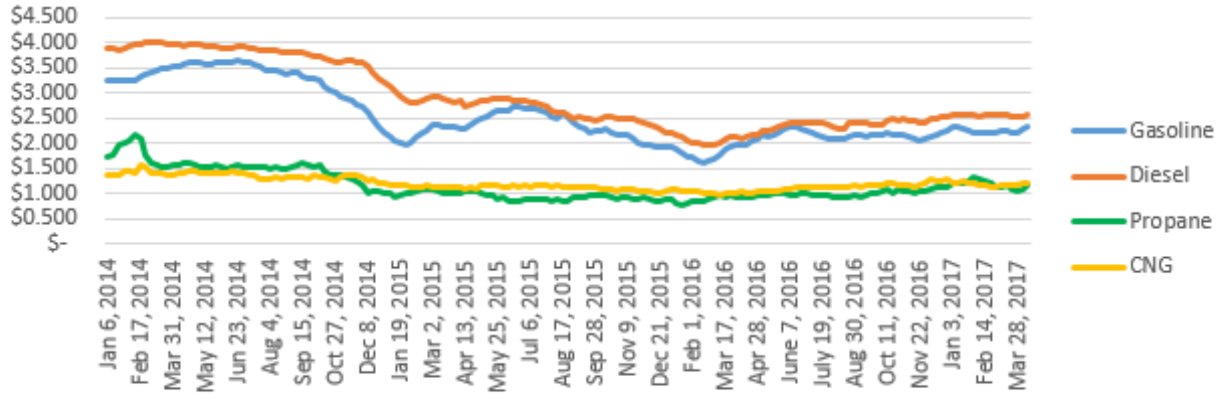


Figure 4: Fuel Prices from 2014-2017

The graph shown above includes four fuel types including gasoline, diesel, propane, and CNG. On average the cost of CNG is 40-50% less than gasoline and 60% less than diesel. Natural gas burns cleaner than gasoline and diesel which reduces the maintenance costs and less wear and tear on the engine. Vehicles fueled by natural gas are more expensive initially, but the cost is offset by the lower fuel and maintenance cost.

Figure 5 displayed below portrays the price of crude oil futures. These future contracts are agreements to buy or sell crude oil at a predetermined price and at a specified time in the future between both parties.

Figure 5: Crude Oil Pricing History in USD

1.4.2 Raw Material History and Analysis

Figure 6 displayed below portrays the current price of corn as of January 27, 2022. The current price indicated is $6.2525 per bushel. The price of corn is especially important since it will be the main source of biomass used.

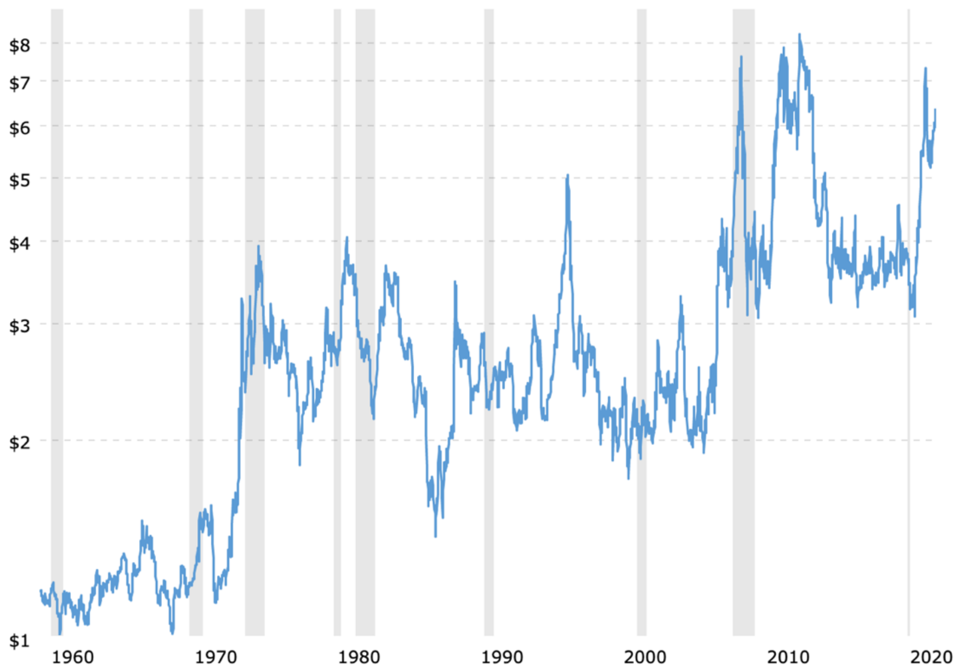


Figure 6: Corn Pricing History per Bushel in USD

Figure 7 found below shows an estimation of the different overall costs which go into the production of corn. These costs are broken down from greatest to least in the following order: harvest, transport, storage, and loading & unloading. This impacts the cost of the chosen bio-mass—corn stover—as the two are directly related.

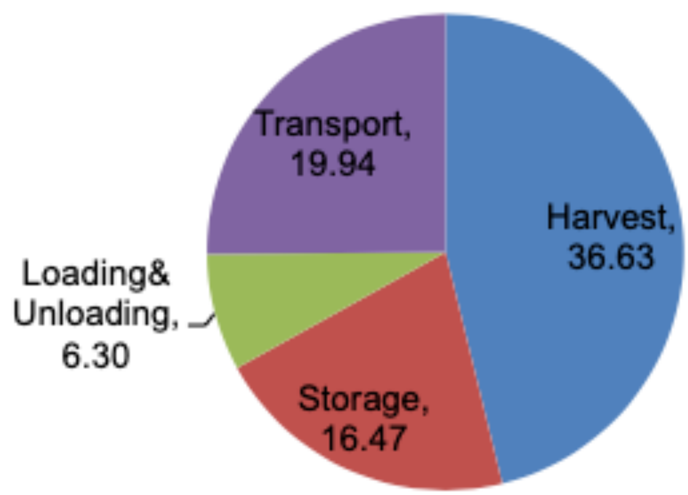


Figure 7: Partition of Estimated Supply Cost for Corn-Soybean Rotation

This complete market survey has been used throughout the project to estimate costs and pricing appropriately based on the information collected. It is important to note here that, as this project is theoretical, all estimated costs are based solely off information like that contained in the market survey. The team has not received any direct quotes of costs or pricing of any materials, equipment, or products included in this project.

2. Raw Material Analysis

2.1 Methods of Corn Stover Collection

The current methods used for the collection of corn stover are forage harvesting, baling and Stakhand. Forage harvesting has no separation of grain and results in high grain damage. Bailing on the other hand has dirt and rock collection and can lead to undesirable usages of plastic twine. It is considered a second pass operation. Stakhand has little cob collection but a high dirt collection and is considered a second pass operation. The fields where this corn stover is collected are composed of various materials. Figure 8 displayed below portrays this.

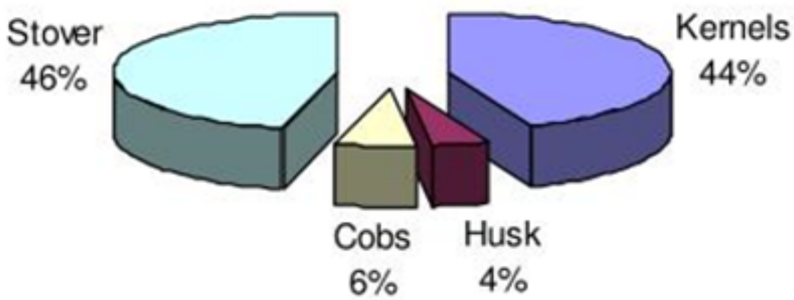


Figure 8: Breakdown of Corn Plant Bio-mass Proportioned by Weight

Figure 8 found above shows the percentage break down of corn plant bio-mass by mass. This information has been used in the coming sections of this project to determine the required heat duty of the bio-mass reactor based on these percentages.

2.2 Composition of Corn Stover

The composition of bio-mass is an important aspect for this process. It will be used to help determine the outputs of the entire process. The typical composition of corn stover is displayed below in Table 2.

Table 2: Typical Composition of Corn Stover

	Corn Stover	Corn Fiber
Glucan (cellulose)	36.2%	14.3%
Glucan (starch)	0.0	23.7
Xylan	21.4	16.8
Arabinan	3.9	10.8
Protein	3.5	11.8
Lignin	22.6	8.4
Acetyl	2.3	NA
Ash	6.0	0.4

As is shown in Table 2, the majority components of corn stover are cellulose, hemicellulose (xylan), and lignin. There are also other extractives and ash which makes up a small percentage of the overall composition.

2.3 Transportation Methods

There are four main transportation methods for corn stover. The first involves a pick-up style with a light truck and trailer combination, either a gooseneck or a bumper-hitch style trailer. The second method is a straight truck. The third method is a truck tractor/semi-trailer combination, this is most often used with flatbed trailers. The last method used is implements of husbandry, a combination of agricultural tractors and wagons.

Table 3: Vehicle Dimension Restriction with and without Oversized Load Permitting

	Vehicle Length Restriction	Load Width Restriction	Load Height Restriction	Approx. Number of Bales Hauled
Pick-up Truck/Trailer	53' Trailer	8'6"	13' 6"	Depends on size of trailer (20-33)
Pick-up Truck/Trailer (With annual wide load permit)*	75' Trailer	12'5"	13' 10"	Depends on size of trailer (33-50)
Straight Truck	41'	8'6"	13' 6"	21-25
Straight Truck (With annual wide load permit)*	41'	12'5"	13' 10"	21-25
Truck Tractor/ Semi-Trailer	53' Trailer	8'6"	13' 6"	Typically 36 bales to a load
Truck Tractor/ Semi-Trailer (With annual wide load permit)*	75' Trailer	12'5"	13' 10"	Maximum is approx. 81 bales (more than likely not allowable due to weight)
Implements of Husbandry	No Restriction	No Restrictions	13'10"	One tractor may pull up to three trailers

Table 3 found above displays the different dimension restrictions that occur with these different methods. These transportation restrictions play a role in the cost of bio-mass and could cause that cost to vary dependent of location and specific regional transportation requirements.

2.4 Production Percentages of Bio-oil

Table 4 found below contains production percentages based on mass for each component in the process. This information was provided to the team by the faculty advisor of this project, Dr. Abdus Salam, and has been included and used in subsequent project calculations.

Table 4: Mass Percentages of Products Based on Process Type Including Conditions

Mode	Conditions	Liquid	Char	Gas
Fast pyrolysis	Moderate temperature, short residence time	**75%**	12%	13%
Slow Pyrolysis	Low temperature, very long residence time	30%	**35%**	35%
Gasification	High temperature, long residence time.	5%	10%	**85%**

A.V.Bridgwater

As is shown in Table 4, the fast pyrolysis process—which is being used in the Direct Pyrolysis process of this project—is typically completed at moderate temperatures with short residence times. Here, "moderate" is a relative term. In the case of fast pyrolysis, the reaction occurs at about 500°C. The estimated production percentages of this process are also included in Table 4 and have been used in the material balance calculation for Direct Pyrolysis which is discussed in a subsequent section in this report.

3. Proposed Design

3.1 Direct Pyrolysis

3.1.1 Process Flow Diagram

A process flow diagram (PFD) has been created following the standard process flow used in fast pyrolysis and is included below labelled as Figure 9.

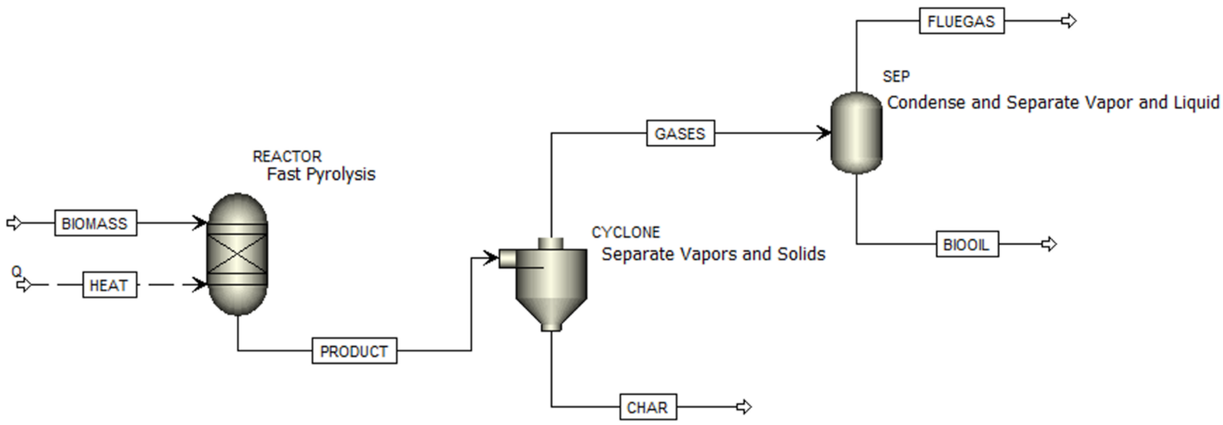


Figure 9: PFD of Fast Pyrolysis Process of Direct Conversion of Bio-mass to Bio-oil

The feeds to the reactor are only the biomass of choice—in this case corn stover including stalks, leaves, husks, and cobs—and heat. The product stream from the reactor then travels to a cyclone which is used to separate the char residue from the vapors produced from the pyrolysis process. The char can then be burned to produce heat for the process, discarded, or sold as a natural fertilizer. The vapors which exit the cyclone then pass through a condenser which condenses most of the vapors into bio-oil while the rest remain as flue gas. These components are separated by phase with one exit stream as liquid bio-oil and the other as vapor flue gas.

3.1.2 Material Balance

The material balance completed for the direct conversion of bio-mass to bio-oil through pyrolysis has been done by hand. The balance is simple and direct with mass fractions based on the information found in Table 4 above. Table 5 below shows the main results of this material balance based on a 65,000 kg/hr bio-mass feed basis. This feed-rate was chosen based on values found in similar projects also estimated at industry level production.

Table 5: Final Material Balance of Direct Pyrolysis

Biomass Feed Rate	65,000 kg/hr
Gases from Reactor Flowrate	57,200 kg/hr
Bio-oil Production Rate	48,750 kg/hr
Char Production Rate	7,800 kg/hr
Flue Gas Production Rate	8,450 kg/hr

The full calculation of these values, as completed by hand, is included in the Appendix of this document labelled as Figure 15. It includes a basic PFD and the straight-forward calculations used to solve for each value found in Table 5 above.

3.1.3 Energy Balance

Two energy balances were completed for the direct conversion of bio-mass to bio-oil process. The first energy balance was performed around the pyrolysis reactor to determine the heat duty necessary for the heat stream entering the reactor. This was broken down into heat necessary for stover—which includes stalks and leaves—cob, and husks to find the total heat requirement. The heat capacities for each of these items was found through research with the source of this data included in the references section of this document (Czajkowski, 2019). The data found in Figure 8 was also used during this computation. Table 6 below shows the main computed values for this energy balance with the complete details of computation found labelled Figure 13 in the Appendix.

Table 6: Energy Balance Values for the Reactor for Direct Pyrolysis

Q_{Stover}	6,472 kW
Q_{Cob}	763.642 kW
Q_{Husk}	591.085 kW
Q_{Total}	7,826.73 kW

The second energy balance completed for the direct conversion of bio-mass to bio-oil through pyrolysis was done around the condenser used in the system. For this computation, it is assumed that there is no heat loss from the reactor to the condenser. The heat duty of the condenser is found using the heat requirement of the bio-oil and the flue gas. Table 7 below shows important values from this balance with the detailed computation found labelled as Figure 14 in the Appendix.

Table 7: Energy Balance Values for the Condenser for Direct Pyrolysis

$Q_{Bio\text{-}oil}$	$-5.5575*10^7$ kJ/hr
$Q_{Flue\ Gas}$	-4013750 kJ/hr
Q_{Total}	$-5.95888*10^7$ kJ/hr

Both Figure 13 and Figure 14—which show the detailed energy balance computations for the direct pyrolysis process—include complete work showing all calculations completed to compute the values presented in Table 6 and Table 7.

3.1.4 Equipment Costing

Table 8 below provides a cost breakdown of both equipment and installation costs necessary for the Direct Pyrolysis process. These costs, as provided, also apply in the combined process for the Direct Pyrolysis portion. The pricing of equipment was determined using the material balance which can be found in Figure 11 in the Appendix based on the necessary capacity of each.

Table 8: Equipment Cost and Installation Cost for Direct Pyrolysis Conversion Process

Unit	Equipment Cost ($)	Installation Cost ($)
Fluidized-Bed Reactor	22,700.00	164,300.00
Cyclones (11)	93,500.00	654,500.00
Biomass Fired Boiler	54,000.00	378,000.00
Condenser	10,300.00	72,400.00
Subtotal	180,500.00	1,269,200.00
Total		**1,449,700.00**

The equipment and installation cost of the fluidized-bed reactor and the condenser are estimated based on data produced by ASPEN PLUS for closely related processes. The installation cost for each of these pieces of equipment are roughly seven times the equipment cost. This relationship has been used in calculating the installation cost of the cyclones and the boiler. The boiler chosen for this process is a biomass-fired boiler which can be fueled using wood chips or corn stover. A determination on which biomass to use will be made for the final progress report. Figure 10 below has been used to determine the number of cyclones needed in this process and, therefore, the cost.

Model number	Air flow m3/h	Resistance kg/m2		Efficiency %	Dimension(L×W×H)mm		Weight kg	
		X	Y		X	Y	X	Y
XLP/A-3.0	750-1060	45-90	39-79	85-99	406×390×6125	460×390×1380	57	43
XLP/A-4.2	1460-2060				556×545×2177	556×545×1880	99	80
XLP/A-5.2	2280-3230				711×700×2701	771×700×2701	165	128
XLP/A-7.0	4020-5700				911×910×3489	911×910×3040	265	213
XLP/A-8.2	5500-7790				1071×1605×4050	1071×1605×3540	364	293
XLP/A-9.4	7520-10650				1226×1222×4616	1226×1222×4050	473	384
XLP/A-10.6	9520-13500				1376×1337×5157	1376×1337×4545	631	483

Figure 10: Cyclone Capacity Data as Provided by Manufacturer

It was determined that 11 cyclones must be run in unison to support the necessary system requirement. This, in combination with the price range provided by the manufacturer, resulted in the estimated equipment cost as seen in Table 8. As shown in Table 8, the total equipment cost is estimated at $180,500.00 with an estimated installation cost of $1,269,200.00. This results in an estimated total cost of $1,449,700.00 for the Direct Pyrolysis process.

3.1.5 Utility Costing

The utility cost for the bio-mass conversion with Direct Pyrolysis was calculated using estimations provided by ASPEN PLUS. There are heating elements, reactors, and condensers that will be considered when estimating required power to operate. Table 9 below provides a cost analysis of the electricity requirement of the equipment necessary for the Direct Pyrolysis process. As shown, the total cost for electricity per year is estimated at $4,379,454.25.

Table 9: Electricity Costing for Direct Pyrolysis

Data	Electricity
Rate (kW)	62.22
Cost/kW	$8.04
Cost/day	$11,998.50
Cost/Year	**$4,379,454.25**

Table 10 below provides a breakdown of the utility cost required for the steam necessary for the Fluidized-Bed reactor's required heat duty as shown in Figure 13. The required utility calculation for the necessary flowrate of steam based on the energy balance for this system can also be found in the Appendix labelled at Figure 17. As is shown in Table 10, the total cost of steam per year is estimated at $338,212.45.

Table 10: Utility Costing for Steam for Direct Pyrolysis

Data	Steam
Flowrate (kg/hr)	33,916
Cost/kg	$0.027320717
Cost/hr	$926.61
Cost/Year	**$338,212.45**

Table 11 below shows a cost analysis of the required cooling water for the condenser in the Direct Pyrolysis process. The utility calculations necessary to find the flowrate of the cooling water are based on the heat duty requirement found in Figure 14. This utility calculation can be found in the Appendix labelled as Figure 16. As is shown in Table 11, the total cost of cooling water per calendar year is estimated at $888,702.00.

Table 11: Utility Costing for Cooling Water for Direct Pyrolysis

Data	Cooling Water
Flowrate (gal/hr)	49,372.5
Cost/1000 gal	$3.00
Cost/hr	$148.12
Cost/Calendar Year	**$888,702.00**

All sample calculations for these computed values are included in the detailed utility calculations labelled as Figure 16 and Figure 17 in the Appendix.

3.2 Coal Gasification Companion Conversion

3.2.1 Process Flow Diagram

A process flow diagram (PFD) has also been created for the companion conversion of coal gasification. This process uses coal, water, char, and oxygen as feeds to the system to gasify the coal and produce a desired companion conversion of syngas. This PFD is included below labelled as Figure 11.

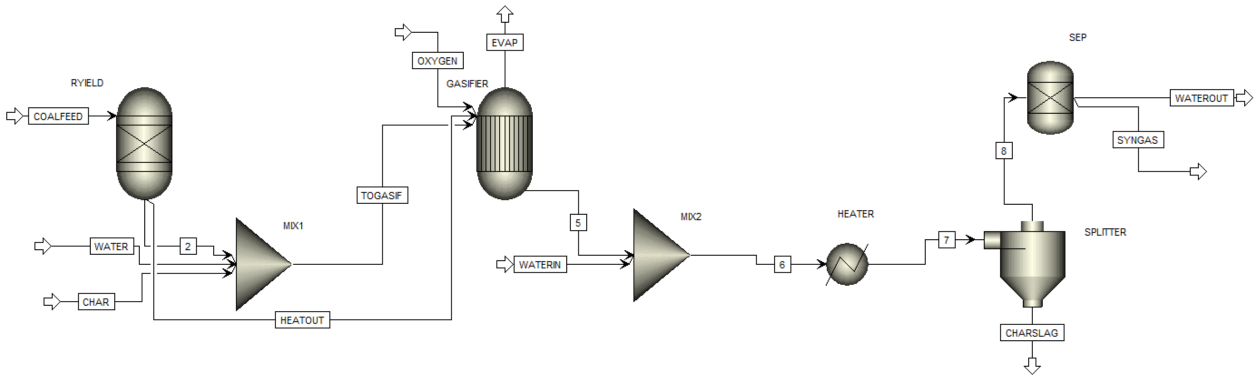


Figure 11: Coal Gasification Process Flow Diagram to Produce Syngas

In this process flow diagram, there is a feed of coal input into a RYield reactor, yielding certain components in the composition of the coal to be mixed later for the gasifier. Water and char are also fed to the system at the mixer which is then sent to the coal gasification process. In the gasification process, oxygen is inputted, and all the mixed components are converted at remarkably hot temperatures, greater than 700°C, without combustion and a controlled amount of oxygen/steam into carbon monoxide, hydrogen, and carbon dioxide. There is also extra heat output from the RYield reactor and input into the gasifier to help with heating, so the process moves more efficiently. Then, the product of the gasifier moves to a mixer with water where it is heated up again to be split so the by-products of char and slag can be removed from the system. Finally, a separator is used to separate the syngas from the extra water and the product is complete for this companion conversion using coal gasification. Overall, this coal gasification process is being used because the extra heat from the gasifier can be used in the pyrolysis process to reduce the spending on heat necessary for the thermal decomposition to take place.

3.2.2 Material Balance

The material balance for the coal gasification companion conversion has also been completed by hand. This balance was completed on roughly a 45,000 kg/hr basis of coal. Table 12 below contains the main two values found in this calculation.

Table 12: Coal Gasification Companion Conversion Material Balance

Coal Feed Rate	44,254.5 kg/hr
Oxygen Feed Rate	33,458 kg/hr
Steam Feed Rate	20,953.3 kg/hr
Syngas Production Rate	77,641 kg/hr
Water Production Rate	21,026 kg/hr

The data presented in Table 12 was calculated by hand with all feed rates being estimated by similar ASPEN PLUS process simulations. These simulations were used strictly as reference for the estimations of these feed rate values to ensure that they are set to a reasonable level for standard industry processes. The detailed computation of these values including all calculations can be found in the Appendix of this document labelled as Figure 12.

3.2.3 Energy Balance

The energy balance for the coal gasification companion conversion to produce syngas is below in Table 13. A simple caloric value was calculated, and the steam rate is determined. Also, a gas yield volume is added for additional information. Figure 15 shows these calculations by hand. Overall, the flow rates and heat duties of this process can be used in the conversion of bio-mass to bio-oil as a supplemental heat source to reduce the cost of the heating requirement for the pyrolysis reaction.

Table 13: Coal Gasification Companion Conversion to Produce Syngas Energy Balance

Steam Rate	0.768 kg/kg of Carbon
Caloric Value	1,880 kCal/m^3
Gas Yield	4.53 m^3/kg of Carbon

The preliminary balance used to completed Table 13 included the same progression of calculation as shown in Figure 12 while instead using a basis of 1kg/hr feed rate of coal to the system. This energy balance has been used in subsequent utility calculations by scaling to an appropriate value before completing said utility calculations.

3.2.4 Equipment Costing

Table 14 below provides a breakdown for the equipment cost and installation cost of the Coal Gasification side process that produces syngas. This side process would be used along with the Direct Pyrolysis process to help provide heat to that system.

Table 14: Equipment Cost for Coal Gasification

Unit	**Equipment Cost ($)**	**Installation Cost ($)**
RYield	44,900.00	154,100.00
Mixer 1	250.00	100.00
Gasifier	22,700.00	164,300.00
Mixer 2	250.00	100.00
Heater	10,300.00	72.400.00
Cyclones	72,100.00	253,700.00
SEP	200,100.00	499,200.00
Total		**1,494,500.00**

Cost estimates were computed using ASPEN PLUS data from a similar process. It was determined that the equipment cost would be $350,600.00 and the installation cost would be $1,143,900.00. This means that the total cost for this side process is $1,494,500.00. This side process's purpose is to provide a more cost-effective way to produce the heat that is needed for Direct Pyrolysis to occur. This equipment costing data will be used to perform a cost saving analysis to determine if adding on this side process will lower the amount of cost to the facility.

3.2.5 Utility Costing

Utility costing for the Coal Gasification process is described in the tables below. These were both estimated by hand and the extra heat from the energy rate will be used from the gasifier to heat the Direct Pyrolysis process in the Combined Process. The utility costing calculations for this are provided in the Appendix labelled as Figure 18. As shown in Table 15 below, the extra heat has a rate of 70.337 kW to heat the gasifier and pyrolysis reactors. As indicated, the estimated cost per year is $2,526,223.70.

Table 15: Utility Cost for Coal Gasification Energy

Data	**Electricity (Energy)**
Rate (kW)	70.337
Cost $/kW	4.10
Cost $/day	6,921.16
Cost $/yr	**2,526,223.7**

Table 16 below describes the amount of cooling water that is necessary for the condenser to cool the product at the end of the Coal Gasification process. As shown, the estimated cost of million gallon of cooling water per year is $122,640.00.

Table 16: Utility Cost for Coal Gasification Cooling Water

Data	**Cooling Water**
Cost (MMgal/hr)	$14.00
Cost (MMgal/day)	$336.00
Cost (MMgal/yr)	**$122,640.00**

The full calculation for both Table 15 and Table 16 can be found in Figure 18 in the Appendix of this document. It shows all calculations completed to compute the values provided in these tables.

4. Economic Analysis

For this project, it can be assumed that all investments directly include equipment and operations of both processes. The capital investment was calculated by using the Lang factor methods. The equipment costs were obtained by utilizing ASPEN PLUS simulations estimations. Once the equipment costs were estimated, the Lang factors can be used to estimate the Fixed Capital Investments (FCI), as well as the Total Capital Investment (TCI) as shown in Equations 1 and 2 below. This was done for both processes which are Direct Pyrolysis and Coal Gasification. The Lang factors were obtained from the textbook "Plant Design and Economics for Chemical Engineers" by M. Peters, K. Timmerhaus, and R. West, specifically Tables 6-9 from the text were used. Please note that the Lang factor is used for a solid processing plant. The FCI factor is 3.97

and the TCI factor is 4.67. The equations shown below are used to calculate the Fixed Capital Investment and the Total Capital Investment.

$$FCI = 3.97 * (Delivered\ Equipment\ Cost) \tag{1}$$

$$TCI = 4.67 * (\ Delivered\ Equipment\ Cost) \tag{2}$$

For the Direct Pyrolysis process, the FCI is approximately \$5,755,331 and the TCI is approximately \$6,770,100. For the Coal Gasification process the FCI is approximately \$5,933,170 and the TCI is approximately \$6,979,320. Based on these calculations, it can be said that overall, the Direct Pyrolysis has a lower FCI and TCI compared to the Coal Gasification process.

For the Direct Pyrolysis, the revenue source is the bio-oil product. The Coal Gasification revenue source is the bio-oil and diesel products. The current price of corn stover is \$6.2525 per bushel as stated previously in the market survey. Additionally, the price of selling raw bio-oil is approximately \$850.25 per ton, and the price of diesel is approximately \$850.23 per ton.

Cash flow tables have been completed for each process—Direct Pyrolysis and the combination with Coal Gasification. Each has been completed on a basis of without the necessity to purchase land and with the necessity to purchase land. In each case, economic indicators have been compiled to be used to gauge which process is more economically feasible.

4.1 Capital Cost Estimate

The FCI and TCI values were calculated by using the textbook "Plant Design and Economics for Chemical Engineers" by M. Peters, K. Timmerhaus, and R. West. This textbook covered capital investments based on delivered equipment costs and the ratio factors in Chapter 6. Tables 6-9 were utilized to estimate the capital investments including the equipment costs when delivered and the ratio factors. The ratio factors are different based on the process including a solid processing plant, a fluid processing plant, and a solid liquid processing plant. For this project, solid processing plant ratio factors will be used.

4.1.1 Direct Pyrolysis

The estimated capital investment was calculated by adding the direct plant costs and the indirect plant costs. The delivered equipment cost was calculated as \$1,449,700.00 for the Direct Pyrolysis process. The value was set at (D) for all direct costs and (I) for all indirect costs. The FCI is approximately 85% and Working Capital (WC) is approximately 15%. To calculate the WC, FCI is divided by 0.85, then this valued is subtracted from the FCI. Table 17 found below shows the completed breakdown of all costs necessary in the estimation of capital investment.

Table 17: Estimating Capital Investment for Direct Pyrolysis

Purchased Equipment (delivered)	$1,449,700.00
Equipment installation (45%)	$652,365.00
Instrumental/controls (18%)	$260,946.00
Piping (installed) (16%)	$231,952.00
Electrical System (10%)	$144,970.00
Buildings (including services) (25%)	$362,425.00
Yard Improvements (15%)	$217,455.00
Service Facilities (installed) (40%)	$579,880.00
Total Direct Plant Cost, D	$3,899,693.00
Indirect Costs	
Engineering & Supervision (33%)	$478,401.00
Construction Expense (39%)	$565,383.00
Legal Expenses (4%)	$57,988.00
Contractors Fee (17%)	$246,449.00
Contingency (35%)	$507,395.00
Total Indirect Plant Costs, I	$1,855,616.00
Fixed Capital Investment = D+I	$5,755,309.00
Working capital	$1,015,642.76
Total Capital Investment, TCI	$6,770,951.76

All values compiled in Table 17 found above have been calculated based on information found in Table 6-9 of the textbook "Plant Design and Economics for Chemical Engineers." The calculations completed follow those as described in that section of this textbook.

4.1.2 Coal Gasification Companion Conversion

The delivered equipment cost was calculated as $1,494,500.00 for the Coal Gasification process. Please note that the actual delivered equipment cost for coal gasification is $2,944,200 since coal gasification is an add on to the direct pyrolysis process. The value was set at (D) for all direct costs and (I) for all indirect costs. The Fixed Capital Investment for the Coal Gasification process is approximately $5,933,165.00, which is $177,854 more than the Fixed Capital Investment of the Direct Pyrolysis process. Please note that the actual Fixed Capital Investment for Coal Gasification process is $11,688,474 since the Coal Gasification processes is an add on to the Direct Pyrolysis

Table 18: Estimating Capital Investment for Coal Gasification Process

Purchased Equipment (delivered)	$1,494,500.00
Equipment installation (45%)	$672,525.00
Instrumental/controls (18%)	$269,010.00
Piping (installed) (16%)	$239,120.00
Electrical System (10%)	$149,450.00
Buildings (including services) (25%)	$373,625.00
Yard Improvements (15%)	$224,175.00
Service Facilities (installed) (40%)	$597,800.00
Total Direct Plant Cost, D	$4,020,205.00
Indirect Costs	
Engineering & Supervision (33%)	$493,185.00
Construction Expense (39%)	$582,855.00
Legal Expenses (4%)	$59,780.00
Contractors Fee (17%)	$254,065.00
Contingency (35%)	$523,075.00
Total Indirect Plant Costs, I	$1,912,960.00
Fixed Capital Investment = D+I	$5,933,165.00
Working capital	$1,047,029.12
Total Capital Investment, TCI	$6,980,194.12

All values compiled in Table 18 found above have been calculated based on information found in Table 6-9 of the textbook “Plant Design and Economics for Chemical Engineers.” The calculations completed follow those as described in that section of this textbook.

4.2 Income and Expenses Analysis

4.2.1 Direct Pyrolysis

Table 19 shown below includes the estimations made for expenses and income for the Direct Pyrolysis process. This information was also used in calculations for the economic factors of the Combined Process in conjunction with the Coal Gasification expenses and income.

Table 19: Expenses and Income Values for Direct Pyrolysis

Expenses	Cost ($/Calendar Yr)	Income	Price ($/Calendar Yr)
Steam	338212.45	Total amount of bio oil sold per year	274142259
Biomass cost based on feed rate	71369656.7		
Cooling water cost	888702		
Electricity	4379454.25		
Total Expenses	**76976025.4**	**Total Income**	**274142259**

As is shown in Table 19, total expenses for this process, including utilities and raw material costs, are estimated at $76,976,025.40 per calendar year on a basis of 6000 stream hours per calendar year. The income is estimated at $274,142,259.00 per calendar year based on the same assumed stream hours per calendar year.

4.2.2 Combined Process

Table 20 shown below is the expenses and income values for the Combined process. The Combined Process includes Direct Pyrolysis and Coal Gasification.

Table 20: Expenses and Income Values for the Combined Process

Expenses	Cost ($/Calendar Year)	Income	Price ($/Calendar Year)
Steam	591425.65	Total amount of syngas sold per year	61273.37
Biomass cost based on feed rate	92491554.4	Combined Income	274203532.4
Cooling water cost	1011342		
Electricity cost	6905677.95		
Total Expense	**101 million**	**Total Income**	**274203532.4**

Total expenses for this process include the utilities and raw material costs for both systems and the income is a combined number from the amount of syngas sold and the amount of bio-oil sold per year. As is shown in Table 20, the expenses of this system are estimated at $101 million with a total estimated income of $274,203,532.40.

4.3 Economic Indicators

4.3.1 Real Estate Included

Table 21 below shows the tabulated economic indicators for the Direct Pyrolysis process with real estate included. The depreciation for the equipment was done using 7 year MACRS depreciation and the real estate was done with a 15 year MACRS depreciation. The full cash flow table for this case can be found in the Appendix labelled as Table 25.

Table 21: Direct Pyrolysis Economic Indicators – With Real Estate

Economic Indicators		
FCI 1	5755309	$
FCI 2	237650	$
WC	898943.85	$
TCI	6891902.85	$
NPV	380461824	$
IRR	22.6270218	%
ROI	22.6214965	%
PBP	0.04420574	YRS
B/C	3.74694512	
EUAW	153169310	$

The FCI for the necessary land—FCI 2—was estimated using the cost per acre of land in Michigan for 10 acres of land. The Minimum Acceptable Rate of Return (MARR) was set to 40% for these calculations. As is shown, the Net Present Value (NPV) is greater than zero which indicates that this project is easily economically feasible with an MARR of 40%. Table 4 also shows the Internal Rate of Return (IRR), Return on Investment (ROI), Payback Period (PBP), Benefit Cost Ratio (B/C), and Equivalent Uniform Annual Worth (EUAW). Each of these values indicates that this project, including the cost of real estate, is economically feasible.

Table 22: Combined Process Economic Indicators – With Real Estate

Economic Indicators		
FCI 1	11.7	MM
FCI 2	0.356	MM
WC	1.8084	MM
TCI	13.8644	MM
AVG CF	123.3735	MM
NPV	292.49734	MM
ROI	8.8985823	%
PBP	0.1123775	Years
B/C	1.4731338	
EUAW	138.1	MM
IRR	8.8963869	%

Table 21 above shows the tabulated economic indicators for the Combined system process with real estate included. A 7-year MACRS depreciation was used for the equipment and the real estate was done using a 15-year MACRs depreciation. The corresponding cash flow table for these indicators can be seen in Table 27 in the Appendix. FCI 2 is the FCI necessary for land estimated using the cost of land per acre in the state of Michigan. Also, the MARR was set to 40% for this. The NPV for this system was greater than zero so this system is economically feasible. The rest of the indicators including the working capital, total capital investment, average cash flow, return on investment, payback period, benefit/cost ratio, equivalent uniform annual worth, and internal rate of return indicate the same conclusion.

4.3.2 Real Estate Excluded

Table 23 found below shows the calculated economic indicators without the inclusion of real estate as an alternate scenario. This would be useful in a situation where it is possible to add this process to an already existing plant.

Table 23: Direct Pyrolysis Economic Indicators – Without Real Estate

Economic Indicators		
FCI	5755309	$
WC	863296.35	$
TCI	6618605.35	$
NPV	356837586	$
IRR	23.560995	%
ROI	23.5566851	%
PBP	0.04245079	YRS
B/C	6.86428961	
EUAW	153109811	$

The full cash flow table for this case can be found in the Appendix labelled as Table 26. The NPV of these calculations again show that this process on its own is economically feasible as it is well over zero. Other values included in Table 23 indicate the same conclusion.

Table 24: Combined Process Economic Indicators -- Without Real Estate

Economic Indicators		
FCI	11.7	MM
WC	1.75	MM
TCI	13.45	MM
AVG CF	124.1226	MM
NPV	275.2242	MM
ROI	9.228448	%
PBP	0.108361	Years
B/C	2.682846	
EUAW	138.395	MM
IRR	9.201031	%

Table 24 shown above is the calculated economic indicators for the combined process without the inclusion of real estate as another alternate scenario. Again, this would be a useful tool when there is an existing plant. The cash flow table for these calculations is found in the Appendix labelled as Table 28. The NPV of this system is again greater than zero concluding a feasible status.

5. Safety and Environmental Constraints

The main thing to consider in both purposed systems is the safety concerns. Very high temperatures and pressures are observed in both systems: thus, it is very important to maintain all the equipment and have regularly scheduled maintenance to ensure the safety of the facility. The type of equipment selected has a high level of corrosion, which is another safety concern. If not properly maintained, equipment malfunction could occur. Explosion and gas leaks are among some of the potential risks if the system is not properly maintained. Active monitoring of this equipment, when in use, is of the utmost importance because of the aforementioned high temperatures and pressures. Due to all the risks mentioned, it is a must to have all employees use adequate personal protective equipment to help prevent accidents from occurring. Gloves that can sustain high heat would be recommended for around the reactors. Also, carbon monoxide monitors and filters can help keep personnel safe in the event of a gas leak. All these dangers and risks can ultimately be avoided if proper safety measures are considered.

There are many environmental concern (Bridger Photonics, n.d.) (Medline Plus, 2022) (Pipe Flow Calculations, 2020) (Pipe Flow Calculations, 2020) (Pipe Flow Calculations, 2020) (Pipe Flow Calculations, 2020; Bridger Photonics, n.d.)s within the two process designs that are suggested. The process first starts off with the decomposition of biomass (corn stover). This leads to several products such as carbon dioxide. This is a very common product that is produced during both processes, such as the burning of the biomass and in coal gasification with a syngas being the product. This is a greenhouse gas that affects the atmosphere and ultimately contributes to global warming. Carbon dioxide also causes many safety concerns to humans such as respiratory acidosis.

Respiratory acidosis is when the lungs cannot remove all the carbon dioxide that the body produces. This then leads to the blood to become acidic (U.S. National Library). Another product during pyrolysis is methane gas which is harmful to the environment and pollutes the air. Methane overall can lead to lower air quality and other various health issues in animals and even premature deaths in some cases (How does methane*)*. Lastly, both the charcoal and bio-oil products should both be analyzed for their composition. This is to help ensure the safety of personnel when handling these materials onsite.

6. Conclusions

In closing, this report has been evaluated for both the design and economic aspects for both biomass processes. To complete this analysis, a market survey and research on distinct processes designs were conducted. Additionally, processes flow diagrams and material balances were created along with the creation of cashflow tables.

The market survey was completed to assess the cost value of raw materials entering the processes in production. Additionally, the market survey considered the coal prices, fuel prices, corn stover costs, and crude oil costs. Please note that the current price of corn Stover is $6.2525 per bushel as stated previously in the market survey. With the use of the market survey, a precise cost analysis was finalized.

The first step was conducting an initial analysis of data of the data, followed by completion of a material balance of the processes. From there two different options of biomass processes were decided on. The first proposed idea was using Direct Pyrolysis processing. The second proposed idea was adding Coal Gasification to the Direct Pyrolysis to potentially reduce the steam requirement as compared to the Direct Pyrolysis process as a stand-alone.

While constructing the cash flow diagrams, there were a few assumptions made. The first assumption made was having a seven-year MACRS depreciation and the real estate was completed with a 15-year MACRS depreciation, with an 21% tax rate. The land used was estimated by using the cost per acre of land in Michigan for 10 acres of land for Direct Pyrolysis and 15 acres for the Combined Process. For the Direct Pyrolysis the total estimated equipment costing was approximately $ 1,449,700.00. For the other process, Coal Gasification, the actual estimated equipment costing was approximately $2,944,200. Please note that this is an add on to the Direct Pyrolysis system and has a total estimated equipment costing of approximately $1,494,500.00 USD. The expected utility cost for Direct Pyrolysis and Coal Gasification is $ $6,770,951.76, and $6,980,194.12 per year respectively.

The total expense for Direct Pyrolysis is $76,976,025.4 with a total income of $2,741,412,259. Additionally, the Direct Pyrolysis process had a net present value (NPV) of $356,837,586, and an IRR value of 23.5%. The return on investment (ROI) for this process was 23.6%, a payback period of 0.04 years (2.09 weeks), and a benefit to cost ratio of 3.75. The profit is $ 2,664,436,234 per year for this process.

For Coal Gasification, the total expense is $101 million with a total income of $274,203,532.4. Additionally, the Coal Gasification process has a net present value (NPV)of $ 292.5 MM, an Internal Rate of Return (IRR) value of 8.89%, and a benefit to cost ratio of 6.86. The return on investment (ROI) for this process was 8.9% with a payback period of 0.11 years (5.7 weeks). The profit is $173,203,532 per year The bio-oil production for both processes is 48,750 kg/hr. Overall it can be concluded that the Direct Pyrolysis is the preferable option based on the all factors as analyzed in this report.

7. Recommendations

For this project the main source for both processes, Direct Pyrolysis and Coal Gasification, is corn stover. The constraints of using corn stover as the main source would be the complications of transportation, storage, and the processing of corn stover. Areas of concern for corn stover is that it has a high moisture content, low density, and issues related to removal of potential nutrients. The logistics that must be considered in this case is the plants proximity to minimize transportation costs to ensure the corn stover is properly stored and not affected by its high moisture content. Additionally, a large storage facility needs to consider compensating the low-density product since it requires considerable storage volume. It would be recommended to choose a source that has a higher density allowing for the transportation to be smoother and cheaper. Since corn stover has limitations such as low initial bulk density, high moisture content, irregular shapes, and low energy density, transportation can become complicated and more expensive. Another reason to choose a different source is because of environmental concerns. Within the two processes corn stover starts off by decomposition of biomass, which leads to several products such as carbon dioxide.

Additionally, it would be recommended to investigate the use of a catalyst for the coal gasification companion conversion. Utilizing a catalyst will help with reduction of reaction temperatures, improvements of gasification rates, and reduction tar formation.

Lastly, it is recommended that an investigation of the possibility of an additional heat exchanger at the end of the processes be considered. The thought process behind this is to attempt to recover the extra heat that is not being used throughout the two processes. In turn, this could potentially reduce heat costs in the system overall.

8. References

Botou Ever Lucky Environmental Protection Machinery. (2022). *Industrial New Conditional Cyclone System cyclone dust collector cleaning machine*. Retrieved from Alibaba: https://www.alibaba.com/product-detail/Cyclone-Dust-Collector-Collector-Machine-Industrial_62446399831.html?spm=a2700.galleryofferlist.normal_offer.d_title.5869418aapuVxz&s=p

Bridger Photonics. (n.d.). *How Does Methane Affect the Environment?* Retrieved from Bridger Photonics Methane: https://www.bridgerphotonics.com/blog/how-does-methane-affect-environment

Cole Hill Associates. (2004). Bio-Oil Commercialization Plan. 56-81.

Czajkowski, L., Wojcieszak, D., Olek, W., & Przybyl, J. (2019). Thermal Propertied of Fractions of Corn Stover. *Construction and Building Materials*, 709-712. Retrieved from Construction and Building Materials.

Inayat, A., Ahmed, A., Tariq, R., Waris, A., Jamil, F., Ahmed, S. F., . . . Park, Y.-K. (2022). Techno-Economical Evaluation of Bio-Oil Production via Biomass Fast Pyrolysis Process: A Review. *frontiers in Energy Research*, 1-9.

Iowa State University. (2022). *Stover Harvest*. Retrieved from Iowa State University Extension and Outreach: https://www.extension.iastate.edu/stover/

Karowe, D. (2022). *Earth's Climate History to Present.* Kalamazoo: Western Michigan University.

MacroTrends. (2022, January 29). *MacroTrends*. Retrieved from Corn Prices - 59 Year Historical Chart: https://www.macrotrends.net/2532/corn-prices-historical-chart-data

MacroTrends. (2022, January 29). *MacroTrends*. Retrieved from Crude Oil Futures - Price & Chart: https://www.macrotrends.net/futures/crude-oil

Medline Plus. (2022, April 1). *Respiratory acidosis*. Retrieved from National Library of Medicine: https://medlineplus.gov/ency/article/000092.htm#:~:text=Respiratory%20acidosis%20is%20a%20condition,blood%2C%20to%20become%20too%20acidic

Odeh, A. O. (2017, July 5). *Pyrolysis: Pathway to Coal Clean Technologies*. Retrieved from IntechOpen: https://www.intechopen.com/chapters/54010

Pipe Flow Calculations. (2020). *Flue Gas Properties Table*. Retrieved from Pipe Flow Calculations: https://www.pipeflowcalculations.com/tables/flue-gas.xhtml

Reidmiller, D., Dzaugis, M., Avery, C. W., Crimmins, A., Dahlman, L., Easterling, D. R., . . . Stewart, B. (2018). *Appendix 5. Frequently Asked Questions.* U.S. Global Change Research Program.

Roush Clean Tech. (2020, March 23). *CNG Price*. Retrieved from Roush Clean Tech: https://www.roushcleantech.com/cng-price/

Taishan Group. (2022). *Biomass Fired Steam Boiler Woodchips Corn Stalk Boiler Superheated Steam Boiler*. Retrieved from Alibaba: https://www.alibaba.com/product-detail/Boiler-Biomass-Steam-Boiler-Biomass-Fired_1600191504591.html?spm=a2700.galleryofferlist.topad_creative.d_title.298c640bOrBMAX

Thompson, J., & Tyner, W. e. (2011). Corn Stover for Bioenergy Produciton: Cost Estimates and Farmer Supply Response. *Renewable Energy*, 1-7.

Timmerhaus, K. D., Peters, M. S., & West, R. E. (2003). *Plant Design and Economics for Chemcial Engineers.* McGraw-Hill Science Engineering.

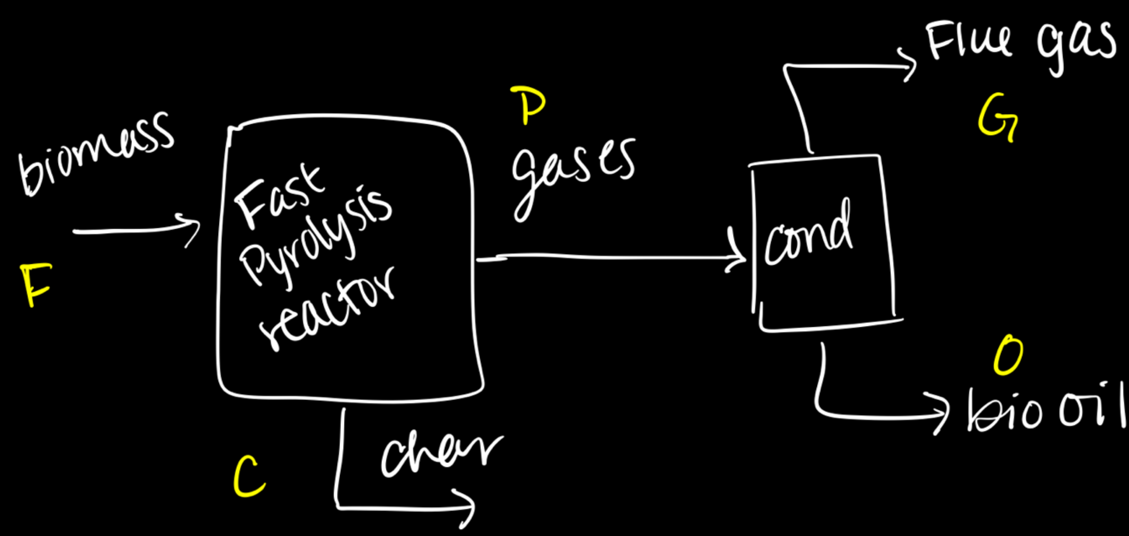
U.S. Department of Agriculture. (2021, September 10). *Biomass Pyrolysis Research*. Retrieved from Agricultural Research Service: https://www.ars.usda.gov/northeast-area/wyndmoor-pa/eastern-regional-research-center/docs/biomass-pyrolysis-research-1/what-is-pyrolysis/

U.S. Energy Information Administration. (2020, October 9). *EIA*. Retrieved from Coal Explained Coal Prices and Outlook: https://www.eia.gov/energyexplained/coal/prices-and-outlook.php

Xu, Y., Hu, X., Li, W., & Shi, Y. (2011, July 27). *Preparation and charaterization of Bio-oil from Biomass*. Retrieved from IntechOpen: intechopen.com/chapters/16645

9. Appendix

9.1 Extensive Material Balances



Fast Pyrolysis Products composition:

75% Biooil

12% Char

13% Flue Gas

Material Balance Based on above percentages

$F = 45{,}000\ \mathrm{kg/hr}$

$\text{Char} = C = 0.12F = 0.12(65{,}000\ \tfrac{kg}{hr}) = \boxed{7800\ \mathrm{kg/hr}}$

$\text{Gases} = P = (1-0.12)F = 0.88(65{,}000\ \tfrac{kg}{hr}) = \boxed{57200\ \tfrac{kg}{hr}}$

$\text{Bio-oil} = O = 0.75F = 0.75(65{,}000\ \tfrac{kg}{hr}) = \boxed{48750\ \tfrac{kg}{hr}}$

$\text{Flue Gas} = G = 0.13F = 0.13(65{,}000\ \tfrac{kg}{hr}) = \boxed{8450\ \mathrm{kg/hr}}$

Figure 12: Final Material Balance of Direct Pyrolysis

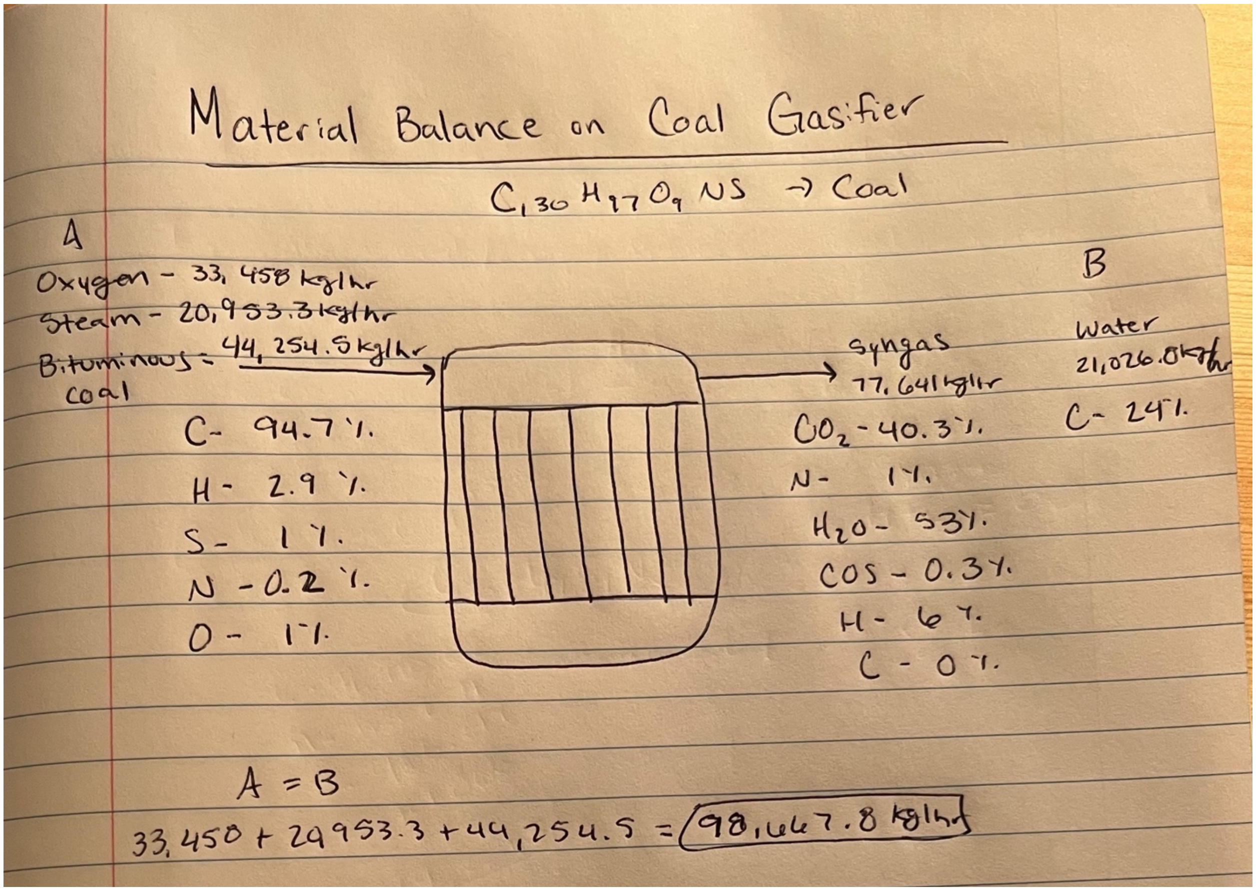


Figure 13: Final Material Balance of Coal Gasification

9.2 Extensive Energy Balances

$$\dot{Q} - \cancelto{\emptyset}{\dot{W}_s} = \Delta \dot{H} + \cancelto{\emptyset}{\Delta \dot{E}_K} + \cancelto{\emptyset}{\Delta \dot{E}_P}$$

no shaft work
no kinetic energy
no potential energy

$$Q = \Delta H$$

$$Q = \dot{m}\, C_p \Delta T$$

C_p units $=$ J/kgK

$\Delta T = (500 - 25)\text{K} = 475\text{K}$

$\dot{m} = 65000$ kg/hr

$$Q_{Total} = Q_{stover} + Q_{cob} + Q_{Husk}$$

stover = stalks + leaves

$$Q_{stover} = 0.46(65{,}000)\left(\frac{1637 + 1644}{2}\right)(475\text{ K})$$

$= 2.32992 \times 10^{10}$ J/hr $= 6.472 \times 10^{6}$ J/s

$= \underline{6472 \text{ kW}}$

$$Q_{cob} = (0.06)(65000)(1484 \text{ J/kgK})(475\text{ K})$$

$= 2.74911 \times 10^{9}$ J/hr $= 763642$ J/s

$= \underline{763.642 \text{ kW}}$

$$Q_{Husk} = 0.04(65000)(1723 \text{ J/kgK})(475\text{ K})$$

$= 2.127911 \times 10^{9}$ J/hr $= 591085$ J/s

$= \underline{591.085 \text{ kW}}$

$$Q_{Total} = 6472 \text{ kW} + 763.642 \text{ kW} + 591.085 \text{ kW}$$

$= \boxed{7826.73 \text{ kW}}$ or $\boxed{2.81762 \times 10^{7} \text{ kJ/hr}}$

↑ Total heat duty required for pyrolysis reactor

Figure 14: Final Direct Pyrolysis Reactor Heat Duty Energy Balance

Assuming no heat loss

$Q_{in} = Q_{out}$

$Q_{out} = (\dot{m} C_p \Delta T)_{oil} + (\dot{m} C_p \Delta T)_{Flue\,gas}$

$Q_{oil} = \dot{m}_{oil} C_{p\,oil} \Delta T$

$C_{p\,oil} = 2.40\ kJ/kg\,K$

$\dot{m}_{oil} = 48750\ kg/hr$

$\Delta T = (25 - 500) = -475\,K$

$Q_{oil} = (48750)(2.4)(-475) = \underline{-5.5575 \times 10^7\ \frac{kJ}{hr}}$

$Q_{Flue\,gas} = \dot{m}_{Flue\,gas} C_{p\,Flue\,gas} \Delta T$

$C_{p\,Flue\,gas} = 1\ kJ/kg\,K$

$\dot{m}_{Flue\,Gas} = 8450\ kg/hr$

$\Delta T = (25 - 500) = -475\,K$

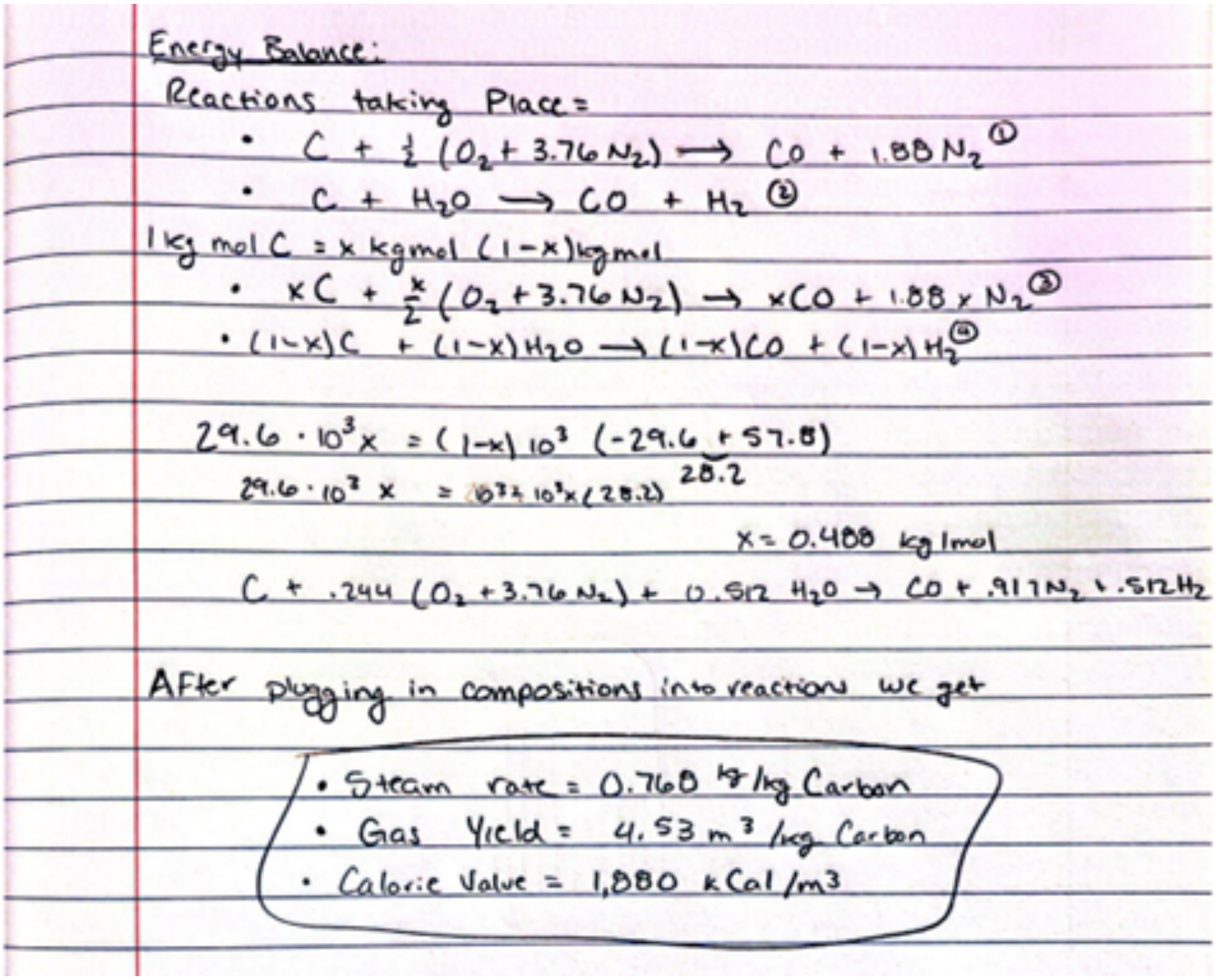
$Q_{Gas} = (8450)(1)(-475) = \underline{-4013750\ kJ/hr}$

$Q_{out} = Q_{oil} + Q_{gas} = -5.5575 \times 10^7 - 4013750$

$= \boxed{-5.95888 \times 10^7\ \frac{kJ}{hr}}$

heat duty of condenser in pyrolysis process $\longrightarrow$ or $\boxed{-1.65524 \times 10^7\ kW}$

Figure 15: Final Direct Pyrolysis Condenser Heat Duty Energy Balance



Energy Balance:

Reactions taking Place =

- $C + \frac{1}{2}(O_2 + 3.76 N_2) \longrightarrow CO + 1.88 N_2$ ①
- $C + H_2O \longrightarrow CO + H_2$ ②

1 kg mol C = x kgmol (1 − x) kgmol

- $xC + \frac{x}{2}(O_2 + 3.76 N_2) \rightarrow xCO + 1.88x N_2$ ③
- $(1-x)C + (1-x)H_2O \longrightarrow (1-x)CO + (1-x)H_2$ ④

$$29.6 \cdot 10^3 x = (1-x)\, 10^3 \, (\underbrace{-29.6 + 57.8}_{28.2})$$

$$29.6 \cdot 10^3 x = 10^3 - 10^3 x (28.2)$$

$$x = 0.488 \text{ kg/mol}$$

$$C + .244 (O_2 + 3.76 N_2) + 0.512 H_2O \rightarrow CO + .917 N_2 + .512 H_2$$

After plugging in compositions into reactions we get

- Steam rate = 0.768 kg/kg Carbon
- Gas Yield = 4.53 m³/kg Carbon
- Calorie Value = 1,880 kCal/m³

Figure 16: Final Coal Gasification Energy Balance

9.3 Extensive Utility Calculations

$$Q_{out} = Q_{oil} + Q_{gas} = -5.5575\times10^{7} - 4013750$$

$$= \boxed{-5.95888\times10^{7}\ \frac{kJ}{hr}}$$

heat duty of condenser in pyrolysis process → or $\boxed{-1.65524\times10^{7}\ kW}$

$$Q = \dot{m}\, c_p\, \Delta T$$

$$c_p = 4.184\ J/g^{\circ}C = 4.184\ kJ/kg^{\circ}C$$

$$Q = 5.95888\times10^{7}\ \frac{kJ}{hr}$$

$$\Delta T = T_2 - T_1 = 75^{\circ}C$$

$$T_1 = 25^{\circ}C$$

$$T_2 = 100^{\circ}C$$

$$5.95888\times10^{7}\ \frac{kJ}{hr} = \dot{m}(4.184)(75)$$

$$\dot{m} = 189894\ \frac{kg}{hr}$$ cooling water

$$\left(189894\ \frac{kg}{hr}\right)\left(\frac{0.26\ gal}{kg}\right) = 49372.5\ \frac{gal}{hr}$$

Figure 17: Utility Calculation for Cooling Water Required for Direct Pyrolysis

$$Q_{Total} = 6472\ kW + 763.642\ kW + 591.085\ kW$$

$$= \boxed{7824.73\ kW} \text{ or } \boxed{2.81762 \times 10^{7}\ kJ/hr}$$

Total heat duty required for pyrolysis reactor

$$Q = \dot{m}\, C_p\, \Delta T$$

$$C_p = 1.996\ kJ/kgK$$

$$\Delta T = T_2 - T_1$$

$$500 - 200 = 300$$

$$2.81762 \times 10^{7} = \dot{m}\,(1.996)(300)$$

$$\dot{m} = 47054.4\ kg/hr$$

$$= 47.0544\ t/hr$$

Figure 18: Utility Calculation for Steam Required for Direct Pyrolysis

Memo 3: Utility Costing for Coal Gasification Process

- 150,000 MW to meet demands — over 15 years

Advanced Coal gasification plant, Costs \$1,500/KW to construct @ 45% efficiency.

Total energy required

$= 150{,}000 \cdot 10 \cdot 15 \cdot 365 \cdot 24 \cdot 3600$

$= 7.09 \cdot 10^{19}$ kJ

7.019...
70190000000000000000

$= 1.9497 \cdot 10^{16}$ kWh total

per yr $= 1.3 \cdot 10^{15}$ kWh

fuel required $= \dfrac{7.09 \cdot 10^{14}}{28 \cdot 10^{4} \cdot .34} = 7.4 \cdot 10^{12}$ tonn

Cost of coal $= \dfrac{1.8 \cdot 10^{12}}{3 \cdot 10^{10}} = \cancel{60}\ 2$ tonn/\$

70.337 kW

so ~~20~~ 220 refridgeration ton to kW $=$ ~~24.0445~~ kW

Data	Electricity
Rate (kW)	70.337
Cost \$/kW	61.11
Cost \$/day	6921.16
Cost \$/yr	2,526,223.7

Data	Cooling Water
Cost (MMgal/hr)	14
Cost (MMgal/day)	336
Cost (MMgal/yr)	122,640

Figure 19: Utility Calculations for Coal Gasification

9.4 Extensive Cash Flow Tables

Table 25: Direct Pyrolysis Cash Flow Table with Real Estate

YEAR	FCI 1	FCI 2	WC	INC	EXP	DEP FACTOR	DEP FAC 2	DEP	DEP 2	PROFIT	TAX	CF	DF	DCF
0	5755309	237650	898943.85	0	0	0	0	0	0	0	0	-6891902.9	1	-6891902.9
1	0	0	0	274142259	76976025.4	0.1429	0.05	822433.656	11882.5	196331918	41229702.8	155936531	0.71428571	111383237
2	0	0	0	274142259	76976025.4	0.2449	0.095	1409475.17	22576.75	195734182	41104178.2	156062056	0.51020408	79623497.9
3	0	0	0	274142259	76976025.4	0.1749	0.0855	1006603.54	20319.075	196139311	41189255.4	155976979	0.36443149	56842922.2
4	0	0	0	274142259	76976025.4	0.1249	0.077	718838.094	18299.05	196429097	41250110.3	155916124	0.2603082	40586246.3
5	0	0	0	274142259	76976025.4	0.0893	0.0693	513949.094	16469.145	196635816	41293521.3	155872713	0.18593443	28982104.3
6	0	0	0	274142259	76976025.4	0.0892	0.0623	513373.563	14805.595	196638055	41293991.5	155872243	0.13281031	20701440.6
7	0	0	0	274142259	76976025.4	0.0893	0.059	513949.094	14021.35	196638264	41294035.4	155872199	0.09486451	14786739.2
8	0	0	0	274142259	76976025.4	0.0446	0.059	256686.781	14021.35	196895526	41348060.4	155818174	0.06776036	10558295.8
9	0	0	0	274142259	76976025.4		0.0591		14045.115	197152189	41401959.7	155764274	0.04840026	7539031.11
10	0	0	0	274142259	76976025.4		0.059		14021.35	197152213	41401964.7	155764269	0.03457161	5385022.05
11	0	0	0	274142259	76976025.4		0.0591		14045.115	197152189	41401959.7	155764274	0.02469401	3846444.44
12	0	0	0	274142259	76976025.4		0.059		14021.35	197152213	41401964.7	155764269	0.01763858	2747460.23
13	0	0	0	274142259	76976025.4		0.0591		14045.115	197152189	41401959.7	155764274	0.01259898	1962471.65
14	0	0	0	274142259	76976025.4		0.059		14021.35	197152213	41401964.7	155764269	0.00899927	1401765.42
15	0	0	-898943.85	274142259	76976025.4		0.0886		21055.79	197145178	41400487.4	156664690	0.00642805	1007048.97

Table 26: Direct Pyrolysis Cash Flow Table without Real Estate

YEAR	FCI	WC	INC	EXP	DEP FACTOR	DEP	PROFIT	TAX	CF	DF	DCF
0	5755309	863296.35	0	0	0	0	0	0	-6618605.4	1	-6618605.4
1	0	0	274142259	76976025.4	0.1429	822433.656	196343800	41232198.1	155934036	0.71428571	111381454
2	0	0	274142259	76976025.4	0.2449	1409475.17	195756759	41108919.4	156057315	0.51020408	79621078.9
3	0	0	274142259	76976025.4	0.1749	1006603.54	196159631	41193522.4	155972712	0.36443149	56841367.2
4	0	0	274142259	76976025.4	0.1249	718838.094	196447396	41253953.2	155912281	0.2603082	40585246
5	0	0	274142259	76976025.4	0.0893	513949.094	196652285	41296979.8	155869254	0.18593443	28981461.3
6	0	0	274142259	76976025.4	0.0892	513373.563	196652860	41297100.7	155869133	0.13281031	20701027.7
7	0	0	274142259	76976025.4	0.0893	513949.094	196652285	41296979.8	155869254	0.09486451	14786459.8
8	0	-863296.35	274142259	76976025.4	0.0446	256686.781	196909547	41351004.9	155815229	0.06776036	10558096.3

Table 27: Combined Process Cash Flow Table with Real Estate

Year	FCI 1 (MM)	FCI 2 (MM)	WC (MM)	INC (MM)	EXP (MM)	DEP Factor	DEP Factor 2	DEP (MM)	DEP 2 (MM)	Profit (MM)	Tax (MM)	CF (MM)	DF	DCF (MM)
0	11.7	0.356	1.8084	0	0	0	0	0	0	0	0	-13.8644	1	-13.8644
1	11.7	0.356	1.8084	274.2	101	0.1429	0.05	1.67193	0.0178	171.51027	36.01716	123.3184	0.714286	88.0846
2	11.7	0.356	1.8084	274.2	101	0.2449	0.095	2.86533	0.03382	170.30085	35.76318	123.5724	0.510204	63.04715
3	11.7	0.356	1.8084	274.2	101	0.1749	0.0855	2.04633	0.030438	171.123232	35.93588	123.3997	0.364431	44.97074
4	11.7	0.356	1.8084	274.2	101	0.1249	0.077	1.46133	0.027412	171.711258	36.05936	123.2762	0.260308	32.08982
5	11.7	0.356	1.8084	274.2	101	0.0893	0.0693	1.04481	0.0246708	172.130519	36.14741	123.1882	0.185934	22.90493
6	11.7	0.356	1.8084	274.2	101	0.0892	0.0623	1.04364	0.0221788	172.134181	36.14818	123.1874	0.13281	16.36056
7	11.7	0.356	1.8084	274.2	101	0.0893	0.059	1.04481	0.021004	172.134186	36.14818	123.1874	0.094865	11.68611
8	11.7	0.356	1.8084	274.2	101	0.0446	0.059	0.52182	0.021004	172.657176	36.25801	123.0776	0.06776	8.339782
9	11.7	0.356	1.8084	274.2	101		0.0591		0.0210396	173.17896	36.36758	122.968	0.0484	5.951684
10	11.7	0.356	1.8084	274.2	101		0.059		0.021004	173.178996	36.36759	122.968	0.034572	4.251202
11	11.7	0.356	1.8084	274.2	101		0.0591		0.0210396	173.17896	36.36758	122.968	0.024694	3.036573
12	11.7	0.356	1.8084	274.2	101		0.059		0.021004	173.178996	36.36759	122.968	0.017639	2.168981
13	11.7	0.356	1.8084	274.2	101		0.0591		0.0210396	173.17896	36.36758	122.968	0.012599	1.549272
14	11.7	0.356	1.8084	274.2	101		0.059		0.021004	173.178996	36.36759	122.968	0.008999	1.106623
15	11.7	0.356	-1.8084	274.2	101		0.0886		0.0315416	173.168458	36.36538	126.587	0.006428	0.813708

Table 28: Combined Process Cash Flow Table without Real Estate

Year	FCI (MM)	WC (MM)	INC (MM)	EXP (MM)	DEP Factor	DEP (MM)	Profit (MM)	Tax (MM)	Cash Flow (MM)	DF	DCF (MM)
0	11.7	1.75	0	0	0	0	0	0	-13.45	1	-13.45
1	11.7	1.75	274.2	101	0.1429	1.67193	171.52807	36.02089	123.7291053	0.714286	88.37793
2	11.7	1.75	274.2	101	0.2449	2.86533	170.33467	35.77028	123.9797193	0.510204	63.25496
3	11.7	1.75	274.2	101	0.1749	2.04633	171.15367	35.94227	123.8077293	0.364431	45.11943
4	11.7	1.75	274.2	101	0.1249	1.46133	171.73867	36.06512	123.6848793	0.260308	32.19619
5	11.7	1.75	274.2	101	0.0893	1.04481	172.15519	36.15259	123.5974101	0.185934	22.98101
6	11.7	1.75	274.2	101	0.0892	1.04364	172.15636	36.15284	123.5971644	0.13281	16.41498
7	11.7	1.75	274.2	101	0.0893	1.04481	172.15519	36.15259	123.5974101	0.094865	11.72501
8	11.7	-1.75	274.2	101	0.0446	0.52182	172.67818	36.26242	126.9875822	0.06776	8.604724

9.5 Equipment Design Specifications

Table 29: Biomass-Fired Steam Boiler Specifications

Fuel	Corn Stover (Biomass)
Steam Capacity	Maximum 400 t/hr
Working Pressure	Maximum 98 bar
Steam Temperature	170-500°C
Thermal Efficiency	85%-90%
Equipment Cost	$54,000.00
Installation Cost	$378,000.00

Table 30: Cyclone Dust Collector Specifications

Material	Carbon Steel
Minimum Particle Size	0.5 Micron
Air Flow Volume	9,520-13,500 m^3/hr
Efficiency	85%-90%
Dimension (LxWxH)	1376mm x 1337mm x 5157mm
Equipment Cost per Unit	$8,500.00
Total Equipment Cost (Combined Process)	$165,600.00
Total Installation Cost (Combined Process)	$908,200.00

Disclaimer: All other unit costs estimated using similar ASPEN PLUS simulations and do not have available equipment specifications