Project Proposal Feasibility Study

Dynamic Organics

Team 2

Kaylea Brase, Aimee Diepstra, Mitchell Groenenboom, Philip Reinken

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Executive Summary

In today’s society, which is becoming ever-more reliant on the petroleum industry, research into alternative options is becoming a greater priority every day. With increasing petroleum prices as well as limited natural resources, the need for an alternative solution is paramount.

Dynamic Organics has investigated two potential solutions: a small scale solution involving the processing of food scraps and a large scale solution for the conversion of cellulosic material into a useable fuel source.

On a small scale, Calvin College could convert cafeteria food waste into biogas using an anaerobic digestion process. This process would eliminate the 700 pounds per day of food waste that Calvin generates by feeding it to a prefabricated digester unit. Inside the unit, bacteria break down organic material, producing biogas consisting of about 60% methane and 40% methane. The benefits of this process include savings on natural gas cost and transportation costs, conserving space in landfills, reducing carbon emissions, and being a leader in renewable energy.

When analyzing whether this process could be implemented at Calvin, the team analyzed two options: 1) converting the biogas to electricity in a combined heat and power unit sold by the digester company or 2) injecting the gas into Calvin’s boilers which generate heat. Based on the maintenance risks, installation process, payback period, and flexibility, the second option was chosen.

From the financial analysis, a payback of 8.8 years was determined, with an initial investment of $33,920 and a discount rate of 4%. This does not meet CERF requirements of 3-5 years for typical projects, but it would meet this requirement if labor costs were eliminated by establishing a student club. Thus the team has demonstrated that the process of treating the cafeteria waste using anaerobic digestion is economically feasible and sustainable through the reuse and recovery of waste as well as energy.

The large scale process of the conversion of cellulosic material to a useable fuel has a different aim. We plan to develop a design process for the conversion of a cellulosic material, which is not also a food source, into a useable fuel, through a process which is economically efficient. To do this we have broken the project down into three sections and have evaluated each portion in our feasibility study. The first section is deciding upon a starting material. Having narrowed the selection to four plants which produce a high biomass yield based upon plant density per acre and the ruggedness of the plant: switchgrass, miscanthus giganteus, fast growing poplar, and corn stalks, we have developed relevant criteria for their evaluation and selected miscanthus giganteus as our starting material. We found that it produces a high yield of biomass for any given amount of farm land and is capable of growing in soil that is unable to produce a food crop.

The second portion consists of the selection of a process for the conversion as well as a product. Two distinct routes were analyzed: an enzymatic route and a synthesis gas route. The enzymatic route involves the processing of cellulosic material with genetically modified enzymes, while the synthesis gas route degrades nearly all of the components of the cellulosic material into synthesis gas and then reassembles the gas into a useable fuel. While each route has its merits, we evaluated the economic feasibility of each route as well their technological practicality. We selected synthesis gas as the more feasible route.
Finally, we must select a product of our process. We are investigating various small chain alcohols or alkanes as a final product and are evaluating their worth and effectiveness as a fuel source. This will extend into second semester, as a final decision cannot be made until a catalyst has been chosen.
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1. Introduction

1.1 Context

The goal of the project is to develop a process for converting cellulosic or waste material into a usable fuel source. Two major solutions have been proposed:

1.1.1 Food Waste to BioGas Project

On a small scale, Calvin College could convert cafeteria food waste into biogas using an anaerobic digestion process. The biogas could be sent to the existing co-generation system where electricity is already produced from natural gas. The process would potentially save money by lowering the amount of natural gas purchased from the gas company and by eliminating costs of transporting the food waste. It would also conserve space in landfills and lower greenhouse gas (GHG) emissions. The team intends to demonstrate that the process of treating the cafeteria waste using anaerobic digestion is economically feasible and sustainable through the reuse and recovery of waste as well as energy.

1.1.2 Cellulosic Material to Biofuel Project

On a larger scale, cellulosic material can be converted to ethanol, butanol, or alkane hydrocarbons. The potential cellulosic material includes cornstalks, switchgrass, Miscanthus Giganteus, or fast growing poplar. None of these feedstock options currently produce important products, nor are they vital to the food industry. In today’s society, which is becoming ever-more reliant on the petroleum industry, research into alternative options is becoming a greater priority every day. With increasing petroleum prices as well as limited natural resources, the need for an alternative solution is paramount.

These solutions are not mutually exclusive. They are united in the idea that each will utilize what is considered “waste” as a resource.
1.2 Team Members

1.2.1 Introduction

Team Members of Dynamic Organics are pictured below in Figure 1.

![Team Members](image)

**Figure 1.** Team members from left to right: Aimee Diepstra, Philip Reinken, Mitchell Groenenboom, and Kaylea Brase

Kaylea Brase grew up in Lino Lakes, Minnesota, where she loves to waterski and cycle. She spent the summer in Lansing, Michigan interning with Granger Energy and Electric, which is a Christian family-owned business that utilizes landfill gas to run engines and generate electricity. At Calvin, she enjoys running for the cross country and track team. She hopes to become a missionary while using her degree to aid in development.

Aimee Diepstra hails from Grand Rapids, Michigan, where she graduated from Grand Rapids Christian High School. During the summer of 2012, she had an internship at Boehringer Ingelheim, one of the world’s leading pharmaceutical companies, in Germany. After graduation, she hopes to find a job working in the petroleum industry.

Mitch grew up in Grand Rapids, MI where he graduated from Grand Rapids Christian High School. Since coming to Calvin, he has done chemistry research for a Calvin professor as well as interning at a specialty chemical manufacturing company: Bridge Organics. After graduating from Calvin, Mitchell would like to attend graduate school, and go on to work in the pharmaceutical industry.

Philip grew up in Morton, Illinois where he graduated from Morton High School, while also developing a passion for the game of tennis. While pursuing his degrees in Chemical Engineering and Chemistry, he has also competed on the tennis team at Calvin. He spent the summer interning with General Motors Components Holdings in Grand Rapids, MI. After graduating from Calvin, Philip hopes to work in the development of alternative energy or fuel sources, particularly in the petroleum industry.
1.2.2 Team Duties

The duties for each team member are as follows:

In the fall semester, Kaylea spearheaded much of the work to be done with the food waste to biogas project. This included meeting with several Calvin College Physical Plant employees and analyzing the feasibility of the project in terms of the economics, including piping and compressor costs, and research into how the digester and co-generation system at Calvin College operates. In the coming semester, the scope of the project will shift towards an international focus. Kaylea will examine the possibility of utilizing these anaerobic digesters on a small scale to serve as cooking stoves in the Third World. This will involve further research into the cultures which might implement these cook stoves, as well as analyzing the economics of creating small scale digesters to be used for this purpose.

During the fall semester, Aimee focused on the enzymatic process for the cellulosic to biofuel project. From the organization of an initial block flow diagram to the results presented in this document, she was the one focusing most heavily on this process. As the enzymatic process has been eliminated from the project scope, she will shift her energy to continue work with the cellulosic project to assist in the creation of a synthesis gas route. In the coming semester, Aimee will be responsible for the feed system to the reactor and all other utilities not associated with the reactors or separation units for the syngas process. For the feed system, a process must be designed to be able to utilize a solid feedstock and feed it into a reactor at 10 times atmospheric pressure. This will require a great deal of research, as well as some simulation in UNISIM or software of the like.

This fall, Mitch analyzed the synthesis gas process in detail. His research focused on the creation of a block flow diagram and determining as much as possible for the process. From initial conception to the data presented in this report, Mitch was responsible for much of the work relating specifically to the syngas process. This coming spring, Mitch will be responsible for the design of the reactor system and the determination of the rate laws for each of the several catalysis reactions that could take place with differing catalysts as well as analyzing the other elements of the reactor design, including size, orientation of the reactors, and design variables such as temperature and pressure. This will require major research as well as extensive modeling in UNISIM.

Phil focused his energy in the fall semester on the many possible feedstock options. He researched other facilities already undertaking the work of utilizing a cellulosic feedstock, and looked into the feasibility of each feedstock to determine which might be most efficient and cost effective in the cellulosic to biofuel project. As the feedstock has been nearly finalized at this point, Phil will shift his work to now be responsible for the task of separating the product fuel from the other byproducts of the reactions. His work will include the design of the components, including sizing and reflux ratios, in UNISIM.
1.3 Work Breakdown Structure

The following list of deadlines is the work that was done in the fall of 2012 semester. This does not include the work that will be done in the upcoming spring semester, although all of the material that has yet to be done is included in the task list in Section 1.2.2. In that section, all of the tasks and overall goals of the final project are laid out and a brief estimation of the time it will take to complete the task is also listed.

1.3.1 General Deadlines

- **WBS completion (2 hours per person) (October 5)**
- **Scheduled WBS (October 15)**
  - Detailed task list, along with duration, starting and end date
  - Show dependencies between tasks
- **Verbal Presentation (October 15) (1.5 hours of preparation)**
  - 5 minute presentation
  - Introduce yourself, the project and scope of the project
  - What will you do, why? what problem are you trying to solve
- **Revised WBS (October 15) (1 hour per person)**
  - More detailed Gantt chart
  - Critically linked task list
- **Project Brief (October 17) (2 total hours)**
  - Prepare a 2-5 page summary about the project for Randy Elenbaas
  - Must include pictures of each team member with names under each one
  - Brief description of your project, the requirements, indicate status, and any major hurdles
- **Consultant Review/Website Posted (1 hour)**
  - Bring detailed requirements, detailed task specifications, detailed budget, and schedule.
  - Bring along design documents, test reports, and any other information the reviewer might wish to see or ask you about.
  - Each team member should be ready to describe in detail their role on the team.
  - Take notes during the review (or appoint one team member to do so)
- **PPFS Outline (October 22) (5 hours total)**
  - Project proposal and feasibility study, listing anticipated chapters, sections and sub-sections
- **Preliminary Cost Outline (5 hours)**
  - Research equipment, materials, processes, energy requirements, and catalyst costs
- **Draft PPFS (November 12) (3 hours)**
  - Exactly what it looks like
- **Updated Poster (November 14) (1 hour)**
- **2nd Verbal Presentation (November 28) (2 hours of preparation)**
  - Between 7 and 9 minutes
  - Requirements posted on Moodle
- **Final PPFS (December 7) (4 hours)**
1.3.2 Task list
Between September and May, several deadlines have been put in place to ensure that the team remains on track to finish the project by May 4, 2013. Separate task lists are in place for each project, and can be viewed in the following pages. The majority of the work for both projects will take place in the months between January and May. By the end of the first semester in December, the team expects to have completed the research phase of both the Food Waste to Biogas and the Cellulosic Material to Biofuel project.

1.3.2.1 Food Waste to Biogas Project

- **Research (23 hours)**
  - Feasibility (10 hours)
    - Amount of waste from Calvin College
    - Compare to Clarkson
    - Cost of Natural Gas
    - Cost of Transporting Wastes
  - Chemistry Breakdown of Food (5 hours)
  - Alternative Options for Food waste (5 hours)
  - Search for grants/funding (3 hours)

- **Develop a Pilot Anaerobic Digester (42 hours)**
  - Consult with advisor from Clarkson about small digester (2 hours)
  - Design digester (10 hours)
  - Obtain materials (10 hours)
  - Construct digester
    - Install heating mechanisms to keep at constant heat (5 hours)
    - Place valves for sample gas collection and analysis (5 hours)
    - Construct insulation layer (5 hours)
    - Connect gas collector (5 hours)

- **Test Process (35 hours)**
  - Obtain food scraps, load digester with effluent (5 hours)
  - Determine major nutrients every two weeks (5 hours)
  - Determine waste mass daily and composition weekly (5 hours)
  - Determine biogas flow and composition once gas starts being produced (5 hours)
  - Characterize total solids by measuring amount of water lost (5 hours)
  - Measure Chemical Oxygen Demand of each meal (5 hours)
  - Graph and record results (5 hours)

- **Establish Calvin Food Sorting/Transporting System (22 hours)**
  - Educate employees (2 hours)
  - Design system of transporting food bags (10 hours)
  - Construct transportation system (10 hours)
1.3.2.2 Cellulosic Material Pathway

- Research
  - Reactors (20-30 hours)
    - Can we simulate this in UNISIM
    - Gasification rate laws
    - Steam aided Gasification rate laws
    - Tar reformer chemistry /rate laws
    - Water-Gas Shift Rate laws
      - Effect of sulfur and nitrogen containing components
    - Effect of Feed composition on reactor conditions and product
    - Product Formation
      - Catalyst
      - Rate laws
      - Current Literature
  - Separations (20-30 hours)
    - Tar purification
    - Absorbers/reactive absorption conditions
    - Purification of reactor 4 Feed
    - Reactor 4 Effluent Purification
    - Product purification
      - Additional purification to reagent grade
    - Methods of product purification
      - Azeotropic/specialized distillation techniques
  - Feed System (10-20 hours)
    - Literature search
    - Patent search
    - Incorporation of an inert gas
  - Output (10-20 hours)
    - Determine the optimal product
    - Azeotropic data
    - Ease of purification
    - Catalysts available for Synthesis gas
      - Availability of catalysts
      - Costs of catalyst
- Process Design
  - Reactors (50+ hours)
    - Modeling reaction systems using UNISIM/Polymath (33 hours)
      - Gasification (6 hours)
      - Steam aided Gasification (5 hours)
      - Tar Reformer ( 6 hours)
      - Water-gas Shift (6 hours)
      - Product Formation (10 hours)
    - Reactor Type (10 hours)
- Catalyst characteristics (5 hours)
- Optimal reaction condition (20 hours)
- Separations (50+ hours)
  - Reactor Effluent Purification (5-10 hours)
  - Removal/purification of Tar (10-15 hours)
  - Rigorous purification of final product (10-15 hours)
    - Distillation train
    - Azeotropic Distillation
    - Absorption
    - Reactive absorption
- Modeling and optimizing separation techniques (10 hours)
- Waste Disposal
- Feed System (50+ hours)
  - Cellulosic Processing (5 hours)
    - Drying
    - Crushing
  - Delivery into reactor 1 (15 hours)
    - Pressurized environment
  - Piping systems (15 hours)
    - Materials of construction
    - Size
- General equipment (15 hours)
  - Material construction
  - Heat exchanger design
  - Compressor design
  - Pump design
- Waste Disposal (5 hours)
- Plant cost analysis (20 hours)

### 1.3.3 Project Gantt Chart

A summary of tasks for the project is shown in **Table 1**. These tasks are sequenced in the Gantt chart for the first semester in **Figure 2** and for the second semester in **Figure 3**.

**Table 1. Task List**

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<td>28</td>
<td>Manage Disposal</td>
<td>7 days</td>
<td>Mon 4/8/13</td>
<td>Tue 4/16/13</td>
</tr>
<tr>
<td>29</td>
<td>Plant Cost Analysis</td>
<td>7 days</td>
<td>Mon 4/15/13</td>
<td>Tue 4/23/13</td>
</tr>
<tr>
<td>30</td>
<td>Report Finalizing</td>
<td>7 days</td>
<td>Tue 4/23/13</td>
<td>Wed 5/1/13</td>
</tr>
</tbody>
</table>
Figure 2. Gantt chart for first semester, corresponding to the task list shown above

Figure 3. Gantt Chart for second semester, corresponding to the task list shown above
2. Food Waste to Biogas Project

2.1 Problem Definition

2.1.1 Need
According to the Environmental Protection Agency (EPA), the United States generated more than 34 million tons of food waste in 2010, less than three percent of which was recovered and recycled. As shown in Figure 4, food waste accounted for 14 percent of the total municipal solid waste (MSW) stream, the largest category besides paper. With 33 million tons of food thrown away each year, “food waste is the single largest component of MSW reaching landfills and incinerators”.

![Figure 4. Waste generated in the United States in 2010](image)

College and university cafeterias are responsible for a large amount of the food waste. The dining halls of Calvin College produce about 700 pounds of food waste per day on weekdays and about 300 pounds per day on Saturday and Sunday. Calvin College is also spending $520 per month on transportation of the

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1 United States Environmental Protection Agency

2 United States Environmental Protection Agency
waste. When this organic waste is brought to a landfill, it is converted to methane gas which contributes greatly to GHG emissions. In fact, the EPA blames landfills for more than 20 percent of all methane emissions. The volume of food waste also limits the life of the landfill and occupies land that could be used more productively. States like Massachusetts have already recognized this problem. “State environmental officials are preparing to ban hospitals, universities, hotels, large restaurants, and other big businesses and institutions in Massachusetts from discarding food waste in the trash beginning in 2014, a measure that in coming years they hope to extend to homes as well.” Thus college and universities will need to find an alternative way to manage food waste. Anaerobic digestion provides a viable alternative because the biogas produced creates safe, reliable, and cost effective renewable electricity and heat while reducing the waste in landfills and the GHG emissions from them. According to the United States Environmental Protection Agency, this solution is becoming more popular in both the United States and Europe, as already about 2,000 anaerobic digestion plants exist in the United States, and more than 10,000 in Europe, where organic waste has been utilized on a large scale for years. Campuses like the University of Wisconsin-Oshkosh, Clarkson University in New York, Michigan State University, the University of Georgia, and Penn State have already taken steps to implement their own anaerobic digestion system.

2.1.2 Approach

An anaerobic digester could be purchased from a manufacturer or constructed from individual components. The faculty of engineering from the Driftmier Engineering Center in Athens Georgia developed a plan with the University of Georgia to anaerobically digest and compost diverted cafeteria food waste. Their system consisted of the physical anaerobic digester, a rainwater catchment system, and a composting station. Their project report outlined a final cost estimate of $41,900 for the sum of the anaerobic digester, rainwater harvesting, gas compression and storage, composting, and effluent management construction materials. The conclusion of the report stated, “The team would recommend installing a prefabricated anaerobic digester system. This would maximize their economic return, while providing a higher degree of operational efficiency and safety.” Based on these results, team Dynamic Organics decided on analyzing the feasibility of purchasing a digester from a manufacturer instead of constructing a digester. One manufacturer of digesters is Feed Resource Recovery, a small company located in Massachusetts that began in 2006. Another option is purchasing a digester called the “Muckbuster” from SEaB Energy, “designer, manufacturer, and installer of renewable energy micro generation systems, specializing in anaerobic digestion and wind energy for small local installations.” This company is based in the United Kingdom, but it has established distributors in the United States. It recently won the UK AD & Biogas Industry Awards for 2012 Best Micro AD Project.

For comparison, the capital cost of the Muckbuster is $33,000. As depicted below in Figure 5, the components of the Muckbuster include a chopper and mixing unit where the waste is loaded, water and recycled liquid are added, and the right consistency is achieved. The buffer tank lowers the temperature of the feed slurry before the pasteurization tanks apply heat to remove harmful bacteria. In the digestion tank, the slurry is converted to biogas and the digestate, or the solid material remaining after digestion, is stabilized over a 3 week period. The biogas is collected in the gas storage tank or sent directly to the

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3 Abel, David. *Boston Globe.*
4 (Andrews, Brannen, Dimitroff, Elliot, Johnson, and Smith 1-32)
5 Feed Resource Recovery Inc.
6 Muckbuster Anaerobic Digester
generation system while the solids and liquids are separated and the solids removed through a screw filter mechanism in the dewatering liquid storage tank.

The biogas created is a mixture of 55-70% methane, 30-45% carbon dioxide, and trace gases such as hydrogen sulfide, hydrogen gas, and nitrous oxides. Natural gas, in comparison, is almost 100% methane with almost no impurities. Biogas has slightly lower energy values, between 55-70% the amount of natural gas, which is about 1000 BTU/m³. This biogas would then be used to generate heat and electricity.

2.1.3 Benefit

An anaerobic digester would not only be another way to dispose of wasted food without having to pay for disposal, but it would also be a supply of natural gas. Natural gas prices have dropped significantly over the last few years due to the development of hydrocarbon cracking, or ‘fracking’ technology, which has made it a much more abundant material. However, it is still widely used as a fuel for energy and heating. By using an anaerobic digester, biogas could be created that would reduce the amount of natural gas that would have to be purchased from an outside source. This would help to reduce the utilities cost of natural gas, and it would reduce the amount of natural gas that must be taken from oil sources.

Biogas would provide Calvin with a renewable energy source that is much more reliable than alternatives such as wind or solar energy. The process would be consistent with Calvin’s “Statement on Sustainability”, particularly in the categories of solid waste reduction and recycling, energy production,

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7 “Muckbuster”
8 "Energy Self-Assessment"
9 "Statement on Sustainability"
transportation, and food services; waste and vehicle movements would be reduced, electrical grid
transportation losses would be reduced, the co-generation system would be utilized, and Calvin would be
a leader in developments relative to alternative energy sources for the future. Additionally, the leftover
digestate could be used for fertilizer, which, if implemented on a wide scale, would displace industrially
produced chemical fertilizers. A potential customer in the fertilizer industry would be Synagro, which has
used biosolid materials to make a recycled fertilizer since 1986.¹⁰

2.1.4 Similar Case Studies
A 2011-2012 student competition analyzed and implemented a system of anaerobic digestion of Clarkson
University cafeteria waste. A self-contained, anaerobic digester co-generation unit was operated and
assessed for feasibility. The results of the study showed that one year of operation would offset $14,900
in electricity costs, remove 110 tons of food from the waste stream, and cut $16,425 of costs associated
with waste disposal. “At an adjusted capital investment of $200,000 for the entire system it is expected to
achieve a payback period of less than 8 years considering positive cash flows of $31,700 in total savings
and a 5% discount rate.” In comparison, Calvin produces about the same amount of waste as Clarkson,
and Michigan has a similar climate as New York in which to operate the digester. The natural gas prices
and transportation costs are slightly lower in Michigan than New York, but these costs would hopefully
be offset by the benefit of adding the gas to a pre-existing co-generation system instead of purchasing the
CHP system.

Ms. Ashley Waldron, a 2012 graduate from Clarkson with a Bachelor of Science in Civil Engineering
degree, provided input on the successes and challenges of the ongoing project. The project team received
the used digester as a donation, so the first task was to remove food from the pipes. Waldron described
how the digester is more efficiently operated when it is in consistent use because when it is not
maintained, food waste will accumulate in the pipes and cause problems. She said that the anaerobic
digester unit provided a good user interface which prompted the operator with directions on how to load
the food waste. Waldron emphasized the importance of operating the digester at maximum capacity in
order to achieve the desired economic return. One major aspect of the Clarkson project included
establishing a system to remove paper waste from food waste and training food service employees how to
transfer the food waste to the digester. A student club was started to gather people who would be willing
to operate the digester. Waldron also described how the fertilizer produced from the digester is used in the
greenhouse at Clarkson, but it could also be fixed with soil or sold to the community. From the
conversation with Waldron, it was evident that she is committed to communicating the benefits of food
waste management. She encouraged Calvin to actively seek new ways to manage its food waste; not only
is food waste management environmentally responsible, but it may be important in the future when some
states, such as Massachusetts, prohibit colleges from sending food waste to landfills. Also, many of the
companies that are providing food to colleges are interested in food waste numbers and use, so food waste
is a problem that has impact on a wide scale.

2.1.5 Design Goals
In order for the anaerobic digestion process to be implemented by the Calvin Energy Recovery Fund
(CERF), the team must demonstrate that the process is economically feasible, with a payback period of 3-6 years. The team must show that the process quantitatively meets the goals of Calvin’s “Statement on

¹⁰ “Synagro”
Sustainability” and that the process is more beneficial than simply composting the food waste. The team must prove that the implementation process is achievable, minimizing campus changes in construction and requiring a minimal amount of maintenance after start-up. The team must have evidence that the process will not harm the co-generation equipment or cause undesirable or harmful side effects such as food or gas odors, methane leaks, or food waste accumulation.

2.2 System Design

2.2.1 Alternatives
One approach to the process is to purchase a combined heat and power unit (CHP) specifically designed by the anaerobic digester manufacturer to produce heat or electricity solely from the digester. The upfront costs would be approximately $13,500 for the unit. The unit is specifically designed to convert biogas to electricity at 35% efficiency. The unit would have to be connected via underground transmission to any of the distribution panels located at each building on campus.

A second approach is to feed the gas directly into the co-generation system, so that either it mixes with the natural gas already being delivered or so that the system runs solely on biogas for certain periods of time and then switches back to natural gas. The storage tank would need to deliver 6.5 mmBTU/hr of gas to completely run the co-generation system by itself. In order to collect this amount of gas, the digester would need to be operating for about 110 days before it could run the co-generating system for 24 hours. Injecting the gas into the engine would not require purchase of a CHP but it would require a compressor to reduce the pressure of the gas. The gas company delivers the natural gas to Calvin at 60 psi and a meter reduces the gas to 1.5 psig. The gas would need to be compressed to 32 psig if it were to be injected into the engine that Calvin operates. Ideally the anaerobic digester would be located in the basement of the Commons, right next to the co-generation system. Because the co-generation system is cramped for space, expansion of the Commons would be required. However, this expansion has already been proposed for Calvin, so the implementation of the anaerobic digester would coincide with the remodeling. A less ideal option would be to relocate the digester and pipe the gas to the cogeneration system.

A third approach is to feed the gas directly into the boilers located at the Commons Dining Hall or the Knollcrest Dining Hall. The biogas would need to be compressed to 1.5 psig before it would be combined with the natural gas. The gas would then be used to generate heat to be distributed throughout campus.

2.2.2 Components

2.2.2.1 Digester
For all three approaches, the digester is a standard prefabricated unit. The digester is a sealed tank that prevents gaseous oxygen from entering the system, allowing production of methane instead of an alcohol or aldehyde. The digester contains a sludge that introduces anaerobic microorganisms which feed on the organic material. As shown in Figure 6, the digester process includes four main chemical stages. The first step is hydrolysis, where the large organic polymers present in the food scraps are broken down and hydrolyzed into smaller molecules like simple sugars, amino acids, and fatty acids. In acidogenesis, a process related to the way milk sours, fermentative bacteria further breakdown the remaining components. The byproducts include ammonia, carbon dioxide, hydrogen sulfide, and volatile fatty acids.
(VFAs). What remains is further digested by microorganisms called acetogens, producing acetic acid, carbon dioxide, and hydrogen. Finally, microorganisms called methanogens convert the intermediate products to biogas, consisting of methane, carbon dioxide, and water. Any dead bacteria and indigestible material is leftover as digestate. The bacteria are sensitive to both temperature and pH, so the digester will need to be maintained at 35-40°C and a pH of 6.5 to 8. The overall process can be summarized by the following equation:

\[ C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4 \]  

**Equation 1**

![Diagram of anaerobic digestion stages](image-url)  

**Figure 6. Process Stages of Anaerobic Digestion**

### 2.2.2.2 Scrubbing System

When determining whether the biogas should be injected into the co-generation system or should be converted to electricity with the combined heat and power unit, one factor that was considered was the process of upgrading biogas to biomethane. Because the engine owned by Calvin is not specifically a biogas engine, the hydrogen sulfide in the biogas could corrode the engine. If the biogas were upgraded to biomethane, which contains more than 95% methane, the product would be equivalent and interchangeable to natural gas for electrical generation, heating, cooling or pumping. The process of converting to biomethane, however, seems involved; \( \text{H}_2\text{S}, \text{moisture}, \text{and CO}_2 \) must be removed, as shown in Figure 7.
Reduction of the hydrogen sulfide is particularly important in order to prevent corrosion of the internal combustion engines. Sulfur dioxide formed during combustion is dissolved into the water present in the biogas, causing it to become acidic and corrode the combustion chamber and exhaust system. The sulfur dioxide formed is also an environmental concern because it is a pollutant. The Sustainable Conservation Foundation lists the following removal processes of hydrogen sulfide:

- Air injected into the digester biogas holder
- Iron chloride added to the digester influent
- Reaction with iron oxide or hydroxide (iron sponge)
- Use of activated-carbon sieve
- Water scrubbing
- Sodium hydroxide or lime scrubbing
- Biological removal on a filter bed

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12 Chen, Patrick, Astrid Overholt, Brad Rutledge, and Jasna Tomic
13 “Westec LLC: Offering Bioscrub H2S Removal”
14 “Biomethane from Dairy Waste: A Sourcebook for the Production and Use of Renewable Natural Gas in California” 47-70
Water must also be removed because \( \text{H}_2\text{S} \) and water react to form sulfuric acid while \( \text{CO}_2 \) and water react to form carbonic acid. These reactions are shown below:

\[
\text{H}_2\text{S} + 4\text{H}_2\text{O} \rightarrow \text{H}_2\text{SO}_4 + 4\text{H}_2 \\
\text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{COOOH}_2
\]

Refrigeration is the simplest means of removing excess water vapor by condensing it on the cooling coils and then capturing it in a trap. The power needed would be less than 2% of the biogas energy content, but the cost of the refrigeration unit would add to capital costs.

The design team would need to determine the amount of carbon dioxide in the biogas in order to apply a specific carbon dioxide removal process. The Sustainable Conservation Foundation lists the following options:

- Water scrubbing
- Pressure swing adsorption
- Chemical scrubbing with amines
- Chemical scrubbing with glycols (such as Selxol™)
- Membrane separation
- Cryogenic separation

Equipment to convert biogas to a usable form of gas is available. However, it may be difficult to find equipment that is compact and economical for the amount of gas produced from the digester. Many suppliers make their smallest scrubbers for a maximum gas flow rate of 80 \( \text{m}^3/\text{hr} \) whereas the anaerobic digester will produce about 80 \( \text{m}^3/\text{day} \). A typical large scale scrubbing system is depicted below in Figure 8. Finding a small scale system applicable to the digester may be difficult.
With this information, the design team decided it would not be economically feasible to convert the biogas to biomethane because the process would require a large capital investment for such a small amount of biogas.

The next step was to determine the risk of adding the gas to Calvin’s existing engine or boilers. The team consulted with Mr. Paul Pennock, the mechanical projects technician at Calvin, who gave details about the equipment and recommendations as to how the project may be best implemented. The co-generation system is a white superior model 6GTLB-1 six cylinder natural gas fired engine rated at 825 hp at 900 RPM coupled to a Kato generator producing 585 to 600 kW. Mr. Pennock said that the engine can burn digester gas if the gas is compressed to 32 psi and mixed with natural gas. Since the concentration of hydrogen sulfide in the biogas is already small, the amount in the engine would be negligible and would be unlikely to cause any significant corrosion. The process of mixing it with the natural gas would be complicated however, so Mr. Pennock advised burning the biogas in the boilers next to the Commons Dining Hall or the Knollcrest Dining Hall. The boilers at Knollcrest produce heat to be used by four different dorms while the boilers at the Commons produce heat utilized by many different academic buildings. Regulation by Calvin’s natural gas provider, DTE Energy with the MichCon pipeline, would not be a problem because the biogas would not enter into the main pipelines. A lock valve prevents the backflow of gas.

2.2.2.3 Compressors

In order to inject the biogas into either Calvin’s engine or boilers, the gas must be compressed. UNISIM was used to calculate the amount of energy to compress the gas by 1.5 psi for the boiler and 32 psi for the engine. The energy input was then used to calculate costs of compressor for each alternative, as shown in Table 2. The cost of compressors was determined via Figure 22.9 in Sieder and Seader’s book\textsuperscript{16} which gives purchase costs for gas compressors.

\textsuperscript{15} “Biogas Upgrading”
Table 2. Calculating Cost of Compressors

<table>
<thead>
<tr>
<th>Pressure Increase</th>
<th>Energy Input</th>
<th>Compressor Size</th>
<th>Compressor Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 psi</td>
<td>0.297 kW</td>
<td>0.5 hp</td>
<td>$600</td>
</tr>
<tr>
<td>32 psi</td>
<td>7.760 kW</td>
<td>11 hp</td>
<td>$13,200</td>
</tr>
</tbody>
</table>

From this analysis, the design team determined the engine alternative could be eliminated because the process of injecting the biogas is more complicated and the cost of the compressor is about 20 times the cost of the compressor for the boilers.

2.3 Design Decision

2.3.1 Cost Analysis
The economic feasibility of two alternatives was analyzed. When determining the economics of the first alternative, that of the digester with the combined heat and power unit (CHP) to generate electricity, the following values and assumptions were made, as shown in Table 3:

- Each digester operates on a minimum of 100 L of waste per day and a maximum of 400 L. If a density of 4.84 pounds of waste per gallon is assumed, as estimated by the study completed at the University of Georgia, Calvin would produce a minimum of 227 L/day and a maximum of 550 L/day. Only one digester would be needed because any additional waste over the 400 L can be added to the smaller load on Saturday and Sunday.
- The capital cost of the digester and CHP unit is listed on the Muckbuster website.
- Installation cost includes the cost of converting the electricity produced from the CHP to the same voltage as that in Calvin’s distribution panel. This involves an inverter and the cost of connection to the panel.
- According to the Muckbuster website, the digester produces 76 m$^3$ of gas/day at 80% capacity, which converts to 400 kWh/day. With a conversion of 35% to electricity, 41,000 kWh of electricity is produced annually.
- Electricity cost is 1¢/kWh$^{17}$
- Fertilizer payback was calculated from the Clarkson University study
- The study at Clarkson University estimated about 10 hours of monitoring and operating the digester per week. The computer-operated sensors would need to be monitored to regulate temperature, pH, and feedstock consistency. The Muckbuster website estimates 30-60 minutes per day for monitoring. This monitoring can be completed by a student or intern, so labor cost was estimated at a rate of $8/hr for 9 hours per week.
- Operating cost is estimated at $0.02/kWh, which is the typical running cost of a biogas electricity generating plant cited by the Bioenergy Site$^{18}$.

$^{17}$ “Make Your Own Green Energy.”
$^{18}$ Navaratnasamy, Edeogu, and Papworth
- The Muckbuster website listed that maintenance by a plumber is usually required every 6 months. Plumbing rates were estimated at $750 per visit\(^{19}\).
- Discount rate is 4%.

These assumptions were employed to calculate a payback of 12.3 years, as shown in Table 3.

**Table 3. Economic Analysis of CHP System**

<table>
<thead>
<tr>
<th>Economic Analysis</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capital Costs</strong></td>
<td>$</td>
</tr>
<tr>
<td>Digester</td>
<td>33,000</td>
</tr>
<tr>
<td>CHP</td>
<td>13,500</td>
</tr>
<tr>
<td>Installation</td>
<td>1,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>47,500</strong></td>
</tr>
<tr>
<td><strong>Savings</strong></td>
<td></td>
</tr>
<tr>
<td>Electricity Savings ($/yr)</td>
<td>4,487</td>
</tr>
<tr>
<td>Transportation Savings ($/yr)</td>
<td>6,240</td>
</tr>
<tr>
<td>Fertilizer Payback ($/yr)</td>
<td>307</td>
</tr>
<tr>
<td><strong>Total ($/yr)</strong></td>
<td><strong>11,034</strong></td>
</tr>
<tr>
<td><strong>Annual Costs</strong></td>
<td></td>
</tr>
<tr>
<td>Daily Inspection</td>
<td>3,744</td>
</tr>
<tr>
<td>Operating Cost ($/yr)</td>
<td>816</td>
</tr>
<tr>
<td>Maintenance ($/yr)</td>
<td>1,500</td>
</tr>
<tr>
<td><strong>Total ($/yr)</strong></td>
<td><strong>6,060</strong></td>
</tr>
<tr>
<td><strong>Payback</strong></td>
<td><strong>12.3 years</strong></td>
</tr>
</tbody>
</table>

When analyzing the economics of the second alternative, that of the boiler system, the values and assumptions listed above with the additional assumptions given below were used to calculate a payback of 8.8 years, as shown in Table 4.

- The biogas produces about 70% of the heat that natural gas can produce because the concentration of methane is smaller. Thus, the natural gas savings are the cost of natural gas multiplied by the amount of biogas produced multiplied by 0.7.
- According to Mr. Dan Slager, Energy Management technician at Calvin’s Physical Plant, Calvin pays a fixed price of $6.06/MCF, or about $0.02/kWh.
- Piping and valve costs were estimated at $10/foot from typical natural gas pipeline costs\(^{20}\).

\(^{19}\) "a Plumbers"

\(^{20}\) "a Plumbers"
Table 4. Economic Analysis of Boiler System

<table>
<thead>
<tr>
<th>Economic Analysis</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capital Costs</strong></td>
<td>$</td>
</tr>
<tr>
<td>Digester</td>
<td>33,000</td>
</tr>
<tr>
<td>Compressor</td>
<td>600</td>
</tr>
<tr>
<td>Piping</td>
<td>200</td>
</tr>
<tr>
<td>Valves</td>
<td>120</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>33,920</strong></td>
</tr>
<tr>
<td><strong>Savings</strong></td>
<td></td>
</tr>
<tr>
<td>Natural Gas Savings ($/yr)</td>
<td>4,166</td>
</tr>
<tr>
<td>Transportation Savings ($/yr)</td>
<td>6,240</td>
</tr>
<tr>
<td>Fertilizer Payback ($/yr)</td>
<td>307</td>
</tr>
<tr>
<td><strong>Total ($/yr)</strong></td>
<td><strong>10,713</strong></td>
</tr>
<tr>
<td><strong>Annual Costs</strong></td>
<td></td>
</tr>
<tr>
<td>Daily Inspection</td>
<td>3,744</td>
</tr>
<tr>
<td>Operating Cost ($/yr)</td>
<td>816</td>
</tr>
<tr>
<td>Maintenance ($/yr)</td>
<td>1,500</td>
</tr>
<tr>
<td><strong>Total ($/yr)</strong></td>
<td><strong>6,060</strong></td>
</tr>
<tr>
<td><strong>Payback</strong></td>
<td>8.8 years</td>
</tr>
</tbody>
</table>

2.3.2 Criteria

2.3.2.1 Short Payback Period

Purchasing the CHP would have higher savings than the boiler option because the output is electricity instead of gas, which is more valuable than the biogas because natural gas is inexpensive in Michigan. Also, the biogas makes about 70% the heat of natural gas, making the actual savings worth 70% of the savings accrued if the gas produced were pure natural gas. However, the initial capital investment is larger than the boiler process because an additional unit must be purchased. Thus, a payback of 12.3 years results in a longer payback period. In comparison, the boiler process results in a payback of 8.8 years.

2.3.2.2 Low Amount of Troubleshooting

For both processes, preventing food and gas odors and leaks must be the highest priority. The CHP is designed specifically to handle digester gas, so it may have a lower amount of troubleshooting and maintenance required. The boiler process will still have a much lower risk of troubleshooting than injecting the gas into the engine however.

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20 “Current Pipe Offering Specials.”
2.3.2.3 Easy Installation/Location Flexibility
Both processes require some installations. The CHP requires connection to Calvin’s electric grid, which can be accessed at many locations because each academic building has a distribution panel. Connecting to this grid requires installing wires from the generator to the wires underground. The boiler system involves sending the gas through a compressor and then through pipes with shut off valves into the boiler. The location of the boiler system is constrained because the digester must be located next to the Commons boilers, the Knollcrest boilers, or the boilers next to the Engineering building.

2.3.2.4 Low Amount of Space Required
The CHP requires extra space for the unit whereas the boiler process employs equipment that is already established.

2.3.2.5 Low Risk of Damaged Equipment
The CHP process incorporates less risk because it is an isolated system whereas the biogas introduces trace gases such as hydrogen sulfide. However, the hydrogen sulfide concentration is minimal, especially because the fraction of biogas mixed with natural gas is small.

2.3.3 Comparison of Alternatives
With the criteria described above, a decision matrix shown in Table 5 was created to determine a decision between the two options.

Table 5. Decision Matrix for Anaerobic Digestion

<table>
<thead>
<tr>
<th>Route</th>
<th>Short Payback Period</th>
<th>Low Amount of Troubleshooting</th>
<th>Easy Installation/Location Flexibility</th>
<th>Low Amount of Space Required</th>
<th>Low Risk of Damaged Equipment</th>
<th>TOTAL SCORE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>9</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>CHP</td>
<td>4</td>
<td>8</td>
<td>8</td>
<td>4</td>
<td>9</td>
<td>270</td>
</tr>
<tr>
<td>Existing System</td>
<td>7</td>
<td>7</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>290</td>
</tr>
</tbody>
</table>

The total score of utilizing Calvin’s boilers is higher than the total score of purchasing the combined heat and power unit. Thus, the design team accessed the boiler system as the best alternative.

2.4 Implementation

From the economic analysis, the design team determined that the project does not meet the Calvin Energy Recovery Fund requirements of a 3-5 year payback typical of most projects. However, Calvin should still consider implementing the digester solution if it wants to continue to be a leader in renewable energy sources. The payback period would be lowered to 4.5 years if the cost of daily inspection could be eliminated. Clarkson University addressed this problem by establishing a club to recruit people who were willing to inspect and operate the digester on a rotating schedule. The report from Clarkson also discussed how the digester is providing many class learning opportunities, so operating the digester once a month for each student in a class relevant to the digestion process would be a way to eliminate the cost of paying
an intern to operate the digester every day. Another point to consider is whether the cost of natural gas will be increasing in the near future, which would increase the value of the biogas produced. The U.S. Energy Information Administration (EIA) predicted in the “Annual Energy Outlook 2012” report that natural gas prices will increase with the cost of developing incremental production capacity, as shown in

Figure 9.
The biogas project could also be implemented with the geothermal project, as the goals and requirements of each project complement each other. The project feasibility report will be presented to Professor Heun to be reevaluated by CERF. If the project were approved by CERF, the digester manufacturers would need to be contacted. If implementation were approved, carbon credits and tipping fees would need to be requested because they would help reduce the payback period. “It is estimated that producing 1 MW of renewable energy is approximately equivalent to reducing 0.65 tonne of CO2 emissions.” Digester startup would involve installation of the digester, connection to the boilers, implementation of a food transport system, creation of a student digester club, and training of food service employees.

21 “Market Trends- Natural Gas.”
22 Navaratnasamy, Edeogu, and Papworth
2.5 Conclusion

The feasibility analysis of an anaerobic digester for Calvin is complete. The unit would pay for itself in 8.8 years, with the payback period reduced to 4.5 years if a student club is established. With this information, the design team would recommend implementing the project. The project would meet the goals of Calvin’s “Statement on Sustainability” and would establish Calvin as a leader in managing food waste. It would care for the environment and the community by slowing the rapid expansion of landfills and compost centers. The digester equipment would also provide many hands-on learning opportunities for classrooms, educating students on biogas as a renewable energy source.

The anaerobic digestion research will take a new direction next semester. The design of the digester will be focused on the household instead of Calvin College. A small-scale anaerobic digester combined with a household stove run by biogas could be very useful in third world countries where many women spend their whole morning searching for firewood and suffer the bad side-effects of wood burning.

3. Cellulosic Material to Biofuel Project

3.1 Problem Definition

3.1.1 Need

According to the U.S. Energy Information Administration (EIA), “the transportation sector accounted for 27 percent of total world delivered energy consumption in 2008, and transportation energy use increases by 1.4 percent per year from 2008 to 203523”. About half of the world’s supplied liquid fuel is consumed by the transport sector, and this proportion is expected to rise, so attempting to reduce the demand significantly is unrealistic. Development of new fuels or sources of energy often require new types of engines and new systems of fuel transport and infrastructure, with the exception of some biofuels made via complicated and expensive processes. Other than recent movements towards the use of biodiesel in air transport, the aeronautics industry has very few alternatives to engines that operate on traditional fuel sources. Since these strides in the production of aviation biofuel have occurred, some airlines have experimented with the use of these alternate fuel sources in their commercial flights, but traditional fuel sources are still the primary selection24. Because of the continued dependency on high energy density liquid fuels, the transport sector will continue to rely mainly on fuel imports. However, a product that is consistent with the products on the marketplace but can be produced sustainably on a domestic level would be an attractive solution.

A constant and affordable supply of fuel is needed for many reasons, including:

i. Energy Security: International markets, industrial activism, technological failures, energy price spikes, or competition for the scarce fossil fuels can disrupt the supply of fuel. Producing liquid fuels from locally grown sources can mitigate the dependency on petroleum products and provide energy security.

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23 “International Energy Outlook 2011”
24 Wassener, Bettina “Airlines Weigh the Advantages of Using More Biofuel”
ii. Sustainability: The raw materials of biofuels can be produced over and over again, unlike fossil fuels, which are not renewable.

iii. Economic Development: Production of biofuels would likely increase national exports, simulate the creation of jobs and income for farmers, diversify the energy supply, and provide cheaper energy from locally available sources. The world energy demand is dramatically rising with global economic growth. “In developing countries, energy consumption is predicted to increase by 84 percent by 2035, and new sources of energy, such as biofuels, may have a role to play in meeting this demand.”

iv. Climate Change: Reducing greenhouse emissions is a way to address climate change as one of the greatest global challenges. When the biofuels are combusted, they only release the carbon dioxide that was absorbed during the plant’s growth, so they can be considered ‘carbon neutral.’ The overall process would require additional energy from an external source that is not necessarily ‘carbon neutral’ for heating, separation, and compression elements, but the emissions would be significantly less than that of fossil fuel processes. Thus the biofuels can immediately lower GHG emissions.

3.1.2 Approach
In years past, corn has been mass-produced as not only a source of food but also as a source of ethanol, a usable fuel base for automobiles. It is estimated that thirty-three percent of the corn grown in the United States is used for livestock feed, with an additional thirteen percent being exported for the same purpose in other countries. Fourteen percent of the corn grown in the United States is used for food and beverage production. The largest portion of United States’ corn production, the remaining forty percent, is used for the production of ethanol fuel. This ethanol is mixed with the octane that we use in vehicles, as mandated by the federal government, in small amounts. While this is a short term solution that is prolonging the inevitable depletion of fossil fuels, team Dynamic Organics is seeking to use other cellulosic material, such as the corn stalks that would otherwise go to waste, to produce a usable fuel. Some of the other cellulosic materials being considered include switch grass, miscanthus giganteus, and fast-growing poplar.

The design team is analyzing which of two processes would most efficiently produce a usable fuel. The first process uses an enzymatic approach to produce either ethanol or butanol from dried cellulosic material. The second process utilizes metal catalysts to produce the fuel via synthesis gas. If the synthesis gas process were to be used, additional products to be considered include various alkanes.

3.1.3 Benefit
A cellulosic process would make a very positive and large impact on the environment. Depending on the scale to which cellulosic processes were utilized to meet the growing petroleum need, the alternative fuels which are able to be produced with cellulosic material would be able to alleviate some of the economic stress on the dwindling supply of petroleum being used to meet a growing global energy need. Because the cellulosics used to produce these fuels are either grown on unusable farmland or are a waste product of an existing source, they represent a promising source of fuel and energy.

25 “Chapter 1-Why Biofuels? Drivers for biofuels production”
26 Carter
Furthermore, these cellulosic materials are entirely renewable from year to year. While the use of cellulosic feedstocks may be somewhat dependent on the growing conditions in a given year, many of the options being considered as part of this analysis are well-known as being able to grow well in very harsh conditions such as drought or extreme temperatures. Because of this, these resources tend to be less dependent on variables out of the control of the consumer. These materials require minimal maintenance, and are able to replenish themselves annually, if not more often.

Another benefit to the use of these cellulosic materials is the fact that these feedstocks can be grown most anywhere. According to the US Department of Agriculture, grasses such as switchgrass or miscanthus giganteus are able to grow throughout all of North America, from the northern regions of Quebec to the deserts of Arizona and Nevada. This versatility allows these materials to be easily produced and processed anywhere.

3.1.4 Similar Case Studies
In 2006, Alliant Energy’s Biofuels Development department did an area study of the feasibility of building a power plant in Marshalltown, Iowa. The power plant was designed to use a fuel source of cellulosic materials. A majority of the cellulosics were corn stalks and switchgrass. The corn stalks are already a byproduct of corn and the stalks are often just left in the field. Based upon preliminary analysis of the farm land encompassing the plant within a fifty mile radius, there is enough usable corn stalk biomass to produce 50 times the necessary requirements to power the entire town of Marshalltown, which is 5,900 MW. Another source of biomass that was considered was woody biomass products such as trees, underbrush, and other cuttings. They also considered using switchgrass in their feed process. Alliant designed their plant to be able to process all of the considered feed stocks at the same time without having to switch any equipment. The official results of the feasibility study were not published publically, but Alliant Energy did end up building a power plant that burns cellulosics in the area of Marshalltown.

Team Dynamic Organics must first look at the feed stock of the process. Alliant uses mostly cornstalks, with some added switchgrass and wood-based products as well. They are capable of producing up to 6.3 million tons of biomass using only corn stalks and an additional million tons when also including switchgrass and wood-based products. In order to power the town of Marshalltown, they only need 130,000 tons of biomass. According to the census of 2011, the city of Marshalltown has 27,775 residents and is growing at a rate of about 1% per year. The amount of biomass that it takes to provide such a large number of residents with power is a little underwhelming. With such a large overproduction of feedstock in the area, the town has opened up a compost pile to the public allowing them to drop off biowaste for a fee. This fee ranges from $4 to up to $90 depending on how big the vehicle is and the type of materials being discarded. Some of this material is used in a compost pile to produce potting soil and the rest is used in their biomass reactor to produce energy. Seeing what is capable from such a small reactor is very promising for use by Dynamic Organics. Although the team is not intending to burn the feedstock, the amount of energy that is available by combustion directly correlates to the amount of potential fuel that can be produced.

27 United States Department of Agriculture
28 Johnson
29 "State and County QuickFacts"
30 "City of Marshalltown"
In 1955, Frysville Farms became involved with the U.S. Forest Service in order to have a continuous mass product of hybrid poplars known as Schreiner Poplars. These hybrid trees have been developed to provide a high density wood after a short amount of time. The poplar trees are big enough to harvest after four years, and a new tree will then grow from the stump of the previous tree. The roots need to be uprooted and replanted after thirty harvests, or one hundred twenty years\(^{31}\). Frysville Farms produces the hybrid poplar in order to provide energy and heat from burning the wood. However, as poplar is a high density cellulosic material, it is possible to use poplar trees as a potential feed into the process of converting cellulosics to fuel. It is a very similar process in that they are producing a significant amount of energy from a material that is not a food or otherwise widely grown material. Although the poplars do require space for planting and growing and they can only be harvested every four years, they are capable of producing a large amount of energy and are a rugged plant.

This feedstock is another encouraging possibility because of the potential amount of energy it can produce per year. Also, these trees will grow right out of the stump of the previous tree, which means that it is only necessary to plant the trees once and then it can continue to produce product for many years after. It is a very dense wood which means that it is an excellent source of both energy and fuel, which is also very promising. Just one acre can produce up to five cords of wood material every year. This amount of wood, if burned, can produce 93.5 BTU’s or the equivalent of 730 gallons of fuel oil\(^{32}\). This is not a direct correlation to the amount of fuel that Dynamic Organics would be able to produce from the stock material, but it does offer a rough estimate of the potential that can be obtained from such a material. However, there are some potential drawbacks to hybrid poplars. Although they are very fast-growing compared to other tree varieties, they cannot be harvested nearly as much as some grasses and other potential feedstocks that can be harvested every year. Hybrid poplars have some potential drawbacks, but there is a lot of promise in the amount of energy and fuel that can be obtained from a wood material source.

3.1.5 Design Goals
In order for either of the potential cellulosic processes to work, the team must demonstrate that the fuel products can be produced and that there is a potential profit that can be made. The team must design the plant in such a way that a fuel source can be produced on a large scale from a cellulosic feedstock using the least amount of energy as possible.

This very complex process will include analysis of the reactors, pumps, heat exchangers, and separation equipment necessary to take the feedstock to product via the chosen process. From the details known so far, the process will need to be continuous within the reactors in order to keep production high enough to sustain a viable process; thus the team must design the reactors as continuous flow reactors and not batch reactors. Also, safety will be a big concern as flammable products are being mass-produced, which involves keeping the fuel to oxygen ratio out of the flammable region for as much of the process as possible. The pumps must be able to withstand the demands of moving the material, in any form, throughout the process. This might include the use of conveyors, the addition of solvents for easier transport, or the analysis of the pressure drop required to move a given amount of material, as prescribed by the product basis by which the plant is operating. Likewise, the separations aspect of the process must

\(^{31}\) "Frysville Farms"

\(^{32}\) "Frysville Farms"
be designed such that the material can be adequately separated in a given time and space constraint. The separations phase will likely involve the design of a centrifuge, as well as at least one distillation column, and may also include analyses of the azeotropes that might hinder easy separation. Finally, the overall cost of the necessary processes must be less than the value of the fuel and energy that is produced in the plant.

3.2 Systems Engineering

3.2.1 Requirements
For the process of converting cellulosic material to a usable fuel, several processes must take place. First, the biomass must be broken down and compressed into some form of pellets or a consistent shape that can be fed into the process. This will involve chippers, grinders, compressors, and some pretreatment. The pre-treatment will allow the material, in whatever its starting form, to be easily compressed into a uniform feedstock. Then, a flow reactor must break the cellulosic material down into complex sugars, either by genetically modified bacteria or by a catalytic process. If the genetically modified bacteria route is chosen, an elaborate process must separate the fuel from the byproducts in order for the fuel to be a high enough quality for use in the automobile industry. In the synthesis gas process, the catalytically broken down materials must be catalytically reformed into alcohol or alkane fuels in another reactor. These fuels must then be separated in order to obtain a pure product.

3.2.2 Alternatives

3.2.2.1 Processes

3.2.2.1.1 Enzymatic Approach
One of two processes which will result in a usable fuel from a cellulosic feedstock is that of an enzymatic approach. Figure 10 displays a block-flow diagram of the necessary stages of this process.
As displayed in the above figure, several steps are necessary to accomplish an enzymatic approach to the creation of a usable fuel. Below is a step-by-step description of the process:

1. Storage and Handling Unit—Feedstock enters the process and is immediately sent here to be processed in a shredder, which will result in a uniform feedstock for the rest of the process.
2. Pretreatment and Hydrolyzate Conditioning Unit—The uniform feedstock is moved into this area of the process where lime, water, acid (likely $\text{H}_2\text{SO}_4$), and steam break down the cellulosic material into gypsum (a byproduct), waste water (which can be reconditioned and recycled) and hydrolyzate.
3. Waste Water Treatment Unit—Waste water from the pretreatment unit is treated and can be recycled back to the pretreatment unit here. This can be accomplished by utilization of enzymes or bacteria, similar to methods done in governmental waste water facilities.
4. Saccharification and Co-Fermentation Chamber—The hydrolyzate is transferred here where an enzyme and some enzyme nutrition is added to break down the complex sugars which make up the hydrolyzate. The resulting products are gases, which can be vented in a later step, and a broth mixture containing fuel product as well as additional water and other impurities.
5. Product Separation Unit—all components leaving the saccharification and co-fermentation Chamber are transferred here and additional steam is added to aid in the separation. This unit likely will contain a centrifuge to remove solid lignin which can be sent to a turbogenerator to be used as an electricity source, followed by one or several distillation columns that will separate the waste gas to be vented from additional water and product fuel.
6. Burner/Boiler Turbogenerator—lignin, the solid waste leaving the separation unit, is sent here to be burned in order to create electricity.
7. Purified Product Storage Unit—purified product fuel is sent here to be housed until ready to be utilized.

3.2.2.1.2 Synthesis Gas Approach
A second alternative process exists which functions by taking in dried plant material and creates fuel via the production of synthesis gas. Figure 11 displays a block flow diagram of this process.

![Syngas Process Diagram](image)

As shown in the diagrams, multiple steps are required for either process, below is a step by step description of the synthesis gas process.

1) Feed Processor – This process involves the drying of wet plant matter as well as the crushing of the dried material into pellets, which will be used as feedstock for the plant. This process consists of a heating and ventilation system in order to dry the material as well as a compressing unit. The water as well as unusable plant material is removed and can be appropriately disposed of.

2) Feed Systems – As the remainder of the system is to be pressurized a specialized feed system must be utilized for the cellulosic pellets to be added to the process, without causing a back flow of synthesis gas through the system. This is most likely done through the addition of an inert carrier gas, raising the pressure of the feed to that of the first reactor.

3) Pre-heater – raising the temperature of the inert/plant material mixture to be suitable to enter the first reactor. This is likely done through pressurized steam or another heat transfer medium.

4) Reactor 1 – Gasification – The first reactor is that which gasifies the majority of the plant material into a combination of CO₂, CO, H₂, CH₄, H₂O and tar. This reaction is likely catalyzed
by a Nickel or Iron based catalyst, and requires temperatures ranging from 900 – 1300 °C as well as pressures ranging from 15 – 25 bar.

5) Reactor 2 – Tar Reformer – The second reactor serves to break down the tar formed in the first reactor. This requires a more specialized catalyst than that used in reactor 1, but is run under similar conditions. This may be forgone if further simulation and research reveals minimal tar formation in the first reactor. The reactor effluent contains CO₂, CO, H₂, CH₄, and H₂O, with most of the tar broken down into more CO and H₂.

6) Cooler – The reactor 2 effluent is cooled to approximately 200 -350 °C using either cooling or saturated water or another heat transfer medium, to reach the operating conditions of the 3rd reactor.

7) Valve – Not shown, to drop the pressure down to that required by reactor 3.

8) Reactor 3 – Water Gas shift – Reactor 3 serves to optimize our CO to H₂ ratio for later use. This is facilitated through the water gas shift reaction, which required temperatures in the range of 200-350 °C and P=10 bar. Methane and other sulfur containing components are also broken down into CO₂ and H₂ with the later also producing H₂S, which creates a need for a scrubber before going forward.

9) Scrubber – Uses water to remove H₂S from the effluent of reactor 3, to ensure the maximum life of downstream equipment.

10) Reactor 4 – Product Formation – Reactor 4 serves converts our freshly optimized amounts of CO and H₂ into final product through the use of the Fischer-Tropsch or a similar process. These require some type of metal catalyst, and temperatures in the range of 150-300 °C and pressures of 1-15 bar.

11) Separation Equipment – Serves to purify the product to fuel standards. The conditions and equipment is unknown at this point. Current plans are to also further purify a small amount of our product to reagent standards to allow us to take advantage of another market.

3.2.2.2 Feedstocks
For either process two or three (processes involving the conversion from cellulosic material) described above, many different feedstocks could be supplied to the reactor. Researching materials which were fast-growing and could be grown in poor soil that was unable to be used for food farming, the team narrowed the options to four possibilities. The possible feedstocks include switchgrass, Miscanthus Giganteus, fast-growing poplar, and corn stalks.

3.2.2.3 Product Fuels
Similarly, for processes two and three, multiple fuel products could be targeted. Some of the alternatives which are being considered are methane, ethanol, and butanol, as well as other alkanes. The type of fuel will depend largely on the process, catalysts available and the economics.

3.2.3 Testing
In order to analyze and compare all of the processes, the team will take into consideration economics, safety, and design norms. All of these factors will weigh into the decision making process displayed throughout the designs. Before making any choices or selections, the team will consult these factors and think about the tradeoffs that must occur within the design process including feedstock and products produced.
One of the major factors that Dynamic Organics will consider is the economic analysis of each process. The process must not only be financially beneficial, but it should be able to be a potential replacement for fossil fuels in the future. Whether it is methane, ethanol, butanol, or an alkane, the product must be worth more than the amount of money it takes to produce it. Ideally, the team will be able to design the processes in such a way that the final product will be able to be sold at a price that is competitive with the current prices of gasoline.

Dynamic Organics considers safety to be one of the most important considerations in determining whether or not a particular design feature is feasible or not. Because the team will be producing fuels in bulk quantities, safety becomes a large factor to consider. Every time the design process is within the flammability range in terms of fuel to air ratios and temperatures, the safety of the entire plant is put at risk. Therefore, Dynamic Organics has determined it a necessity that the number of times that each process is in the flammability region is minimized to the fullest extent of their abilities. Also, some of the intermediate products and byproducts have high flammability and/or toxicity and must be contained and disposed of in a responsible manner. In addition, there will be high temperatures (upwards of 1000 °C) and pressures (20-25 bar) used throughout the processes and thus safety will need to be a priority when designing these features, both in material construction and control methods.

In every aspect of the design process, design norms will play a large role in determining whether or not a design is feasible and sufficient for implementation. Transparency is a consideration throughout all of the processes. Dynamic Organics believes it is vital to identify and design around any potential safety factors in each of the design processes. Dynamic Organics believes the design norm that they best represent is stewardship. They are utilizing an inedible, unusable product in order to create a fuel that will be able to power vehicles, power plants, and heating systems. The team believes that throughout the project, they are caring for God’s creation by conserving valuable fossil fuels and utilizing a renewable source instead. The goals of the designs being considered do conflict with some other design norms however; in particular justice and trust. Some of the oil providing companies and countries that currently depend on the high price of fossil fuels will not be as wealthy or successful if everything in Dynamic Organics’ design plans were to be implemented. The process could potentially, if done on a very large scale, reduce the economic growth of wealthy Middle Eastern countries, or more consequentially, unstable and economically poor countries such as Nigeria and Libya that depend on oil production. This would not be displaying justice because they may not be able to grow biomass in the regions that they are located and thus cause them to suffer economically, which would also make them politically less stable as well. Also, because Dynamic Organics seeks to make the prices of the biofuels at competitive prices, it could be seen as a conflict of interest because other companies may not be able to compete with lower prices of fuel.

The team does not desire to put anyone else out of business or hurt anyone else economically, but they do seek to produce usable fuels for lower prices to benefit everyone as a whole. There are some conflicts between what Dynamic Organics intends to accomplish and some of the design norms; however, the team believes that the outcome of the project will be showing love to God and His creation despite the conflicts.
3.2.4 Design Decision

3.2.4.1 Feedstock Selection

Plants are able to have a variety of different cell structures and thus different types of plants can have very different properties from other plants. Some of the more crucial aspects for our design project include the cellulose composition, hemicellulose composition, extractible ethanol content, and the production or growth density rate. These values were gathered from Bioenergy’s article as well as Sannigrahi’s article and compiled in the following table.

Table 6: Selected Composition and Production Data for Possible Feedstocks

<table>
<thead>
<tr>
<th>Plant Source</th>
<th>Production (Tons/acre)</th>
<th>Cellulose Content (wt%)</th>
<th>Hemicellulose Content (wt%)</th>
<th>Ethanol (gal/acre)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switch Grass</td>
<td>4.6</td>
<td>40</td>
<td>29</td>
<td>421</td>
</tr>
<tr>
<td>Miscanthus Giganteus</td>
<td>13.2</td>
<td>45</td>
<td>24</td>
<td>1198</td>
</tr>
<tr>
<td>Corn Stalks</td>
<td>3.3</td>
<td>38</td>
<td>26</td>
<td>300</td>
</tr>
<tr>
<td>Poplar</td>
<td>8</td>
<td>45.1</td>
<td>21.5</td>
<td>1050</td>
</tr>
</tbody>
</table>

In order to select the most appropriate feedstock of cellulosic material for our process, we developed the decision matrix displayed below (Table 7) based on relevant criteria determined both through research and our relevant design norms. We then assigned a weight to each category based on the importance to our project and ranked each cellulosic source in each category, the plant with the highest weighted score is then the most ideal plant to be used. The four plants to be critiqued were switch grass, corn (stalks), miscanthus giganteus and Fast growing Poplar. Each of these plants was shown to be capable of relatively high yields of biomass in a given year, with the exception of cornstalls which is present as a control, as it has been the standard source of biomass in the past.

Table 7. Decision matrix for determining the ideal feedstock for conversion to biofuel

<table>
<thead>
<tr>
<th>Source of Fuel</th>
<th>(Tons/acre)/year produceable</th>
<th>Ruggedness</th>
<th>Ease of Processing</th>
<th>Waste management</th>
<th>Ease of Harvesting</th>
<th>Total Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switch Grass</td>
<td></td>
<td>4</td>
<td>10</td>
<td>10</td>
<td>7</td>
<td>161</td>
</tr>
<tr>
<td>Corn Stalks</td>
<td></td>
<td>2</td>
<td>3</td>
<td>7</td>
<td>10</td>
<td>88</td>
</tr>
<tr>
<td>Miscanthus Giganteus</td>
<td></td>
<td>10</td>
<td>5</td>
<td>8</td>
<td>7</td>
<td>177</td>
</tr>
<tr>
<td>Fast growing poplar **</td>
<td></td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>5</td>
<td>133</td>
</tr>
</tbody>
</table>

The category to which we assigned the highest weight was (Tons/acre)/year producable. This category was deemed to be the most important as we want to maximize the total producible amount of biomass per given area of land. This limits the cost of the land and maximizes the land that is available for the production of food or other resources. The plant scores of this category were scaled directly from
As miscanthus giganteus produced the largest amount of biomass on an annual
basis of the plants considered, it was assigned a 10, with the others scaled down based on their relative
biomass yields. One fact to note is that the total biomass production of land correlates fairly linearly with
the total biofuel producible from the biomass grown on a given amount of land; as a result, this category
serves as both an estimate of the biomass and the biofuel producible for a given area of land.

The second most important category was ruggedness, which we have defined as the ability of a plant to
grow in less than optimal soil conditions. This criterion is important as one of our main goals is to avoid
the use of a potential food source for the production of biofuel, and we also want to avoid the use of land
which would be used for the production of food. A higher score implies that a plant can adequately grow
in poor soil conditions. Switch grass, which can be grown in soil unsuitable for the growth of much else
was assigned the high score, with poplar and miscanthus giganteus scoring middle of the line as they can
be grown in most environments, but require more nutrients and care. Corn was the lowest as it requires
standard farmable land.

The ease of processing is relevant as we need to consider the difficulty of preparing the feedstock to
viable initial conditions for our process. This includes the need to dry, or break up our starting material.
Plants that had higher moisture content (more drying required) or plants that require more rigorous
processing, i.e. wood requires a wood chipper to be broken down to an adequate size, would earn lower
scores. For these reasons, switch grass scores the highest as it has naturally low water content, and is
easily broken apart. Cornstalks and Miscanthus Giganteus are marked down as their moisture content is
higher, and Poplar scores the lowest as it requires both drying and to be broken down in a wood chipper
before being useable.

Waste management is important as we need to know the waste and byproducts that will be produced for
each biomass source as well as the quantity. This is to ensure that we have the capacity to dispose of the
generated wasted. This is dependent on both the starting material and the process to be used. For example,
plant cell composition varies wildly plant-by-plant and some of these cellular components are unable to
be converted to biofuel. The types and amount of these unconvertible components varies based on the
catalyst used for generation. Therefore, values for this category have not yet been assigned as an optimal
catalyst has not yet been determined.

The last category that we considered was the ease of harvesting, where the easier a feedstock is to harvest,
the higher the score it will receive. For this process corn was assigned the highest score as current
infrastructure exists for the harvest and collection of corn stalks. Poplar, on the other hand, received the
lowest score, as tree harvesting requires more machinery and manpower.

Comparing all of these criteria, Miscanthus Giganteus appears to be the ideal feedstock as it has the
highest weighted score. However, until we have more information on the process that we plan to use, a
final decision cannot be made.

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15 Heaton, Emily A., Nicolas Boersma, John D. Caveny, Thomas B. Voigt, and Frank G. Dohleman. "Miscanthus for

*Poplar yield for ¼ acre (1 acre can only be harvested once per four years)

**yield assumed to be after year two of growth
3.2.4.2 Product Fuel Selection
When Cornell University did a study in 2005\textsuperscript{34} on the effects of using a butanol-based fuel in the engine of automobiles, some interesting results were discovered.

The reasons for choosing butanol as the fuel source of interest had to do with the fact that butanol is a 4-C molecule whereas ethanol has two C atoms. Table 8 illustrates the way in which butanol’s larger molecule translates into more energy: 110,000 BTU/gallon versus the 78,000 BTU/gallon associated with ethanol. Table 8 also illustrates that butanol is safer to use than both ethanol and gasoline as a result of its lower vapor pressure—it is difficult to ignite and it burns slowly. Like diesel fuel, a match must be held to it for ignition; butanol is combustible but not flammable, whereas ethanol and gasoline are flammable and potentially explosive.

Table 8 Properties of Fuel-Grade Alcohols and Gasoline
\begin{tabular}{|l|c|c|c|}
\hline
 & Ethanol C\textsubscript{2}H\textsubscript{5}OH & Butanol C\textsubscript{4}H\textsubscript{9}OH & Gasoline \\
\hline
Energy Content (BTU/gallon) & 78 k & 110 k & 115 k \\
\hline
Motor Octane & 92 & 94 & 96 \\
\hline
Air:Fuel Ratio & 9 & 11-12 & 12-15 \\
\hline
Vapor Pressure (psi@100\textdegree F) & 2 & 0.33 & 4.5 \\
\hline
\end{tabular}

When the University considered that an average car gets approximately 22 miles to the gallon using gasoline, and assumed a modest estimate for the cost of gasoline at $3.00/gallon, the results of this study are presented in Table 9.

Table 9: Costs per mile for E85, Gasoline and Butanol
\begin{tabular}{|l|c|c|}
\hline
 & Cost/gallon & Cost Per Mile \\
\hline
Cost/gallon & E85 & $2.80 \\
& Gasoline & $3.00 \\
& Butanol & $3.00 \\
\hline
Average mpg & E85 & 17.6\textsuperscript{*} & $0.16 \\
& Gasoline & 22 & $0.14 \\
& Butanol & 25 & $0.12 \\
\hline
\end{tabular}

\textsuperscript{*}20\% less than for Gasoline

Because this study was done in 2005, the numbers for fuel cost have fluctuated from the values displayed in the table, however, the lower cost per mile associated with butanol is highly encouraging. It suggests that regardless of the way in which the numbers fluctuated, butanol would still result in a more financially reasonable option.

34 Ramey, David E. "Butanol: the Other Alternative Fuel."
Another important consideration for choosing a product fuel is the azeotropic data for various fuel options with water. Azeotropic mixtures cannot be easily separated by ordinary distillation methods, and in some cases, like that of ethanol and water, this creates a purity restriction. The azeotropic data for ethanol and butanol with water can be found below.

**Table 10: Azeotropic Data for common Fuel Alcohols with Water, b.p.=100°C**

<table>
<thead>
<tr>
<th>Component</th>
<th>Boiling point of Component (℃)</th>
<th>Boiling point of Mixture (℃)</th>
<th>% by weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethanol</td>
<td>78.4</td>
<td>78.1</td>
<td>95.5</td>
</tr>
<tr>
<td>1-Butanol</td>
<td>No Azeotrope with Water</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Clearly, the use of butanol as a fuel appears to be a more practical option than the use of ethanol. The main reason for this thinking is that if butanol was used, the separation step, regardless of the process used, would be significantly simpler because the separation would not have to be made around the azeotrope.

Despite the analysis that has been done towards determining the end product in these processes, the product fuel still cannot be determined. At this point, while process and feedstock is more or less established for the project, there are unknowns yet to be weighed, such as the cost of the catalyst, which will come into the decision of what product is made at the end of the process. Butanol appears to be a much more feasible option than ethanol, given the data presented in Table 8 for the two product’s energy capacity, and the data in Table 9 referring to cost per mile in an automobile. Further, the vapor pressures in Table 8 suggest that butanol would be the safer alternative. The team’s objectives for design include providing a safe alternative fuel, coinciding with the design norm of trust, which is best suited by butanol between the two alcoholic fuels.

### 3.2.4.3 Process Selection

Because both the synthesis gas and enzymatic processes have been done in other settings before, there was little that needed to be decided in terms of feasibility. Based on our research, it is clear that both of these processes would be feasible given the proper time and resources. Because the nature of this project is that it can require no more than approximately 9 months and must fall under a strict budget, the feasibilities of each project were reconsidered with this in mind.

In an attempt to quantify which process would be more feasible to accomplish within the constraints of time and budget on this project, a decision matrix, viewable below, was created. The result of this endeavor was that the Synthesis Gas process would be significantly more feasible.

---

Table 11: Decision Matrix for Cellulosic Processes.

<table>
<thead>
<tr>
<th>Synthesis Route</th>
<th>Budget Effectiveness</th>
<th>Necessary Equipment</th>
<th>Technological Availability</th>
<th>TOTAL SCORE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>8</td>
<td>6</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Enzymatic</td>
<td>5</td>
<td>6</td>
<td>5</td>
<td>126</td>
</tr>
<tr>
<td>Synthesis Gas</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>194</td>
</tr>
</tbody>
</table>

Each category of interest was weighted and ranked on a 1-10 scale, with a 10 being a high score and a 1 being the lowest score. As a result of the decision matrix, the synthesis gas method was a clear winner with a score of 194.

In the category of budget effectiveness, the synthesis gas method received a score of 7 because while the metal catalysts can be expensive, compared to the costs associated with securing the appropriate genetically modified enzymes, the costs can be assumed relatively low.

In the category of necessary equipment, the synthesis gas method also requires significantly less equipment. For the enzymatic process, several reaction chambers will be necessary in order to properly break down all the complex sugars found in the cellulose. For example, cows are able to digest cellulose because of their multiple stomachs\(^{36}\). These multiple stomachs allow for the cow to break down these more complex sugars in stages, by the process that would be similar to the enzymatic method. In the synthesis gas method, the entire conversion of cellulose to the syngas can take place in one continuous stage, which will likely require much less equipment.

Finally, in the category of technological availability, the synthesis gas method again outranks the enzymatic method. Technological availability refers to the ability for us to get the necessary material to simulate the process. With the enzymatic method, the technology is available, but is much more difficult to find information on. This is an incredibly crucial category because as of late, the majority of our decisions have been based on previous research, so the ability for us to locate relevant research and literature is critical.

3.3 Components

3.3.1 Division Into Process Steps
For each of the two processes being considered in the cellulosic material to fuel project, there are many different components that must be considered in depth:

3.3.1.1 Genetically Modified Bacteria Route\(^{37}\)
   i) Handling and Pretreatment – The first vessel in this process shreds the feedstock into smaller pieces for easier pretreatment and processing in later steps. After the feedstock has been

\(^{36}\) de Ondarza, Mary Beth. "The stomach of the dairy cow."
\(^{37}\) Huang, Ramaswamy, Al-Dajani, Tschirner, and Cairncross 234-46
shredded, the cellulosic material requires some initial pretreatment in order to break the cellulose down into sugars such as Xylose and Glucose. This pretreatment can be accomplished by the addition of acid, usually H$_2$SO$_4$.

ii) Saccharification and Co-Fermentation Chamber – Here, the main reaction occurs where more complex sugars are broken down into simpler sugars, mainly glucose. This can be accomplished with the addition of enzymes and other “Nutrition” in water, meant to help the enzymes work more efficiently. In a simultaneous reaction, yeast can be added to convert any formed glucose into ethanol. This stage will also require venting of some kind—perhaps a valve or scrubber system to remove the sulfur compounds from solution.

iii) Separations – This multicomponent stage of the process will include a centrifuge to remove any additional lignin not converted to a broth of ethanol, water, and residual reagents. Additionally, a distillation column, or series of columns, will be required to adequately separate the broth into a sufficiently pure ethanol stream to be used as a fuel. This step is still being researched, but we anticipate a large capital cost and high energy input will be required for this section.

3.3.2 Requirements
The units which are set up as pre-treaters will require some optimization, such as size of product at the output, in order to accurately determine the best choice for a given process. This will be determined likely by looking at values for capital costs often associated with the equipment in question and the duties associated with each piece of equipment.

In terms of the individual components, we must determine many requirements, but not enough information has been gathered. For example, we know that in the reactor, we must specify a temperature and pressure that will allow the reaction to occur according to the kinetics for the chemistries involved. Similarly, we know that some reactor formations will be more efficient than others, but have not yet determined which ones.

Finally, in terms of the separation units, we are vaguely aware of the equipment that will be required, but still know little or nothing about the optimum settings on these pieces of equipment. Details such as the feed tray location, number of trays, reflux ratio of the columns, and speed and time in the centrifuge will all need to be optimized according to the economics associated with the systems.

3.3.3 Criteria
In this section, data for the optimization of the various pieces of equipment presented in the requirements section above will be discussed. This will include several small decision matrices and how each criterion was given weight based on its overall importance in the decision.

3.3.4 Design Decision
Here we will include information as to the decisions made based on the design matrices found in the section above. These “Decisions” will be for equipment decisions, and not decisions for the overall process such as for feedstock, product or process method.
3.3.5 Implementation

In the spring, we plan to implement our research into a full design, including UNISIM simulations. Here, we will present the results of the UNISIM as well as explain how the values which were decided upon above were utilized in the simulation.

3.4 Business Plan

Dynamic Organics used the Order-of-Magnitude Estimate in order to obtain a very rough estimate of the cost of the biofuel production facility as laid out in Seider’s book. This method is known to have an error range potential of being under the actual value by one hundred percent or over the actual value by eighty percent. The positive of this preliminary cost analysis is that it only requires two pieces of information. It requires the estimated production rate of the facility and a basic block flow diagram of the process with some idea of what types of temperatures and pressures will be occurring inside. This model does not include heat exchangers and liquid pumps, but does include reactors, compressors, and separations equipment. Also, energy, water, other possible utilities, and materials of construction are not included in this analysis, but will be analyzed and designed in depth for the final design report.

The first step of the Order-of-Magnitude Estimate is to scale the overall size of the plant with the production rate factor. This involves the following equation:

\[ F_{PR} = \left( \frac{\text{Main Product Flow Rate}}{\text{Standard Size of Similar Plant}} \right)^{0.6} \]

In Dynamic Organics’ analysis of the plant, the product flow rate was assumed to be forty million gallons per year, which is equivalent to two hundred seventy million pounds of butanol per year, of which the current industry standard is one hundred million pounds of butanol per year.

The second step in the preliminary cost analysis is to calculate the module cost for all of the major components of the design process. In the Biofuel process, the known major components include the following: an evaporator, a compressor, four separate reactors, an absorber, and a distillation column. The estimated cost of each component is multiplied by a material factor, a pressure ratio, and the production rate factor from step one. The module cost is calculated using the final equation:

\[ C_M = F_{PR} F_M \left( \frac{\text{Design Pressure}}{100} \right)^{0.25} \times \text{Estimated Cost} \]

For initial safety considerations, the team decided to use a material factor for stainless steel for all of the individual modules except the basic evaporator and compressor, which will initially use carbon steel. The evaporator is able to function at low pressure and thus the pressure ratio is negligible, however, the rest of the process will be operating in pressures between fifteen to twenty-five bar. These pressures require a higher pressure ratio to come into effect, which after being multiplied out, is approximately 1.3. The cost of each module, as estimated in Perry’s Chemical Engineers’ Handbook, is shown in Table 12.

---

39 Perry, Robert H. “Perry’s Chemical Engineers’ Handbook” pg.9-69
Table 12: Estimated Individual Module Costs

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Material Factor</th>
<th>Pressure Ratio</th>
<th>Estimated Cost</th>
<th>Module Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaporator</td>
<td>1</td>
<td>1</td>
<td>$73,000.00</td>
<td>$132,594.92</td>
</tr>
<tr>
<td>Compressor</td>
<td>1</td>
<td>1.305</td>
<td>$133,000.00</td>
<td>$315,250.04</td>
</tr>
<tr>
<td>Reactor 1</td>
<td>2</td>
<td>1.305</td>
<td>$93,000.00</td>
<td>$440,876.00</td>
</tr>
<tr>
<td>Reactor 2</td>
<td>2</td>
<td>1.305</td>
<td>$93,000.00</td>
<td>$440,876.00</td>
</tr>
<tr>
<td>Reactor 3</td>
<td>2</td>
<td>1.305</td>
<td>$93,000.00</td>
<td>$440,876.00</td>
</tr>
<tr>
<td>Reactor 4</td>
<td>2</td>
<td>1.305</td>
<td>$93,000.00</td>
<td>$440,876.00</td>
</tr>
<tr>
<td>Absorber</td>
<td>2</td>
<td>1.305</td>
<td>$600,000.00</td>
<td>$2,844,361.28</td>
</tr>
<tr>
<td>Distillation Column</td>
<td>2</td>
<td>1.305</td>
<td>$3,300,000.00</td>
<td>$15,643,987.04</td>
</tr>
</tbody>
</table>

From Table 12, it is clear that a bulk of the total cost of the plant will be an investment into the separation of the desired product from the byproducts.

The third step in the cost estimation is find the bare-modulus investment, which is done by adding all of the module costs and multiplying their sum by the indexing ratio and a piping factor. In the design, the entire process will be liquid and gas handling, which requires a piping factor of 2.15. The indexing ratio was assumed to be 0.6 because of the various operations in the design. The current design requires two main sub-processes: formation and separation. The indexing factor for complex separations is listed as 0.6, while the indexing factor for the production of butanol is 0.4. The team chose to use the greater of the two values in order to ensure that we were on the high end of any estimate. The equation used to find the total bare-modulus investment is as follows:

\[ C_{TBM} = F_{P1} \times \text{Indexing Ratio} \times \sum C_M \]

The total bare-modulus provides the team with a very rough estimate of the additional costs of piping and transportation of materials around the plant. The total bare-modulus investment cost estimate of the plant is twenty-seven million dollars.

The fourth step in estimating the cost of the plant is adding the construction and facility status factors, which is done by calculating the direct permanent investment. The first of the two factors involves where the construction will take place; it can be outdoor, indoor, or a combination of the two. The second factor is adjusted based on the type of construction in terms of whether it is adding minor additions or major additions to a plant or constructing a plant from scratch. The equation for the direct permanent investment is as follows:

\[ C_{DPI} = (1 + F_1 + F_2) \times C_{TBM} \]

Based on the calculations, the direct permanent investment for the plant is fifty-two million dollars. This is the total amount of money that Dynamic Organics would have to pay directly in order to prepare for operations.

The fifth and final step in the Order-of-Magnitude Estimate of the total plant cost is to find the total permanent investment and the total capital investment. For these values the following equations will be used:
\[ C_{TP1} = 1.50 \times C_{DP1} \]
\[ C_{TCI} = 1.15 \times C_{TPI} \]

From these equations, Dynamic Organics has calculated a total permanent investment of seventy-eight million dollars and the total capital investment of ninety million dollars. Therefore the estimated cost of creating a Biofuel plant would be ninety million dollars with an uncertainty of +100% or -80%. Although this is a very rough estimate of the cost of building the team’s facilities, it is a necessary step in determining the feasibility of the overall design.

Assuming a continuous yearly production of butanol of forty million gallons per year and an estimated fuel-grade cost of butanol from 2005 of three dollars per gallon, Dynamic Organics estimates that the total revenue developed by the plant will be one hundred twenty million dollars per year, which is far more money than the originally estimated cost of the production facility. Also, the price of fuel has increased since the estimated fuel cost of butanol was discussed, which implies that the facility could make even more money than we can currently predict. This is a very rough estimate that does not take into consideration taxes, fees, and additional costs that are currently not factored into the analysis, but it does provide us with a measure of hope that our designs are feasible and that this could be a beneficial investment.

### 3.5 Conclusion

Dynamic Organics has determined that it will be more beneficial to pursue the synthesis gas process as opposed to the enzymatic process. This process will entail a drying section, a compressor section, a complex reactor system, and a complex separation system. Dynamic Organics selected miscanthus giganteus as the feedstock to the system. This feedstock was selected due to its cellulose density combined with its ability to thrive in very harsh conditions. In the future, Dynamic Organics will attempt to optimize the target fuel that will be product of the system. The team will research catalysts and optimize the objective product for the system, and then optimize each individual component of the process in order to produce a very accurate and specific financial estimate of a biofuel production facility.
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References


