A Life Cycle Assessment and Techno-economic Analysis of a Corn Ethanol Bio-Refinery in Comparison to a Novel Bio-refinery

By

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Abstract

A lifecycle assessment and economic analysis of a dry-mill corn ethanol facility based on the IGPC Ethanol plant in Ontario, Canada was completed and compared to a novel bio-refinery. The two facilities both produce ethanol, with the traditional facility also producing dry distillers' grains and solubles (DDGS), Hi-Pro and fiber plus syrup, all utilized as animal feed alternatives. The novel facility produces distillers' dried grains, while costly evaporation of solubles is avoided and instead, solubles are utilized in a novel anaerobic digester. The effluent from the digester is then be aerobically treated before being utilized for the cultivation of *Chlorella sorokiniana*, which will be used to supplement the corn required for the biorefinery. The treatment will also produce struvite, a product that can be applied as an industrial fertilizer.

The biorefinery was proposed in order to reduce the corn input, energy consumption and greenhouse gas (GHG) emissions associated with ethanol production. The analysis focused on plant specific data for IGPC Ethanol but was supplemented with databases such as Greenhouse Gases and Regulated Emissions in Transportation Fuels (GREET) and ecoinvent databases. In order to determine the environmental effects of the two systems, a life cycle assessment was necessary to determine the environmental impacts of each facility. An economic analysis was also completed to determine the changes to capital and operational costs for the novel biorefinery, which will determine the commercial viability of the novel facility in comparison with the traditional corn ethanol process.

The results show that algae produced in the novel biorefinery does not have a significant impact in reducing the amount of corn used as feedstock. However, the reductions in primary energy use and increased co-product production led to decreases in 5 out of the 7 environmental impact categories for the novel biorefinery, with eutrophication impacts being the only categories not reduced. The economic analysis indicated that the overall revenue decreased in the novel biorefinery when capital, operating and material costs were taken into consideration. The cost analysis indicated that cheaper sources for magnesium addition for the precipitation of struvite could lead to an economic advantage for the novel facility.

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Chapter 1 Introduction

1.1 Background

Ethanol production is a major industry for both the petroleum and the chemical field. There are two main process routes for its production; the petrochemical route is a simple process that involves the hydrolysis of ethylene into ethanol, with the main suppliers being from South Africa and Saudi Arabia (Mohsenzadeh, Zamani, & Taherzadeh, 2017). However, most ethanol is now produced through fermentation of biomass and is termed bio-ethanol. Bio-ethanol is produced from renewable resources with feedstocks such as sugarcane, wheat and corn. The production of bio-ethanol provides incentives for suppliers in many countries to collect revenue for the production of fuel from renewable sources.

Currently, the most common use for ethanol is as a fuel additive for gasoline, but it was also one of the first automotive fuels used in the US. However, post World War 2 there was little incentive for its use due to relatively abundant and cheap resources for fuel. Then the oil supply disruptions in the Middle East during the 1970's renewed interest in ethanol as fuel and provided incentive to advance the technology (Bothast and Schlicher, 2005).

Ethanol use increased significantly in 2002 as the U.S. began to ban the use of methyl tertiary butyl ether (MTBE) because of concerns associated with MTBE as groundwater contaminant. MTBE was used as an oxygenate in gasoline to enhance fuel combustion and reduce GHG emissions, and ethanol quickly replaced MTBE as a gasoline oxygenate across the country (EIA, 2018). Now, ethanol typically makes up 10% or less of gasoline used in gasoline engines but in specially designed engines, denoted as E85, up to 85% of the gasoline can consist of ethanol. Ethanol does contain a lower energy content than that of petroleum fuel (75,600 btu per gallon of ethanol [btu/gal] and 115,000 btu/gal, respectively for lower heating value) but ethanol is often employed as a blending agent with gasoline to increase octane and cut down carbon monoxide and other smog-causing emissions; roughly 97% of gasoline in the U.S. contains some ethanol (U.S. Department of Energy Efficiency and Renewable Energy). Bio-ethanol also has the potential to have a lower environmental impact compared to traditional gasoline production due to the use of renewable resources.

The increase in production of bio-ethanol was the result of two pieces of legislature that mandated that the supply of transport fuel contain minimum quantities of renewable fuels. The

Renewable Fuel Standard (RFS), which included a schedule that started at 4 billion gallons of bio-ethanol in 2006 and rose to 7.5 billion gallons by 2012. Then two years later, the standard was replaced by RFS2, which required biofuel use to achieve rates of 9 billion gallons per year in 2008 and ramp up to 36 billion gallons of ethanol use per year in 2015 and continue until 2022 ("A Life-Cycle Analysis of the Greenhouse Gas Emissions of Corn-Based Ethanol," 2017). The standard also states that a certain percentage of this must be advanced biofuel, which includes cellulosic biofuels that achieve above a 60% reduction in GHG emissions (USDA, 2007). Canada has similar regulations that require petroleum producers and importers to have an average of 5% renewable fuel content in gasoline and 2% renewable fuel content in diesel fuel (CEPA, 2010). This gives support to fuels that have reduced environmental impacts compared to fossil fuels and gives incentives for production of biofuels. Policies aimed at reducing GHG emissions from transportation have led to increased consumption of renewable and low-carbon biofuels in Canada (Moorhouse & Wolinetz, 2016).

The increased production of bio-ethanol brings hopes of decreasing GHG emissions and reducing dependence on imported fossil fuels. There have been many studies assessing the environmental impacts of producing ethanol from renewable resources, with many of the discussions focused on the sign of the net energy of ethanol, to determine whether manufacturing ethanol requires more energy than the resulting fuel provides (Farrell et al., 2006). However, the Environmental Protection Agency (EPA) in the U.S. has predicted GHG mitigation values for corn ethanol to yield 21% lower emissions than an energy equivalent quantity of pure gasoline ("A Life-Cycle Analysis of the Greenhouse Gas Emissions of Corn-Based Ethanol," 2017).

Based on lifecycle carbon intensities reported by government contacts and obtained from databases such as GHGenius, renewable fuel consumption, including ethanol, has avoided 34.3 $MtCO_{2\,eq}$ emissions between 2010 and 2017 (Wolinetz, Hein, & Moawad, 2019). This is because the production of ethanol creates less GHG emissions compared to the petroleum sources that make up the remaining fuel composition. This illustrates how the use of biofuels provides a positive impact for carbon mitigation and helps decrease the reliance on petroleum fuels.

There is a lack of studies based on bio-ethanol production in Canada, which now produces 1.8 billion liters of ethanol a year (L/yr) and consumes approximately 3.2 billion L/yr (Harvey, 2019). Canada currently has to import bio-ethanol in order to meet its carbon mitigation regulations, this provides an opportunity to expand the market. Canada has distinct conditions that vary from other regions studied, including the electricity configuration, corn cultivation conditions and feed transportation. Canada's corn belt rarely requires irrigation, and processing plants in Ontario typically transport corn grain less than 80 km to processing facilities; all of which can potentially decrease attributed GHGs. Plant specific conditions also create changes in the processing depending on the fuel used, plant energy efficiencies and technologies employed. This demonstrates the importance of a plant specific study on the corn ethanol industry in Canada.

The production of corn-ethanol is based on converting the starch within corn into sugars followed by fermentation into a dilute ethanol which is then distilled and purified. The unfermentable portions of the corn, called thin stillage and distillers' grains, are evaporated, dried and further processed into animal feed products, and fat from the corn is removed as a corn oil product. The overall process requires a large amount of water (3.81 gallons per gallon of ethanol produced [GREET, 2018]). This process is known as the dry-mill corn ethanol process and is the most commonly used method.

1.2 Objectives

Advances in corn-ethanol production are promising, but a lifecycle analysis on the cradle-to-gate process needs to be performed in order to fully demonstrate the environmental impact of the process. This study focuses on the processing of corn into ethanol and its by-products at IGPC Ethanol in Alymer, Ont. Both the direct agricultural processes as well as the indirect supporting processes have an impact on the environment, so both need to be considered in the assessment. The current corn-ethanol process is resource, water and energy intensive, but recent technology improvements such as improvements in co-product production and increases in water-recycling has led to reducing the environmental impacts.

The IGPC facility balances the economics of ethanol production by producing co-products such as corn oil, distiller's dried grains and solubles (DDGS), Hi-Pro and Fiber with syrup. The processing of these co-products can use one third of the energy in the plant (Drosg et al., 2013), but can also improve the financial profile and have made a positive contribution on the feed industry (Kim et al., 2008). Further changes to the processing of co-products may help improve the economic and environmental balance. The changes this study suggests focuses on the treatment of the thin stillage, by removing the energy intensive evaporation steps and reducing the drying required for the co-products, in a process described as a novel corn-ethanol bio-refinery.

Two conservational concerns can be presented for the current state of corn ethanol processing. The first consists of the large volume of water consumed in the process, in the form of water for irrigation, for process water within the plant, evaporation, drift and blow-down from the cooling tower and evaporation from drying (Wu et al., 2009). The corn-ethanol process can use over three times the water (8.35 gallons per bushel of corn) compared to the ethanol produced (2.74 gal/Bu). The water use in total can range from 39 gallons to as high as 634 gallons of freshwater per bushel of corn used (Wu et al., 2009).

Fresh water is only introduced to the facility in a few processes, with the rest being recycled within. Condensate is produced in the multiple effects evaporators and is then directed to a biomethanator, which is essentially an anaerobic digester used to convert organic material present in the process condensate into methane that can be used as an energy source in the feed dryers. This increases the water quality and enables recycling of the process water within the plant to the liquefaction stage.

The second concern relates to the energy profile of the corn ethanol plant. In all dry-mill corn ethanol plants, the liquid by-product called thin stillage goes through an energy intensive evaporation and drying process before being incorporated in an animal feed. In our proposed novel bio-refinery, thin stillage will be treated anaerobically and then aerobically so that the digestate can be used to cultivate algae. Ultimately, the treatment is hypothesized to produce energy from thin stillage in the form of methane and simultaneously improve the thin stillage nutrient characteristics so that it can be reused within the process. This is also expected to decrease the energy profile and improve the water recycling within the process. An LCA will be completed to determine the environmental impacts of both processes while a techno-economic assessment will be completed to compare the costs to incorporate the novel process.

In summary, this study proposes a novel biorefinery based on corn-ethanol production including an anaerobic baffled reactor (ABR), an aerobic treatment reactor and a microalgae cultivation system. The proposed system is expected to exhibit the following benefits:

- Treatment of the organic matter present in thin stillage
- Reduced nitrogen and phosphorus levels discharged to the environment

- Decreasing natural gas use by elimination of evaporators and decrease in volume entering drum dryers
- Producing methane in an ABR as a new energy source for heat
- Producing struvite as a new value-added product
- Increased mitigation of CO_2 emissions by utilizing it for microalgae cultivation
- Increased recycling of nutrients within the bio-ethanol production process
- Recycling starch-rich microalgae into the front-end of the process to partially reduce corn required for ethanol production

1.3 Organization of the Report

Chapter 2 of the thesis will review the process basics for IGPC Ethanol and the novel biorefinery and presents the differences between the two facilities. Chapter 3 will investigate scientific studies and datasets that look at similar corn ethanol LCAs, and other processes relevant to the novel biorefinery. Chapter 4 introduces the process design for the study with literature comparisons. This chapter includes the methodology for the life cycle assessment highlighting the scope of analysis, impact categories and co-product treatment methods.

Following this, Chapter 5 introduces the detailed process flow and mass balance for both IGPC Ethanol as well as the novel biorefinery. The data is compiled from multiple relevant databases. Using this data, a lifecycle inventory is created which is then applied to the openLCA software to determine the impacts of both processes. Chapter 6 will present the lifecycle inventory for both facilities. This dataset will be used for Chapter 7 where the results of the openLCA analysis will be investigated. It will also be used to suggest where further research should be focused.

The economic analysis will begin in Chapter 8 where the operating, capital and material costs are explored and proposed. An analysis is completed in Chapter 9 to determine the overall projected revenues for both facilities. Finally, a sensitivity analysis is presented in Chapter 11 to determine how various parameters effect the overall project results.

Chapter 2 Process Summaries

2.1 Conventional Dry Mill Corn Ethanol Process

The growth of the corn-ethanol industry has led to a great deal of research in improving the environmental, economic and energy profiles of the process. The environmental profile of a process can be complex and a life cycle assessment (LCA) on the process needs to be performed in order to fully demonstrate the environmental impacts of a process. An LCA is an important step in determining the environmental implications of a process or product and can help addressing questions regarding where the environmental impacts of a process occur. In order to complete an LCA, the steps involved in the traditional corn-ethanol process are outlined first, and an introduction to the site-specific IGPC facility process will be introduced in the following chapter.

The first step in the corn-ethanol production is the cultivation of the corn. The increased use of corn for biofuels has put new demands on agriculture to increase crop yield, develop better energy crops, better utilize livestock manures and conserve natural resources (Stone et al., 2010). As corn ethanol production increases, the demand and price for corn may also increase. Additionally, as the demand for corn increases, some acreage may be shifted to corn away from other crops such as soybean, wheat or forestry. This is due to the fact that US farmers make their planting decisions based on demand from the marketplace (NCGA, 2005). This can influence land use change parameters, which are a major emission category for the environmental impact assessment.

The cultivation stage has the most uncertainty for biofuel production, as the crop yield is highly dependent on local weather and climate. Weather variability including droughts and floods can greatly impact available bioenergy; weather induced changes in corn production has been twice as variable as oil imports for the last 40 years (Stone et al., 2010). This can cause concerns for the dependability of the corn ethanol industry and the pricing of corn would increase, which impacts the already economically sensitive ethanol industry.

Depending on climate, some areas require irrigation for cultivation. Gravity or pump fed irrigation may be used and this produces an impact on the environment. The impact of irrigation is related to the use of fossil fuels for moving the water. The cultivation process also includes the use of fertilizers and pesticides that are typically synthesized or from animal manure (Xue et al, 2014). It also includes the use of farming equipment used for fertilizing and harvesting.

Other factors also affect the corn cultivation, such as fertilizer and pesticide use, which can have significant effects on eutrophication and acidification impacts. These product streams for the farming sector have upstream costs related to their production and dispersion. It should be noted that nitrogen use on a per bushel (of corn) basis has declined by about 20% from the mid-90s to 2015 (Gallagher, Yee, & Baumes, 2016). This is due to increased nitrogen fertilizer efficiency, which is estimated as the increase in grain yield due to applied nitrogen (Liska et al., 2009) and more conservative tillage practices. This is particularly important because fertilizer production and the direct energy use on the farm are the largest energy components for corn production. Gallagher et al., (2016) also reported general declining energy use (and diesel use) on a per bushel basis due to declining application rates and rapidly increasing corn yields.

Most corn-ethanol production uses the dry milling process as shown in Figure 2-1, where the typical outputs are ethanol and distillers dried grains and solubles (DDGS) (Pieragostini, Aguirre, & Mussati, 2014). The ethanol yield is a standard to describe the efficiency of ethanol production, while a bushel is a standard unit of corn used for corn ethanol production. For general dry-milling without corn oil extraction, the average yield is 2.86 gallons of ethanol produced per bushel (gal/bu), while it increases to 2.88 gal/bu when corn oil is extracted and also produces 0.54 lb/Bu of corn oil (GREET, 2018). The extracted oil can be used as raw materials for biodiesel production, but the majority of the oil is added to chicken feed to increase the energy content (Reis, Rajendran, & Hu, 2017).

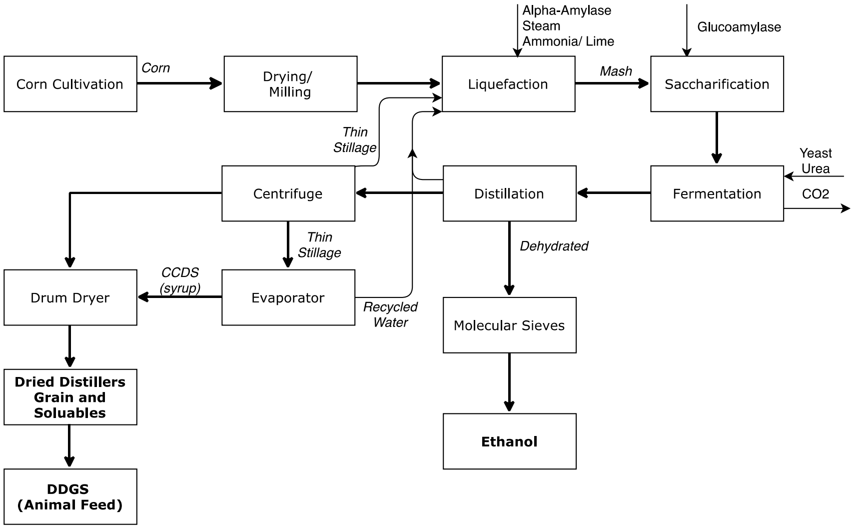


Figure 2-1: Conventional dry-grind corn ethanol facility

Once the corn arrives on-site, the moisture content can vary so it is first dried then crushed to break down the coating and expose the starch. It is then transferred to a new vessel for a process called liquefaction where water is added to form a mash. The starch cannot be metabolized directly by yeast; it must be broken down into simple six carbon sugars prior to fermentation (Bothast and Schlicher, 2005). Alpha-amylase is added to reduce the starch into dextrins using enzymatic hydrolysis.

The solution is heated while lime and ammonia are added to adjust the pH of the solution and the mash is then heated in order to reduce contamination by bacteria and other microorganisms (Soccol et al, 2016). Liquefaction takes place at pH 6.5 and is initially held for 60 min at 88°C. The solution is then cooked at 110°C for 15 minutes before being transferred to a new tank for saccharification (Kwiatkowski et al, 2006). For saccharification, gluco-amylase and sulfuric acid are added to convert the dextrins to glucose at 60°C and a reduced pH of 4.5 (Kwiatkowski et al, 2006). The solution is then transferred to another tank for fermentation, but the gluco-amylase remains active.

For fermentation, the solution is cooled down to 32°C while yeast is added to convert this glucose from the corn into ethanol and carbon dioxide. Often a nitrogen source such as ammonium sulfate or urea is added for the propagation of the yeast (Bothast and Schlicher, 2005). The facility wants to ensure sufficient nutrients are in place so the yeast can consume all available sugar. Any available sugar not converted is a loss of ethanol production and also introduces problems later in the facility, where sugar in the unfermentable stream may burn in the evaporator units. The carbon dioxide produced from the facility may be released to the environment or be captured, treated and sold when economically applicable. When captured, it presents a great opportunity to mitigate GHG emissions produced in the process.

Following fermentation, the beer mash is only about 10% ethanol, the distillation step separates out the ethanol from the water and non-fermented material, known as the whole stillage. The beerwell feeds into the distillation column and the alcohol content here determines the amount of energy that will be required to distill the ethanol. The distillation is typically done in multiple steps; the beer column captures nearly all the ethanol and an almost equal amount of water (Kwiatkowski et al., 2006). A rectifying column then concentrates the ethanol to 92.5% (Humbird, 2011). The distillation process is energy intensive but allows most of the removed water to be recycled within the process. The process must remove the remaining water so that the ethanol can be used as fuel, molecular sieves are used to dehydrate the ethanol. The sieves are composed of microporous beads that selectively separate the ethanol based on molecular size and the resultant ethanol is over 99% pure (Kwiatkowski et al, 2006). The anhydrous ethanol is typically denaturalized with 1.5% gasoline at this point to avoid it being used for consumption (Pieragostini et al, 2014).

The unfermentable material left over, called whole stillage or spent mash, also needs to be processed. The whole stillage contains the unfermented solids from distillation mixed with water. The whole stillage (15% solids) is put in a centrifuge to remove the liquid and produces a solid portion called wet distiller's grain (37% solids), and a liquid portion called thin stillage (9% solids). The liquid portion requires further processing, but a portion gets recycled as feed for liquefaction (Kwiatkowski et al, 2006) and the solids portion is eventually used for feed. The recycling decreases the costly processing of the thin stillage, provides critical nutrients for the yeast during fermentation and also reduces the amount of fresh water required for the process (Kwiatkowski et al., 2006). The rest of the thin stillage proceeds to an evaporator to increase its solid content to about 35% (Kwiatkowski et al., 2006). This processed thin stillage is referred to as corn condensed distillers solubles (CDS) and is high in fat content. The water content from the thin stillage is evaporated and may be reused within the process after treatment or sent to wastewater treatment.

The wet distiller's grain (WDG) is further dried with a rotary dryer to produce distiller's dried grains (DDG). The CDS is then added to the DDG and either marketed directly as wet distillers' grains with solubles (WDGS) or sent to the rotary dryer to lower the moisture content to produce DDGS, with the latter being the more accepted route. The rotary dryer reduces the moisture content from 63.7% to 9.9% (Kwiatkowski et al., 2006). The DDGS can be marketed and sold as animal feed. The drying process involves a significant amount of energy for drying and evaporation but the final product has a much longer shelf life and thus it can be sent to further markets.

As mentioned, some dry-grind corn ethanol plants now incorporate corn oil extraction in their production of ethanol. Corn oil removal occurs during the evaporation of the stillage, the thin stillage is removed mid-stream and subjected to a horizontal centrifuge, which is used to separate the solids, water and oil. Although this step requires additional infrastructure, it helps improve the economics of the process because it creates an additional co-product available for sale. It also reduces the environmental impact, as the impacts are spread over more products. The removal of corn oil does affect the composition of the animal feed product, DDGS, as it reduces the fat content of the feed, however, there is no separate distinction for this oil-removed DDGS as it is still marketed the same as traditional DDGS (Wang, Dunn, & Wang, 2014).

2.2 IGPC Process

The process used at IGPC Ethanol Inc. is based on dry milling with corn oil extraction described above, but a few adaptations have been made to increase revenue and decrease costs. IGPC has integrated fiber separation technology (FST) that separates fiber from the corn prior to fermentation; this increases the efficiency of the fermentation process. This technology removes the nonfermentable portion of the corn prior to fermentation, allowing for higher starch loading for the fermentation tanks. This leads to increase in both the ethanol production (by up to 10%) and the oil recovery (by up to 15%) (ICM, 2017).

The fermentation process occurs in 16 tanks and converts the available sugars into a dilute ethanol product. The reaction also creates a large quantity (34.5 tonnes per hour) of carbon dioxide. IGPC Ethanol coupled with a process gas company to capture and utilize this stream as a product, the CO_2 is purified, compressed, liquified and shipped out to a variety of customers.

The other co-products produced at IGPC also differ from the conventional dry mill facility, the process is shown in *Figure* 2-2. Co-products are implemented to improve economics and can also reduce waste from the process. Hi-Pro is dried distillers grain from fiber extracted corn which does not contain any fiber or syrup. By removing these portions, the Hi-Pro maintains higher protein content (43%) compared to traditional DDGS (28%) (IGPC, primary data, 2019). Studies have shown that the FST's Hi-Pro with syrup feed has shown the greatest average daily weight gain for cattle (ICM, 2017). This is beneficial to farmers that utilize this feed, and according to IGPC revenue, it receives a higher market price than traditional DDGS.

The extracted fiber is also incorporated in a feed product at IGPC Ethanol. A portion of the syrup is added to the fiber that was previously removed and it is marketed as fiber with syrup (FWS). FWS provides new opportunity for a high fat yield cattle feed, FWS resulted in a 9% improvement for calf-fed steers and a 5% improvement for yearling steers compared to the (corn-fed) control (Garland et al., 2018). DDGS and FWS have a higher market value than CDS alone, making it beneficial to apply the CDS to co-products rather than to sell it separately (S. Holt, personal communication, May 1, 2019). Additionally, the nutrient digestibility for Hi-Pro or FWS is similar to traditional dry or wet DDGS while the overall performance of the feed increased (Garland, et al. 2018). An important implication is the economic and nutritional value of Hi-Pro and fiber with syrup in comparison to DDGS, as few papers discuss co-products from the corn-ethanol process other than DDGS. These co-product pathways provide new value for the facility, and because the oil and fiber that is extracted is non-fermentable, efficiency of the overall ethanol process is improved over the traditional dry-grind facility (N. Singh & Cheryan, 1998). Equally important, the production of Hi-Pro and fiber plus syrup allows IGPC to diversify their feed markets and provide these by-products to a range of consumers.

IGPC also utilizes a methanator on-site for water treatment. The methanator is an anaerobic digester that treats condensate containing volatile organic carbon, which is generated in the process of evaporation of thin stillage so that this process water can be recycled and reused in the process. The organic materials present in condensate are converted to methane that is utilized in the drum dryers for DDGS production. Collectively, this process results in methane production, utilized internally as a source of energy, as well as improving the process water quality to be recycled into the front-end of the plant and reducing the amount of wastewater produced.

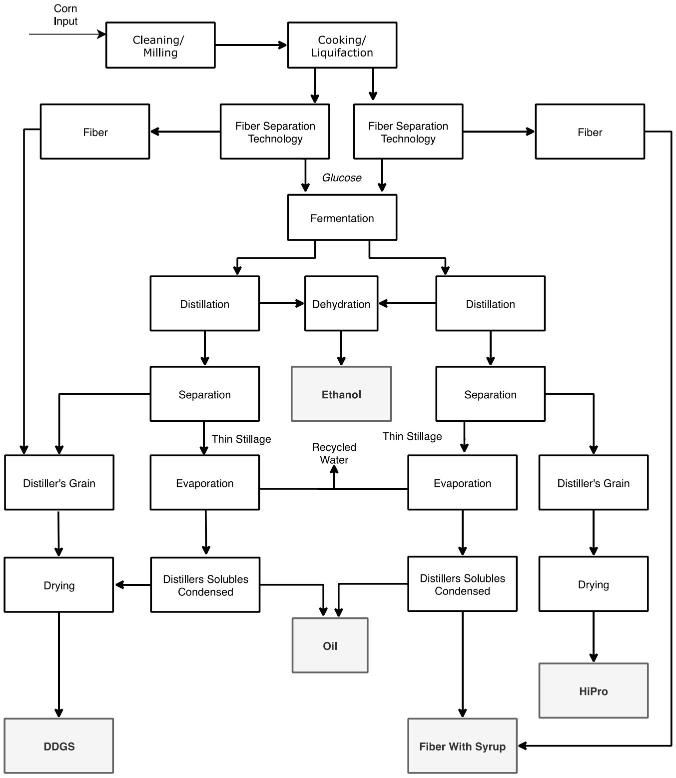


Figure 2-2: The IGPC dry mill process

2.3 Novel Biorefinery Process

The focus of the proposed novel biorefinery is on the co-product processing because currently the processing of thin stillage is non-profitable and it should only be regarded as a disposal method (Hill et al., 2006). The conventional corn ethanol plant uses a significant amount of energy for treatment of thin stillage and processing of co-products. The high chemical oxygen demand (COD) of thin stillage prevents it from being able to be discharged directly to the environment. Some alternatives have been introduced as a means to decrease the energy use and increase revenues of corn ethanol plants. Some of these technologies include the extraction of high value chemicals from thin stillage including glycerol, phytic acid and beta-carotene (Reis et al., 2017). This sought to increase the costs for processing ethanol and instead focus on co-products with a higher commodity price. Other studies introduced the processing of thin stillage through anaerobic digesters (Alkan-Ozkaynak & Karthikeyan, 2011; Liska et al., 2009; K. Wang et al., 2013).

Normally, with the evaporation of thin stillage into syrup, nutrients and chemicals in the stillage can be concentrated to up to three times their initial concentration, which can cause issues in the animal feed (K. Liu, 2011). Anaerobic digestion will avoid this concentration step and can treat the organic matter within the stillage. In a typical ethanol plant, up to 20 L of thin stillage can be generated per liter of ethanol (Rosentrater, 2006) and studies indicate that its balanced composition of COD, BOD, volatile solids and carbohydrates make it a strong candidate for AD substrate (Eskicioglu & Ghorbani, 2011; Nasr et al., 2012). Usually, due to the solids build up and toxicity to yeast caused by lactic acid, acetic acid, glycerol, and sodium, only 50% or less of thin stillage is recycled as backset for fermentation (Andalib et al., 2012). This limits the ability to facilitate water reuse and nutrient recycling in the conventional plant. The anaerobic digestion of treated thin stillage can be expected to improve the water and energy efficiencies of dry grind corn ethanol plants. The analysis showed that the digestate would be of suitable quality for process water and the incorporation of AD improved energy efficiency by eliminating evaporator and producing biogas that can be used for drying (Alkan-Ozkaynak & Karthikeyan, 2011). The volatile solids reduction of thin stillage lends to improved water recycling, and natural gas displacement of between 43-57% for a dry grind facility (Reis et al., 2017).

However, it was also found that the recyclability of AD-treated thin stillage into fermentation streams presents inhibitory effects for the fermentation performance of *Saccharomyces cerevisiae* (Reis et al., 2017). This means the AD-treated thin stillage was not able to be directly employed as a water and nutrient source for the front-end of the process. This limits the applicability for recycling the process water and necessitated the need for additional treatment within the novel biorefinery.

Struvite precipitation is employed to overcome the inhibitory effects of the digestate on the fermentation process, this also improves the nutrient removal. This treatment of the thin stillage will improve its nutrient characteristics, by removing nitrogen and phosphorus, so that it is a suitable medium for algae cultivation. It also creates an additional fertilizer product which enhances nutrient recovery within the process. Aerobic treatment was also incorporated for the recycling of digestate for algal cultivation due to the ammonium concentrations present in the digestate. Other studies have investigated the reuse of digestate for ethanol processing but high dilution rates were required for its implementation (Alkan-Ozkaynak & Karthikeyan, 2011; Praveen, Guo, Kang, Lefebvre, & Loh, 2018). Dilution creates issues within the lifecycle assessment and practical issues due to the high water-use required to facilitate this on a full-scale application.

The novel process is introduced in Figure 2-3, overall the objective is to decrease the environmental impacts of the corn ethanol process by recycling the thin stillage within the process, reducing energy use, and displacing some corn use through algae cultivation. Research by Lee et al., (2011) shows that the net energy use for a corn ethanol plant can be greatly reduced for a plant incorporated with an anaerobic digester. This comes from a combined energy savings from co-product treatment and increased energy production that leads to 57.1% energy recovery with anaerobic digestion (AD) incorporation (Lee et al., 2011). The novel process also has the added benefit of producing additional co-products, methane and struvite.

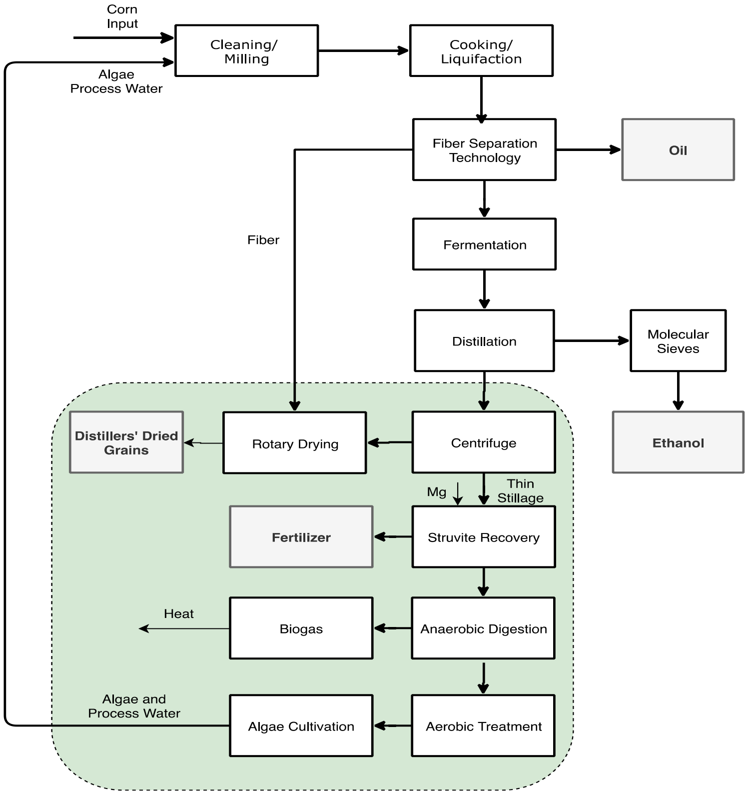


Figure 2-3: Novel process with anaerobic digestion, the highlighted region indicates the changes for the novel biorefinery

For the treatment of digestate, it is important to consider it from a perspective of nutrient recovery as well as wastewater treatment. The process should be optimized in order to recover biogas, struvite, as well as to cultivate algae, but also needs to be considerate of recycling the water used within the process; where nutrients and organic matter from the effluent need to be removed. The introduction of new material inputs to the process should be minimized in order to maximize the economics of the process.

The success of the novel biorefinery depends on the efficiency of the cultivation and utilization of the algae as a starch source for ethanol. Algal production for biofuel has many environmental challenges including large fertilizer and nutrient requirements, significant harvesting costs, and high energy use for production and delivery of CO_2 to the biomass (Brentner, Eckelman, & Zimmerman, 2011). Strategies proposed to mitigate the sustainability challenges of algal biofuel include utilization of nutrient rich digestate, avoiding harvesting and employing waste CO_2 produced on-site. The significant energy use for dewatering the algae for harvesting is mitigated in this biorefinery arrangement by recycling both the process water and the algae biomass to the front-end of the process. The intensive nutrient requirement for the algae growth is mitigated by the phosphorus and nitrogen available in the treated digestate. Typically, a portion of the thin stillage (~30%) is recycled to the liquefaction stage to provide nutrients for yeast propagation. However, in the proposed novel biorefinery, the entire thin stillage fraction will be sent to the AD, as it is anticipated that the recycling of the process water following algae cultivation will be able to supply the nutrients for yeast growth. Similar studies have also suggested that this recycling of the digestate will replace both process water and the artificial nitrogen source (ammonia, urea) that is required for the yeast fermentation (Alkan-Ozkaynak & Karthikeyan, 2011).

The choice of reactor type for algae cultivation has a significant impact on the environmental impact of the novel biorefinery. Photobioreactors have more capacity, higher productivity rates and are advantageous for small areas (Chu, 2017). Open pond raceways (OPR) suffer from contamination issues and lower productivity but ultimately are a much simpler design and require lower energy and capital costs (Borowitzka & Vonshak, 2017), for this reason OPR was the reactor chosen. This means a larger area will be required for the cultivation but should decrease capital and operational costs. While OPR may not allow for year-round cultivation at the current site due to the climate, it can give projections for more temperate climates.

2.3.1 Struvite Recovery

The microbial population in the AD cannot metabolize nitrogen and phosphorus, both present in the thin stillage, therefore the effluent will need further treatment before being discharged (Fang, 2010). Anaerobic digestion will affect the concentration and composition of many constituents in thin stillage. Certain constituents (phosphorus) will not be removed at high levels resulting in their potential accumulation upon recycling of the digestate. An increase in the phosphorus content may not be toxic or inhibitory to the yeast, however it may contribute to increased P levels in the co-products. Feeding P-rich co-products to animals results in increased P concentration in the manure, which could then be transported to water bodies upon land application in agricultural fields. This also highlights the importance of incorporating eutrophication as an LCA impact category for this study.

Struvite ($MgCl_2.6H_2O$) was found to naturally precipitate within the anaerobic digester, this is also common in wastewater treatment systems. Analysis of the digestate found that magnesium was the limiting reagent for the precipitation, introduction of an external source of magnesium led to further nitrogen and phosphorus removal of 44% and 81% from the treated digestate, respectively. This indicates the potential of the digestate for nutrient recycling (Sayedin et al., 2019). The removal of struvite is key to reduce the phosphorus and nitrogen ratio to suitable levels for algal growth. The algal growth subsequently decreases the corn input necessary for ethanol production and also the improves the water quality for recycling of the thin stillage within the plant. Analysis by Sayedin et al. (2018), promoted struvite recovery post anaerobic digestion, however this allowed the struvite to precipitate and accumulate within the digester which can cause equipment blockages, for this reason the struvite recovery was promoted to prior to AD. This also allows for a higher recovery rate for the struvite.

2.3.2 Anaerobic Digester

The anaerobic digestion of thin stillage from the corn ethanol facility will allow for the production of methane and also lower the chemical oxygen demand (COD) of the thin stillage. This process requires the identification of the most suitable anaerobic digester (AD) for the process, as well as optimization to obtain the maximum COD removal efficiency, highest biogas (and methane) production, as well as being able to process the high rate of production of thin stillage from the ethanol plant.

Literature presents a few different options for incorporating an anaerobic digester into the bioethanol production, including through AD of whole stillage, thin stillage or just condensate (Drosg et al., 2013; Wang et al., 2013; Wilkie, Riedesel, & Owens, 2000). The AD of thin stillage focuses on the liquid portion of the separated whole stillage, while whole stillage includes both the liquid and solids portions and nets no dry grain product for animal feed. The digestion of thin stillage was suggested to the application of the dry stillage as an animal feed by-product, and the fact that the thin stillage (at only 6% solids) requires a large volume of liquid to be evaporated. Additionally, when the thin stillage is instead directed to an AD, the flow to the DDGS dryer decreases by over 30%. This provides an opportunity for increased capacity of ethanol production.

The configuration of the digester influences the ability of the digestate to be recycled within the process as well as the biogas production rate. This process requires the identification of the most suitable anaerobic digester (AD) for the process. The choice of AD was determined by Sayedin et al. (2018) but was based on organic loading rate, methane production, extent of removal efficiency and energy efficiency. The prospective use at a full-scale corn-ethanol plant also requires high plant availability and the avoidance of AD technologies prone to membrane fouling and high maintenance costs.

For the comparison between thermophilic (Schaefer & Sung, 2008) and mesophilic (Lee et al., 2011) anaerobic digestion of thin stillage in CSTRs indicates that there is not a considerable difference between their performance in the term of COD removal and methane yield. However, thermophilic digestion requires considerably higher temperatures in order to achieve sufficient digestion. Given that the temperature of the thin stillage entering the AD will be in the range of 80°C, no external heat source would be required for mesophilic digestion and the process can maintain high COD removal rates.

Many different ADs have had great success in COD removal from thin stillage (as high as 99%), however membrane fouling and operating costs are the main barriers for their application in wastewater treatment (Lin et al., 2013). Anaerobic baffled reactors (ABR) have the advantage of being a simple design with limited electricity requirements; only a small amount of electricity is required to run a pump to flow the effluent. A novel ABR was chosen because sludge washout is a significant drawback of conventional ABRs, which can lead to lower biomass concentration and lower stability, COD removal and biogas production (Barber &

Stuckey, 1999). The ABR has baffles that create compartments for the bacterial accumulation and allows gas to vent through the top for collection. The baffles allow the solids retention time (SRT) to be separated from the hydraulic retention time (HRT) (Metcalf & Eddy, 2014). This means the solids can settle within the compartments while the baffles allow the solution to continue to flow and create a longer residence time within the reactor (Connolly et al, 2015). By uncoupling the two retention times the ABR has the potential to handle higher loading rates (Wilkenson, 2011). This longer residence time increases the time available for the microbes to break down the organic material in the thin stillage.

Alkan-Ozkaynak & Karthikeyan (2011) observed that at a COD removal of 80.6% the digester supernatant was found to contain both organic and inorganic constituents at levels that would cause no inhibition to ethanol fermentation. Sayedin, Kermanshahi-pour & He (2019) did considerable work on the anaerobic digestion of thin stillage and the optimization of a novel ABR. An ABR was the reactor of choice because the two-phase reactor provides more robustness and enhanced bacterial activity, and it provides a gradient of pH and volatile fatty acids that allows for separation of the bacteria for acidogenesis and methanogenesis down the reactor (Sayedin, Kermanshahi-pour, & He, 2019). The acidogenesis and methanogenesis require different conditions for optimal activity. The first compartment of the ABR is usually dominated by acidogens with the optimal pH of 5-6.5, while the microbial population of methanogens increases in the later compartments where the pH ranges from 6.6 to 7.5 (Zhu et al., 2015). This separation helps the reactor to better handle system shocks (Metcalf & Eddy, 2003), which can be difficult with a variable influent such as thin stillage.

The characteristics of the thin stillage also need to be investigated to determine the extent of treatment. The values obtained for thin stillage from IGPC Ethanol are presented below from Sayedin et al. (2019). These values were used for an ABR with a working volume of 27.5 L. An important parameter for the efficiency of the AD is the recycle ratio of the effluent. In Sayedin et al. (2019), the recycle ratio (RR) was varied between 10 and 20, therefore 10-20 times the flow rate into the AD was recycled back through the AD after exit. When the RR was decreased from 20 to 10, the COD removal efficiency increased slightly from 91.2 to 93.5%. This trend was observed in other studies and the reason lies in the fact that when the RR increases, the reactor approaches a completely mixed system which leads to a lower concentration gradient for COD removal (Barber & Stuckey, 1999).

Table 2-1:Thin stillage and AD characteristics from Sayedin et al. (2019)

Parameter	**Value**
COD (filtered thin stillage)	69.8 g/L
COD Removal Rate	92.5%
Organic Loading Rate	5.8 kg COD/m^3d
Methane Production	0.31 L CH_4/g COD removed
Recycle Ratio (RR)	10

A chemical oxygen demand removal, sulfate removal and methane yield of 92.5-78.9%, 97-93% and 305-275ml CH_4/ g $COD_{removed}$, respectively was able to be achieved at an OLR of 3.5-6 kg COD/ m^3d, HLR of 20-11.7 d and recycle ratio of 15 (Sayedin et al., 2018). The conditions for industrial treatment were chosen to maximize methane production and to increase the flow into the reactor and thus the required reactor size. Table *2-2* presents the results for the anaerobic digestion of treated thin stillage. It was identified that further processing in the form of magnesium addition and struvite recovery is necessary in order to decrease the concentrations of nitrogen and phosphorus to a suitable ratio for algal growth. Post AD treatment in the form of settling tanks will also be required prior to algal cultivation in order to increase the light permeability of the effect to optimize algal growth.

Table 2-2:Results for the characterization of thin stillage from Sayedin et al., 2019

Parameter	Initial (filtered)	After Anaerobic Digestion
Chemical Oxygen Demand	69.8 g/L	5.24 g/L
Nitrogen	1220 g/L[1]	478 mg/ L
Total Phosphorus	1191 mg/ L[1]	508 mg/L
Magnesium	629 mg/L[1]	113 mg/

[1] These results are from Sayedin et al., 2018

2.3.3 Aerobic Treatment

In order to close the loop on process water recycling within the plant, the cultivation of algae on thin stillage digestate was considered, which allows for the production of third generation bio-ethanol. The nutrient-rich digestate from the corn-ethanol process has been considered as a suitable growth media for microalgae in many studies, to produce biomass while treating the wastewater stream (Franchino, Tigini, Varese, Mussat Sartor, & Bona, 2016;

Praveen et al., 2018). This creates a starch-rich product which can be converted to ethanol through a process similar to the corn-ethanol process. However, the inhibitory effects of some components in the digestate has to be addressed before this process can be incorporated. High ammonia concentrations (about 2.3 μM) present in anaerobic digester effluents is often responsible for microalgal growth inhibition (Cho et al., 2013). This was thought to be related to the combination of high ammonia level and basic pH (above 8) of the digestate, shifting the chemical equilibrium from NH_4^+ to NH_3, which is toxic to most microalgae (Ayre, Moheimani, & Borowitzka, 2017).

Some studies have investigated the recycling of digestate and found differing results. Alkan-Ozkaynak & Karthikeyan (2011) applied anaerobic digestion of thin stillage for energy recovery and water reuse in corn ethanol plants and observed that the digester supernatant was found to contain organic and inorganic constituents at levels that would cause no inhibition to ethanol fermentation when recycled in the system.

However, Sayedin et al. (2019) showed that none of the microalgae species investigated were able to grow in anaerobic digestate (478±11 mg/L $N\text{-}NH_3$) or struvite removed digestate 267±13 mg/L $N\text{-}NH_3$) without dilution. In order to reduce the inhibitory effect of digestate and make it more suitable for the microalgae, various pretreatments have been applied to digestate. The preferred strategy is to dilute the digestate with water or seawater (Xia & Murphy, 2016). This approach has been successful in mitigating NH_4^+-N inhibition, lowering the turbidity, and enhancing the phosphorus to nitrogen (P/N) ratio.

Following pretreatment consisting of struvite recovery and two times dilution with water the algae strain, *C. sorokiniana,* was able to be successfully cultivated on thin stillage digestate (Sayedin et al., 2018). However, this would require large amounts of freshwater to be added to the corn ethanol process. This can pose challenges on scale-up, and also causes an increase in the environmental impact for water use and wastewater treatment in the LCA. Alternative methods need to be established in order to provide an ecologically efficient way to incorporate algae growth.

An alternative to achieve lower ammonia concentrations without dilution is the introduction of an aerobic treatment stage. Aerobic treatment reduces water use but does have higher energy requirements for aeration and increases the sludge production in the process. Praveen et al. (2018) investigated this through the protection of microalgae from NH_4^+-N toxicity, which can be achieved by changing the oxidation state of nitrogen to a more amenable form, such as nitrate (Svehla et al., 2017). The nitrification process can not only reduce ammonia toxicity, it may also reduce the concentrations of organic compounds and improve N/P ratio for microalgal cultivation. Praveen et al. (2018) was able to show that a process based on synthetic food digestate nitrification followed by microalgae cultivation can be suitable for nutrient recovery for digestate with ammonia concentrations varying from 20 to 120 mg/L. A similar study utilizing food waste digestate was able to use an aerobic pretreatment approach using activated sludge which led to robust algal growth on full strength digestate (Q. Wang, Prasad, & Higgins, 2019).

A study on the effect on anaerobic-aerobic (An-Ae) treatment of thin stillage from the cassava-ethanol process was able to identify that anaerobic treatment followed by aerobic treatment of the thin stillage was able to be recycled within the process and to produce ethanol at the same rate as when fresh water was used (Yang, Wang, Wang, Zhang, & Mao, 2017). This shows that An-Ae treatment can successfully treat thin stillage to below inhibition of *S. cerevisiae* but the treatment required aerobic digestion and then further treatment by chloride anion exchange resin. The additional steps portrayed in this study may limit its applicability to a full-scale facility. The novel biorefinery presented in this study will attempt to cultivate algae on treated digestate without the requirement of anion exchange.

2.3.4 Distillers' Dried Grains from Novel Biorefinery

An important consideration for the novel biorefinery is the impact on the animal feeds produced at IGPC and the novel biorefinery. When DDGS was introduced from the corn ethanol industry it was surmised that it would be rapidly adopted for animal feed applications, however, this has not been observed based on inconsistency of the product stream and other logistics-related risks, especially toxigenic contaminants (F. Liu et al., 2017). It was also surmised that the use of DDGS has been largely limited to ruminant diets because of its high fiber content and nutrient variability (Rausch and Belyea, 2006). In the novel biorefinery, syrup will no longer be added to DDGS and distiller's dried grains (without solubles) (DDG) will be produced. The removal of thin stillage from DDGS results in a lower fat content in the animal feed as well as a lower volume of feed to be produced, which will impact its economic value. The fat content of the syrup traditionally has a positive effect and contributes to weight gain in cattle or the ruminant animals. Gross energy of the animal feed can also be correlated to the oil content of the DDGS (Kerr, Dozier, & Shurson, 2013).Therefore, for the DDG produced in the novel biorefinery to be a positive economic impact, the value of the animal feed (DDG) plus the savings due to reduced natural gas consumption, must be higher than the reduced revenue due to the loss in feed quantity (Agler, Garcia, Lee, Schlicher, & Angenent, 2008).

Traditional wet and dry DDGS did provide increased energy intake for beef cattle when compared to a corn diet alone, however these diets resulted in decreased digestibility compared to traditional feeds (Garlund, 2018). Fortunately, the DDG produced in the novel process may be a higher value animal feed than DDGS due to an increase in protein concentration due to a relatively lower concentration of salts (K. Wang et al., 2013). Drosg et al. (2013) also identified a higher protein content for DDG due to the lower protein content in the thin stillage added to DDGS. The higher protein content would lead to an increased market price for DDG in comparison with DDGS (Belyea, et al., 2006; Y. Kim et al., 2008). However, the value of the feed depends on parameters other than just protein, including fat and salt content.

Mathews & McConnell (2012) also looked at the nutritional impacts of feeding cattle DDG in comparison to DDGS to determine the market values of the products and showed that the DDG increased nutritional content compared to DDGS. This would most likely translate to an increased market value for DDG. To avoid potential health issues, DDGS should be limited to 30% of intake on a dry-matter basis (Stewart, Segers, & Hammond, 2019). This means the DDGS currently produced must be supplemented by other feed, typically corn. High fat levels in distillers' grains and excess sulfur may be the limiting factor for inclusion rates above 40% (Stewart et al., 2019). The removal of thin stillage syrup may allow a higher diet inclusion for DDG, as the thin stillage syrup contains most of the fat and sulfur present in the DDGS. This may also increase the value of the DDG as an animal feed supplement, as more can be incorporated into cattle diets.

The novel biorefinery may also be able to help with toxins that limit the supply of corn to the facility. Primary data from IGPC (Sept 2019) identified that an ongoing issue for the plant is the presence of mycotoxin in the corn. Mycotoxin is a secondary metabolite from fungi in the corn that can be highly toxic to some species. This issue is exacerbated by the concentrating of the mycotoxins in the corn-ethanol process, as they can only exit via the distillers grains, resulting in concentrating mycotoxin to more than three times the original concentration in the

DDGS. Mycotoxins can cause digestive issues in animals fed with the infected DDGS product (primary data, IGPC Ethanol, Sept 2019). Due to this, IGPC has to test incoming corn to the facility for this toxin. This results in the plant providing a lower rate for the affected corn or outright turning away corn shipments if the toxin concentration is too high.

Mycotoxins are reported to be heat stable and therefore cannot be destroyed within the processing of DDGS. However, the mycotoxins that are present in the thin stillage can be anaerobically degraded, which is the case for deoxynivalenol (DON) (Binder et al., 1997). DON is a particularly relevant mycotoxin because this is the most prevalent mycotoxin in the area of the IGPC facility (primary data, IGPC, Sept 2019). By degrading DON, this could reduce issues surrounding mycotoxins in the corn, and allow the IGPC facility to accept corn that would previously have been rejected by the plant. Drosg et al., (2008) reiterates the advantage of AD in the ability to use grains contaminated with mycotoxins, as these toxins have no negative effect on ethanol production and their residues can be converted to biogas with an AD.

An additional concern with traditional DDGS is the high phosphorus content in the feed. Research has documented that phosphorus requirements for beef finishers cattle are met by diets containing 0.1% phosphorus. While diets consisting of DDGS and corn gluten feeds result in phosphorus concentrations of 0.4% or greater (Geisert, 2004), the animal is not able to retain any excess phosphorus, resulting in excess phosphorus being excreted in manure. This produces ecological effects such as eutrophication and subsequent oxygen depletion in bodies of water when the manure is applied as nourishment to crop fields. This was further investigated with the nitrogen and phosphorus balance in Chapter 6. For the novel biorefinery, the phosphorus will be retained within the thin stillage and appropriately treated with the precipitation of struvite and assimilation by microalgae, therefore avoiding the release into the environment.

In summary, the incorporation of thin stillage anaerobic digestion can reduce the energy required for the plant by over 30% through the elimination of the thin stillage evaporation (Wang et al., 2013) and decreased drying, as well as decrease natural gas use by utilizing produced biogas. The AD of thin stillage may also increase the value of the feed products by producing higher protein DDG opposed to DDGS and is expected to decrease the requirement of a supplemental nitrogen source for yeast fermentation. The AD may increase the economics of the plant by allowing it to process corn that contains concentrations of mycotoxins that may have previously been rejected by IGPC, which benefits both the plant as well as local farmers. Finally, AD may decrease eutrophication impacts from applied manure due to incorporating the excess phosphorus in thin stillage into the struvite product.

2.3.5 Front-End Corn Oil Extraction

The changes required for the novel biorefinery limit the ability to have back-end corn oil removal at the IGPC plant. In the conventional IGPC plant, corn oil is removed from the mid-stillage, usually in the sixth evaporator in the sequence. This is accomplished using a tricanter which uses centrifugal force to separate the solids, water and oil, before recombining the solids and water and returning to the evaporation (primary data, IGPC). In the novel biorefinery the thin stillage is no longer evaporated and added to the DDGS so the typical corn-oil extraction from the mid-stillage can no longer be applied.

Back-end corn oil extraction is a popular method of oil removal because it is a bolt-on technology that is able to be deployed to an existing facility without large infrastructure changes. Back-end corn oil extraction allows for recovery of 30% of the oil found in the corn (equivalent to about 0.7 lbs/Bu of corn) from the DDGS prior to drying (N. Singh & Cheryan, 1998). Some oil is deliberately left in the condensed distillers' solubles in order to maintain a higher fat content in the produced DDGS (U.S. Grains Council, 2012).

In the novel biorefinery the stillage is no longer added to the DDG. As the fat content is not expected to have an impact on the algal cultivation, a higher volume of the oil is able to be extracted without impacting downstream processes. This creates the opportunity for additional revenue from oil production.

Another process for corn oil extraction that is less commonly employed is front-end fractionation. This process uses a series of milling techniques to separate the kernel into 3 streams: germ, endosperm and bran; this is in lieu of the traditional whole kernel grinding (Lin, Rodríguez, Li, & Eckhoff, 2011). This would be beneficial to employ at IGPC because the facility already incorporates front end fractionation in the form of fiber removal technology. However, the capital costs for its implementation is usually higher than the bolt-on back-end extraction.

In front-end corn oil removal between 1.2 -1.4 lb oil is extracted from the germ stream per bushel of corn processed (Jessen, 2014). This would substantially increase the oil extraction available at the facility (currently 0.54 lb/Bu is extracted). Additionally, this oil can be sold as a food grade corn oil, because it is taken out prior to fermentation, or can be sold for biodiesel production (Reis et al., 2017). This would increase the revenue from the corn oil sales as the market options are expanded.

The high fiber bran would still be separated and used as a ruminant feed, similar to the current facility. The post-oil extraction germ can be used as germ meal (an animal feed ingredient). Despite a high capital cost, installing front end fractionation allows to diversify co-product production (Nelson, 2015). Ultimately, front end fractionation can allow plants to diversify co-products, save energy by sending fewer products through fermenter and dryer, and increase plant profitability.

Chapter 3 Literature Review

3.1 Introduction to Life-cycle Assessments

Lifecycle assessments are used to evaluate the impact of a process or product on the environment and human health. They are often used as a tool to help develop policies or inform industry. They are beneficial in their ability to not only address the direct impacts of a process but also the impacts established from the product inputs, its use and disposal. LCA’s require extensive data in order to obtain consequential results but they can be used to determine the overall impact of a product or process (Hauschild & Huijbregts, 2015). Generally, LCA’s consist of a goal and scope of the project, an inventory compilation, an impact assessment and an interpretation of the results. LCA’s are often utilized as a method to decide on a process or product route to reduce the environmental and human health impacts.

ISO 14044 covers the LCA framework and creates a standardized process for studies investigating the lifecycle impacts of a process or product (ISO, 2006). Comparing the results of different LCA or LCI studies is only possible if the assumptions and context of each study are equivalent. Therefore, this international standard contains several requirements and recommendations to ensure transparency on these issues. This allows for LCA’s to be compared to previous studies and to be used in comprehensive decision making.

The goal of the analysis identifies the purpose of the LCA and addresses the expectations of the study. The scope of the analysis determines what will be considered in the LCA study and includes the system boundaries and functional unit. The scope encompasses all parts of the process which are to be analyzed. The boundary for the analysis is important as it can impact how accurately the LCA portrays the process, but consequently it can also increase the complexity of the assessment (Hauschild & Huijbregts, 2015). A compromise is often necessary in order to present the LCA as completely as possible but without putting overdue burden on data that may have a limited impact on the outcome of the LCA. Generally, LCA’s can be either cradle-to-grave or cradle-to-gate. Cradle-to-grave LCA’s involves a comprehensive evaluation of all upstream and downstream inputs and environmental emissions of a process. A Cradle-to-gate analysis involves set boundaries in order to examine a particular portion of a process, this is a streamline technique to reduce the time and cost of an LCA. The functional unit is the frame of reference for the analysis, it is important for consistent results and for comparisons between studies.

Following this, the compilation of a lifecycle inventory is perhaps the most important aspect of the LCA. In order to produce an LCA for a product or process, an inventory must first be established. This includes all the energy, materials and emissions in the lifecycle of the product or process, including all relevant upstream products and emissions in order to get an accurate depiction of the process. The accuracy of this data defines the how the process is portrayed in the LCA (ISO, 2006). The method chosen depends on the goal of the LCA and the scope of the analysis.

The inventory elements can then be converted into as assessment of the environmental performance of the process using an impact assessment method. The impact assessment method translates the lifecycle inventory into environmental impact scores for each category and characterizes the impact of each input or emission on the overall environmental and human health (ISO, 2006). There are a number of options for impact methods which depends on what impacts are being investigated and the timeline represented by the study; near, mid or end-point.

The end-point analysis portrays the damage to human health, ecosystems and resource availability for a process. The endpoint method looks at environmental impact at the end of a cause-effect chain, for example the extinction of a species. This method has more uncertainties because it is used to look further down a chain of events but also presents more tangible impacts (Taherzadeh et al., 2019). The endpoint analysis looks at characterization indicators which can be easier to reflect on the relative importance of emissions, by looking at the end-impacts on the environment. The endpoint analysis has damage categories that are easy to understand and portray to results better to stakeholders with a lower level of environmental expertise (Yi, Kurisu, & Hanaki, 2014).

The midpoint method looks at the impact earlier along the cause-effect chain, before the endpoint is reached. This method focuses more on changes to the environment, without the long-term outlook; this presents the environmental consequences of a process without the uncertainty of the endpoint analysis. The midpoint method has a diverse selection of up to 18 indicators, which can pinpoint where the impact is suffered, such as in climate change or eutrophication (Taherzadeh et al., 2019). An example is the increased concentration of a chemical in the environment which may cause acidification effects, but the final effect on the environment in terms of damage to the environmental health is unknown. The mid-point method was chosen for this assessment because it gives more categories to express the impacts of the LCA and has less uncertainty in its results. The limitation with the midpoint method is that separated midpoints with different units cannot be integrated together for simplified reinterpretations (Yi et al., 2014) and the categories from midpoint analysis are more difficult to interpret especially for decision-making applications (Reap, Roman, Duncan, & Bras, 2008).

Next, the impact method must be chosen, once again each method portrays results in a slightly different manner and provides a different number of factors that are taken into account for the LCA. While each method will not be discussed in detail, ReCiPe was chosen for this analysis. This method combines two other impact assessment methods, CML and Eco-indicator 99 into an updated version. ReCiPe is used to transform the long list of life cycle inventory results into a limited number of indicator scores, these can be used to address the severity of the impacts and allow comparisons between processes. ReCiPe uses multi-media models for the determination of the fate factors, and provides characterization factors for specific emission compartments at different scales (Pizzol, Christensen, Schmidt, & Thomsen, 2011). ReCiPe was chosen as the impact assessment method due to its extensive impact categories and midpoint analysis (Pieragostini et al., 2014).

Within ReCiPe, the method can be broken into three categories based on the different perspectives for the method. The uncertainties in the models are based on ambiguities in the way the environmental mechanisms work and on the timelines for the analysis. The hierarchical method is the most common policy in regard to time-frame and presents a mid-range 100-year perspective for impact categories such as climate change, eutrophication and acidification (Pizzol et al., 2011). The hierarchy method includes facts that are backed up by scientific and political bodies with sufficient recognition (Pieragostini et al., 2014). The hierarchical view is the most common in the scientific community and is based on a moderate timescale for the study and its impacts.

Once the emissions for each process are tabulated in the inventory, they can be separated into their impacts. As mentioned, a total of 18 midpoint impact categories are available in ReCiPe, however not all are applicable in every LCA. They consist of a variety of impacts to water, ecosystems, and human health such as global warming potential, eutrophication and acidification impacts.

Finally, an analysis of the impacts is done to evaluate opportunities to reduce energy, inputs or environmental impacts at each stage of the product life-cycle. Often, the analysis is done as a comparison between two product systems, this helps identifies areas within each stage that can be improved. The analysis can also be used to evaluate the impacts of new technologies and stages of processing that have the largest impacts on the environment.

3.2 Co-product Credit System

In a multi-output lifecycle assessment, it is important to determine a method to account for the other products in the system. A co-product credit system defines the way the various products are accounted for in the LCA. Some value comes from the outputs that are produced in the process besides the main product, in this case the main product is ethanol. This is an evolving process for LCAs, as authors adjust to the changing methods for co-product crediting.

The choice of crediting system is important to determine how the impacts from the system are distributed to the different outputs formed in the process. For example, Wang et al., (2012) looked at the LCA GHG emissions for the co-product corn oil, to determine how sensitive the system is to the choice of co-product treatment method. In this particular case, the division of impacts is particularly important because it is used to determine, whether corn oil receives at least a 50% reduction in GHG emissions compared to conventional diesel, which allows it to receive renewable identification numbers (M. Wang et al., 2012). This would allow the corn oil to be eligible for subsidies as considered a renewable fuel and these subsidies help to reduce the cost of production. This can impact policies which aim to decrease GHG emissions because it provides differing impact results depending on which method is chosen. ISO 14001 (2006) defines that impact allocation should be done so that the product system is expanded to include the additional functions related to the co-products,

The two main methods for accounting for these co-products are through allocation and system expansion. Allocation accounts for the by-products by distributing the environmental impacts of the entire process over all the products produced in the system, this is done through the physical mass, the economic value or the energy value of each product in the system (Hauschild & Huijbregts, 2015). This method will allow a smaller burden of the environmental impacts to appear for ethanol, as DDGS, corn oil and carbon dioxide will also share in the environmental burden of the process. Issues arise with the allocation method when trying to determine a common unit, such as mass or energy, for each product.

Another measure for accounting for co-products is through system expansion. As the name suggests, in system expansion the boundary of the LCA is expanded, which allows it to include the processes for producing the co-products in the system. For this method, the entire burden of the environmental impact is contributed to the main product, ethanol, but the impacts from the alternate processes to create the co-products displace some of the impacts on the main product. For example, in the case of the co-product corn oil, the oil can be used in feeds or biofuels, and it displaces another product known as soy oil; any corn oil produced reduces the requirement for soy oil production. Therefore, all the environmental impacts from producing the soy oil that is displaced, are avoided environmental impacts and can be subtracted from the total environmental impacts of producing the corn ethanol. This is also the case for the DDGS and carbon dioxide produced in the process, which displace corn feed and liquid carbon dioxide production, respectively. To complete this method, the ratio at which the displacement occurs must be taken into consideration, for example, DDGS is more efficient at supplying nutrients than corn feed, and therefore 1 kg of DDGS can displace 1.1 kg corn as animal feed (GREET, 2018).

3.3 Conventional Corn Ethanol LCA Studies

Ethanol is regularly added to gasoline as an oxygenate to reduce GHG emissions for the combustion of fuel. This relies on the assumption that the addition of ethanol to fuel creates a product which has a smaller impact on the environment than gasoline alone. The growth of the corn-ethanol industry has led to a great deal of research in improving the environmental, economic and energy profiles of the process. Most studies have concluded that ethanol derived from corn grain can displace gasoline used in the transportation sector and reduce GHG emissions (Kim & Dale, 2008). In order to achieve this consensus, a variety of studies on the environmental impact of the corn-ethanol process have been completed.

The studies presented in literature vary by the location, scope, functional unit and choice of energy and by-products for the system. These changes can produce LCA findings that present some differences in results, especially when new technologies and energy saving innovations are introduced. Ethanol yield, energy efficiency and agricultural productivity within the sector have also gradually improved, which impacts the environmental analyses. Based on historic, surveyed trends, thermal energy consumption in 2015 corn ethanol plants are currently estimated to be (on average) 42% less than energy needs of 2001 plants (Mueller, 2015). These changes make early life cycle modelling studies outdated and their results are not indicative of the current state.

Most corn-ethanol processing uses the dry milling process, where corn is ground and processed into ethanol, DDGS and often corn oil and carbon dioxide. The GREET model is often employed to compute the energy requirements and GHG emissions for the production of ethanol. Most LCA analyses consider a variety of subsections; (i) the production of inputs used in growing corn, including seed, fertilizer (e.g., nitrogen, phosphorous, potassium), herbicide, pesticide, and energy; (ii) the application and utilization of inputs and the harvest of corn grain; (iii) the transportation of corn to biorefineries; and (iv) the conversion of corn to ethanol at biorefineries and the eventual burning of ethanol as transportation fuel (Farrell et al., 2006). The emissions and energy use within these sectors contribute to the overall life cycle assessment of the process.

There are some limitations to the use of lifecycle assessments in the determination of the impact of a process or product; specifically with regard to the LCA's impact assessment and interpretation of results (Reap et al., 2008). These difficulties arise from the lack of standardization of impact categories. There are also discrepancies between LCA methods, and the process now favours ReCiPe as opposed to other methods such as Eco-invent 99, while often both impact assessment methods are employed.

The interpretation of LCA results through impact categories requires the quantification and comparison of the value of different environmental impacts even when their units and scales differ (Reap et al., 2008). This makes interpreting results through several impact categories difficult. To address this, numerous weighting methods have been proposed and applied, through normalization factors. Normalization factors allows for researchers to compare the LCA results between different impact categories. However, accuracy can suffer when taking individual impact categories and aggregating them into a single composite score. Therefore, it may be preferential to maintain separate impact categories and complete comparisons individually.

Kim and Dale (2008) investigated the environmental and economic performance of corn-based ethanol as fuel in various counties in the U.S. This included the combustion in passenger vehicles and the impacts of nitrogen losses from soil. The greenhouse gases analyzed include carbon dioxide, methane, and nitrous oxide (Kim and Dale, 2008) and the assessment was based on 1kg of ethanol used in an E10 (fuel with 10% bio-ethanol) vehicle. Predictably, the co-product DDGS helped to reduce the environmental impacts of the overall process due to the avoided use of animal feed. However, without the avoided impacts, the refinery system (transformation of corn into ethanol) would release more GHG emissions than the corn cultivation system.

Kim and Dale (2008) found that E10 fuel was able to reduce GHG emissions in comparison to conventional fuel, but increased local impacts like acidification, eutrophication and photochemical smog. These local impacts are found to be a result of the emissions from soil due to fertilizer use required for corn-ethanol. This highlights the importance of comparisons among different impact categories and also which environmental impact categories should be reflected in the LCA.

For Pieragostini et al. (2014), a cradle to gate LCA for corn-based ethanol production in Argentina was completed. The scope of the analysis included raw material production up to anhydrous ethanol production from dry milling. The functional unit for this process was 1 MJ of anhydrous ethanol and the refinery for this study is modeled based on production of 74,300 tons per year of ethanol. A focus in the study was put on defining two subsystems: the agricultural subsystem and the refinery subsystem. This allowed the authors to compare and determine the extent of the environmental impact of each system. The study incorporated both Eco-indicator 99 and ReCiPe as the life cycle impact assessment methods, which allows for the comparison of environmental impact results. EcoInvent database was used as an inventory, along with the corn production data in Argentina from 2002 to 2010. The GREET model was used to compute energy requirements and GHG emissions for the upstream processes (Pieragostini et al, 2014). The results were characterized into environmental impact categories based on the two LCA methods; Eco-indicator 99 and ReCiPe and were also divided according to the subsystems of the process. While the results for this study are based in Argentina, the authors found that the use of fertilizer and the drying of co-products were the most significant impacts; this highlights two areas of the corn-ethanol process that could use improvement. These emissions are also contingent on the fuel source within the plant; coal or natural gas. Due to the LCA results being end-point oriented, the results can be normalized and compared. Corn production was found to have the highest environmental impact, mainly due to the resource intensive fertilizers required, with more than 50% of impact in 7 of the 11 impact categories explored in the agricultural subsystem.

Muñoz et al. (2014) proposed an LCA on bio-based ethanol from different agricultural feedstocks in order to assess the main drivers for environmental impacts in the production of bio-based ethanol and its performance in comparison with fossil fuels. This analysis had many different aspects to it compared to a traditional corn-ethanol LCA. The authors proposed a cradle to grave analysis, but assumed the ethanol was used as a feedstock for the chemical industry as opposed to a fuel source for combustion; this changes the end-of-life emissions. ReCiPe was chosen as the impact assessment method with the following indicators: terrestrial acidification potential, marine eutrophication, photochemical oxidant formation potential, agricultural land occupation and global warming potential.

Co-products were credited using economic allocation, which was chosen due to its use in EcoInvent 2.2. The comparison was completed between sugar-cane, corn and lignocellulosic ethanol and with fossil fuel-based ethanol, with all bio-based fuels achieving lower environmental impacts than gasoline based impacts. Sugar-cane ethanol ultimately had the lowest GHG emissions, likely due to its high yield, with maize and stover based ethanol performing poorer due to their high fertilizer requirements (Muñoz et al., 2014). However, similar to Kim and Dale (2008), the local impacts, such as eutrophication, acidification and land use, are higher for all bio-based ethanol's. While the results vary in terms of emission categories, all bio-based ethanol involve lower cradle-to-grave emissions for their production routes than the fossil-based ethanol.

There are also a variety of studies focusing on the GHG emissions of the corn ethanol process (Feng, Rubin, & Babcock, 2010; Liska et al., 2009; M. Wang et al., 2012). Wang et al. (2012) investigated the well-to-wheels energy use and GHG emissions of various bio-ethanol sources. The results were given for the fossil fuel consumption and general GHG emissions of the process and were modelled from gate (corn production) to wheels (combustion) for 1 MJ of fuel. This functional unit allows for the comparison between fuels with different heating and caloric values. The results indicate that corn-ethanol had the highest fossil energy use due to the intensive use of fertilizer and high energy use in processing the ethanol. However, all bioethanol fuels produced lower GHG emissions than the fossil-based fuels, based on combustion emissions being the most significant GHG source for all fuel pathways but in the bioethanol pathways the biogenic CO_2 offsets the combustion emissions almost entirely. Wang (2012) found that the greatest contributor to GHG emissions for bio-ethanol is the production of ethanol itself. This differs from the LCA analyses which include environmental impacts such as land use, eutrophication and acidification.

Particular attention was paid to corn-ethanol studies completed in Canada, as these can depict the same conditions for corn harvesting and treatment. Burt (2013) analysed the GHG emissions of the corn ethanol process at a Suncor plant adjacent to the IGPC ethanol plant, this analysis was done using GHGenius, a Canadian emissions database for transportation fuels with a comparison to GREET. The impacts were tabulated on an emissions footprint ($CO_{2equvilant}$ per MJ of fuel energy provided) opposed to lifecycle assessment impacts but can still depict information on the state of the industry. Similar to the current study, the author adapted an independent GREET model to Ontario values (ie. electric grid mix, transportation distances, primary fuel types, etc.), where available. The model also replaced generic corn-ethanol data from GREET with plant specific data, as actual operating data has much less uncertainty and does not rely on assumptions or defaults (Burt, 2013). The study does not consider the combustion of the ethanol and analysis is done using the displacement method for co-product crediting. Burt (2013) found that displacement of conventional transportation fuel such as modern Reformulated Gasoline (RFG), with bioethanol fuel can reduce life cycle CO_2e emissions by 40 – 60 g CO_2e / MJ depending on the agricultural practices used, credits assigned to co-products, production facility energy sources, and the direct and indirect land use changes caused by the additional farming. It was identified that the vast majority of the processing emissions come from combustion of fossil fuels for process heat, while the majority of overall GHG emissions come from agricultural chemical production (30.2 g CO_2e/MJ out of a total 53.4 g CO_2e/MJ).

A well-to-wheel analysis for the GHG emissions for mid-level blends of fuel (15-30% ethanol) in Canada's light-duty fleet was also completed to determine how these fuels compare to conventional gasoline (Milovanoff et al., 2019). The analysis depicted ethanol as a mature fuel, as it currently makes up 6.6% of gasoline blends by volume. Mid-level blends were investigated because this level of ethanol blend increase does not require changes to vehicle technologies (Milovanoff et al., 2019). While this study did not focus exclusively on corn-ethanol, corn-based ethanol makes up 85% of the ethanol produced in Canada. This analysis considered the well-to-wheels impacts of the process; however, the combustion of ethanol is often characterized as carbon neutral as carbon dioxide (CO_2) released during combustion originates from atmospheric CO2 absorbed during biomass production (Van Der Voet, Lifset, & Luo, 2010). Results from a prominent Canadian LCA model (GHGenius) reported that the average domestic well-to-wheels GHG emission intensities of gasoline and ethanol from corn at 98.4 and 54.8 g CO2 eq./MJ, respectively in 2015 ("GHG Emission Reductions from World Biofuel Production and Use- 2015," 2015). Overall, it was determined that mid-level blends of fuel had the ability to significantly decrease total GHG emissions compared to conventional gasoline.

As shown, the literature studies can differ in terms of location, scope, function unit, LCA method and end-use for the ethanol. Most recent studies reach the conclusion that corn-ethanol is successful in reducing the lifecycle impacts when added to gasoline, therefore this comparison will not be explored in this study. The studies also indicated that attention should be given to the corn cultivation stage, as this sector seems to invoke the highest environmental impacts, mainly due to the high fertilizer needs. The combustion of fuel is also important for studies comparing ethanol to fossil-based fuels; however, this is less applicable when comparisons are done between different ethanol production processes, and therefore will not be addressed in this study.

Chapter 4 Methodology

4.0 LCA Process Design

Biofuel production from conventionally farmed crops such as corn has resulted in numerous sustainability challenges, particularly with regard to water consumption, land use, fertilizer and pesticide application, overall energy use and emissions. The parameters defined in an LCA can have a large impact on the outcome of the LCA study, therefore this analysis follows ISO 14044; the requirements and guidelines for life cycle assessments (ISO, 2006). As presented in the literature review, particular attention should be paid to the scope, co-product credit system, and the impact assessment method used. Previous studies on the impact of the corn ethanol system show conflicting results, this is often a result of differing units, system boundaries and co-product credit analysis (Farrell et al., 2006).

4.1 Goal and Scope of Analysis

The goal of this analysis is to complete a lifecycle assessment and economic analysis of the conventional corn-ethanol process at IGPC Ethanol and a novel proposed novel biorefinery. As mentioned, the standards outlined in ISO 14044 were followed for this analysis. The report was commissioned in order to analyze the life cycle impacts of both processes, allowing for comparison between these two facilities. Stakeholders for this study include members of the corn-ethanol industry, as this analysis may have an impact on the GHG emissions and energy efficiency of the process. The current corn-ethanol process is resource, water and energy intensive, and this study intends to assess the implications of process improvements that are designed to reduce the environmental impacts through the implementation of a novel biorefinery. This study is carried out in order to determine if improvements are warranted for the conventional process and whether the novel biorefinery reduces the environmental impacts of the process.

For this project the scope is a cradle-to-gate analysis, which includes all upstream processes, including infrastructure and fertilizer, pesticide and diesel use, up to and including the production of anhydrous ethanol at the plant. This was chosen to allow a direct comparison between the two ethanol processes without including unnecessary overlap. The endpoint was chosen to be the factory gate due to the fact that the additional processing, including denaturing, transport and eventual ethanol combustion, are common to both pathways, and not included in the analysis. The study will allow a direct comparison of the processing of corn into ethanol for both pathways.

The location of the analysis is important for certain pathways as well. While this study may be relevant to more than just one geographic area, the focus of the study will be for the IGPC Ethanol facility, which is located in Alymer, Ontario. This influences the LCA based on the general distance from field to processing plant, as well as the distance to market for DDGS and other co-products. The electricity composition for the analysis is based on the Ontario grid make-up in 2018 (most recent for GREET 2018), this impacts the LCA based on the type of energy source, used to produce the electricity in the region (natural gas, coal, hydro-electric etc.). Finally, the technology and age of the plant has a general impact on the type of fuel used, whether coal or natural gas. IGPC Ethanol exclusively uses natural gas. Inventory inputs taken from GREET are North American industry averages and are assumed to be representative of IGPC Ethanol.

The functional unit chosen for LCA of bio-ethanol production plant is typically referred to the energy content of the ethanol produced, often per 1 million british thermal units (1mmbtu) of ethanol. It can also be in terms of the volume or mass (1 kg or 1 gallon) of the ethanol produced, however this limits the comparison to other fuel pathways, which may have different energy content than ethanol. A functional unit in terms of energy allows for a comparison to other fuels. In GREET, the standard functional unit is the energy unit of 1 mmbtu of ethanol (Wang, Dunn, & Wang, 2014).

The analysis focused on techniques to reduce inaccuracies in data quality for the study. The data focused on near-term studies and input data from the most recent databases available (2018 for GREET). The data was also adjusted for geographic coverage to ensure it satisfies the scope of the analysis. For these reasons, plant specific data was prioritized for this study.

4.2 Life Cycle Inventory

In order to produce an LCA for a product or process, an inventory must first be established. This includes all the energy, materials and emissions in the lifecycle of the product or process. For this LCA on corn-ethanol, the data must be compiled from various sources. Much of the required data was primary data collected directly from IGPC Ethanol Inc. This allows the LCA to be based directly on one Canadian plant, as opposed to a national or worldwide average. The collected data is utilized to quantify the inputs and outputs of a unit process, and details about the collection process for primary data is shown individually and calculations are explicitly documented. The data was supplemented with, and compared to, data collected from GREET 1.8d. Published reports and research papers were also used to obtain some data particular to some region or technology. Mass and energy balances provided by IGPC were used to ensure data validity. Additional resources such as Kwiatkowski et al. (2006) provide intricate information about the corn ethanol process and mass balance of the system.

An independent GREET model was adapted to Ontario values (ie. Transportation distances, electric grid mix, fuel use, fertilizer applications etc.) when available. When considering the processing of corn into ethanol, generic data from GREET for North American plants was replaced with site-specific data from IGPC Ethanol when available. The use of actual operating data creates a database that is representative of the process to be modelled and has less uncertainty and reliance on estimates or assumptions.

For the creation of the LCA, the data from the lifecycle inventory was entered as input into openLCA 1.9, which was created and maintained since 2006 by GreenDelta. openLCA is an open-source software that allows for reliable calculations for life cycle assessments and detailed insights into analysis results. The analysis allows for the breakdown of the impacts based on each input, emission, or part of the process. The Ecoinvent database was used to provide transparent and consistent results that can be compared to other studies. Ecoinvent 3.6 was used to provide an up to date inventory database. The Ecoinvent maize ethanol process provided the basis for the LCA and was updated with data relevant to this particular study.

This analysis considers an attributional LCA on the corn ethanol process, for this reason the downstream emissions and impacts of the avoided co-products, including nitrogen and phosphorus emissions are not considered within the scope of this analysis. Alternatively, a consequential LCA could consider these downstream impacts.

An important parameter for the LCA is the co-product credit system or allocation for a multi-output process like the corn-ethanol process. The inputs and outputs are allocated to different products according to the allocation procedure. The ISO 14040 and 14044 documents recommend avoiding allocation whenever possible either through subdivision of processes or by expanding the system boundaries to include the functions associated with the co-products generated (Pereira et al., 2019). For this reason, system expansion was chosen as the primary co-product credit system for this analysis. This method is commonly employed for LCAs and allows for a method consistent with literature. System expansion considered the avoided products displaced due to the production of co-products. It was also chosen because a consistent unit (as required in allocation) between ethanol, corn oil, DDGS and carbon dioxide is difficult to achieve. However, the LCA analysis includes linked processes within the ecoinvent database; these processes were allocated as they were defined in the processes. The analysis will also include a comparison between system expansion and allocation in order to determine its effect on the LCA results.

4.3 Life Cycle Impact Assessment

As outlined in the ISO14044 guidelines, the life cycle impact assessment (LCIA) will include the selection of impact categories, classification of LCI results to the selected impact categories and the characterization of indicator results. The midpoint ReCiPe LCIA method was used to transform the lifecycle inventory results into a limited number of indicator scores in order to indicate the severity of the environmental impact. A midpoint hierarchist perspective was used for this analysis to interpret the results on a moderate timeframe of 100 years. The impact assessment will determine the lifecycle impacts in terms of a limited number of mid-term impact categories. The midpoint analysis was chosen because it provides lower uncertainty but does have less information on the environmental relevance of the flows compared to an endpoint analysis (Hauschild & Huijbregts, 2015).

The impact categories chosen for the corn ethanol comparison include global warming, land use, marine and freshwater eutrophication, terrestrial acidification and water consumption. These impact categories were chosen due to their relevance to the corn-ethanol process as well as their use in previous studies (Kim & Dale, 2008; Pieragostini et al., 2014). Global warming was chosen due to the fossil fuel use in corn-ethanol plant and GHG emissions from agriculture, this will highlight the changes in energy and fossil fuel use between the two processes. Land use is based on the changing of environmental areas into areas that can cultivate agriculture. The impact of land use stems from the carbon that can be sequestered by a natural environment, such as a forest, compared to an agricultural product such as corn that is harvested and produces CO_2 during transformation into ethanol. Land use was used to demonstrate the impact changes by anticipating using less corn in the novel biorefinery. However, the land use change within the area of IGPC Ethanol should be minimal, as agriculture is well-established in this area and no new farmland is being cleared from forest in Ontario for this production or any other expanding crops (Burt, 2013).

Eutrophication is characterized by decreases in dissolved oxygen due to the excess growth of some species such as algae, resulting in the death of other aquatic species. Eutrophication occurs due to nutrient (nitrogen and phosphorus) run off over the ground into the body of water, resulting in disproportionate growth of waterweeds and shock to the ecosystem. The selection of eutrophication as an impact category will help to understand the wastewater changes between the conventional and novel biorefinery, where thin stillage is treated in an anaerobic digester, followed by struvite recovery and microalgae cultivation to limit nutrient accumulation. Additionally, by reducing the amount of corn required in the novel process, the amount of fertilizer, and thus nitrogen and phosphorus, can potentially be reduced.

Acidification is included as an impact from acidic solutions released to the environment and is particularly important for fertilizer use. Acidification is largely due NO_x and SO_x air emissions, which result in the decrease in pH level of water sources. The recovery of struvite in the novel biorefinery will have an effect on this impact category. Finally, water consumption is a simple metric that compares the water use of the two processes. This takes into account both the water consumed and removed from the water table, and the wastewater that is produced. This will highlight the effect of process water recycling within the novel biorefinery. For this reason, a direct water balance was tabulated for the plant.

4.4 Interpretation

The inventory data for both the IGPC facility and the novel biorefinery are used to create distinct processes within openLCA. The software allows for inventory data to be tabulated and a provider for the input selected; which allows products from around the world to be presented from the most accurate source for each input. The interpretation consists of the identification of significant issues based on the results of the LCI as well as an evaluation that considers completeness, sensitivity and consistency checks (International Organization for Standards [ISO], 2006). This stage also includes the identification of the limitations of the study.

Chapter 5 Process Descriptions and Process Flow Diagrams

5.1 IGPC Process Flow

The IGPC facility located in Alymer, Ontario produces 100 million gallons per year of ethanol through a dry-grind corn ethanol process. New initiatives are implemented to enhance the economics of the process including incorporating corn oil recovery, energy recovery through heat exchange, and decreased energy use for co-product processing. The facility also includes an enhanced fractionation technology called Fiber Separation Technology. An area of interest for innovation is the processing of the thin stillage created as a by-product of the fermentation. Thin stillage requires extensive drying before being incorporated in the feed co-products, which is energy intensive and costly. Figure 5-1 presents the dry-grind corn ethanol process as modelled at IGPC Ethanol. The flows are represented numerically and are highlighted in the mass balance in Table 5-1. The mass balance represents the complex flow of materials within the process. A detailed process description for IGPC is presented in the literature review.

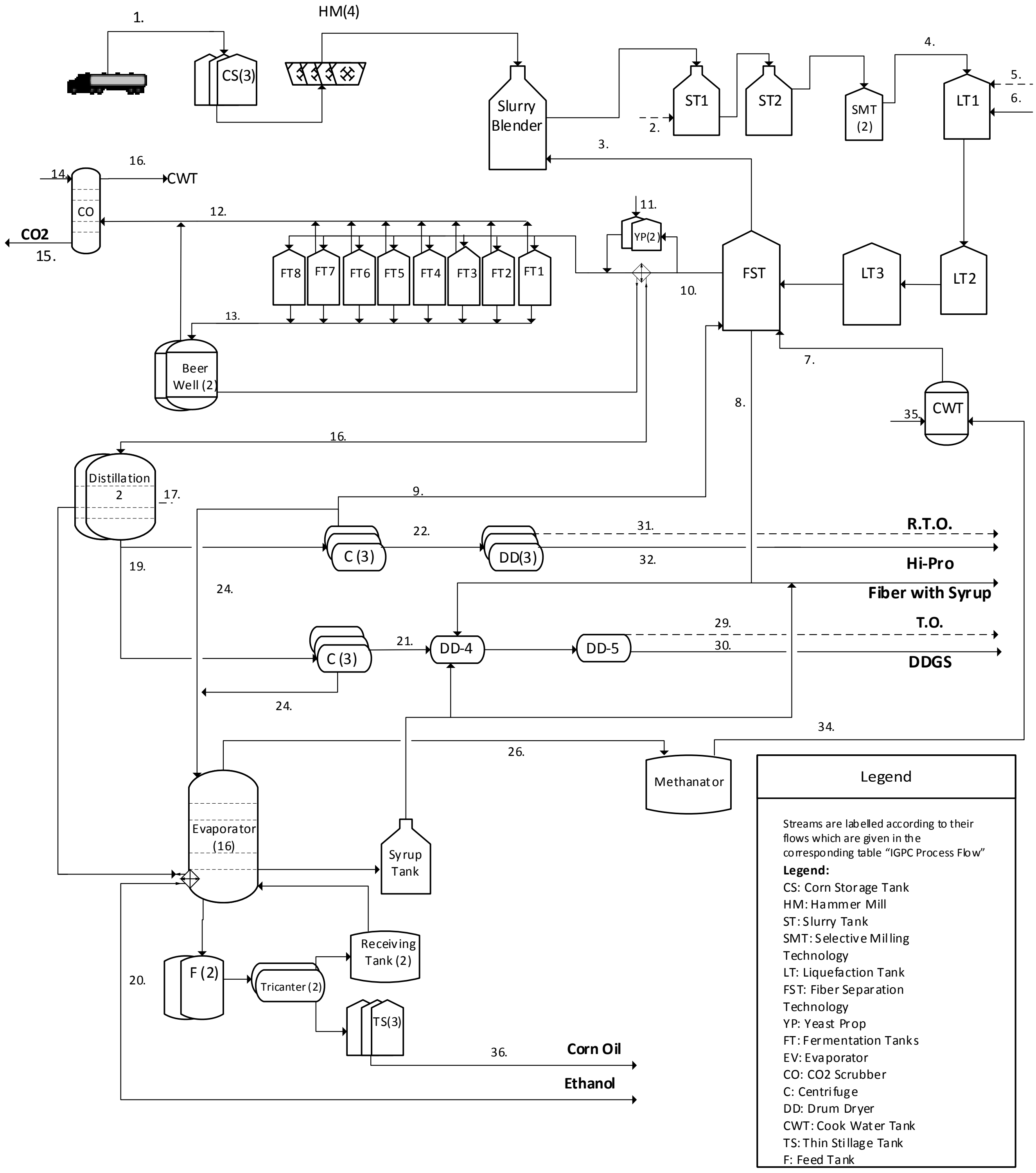


Figure 5-1: IGPC Corn Ethanol Facility Flow Diagram

5.1.1 IGPC Mass Balance:

The mass balance for the IGPC plant is described in Table 5-1. The values are based on personal communication as well as a mass and energy balance provided by IGPC. The flow numbers correspond to the process flow diagram, presented in Figure 5-1.

Table 5-1: Mass balance of the IGPC Process

Process Unit	Flow #	Description	Mass Flowrate (t/h)
Slurry Tanks	1	Yellow corn	110
	2	Steam	3
	3	Backset from liquefaction	209
	4	Outlet to liquefaction	-322
Liquefaction and Fiber Separation Technology	4	From slurry tanks	322
	5	Steam	1
	6	Water from distillation	37
	7	Water from cook-water tank	83
	8	Fiber removal (FST)	-21
	9	Backset from thin stillage	89
	3	Backset to slurry tanks	-209
	10	To fermentation tanks	-303
Fermentation Tanks	10	From liquefaction	303
	11	Yeast and process water	6
	12	CO_2 produced	-35
	13	Dilute ethanol stream	-273
CO2 Scrubber	12	CO_2	35
	14	Scrubber water	25
	16	Water to cook-water tank	-25
	15	CO_2 to product	-35
Beer Well	13	Dilute ethanol from fermentation	273
	16	To Column	-273
Distillation Column	13	Dilute ethanol from beer well	273
	17	Steam from evaporators	59
	18	Steam from side stripper	11
	19	Whole stillage to centrifuge	-270
	4	Steam to liquefaction	-37
	20	Alcohol to market	-36
Centrifuge	19	Whole stillage from distillation	270
	21	Wet distillers' grain to DDGS dryer	-15
	22	Wet distillers' grain to Hi-Pro dryer	-15
	9	Thin stillage to liquefaction	-89
	24	Thin stillage to evaporation	-151

Evaporator	24	Thin stillage from centrifuge	151
	25	Steam to distillation	-59
	26	Process water to methanator	-57
	27	Syrup to Fiber With Syrup	-12
	36	Corn oil removal	-1.2
	28	Syrup to DDGS dryer	-12
DDGS Dryers	28	Syrup from evaporator	12
	21	Wet distillers’ grain from centrifuge	15
	8	Fiber from Liquefaction (FST)	11
	29	To thermal oxidizer	-20
	30	DDGS to market	-16
Hi-Pro Dryers	22	Wet distillers’ grain from centrifuge	15
	31	Air to regenerative thermal oxidizer	-9
	32	Hi-Pro to market	-6
Cook Water Tank	33	From CO_2 scrubber	25
	34	From methanator (evaporator)	57
	35	From floor wash	1
	7	To liquefaction	-83

5.1.2 IGPC Energy Balance:

An energy balance for the individual units was produced to show the energy flows throughout the plant, this balance also helps identify areas for energy efficiency improvement. The energy balance required some assumptions to be made surrounding flows. The energy provided by each flow was calculated based on the heat capacity, the latent heat of the solution, and the temperature and pressure of the solution. In many process units the temperature and pressure of the flows was not identified, so some assumptions were required. Additionally, in the balance provided by the facility, the flows of energy for distillation and evaporation process were not provided for each unit individually.

The heating for each unit is provided by either supplied steam or from heat exchangers using flow from other areas of the plant. The energy balance provides an opportunity to outline the flow of energy throughout the plant and where energy improvements may be made for the novel biorefinery.

Table 5-1: Energy balance for the IGPC Facility

Process Unit	Flow #	Flow	Volume (kg/Bu)	Energy (MJ/Bu)	Net Energy (MJ/Bu)
Slurry Tank	1	Yellow corn	25.4	1	
	2	Steam	0.7	2	
	3	Liquefaction backset	48.3	17	
	4	To liquefaction tanks	-74.4	-21	-1
Liquefaction and Fiber Separation Technology	4	From slurry tanks	74.4	21	
	5	Steam	0.2	1	
	6	Water from distillation	8.5	3	
	7	Water from cookwater	19.2	7	
	8	Fiber extraction to DDGS	-4.9	-2	
	9	Backset from thin stillage	20.7	7	
	3	Backset to slurry	-48.3	-17	
	10	To fermentation	-70.2	-21	0
Fermentation Tank	10	Flow from liquefaction	70.2	9	
	13	Flow to distillation	-63.2	-8	0
Distillation Column	13	Flow from beer well	63.2	15	
	17	Steam from evaporator	13.7	37	
		Heat exchange (latent)	5.0	11	
		Heat loss (during condensation)	-8.7	-8	
	18	Steam (injection)	2.5	6	
	4	To liquefaction	-8.5	-3	
	19	Whole stillage	-62.6	-21	
		Water condensate (sieves)	-0.4	-1	
	20	Ethanol to market	-8.3	-9	27
Centrifuge	19	Whole stillage from distillation	62.6	21	
	9	Thin stillage	-55.6	-18	
	22	Wet distillers' grains	-7.0	-2	1
Evaporator	20	Latent heat from ethanol	8.3	7	
		Heat from exchange (latent)	9.7	22	
	9	From thin stillage	35.0	12	
	36	Corn oil removal	0.27	0	
	17	To distillation	-13.7	-37	
		To methanator	-13.2	-5	
	28	To DDGS dryer	-5.7	-2	-3
DDGS Dryer	28	Thin stillage syrup	2.8	1	
	8	Fiber from FST	2.4	1	
	21	Whole stillage	3.5	1	
	29	To thermal oxidizer	-4.6	-1	
	30	DDGS to market	-3.8	-1	1
Cookwater Tank	33	From CO_2 scrubber	5.8	1	
	34	From methanator	13.2	2	
	7	Output to liquefaction	-19.1	-2	0

The net energy transfer within each process was given in the last column. These values showed greater deviation from zero than in the mass balance because there is more uncertainty in the flow of energy, and also an increased complexity for energy transfer.

The energy balance within the evaporator is of particular interest as evaporation is the major energy intensive process within the plant. The thin stillage enters the evaporators at about 6% total solids and exits at 40% total solids, with 116,000 kg/hour of steam directed to the distillation column or sent to the methanator for water treatment (S. Holt, personal communication, May 1, 2019). There is a total of 16 evaporators at the IGPC facility consisting two sets of 8. The thin stillage enters the evaporation stage through evaporator 8 from the thin stillage tank. By entering the evaporators through a second effect reboiler evaporator, the thin stillage enters a lower temperature system, which avoids degradation of the thin stillage (S. Holt, personal communication, Sept. 2019).

The heat for the evaporation is provided from a variety of sources as shown in Figure 5-2. Heat for evaporator 1 through 3 originates from steam coming from the thermal oxidizer (or regenerative thermal oxidizer for evaporator set 2). While energy for evaporator 4 is provided from the ethanol stream. The 200-proof ethanol vapors are condensed into a liquid in a heat exchanger, providing the latent heat for evaporation of thin stillage in evaporator 4. The cumulative steam from evaporators 1 through 4 enters the second effect reboiler, which provides the heat for evaporators 5 through 8. Following this, the process condensate and steam is utilized directly in the beer column as process water. The thin stillage then flows through evaporators 1 through 7 in order. Following evaporator 6, the solution, now called mid stillage due to the increased total solids concentration, gets directed to the oil recovery process, as shown in Figure *5-1*. This includes a horizontal centrifuge called a tricanter which separates the oil, solids and water. The water and solids are recombined and sent to the final evaporator, while the corn oil is sent to a process tank. The condensed distillers' solubles enter a syrup tank before eventually being applied to distillers' dried grains or the extracted fiber. The overall process is energy intensive but is also designed to utilize excess heat from other areas within the plant.

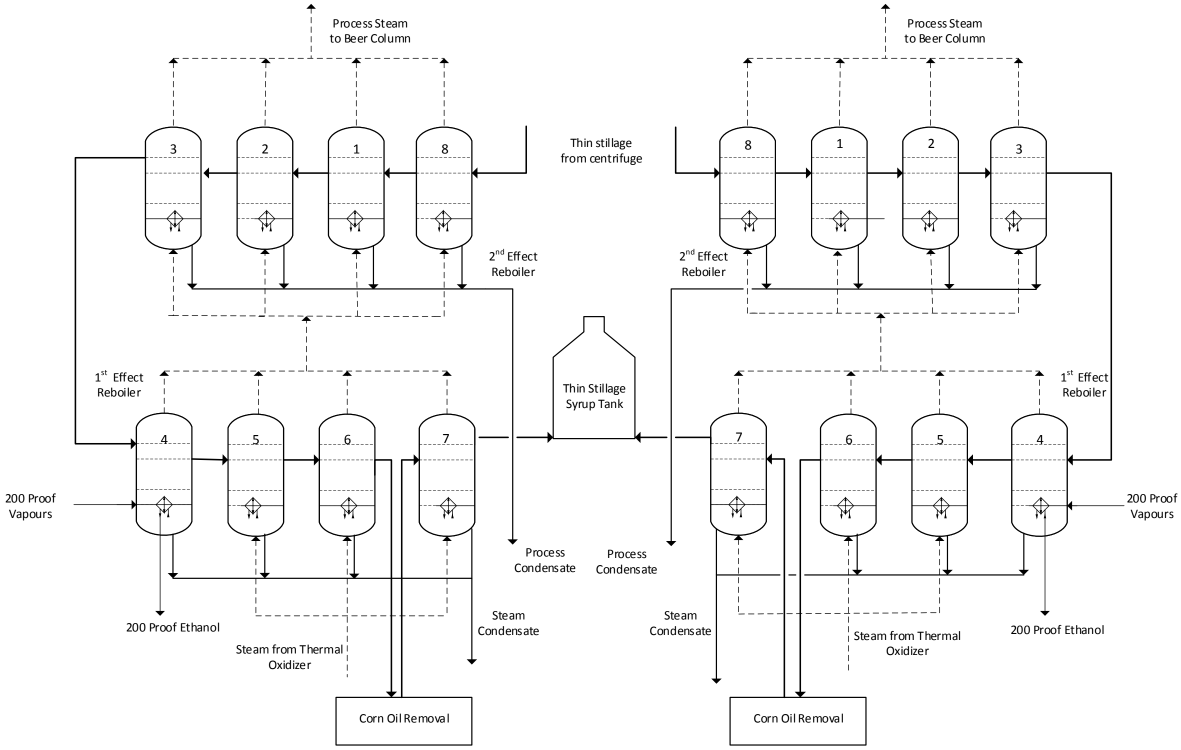


Figure 5-1:Energy flow through the evaporation step of the dry grind process. Dashed lines represent flow of steam.

5.2 Novel Biorefinery Process Flow

The novel biorefinery is expected to decrease GHG emissions and other environmental impacts of the traditional corn ethanol production. By eliminating the need for evaporators for thin stillage, and instead using struvite precipitation, anaerobic digestion, aerobic treatment and algae cultivation, the process is hypothesized to decrease energy use as well as increase the circular nature of the process by incorporating the algae as a starch source for ethanol production. Additionally, the process promotes utilization of nitrogen and phosphorus by forming a product, struvite, and by recycling the process water containing algae to the front end as a nutrient source for the yeast. In the typical corn ethanol facility, a portion of the nutrient rich thin stillage is back-set to the front of the process as a source of nitrogen, as well as macro and micronutrients for yeast propagation (S. Holt, personal communication, Sept. 2019). This thin stillage backset can be eliminated with the flow of process water containing algae to the front of the process.

In the current facility, evaporation of thin stillage and drum drying of the distillers dried grains and syrup constitute 45% of the energy use according to the estimation using SuperPro Designer (Kwiatkowski, McAloon, Taylor, & Johnston, 2006). IGPC Ethanol has three drum dryer trains, dryers A & B receive wet DGS for drying, while Hi-Pro is dried using dryers A, B or C. The change in thin stillage processing affects the need for drying capacity for dryers A & B of the novel process. This impacts the net energy use for the corn ethanol process, and incurs a large energy use exclusively for the production of the feed by-product and waste treatment.

Following evaporation, the thin stillage syrup, now called condensed distillers' syrup (CDS) is typically added to the distillers dried grains (DDG). Generally, this was used as a method to increase the fat content of the feed, but it also helps to improve the consistency of the feed (S. Holt, personal communication, Sept. 2019). In the novel process, the thin stillage is no longer available for addition to the animal feeds, and the resultant product is DDG.

Corn ethanol production is an energy intensive process with the IGPC process using 6.8 MJ of natural gas per liter of ethanol produced (S. Holt, personal communication, May 2019). The decision to recover the energy from methane as heat rather than using a combined heat and power plant is based on the fact that in a bioethanol plant 88% of the required energy is thermal energy (Murphy & Power, 2008). This is due to the recovery of heat having a higher efficiency than the recovery of electricity (Usack, Van Doren, Posmanik, Tester, & Angenent, 2019), and since it can be used on site, heat was assumed to be the only energy generated from the biogas combustion.

In order to use the methane within the facility the biogas must be treated. Hydrogen sulfide must be removed from the chambers in order to alleviate inhibition of the microorganisms within the ABR. The H_2S gas is produced due to the sulfuric acid added to maintain plant pH during liquefaction and to improve corn oil separation (S. Holt, personal communication, May 2019). While H_2S gas is not produced directly in the traditional facility, increased sulfur content in distillers' grains causes ruminant animals to erupt H_2S gas. This can cause both environmental issues and feedlot polio. Within the novel biorefinery, the baffled ABR improves H_2S removal and allows most of the sulfur removal to occur in the first chamber within the ABR where it can be effectively treated. Sayedin et al. (2018), reported that H_2S gas was only significant within the first chamber of the ABR.

Anaerobic digesters are well documented for treating organic material. The digestate can be used directly as fertilizer, however it is limited due to its nutrient specific parameters and the possibility for land contamination (Fuldauer, Parker, Yaman, & Borrion, 2018). The anaerobic digestion is also not able to significantly impact the nutrient concentrations of phosphorus and nitrogen in the thin stillage (Wilkie et al., 2000). The nutrient rich digestate will lead to eutrophication if discharged without being properly treated.

Struvite ($NH_4MgPO_4 \cdot 6H_2O$) precipitation occurs naturally in wastewater treatment and can improve the nitrogen to phosphorus ratio present in the digestate for microbial population. The precipitation occurs when the combined concentrations of Mg^{2+}, NH_4^+ and PO_4^{3-} exceed the struvite solubility for the wastewater. This precipitation can reduce the concentration of ammonia and its toxic effect and also increase the N/P ratio of digestate (Sayedin et al., 2019).

Struvite solubility is a function of the pH. As pH increases, struvite solubility decreases, with a suitable pH range for struvite formation at 8 to 9.5 (Battistoni, De Angelis, Pavan, Prisciandaro, & Cecchi, 2001). Therefore, anaerobic digestion processes, which show a higher pH than the earlier stages of the wastewater treatment, are more susceptible to struvite formation (Marti, Bouzas, Seco, & Ferrer, 2008). Struvite precipitation can cause operational problems during sludge treatment, as it can accumulate on pipe walls and equipment surfaces during AD.

When investigating the rate of struvite precipitation, the addition of magnesium ($MgCl_2.6H_2O$) was found to increase the removal of nitrogen and phosphorus by 44% and 81%, respectively, in the treated digestate (Sayedin et al., 2019). Sayedin et al., (2019) determined the precipitation of struvite was able to improve the nitrogen to phosphorus ratio (N/P) from 2.1 to 14.4, which is closer to the optimum ratio (16) for microalgae growth (Choi & Lee, 2015; Y. Li et al., 2011). This does necessitate the use of a source of magnesium to provide a P:Mg ratio of approximately 1:1 but the recovered struvite can be marketed as a fertilizer product to improve the economics of the process. By enhancing the struvite removal through the addition of magnesium, the struvite can be removed prior to the AD and avoid the build-up within the system.

Aerobic treatment is introduced to further remove COD and to prevent ammonia inhibition for algae growth. As mentioned in Chapter 3, the aerobic treatment increases energy use and capital costs but allows for the process to be completed without the need for the dilution of the thin stillage. The treated digestate will then be allowed to settle to increase the light permeability of the solution. Algae use the process of photosynthesis to convert CO_2, water, and light into biomass.

Algae was chosen due to its efficient biomass productivity and rapid growth cycle of 10-14 days, which permits several harvests in a short time period. Microalgae can also readily utilize CO_2 generated from a point source such as flue gas (Kobayashi et al., 2013). The production of microalgae on thin stillage digestate provides an opportunity for simultaneous nutrient recovery and wastewater treatment.

The screening and isolation of high tolerance microalgae species and strains is crucial to achieve high growth efficiency (Chiu et al., 2015). Algal species were chosen based on biomass productivity and nutrient removal efficiency for nitrogen and phosphorus (Sayedin et al., 2019). The species capability on growing on digestate as well as their tolerance to toxic components such as ammonia was also crucial.

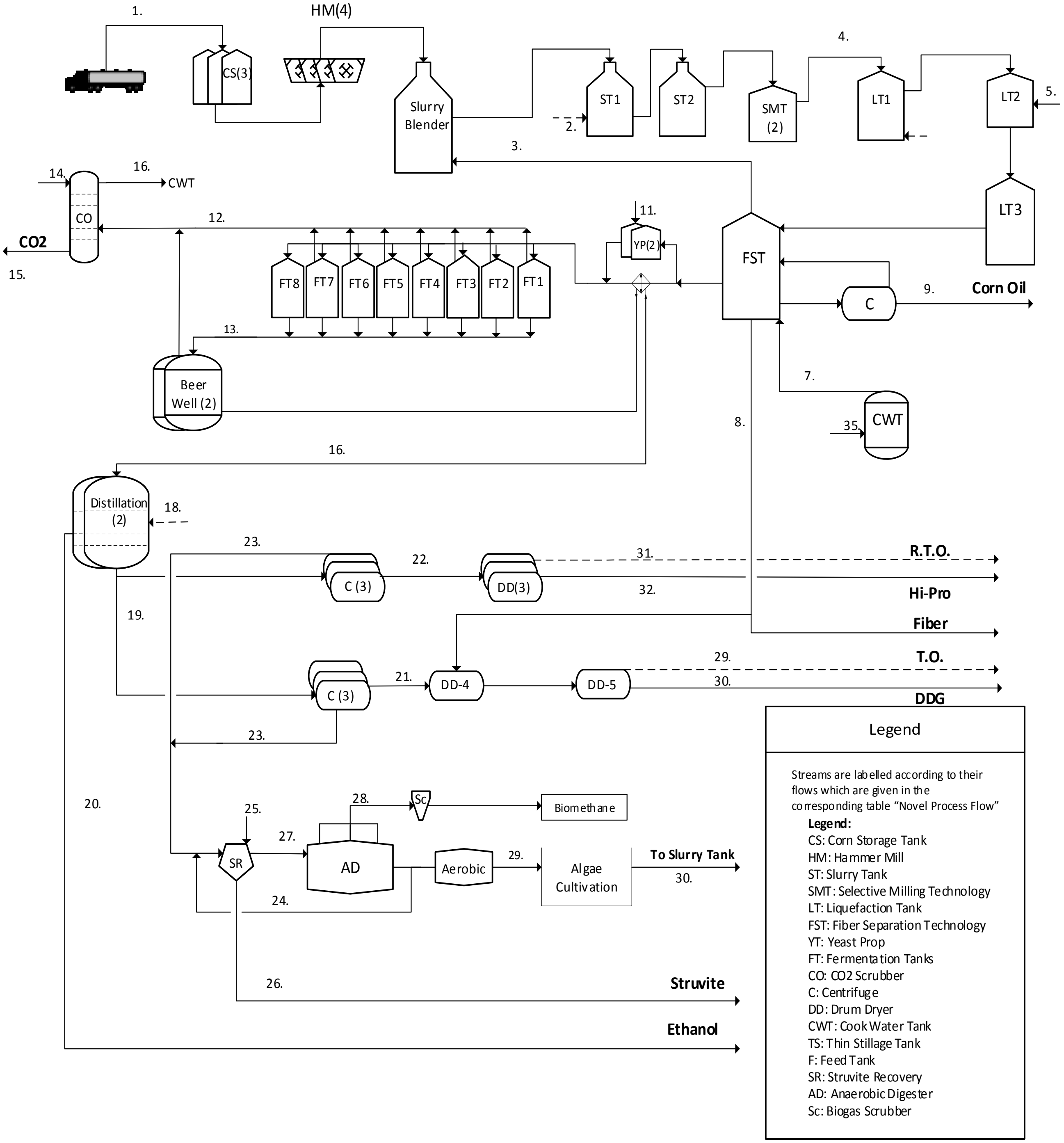
Utilization of algae in wastewater treatment has gained attention for its ability to remove and recover nutrients (Cai, Park, Racharaks, & Li, 2013). Ammonia is the main source of nitrogen, which is imperative to algae growth. Therefore, the nitrogen removal efficiency by the algae species ultimately impacts the extent of biomass production within the system. The light intensity, pH, salinity, nutrient availability and temperature of the medium also impacts the performance of algal cultivation.

The algae for this analysis, *Chlorella sorokiniana,* has been reported to achieve starch content as high as 27% (Li et al. 2015), while Sayedin et al. (2019) was able to achieve a starch content of 17.8%. The high starch content means the algae can supplement the corn in the ethanol process and decrease the corn input required for ethanol production. The protein in the microalgae will end up in DDG and increase its protein content and may improve the quality of animal feed.

Typical algae growth economics is limited by the high costs of harvesting and fertilizer for growth, while the proposed process would allow the mixture of treated effluent and algae to be recycled upstream to be mixed with corn, avoiding the need for harvesting. The water and algae mixture would then be processed in the same system as the corn and used to supplement the corn required for the process. If the desired amount of algae is produced, the amount of required corn and therefore, resources and cost associated with corn cultivation will be reduced. The energy intensive process of algae harvesting can be avoided by directly incorporating both the treated digestate and the algae in the overall corn ethanol process. By utilizing the phosphorus and nitrogen present within the digestate, the fertilizer requirement for algal growth can also be negated.

Bio-ethanol plants such as corn-ethanol plants already have equipment for microalgae to ethanol conversion. Using microalgae for ethanol production is more advantageous than crop-based ethanol production due to their low content of hemicellulose and lack of lignin content, as well as being able to grow on salty or wastewater streams or in areas unsuitable for agricultural purposes (Harun, Jason, Cherrington, & Danquah, 2011). Thus, microalgal biomass can be used as a supplement to substitute part of the primary feedstocks such as corn, taking advantage of existing technologies and facilities. This allows for efficient transformation of starch from microalgae into ethanol with less pre-treatment required.

The proposed corn ethanol bio-refinery with integrated microalgae cultivation is presented in Figure 5-2. The incorporation of an anaerobic digester process introduces two new streams to the process; methane and struvite. In comparison to the corn ethanol facility, the bio-refinery aims to decrease the energy costs, produce methane to be utilized within the plant, allow further process water recycling, produce struvite to be used as fertilizer and reduce the corn requirements through partial substitution of corn with algae.



Legend

Streams are labelled according to their flows which are given in the corresponding table "Novel Process Flow"

Legend:
CS: Corn Storage Tank
HM: Hammer Mill
ST: Slurry Tank
SMT: Selective Milling Technology
LT: Liquefaction Tank
FST: Fiber Separation Technology
YT: Yeast Prop
FT: Fermentation Tanks
CO: CO2 Scrubber
C: Centrifuge
DD: Drum Dryer
CWT: Cook Water Tank
TS: Thin Stillage Tank
F: Feed Tank
SR: Struvite Recovery
AD: Anaerobic Digester
Sc: Biogas Scrubber

Figure 5-2: Proposed novel corn-ethanol biorefinery

5.2.1 Novel Biorefinery Mass Balance

The mass balance for the novel biorefinery differs from the traditional corn ethanol process based on the changes to the thin stillage handling. After consideration for different scenarios, it was determined the best route is to direct all thin stillage from the centrifuge to the anaerobic digester. This allows for the largest volume of thin stillage to be treated within the anaerobic digester and used to cultivate algae. Due to the algae and process water being recycled to the front end of the process for ethanol production, it was predicted that the nutrients typically supplied for yeast growth from the thin stillage back-set can be provided by the algae and process water. This was demonstrated in Wang et al., (2013), where utilizing anaerobic digestion effluent in the ethanol process did not require supplemental nitrogen source for fermentation.

Research has shown that significant improvements can be made by incorporating an anaerobic digester into the corn ethanol process (Lee et al., 2011; Ráduly et al., 2016; Yang et al., 2017). The energy savings for the process are two-fold, with energy use for evaporation being eliminated and DDGS drying being reduced, as well as the methane production that occurs from the anaerobic digester. Schaefer and Sung (2008) observed that using the methane recovered from the anaerobic digester in a corn ethanol plant contributed to an estimated 43-59% reduction in natural gas consumption. The savings would amount to $7 to $17 million for an ethanol plant with capacity of 360 million liters per year (Schaefer & Sung, 2008).

Based on research by Sayedin et al. (2019), the effluent is required to be recycled back into the process at a ratio of 10:1. This recycling does increase the size of AD required, but it is currently required in order to maintain a buffer capacity within the system and helps to maintain pH in the system.

Table 5-2:Mass balance of the novel biorefinery

Unit	Number	Flow	t/h
Slurry Tanks	1	Yellow corn	110
	30	Algae and water backset	239
	2	Steam	3.2
	3	Backset from liquefaction	89
	4	To liquefaction	-322
Liquefaction and Fiber Separation Technology	4	From slurry tanks	322
	5	Steam	0.8
	6	Water from distillation	37
	7	Water from cook water	55
	8	Fiber removal	-21
	3	Backset to slurry	-209
	9	Front-end corn oil removal	-2.5
	10	To fermentation	-301
Fermentation	10	From liquefaction	301
	11	Yeast and process water	6
	12	CO_2	-35
	13	Dilute ethanol	-273
CO_2 Scrubber	12	CO_2	35
	14	Scrubber water	25
	15	CO_2 to market	-35
Beer Well	13	Dilute ethanol from fermentation	273
	16	To distillation column	273
Distillation Column	13	Dilute ethanol from the beer well	273
	18	Steam	64
	20	Alcohol to market	-36
	4	Steam to liquefaction	-33
	19	Whole stillage to centrifuge	-267
Centrifuge	19	Whole stillage from distillation	267
	21	Wet distillers' grain to DDGS dryer	-15
	22	Wet distillers' grain to Hi-Pro dryer	-15
	9	Thin stillage to struvite recovery	237
Struvite Recovery	23	Thin stillage	237
	24	From recycle ratio (10x)	2370
	25	Magnesium ($MgSO_4$)	0.8
	26	Struvite to market	-2
	27	To anaerobic digester	-2610
Novel Process	27	Flow from struvite precipitator	2610
	28	Methane production (m^3)	7.9
	24	Recycled flow	2370
	29	Flow to algae	238

Algae Production	29	Flow from anaerobic digester	-238
		Algae production	0.8
	30	Flow to front of process	238
DDG Dryer	21	Wet distillers' grain from centrifuge	15
	8	Fiber from liquefaction (via FST)	11
	33	To thermal oxidizer	-20
	34	DDG to market	-11
Hi-Pro Dryer	22	Wet distillers' grain from centrifuge	15
	31	Air to regenerative thermal oxidizer	-9
	32	Hi-Pro to market	-6
Fiber	8	From FST	11
	8	Fiber to market	11

Chapter 6 Life Cycle Inventory

In order to determine the environmental burdens of the conventional and novel corn ethanol facilities a complete inventory for the process was created. The inventory relates to the resource consumptions as well as the emissions in the corn-ethanol process. These values vary within the industry therefore, whenever possible, plant specific data from IGPC Ethanol was used, while some data was supplemented from GREET 1.8.

The data taken from GREET was adjusted so that no allocation was taken into account. This was to ensure that double-counting of co-product crediting did not occur and all co-product crediting is done in the openLCA software. This allows comparisons to be made in the sensitivity analysis for allocations including economic, physical and market based, as well as system expansion. The inventory is provided to represent the data used in the openLCA software for both the IGPC facility as well as the novel biorefinery and comparisons are provided between data from IGPC, GREET and the default ecoinvent process "ethanol production from maize| ethanol, without water, in 95% solution state, from fermentation | Cutoff, U."

6.1 LCI for IGPC Ethanol

The following inputs were compiled for the IGPC facility using plant specific data from IGPC. The inventory is used to compile all the data for the LCA, each category below is an input, output or an emission for the process.

Transport, by tractor and trailer:

This input represents the distance travelled by tractor to deliver the corn from the field to the farm. This value is given a unit representing the volume of corn and the distance travelled in terms of tonne kilometers (t*km). This input was calculated as the total mass of corn (per mmbtu of ethanol) in tonnes (0.118 t) multiplied by the average distance travelled by tractor in the field, which is 10km (Jungbluth & Chudacoff, 2007) to give a value of 1.18 t*km.

Maize grain:

Corn use was obtained from primary data on IGPC, which indicates a production of 2.83 gal/Bu. For the ecoinvent process, the transport of corn to the factory was also included in the corn input. This was done by adjusting the provider in openLCA to "market for maize, IGPC," this allows for the inclusion of the transport of the corn to the ethanol plant. In the case of IGPC, it was stated that corn comes almost exclusively from within 80km from the plant (primary data, S. Holt, 2019). The transport was 80 km by truck (dictated as lorry in openLCA), the transport by tractor (for the field) is accounted for in transport, by tractor and trailer. The transport boundaries are displayed in Figure 6-1 below.

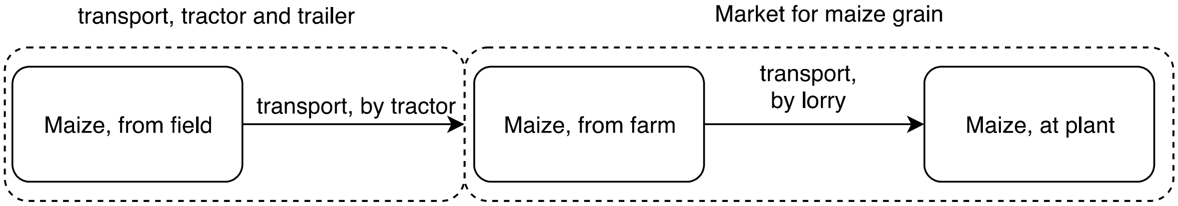


Figure 6-1: Boundaries for the Ecoinvent inputs for transport to ethanol processing

Electricity use:

The electricity use was also taken from personal communication with the IGPC facility, which uses 6600 kWh ($2.25x10^7$ btu) based on processing 4320 bushels of corn per hour at a production rate of 2.83 gallons of ethanol per bushel of corn. According to GREET (2018), the lower heating value for ethanol is 76,330 btu/gal, or 13.10 gallons of ethanol per million btu (mmbtu). This yields 24,130 btu of electricity per million btu (btu/mmbtu) of ethanol for the IGPC facility. A comparison with GREET gives 26,070 btu/mmbtu (1990 btu/gal) as an industry average for dry milling with corn oil extraction, this projects that the electricity use at IGPC Ethanol is almost 10% less than the industry average.

In terms of modelling electricity use in openLCA, the electricity grid make-up was adjusted to reflect the Ontario grid make-up. The provider was switched to “market for electricity, medium voltage, CA-ON” to reflect electricity production for the most recent year available (2014) in Ontario. It is important to model the electricity production for the local area because regions have different sources for electricity generation (e.g. Coal, natural gas, nuclear etc.)

$$LHV\ Ethanol{:}\frac{1*10^6 btu/mmbtu}{76{,}330\frac{btu}{gal}} = 13.101\ gal/mmbtu\ ethanol$$

$$\frac{6600kW}{4320\frac{Bu}{h}*2.83\frac{gal}{Bu}} = 0.54\frac{kWh}{gal}$$

$$0.54\ kWh/gal * 13.101\frac{gal}{mmbtu\ ethanol} * 3412\ btu/h\ electricity/kW$$
$$= \mathbf{24,130\ \ btu\ electricity/mmbtu\ of\ ethanol}$$

Electricity use (for CO_2 capture):

As mentioned IGPC captures carbon dioxide from the fermentative gases, which requires additional electricity. The CO_2 from fermentation is sent to a third-party company for treatment and capture. The carbon dioxide capture is included in the inventory because the captured CO_2 is a product of ethanol production at IGPC, therefore the electricity use for it has to be considered as well. The IGPC plant budgets to capture 120,000 tons of CO_2 per year. Primary data from IGPC (December 2019) suggested that over the month of November 2019, 177,000 kWh of electricity was used in the capture of CO_2. Assuming 8000 hours of operating plant hours per year, this works out to 0.28 kWh (955 btu) of electricity per mmbtu of ethanol.

$$\frac{177{,}000KWh/month}{667\ \ hours/month} = 266\ kWh/h$$

$$= \frac{266KW}{4320\frac{Bu}{h}*2.83\frac{gal}{Bu}*\frac{1\ mmbtu}{13.101\ gal}} = \mathbf{0.28\ kWh\ /mmbtu\ ethanol}$$

Carbon dioxide:

Carbon dioxide is produced from the fermentation process at IGPC Ethanol, with some of this CO_2 being captured and utilized, while the rest is vented to atmosphere. All other carbon dioxide produced, including from processes such as the burning of fossil fuels, is accounted for in the provider for the input (e.g. Carbon dioxide from the heat produced by natural gas is accounted for in the provider for heat from natural gas). For this reason, the CO_2 production given in GREET is not accurate to use for this LCA since GREET includes the carbon dioxide produced from all processes in the corn-ethanol process.

The carbon dioxide emission is the CO_2 released to the environment and is the difference between the CO_2 produced from ethanol fermentation (calculated stoichiometrically) and the CO_2 captured at the facility.

$$C_6H_{12}O_6 \rightarrow 2CO_2 + 2C_2H_5OH$$

Alcoholic fermentation converts one mole of glucose into 2 moles of carbon dioxide and two moles of ethanol. Using a production volume based on our reference product of 1 million btu of ethanol (13.101 gal ethanol) and the density of 789 g/L leads to 39.1 kg of ethanol, taking into account the molar masses of both ethanol and carbon dioxide, this creates about 37 kg of CO_2 per mmbtu of ethanol produced in the process.

According to IGPC Ethanol, 17.6 lb of CO_2 per bushel (or 36.97 kg CO_2/mmbtu) produced in fermentation is sent to the carbon dioxide capture plant. As mentioned, IGPC budgets for the capture of 120,000 tons of CO_2 per year, which means that about 40% of the CO_2 (equivalent to 14.26 kg CO_2/mmbtu of ethanol) is sent to the capture facility, with the rest presumably released to the atmosphere.

$$\begin{aligned} & CO_{2(fermentation)} - CO_{2(captured)} \\ & = 36.97 - 14.26 \\ & = 22.71\ kg\ CO_2/mmbtu\ ethanol \end{aligned}$$

The carbon dioxide emission from fermentation to the environment is therefore 22.7 kg/mmbtu of ethanol. The captured carbon dioxide also needs to be included as a product of the system. This flow will have an avoided product for the production of CO_2 (carbon dioxide production, liquid | Cutoff, U) and is equal to 14.3 kg CO_2/mmbtu ethanol.

Ethanol fermentation plant:

This input assumes the environmental impacts from the building and use of the facility over the lifetime of the facility. Ethanol plant infrastructure includes the transformation and occupation of land, materials, energy uses, emissions, and dismantling of the plant (Jungbluth & Chudacoff, 2007). This was taken from the ecoinvent database.

Heat, natural gas:

Primary data from IGPC indicates their natural gas use is 347.1 GJ/hr (3.29x10^8 btu/hr). The same conversions used for electricity use above translates this value to 352,600 btu/mmBtu. This aligns within 5% of GREET's 370,260 btu/ mmbtu for corn ethanol dry-milling.

$$\frac{347.1\frac{GJ}{h}}{4320\frac{Bu}{h} * 2.83\frac{gal}{Bu}} = 0.028\ GJ/gal$$

$$0.028\frac{GJ}{gal} * \ 948x10^5\frac{btu}{GJ} * 13.101\frac{gal}{mmbtu} = \mathbf{352,600\ btu/mmbtu}$$

Sulfuric acid:

According to personal communication with IGPC, the plant uses 3.11 million kg sulfuric acid per year. This value was divided by the ethanol production (100MGPY) to give a value of 0.408 kg/mmbtu. This value is greater than the use dictated by GREET (0.0616 kg/mmBtu). A comparison between GREET, IGPC and the ecoinvent database is given in Table 6-2.

$$\frac{3.11x10^6 kg\ H_2SO_4/year}{100x10^6\ gal\ ethanol/year} * 13.101\ \ gal/mmbtu = \mathbf{0.408\ kg\ H_2SO_4/mmbtu}$$

Water use:

Water use was also taken directly from IGPC with reported usage at 21.14 lb water/ bushel of corn (lb/Bu) plus an additional 44.64 lb/Bu of process steam. Personal communication with IGPC determined 440 gallons of water per minute is received from the city, and that converts to the facility using 2.16 gallons of water per gallon of ethanol. This is lower than GREET's water use for dry mill facilities using corn oil extraction.

Industry Average (GREET): 36.16 gal water/mmBtu (2.76 gal water/gal ethanol)
IGPC: 28.30 gal/mmBtu (2.16 gal/gal ethanol)

Sodium Hydroxide:

The neutralizing agent use was provided by IGPC as 1.434 million kg/year, which equates to 0.188 kg/mmbtu. GREET dictates a value of 0.2958 kg/mmbtu. These values differ by a large margin and are outlined in Table 6-2.

$$1.434\ million\ kg\ NaOH/year$$

$$\frac{1.434x10^{6} kg\ NaOH/year}{100x10^{6}\ gal\ ethanol/year} * 13.101\ \ gal/mmbtu = \mathbf{0.188\ kg\ NaOH/mmbtu}$$

Urea, as N:

IGPC uses urea as a nitrogen source for yeast and the facility uses 2785 kg of urea per fermenter (at a 50% concentration) (primary data from IGPC). IGPC budgets to produce 1258 fermenters per year (for approximately 100 million gallons of ethanol per year). This yields 0.237 kg urea per mmbtu of ethanol. The GREET database uses ammonia as the nitrogen source for the yeast and consumes 0.2358 kg/mmbtu (based on 18 grams/gal ethanol). The comparison can be seen in Table 6-2.

$$2875\ \ kg/ferm * 1258\ ferm./year\ \ * 50\% = 1.81x10^{6} kg/year$$

$$\frac{1.81x10^{6} kg/year}{100x10^{6} gal/year} * 13.101\ \ gal/mmbtu = \mathbf{0.237\ kg\ urea/mmbtu}$$

Water (emission to air):

This water emission is an emission to air, generally in the form of steam, and is taken from IGPC's mass balance. This corresponds to the water given off by the DDGS dryer stack and the regenerative thermal oxidizer and is equal to 14.86 lb water/Bu (32.25 kg/mmbtu).

Water (emission to water):

The plant also emits water into local water sources through wastewater treatment. The wastewater is emitted to the environment following treatment. This discharge was calculated using a water balance for the facility. As mentioned, IGPC receives 440 gal/min from the city water utility, this water is used to process the corn into ethanol, which necessitates water also being discharged.

$$\frac{440\ \ gal/min}{72\ Bu/min} = \frac{6.11\ gal\ water/Bu}{2.83\ gal\ ethanol/Bu} = 2.16\ gal \frac{water}{gal} ethanol$$

The mass balance of water includes the water from the corn input as well as the water received from the city, while the total water output involves the water imbedded in the feeds (moisture content of DDGS, Hi-Pro and Fiber plus syrup), the water emission to air (from the thermal oxidizer and the regenerative thermal oxidizer), and the water emission to water. The water emission (to water) is calculated as the difference in the water balance mentioned above, which was 80.83 kg H_2O per mmbtu of ethanol. This water is emitted to the water treatment plant and was outlined as a negative input in order to follow the waste logic method for LCAs.

$H_2O_{in} = H_2O_{out}$

$H_2O_{corn} + H_2O_{from\ tap} = H_2O_{feeds} + H_2O_{RTO/TO} + H_2O_{wastewater}$

0.40 gal H_2O/gal ethanol + 2.16 gal/gal = 0.65 gal/gal + 0.35 gal/gal + $H_2O_{wastewater}$

$H_2O_{wastewater}$= 1.63 gallons of water per gallon of ethanol

$$1.63\ \frac{gal\ H_2O}{gal\ ethanol} * 13.101\ \frac{gal\ ethanol}{mmbtu} * 3.785 \frac{L}{gal} = 80.83\ \frac{kg\ H_2O}{mmbtu\ ethanol}$$

DDGS:

IGPC Ethanol produces the following feed products at its facility: DDGS, Hi-Pro and Fiber plus syrup. These products have slightly different uses and market values however the typical feed produced at dry mill facilities across North America is DDGS only. GREET and Ecoinvent databases contain only information on DDGS production, therefore, the three products produced at IGPC Ethanol are combined into one flow, DDGS.

As shown in Table 6-1, the co-product production given for IGPC, which is based on the 3 combined feeds (48.27 kg/mmbtu) is over 10% lower than the industry average given by GREET for corn ethanol facilities with corn oil removal (55.93 kg/mmbtu). This could be due to the strain of corn used or the slightly different processing technique employed at IGPC.

Table 6-1: Mass flowrate of wet feed co-products produced at IGPC

Feed co-products	Volume Produced IGPC (kg per mmbtu of ethanol)	GREET Feed Products (kg per mmbtu of ethanol)
DDGS	17.59	55.93
Hi-Pro	6.34	-
Fiber with Syrup	24.3	-
Total	**48.27**	**55.93**

IGPC Lifecycle Inventory

The inputs, outputs and emissions for the IGPC facility are presented in Table 6-2. This allows for comparisons to be made between IGPC data and the databases for GREET and the Ecoinvent process. The GREET database is updated regularly, while the Ecoinvent process is based on data from 1990 to 2006. Since some technology has advanced, especially with respect to energy and water use, some discrepancies can be seen. The data for the openLCA process was taken from IGPC when available and supplemented with GREET when necessary.

Table 6-2: Comparison between input amounts from GREET, IGPC and Ecoinvent are shown

Inputs (per mmbtu)	**IGPC**	**Ecoinvent**	**GREET**
electricity, medium voltage (btu)	24,130	53,620	26,070
electricity, medium voltage (CO_2 capture)	970	-	-
ethanol fermentation plant (items)	-	1.98E-08	-
heat, district or industrial, natural gas (btu)	352,570	520,630	370,260
Enzyme, alpha-amylase (kg)	.0333	-	.0055
Enzyme, glucoamylase (kg)	.0456	-	.0025
maize grain (kg)	117.6	127.6	115.6
sulfuric acid (kg)	0.408	0.951	0.0616
tap water (kg)	107.1	167.1	136.9
transport, tractor and trailer (t*km)	1.18	1.28	-
Nitrogen (urea or ammonia) (kg)	0.237	0.382	0.236
neutralizing agent, NaOH (kg)	0.188	-	0.296
Wastewater, from residence (kg)	-80.83		

Outputs (per mmbtu)	**IGPC**	**Ecoinvent**	**GREET**
Corn Ethanol Production (btu)	$1x10^6$	$1x10^6$	$1x10^6$
Carbon dioxide, non-fossil (kg)	22.71	13.66	23.20
Water, to air (kg)	32.25	31.1	-
DDGS, wet (kg)	48.27	-	55.93
Corn Oil (kg)	1.25	-	1.13

6.2 LCI for Novel Biorefinery

The LCI for the novel biorefinery can be divided into two parts; changes to existing inputs and implementation of new processes for the treatment of thin stillage and algae cultivation. The former identifies changes in natural gas and water use to the existing method.

The processing of the thin stillage in the novel biorefinery will be modelled as thin stillage treatment. This includes the primary filtering, anaerobic digestion, struvite recovery, aerobic digestion followed by algal cultivation. This is done so that changes to the treatment of the thin stillage can be done as a system and modelled within openLCA.

In order to model the process in openLCA the energy use, sludge volume, biogas volume and composition, and characteristics of the wastewater need to be determined. Energy will be required for filtering, pumping, aerating, hydrogen sulfide treatment as well as algal cultivation. The process created in openLCA is based on the treatment of bio-waste by anaerobic digestion and modified with literature research and relevant data.

6.2.1 Changes to Existing Process Inputs

Heat, Natural gas:

The natural gas use for the novel biorefinery was reduced due to the methane produced in the anaerobic digester and the decrease in energy required for processing the thin stillage. The natural gas use for the process decreased from 347.1 GJ/hr (352,600 btu/mmbtu) to 238 GJ/h (241,720 Btu/mmbtu) in the novel biorefinery, which is a 30% decrease in natural gas use. This is due to the energy changes in processing the thin stillage.

Table 6-3: Natural gas use for IGPC and the novel biorefinery

IGPC Natural Gas Use:	**IGPC**	**Novel Biorefinery**
Grain Handling and Milling	25.8	25.8
Ethanol Distillation	87.6	87.6
Evaporators	85.0	0
Dryer A & B (DDGS)	66.5	45.5
Dryer B (Hi-Pro)	34.8	34.8
Dryer C & RTO	36.9	36.9
Dryers (TOTAL)	**138.2**	**117.2**
HRSG (A side steam)	3.9	2.0
CB Boiler (B side steam)	2.8	1.4
Steam Turbine Generator	3.9	3.9
Total (GJ/h)	**347.1**	**238**
Btu of natural gas/mmbtu ethanol	**3.53x10^5**	**2.42x10^5**

The energy use was impacted by the elimination of the evaporators, the reduced volume entering the co-product dryers and the reduced steam generation for the process. IGPC consists of three drum dryer trains, dryers A & B receive wet DGS for drying, while Hi-Pro is dried using dryers A, B or C. Therefore, only dryer A & B receive thin stillage and will be affected by the change in DDGS composition. In order to account for the reduced volume of steam required for drying, the natural gas use for the heat recovery steam generator (HRSG) and the Clever-Brooks boiler was modified. These two units use electricity and natural gas to produce steam for use within the plant, with the reduction in drying, a lower capacity of steam is required.

The steam use within the plant was determined using a mass and energy process flow diagram for IGPC, as well as doing an energy audit for the individual units within the plant. The steam use for each unit was calculated and used to determine the natural gas use required for producing steam for the facility. According to the developed mass and energy balance, almost 50% of the steam used within the plant is for the evaporation of thin stillage, the decrease in steam use directly decreases the natural gas that is used for steam production by 48%.

Table 6-3: Steam use within IGPC and the novel biorefinery

Process Unit	**IGPC Steam Use (MJ/L)**	**Novel Biorefinery Steam Use (MJ/L)**
Slurry Tanks	0.18	0.18
Evaporator	1.84	0
Distillation	1.42	1.42
Cook Water Tank	0.15	0.15
Others	0.26	0.26
Total (per L)	**3.83**	**1.99**

The total natural gas use in the plant decreased by 31% when accounting for the evaporators, dryers and steam use. The anaerobic digester in the novel biorefinery also produces methane from the biogas and this also needs to be included in the natural gas inventory. The production of biogas in the AD will offset natural gas used in the plant and further reduce the natural gas required. Research by Sayedin et al., (2018) achieved a methane production of 0.31 L CH_4/g total chemical oxygen demand (COD) removed from the thin stillage. Using the thin stillage flow rate (240,000 kg/h), COD removal rate (92.5%) and the lower heating value of methane (35.8 kJ/L), a methane production rate of 170 GJ/h was determined. The methane produced was multiplied by its lower heating value in order to compare to natural gas use within the plant.

$$0.31\,L\frac{CH_4}{g}TCOD * 68.9\,kg\frac{COD}{L}thin\ stillage * 240{,}000\ \frac{kg\ thin\ stillage}{h}$$

$$* 92.5\%\ COD\ removal * 35.8\frac{kJ}{L}$$

$$= 169.8\ GJ/h$$

This led to the total natural gas use for the novel biorefinery to be reduced to 68 GJ/h (69000 btu/mmbtu) or a reduction in an 80% reduction in natural gas use from the IGPC corn ethanol facility (347 GJ/hr to 68 GJ/h).

Table 6- gives the methane production from the AD in the novel biorefinery. The AD converts organic matter in the thin stillage into biogas. The methane in the biogas is used to supplement the natural gas use within the plant; this is subtracted from the natural gas required.

Table 6-5: Methane production from thin stillage (Sayedin et al., 2018)

Methane Production	0.31 L CH_4/gTCOD
Thin Stillage COD	0.0689 kg COD/ thin stillage
Thin Stillage Flow (total)	240,000 kg/h
COD Removal Rate	92.50%
Lower Heating Value (CH_4)	35.8 kJ/L
Density (approximate)	1.0 kg/L
Methane Production	**169.8 GJ/h**
	0.182 GJ/mmbtu

Maize grain use:

The maize grain use in the novel biorefinery is supplemented by the algae produced in the system. Sayedin et al., (2018) was able to achieve a biomass concentration of 1.62 g algal biomass per litre of thin stillage (on day 18), which consisted of 17.8% starch, 37.8% protein and 8.9% lipid for *Chlorella sorokiniana*. While the fat and protein will contribute to the DDGS, the starch content of algae will displace a portion of corn for the process. The biomass productivity is fairly low, producing 780 kg/h (0.834 kg/mmbtu ethanol).

The corn cultivation stage has the highest impact on the LCA with fertilizer and pesticide use being two of the most prominent processes in this stage (Pieragostini et al., 2014). The displacement of corn by algae allows for the reduction in fertilizer, nutrients and corn drying which has reduces the lifecycle impacts of the process through fossil energy use and human impacts from chemical use. Furthermore, land use change is a major impact on the corn ethanol LCA (Muñoz et al. 2014; Pieragostini et al., 2014). The novel biorefinery can reduce the harvested area of the corn crop by implementing the novel biorefinery, and therefore reduce the lifecycle impacts.

By using the relative starch content of the algae (17.8%) and corn (70%), this led to a replacement of 0.18% of the corn input. The maize use for the process changes slightly from 117.6 kg/mmbtu ethanol to 117.3 kg/mmbtu ethanol for the novel biorefinery. Further research will also utilize the waste steam from other sources, such as agricultural waste, in the AD which will increase the amount of algae able to be produced. Analysis will be completed to determine the volume of agricultural waste required that would have a significant impact on the corn required for the novel biorefinery, in this case a replacement of 5% of the corn used for the process will be used for the benchmark. This will be done to determine if the co-digestion of agricultural waste will have an impact in the volume of starch-rich corn required for the process and is investigated in the sensitivity analysis. This supplementation of digestate would be beneficial due to the close proximity to cattle feedlots and the existing relationship used for the DDG(S) co-product.

The displacement of corn can also be increased if we assume the starch portion of the algae biomass was able to achieve starch content as high as 27%, as reported in Li et al. (2015). However, this method alone would only increase the biomass productivity by 51%, or a reduction in corn use to 117.26 kg/mmbtu, which is virtually the same result as with the starch content achieved by Sayedin et al (2019). Another method that should be investigated to increase the corn displacement is by increasing the biomass productivity of the algae on thin stillage digestate. Sayedin et al. (2019), was able to achieve a biomass productivity of 1.62 g/L on two times diluted struvite removed digestate. Improvements to this productivity would directly impact the results of the LCA by reducing the corn required. A combination of the effects of these changes is presented in the sensitivity analysis of this report.

DDGS Feeds:

The feeds produced by IGPC consist of fiber plus syrup, DDGS and HiPro, but for the lifecycle assessment, the total volume going for animal feed product will be accounted for under DDGS. The total volume produced in the biorefinery changes due to the removal of thin stillage syrup from the streams. Fiber plus syrup becomes only fiber while DDGS becomes DDG. The total volume goes from 48.3 kg of DDGS per mmbtu of ethanol to 36.4 kg DDG per mmbtu of ethanol, due to the elimination of thin stillage syrup. The impact of the nutritional value of DDG compared to DDGS was also investigated to see if the market value of the DDG will be reduced.

Research by Drosg et al., (2013) concluded that DDG contains a higher protein content than DDGS due to the thin stillage conventionally added having a lower protein content compared to the wet cake. The higher protein content would lead to an increased market price for DDG in comparison with DDGS (Belyea et al., 2006; Y. Kim et al., 2008). Therefore, the market value for DDG should be at least similar to the value of DDGS.

The production rates for each feed product was specified for IGPC and used to calculate for the novel biorefinery. The Hi-Pro production does not change as no CDS (or thin stillage) is added to this stream. The DDGS production for the novel biorefinery was calculated for the DDG product being produced at the same moisture (total solids) content as IGPC Ethanol's DDGS. The volume of DDG produced decreases as the thin stillage stream (12.46 lb/Bu) is no longer added to the feed, as shown in Table 6-. At IGPC, 6.23 lb of thin stillage per bushel is added to the DDG which represents the majority of moisture content (40% total solids) of the DDGS. The DDG at the novel biorefinery will be dried to the same total solids content (89%) as the DDGS, which results in a DDG feed production of 5.56 lb/Bu. However, an additional stream is available to the DDG production; solids from the filtering the thin stillage prior to anaerobic digestion. These solids are removed during the thin stillage processing but would conventionally end up in the CDS so should have no negative effects on the DDG product. This increases the volume of DDG produced to 8.94 lb/Bu.

For the fiber stream, the CDS (6.23 lb/Bu) is no longer added so the volume of fiber (without syrup) produced was reduced by this amount (to 5.35 lb/Bu). As mentioned, the product is measured as a factor of producing DDG alone, the total feed co-product is reduced from 48.3 kg/mmbtu to 36.4 kg/mmbtu.

Table 6-6: Feed co-products for IGPC and the novel biorefinery

Feed Co-products

DDG(S) Production (lb/Bu)	**Flow into Dryer**	**Flow out**
IGPC Facility	19.28 (38.6% TS)	8.37 (89% TS)
Novel biorefinery	16.43 (37.9% TS)	8.94 (89% TS)

Hi-Pro Production (lb/Bu)	**Flow into Dryer**	**Flow out**
IGPC Facility	7.7	3.03
Novel Biorefinery	7.7	3.03

Fiber Feed	**Flow into Dryer**	**Flow out**
IGPC Facility	11.58	11.58
Novel Biorefinery	5.35	5.35

IGPC output and Novel Biorefinery Output

Total for feeds	**lb/Bu**	**kg/h**	**kg/mmbtu**
IGPC Facility	22.98	45020	48.25
Novel Biorefinery	17.32	33930	36.38

Electricity Use:

A detailed breakdown was done for each component in the IGPC based on the changes for the novel biorefinery. The energy use for drying the DDGS decreases, the evaporators are eliminated, and the electricity used for generating steam is decreased. The changes for the biorefinery have less of an impact on electricity use than natural gas because the processes upstream of co-product handling (milling, fermentation and ethanol distillation) use the majority of the electricity within the plant. The electricity use was determined to be reduced from 241,000 btu/mmbtu of ethanol to 218,000 btu/mmbtu (9% reduction).

The electricity use breakdown is presented for the IGPC and the novel facility. This only includes the changes to the existing electricity used at IGPC. The electricity use was calculated similar to natural gas use with the changes incurred for the drum dryers, evaporators and electricity use for generating steam.

Table 6-7: The breakdown of electricity within the plants

Energy Use: kWh	**IGPC**	**Novel**
Grain Handling and Milling	1890	1890
Fermentation	1600	1600
Distillation and Ethanol Dewatering	1090	1090
Evaporators	200	0
Dryer A & B (DDGS)	390	267
Dryer B (Hi-Pro)	100	100
Dryer C & RTO	560	560
Dryers (TOTAL)	**1050**	**927**
Centrifuge	370	370
HRSG (A side steam)	340	177
CB Boiler (B side steam)	340	177
Steam Turbine Generator	-800	-800
Electricity use (kWh)	6600	6004
Electricity use (btu/mmbtu)	**2.41x10^{4}**	**2.18x10^{4}**

Corn Oil:

The corn oil removal at IGPC occurs during the evaporation of thin stillage to condensed distillers solubles, also known as back-end corn oil extraction. With the removal of the evaporator from the novel biorefinery, the corn oil is no longer able to be extracted from the thin stillage syrup and is now extracted through front-end extraction as introduced in Chapter 2. Corn oil extracted from the front-end of the process, opposed to the back-end, is suitable for human consumption (Reis et al., 2017), this increases the markets available for sale.

An additional benefit of front-end extraction is that 1.2-1.4 lb of corn oil per bushel of corn can be extracted; this is in contrast to the 0.61 lb/Bu extracted at IGPC using back-end extraction. Back-end corn extraction typically does not remove as much oil as the front-end extraction because some oil is maintained in the thin stillage to allow a higher fat content for the DDGS. Since the thin stillage is no longer added to the DDG, more oil can be removed. An average of 1.3 lb/Bu was chosen, which is converted to a mass per million btu of ethanol produced. This gives a value of 2.73 kg/mmbtu (compared to 1.25 kg/mmbtu for IGPC).

Water Use:

Sayedin et al. (2018) found that the thin stillage must be diluted two times to make an appropriate media for algae cultivation. Dilution was required due to the inhibitory effect of ammonia on microalgae cultivation. This would require a significant amount of dilution water, equivalent to the flow of thin stillage (120,000 kg/h).

However, additional research has shown that anaerobic digestion coupled with aerobic digestion should be able to reduce ammonia concentration to below the level of inhibition for *chlorella sorokiniana* (Praveen et al., 2018). The results from this and similar studies is discussed in Chapter 2. Further research is still required to ensure that aerobic treatment will be able to bring the ammonia concentration for treated thin stillage digestate to a level sufficient for algal cultivation. This negates the requirement of extensive dilution water.

A water balance for the novel biorefinery was conducted to ensure water conservation. The treated digestate is recycled to the front end of the process with the algae biomass in the novel biorefinery. This creates an additional stream of 257.5 kg water/mmbtu to the process that would normally be discharged through the thermal oxidizer (through thin stillage evaporation) or directly through wastewater treatment. At IGPC, 107.1 kg of water/mmbtu is added to the process in order for fermentation to occur, along with 95.7 kg thin stillage/mmbtu that is normally recycled as backset. This means the water typically added at IGPC can be entirely composed of the recycled process water (after undergoing anaerobic digestion and aerobic treatment), with the leftover process water being released as an emission, without requiring further wastewater treatment. This negates the need for an external water source aside from make-up water. Make-up water was estimated to be equal to 10% of the water required for the conventional facility, this water loss is a result of thermal oxidizers, DDG dryers and distillation. Further research should be done to investigate the build-up of potentially inhibitory compounds within this recycling loop. Of note, the mass balance of water use has some discrepancies with regard to water discharge at IGPC, and this is a result of water losses and water leaving the facility incorporated in animal feeds. The overall wastewater discharge at IGPC Ethanol and the novel biorefinery are 80.83 kg/mmbtu and 54.7 kg/mmbtu, respectively.

Table 6-4: Water balance at IGPC and the novel biorefinery

Water use	IGPC (kg/mmbtu)	Novel biorefinery (kg/mmbtu)
New water used in process	107.1	10.7
Backset from thin stillage	95.7	-
Water recycled in novel biorefinery	-	257.5
Water emission to air (T.O.)	32.25	-
Wastewater discharged	80.83	54.7

Enzyme and process inputs:

These are the inputs for the processing of corn into ethanol, the novel biorefinery will use essentially the same amount for corn processing, as the corn input is not significantly impacted. This includes sulfuric acid, sodium hydroxide, glucoamylase, and alpha-amylase. The recycling of process water in the novel biorefinery is predicted to replace the requirement of urea for yeast growth during fermentation. Research has shown that recycling digestate water, under toxic levels, can represent economic savings for an ethanol plant not only for decreasing the water input, but also on the replacement of the traditional urea used as nitrogen source to nitrogen sources derived from AD (Reis et al., 2017; K. Wang et al., 2013). This impacts the upstream environmental and economic costs associated with urea production.

The corn ethanol process requires the use of enzymes such as glucoamylase, and alpha-amylase, however the ecoinvent database, as well as similar studies (Pieragostini et al., 2014) does not take them into consideration in their process. They were included in this study as they may constitute an impact to the LCA. The same volumes were used for both the IGPC and the novel biorefinery LCA. There is no indication that any other process inputs, other than urea, will be significantly impacted given the small percentage change in corn use.

6.2.2 Thin Stillage and Algae Cultivation Processes

Thin Stillage Filtering

Thin stillage contains organic matter in suspension and the solids content of the received thin stillage is very high, therefore direct feeding of the anaerobic baffled reactor with thin stillage may cause clogging in the system (Sayedin et al., 2018). Solids removal from the thin stillage prior to anaerobic digestion and struvite recovery is required in order to reduce the total solids in the thin stillage so it can be treated in the anaerobic digester. Removal of this matter may be accomplished by physical, chemical and biological methods. The method used depends upon the degree of treatment required. Settleable organic and inorganic materials in the raw stream are frequently removed by gravitational sedimentation or filtration (Edmonds,1965).

It is suggested that sedimentation of the solids is able to appropriately reduce the solids present in the thin stillage to a level acceptable for anaerobic digestion. The stillage is primarily liquid (8% solids) with a total solids content of 59.8 g/L (Sayedin et al., 2019). Physical sedimentation would allow for the collected solids to be dewatered and added to the DDG feed. The IGPC Ethanol facility currently has a thin stillage tank with a volume 553,000 kg of thin stillage, which would allow for a sedimentation period of 2 hours. The analysis on the filtered thin stillage, which was used in the experimental procedure, was found to be 32.2 ± 0.4 g of total solids per liter. The solids that result from the primary filtering can be calculated as the difference in total solids between the filtered and unfiltered samples and multiplied by the flow rate of thin stillage (from primary data) per mmbtu of ethanol produced. This stream can be added to the DDG stream because it would also be present in the DDGS in the conventional plant. This creates a DDG stream of 36.4 kg DDG/mmbtu as outlined in DDGS production.

Struvite Production

The precipitation of struvite in the novel biorefinery needs to be accounted for in the lifecycle assessment. Struvite is produced as a fertilizer and can negate the use of other mineral fertilizers for industrial use. The resources and emissions avoided for the production of industrial fertilizer are calculated from production data for "monoammonium phosphate" (MAP) available in the Ecoinvent database, which assumes that nitrogen and phosphorus in struvite can replace these nutrients in MAP on a 1:1 basis (Bauer, Cheng, & Colosi, 2019). MAP was chosen as the displaced fertilizer because it has similar nutrient characteristics to struvite.

The production of MAP in Ecoinvent is given as two sets; per kg nitrogen and per kg phosphate. These two must be produced together, with "MAP, as nitrogen" being produced to displace nitrogen fertilizer, and "MAP, as P_2O_5" being produced to displace phosphate fertilizer, this is confirmed by the Ecoinvent database, which states that the two products must always be used simultaneously. As explained in Bauer et al. (2019), the allocation for each MAP process was based on struvite being able to replace the fertilizer on a 1:1 basis.

In many cases in struvite recovery, particularly those where animal and agricultural waste is the main source of N and P, Mg must be supplemented into the system to promote crystallization (Sengupta, Nawaz, & Beaudry, 2015). Magnesium was added in the form of $MgSO_47H_2O$ in order to match the molar concentration of phosphorus. Some magnesium was available from the thin stillage (529 mg/L) but this was supplemented with additional magnesium sulfate (4230 mg/L), this brought the total Mg concentration to 42.4 mmol.

The trials completed by Sayedin et al. (2019) were able to recover 75% of the magnesium from the treated digestate which led to a recovery of 3440 mg/L of digestate. For these trials, the struvite precipitation occurred after anaerobic digestion, this led to the partial precipitation of struvite in the AD. This can cause build-ups in the digesters and efficiency losses for the recovered struvite, therefore the novel biorefinery will precipitate struvite prior to the AD, which can increase the recovery efficiency. Because the struvite precipitated in the AD will be limited in this method, the struvite recovery efficiency will be based on large scale crystallizers. The phosphorus removal efficiencies through struvite precipitation varied from 70-90% depending on the feedstock used (Desmidt et al., 2015; Kataki, West, Clarke, & Baruah, 2016). Other parameters including pH and molar ratios of Mg:P influence the recovery of struvite (Sayedin et al., 2019). For this analysis, all precipitated struvite was considered recovered, and the struvite precipitation efficiency was based on a phosphorus removal efficiency of 85%, within the range of other studies. For this reaction, the limiting reagent (in terms of mmol) was multiplied by the recovery efficiency of 85% to give the total concentration (in mmols) of struvite recovered. Using the same recovery efficiencies, a recovery of 8839 mg/L of digestate was achieved based on processing 257.5 L thin stillage per mmbtu of ethanol, this creates a product of 2.28kg struvite/mmbtu of ethanol.

Table 6-5: Thin stillage composition for the biorefinery after magnesium addition and struvite recovery

	Prior to Magnesium Addition		**After Struvite Removal**	
Thin Stillage Composition	**Concentration (mg/L)**	**Concentration (mmol/L)**	**Concentration in filtrate (mmol/L)**	**Concentration in Filtrate (mg/L)**
NH_3-N	1960	69.9	28.8	808
Total Phosphorus	1496	48.3	7.2	224.4
Magnesium	629	42.4	1.3	32.1
$MgSO_4$ 7H2O (added)	**4230**	-	-	-
Struvite Recovered	**-**	-	36.0	**8839**

This can be modeled differently depending on the co-product credit method. For system expansion, the struvite will be modeled as an avoided product for industrial fertilizer, monoammonium phosphate. As mentioned, there are two different processes for displacement of nitrogen or phosphate, however the two are in the same product and thus are displaced together. The thin stillage treatment process will produce the two products for MAP.

Table 6-6: Struvite displacements for the LCA model

Product for struvite Recovery	**Volume per mmbtu**
MAP, as P_2O_5	2.28 kg/mmbtu ethanol
MAP, as N	2.28 kg/mmbtu ethanol

Magnesium source

Struvite is utilized as a product but also precipitated out to avoid accumulation within the reactors. Sayedin et al., (2018) was able to naturally precipitate out phosphorus and nitrogen in the form of struvite and determined that the limiting reagent in the precipitation was magnesium. The thin stillage was found to have a magnesium concentration of 25.9 mmol (629 g/L) which was significantly lower than the molar concentrations of NH_3 and total phosphorus (TP) of 69.9 and 43.3 mmol, respectively (Sayedin et al., 2019). Magnesium sulfate ($MgSO_4 \bullet 7H_2O$) was added in order to match the molar concentration of phosphorus in the thin stillage. An additional 16.5 mmol of Mg was added to better match the molar concentrations and promote the precipitation of struvite. The magnesium concentration calculated below can be compared to the phosphorus and nitrogen concentrations found in Table 6-5. As shown, this required 4.23g $MgSO_4 \bullet 7H_2O$ per L thin stillage (0.82 kg/mmbtu ethanol).

$$\frac{4230 \frac{mg\ MgSO_4 \cdot 7\mathrm{H_2O}}{L}}{246.47 \frac{g}{mol}} = 17.2\ mmol/L\ MgSO_4$$

$$17 \frac{mmol}{L} Mg + 26 \frac{mmol}{L}\ Mg = 43\ \ mmol\ Mg$$

Energy Use for Struvite Recovery

The energy use for the struvite recovery was determined from similar industrial processes. For the nutrient recovery from municipal wastewater, pH and magnesium dose is used to control the process. The process for struvite recovery was modeled using extractive nutrient recovery, in which energy and resource are used to accumulate and produce a nutrient product (struvite) that has value in a secondary market (Theregowda, González-Mejía, Ma, & Garland, 2019). Westerman (2009) estimated electricity costs for struvite recovery from anaerobically treated hog effluent at 2.26x10^7 J/kg struvite recovered. However, under industrial treatment, the energy use for the process averaged 6.4x10^8 J/ton (7.1x10^5 J/kg) struvite recovered (Theregowda et al., 2019). This value was used to calculate the amount of electricity used to precipitate and capture struvite for the novel biorefinery, based on the recovery of 2.28 kg struvite/mmbtu of ethanol. This yields an energy use of 1.6x10^6 J/mmbtu ethanol (1514 btu/mmbtu ethanol).

$$7.1x10^5\,J/kg\ struvite\ x\ 2.28\ \ kg\ struvite/mmbtu = 1.6x10^6 J/mmbtu$$

Anaerobic Digestion

The energy use for the anaerobic digestion of thin stillage consists of the energy used to pump and recycle the effluent, as well as the energy to treat the hydrogen sulfide from the 1st chamber of the ABR. Hydrogen sulfide was found to be mainly contained within the first chamber of the ABR, therefore this will be the stream that requires H_2S scrubbing. According to Sayedin et al. (2018), at an OLR of 3.5 kg COD/m^3d, approximately 45% of COD removal occurs in the 1st chamber of the novel ABR. This also makes the first chamber the most productive in terms of producing biogas.

Biogas is composed of mainly methane and carbon dioxide with varying concentrations of hydrogen sulfide, ammonia, water vapour, oxygen, etc. The removal of these contaminants, especially hydrogen sulfide and carbon dioxide will significantly improve the quality of biogas. In the case of H_2S removal, it is required in order to avoid the corrosion and mechanical wear on upstream units. Carbon dioxide is typically removed because its presence reduces the energy density of the biogas.

For H_2S removal, the upgrading process takes place in conventional gas-liquid fluid contactors (packed bed or spray towers) using physical absorption or aqueous chemical solutions to convert H_2S to elemental sulfur or metal sulfide (Cosoli, Ferrone, Pricl, & Fermeglia, 2008). The physical process normally takes place in water or organic solvent.

The biogas upgrading process is outlined in the Ecoinvent process "biogas purification to methane 96% by volume." The process outlines the electricity consumption and emissions from the raw gas compression, H_2S removal, gas conditioning and methane enrichment of biogas.

Table 6-7: Process inputs and outputs for biogas upgrading as defined in Ecoinvent

Process Inputs	**Amount**
Biogas	1.5 m^3
Chemical factory (construction)	4.0×10^{-10} items
Electricity, medium voltage	0.5 kWh

Process Outputs	**Amount**
Carbon Dioxide	0.866 kg
Hydrogen Sulfide	3.49×10^{-6} kg
Methane, 96% by volume	1.00 m^3
Methane, non-fossil	0.0222 kg
Sulfur dioxide	5.5×10^{-4} kg

These inputs and outputs are for the production of 1.00 m^3 of 96% methane from 1.5m^3 of biogas. The production of biogas for the novel biorefinery is 0.31 L CH_4/ g $COD_{removed}$, with the ABR being able to remove 91.8% of the total COD in the filtered thin stillage (64.1 g$COD_{removed}$/L thin stillage) (Sayedin et al., 2019). The composition of biogas is primarily methane and carbon dioxide, 60-70% and 30-40%, respectively. Assuming the biogas is 65% methane, this means the total biogas produced would average around 0.48 L biogas/g $COD_{removed}$. The total flow of thin stillage in the novel biorefinery is based on the mass balance and is equal to 257.5 kg/mmbtu of ethanol.

$$\frac{0.31\ L\, CH_4/g\ COD_{removed}}{65\%\ methane} = 0.477\, L\ biogas/g\ COD_{re}$$

$$0.477\, L\ biogas/g\ COD_{re} * 64.08\, g\ COD_{re}/L\, thin\, stillage\ = 30.56\, L\ biogas/L\, t.s.$$

$$30.56\, L\ biogas/L\, thin\ stillage * 257.5\, kg\ thin\, stillage/mmbtu\, ethanol = 7.87\ m^3/mmbtu$$

The process will create 7.87 m^3 of biogas per mmbtu of ethanol. Based on the COD removal, the biogas produced in the 1st chamber should yield 45% of the total biogas (3.54 m^3/mmbtu). The 1st chamber is hypothesized to be the only chamber that requires scrubbing due to its high H_2S concentrations. This can be used to modify the Ecoinvent biogas upgrading process, the electricity use for the scrubbing of biogas will ultimately be 1.2 kWh/mmbtu (3990 btu/mmbtu).

To model this in openLCA, the methane production was used to displace the natural gas use within the plant. The methane production is accounted for in natural gas consumption, and therefore the process used here will not include an output for methane production. The calculation for biogas production above is simply to determine the energy costs for H_2S gas treatment, which is included in the thin stillage processing.

Aerobic Treatment Energy Use

Aerobic treatment will be incorporated following the anaerobic digestion of the thin stillage. In previous studies, the AD treated thin stillage had to go through significant dilution in order to overcome algal inhibition (Ayre et al. 2017; Sayedin et al. 2019; Uggetti et al. 2014). This dilution causes environmental impacts and also creates issues for water use within the plant.

The addition of an aerobic step was highlighted as a way to mitigate the high ammonia concentrations and overcome microalgae inhibition. The addition of aerobic treatment requires significant energy use, with aeration of the digestate being the primary energy user. More than 60% of contacted wastewater treatment plants consume more than half of their energy just for aeration studied (Maktabifard, Zaborowska, & Makinia, 2018). The energy consumption for different plants throughout Europe was studied and the average energy use was 1.00 kWh/kg $COD_{removed}$ with results ranging from 0.49-1.88 kWh/kg $COD_{removed}$. The smaller wastewater treatment plants generally use the higher energy rates. The aerobic treatment for wastewater treatment consumes an average of 53% of the energy used across the plants studied (Maktabifard et al., 2018), which creates a rate of 0.53 kWh/kg $COD_{removed}$ for aerobic treatment.

Similar papers researching the treatment of thin stillage by use of combined anaerobic-aerobic treatment found that aerobic treatment decreased the COD from 1.22 g/L to 0.155 g/L (Yang et al., 2017), a decrease in COD by 87%. The treated thin stillage has significantly higher chemical oxygen demand at 9.13 g COD/L thin stillage (Sayedin et al., 2019), however a similar reduction in COD was assumed. The aerobic treatment of thin stillage following AD will require 1.09 kWh (3720 btu) per mmbtu of ethanol produced.

$$9.13\ g\ COD/L * (0.87) = 7.97 g\ COD_{removed}/\,\text{L thin stillage}$$

$$7.97\frac{g\ COD_{removed}}{\text{L thin stillage}} * 257.5\ L\ thin\ stillage/mmbtu\ ethanol = 2.05\ \frac{kg\ COD_{removed}}{\text{mmbtu}}$$

$$2.05 kg\ COD_{removed} * 0.53\, kWh/kg\ COD_{removed} = \mathbf{1.09}\ \boldsymbol{kWh/mmbtu}$$

Carbon Dioxide (for utilization by algae):

The cultivation of algae on treated digestate requires a carbon source. Sayedin et al. (2018) used 2% CO_2 as the carbon source for the cultivation of *chlorella sorokiniana* and measured the CO_2 fixation. For the industrial process, flue gas from the natural gas use has a gas concentration of 10-15% CO_2 but contains other compounds which may impede algae growth. Fermentative carbon dioxide is preferred to avoid these toxins; however, this could compete with carbon dioxide already being captured.

To determine the carbon required for algae biomass a simplified calculation was used which assumes 1kg of biomass utilizes 1.88 kg of recycled CO_2 (Adamczyk, Lasek, & Skawińska, 2016). This is carbon dioxide that can be displaced from the CO_2 released to the environment during fermentation (as not all the CO_2 is captured). As previously mentioned, IGPC and their affiliates only capture about 40% of the fermentative gases, therefore 22.71 kg of fermentative CO_2 per mmbtu of ethanol is available for algae cultivation.

The algae production is based on the thin stillage flow because it provides the nutrient source for cultivation. The growth rate was determined in Sayedin et al. (2018) as 1.62g L^{-1} d^{-1} of digestate, and a dilution factor of 2 for the thin stillage was used. As shown in Table 6-8, a total of only 1.57 kg CO_2/mmbtu from fermentative CO_2 will be utilized to grow 0.83 kg algal biomass/mmbtu ethanol. This will not impede CO_2 collected as a product at IGPC.

Table 6-8: Algae production and CO2 uptake

	kg/h	**kg/mmbtu**
Thin stillage flow	240310	**257.5**
Algae Production	780	**0.83**
Carbon dioxide uptake	1464	**1.57**

Algae Cultivation

An open pond raceway was chosen for algae cultivation because of its simpler design, and lower energy and capital costs. The energy for the cultivation will include the electricity for a paddle wheel for mixing, aeration and outflow pumping, these parameters were adjusted from literature (Brentner et al., 2011). Open pond systems allow the algae to grow under natural light, as the energy and capital costs of artificial light are often prohibitive in terms of investment and operation in massive cultures (Blanken, Cuaresma, Wijffels, & Janssen, 2013).

Energy use for the open pond system varies from studies, but most studies seem to cluster between ~0.6 and 2 MJ/kg produced algae, with an average of 1.7 MJ/kg. This average is in good agreement with the baseline algae cultivation scenario recently assumed by other LCA practitioners in the default GREET algae production scenario (Handler et al., 2012).

The algae production predicted based on research by Sayedin et al., (2019) suggested a biomass productivity of 1.62 g L^{-1} d^{-1}. Other research was able to produce *Chlorella sorokiniana* at a biomass productivity of 12.0 $g/m^2/d$ on anaerobically treated cheese whey (A. Singh, Nigam, & Murphy, 2011). Therefore, with optimization, a higher biomass productivity is likely able to be achieved. Using the productivity achieved by Sayedin et al. (2019), an algae biomass productivity rate of 0.83 kg algae/mmbtu of ethanol was estimated. This means 1.41 MJ (1337 btu) of energy is required to produce the algae.

Table *6-9* shows the energy use for the thin stillage processing. As expected, aerobic treatment is the most energy intensive process. The energy use for biogas processing is reduced by only treating the biogas with significant concentration of H_2S gas (1st chamber). The electricity use was added to the process as "electricity (for processing of thin stillage)."

Table 6-9: Total electricity use for thin stillage processing:

Process Unit	**Electricity use (btu/mmbtu)**
Filtering and Pumping	negligible
Struvite Precipitation	1514
Upgrading biogas	3990
Aerobic Treatment	5080
Algae Production	1340
Total	11,929
Total (btu/L thin stillage)	46.33 btu

6.3 Nitrogen and Phosphorus Balance

Corn requires large amounts of nitrogen and phosphorus, achieved through fertilizers in order to supplement their growth. Nitrogen is used in the photosynthesis process and is present in the chlorophyll while phosphorus is involved in many critical metabolic functions in the plants cells (Johnston & Dowbenko, 2004). For this reason, a sufficient supply of nitrogen and phosphorus is required for growth.

Much of the nutrients applied to the fields during cultivation is not able to be absorbed by the corn, this results in phosphorus and nitrogen run-off. This impacts nearby waterways and can cause eutrophication, which can starve rivers and streams of oxygen. The increased demand for biofuels from corn and soybeans could result in an increase of nitrogen flux if not managed properly. The nutrient discharges from the corn-ethanol plant should also be considered as a source emission of nitrogen and phosphorus.

A nutrient mass-balance on the nitrogen and phosphorus used within the corn ethanol process can dictate the flow of the elements within the process and help to determine the concentration of the elements in wastewater and feed outputs. In terms of wastewater, the nitrogen and phosphorus present are unlikely to get removed before being introduced to the environment as a discharge. For animal feeds, such as DDGS, the nitrogen and phosphorus present can be considered an indirect discharge. This is a result of the feed being introduced to cattle or other ruminants at levels far above their ability to metabolize. Research has documented that phosphorus requirements for beef finishers cattle are met by diets containing 0.1% phosphorus. While diets consisting of DDGS and corn gluten feeds result in phosphorus concentrations of 0.4% or greater (Geisert, 2004). Therefore, the vast majority of the phosphorus required in finishing cattle can be met by corn grain alone. Excess phosphorus will be excreted by cattle and applied to fields as manure and urine and may lead to eutrophication impacts.

Corn is the main source of nitrogen and phosphorus introduced to the corn-ethanol process. In terms of elemental composition of the corn, nitrogen and phosphorus constitute 3.20% and 0.29% of the corn, respectively. These values are multiplied by the volume of corn used in the process (117.3 kg corn/mmbtu ethanol) to achieve the input rates, as shown below.

$$3.20\%\, N \times 117.3\ kg\ corn/mmbtu\ ethanol = 340.1\ \ g\ N/mmbtu\ ethanol$$

Equation 1: Sample calculation for the Nitrogen present in corn used in the corn-ethanol process

Nitrogen is also introduced to the traditional process through urea addition prior to fermentation. The nitrogen and phosphorus are removed from the ethanol process through a variety of sources including DDG(S) feeds, thermal oxidizers, wastewater discharge, and in the case of the novel biorefinery, also through struvite precipitation and algae cultivation. Phosphorus levels for DDGS, Fiber with syrup and Hi-Pro were directly reported from IGPC as 0.96%, 0.56% and 0.51%, respectively. These were multiplied by the production rate of each feed co-product per million btu of ethanol produced. The phosphorus and nitrogen removed through struvite precipitation was determined using tests on thin stillage from IGPC Ethanol. Struvite was shown to contain 411 mg of phosphorus per liter of thin stillage and 211 mg of nitrogen per liter of thin stillage (Sayedin et al., 2019). The algae cultivation removed nutrients with phosphorus and nitrogen also remaining in the recycled process water. Sayedin et al., (2019) found the algae cultivation was able to remove 125 mg/L of nitrogen and 15 mg/L of phosphorus from the treated thin stillage. These values were multiplied by the flow rate of thin stillage in order to obtain the amount removed from the process.

Overall, the total phosphorus discharged to the environment was calculated as the sum of the phosphorus within the animal feeds, wastewater and the thermal oxidizers. This is a result of very little of the phosphorus included in the DDG(S) feeds being retained by finished beef cattle. Simply put, at the traditional corn ethanol refinery, all phosphorus introduced through the use of corn and fertilizer was presumed to be later discharged to the environment. The novel biorefinery is able to utilize and redirect a portion of the phosphorus in the process through the precipitation of struvite, cultivation of algae, and recycling of process water to the front end of the process. The removal of wastewater emission from the novel biorefinery also eliminates the discharge of phosphorus through this stream, as the effluent is now used as process water.

Table 6-10: Phosphorus mass balance within the corn-ethanol processes

Phosphorus Inputs	**IGPC (g/mmbtu)**	**Novel Biorefinery (g/mmbtu)**
Corn	340.1	340.0

Phosphorus Outputs	**IGPC (g/mmbtu)**	**Novel Biorefinery (g/mmbtu)**
DDGS	168.7	121.8
Hi Pro	35.6	35.6
Fiber with syrup	124.0	57.3
Struvite	-	105.8
Algae	-	1.2
Process Water	-	4.6
Discharged through wastewater	11.7	0
Total Phosphorus discharged	**340.1**	**214.7**

In terms of the nitrogen mass balance, the flow of nitrogen was more difficult to decipher. In the corn-ethanol facility nitrogen is released through wastewater, thermal oxidizers and the animal feeds, such as DDGS. Nitrogen is provided to the process through corn use and additional nitrogen is added to the conventional process through the use of urea and backset of a portion of the thin stillage. IGPC Ethanol adds urea to the process at a rate of 0.237 kg/mmbtu of ethanol. It was determined that this nitrogen source will not be required in the novel biorefinery due to the recycling of process water (Alkan-Ozkaynak & Karthikeyan, 2011). The nitrogen levels in the animal feeds were not directly reported by IGPC Ethanol, but the nitrogen is in the form of protein and is metabolized and retained by the animal, therefore it is not discharged to the environment. The nitrogen content was determined using the crude protein content of the various feeds as well as the production rate. It was determined that crude protein has a nitrogen content of approximately 16%, this is often used as a method to determine the protein content of animal feeds (Mariotti, Tomé, & Mirand, 2008). It was also determined that nitrogen composes 1.54% of the corn (1811 g N/mmbtu) (Boone, Vasilas, & Welch, 1984). The crude protein concentrations of DDGS, fiber with syrup and Hi-Pro are 28.3%, 9.56%, and 11.2%, respectively (IGPC, 2020). A sample calculation for the determination of the nitrogen released and retained through DDGS was calculated below.

$$83.0\ g\ protein\ /kg\ DDGS\ (28.3\%) \times 16\%\ N\ in\ protein\ \times\ 17.58\ kg\ \ DDGS/mmbtu$$
$$= 796\ g \frac{N}{mmbtu}$$

Equation 2: Calculation for the amount of N in the DDGS Feed

Thermal oxidizers (T.O.) are commonly used to treat the VOC and CO emissions because they have very high destruction removal efficiencies. The major sources of nitrogen oxide emissions in the corn-ethanol process is through the use of boilers and dryers (Brady & Pratt, 2007). While exact concentrations of the nitrogen emitted through the thermal oxidizers at IGPC Ethanol is difficult to determine, the exact point of emissions is not necessarily relevant for the mass balance. At IGPC, all nitrogen and phosphorus emitted to the environment through the thermal oxidizers or wastewater are considered direct emissions to the environment and should be considered in the lifecycle assessment. In terms of the elemental emissions through DDG(S) feeds, the nitrogen in these feeds is retained and metabolized by the animal and is not considered an emission. The nitrogen concentrations for struvite, algae and the recycled process water were 211 mg N/L thin stillage (t.s.), 6.2 mg N/L t.s., and 124.7 mg N/L t.s. (Sayedin et al., 2019).

$$\frac{211\ \ mg\ N/kg\ t.s.}{1000\ \ mg/g} \times 257.5\ \ kg\ t.s./mmbtu = 54.3\ g\ N/mmbtu\ \ (struvite)$$

Equation 3: Calculation for nitrogen content of struvite per mmbtu of ethanol produced

Table 6-11: Nitrogen balance for the corn-ethanol processes

Inputs:	**IGPC ethanol (g/mmbtu)**	**Novel Biorefinery (g/mmbtu)**
Corn	1811	1806
Urea	229	-

Outputs		
DDGS	796	796
FWS	372	372
Hi-Pro	114	114
Struvite	-	54
Process water	-	2
Algae	-	32
Total N discharged	**719**	**389**

Overall the phosphorus released to the environment is decreased with the introduction of the novel biorefinery by 33%, while the nitrogen released is reduced by 46%. This represents a decrease in the environmental impacts of the process. Nitrogen and phosphorus discharges into water cause nutrient pollution and can lead to algal blooms which starve the waterways of oxygen. The phosphorus releases were considered an emission to soil as the majority is released through animal feeds. For nitrogen, the emissions were considered as an emission to wastewater, as the nitrogen in animal feeds is retained and most nitrogen is released through wastewater. By utilizing struvite precipitation and algal cultivation, the nutrients discharged to the environment can be reduced and utilized as products. These reductions in nitrogen and phosphorus will have an influence on the local eutrophication impacts of the LCA. However, for this attributional LCA, the emissions of nitrogen and phosphorus to the environment are already accounted in the DDG(S), wastewater treatment and struvite production. Addition of this emission to the life cycle inventory would result in double counting of emissions.

6.4 Total Lifecycle Inventory

The total inputs, outputs and emissions for IGPC and the novel biorefinery are presented in Table 6-12 which allows a comparison between the two processes. The inputs and outputs for the additional processing of thin stillage within the novel biorefinery is shown in Table 6-13.

Table 6-12: Process inputs, outputs and emissions data for IGPC and the novel biorefinery

Inputs	**IGPC (per mmBtu)**	**Novel Biorefinery (per mmBtu)**
Electricity, medium voltage (kWh)	24,130	21,760
Electricity, medium voltage (CO_2 capture)	970	970
Ethanol fermentation plant (items)	1.98E-08	1.98E-08
Heat, district or industrial, natural gas (btu)	352,570	69,020
Market for maize grain, IGPC (kg)	117.60	117.28
Sulfuric acid (kg)	0.408	0.408
Tap water (kg)	107.1	107.1
Transport, tractor and trailer, agriculture. (t*km)	1.176	1.176
Urea, liquid (kg)	0.237	0
Neutralizing agent, NaOH (kg)	0.188	0.188
Enzyme, glucoamylase (kg)	0.0456	0.0456
Enzyme, alpha-amylase (kg)	0.0333	0.0333
Magnesium ($MgSO_4.7H_2O$) (kg)	-	0.817

Outputs

Corn Ethanol Production (btu)	1,000,000	1,000,000
Carbon dioxide, non-fossil (kg)	22.71	21.14
Carbon dioxide, liquid (kg)	14.26	14.26
Water, emission to air (kg)	32.25	32.25
Maize grain (displaced DDGS) (kg)	53.1	40.02
Soy oil (displaced corn oil) (kg)	1.25	2.73
Wastewater (L)	80.83	
Monoammonium phosphate (MAP), as N (kg)	-	2.28
MAP, as P (kg)	-	2.28
Thin stillage (kg)	-	257.5

Of particular importance are the changes in electricity use and natural gas use between the two plants, as well as the changes in co-product production. Total electricity use will increase by 38% (from 25,100 kWh/mmbtu to 34,652 kWh/mmbtu) and natural gas will decrease by 80% (from 352,570 btu/mmbtu to 69,020 btu/mmbtu).

The inputs and emissions for the processing of the thin stillage digestate was tabulated separately from the rest of the process, this allows the processing to be calculated per unit of thin stillage. As shown in Table 6-12, thin stillage is an output for the novel process and will then serve as an input into the treatment of thin stillage processing in the novel biorefinery. The corn-ethanol process produces 257.5 kg of thin stillage per mmbtu of ethanol, and in the biorefinery this is treated to cultivate algae. The inputs for this system, per liter of thin stillage processed, are shown in Table 6-13.

The inputs for the process are straightforward, the electricity use for the thin stillage processing is taken from Table *6-9*. The anaerobic digestion plant takes into account the capital costs for producing the plant, this is based on the Ecoinvent database for "treatment of biowaste by anaerobic digestion."

Additional water for the processing of the thin stillage was another consideration for the anaerobic and aerobic treatment. It is suggested that an additional source of water will not be required as the thin stillage is at approximately 92% water with minimal solids after filtering.

Table 6-13: Inputs and emissions for the treatment of thin stillage in novel biorefinery

Inputs (per kg thin stillage)	**Amount**
Thin Stillage (kg)	1.00
Electricity, medium voltage (btu)	46.3
Anaerobic digestion plant, for biowaste (item)	$1.67\text{x}10^{-9}$

Outputs (per kg thin stillage processed)	**Amount**
Carbon dioxide, non-fossil (kg)	0.088
Dinitrogen monoxide (kg)	$3.3\text{x}10^{-5}$
Hydrogen sulfide (kg)	$3.8\text{x}10^{-6}$
Nitrogen, total (kg)	$6.2\text{x}10^{-6}$
Phosphorus (kg)	$4.8\text{x}10^{-6}$

The carbon dioxide, dinitrogen monoxide, and hydrogen sulfide are all components of the biogas produced from the AD. Absent from this list is the methane produced which is utilized as a heat source, this was already accounted for in the reduction of natural gas use for the plant. The H_2S gas is produced from the sulfate present in the thin stillage. While the hybrid ABR was able to remove 94-97% of the sulfate, some is still present in the digestate, this was calculated using the analysis by Sayedin et al. (2019). A complete biogas analysis was done based on the typical biogas composition from anaerobic digestion; this was done for the carbon dioxide and dinitrogen monoxide shown above.

The nitrogen and phosphorus emissions are a result of the nutrients remaining in the process water after the anaerobic digestion and aerobic treatment in the novel biorefinery. The nitrogen and phosphorus levels in the thin stillage after microalgae cultivation were decreased from 130.9 mg/L and 21.8 mg/L to 6.2 mg/L and 4.8 mg/L, respectively (Sayedin, et al., 2019). The cultivation of *C. sorokiniana* was able to remove 95.3% of $N\text{-}NH_3$ and 78.3% of total phosphorus which helped with algal growth as well as nutrient removal. While these nutrients will not be directly discharged to the environment (as the process water is recycled) they may accumulate, and can cause environmental issues when eventually dismissed, such as eutrophication.

One of the drawbacks of aerobic treatment is typically the sludge produced from the process needs to be treated and sent to waste. Generally, the sludge production is based on the chemical oxygen demand or the biological oxygen demand removed from the digestate, as part of the COD is converted to biomass (von Sperling, Fernandes, & Andreoli, 2007). Due to the high COD removal in the ABR, the aerobic digestion is unlikely to treat a high volume of COD so the sludge production will be limited. Additionally, there are increasing numbers of municipal and industrial treatment systems that employ anaerobic digestion to convert organic matter and bacteria biomass (e.g. excess sludge from aeration tanks) into biogas and digestate (Q. Wang et al., 2019). This means the sludge from both the AD and aerobic treatment systems can be processed in a dry AD system for the processing of solid waste, improving the recycling within the system.

6.5 Co-Product Handling

As mentioned, there are multiple methods for co-product handling for lifecycle assessments. The following values were used to allocate the environmental impacts for ethanol production by economic and physical methods. System expansion was the chosen method and was completed using DDGS replacing corn feed, corn oil replacing soy oil and carbon dioxide as a product.

Allocation Method:

Physical Allocation:

This allocates the environmental burdens based on the physical weight of each product. The product weights were taken from the mass balance for the IGPC facility.

Corn Oil: 1.25 kg (1.4%)
DDGS: 48.27 kg (54.5%)
Ethanol: 1 mmbtu or 39.1 kg (44.1%)

Economic Allocation:

The market values for the various products were obtained from GREET and from the average market price for each product over the period of 2012 to 2015 (USDA). This represents the percent of revenue that comes from each product stream, this allows us to allocate the environmental burden of the process based on the market value of the product.

Table 6-14: Market price for the IGPC Ethanol products

Product	Value	Volume	Market Allocation
Ethanol Price	$2.36/gal	39.1 kg (49.6 L)	$30.92 (70.8%)
DDGS Price	$217/ton (wet)	48.27 kg	$11.55 (26.4%)
Corn Oil Price	$0.97/kg	1.25 kg	$1.21 (2.8%)

System Expansion

This co-product method considers the co-products as avoided products. Table 6-16 displays the system expansion calculations for the novel biorefinery, this table identifies a new co-product, struvite, which is a fertilizer product. This displaces two fertilizer products, for nitrogen and phosphorus, as monoammonium phosphate. The displacement ratios are also included for the avoided products.

Table 6-15: System expansion calculations for the IGPC facility

Co-product	Amount (kg/mmbtu)	Product Uses	Displaced Product	Displacement Ratio	Volume displaced (kg/mmbtu)
Corn oil	1.25	Feeds, diesel	Soy oil	1	1.25
Feed Products	48.27	Animal feeds	Corn	1.1	53.10
Carbon dioxide	14.26	Beverage, chemical	Carbon dioxide	1	14.26

Table 6-16: System expansion calculations for the novel biorefinery

Co-product	Amount (kg/mmbtu)	Product Uses	Displaced Product	Displacement Ratio	Amount of displaced (kg/mmbtu)
Corn oil	2.73	Animal feeds, biodiesel	Soy oil	1.0	2.73
DDGS	32.25	Animal feeds	Corn	1.1	32.25
Carbon dioxide	14.26	Beverage, chemical	Carbon dioxide	1.0	14.26
Struvite	2.83	Fertilizer	MAP, as Phosphate MAP, as Nitrogen	1.0 1.0	2.83 2.83

The novel biorefinery also produces methane, a by-product which is treated and upgraded to displace natural gas in the corn ethanol plant. In effect, this is a system expansion method, however the displacement occurs within the plant. For this reason, methane production is not accounted for in the displaced co-products and is instead used to displace natural gas, this should have virtually the same effect in terms of the LCA. The same occurs for algae production, a small volume of algae (0.83 kg/mmbtu) is produced in the novel biorefinery, the starch content (17%) is available to displace corn for fermentation into ethanol. The algae biomass is not an output of the system because it instead gets utilized directly in the liquefaction at the front end of the process, in order to displace corn use and some of the nutrients required for yeast cultivation. The corn displaced also represents energy and resource savings through the savings of fertilizers, pesticides and transportation.

Chapter 7 Results of Lifecycle Assessment

The inventory data for both the IGPC facility and the novel biorefinery from Chapter 4 was used to create distinct processes within openLCA. The software allows for inventory data to be tabulated and a provider for the input selected; this allows products from around the world to be presented from the most accurate source for each input. Once the input for each process of the inventory data is chosen, a product system was able to be completed and used to present the results of the LCA. As mentioned, the impact analysis method ReCiPe Midpoint Hierarchy was chosen for this study. The inventory data is classified based on selected impact categories under the ReCiPe midpoint analysis. The relevant impact categories chosen include global warming, land use, marine and freshwater eutrophication, terrestrial acidification and water consumption. No normalization factors are available for ReCiPe midpoint, so comparisons between impact categories is not available, and the analysis will be done for each impact category. Normalization factors, when available, are useful for determining the contribution of each category to the overall lifecycle impact.

A characteristic breakdown for the individual impact categories allows for seeing the percentage contribution of each process to the total environmental impact. This helps to highlight areas that consistently incur the highest environmental impacts and helps to determine how to best reduce the effect of an impact category. The corn-ethanol process can also be broken into two separate categories, where the agricultural production processes include fertilizer and agrochemical manufacturing processes, fuel use, and the corn to ethanol processing includes all steps to convert corn delivered to the processing plant into anhydrous, denatured ethanol.

7.1 LCA Results

The results for this study consist of a lifecycle assessment according to ISO 14044 using openLCA to compare the IGPC facility and the novel biorefinery based on the dataset presented in Chapter 6. The results are broken down into LCA impact categories and a comparison is made between each. The impact results indicate that the novel biorefinery decreases the LCA results for each impact category within the method, with the exception of some eutrophication impacts. This supports the application of the novel biorefinery from an environmental standpoint. An analysis of the LCA results can pinpoint which improvements within the novel biorefinery had the largest impacts on the LCA.

Table 7-1: LCA Impact Results Comparing IGPC and the Novel Biorefinery

Impact	IGPC (per mmbtu)	Novel (per mmbtu)	Unit
Global warming	42.12	31.59	kg CO2 eq
Land use	0.43	-1.84	m^2a crop eq
Fossil resource scarcity	8.65	0.78	kg oil eq
Marine eutrophication	0.10	0.24	kg N eq
Freshwater eutrophication	0.01	0.01	kg P eq
Terrestrial acidification	0.56	0.54	kg SO2 eq
Water consumption	1.17	0.68	m^3

In terms of individual impacts, the global warming impact for the novel biorefinery was reduced by 26% compared to the IGPC facility. The most significant impact in terms of global warming for both IGPC and the novel biorefinery is maize grain production, which has a similar impact for both IGPC and the novel biorefinery, 70.5 kg CO_2 equivalent and 70.3 kg CO_2 equivalent respectively. This sizable impact is due to the high emissions from the use of nitrogen fertilizers as well as the drying of the corn. This also coincides with the impact assessment from various studies which suggest the greatest impacts for the corn-ethanol process are from the corn production stage (Pieragostini et al., 2014; K. Wang et al., 2013). However, this also creates benefits for the novel biorefinery from the implementation of struvite recovery and its use to offset fertilizer use.

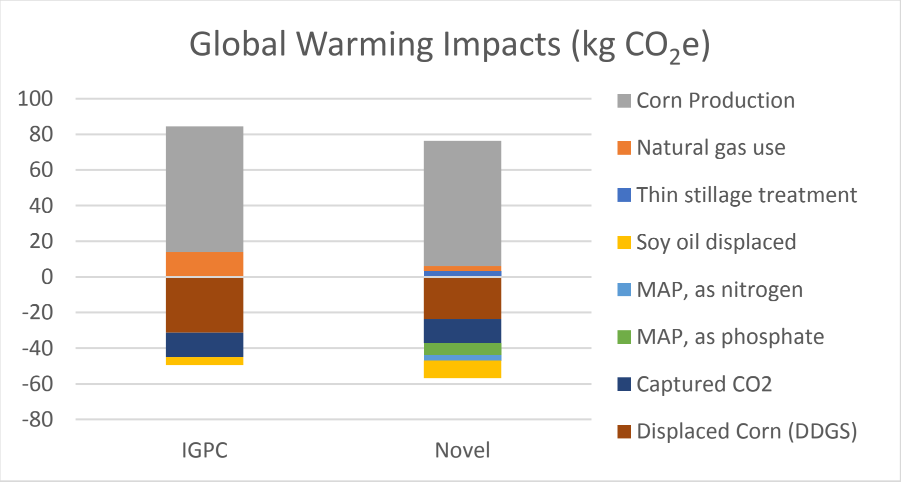


Figure 7-1: Global warming impacts by process category

The natural gas use within the plants is another large global warming impact for both systems, but as shown in Figure 7-1, the decreased use in the novel biorefinery reduces the impact (14.0 kg CO_2 equivalent in IGPC compared to 2.7 kg CO_2 equivalent in the novel biorefinery). This is due to the direct offset of natural gas use through the use of methane from the produced biogas, as well as a reduction in natural gas use from removal of the evaporation step. Primary energy use typically has a large impact on global warming due to the carbon dioxide emissions it produces.

In both systems, there are various processes that have a negative contribution to the global warming impact; these are processes that reduce the overall emissions. These are all a result of co-products produced in the ethanol process. The major ones being for the production of the co-product DDGS, which displaces corn used for animal feed, and for the captured carbon dioxide for both plants. The novel biorefinery also has some negated impacts from the increased production of corn oil compared to IGPC. While corn oil is produced at a small rate compared to other products in the corn-ethanol process, the increased production from front-end extraction in the novel biorefinery contributes to the lower global warming impacts of the novel process.

The other major difference between the two processes is the negated emissions from producing struvite, which displaces fertilizer as both phosphate and nitrogen, in the form of monoammonium phosphate (MAP). This displaces all the upstream impacts typically associated with the production of MAP. Overall, the global warming impact is reduced from 42.2 kg CO_2 equivalent at the IGPC facility to 31.6 kg CO_2 equivalent for the novel biorefinery (a reduction by 25%).

The impact category for land use is based on the cultivation area required for each process and the conversion of land from natural ecosystems to agricultural land. The dominant contribution for land use impacts for both facilities is the growth of corn; from the fertilizer use and production to the cultivation of corn.

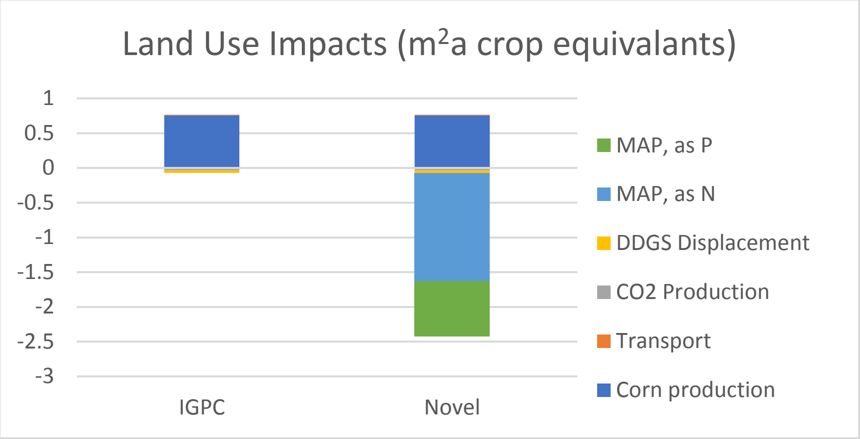


Figure 7-2: Land use impacts for the IGPC and novel facility

The novel biorefinery displayed a negative impact for land use compared to the conventional facility, with -1.84 m^2a crop equivalent and 0.43 m^2a crop equivalent, respectively. This is also a result of co-product production offsetting land use by other products. DDG(S) did have an impact on the land use, however the major land use changes are due to the production of struvite. This is due to the use of struvite as a fertilizer to displace monoammonium phosphate, which leads to an overall reduction in land use for producing these fertilizers. The changes between the two plants helps to highlight the importance of co-products in analysis of the LCA; without the additional co-products produced in the novel biorefinery, the impacts for this category would be virtually the same for both facilities.

The negative land use impacts for the novel biorefinery is an important caveat for the ethanol industry as much debate occurs due to the changing of land from uses such as forestry over to agricultural land in order to meet the demand for bioethanol production. By implementing the novel biorefinery, the analysis suggests that the novel biorefinery will actually allow less farmland to be required for bioethanol production. This is primarily a result of the farmland no longer being required to produce fertilizers such as MAP, which are naturally precipitated as a product at the novel biorefinery.

The next impact category, fossil resource scarcity, is a measure of the damage to resource availability for fossil fuels. This impact category relates to the extraction costs of future fossil resources, and the major contribution for both facilities is the maize grain production. This impact indicator is significantly lower for the novel biorefinery (0.78 kg oil eq compared to 8.65 kg oil eq). This is attributed to a number of category changes including a significant reduction in natural gas use at the novel biorefinery. The novel biorefinery also has a much lower value due to the offset by the production of monoammonium phosphate. Carbon dioxide capture and DDGS production improve the fossil resource scarcity impact for both IGPC and the novel biorefinery.

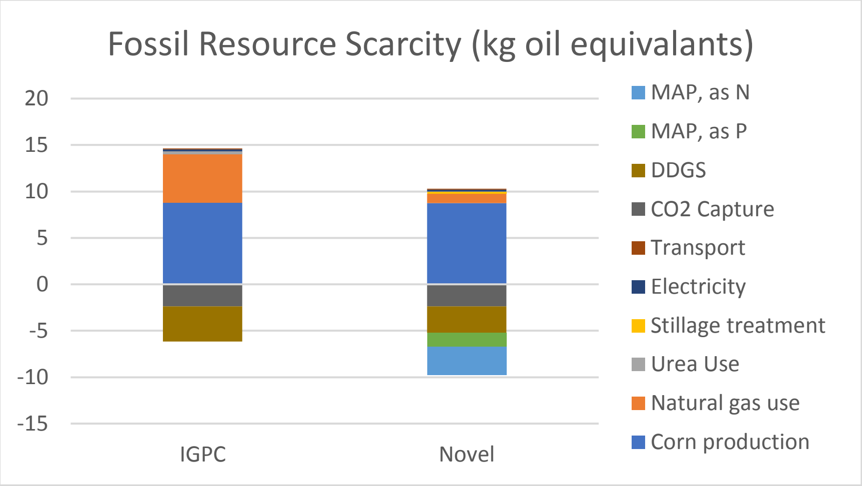


Figure 7-3: Fossil resource scarcity for both IGPC and the novel biorefinery

The eutrophication impacts for both freshwater and marine water were very similar for both facilities. This impact is related to nitrogen and phosphorus emissions, which again primarily relates to fertilizer use in the corn cultivation stage, as this is a major source of nitrogen losses. It was stated that the dominant factor determining most environmental impacts considered (i.e., greenhouse gas emissions, acidification, eutrophication, and photochemical smog formation) is related nitrogen losses (S. Kim & Dale, 2008), for this reason a nitrogen and phosphorus balance was completed in Chapter 6. Improved nitrogen cycling is reported within the novel biorefinery, through the use of struvite recovery and reductions in wastewater production. The nitrogen captured in the struvite production results in a decrease in nitrogen emissions to the environment. This analysis focuses on an attributional LCA, therefore the downstream impacts of indirect nitrogen and phosphorus emissions (outlined in the nitrogen and phosphorus balance) were not considered in the LCA. Further examination showed that if the mass balance and indirect emissions of nitrogen and phosphorus in both systems were considered, the eutrophication impacts for the conventional IGPC facility were higher than that of the novel biorefinery.

The production of DDG(S) at both facilities also offsets a great deal of the eutrophication effects because it decreases the amount of corn required for animal feed. The reduction in wastewater treatment and carbon dioxide emissions at the novel biorefinery also has a minor influence on eutrophication impacts.

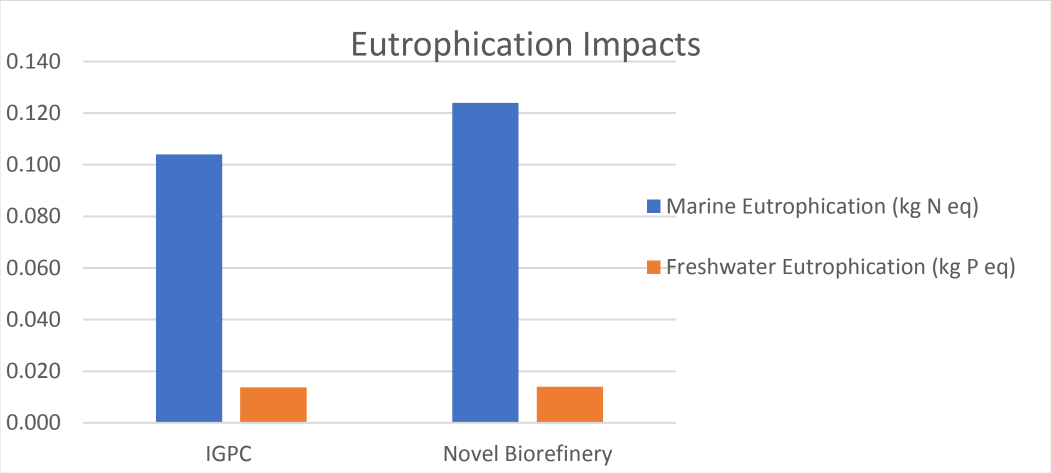


Figure 7-4:Eutrophication impacts for IGPC and the novel biorefinery

Acidification impacts are also similar for both processes, which are directly dependant on the corn cultivation. Emissions such as NO_x and SO_2 come down to the ground as acid rain, mist, or snow to be absorbed into lakes, rivers, and soil. As a result, surface water, ground water, and soil are acidified in ways that cause devastation of forests and many animals (T. H. Kim & Chae, 2016). The mineral deposits from ammonia and nitrogen oxides acidify the chemical properties of the soil, this can decrease the productivity of the soil (Azevedo, Van Zelm, Hendriks, Bobbink, & Huijbregts, 2013). The major components of acidification impacts are the same for both processes. Energy use in the form of natural gas and electricity use had a minimal impact on the acidification impacts. The largest contributors were for the production of maize grain, making up 99% of the total impacts. This highlights the results by Kim and Dale (2008), that using corn ethanol reduces non-renewable energy and GHG emissions but increases local impacts like eutrophication and acidification with the dominant sub-process being corn cultivation. DDG(S) production in both facilities offset 45-65% of the total acidification impacts.

Finally, the water consumption impact was an important characteristic of our novel biorefinery as the process was aiming to increase water recycling within the process. The water consumption for both processes was outlined in the water balance introduced in Chapter 6. Studies have reported the major water consumers as irrigation for biofuel feedstocks, as well as hydro- and thermo-electric power plants (M. Wang et al., 2012). However, irrigation of Canadian corn stalks is rare, this analysis indicated that the largest impacts for both systems stem from the electricity use, specifically for hydro-electric and nuclear power, which makes up a large segment of electricity production in Ontario. The cultivation of corn does create a large requirement for water through its use for the production of fertilizers, such as through the use of urea. The novel biorefinery removes the requirement for an external nitrogen source for yeast through the recycling of treated digestate, this also reduces the water consumption from urea processing.

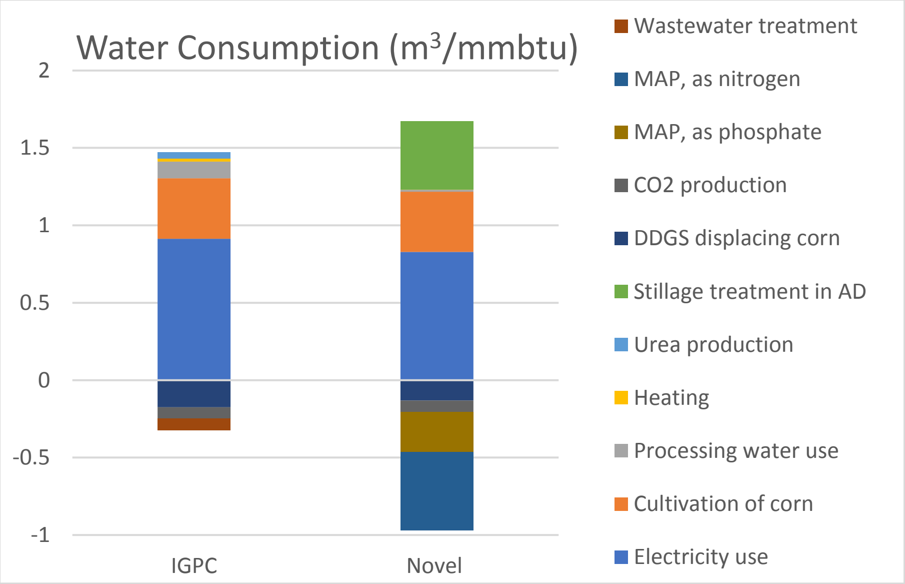


Figure 7-5: Water consumption impacts by process category

The process water recycling within the novel biorefinery also decreases water consumption, however this didn't have a large impact on overall water use. The treatment of the thin stillage in the novel biorefinery process is a major consumer of water, once again due to the high electricity usage in the processing. The displaced water use for the novel biorefinery comes from the production of struvite, used as monoammonium phosphate, as well as for the treatment of wastewater. As seen in Figure 7-5, the substantial displacement of water use by co-products reduces the water use at the novel biorefinery to 0.68 m^3/mmbtu compared to 1.17 m^3/mmbtu at the traditional facility.

7.2 LCA Conclusion

The environmental performance of the two corn-ethanol processes was evaluated through an LCA framework following ISO 14044 standards. This research is intended to provide insight into traditional corn-ethanol process inefficiencies and suggests a method to improve the lifecycle impacts of the process. Most LCA studies are based in the midwestern U.S.A. while this study attempts to approach the corn-ethanol industry from a Canadian perspective, based out of London, ON, Canada. Impact assessment categories were chosen in order to portray where the corn-ethanol processes affect the environment and assess the environmental burdens in the most complete way possible. Limitations in the LCA results do exist and stem from the extrapolation of lab-scaled novel biorefinery processes to the scale of the proposed system, as well as assumptions in the data achieved through industry averages.

The impact assessment provides opportunities to improve upon the traditional corn-ethanol process. The assessment indicates that within the corn cultivation stage, fertilizer and pesticide use (through corn cultivation), as well as corn drying contribute a majority of the impacts. While in the corn-ethanol process, the fossil energy use is the significant source of environmental impacts for the process. This correlated with other studies suggesting that corn cultivation has the greatest impact on the LCA due to the high fertilizer use (Muñoz et al., 2014; Pieragostini et al., 2014)

The corn drying and fossil energy use can both be reduced in the novel biorefinery through the use of biogas from the anaerobic digestion process. This helped to confirm the decision to use methane from the biogas production to displace natural gas within the plant opposed to a co-generation system for electricity production. The corn cultivation impacts are slightly reduced through the novel biorefinery, although further research should be done to increase this corn reduction. This can be accomplished through increased algal biomass productivity or co-digestion with other wastes to increase the algal biomass able to be produced.

The indirect impacts of land use change should also be considered since land used for food is devoted to bioenergy feedstock production. Then, as demand for food increases, agricultural production is shifted to other places (Pieragostini et al., 2014). This provides incentive for the novel biorefinery as the production of struvite has a major impact on land use change. Struvite is able to displace other fertilizer production, such as monoammonium phosphate, which leaves more land available for alternative uses such as food production. This creates the opportunity for the novel biorefinery to reduce the land use impact that corn-ethanol production has on farmland.

Thin stillage processing in the conventional process is problematic, and it has significant negative impact on DDGS as animal feeds. Thin stillage is produced at scales up to 15 times the volume of ethanol produced and concentrating it into to condensed distillers solubles is one of the most energy intensive processes in the corn ethanol biorefinery (Reis et al., 2017). By removing the evaporation step the novel biorefinery is able to reduce energy use within the ethanol process. Furthermore, the novel biorefinery is able to treat thin stillage as a method to increase co-product production; through production of struvite, biogas and corn oil, rather than simply a waste treatment method.

Overall, it is clear that corn cultivation dominates most impact categories for both LCAs. Pieragostini et al. (2014) found that corn production has more than 50% contribution in 10 of the 17 categories considered. This highlights the fact that changes within the process, including primary energy use and water use are significant, but may be dwarfed by changes to corn required for the processing. Therefore, it is important to focus further research on improving the LCA of the novel biorefinery through increasing the volume of corn displaced by the algae production. In the corn production (agricultural subsystem), the use of fertilizers and resources has the most relevant impact on the LCA (Pieragostini et al., 2014).

The co-product credit method used, system expansion, allows for the produced products to displace the impact from the production of another product. The recovery of co-products is one of the key drivers for the economic sustainability of ethanol manufacturing; DDGS can account for nearly 25% of the total revenue for some ethanol plants (Hill et al., 2006). DDGS and other co-products within the system also provide the greatest opportunity to decrease environmental impacts, through the displacement of other products. As in Kim and Dale (2008), this analysis showed that co-products had a significant impact on GHG emissions and impacts. The most relevant impact of DDGS' use is in land use category because of land use for animal feed is avoided. The second most favored category is acidification/eutrophication since the use of fertilizers is also avoided (Pieragostini et al., 2014). The novel biorefinery's ability to increase the co-product production has a significant impact on reducing the environmental impact. This allows many of the upstream environmental impacts from processing to be avoided. The novel biorefinery is able to expand on this opportunity by introducing the production of struvite as well as increased corn-oil production.

Co-products produced in the process create most of the displaced impacts for the various categories. Nitrogen and phosphorus fertilizers largely impact the water consumption, global warming and land use of the process. The production of these products through the co-product struvite presents positive impacts on the LCA of the novel biorefinery. DDGS, corn oil and carbon dioxide production present other opportunities to decrease the environmental impacts of the two systems. The increased corn oil production in the novel biorefinery through front-end oil extraction provides a better chance for decreased impacts as a greater volume of corn oil is produced compared to the conventional facility. This is a result of corn oil displacing the use of other products, particularly soy oil.

More research should be done to identify differences between the feed co-product from traditional dry mill facilities (DDGS), and the novel biorefinery (DDG). Preliminary research suggests that DDG should be at least as productive as feed rations. However, the ratio for DDGS/DDG replacement as corn feed will have a major impact on the volume of corn negated from both processes, which as discussed, has a major bearing on many of the LCA impact categories.

The impacts from the combustion of the ethanol fuel through E10 or E85 fuel are not included in this analysis. In LCA, the combustion of ethanol is often characterized as carbon neutral as carbon dioxide (CO_2) released during combustion originates from atmospheric CO2 absorbed during biomass production (Van Der Voet et al., 2010). Since these processes would be common to both facilities, the combustion won’t bear an impact on the overall LCA comparison between the two facilities.

Chapter 8 Technoeconomic Analysis (TEA)

8.1 TEA Abstract

This chapter will complete an economic assessment of the traditional corn-ethanol process, modelled by IGPC Ethanol in comparison to the novel biorefinery. There has been a variety of studies addressing the economic feasibility of the corn-ethanol industry, particularly from the perspective of changing input prices and co-product processing technologies (Kwiatkowski et al., 2006; Wood, Rosentrater, Muthukumarappan, & Gu, 2013). It is important to address how technology affects the handling of ethanol co-products and the economics of the process. For this reason, the novel biorefinery will be compared to the traditional processing at IGPC Ethanol Inc. to determine the proposed changes will have an impact on overall plant revenues.

The major cost associated with algae cultivation for biofuel or chemical use is related to harvesting and extraction costs. It has been estimated that harvesting can account for 25–60% of the total cost of microalgae production (Grima et al. 2003). This is a result of the low biomass yields usually achieved in microalgal cultivation systems. These costs sometimes inhibit the utilization of algae as a feedstock. However, cultivation of algae on digestate is still perceived as a possible option due to the nutrients present (such as nitrogen and phosphorus) that generally account for half of the cost and energy input in cultivation (Levine, Costanza-Robinson, & Spatafora, 2011).

The novel biorefinery aims to remove the harvesting costs by utilizing direct recycling of algal culture into the front-end of the process to be mixed with corn-water slurry can enhance the process economics. The starch within the algae will be converted into ethanol to decrease corn requirements, and the protein and carbohydrates will become imbedded into the DDG product. It is suggested that the algae blend easily in animal feed (DDG) and are more nutritious than grains alone (Logan & Visvanathan, 2019).

The goal of the economic assessment is to determine if the novel biorefinery process can provide financial incentive to the corn ethanol industry. The novel biorefinery may be able to overcome the high capital costs of employing new technologies based on the reductions in process energy, implementation of better nutrient recycling and its utilization of produced biogas.

8.2 Introduction to TEA

In light of the current demand in Canada for ethanol, IGPC Ethanol recently doubled their production capacity while implementing technology aimed to increase loading of corn and also utilizing technologies to increase by-product value. This process has been successful at increasing production and diversifying the co-product market, but this study suggests that other technologies may be able to decrease operation costs while improving the net energy value of the plant. The results of the LCA comparing the IGPC facility and the novel biorefinery presented environmental motivation for the novel biorefinery, but further research needs to examine the economic viability of the novel plant. This aspect of the analysis is important as most research stems on either the environmental impacts or the economic prospect, but this does not consider the combination of environmental and economic aspects for a comprehensive analysis.

Ideally, a techno-economic analysis (TEA) is used to compare a set of well-established processes with existing or developing technologies to discuss whether market-driven prices can be achieved and economic feasibility can be determined from economic aspects or not (Swanson et al., 2010). A well-established process has the advantage of being a proven design with values that are generally thoroughly tested with a high reliability. In all TEA's, the efficiency of a process is fundamental, this relies on dependable data for productivity, inputs and the energy flow within the process. In general, a TEA is used to consider the cost-benefit relationship of a process, which is particularly relevant when two competing processes are considered (Ahuja & Walsh, 1983), as is the case for this study.

8.3 TEA Method

The total ethanol production costs will be evaluated using the SuperPro Designer software and available literature on comparable processes. The capital and operational costs for the traditional corn-ethanol facility will be provided from primary data from IGPC Ethanol Inc., as well as literature data when necessary. The mass and energy balance completed during the lifecycle assessment will be used to determine the energy and operational costs for the processes. The operational conditions for the novel biorefinery was based primarily on data provided from research collaborators (Sayedin et al., 2019), while some conditions were modified based on available literature from relevant studies (Barta, Reczey, & Zacchi, 2010; Davis, Aden, & Pienkos, 2011; Richardson, Johnson, & Outlaw, 2012).

Some parameters regarding IGPC and Canadian economic conditions such as raw materials costs, labour salaries and interest rates were incorporated in order to limit geographic cost uncertainties. Equipment calculations were performed and adjusted according to SuperPro Designer, which uses a model originally constructed by Kwiatkowski (2006). This study utilizes market conditions, literature data, data specific to plant conditions and modelling designs to explore some effects of various price factors on the profitability of the corn ethanol plant. Additionally, this study investigated how some efficiency improvements through the novel biorefinery may impact the economic viability of the plant.

The operational process will be based on the construction and implementation of a new 100 million gallon per year (MPGY) corn-ethanol facility operating in Ontario, Canada. The analysis will include the capital, material and utility, labour and insurance costs for both facilities. The analysis will be completed to determine the cost of producing 1 million btu of ethanol at the IGPC Ethanol plant and the novel corn ethanol biorefinery.

8.4 Literature Review

8.4.1 Overview of Cost Analysis of Corn Ethanol Production

Corn-ethanol production presents an opportunity to decrease reliance on foreign oil while also reducing GHG emissions in the transportation fuel sector. However, the process has a high dependence on material inputs and uses a considerable amount of energy. The economic analysis is dependent on the particular parameters of a specific plant and should be region specific.

The market price of commodities has a significant influence on the economic stability of the corn ethanol process including the cost of corn, ethanol, DDGS, carbon dioxide, electricity, energy, and other feed co-products. However, for the conventional facility, the overall profitability is largely determined by the relationship between ethanol prices and corn prices (Wood et al., 2013). The rising price of corn and high ethanol inventory has brought operating margins in the U.S. to lows in 2019, this can cause processors to cut or pause production (Hanson & Hill, 2018).

In recent years the ethanol production has been driven higher due to the Renewable Fuel Standard (RFS); the program administered by the U.S. Environmental Protection Agency that mandates the blending of biofuels into the nation’s fuel supply (Hanson & Hill, 2018). Subsidies for ethanol production from renewable resources provide economic incentive for production. The

EPA provides a subsidy in the form of a tax credit called the “blender’s credit” which provides a tax credit for every gallon of pure ethanol blended with gasoline (the subsidy varies but is in the range of $0.45/gal) (Murse, 2019). The rational for the subsidy is to reduce the foreign oil needed to produce gasoline and reduce GHG emissions. While Canada does not have a similar subsidy program, they do mandate the use of ethanol to be used in gasoline and diesel fuels. These incentives favourably affect the economics of ethanol production and help maintain its profitability. Any subsidies or acts, which impact ethanol production should be included for a full transparent financial analysis, however researchers should be cautious of programs which may not last the entire lifespan of a project, as this could create uncertain economics in the future of a project.

The volatility of the oil and gas sector can also have a major impact on the corn-ethanol industry, if demand for oil and gas decreases, the demand for the ethanol oxygenate used in gasoline will decrease as well. This means fluctuations within the price of ethanol is quite common; this can pose risks to investors within the industry. The U.S. Energy Information Administration (EIA) provides estimates for the operating margins for AnMBR plants by taking the sum of the revenue from the sale of ethanol and co-products and subtracting variable and fixed costs associated with producing ethanol. These margins can give good insight into the profitability of the industry, especially in response to drastic changes to supply or demand.

The EIA forecasts continued growth in ethanol production and increased consumption of ethanol in the U.S.A. (Hanson & Hill, 2018). With Canada currently requiring a net import of ethanol in order to satisfy ethanol demands, this projects positive future prospects for the Canadian corn-ethanol industry and increased security in technologies that increase revenue for the corn ethanol industry.

An in-depth economic evaluation should include the costs for raw materials, labour, utilities, maintenance, plant overhead, administrative and financing costs. An important parameter is determining the total capital costs and operating costs for the facility. The annualized cost for the plant is a useful tool for predicting the yearly infrastructure costs based on the capital costs for the plant, the lifetime of the plant and the finance rate.

Both the annual revenue and the operating costs are volatile in the industry, which was mainly determined by the market price of raw materials and products. Corn is the major recurring cost for a corn-ethanol facility and most of the cost variability for the industry relates to the changes in net corn price (corn cost minus co-product revenue) (Gallagher et al., 2016). Wood et al. (2014) examined the variability of corn prices between 2005 and 2011 and identified the impact corn price has on the overall profitability of the industry. The results of the changes in market conditions for various inputs and utilities is shown in Table 8-1. This can also be compared to the 2019 price of corn at \$3.85/Bu (\$0.151/kg). The market price for corn is very dependent on weather conditions for the year and thus predicting future revenues for corn-ethanol facilities is difficult.

Table 8-1:Input prices used for simulation (Wood et al., 2014)

Inputs	**Kwiatkowski (2005)**	**Market Prices (2011)**
Corn (\$/kg)	0.087	0.286
Steam (\$/kg)	0.017	0.013
Natural gas (\$/kg)	0.289	0.196
Electricity (\$/kW h)	0.050	0.060
Outputs		
Ethanol (\$/kg)	0.610	0.793
Corn oil (\$/kg)	0.558	0.558
DWG (\$/kg)	0.049	0.077
DDGS (\$/kg)	0.125	0.220

The prices of utilities remained largely the same or even decreased as in the case with natural gas and steam, while corn prices used in the models increased by 337% in just 6 years (and decreased by 47% by 2019). The prices of the products did not increase at the same rate, ethanol increased by 30% while DDGS and DWG had a more moderate increase in price, 76% and 57%, respectively. The increase in price for DDGS and DWG is likely related to its use as animal feed which can replace corn in the beef and dairy industry

Computer simulations are an important tool to model and predict the costs of production. They provide the ability to estimate the effect of increasing costs of raw materials or utilities, variations in material composition, and the incorporation of new technologies (Kwiatkowski et al., 2006) or depict general corn-ethanol production. Kwiatowski et al. (2006) modelled a general

40 million gallon per year dry-grind corn-ethanol facility in SuperPro Designer; the facility includes DDGS processing but does not include corn-oil production. SuperPro Designer is able to model both process and economic parameters for processes. The model was developed in 2006 so some changes have occurred to the processing technology and energy consumption. However, comparisons of the electricity usage between Kwiatkowski et al. (2006) and the GREET model by Argonne National Laboratory show a difference in electricity use of less than 3%. The GREET model is updated based on estimates from facilities within North America in order to accurately depict energy use within the market sector. The electricity use from both sources is displayed in Table 8-2.

Table 8-2: Energy use as depicted in Kwiatowski et al. (2006) and recent GREET results

	SuperPro (Kwiatkowski 2006)	GREET (2018)
Electricity Use (btu/gal)	2382	2533

SuperPro Designer remained the choice for several works on the economics of the corn-ethanol process (Rajagopalan, Ponnampalam, McCalla, & Stowers, 2005; Somavat, Kumar, & Singh, 2018; Wood et al., 2013) due to the ability to customize the process as well as the vital economic information available.

8.4.2 Capital Costs

In order to complete a technoeconomic analysis on the corn ethanol industry, the capital cost of the facility needs to be determined as the amortized cost has a significant impact on the overall plant revenue. The capital costs are the initial investment in plant infrastructure and are typically defined over the lifetime of the facility. Different from the labour cost and operating cost, the capital cost is independent on the level of output at the facility (Zhang et al., 2017).

Kwiatkowski et al. (2006) created a generic model for a 40 million gallon per year corn-ethanol plant using SuperPro which included all the individual commodities and produced an economic assessment on the process. This model was then updated various times in order to update the material and processing costs as well as introduce new, relevant technologies to the model (Somavat et al., 2018; K. Wang et al., 2013). Modelling the economics of corn ethanol production in future years is difficult due to the high variability in operating costs, particularly corn costs.

The capital costs for facilities depends on the ethanol processing capacity of the facility, this also dictates the revenue that will be generated. Comparisons between facilities of different capacities creates difficulties because equipment costs do not necessary scale with the change in equipment size. An analysis comparing small capacity (50 MGPY) and large capacity (100 MGPY) found that the total asset build-up for large capacity plants was 1.89 times higher than small enterprise plants (Bacho & Murova, 2017). These logistics are in agreeance with economies of scale; a plant that has double the capacity should have infrastructure costs less than double the small scale capacity. The costs for a facility largely depend on the energy choice, technologies employed and ethanol capacity, however industry standards can be used to determine average costs. These costs have been tabulated in literature with studies based on either industry averages or from modelling, relevant studies were compared and available in Table 8-3. The cost per gallon of ethanol capacity is a unit which allows comparison between plants of differing size.

Table 8-3: Capital Costs from literature

Plant Size (MGPY)	**Publication Type**	**Capital Cost (millions)**	**Capital cost ($/gal of capacity)**	**Publication**
120	Model	136.6	1.14	Zhang et al., 2017
100	Study	153.3	1.53	Bacho et al., 2015
40	Model- SuperPro Designer	87.7	2.19	Somavat, 2018
120	Model- SuperPro Designer	143	1.19	Srinivasan,2005
40	Model- SuperPro Designer	58	1.45	Wood et al., 2015
100	Study	158	1.58	Gallagher, 2016

The purchased costs for major equipment items was based on budgetary quotations from equipment suppliers, on equipment data from literature and from SuperPro Designer. In some cases the capacities of the equipment in the model and literature vary from the capacities for which quotations were received, the quoted costs were adjusted through the use of equipment and cost scaling factors (Kwiatkowski et al., 2006). When cost scaling was required for literature papers, the cost for the equipment under IGPC's capacity (100 MGPY) was determined using a scaling factor (SF) shown in Equation 1 (Somavat et al., 2018). The scaling factor in this study was determined through literature price comparisons.

$$Cost_{IGPC} = Cost_{base} \text{x} \left(\frac{Size_{IGPC}}{Size_{base}}\right)^{SF}$$

Equation 4: Equation for cost factoring of IGPC equipment

While not all literature on the techno-economic analysis of corn-ethanol dry milling includes a breakdown on the processing equipment, some is available and can be used as a baseline for the IGPC facility. Particular attention is paid to reviews within 5 years because technology improves and costs change. Kwiatowski et al. (2006) maintains an in-depth analysis of the process with many studies based on his SuperPro Designer model, however the facility model is dated and at a total capital cost of $46.7 million for a production capacity of 40 million gallon of ethanol (Kwiatkowski et al., 2006), it does not likely represent a modern facility cost.

The capital costs consist of the initial investments put into the plant and can be separated into various process sections such as fermentation, ethanol processing, co-product processing etc. This separation allows for the costs for each area of the plant to be determined separately which determines where major expenses occur. For co-product processing, the capital costs consist of the thin stillage evaporators, dryers and corn oil removal equipment, these combined contribute more than 43.5% of the total capital costs for the facility, while ethanol processing (distillation, ethanol recovery, ethanol denaturing) only contributed 16.5% of the total capital costs (Wood et al., 2013). Other research has shown the processing of co-products may contribute as much as 51.4% of the total capital costs (Zhang et al., 2017), while ethanol production makes up nearly 80% of the annual revenue for the plant (Wood et al. 2013, Zhang et al. 2017). This outlines that equipment with no direct impact on ethanol production assumes up to 51% of the capital costs while providing minimally to the overall revenue of the facility.

8.4.3 Operating Costs

The operating costs constitute the cost to run the facility yearly and include the expenditures for chemicals, labour, fuel, electricity and other consumables used on-site. The consumables include caustic soda, sulfuric acid, corn, yeast, octane, ammonia, glucoamylase, and alpha-amylase.

The material inputs consist of the corn, enzymes, chemicals, and other inputs used for the processing of corn into ethanol. Changes to commodity prices of these goods impact the overall revenue predicted by the refinery. Somavat et al (2018), investigated the cost of ethanol production for a variety of processes and the material prices are presented below.

Table 8-4: Material costs for the traditional corn ethanol process (Somavat et al., 2018)

Material Costs	**Price ($/gal ethanol)**
Alpha amylase	0.014
Glucoamylase	0.020
Caustic	0.005
Corn	1.137
Lime	0.001
Liq. Ammonia	0.004
Octane	0.049
Sulfuric Acid	0.002
Yeast	0.004
Total	**1.236**

Of the total annual operating costs, it is suggested that the material prices comprise around 76% of the annual operating costs of the processing facility. Of these materials, corn was the largest contributor, contributing an average 92% of the material costs (Wood et al., 2013). However, this can vary greatly by corn production for the year. This means the economic feasibility of ethanol production is overtly reliant on the price of corn and any changes to supply and demand for corn impacts the price. As corn prices increase, the annual operating cost of the plant will rise significantly and the value of the products must also rise in order to keep the process viable. Corn price was found to have the greatest impact on the overall operating costs for the ethanol plant, while the market price of ethanol had the greatest impact on annual revenues (Wood et al., 2013).

This may explain the introduction of new products to the industry such as corn oil, fiber plus syrup and Hi-Pro; these commodities help to bring new revenue to the industry which can offset some variance in material cost. This is particularly beneficial for the feed co-products which can be used to displace some of the corn used within those industries.

In terms of utility costs, most analyses consist of the costs of electricity, natural gas, steam and chilled water. For IGPC, the steam production costs are already factored into the natural gas use on-site and therefore is not included. The utility prices fluctuate greatly by study and are important to the overall costs for the facility. Zhang (2017) found that the costs of electricity and natural gas led to a contribution of between 6.92% to 20.74% of the overall operating costs. This results in the energy use at the plant being a primary factor in determining the economic viability of the novel plant. Another important comparison for the novel biorefinery is the type of energy used in processing, as the type of energy that will be consumed by the processing must be taken into consideration as it will have a significant impact on the utility costs and some impact on the annual operating cost of the plant (Wood et al., 2013).

There are several modifications that can reduce costs including, producing wet distillers' grains if located spatially close to feedlots. According to a recent survey, drying distillers' grains requires 12,936 British thermal units (Btu) per gallon of natural gas and 0.155 kilowatt hours (kWh)/gallon of electricity (Gallagher & Shapouri, 2009). Therefore, the cost of a gallon of ethanol could be reduced by $0.066/gal if the distillers' grains are not dried.

8.4.4 Revenue

Revenue for the facility depends on the sale of ethanol and DDGS, with many new facilities also producing corn oil and capturing carbon dioxide from the fermentation process. The ethanol production is the main product and revenue generator for the facility despite new co-product changes. According to Wood et al. (2013) ethanol maintains the most abundant product (at 31% of the total product by weight) while contributing an average of 77% of the revenue. This means that all other products make up almost 70% of the commodities (by weight) but contribute less than 25% of the revenue. Part of this is due to the fact that captured carbon dioxide averaged 30% of the total product and was considered to bring no revenue to the plant (Wood et al., 2013). However, the capture of carbon dioxide does mitigate CO_2 emissions and can have an impact on the lifecycle assessment for the facility.

Therefore, the processing of the co-products presents revenue to the facility, but the capital costs of processing is large due to the requirement of evaporators and dryers. This is also represented by the high use of utilities in the co-product processing. This solidifies remarks that co-product production should be denoted as more of a waste treatment method than a general revenue stream and also gives motivation for the introduction of the novel biorefinery. Even if a co-product contributes greatly to the overall revenue (i.e. DDGS), it is not necessarily beneficial if the processing costs are too great (Wood et al., 2013).

8.5 Novel Biorefinery Economic Analysis

The novel biorefinery economic analysis will be based on the conventional facility but with some changes regarding the capital costs and operating costs. The facility will no longer require the downstream processing units for treating the thin stillage, such as the evaporators and some drying equipment. This is important as the stillage handling is the most energy consuming process; drying and evaporation of stillage consumes more than 35% of the total energy consumption (Stover et al., 1985). Aside from energy consumption, thin stillage also has a considerable potential for pollution of the environment. Thin stillage is a high strength wastewater and its processing should be considered as waste treatment.

A range of new equipment will be also be required to treat the thin stillage in an anaerobic-aerobic system before being incorporated in an open-pond algae cultivation system. The additional processing costs will be determined by literature review, as the full process is not available commercially. There will also be modifications to the products produced at the facility; particularly the feed products.

8.5.1 Thin Stillage Treatment

The ethanol processing for both facilities remains fundamentally the same, however the processing of thin stillage changes. The raw thin stillage exits the existing bioethanol process from a series of centrifuges at a flow rate of 240 tonnes per hour and a temperature of 82°C (personal communication, IGPC, May 2019). In the novel biorefinery a series of clarifying tanks are required to allow the residual solids present in the thin stillage to settle. The stillage is primarily liquid (8% solids), but the suspended solids may not be readily digestible in the anaerobic digester and may impede further treatment. This step also helps to stabilize any changes in flow from the ethanol plant so the flow rate of the thin stillage into the subsequent steps can be pumped at a constant rate. These clarifiers allow for continuous removal of the deposited solids from sedimentation. These solids are removed, dried and added to the DDG stream as an additional volume for this stream; this should not pose any risk to DDG, as in the conventional facility, these solids would already be present in the DDGS.

The IGPC facility currently has a thin stillage tank with a volume of 146,000 gallons (553,000 L). This tank will be sufficient for appropriate settling to occur and also can be implemented as a method to reduce the temperature of the thin stillage to a level suitable for mesophilic digestion (<42°C). A simple series of heat transfer units will be able to achieve the moderate decrease in temperature required, while also providing a potential supply of heat for elsewhere within the plant. This is important for plant design as thermophilic anaerobic digestion approached by similar studies have ran into complications from requiring additional heating for digestion (Schaefer & Sung, 2008).

Following the clarifier tanks, a series of tanks for the precipitation of struvite is required. Struvite is a slow release fertilizer composed of nitrogen, phosphorus and magnesium that can be readily removed from the treated digestate stream and has been widely used for the recovery of phosphate in wastewater. Struvite production is beneficial for increasing availability of phosphate resources, as there is a decrease in the quality of rock phosphates worldwide and an increase in fertilizer consumption (FAO, 2010). Phosphorus recovery from wastewater effluent as struvite presents a number of advantages: it can help to solve and prevent scaling problems in WWTPs, it reduces pollution linked to excess discharge of nutrient (N and P) in wastewater effluents, and its potential use as a fertilizer (Doyle & Parsons, 2002). This provides a new revenue source while also reducing the phosphorus levels in effluents. It also reduces the risk of accumulation of struvite throughout the reactor, as struvite naturally occurs under the specific condition of pH and mixing energy in specific areas of wastewater treatment plants (e.g., pipes, heat exchangers) when concentrations of magnesium, phosphate, and ammonium approach an equimolar ratio 1:1:1 (Le Corre, Valsami-Jones, Hobbs, & Parsons, 2009).

The conditions of the treated thin stillage is important, it has been shown that increased temperature coupled with decreased pH of the wastewater can enhance struvite precipitation (Fang, Zhang, Jiang, & Ohtake, 2016). Optimizing this recovery is important in order to achieve better nutrient removal rates and faster retention times. The retention time for chemical struvite precipitation in fluidised reactors range from 0.5–9 h (Le Corre et al., 2009). For this process, a source of magnesium, such as $MgCl_2.6H_2O$ or $MgSO_4$ $7H_2O$, is required to supplement magnesium as the limiting reagent present. Struvite within wastewater systems can provide issues by depositing within equipment and pipes and causing build-up, for this reason the struvite precipitation occurs early in the novel process. In order to achieve this precipitation at an industrial level a vessel with mixing and pH monitorring is required. A vessel with a combined volume of 500,000 L would allow for a retention time of approximately 2 hours to allow the struvite to precipitate. The struvite will deposit naturally on the bottom of the vessel, requiring some treatment to remove impurities and optimizing particle size for fertilizer use.

Following struvite recovery, the treated thin stillage can be pumped directly into the baffled anaerobic digester. Anaerobic and aerobic processes have been used to treat organic matter in wastewater streams while producing biogas that can be used for heating. Mesophilic digestion was chosen due to its lower energy requirement for processing compared to thermophilic digestion. Additionally, the bacterial population is more robust in mesophilic digestion which allows it to be more adaptable to changing conditions in the feedstock. It also does not require the higher temperatures that are fundamental to thermophilic digestion. The drawback is the requirement for a longer retention time to achieve the same biogas productivity as the thermophilic digestion. It was chosen in order for its cost efficiency as well as productivity.

A series of anaerobic reactors with a combined volume of 63,000 m^3 will be required to treat the large volume of thin stillage produced at the facility. The anaerobic digestion takes place in a two-phase reactor, where first the complex materials such as fats, proteins and carbohydrates are hydrolyzed, fermented and biologically converted into simple organic acids, in the second phase the methane fermentation occurs. The second phase produces a biogas which consists of mainly methane, carbon dioxide with trace amounts of other gases such as hydrogen sulfide.

An anaerobic baffled reactor was chosen for the treatment of thin stillage due to its robust construction and ability to separate the stages of biological digestion (Sayedin et al., 2019). The two-phase systems enhance the stability of the system to fluctuation in environmental conditions such as temperature and pH (Zhu et al., 2015) and the separation between acidogenic and methanogenic steps in anaerobic digestion provides enhanced stability to the different groups of microorganisms (Demirel & Yenigün, 2002). It also reduces mixing of microbial population and may increase the stability of the digestion. Finally, the chambered reactor allows for the separation of hydraulic retention time and the solids retention time which means the reactor can maintain its bacterial populations. However, multiphase reactors typically incur a higher capital cost and may be more complicated to operate.

For anaerobic digestion to take place, the thin stillage must have sufficient macronutrients and micronutrients to encouragement bacteria growth. Various studies have supported the use of anaerobic digestion for the treatment of thin stillage, therefore this was not investigated further (Alkan-Ozkaynak & Karthikeyan, 2011; Lee et al., 2011; Schaefer & Sung, 2008).

The effluent from the digester is collected in a buffer tank then recycled back with the fresh feed to form the influent. A recycling rate of 10x was employed; higher recycling rates provides higher capacity to toxic substrate and high concentration wastewater by diluting the influent and maintaining the buffer capacity (Zhu et al., 2015). The recycling rate is often used to modify the operating parameters of the AD, however it can reduce the COD removal efficiency of the AD and increases the energy required by the system.

Analysis was conducted on thin stillage from IGPC Ethanol in order to maximize the biogas production and the methane content from anaerobic digestion. The majority of COD removal (66%) and consequently biogas production occurred within the 1st compartment of the reactor (Sayedin et al., 2019). Sulfides present in the thin stillage from the use of sulfuric acid in processing can inhibit the methane producing bacteria (Alkan-Ozkaynak & Karthikeyan, 2011). These sulfides are converted to hydrogen sulfide in the biogas, which has corrosive properties. The two-phase ABR is able to efficiently treat the sulfate in the first chamber of the ABR and therefore limit the production of hydrogen sulfide within the reactor. The full biogas treatment including energy use and processing are characterized in Chapter 6.

Following anaerobic digestion, aerobic treatment is used to reduce the high ammonia concentration in the digestate which would inhibit algal growth. In this case, aerobic biological treatment was chosen in order to enhance the phosphorus and nitrogen removal. This nutrient removal would still be required without the application of microalgae cultivation, due to the high nutrient levels which likely inhibit the direct discharge of digestate to the environment.

Sayedin et al. (2019) diluted the digestate in order to overcome microalgae inhibition. However, the potentional for nitrification in an aerobic reactor can be employed as a means to reduce the concentration of ammonium and its subsequent inhibitory effect to microalgae was identified. The aerobic digestion is composed of an aeration tank, followed by a clarifier for sludge removal. The oxygen required for the aerobic treatment is estimated at 0.9-1.3 lb of oxygen per lb of biological oxygen demand (BOD) removed (Metcalf & Eddy, 2003). Aerobic digestion typically creates a substantial volume of sludge in typical wastewater treatment, however the anaerobic digestion removes over 90% of the COD prior to introduction to the aerobic basin. Therefore the sludge produced in the process will be reduced.

8.5.2 Algae Cultivation

The clarified digestate effluent is still rich in nitrogen and phosphorus, and has become a bottleneck in the development of the biogas industry (Xia & Murphy, 2016). The simplest treatment method is to directly spread on local agricultural land; land application of liquid digestate, however, can have eutrophication impacts of nearby water. Alternatively, the high nutrient levels make the digestate of sufficient water quality to be used as a medium for microalgae growth, as the nitrogen to phosphorus ratio following digestion is more appropriate for algal growth.

Algae was chosen because of its efficiency at converting solar energy into biomass while submerged in an aqueous ecosystem for efficient access to water, CO_2 and nutrients, as well as its rapid growth (Souza, Gopal, & Seabra, 2015). The microalgae will act as a feedstock for ethanol production, as its high starch content allows the treated digestate to aid in the displacement of corn feed for the process. The protein and fat content present in the algae would be beneficial to the feed by-products and corn oil produced in the corn-ethanol process. Integration of microalgae to the ethanol process allows the treated digestate to be fully recycled within the process and may reduce operating costs within the plant. By directly employing the microalgae and process water to the front end of the process, the harvesting and extraction costs which can deter industrial integration of algae can be eliminated. The proposed process addresses the challenges associated with cultivation of algae; the energy-intensive product recovery which limits the commercialization of algal bioproducts (Alhattab et al., 2019).

It has been demonstrated that nutrient procurement is one of the most energy intensive processes for algae cultivation and can constitute up to 50% of energy consumption during algae cultivation (Clarens, Resurreccion, White, & Colosi, 2010; Stephenson, Dennis, Howe, Scott, & Smith, 2010). The use of partially treated wastewaters as nutrient source for mass algae culture has been shown to improve the environmental performance of algae-to-energy systems by reducing virgin fertilizer consumption and also offsetting energy requirements for N and P removal in a municipal wastewater treatment plant (Clarens et al., 2010; Lundquist, Woertz, Quinn, & Benemann, 2010; Pittman, Dean, & Osundeko, 2011). The combination of on-site liquid digestate treatment and microalgal cultivation can significantly reduce the nutrient cost (Xia & Murphy, 2016).This treatment should also be seen as a waste treatment method for the high phosphorus and nitrogen levels present in the digestate which inhibit it from direct discharge to the environment.

A similar study investigated the environmental and economic assessment of integrated systems for dairy manure treatment coupled with algae bioenergy production on a small cattle farm. The authors examined the anaerobic digestion of manure followed by open pond cultivation of algae (Y. Zhang, White, & Colosi, 2013). The algae were then used directly as a biomass source for the production of electricity from biogas; this mitigated the capital and energy intensive harvesting and extraction process for the algae growth. IGPC has the opportunity to bundle with nearby cattle lots in order to increase the material available for anaerobic digestion.

It has been previously demonstrated that algae exhibiting lipid contents less than 40% are unsuitable for biodiesel production and are thus better leveraged via anaerobic digestion (Sialve, Bernet, & Bernard, 2009). This is based on the standard use of algae as a source of biodiesel based on the high economic costs associated with harvesting and extraction of algal lipids. New economic assessments on the process needs to be completed to adjust for the direct injection of the treated digestate and algae into the ethanol process.

It is hypothesized that the addition of algae cultivation could improve both the amount of digestible biomass produced and improve the nutrient management. The algae was able to be cultivated in treated digestate at ambient temperatures (23°C) and 210 μmol m^{-2} s^{-1} light intensity with a 13/11 light/dark cycle under mixing at 400 rpm (Sayedin, 2019). Therefore, the cultivation requires only moderate mixing with no external heat. The algae will be grown in open pond systems using natural light to minimize operating and capital costs for the project. This introduces issues for year-round cultivation for the current climate at IGPC, but results can be extrapolated to more temperate climates. Open pond systems require larger areas for cultivation than photobioreactors, and can be susceptible to culture crashes and evaporation, however the cultivation can take place on marginal land that would not be viable for conventional farming. An external carbon dioxide source is required to provide a 2% flow to the pond system; however, this carbon dioxide source is readily available on-site from either the biogas produced at the AD or from the fermentation process. In open systems not all of the supplied CO2 will be absorbed, so fermentative CO_2 is added in excess. The racetrack open-pond system will use a low-impact paddle wheel to keep the algae circulating.

The benefit of algae utilization in the novel biorefinery is the removal of the extraction phase used in conventional algal farming. In the novel process, both the process water and algae will be recycled to the front end of the process, thus eliminating the costly harvesting phase. It is estimated that 14%, 10%, and 16% of total production costs for algal farming come from harvesting, drying, and oil extraction, respectively (Yuan, Shen, Pei, Wu, & Mao, 2009). These process costs are not required for the novel biorefinery, as Sayedin et al. (2019) demonstrated that algae populations can effectively cultivate on treated digestate from the IGPC facility.

The algae and process water are recycled to the slurry tanks to be directly incorporated back in the process. The process water provides nitrogen which can exclude the urea typically employed in the corn-ethanol process at IGPC, further reducing treatment costs. Similar studies have suggested that this recycling of the digestate will replace both process water and the artificial nitrogen source (ammonia, urea) that is required for the yeast fermentation (Alkan-Ozkaynak & Karthikeyan, 2011). The cultivation of *C. sorokiniana* on the treated digestate was able to remove chemical oxygen demand, ammonia-nitrogen and total phosphorus up to 83.8±0.6%, 95.3±1%, and 78.3±1.1%, respectively from the digestate (Sayedin et al., 2019). This allows the digestate to be reinjected into the process and enhance the water recycling within the plant. Moreover, the produced microalgal biomass had a significant content of potential bioproducts such as protein (37.8±3.4%), starch (17.8±0.8%) and lipid (8.9±0.3%), (Sayedin et al., 2019) which can be integrated into an existing corn ethanol plant to reduce the corn consumption and increase the protein content of the dried distiller’s grain and corn-oil yield.

A great debate exists about the economic feasibility of commercial algae production and numerous studies have been published on the topic (Richardson et al., 2012). The benefit from microalgae cultivation in the novel biorefinery is not limited to just ethanol production from the microalgae, but also should be condsidered as wastewater treatment, as additional processing would be required in order to discharge the treated thin stillage into the environment.Therefore the novel process is able to improve nutrient management within the corn-ethanol industry.

While the microalgae cultivation on the treated digestate was investigated, uncertainties are present for the ethanol yield on the corn-algae-ethanol production. More research also needs to be completed to identify any inhibitions in ethanol production. It is particularly important to identify the ability of the yeast to access the starch residing in the algae in order to achieve fermentation. While higher value products are available from the cultivation of algae, the current approach is advantageous based on the elimination of the costing extraction process.

Chapter 9 Technoeconomic Results

9.0 Process Yields:

Ethanol is the main product for the dry-grind facility with the total products produced at IGPC and the novel biorefinery presented in Table 9-1. The ethanol yields for both facilities were the same because the starch supplied by the algal recycling is used to displace corn used in the novel process. The DDGS stream is modified to a DDG (without solubles) stream in the novel biorefinery, as the thin stillage is now processed in the anaerobic digester which also reduces the volume of DDG produced. Corn oil removal is facilitated at the front-end of the process in the novel biorefinery where a higher quantity can be removed because the process is no longer considering the impact of fat removal from the DDGS feed. In traditional corn-ethanol facilities this oil removal is highly regulated in order to allow some to remain as a fat source within the DDGS feed. The fiber plus syrup stream becomes fiber alone, while the Hi-Pro stream remains unchanged. Carbon dioxide is an additional product that often retains no market value but is captured in order to negate carbon emissions, this stream is slightly decreased in the novel biorefinery (22.7 kg/mmbtu to 21.1 kg/mmbtu) due to its use for the cultivation of microalgae. Struvite is also produced in the novel biorefinery as a result of its precipitation following the addition of magnesium to the thin stillage.

Table 9-1: Process outputs for the corn-ethanol processes

Output (per mmbtu of ethanol)	IGPC	Novel Biorefinery
Corn Ethanol Production (btu)	1,000,000	1,000,000
Carbon dioxide, non-fossil (kg)	22.71	21.14
Carbon dioxide, product (kg)	14.26	14.26
Water, emission to air (kg)	32.25	32.25
Distiller's Dried Grains with solubles (kg)	48.25	-
Distiller’s Dried Grains (kg)	-	36.37
Corn Oil (kg)	1.248	2.73
Struvite (kg)	0	2.01

9.1 Revenue

Revenue from the facility stems from the income from the sale of ethanol, DDGS, Hi-Pro, fiber plus syrup, and corn oil. Some revenue may also be earned from subsidies (such as mitigation of GHG emissions from CO_2 capture), but these were not included in the revenue analysis. While the novel biorefinery focuses on changes to energy use and corn requirements, there are also changes related to co-products. Distiller's dried grains (without solubles) replaces DDGS, and struvite is also produced as an industrial fertilizer.

IGPC Ethanol reports feed co-product market prices for DDGS, Hi-Pro and Fiber with syrup as \$138/tonne, \$207/tonne, and \$138/tonne, respectively. The ethanol price is the largest revenue source for the plants, but the price varies considerably, the 2019 yearly commodity price of \$1.442/gal of ethanol (USDA, 2020) was used for this analysis.

It is suggested the DDG produced at the novel biorefinery is able to achieve the same market value as Hi-Pro. This is due to the higher protein and lower fat content that should increase the amount available for diet inclusion. It should be noted that the overall production of feed products will decrease due to the removal of thin stillage, but the overall value of products is not overly impacted.

At IGPC, the carbon dioxide is transferred to a production facility on site which purifies and compresses the CO_2 into a liquid product for use in beverages. This process mitigates GHG emissions but often provides no revenue for the corn-ethanol facilities. It is included as a product because of its ability to alleviate GHG emissions from the corn ethanol process, but it is currently not considered a revenue source for the process plant.

Recovered struvite can be used as a fertilizer because of the similar composition and properties to conventional fertilizers (Ahmed, Aminuddin, & Husni, 2006; Molinos-Senante, Hernández-Sancho, Sala-Garrido, & Garrido-Baserba, 2011). Because commercially available fertilizers are often multi-component products, it is not easy to determine the price of each individual nutrient component (Dockhorn, 2009). The market value should be analyzed as a product for industrial fertilizer and its nutrient value. Various market value estimates are available, Dockhorn (2009) estimated the value at 900 USD per ton (\$.99/kg) as reflective of the nutrient composition of the product.

Table 9-2: IGPC and novel biorefinery revenue breakdown

IGPC Revenue

	Volume (kg/mmbtu)	Value ($/kg)	Revenue ($/mmbtu)
Ethanol	49.59	$0.482	23.95
DDGS	17.58	$0.138	2.421
Hi-Pro	6.36	$0.207	1.315
Corn Oil	1.248	$0.620	0.773
Fiber with Syrup	24.32	$0.138	3.350
CO_2	36.96	-	-
Total			**$31.80**

Novel Biorefinery Revenue

	Volume (per mmbtu)	Value ($/kg)	Revenue (per mmbtu)
Ethanol	49.59	$0.482	23.95
DDG	12.69	$0.207	2.622
Hi-Pro	6.36	$0.207	1.315
Corn Oil	2.73	$0.620	1.693
Fiber without Syrup	11.23	$0.138	1.550
CO_2		-	-
Struvite	2.01	$0.992	1.99
Total			**$33.12**

The primary product, ethanol, comprises approximately 75% of the estimated revenue for both facilities. The increased corn oil removal due to utilizing front-end oil extraction increases the revenue brought in for the novel biorefinery, however the greatest change is the introduction of struvite recovery. Struvite recovery comprises almost 6% of the revenue for the novel biorefinery. In total, animal feed products provided a significant portion of the revenue for IGPC and the novel facility (22.2% and 16.5%, respectively), however are dwarfed by the revenue from the ethanol.

9.2 Capital Equipment Costs

9.2.1 IGPC Ethanol Inc.

For economic calculations, the year 2019 was used as the basis and all costs reported were in U.S. dollars. The model of this study was based on 330 working days per year to mirror the industry process, which generally operates 24 hours per day with time for maintenance during shutdowns. Costs of specific equipment used in the conventional dry grind process were used from the previous dry grind model (Kwiatkowski et al., 2006; Wood et al., 2013). Equipment costs were modified to reflect present day processing technologies in place at IGPC and supplemented with literature data when required. To allow accurate comparisons between the two facilities, the capital costs will be considered as a new project. The capital costs are being used as a direct comparison to the novel biorefinery, therefore the terms of finance are inconsequential. The model did not consider government support and other factors directly, though they may be reflected in some commodity prices.

SuperPro Designer can be used to estimate the capital expenditures of a process. The traditional corn-ethanol facility as presented in SuperPro Designer is shown in Figure 9. The capital costs are based on the purchase costs of the required equipment units. The SuperPro model was combined with a literature assessment of studies on dry milling corn ethanol facilities.

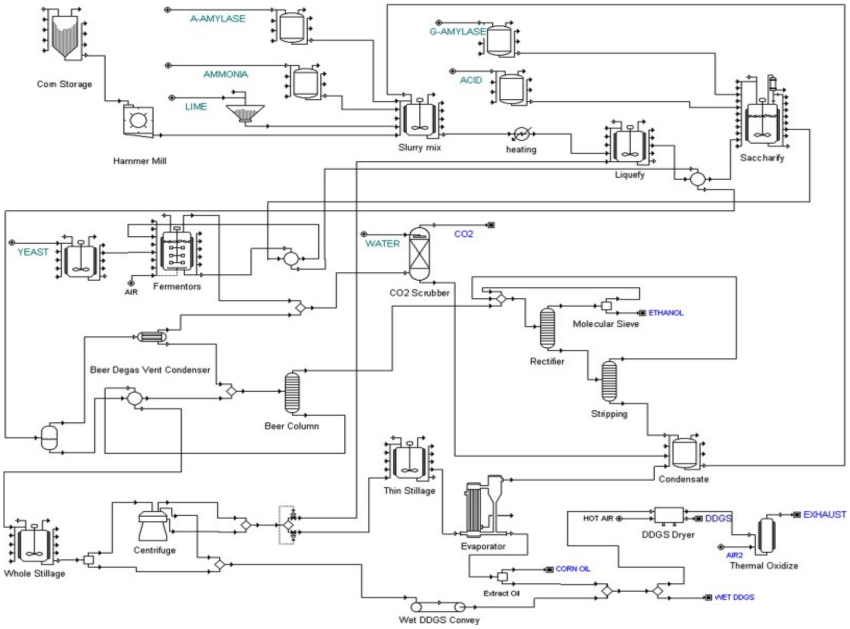


Figure 9-1: Conventional dry-grind corn ethanol facility (Zhang et al., 2017)

In addition to the typical dry grind configuration presented above, IGPC has fiber separation technology from ICM® which improves the ethanol throughput by 10% and the oil recovery by 25%. This increases the product revenues and decreases energy use within the plant by as much as 3,000 btu/gallon of ethanol produced (Fiber Separation Technology, 2019). The add-on technology used for the fiber separation is an additional capital expense for the facility.

Results from Zhang (2017) are in agreement with similar studies (Rajagopalan et al., 2005; Somavat et al., 2018) in cost estimates. The equipment cost breakdown for IGPC Ethanol is presented in Table 9-3. The costs were adjusted to account for inflation and based on the year 2019. The capital costs for ICM Fiber Separation Technology were taken from a similar sized plant reporting initial equipment costs (United states : Redfield Energy makes investment in ICM fiber separation technology, 2015). The total equipment investment of \$147.9 million for a plant producing 100 million gallons of ethanol per year equates to a cost per gallon of capacity of approximately \$1.48 per gallon.

Table 9-3: IGPC capital costs estimate

Process Equipment	**Capital Costs (millions)**
Grain handling and milling	8.32
Common support systems	2.29
Fermentation	25.86
Ethanol processing	15.30
Co-product processing	70.52
Starch to sugar conversion	8.94
ICM Fiber Separation Technology	\$16.67
Total Equipment Investment	**\$147.90**

9.2.2 Novel Biorefinery Capital Costs

The baseline equipment capital costs for the traditional corn ethanol facility were modified to depict the novel biorefinery. Individual equipment costs were also modelled primarily from literature to depict the anaerobic and aerobic treatment, algae cultivation and other process modifications while the cost savings from the co-product processing were modelled from SuperPro Designer.

The major process changes from the traditional facility is based on the removal of the by-product processing equipment primarily for evaporation and drying. An analysis on the capital costs for the construction of a 120 million gallon of ethanol per year facility, the co-product processing requires over half the total capital costs (\$77 million of a \$143 million facility) (Wood et al., 2013). This impacts the economic outlook of the novel biorefinery as the co-product processing capital costs can be greatly reduced with the elimination of evaporators and decreased requirement of drying. The updated equipment costs for the novel biorefinery are presented with reduced drying equipment due to the removal of the thin stillage stream, while the whole stillage continues to require some drying capacity.

The mass energy balance shows the flow of distillers grains to the DDGS dryer is reduced by 32% (19.28 lb of DDG/Bu to 13.05 lb/Bu), however the flow to the Hi-Pro dryer (7.7lb/Bu) remains the same as no thin stillage is added to this stream. The novel biorefinery also allows for the total elimination of the evaporator system. According to the corn ethanol refinery modelled in SuperPro Designer from Kwiatkowski et al. (2006), the thin stillage processing capital costs constitutes $3.93 million out of a total co-product processing capital cost of $7.52 million. While the corn oil extraction infrastructure costs an estimated $2 million of the co-product processing costs for a 40 MGPY facility ($3.9 million for 100 MGPY facility).

In terms of DDG drying, the drying capacity can be decreased as the thin stillage is no longer combined with the DDG prior to drying. Based on the mass energy balance, the three co-product rotary dryers present at IGPC can be reduced to two and the associated costs decreased. The novel biorefinery costs are scaled to the capital costs for a 100 MGPY corn-ethanol facility and presented in Table 9-4. The results are adjusted to 2019 as the year of construction. The results suggest that the base equipment for the novel biorefinery provides a 29% reduction in equipment costs (from $147 million to $105 million). Additional equipment costs are required in order to process the thin stillage and for algae cultivation and are explored below.

Table 9-4: Capital costs for the base equipment at the novel biorefinery

Process Equipment		**Capital Costs (millions)**
Grain handling and milling		$8.32
Common support systems		$2.29
ICM fiber separation technology		$16.67
Fermentation		$25.86
Ethanol processing		$15.30
Co-product processing:	Evaporation	$0
	Oil extraction	$3.93
	DDG drying	$24.03
Starch to sugar conversion		$8.94
Base Equipment Investment		**$105.34**

9.3 Additional Novel Processing Capital Costs

9.3.1 Anaerobic Digester

The major cost relating to the novel biorefinery is the anaerobic digestion stage. This unit is responsible for decreasing the high chemical oxygen demand of the thin stillage and producing biogas suitable of utilizing within the plant. Analysis of the IGPC facility has shown that the use of a mesophilic in-ground anaerobic digester with insulation at IGPC would not require external heating.

Many of the anaerobic digesters mentioned in literature are able to successfully treat sewage waste or animal manure, but rarely at the high rate required at IGPC. However, a similar study completed a techno-economic evaluation of stillage treatment with anaerobic digestion in a softwood-to-ethanol process under mesophilic conditions (Barta et al., 2010). The digesters are continuous stirred tank reactors with a volume of around 3500 m^3 each and their number varies between 2 and 12 (volume of up to 42,000 m^3).

The capital costs and design data were obtained from a supplier of wastewater treatment plants with experience in the treatment of wastewater from the pulp industry (PURAC AB, Lund, Sweden) based on the thin stillage flow and estimated COD content (Barta, Reczey, and Zacchi, 2010). While this literature was based on the production of lignocellulosic ethanol, the treatment of the thin stillage in the novel biorefinery should also be applicable given the similar flow and composition in both processes. The process flow for the IGPC novel process is just over 16,000 kg COD/h based on filtered thin stillage results (Sayedin et al., 2018) while Barta et al., (2010) has a flow of 9,700 kg COD/h. Thin stillage has been treated in various types of anaerobic digesters with a COD removal range of 82-99% and organic loading rate (OLR) of 2.9-29 kg COD $m^{-3}d^{-1}$(Agler et al. 2008; Andalib et al. 2012; Dereli et al. 2014; Lee et al. 2011; Sayedin et al., 2019). The volume of the full-scale reactor was calculated based on the flow of thin stillage, the filtered thin stillage TCOD of 69.8 g/L and the organic loading rate of 3.5 kg COD/m^3d achieved by Sayedin et al., (2019). This would require a reactor volume of approximately 63,000m^3. The costs for the anaerobic digester in this study were adjusted from Barta et al. (2010) based on COD, organic loading rate and flow of organic matter, and equate to $13 million USD.

Table 9-5: Anaerobic digester costs for the novel biorefinery based on Barta et al., (2010)

	Barta et al., (2010)	**This study**
Influent COD (g/L)		69.8
Organic Loading Rate (kg COD/m^{3}d)	10	3.5
Hydraulic Retention Time (d)	6.2-9.9	11
COD removal	60%	79-94%
Organic matter (kg COD/h)	9,700	16,000
Volume of reactor (m^3)	42,000	63,000
Cost (million USD)	8.6	13

Further work should be done in the novel baffled reactor to maximize the organic loading rate without disturbing the stability of the reactor. Any increases in loading rate can decrease the associated costs with a higher volume AD.

9.3.2 Biogas Upgrading Equipment

The biogas from the AD is used to produce heat only energy, as opposed to a combined heat and power (CHP) plant. This removes the high start-up costs for distribution of electricity that are based on connecting the producer to the grid and negotiating tariff agreements for the electricity. An analysis of 38 existing U.S. AD systems indicates that the omission of electrical generation equipment would lower the initial digester capital cost by approximately 36 percent (USDA, 2010).

Burning biogas on-site also requires little to no processing therefore the biogas upgrading costs are minimized by producing heat alone. This means that less refining is required for burning the natural gas directly opposed to utilizing turbines for electricity generation. Biogas can also be used readily in all applications designed for natural gas, such as direct combustion. The high heating requirements of a corn ethanol facility combined with the high start-up costs of electrical generation suggest that the best route for biogas is direct combustion for a reduction in natural gas usage.

Some biogas upgrading is required to remove the hydrogen sulfide that is produced in the AD. The hydrogen sulphide and other volatile organic compounds need to be removed to decrease emissions and prolong equipment lifespan. The upgrading process typically recovers up to 99% of the methane in the biogas (USDA, 2010). There are a variety of methods able to be used for the carbon dioxide separation and hydrogen sulfide removal.

Fortunately, due to compartmentalized configuration of the ABR, sulfate is mainly removed in the first compartment (Barber & Stuckey, 1999; Saritpongteeraka & Chaiprapat, 2008) and as a result the hydrogen sulfate is mainly contained in the biogas from the first compartment (Sayedin et al., 2019).

Natural gas has a heating value of approximately 31,800 to 35,300 British thermal units (Btu) per cubic meter while biogas has an average of 21,200 Btu per cubic meter for a biogas with 65% CH_4 (USDA, 2010). While many AD systems, including on farm, require heating for the AD system to maintain operational temperatures, the temperature of the thin stillage entering the AD is sufficient to maintain operating temperatures. For direct use of the biogas, only H_2S and moisture require some level of removal as CO_2 will not cause complications during combustion.

For the novel biorefinery, the biogas production rate for the 1st chamber of the AD from Chapter 4 was used to identify capital costs for H_2S removal based on the production of 3300 m^3 biogas per hour. Literature values suggest biochemical scrubbing for H_2S removal at this flow rate would have a capital investment of approximately $355,000 (Kvist, 2011). These costs are attributed to the removal of sulfur from 600 ppm H_2S laden gas (Allegue & Hinge, 2014).

9.3.3 Aerobic Treatment

Aerobic treatment is required for further treatment of the digestate in order to reach ammonia levels below inhibition for microalgae cultivation. For a general anaerobic digester, a digestate management plan may be required depending on the total solids content and carbon to nitrogen ratio of the digestate. Aerobic treatment is generally less expensive than anaerobic treatment as it is quicker and less complex, however the energy requirements, as outlined in the LCA, are higher due to the pumps and mixers required. Aerobic treatment requires aeration basins, clarifiers and sludge processing units. However, due to the high COD removal achieved in the AD, sludge processing will be minimized.

The aeration basins require energy in order to provide a sufficient flow of oxygen in order to complete aerobic digestion. Clarifiers help to remove suspended solids remaining in the digestate, including particulate nitrogen and phosphorus (von Sperling et al., 2007). A big factor in the cost of biological wastewater treatment systems is the flow and character of the stream to be treated. The chemical oxygen demand of the treated digestate is 9.13g COD/L thin stillage with ammonia and total phosphorus concentrations of 267 mg/L and 97 mg/L, respectively (Sayedin et al., 2019). Exact costings for aerobic treatment is difficult to decipher, however medium strength wastewater treatment plants treating between 1-10 million gallons of wastewater per day (mgd) cost 1.742 million/mgd in capital costs (WEF, 2009). These values were modified to depict the characteristics of the digestate from the AD.

Table 9-6: Parameters for aerobic treatment

Parameter	Value
Flow of treated thin stillage	1.52 million gallons/day
Cost for aerobic treatment (capital)	$2.61 million
Electricity Use (from Chapter 4)	1.09 kWh/mmbtu ethanol
Operating costs (electricity from Ch.4)	$1710/day

9.3.4 Algae Cultivation

For this study, the capital and operating costs for the open-pond raceway are obtained from secondary sources. Most literature studies focused on microalgae cultivation for lipid extraction for bio-diesel production, these were modified to fit the case study of this report. In Davis et al. (2011) the production of 10 million gallons per year of raw algal oil (based on 25% dry lipid content in harvested starch) is subsequently upgraded to a “green diesel” blend stock via hydrotreating which requires additional treatment not required by the novel biorefinery.

The algal productivity was based on 25 $g/m^2/day$ which is significantly higher than the productivity achieved on IGPC’s treated digestate, but the adjusted costs remain applicable to this study. The economic analysis for the algae cultivation for this study differs in the requirements for harvesting, extraction, warehouses, carbon dioxide sources, fertilizer and the net water demand. These categories are either not required by the process or included in the analysis of the core corn-ethanol process. The process was modeled for an open-pond system in the Midwest to achieve a site location which receives high year-round solar exposure. The nutrient requirements for the algal cultivation are assumed to be met by the phosphorus and nitrogen content of the treated digestate recycled within the process, as this was demonstrated by Sayedin et al. (2019).

The cultivation costs are dependant on the biomass productivity rate of the algae on the liquid digestate. The biomass productivities and concentrations (dry weight) of microalgae cultivated in liquid digestate were found to be in the ranges of 0.03–0.67 g/l/d and 0.4–4.8 g/l (Cheng et al., 2015), which falls in line with Sayedin et al, (2019) where a biomass productivity of 0.09 g/l/d and 1.62 g/l was established. The algal biomass productivity rate of 1.62 g/l at day 18 (Sayedin et al., 2019) was extrapolated to represent a total yearly biomass productivity of 6.26 million kg algae per year, based on 8000 hours/year of operational time.

$$1.62\ \mathrm{g\ L^{-1}d^{-1}} * 2\ (dilution\ factor) * 240{,}305\ kg\ thin \frac{stillage}{h} * 8000 \frac{hours}{year}$$
$$= 6.26x10^6 kg\ algae/year$$

Equation 5: Algal biomass productivity for the novel biorefinery

The results for the analysis by Davis et al. (2011) were scaled to match IGPC's flow of thin stillage and algae productivity and shown in *Table 9-7*.

Table 9-7: Novel biorefinery operating parameters

Thin Stillage flow	$1.903x10^9$ kg/year
Algae Productivity	3.24 g/L thin stillage (based on 1.62g/L diluted thin stillage)
Operating days	330
Algae Production	$6.26x10^6$ kg algae/year

The algal growth rates for the novel biorefinery were based on the IGPC mass balance which simulates the production of 100 million gallons of ethanol per year, and the algae biomass productivity rate achieved by Sayedin et al. (2019) of 1.62 g/L at day 18. This volume is scalable to the comprehensive techno-economic analysis by Davis et al. (2011) based on algal fuel production. The updated capital costs are for the novel biorefinery are shown in Table 9-8 for the cultivation of algal in an open pond system based on the production predicted for the novel biorefinery. The costs for the system are reduced by 55% through the removal of the harvesting, extraction, digesting and hydrotreating equipment utilized for the removal of algal oil (Davis et al., 2011). The land costs are based on a value of $3000/acre as low value land can be utilized for the open pond system.

Table 9-8: Direct installed capital costs for open pond system (based on Davis et al., 2011)

Direct Installed Capital Costs	**Costs**
Ponds	\$1.3 million
CO_2Delivery	\$0.5 million
Innoculum System	\$1.1 million
Land Costs	\$1 million
Total	**\$3.9 million**

9.3.5 Total Biorefinery Capital Costs and Annualized Cost

The total capital costs for the novel biorefinery based on the capital costs represented above are shown in Table 9-9. The novel biorefinery represents a capital cost reduction of 12% (\$22.7 million). The cost savings are a result of the savings from the reduction in drying equipment required at the novel biorefinery. These savings are despite the additional equipment costs stemming from the additional processing at the novel biorefinery.

Table 9-9: Capital investment for 100 million gallon per year novel biorefinery

Equipment	**Capital Costs (millions)**
Novel Facility base equipment	105.3
Anaerobic digester	13.0
Biogas scrubbing	0.36
Aerobic treatment	2.61
Open pond cultivation	3.9
Total Investment for novel biorefinery	125.2

The annualized cost for both facilities was determined so that the costs can be compared on a per unit basis. This helps to relate the capital costs for each facility to the ongoing operating costs to depict an accurate cost for producing ethanol. The annualized cost assumes a maintenance cost of 5% of the installed equipment costs (Wood et al., 2013), a plant lifetime of 30 years, and a discount rate of 5% (cost of capital).

$$A = C * \frac{DR}{1-(1+DR)^{-P}} + (M * C)$$

Equation 6: Annualized cost for capital expenses where A-Annualized cost, C- capital costs, P-lifetime of facility, DR-discount rate, M-annual maintenance cost

The results dictate an annualized cost for IGPC Ethanol that is 15% higher than the capital cost for the novel biorefinery (\$17.02 million and \$14.40 million, respectively). These annualized capital costs are then broken down to give a capital costs per mmbtu of ethanol produced. This equates to \$2.23/mmbtu and \$1.89/mmbtu for IGPC and the novel biorefinery, respectively.

9.4 Operating Costs

The annual costs for both facilities consist of the operating expenses such as labor, materials, and utilities used at the plants and also the administrative, maintenance and insurance costs.

Facility Costs

The facility costs include the costs related to maintenance, insurance and miscellaneous expenses. These costs are based on the size and output of the facility, for this reason the costs are based on a percentage of the capital investment of the plant. The maintenance costs, insurance, and miscellaneous expenses were assumed to be 5%, 0.8%, and 0.75% of the direct fixed costs for the plant (Wood et al., 2013). The maintenance costs for both facilities are included in the annualized capital costs.

Labour Cost

This is the cost of employment for operating the process and does not include any construction labour costs. The labour costs were determined by an estimate of working hours per year. The plant is assumed to operate 24 hours a day, 330 days a year with the unused days used for annual maintenance shutdowns.

The cost for employees is region and skill dependant but is assumed to be the same for both facilities. The number of working hours (47,520 labor-hours) was kept as set in previous studies (Wood et al., 2013). The cost of labor (set by McAloon and Yee, 2011) was determined based upon a lump estimate of number of working hours per year, \$2.5 million/y for both scenarios (Wood et al. 2013). While there is a possibility the novel biorefinery would require additional labour for the increase in complexity, the labour costs were assumed the same, as the algae pond operating conditions include the labour required for production.

Table 9-10: Operating costs for IGPC and the novel biorefinery

Facility Expenses	IGPC Cost (millions/yr)	Novel Biorefinery Cost (millions/yr)
Insurance	1.09	0.96
Labour	2.50	2.50
Miscellaneous	1.02	0.90

Utility Costs

In the SuperPro model, the utility costs consist of the costs of electricity, natural gas, steam and chilled water. A comparison between the amount of energy used in the novel biorefinery compared to the conventional facility has an important impact on the economics of the two processes. The utility costs (including steam, chilled water, electricity and natural gas) contributed over 14% of the overall operating costs for the plant (Rajagopalan et al., 2005). By decreasing overall energy use, the operating costs for the facility can be decreased.

The changes in energy use between the two facilities is demonstrated in Table 9-11 for both electricity use and natural gas use. The results stem from the energy balance presented in the LCA. The additional novel processing energy use is the electricity and natural gas required for the add-on processing for the anaerobic digester, aerobic treatment and the algae cultivation. In terms of natural gas, the additional processing is negative as the novel process provides additional energy in the form of biogas produced in the anaerobic digester which can be utilized in the plant.

Table 9-11: Utility costs for IGPC and Novel biorefinery

Energy Use: Main Units	**Electricity (kWh/h)**		**Natural Gas (GJ/h)**	
	IGPC	**Novel**	**IGPC**	**Novel**
Grain Handling and Milling	1890	1890	25.79	25.79
Fermentation	1600	1600	0	0
Ethanol Processing	1090	1090	87.61	87.61
Evaporators	200	0	85.03	0.00
Tricanter	240	240	0	0
CO_2 blower	280	280	0	0
Dryers	1050	927	138.21	117.24
Centrifuge	370	370	0	0
HRSG (A side steam)	340	177	3.85	2.00
CB Boiler (B side steam)	340	177	2.77	1.44
Steam Turbine Generator	-800	-800	3.87	3.87
Energy Use (kWh or GJ/h)	**6600**	**5951**	**347.14**	**237.95**
Energy Use (btu/mmbtu of ethanol)	24133	21759	3.53×10^5	2.42×10^5
Additional Novel Processing (btu/mmbtu)	0	11768	0	-1.73×10^5
Total energy (KWh/L or MJ/L)	0.14	0.20	7.50	1.47
Change in energy use		**38.93%**		**-80.42%**

The electricity use increases by over 38% for the novel biorefinery due to the additional electricity used for the aerobic treatment and algal growth. The natural gas use is significantly decreased (80% reduction) because of the reduction in co-product drying and the utilization of the methane from the biogas production. However, to determine how these will impact the operational costs for the economic analysis, the costs of electricity and natural gas use for IGPC was determined. Keeping consistent with the LCA, the calculations will be made per million btu of ethanol produced, or per about 50L of anhydrous ethanol. The natural gas price was set at \$3.51 per million btu and the electricity rate was \$0.07 per kWh (Somavat et al., 2018). The price of steam used was not included as it is incorporated in the natural gas used. Table 9-12 presents the full costs of utilities for both IGPC and the novel biorefinery.

Table 9-12: Cost of utilities for both facilities

Cost of production	Energy Use (btu/mmbtu)		Cost ($/mmbtu)	
	IGPC	Novel Biorefinery	IGPC	Novel Biorefinery
Natural Gas	3.53×10^5	2.42×10^5	1.24	0.85
Electricity	7.07	9.83	0.495	0.688
Total cost ($/mmbtu)			**1.735**	**1.538**
Total cost ($/gallon ethanol)			**0.132**	**0.117**

The novel biorefinery introduces a decrease in utility costs by approximately 11% over the IGPC facility. This would be equivalent to a savings of 1.4 cents/gallon or a cost savings of $1.40 million/year (based on 100MGPY production). This is significant savings but should be compared to the capital and other operating costs for the implementation of the additional processing.

Material Costs:

The materials at the plant consist of caustic soda, sulfuric acid, corn, yeast, octane, ammonia, glucoamylase, and alpha-amylase. The corn cost has the greatest impact on the processing cost for the facility, as IGPC consumes approximately 35 million bushels of corn per year. The price per bushel is variable and is dependent on weather conditions and demand in the market. The current average market prices for Ontario, Canada (2019) are $3.85/Bu ($0.151/kg) of corn. Other costs are based on literature data (Somavat et al., 2018) or site specific data when available. Although struvite begins to precipitate naturally, a magnesium source, typically a salt, is required to promote struvite precipitation in the novel biorefinery. Dockhorn (2009) identifies Mg-source as the most dominant contributor of the struvite precipitation process cost constituting 75% of the total operational cost, and a struvite cost of $3.67/kg Mg^{2+} was identified.

The costs for struvite recovery are dictated by the chemical addition of magnesium to supplement the process and the market price of the struvite as an industrial fertilizer. The recovery of struvite has been investigated in wastewater treatment plants as a way to offset treatment costs and raise the general profitability of the process (Dockhorn, 2009). Because wastewater treatment is currently considered in the capital costs at IGPC, only the additional wastewater treatment costs for struvite recovery are investigated. Dockhorn (2009) identified a slightly over stoichiometric ratio of Mg:P of 1.2:1 at an assumed $MgCl_2$ cost of \$3.67/kg Mg^{2+}.

Studies have dictated that the feasibility of struvite recovery can be improved by using seawater as a magnesium source, however this requires a plant to be located near a seawater source (Shin & Lee, 1998). Shaddel et al. (2020) concluded that seawater is a potential alternative to pure magnesium sources in struvite production, while studies in larger scale and continuous mode are needed for further verification before full-scale applications. However, this increases the dilution of the process water and could impact the lifecycle assessment.

Table 9-13: Material costs for corn-ethanol

Materials	**Cost (\$/kg)**
Corn	0.151
Denaturant (octane)	2.25
Sulfuric acid	0.11
Urea	.22
NaOH	.012
Enzyme, glucoamylase	2.25
Enzyme, alpha-amylase	2.25
Magnesium ($MgSO_4.7H_2O$)	3.67

Table 9-14: Material costs for IGPC and the novel biorefinery

	Cost (\$/mmbtu)	
Materials	**IGPC**	**Novel Biorefinery**
Corn	17.758	17.709
Denaturant	0.645	0.645
Sulfuric acid	0.045	0.045
Urea	0.050	0
NaOH	0.002	0.002
Enzyme, glucoamylase	0.103	0.103
Enzyme, alpha-amylase	0.075	0.075
Magnesium	0.000	4.000
Total (\$/mmbtu)	**18.678**	**22.579**

The material costs for the IGPC process ($1.43/gal) is in close agreement to the costs displayed in Kwiatkowski et al (2006) ($1.62/gal).As mentioned, corn represents the dominant material cost for both IGPC and the novel biorefinery (95% and 78%, respectively). This was in agreement with studies which corn contributed to at least 85% of total raw material costs in all processes (Kurambhatti, Kumar, & Singh, 2019). The octane denaturant maintained the second highest contributor to the material costs for IGPC which coincides with other studies (Somavat et al, 2018; Wood et al. 2013). The high material costs for the magnesium source limits the applicability of the novel biorefinery by significantly increasing the costs. Dockhorn (2009) also found that high costs of struvite production using chemical precipitation to be inhibitory based on the current market value of phosphorus as fertilizer. Cheaper Mg sources should be investigated including the feasibility of using seawater, however, its effect on microalgae cultivation needs to be examined.

Operating Costs for Open Pond Algae System

The net operating costs for the algae system were also adapted from Davis et al., (2011) and Aspen modelling with some literature being used for cost assessments. A stipulation for the open pond system is that the operating costs were minimized by employing carbon and nutrient recycling from the novel biorefinery, as well as relying on the water found within the treated digestate as the prominent source for the algae cultivation therefore no external nutrient sources are required. Furthermore, the costs are minimized for this study by negating the need for expensive extraction chemicals typically employed in harvesting of lipids for oil applications (Davis et al., 2011; Yuan et al., 2009). The annual operating costs for the open pond system include CO_2 delivery, labour, maintence, tax and insurance costs. As in Davis et al. (2011), the open ponds have a water depth of 20 cm and are in unlined ponds which are mixed using paddlewheels, while CO_2 is delivered via sumps to the open ponds. The novel biorefinery also negates the costs for wastewater disposal based on the recycling of the treated process water which provides nutrients for the open-pond system. The open pond system costs were modified from Davis et al. (2011), but would require a geographic location with consistent year round solar exposure.

The CO_2 demand for the process is only 1.57 kg/mmbtu of ethanol produced, and this carbon dioxide is supplied directly from the fermentation process but requires a system for delivery and bubbling throughout the system. The yearly operating costs for the open pond system are shown below. This totals a cost of \$625,000/year or a meger \$0.08/mmbtu of ethanol.

Table 9-15: Operating costs for the open pond algae cultivation

Open Pond Operating Costs	**Operating Costs (\$/year)**
CO_2 Delivery	142,700
Labour and Overhead	438,200
Utilities	44,100
Total	**\$625,000**

9.5 Economic Assessment Conclusion

By implementing the novel biorefinery, corn-ethanol producers can increase their gross revenues by almost 4% and also ensure reduced operating costs through energy-saving initiatives. Additionally, the capital costs and annualized costs for the facility are decreased by 15% by implementing the novel biorefinery. However, some assurances are required as new technology implementation typically has high risk in terms of adoption, especially in a sector that is somewhat mature like the corn-ethanol industry. The total costs for the production of ethanol at IGPC and the novel biorefinery are \$1.77/gal and \$2.03/gal, respectively.

Table 9-16: Cost and revenue breakdown for IGPC and Novel biorefinery

Cost sectors	**IGPC cost per mmbtu**	**Novel biorefinery cost per mmbtu**
Capital cost	2.23	1.886
Insurance, labor and miscellaneous	0.604	0.571
Utility costs	1.735	1.538
Material costs	18.678	22.579
Additional costs (algae, AD)	-	0.082
Total costs	**\$23.25**	**\$26.66**
Total Revenue	**\$31.80**	**\$33.12**

The cost to revenue for both facilities is similar, with the IGPC facility returning a gross profit (without taxes) of \$8.55/mmbtu of ethanol (\$0.65/gal), and the novel biorefinery at \$6.46/mmbtu of ethanol (\$0.49/gal). The results indicate that the costs associated with capital cost, labor and utility costs make a minimal impact on the overall economics of the process. Corn costs for both facilities represent 77% and 64% of the total variable and fixed costs for IGPC and the novel biorefinery. This aligns with literature suggesting the cost of corn is the major input cost at about 80 percent of variable and fixed costs on average (Irwin, 2020). Gallagher et al. (2016) found a much lower cost of production at $1.298/gal, but this was based on a net corn cost consisting of just 55% of the cost of production. The material costs for IGPC at $1.43/gal aligns with similar studies suggesting material costs of $1.37/gal (Kwiatkowski et al., 2006) and $1.24/gal (Somavat et al., 2018). As mentioned, these costs can vary greatly by year and region due to local corn prices.

The novel biorefinery was unable to significantly reduce the corn costs due to the low biomass productivity achieved by the microalgae cultivation. An increase in this sector, perhaps by utilizing co-digestion material from nearby cattle farms, as well as more research in optimizing the algae cultivation without requiring harvesting technology could make the novel biorefinery much more appealing

The novel biorefinery provides incentives in terms of reduced capital and utility costs, but an increase in the material costs due to the high price of magnesium as a source for struvite precipitation. Struvite recovery comprises almost 6% of the revenue for the novel biorefinery. This means struvite provides more revenue than corn oil extraction, which was considered an economic safe-guard for the industry when introduced in the early 2000's. However, struvite production costs do not currently offset the costs of magnesium for the process. The Mg^{2+} costs were double the revenue provided by the struvite ($4.00/mmbtu compared to $1.99/mmbtu). However, the removal of struvite avoids its natural precipitation in the anaerobic digester which may cause operational issues. As mentioned, cheaper Mg^{2+} sources should be investigated in order to reduce costs.

A great debate remains about the economic feasibility of commercial algae production. Numerous studies have been published on the topic and much of the costs are related to the nutrient supply costs and algae harvesting and extraction costs (Richardson et al., 2012).The novel biorefinery also provides a great opportunity for reduction in GHG emission through the decreased use of utilities, such as an 80% reduction in natural gas use. The high capital and operating expenses for evaporating and drying a low value co-product like thin stillage provide an opportunity for plant modifications.

Overall, the additional revenue from the novel biorefinery in terms of the struvite recovered and additional corn oil removal was unable to overcome the high material costs for magnesium supplementation. If the costs for the magnesium addition was negated, the material costs could be decreased to \$18.578/mmbtu of ethanol and the overall novel process would provide a gross profit of \$10.55/mmbtu (21% higher than IGPC). This may be achievable in the near term with research into the implementation of seawater as a magnesium source for struvite precipitation. However low magnesium concentrations in seawater could result in large volumes of seawater being required, which would result in larger environmental impacts for the process. A further investigation should be done to determine the lifecycle impacts of this substitute.

Chapter 10 Conclusion and Future Work

In summary, this study completed an LCA and economic analysis comparing a conventional corn-ethanol biorefinery in comparison to a novel biorefinery. The novel process was based on the implementation of treatment including struvite recovery, an ABR, an aerobic treatment reactor and a microalgae cultivation system. This was proposed in order to reduce the impacts from the conventional treatment of thin stillage in the traditional facility as well improve water recycling, nutrient recovery and increase co-product production.

This analysis involved the construction and analysis of datasets for the IGPC facility and the novel biorefinery. The datasets were formed through the use of site-specific data when available and was completed to accurately represent the cradle-to-gate analysis for IGPC Ethanol and the novel biorefinery. Detailed mass-balances were created for both processes to identify inefficiencies and better understand the flow of materials and energy within the processes.

The LCA analysis investigates impact categories that are relevant to the industry. These impact categories included global warming, land use, fossil resource scarcity, marine and freshwater eutrophication, acidification and water consumption. Most impact categories such as global warming and land use decreased in the case of the novel biorefinery, while minimal changes in eutrophication and acidification impacts were observed. Additional co-products, decreases in fossil energy use and increased water recycling led to decreases in the other impact categories for the novel biorefinery. The production of struvite, which replaces industrial fertilizer MAP, had a particularly large influence on the novel biorefinery impacts. The primary energy use reduction, through the removal of the evaporation vessels, decreased drying and utilization of recovered methane from AD, also reduced the environmental impacts for the novel process. However, the limited displacement of corn through the use of algae in the novel biorefinery had a minimal impact on the lifecycle impacts of the process.

The novel biorefinery was found to increase costs in the economic assessment. This was mainly a result of the use of magnesium for struvite production in the novel biorefinery. It should be further investigated to determine if cheaper sources are available that can promote struvite precipitation and thus reduce costs for the novel process. The production of algae had a minimal impact on the economic analysis of the corn-ethanol processes. This is an important caveat, as the corn costs dominated the economic analyses for both plants.

Future work should focus on some assumptions related to proposed process integration within the novel biorefinery that were used in this analysis. The primary assumption was that the starch within the *C. sorokiniana* can be readily accessed by yeast using the enzymes and conditions already present for the production of ethanol from corn. This should be investigated to determine if the starch is readily able to be converted into ethanol. An analysis should also be done to verify whether recycling of process water within the novel biorefinery yields inhibitory effects on yeast growth and performance in fermentation. Furthermore, the impacts of the non-fermentable portion of algae should be examined to determine its impact on the production of animal feeds within the novel biorefinery.

The biomass productivity and starch content of the algae should also be investigated to determine if changes can be made to enhance the displacement of corn. Corn production has demonstrated the largest influence on lifecycle impacts so any increases in its displacement by algae will yield environmental benefits.

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Appendices and Sensitivity Analysis

Algae Cultivation

Many comparable studies completing technoeconomic analyses on corn-ethanol industry identify that corn feedstock contributes the overwhelming majority of the operating costs for the industry (Wood et al., 2013). While the novel biorefinery introduces a small decrease in the corn use, it has a minimal impact on the process. This stems from the combination of low biomass productivity on the treated thin stillage digestate (1.62g/L digestate), as well as the comparably low starch content of *C. Sorokiniana* (17.8% starch compared to 70% for corn). If these two issues could be addressed, the novel biorefinery may have a larger impact on the corn-ethanol industry.

Algae is highly efficient at producing biomass and can accumulate a significant amount of energy-rich carbohydrates in different conditions. The high nutrient availability of digestate makes it a good candidate for the cultivation of microalgae. The nutrient-rich digestate has been considered as a suitable growth media for microalgae in many studies, producing biomass while treating the wastewater stream (Franchino et al., 2016; Praveen et al., 2018). However, industry has failed to bring about widespread applications for the industry primarily due to concerns regarding the economic and environmental sustainability associated with pre-treatment or dilution of the waste before growth of microalgae (Ayre et al., 2017).

Additionally, Sayedin et al. (2019) did not investigate nitrification as a method to reduce inhibition for microalgae cultivation. This could result in changes to the biomass productivity of *C. Sorokiniana.* Sayedin et al. (2019) was able to achieve a biomass productivity as high as 2110 mg/L when using IGPC thin stillage digestate under two-times dilution coupled with struvite recovery and chitosan flocculation. This 30% improvement in biomass productivity compared to the base case biomass productivity of 1620 mg/L would likely be achievable with minimal changes.

C. sorokiniana was chosen due to its high biomass concentration achieved on IGPC's thin stillage digestate (Sayedin et al., 2018). The algae for this analysis have been reported to achieve starch content as high as 27% (Li et al., 2015). Due to the high starch content, the algae can supplement the ethanol process and decrease the corn input required for ethanol production.

By maximizing the biomass productivity and starch content of the algae, the costs for corn feed for the plant can be adjusted.

Table 0-1: Changes in corn cost based on an increase in starch content and microalgae biomass productivity

Facility	**Starch Content**	**Biomass Productivity**	**Material Corn Cost (million/ year)**
IGPC Ethanol Inc.	-	-	\$136.0
Novel Biorefinery	17.8%	1620 mg/L	\$135.7
Modified Novel Biorefinery	27%	2110 mg/L	\$135.4

For the improved microalgae cultivation, savings on corn use double to \$600,000/year. Better micro-algal strains and maximizing algal starch content are the primary means to reduce production cost, which may cause these methods to be more competitive in commercial reality.

Co-digestion of Animal Waste

In order for the production of algae to have a significant impact on corn use it was hypothesized that it would need to replace approximately 5% of the corn use at IGPC Ethanol. It was first investigated what the effective biomass productivity of the algae would have to be in order to achieve this level of displacement. Currently, the biomass concentration was measured as 1.63 g/L of thin stillage at day 18, the biomass productivity per day is therefore 0.091 g $L^{-1}d^{-1}$. Similar studies were able to maximize the biomass productivity for *Chlorella sorokiniana* cultivation on anaerobic digestion. Riaño et al. (2016) cultivated the algae whey cheese digestate and was able to achieve a biomass productivity of 12.0 g $L^{-1}d^{-1}$. This productivity rate was used to determine the volume of algae required to have a significant impact on the corn-ethanol process. The starch content of *Chlorella sorokiniana* has been found to be optimized to 27% (F. Liu et al., 2017). This alga is used to displace corn for the conversion of starch into ethanol, so both starch contents are considered (algae at 17.8% starch, corn at 70% starch). Algae produced under these conditions will be able to displace 1.01% of the total corn received at the facility. This is a significant increase compared to the 0.18% suggested based on the current biomass yields.

$$12.0\frac{g}{L\times d} * 240{,}305\ kg\ \ thin\ stillage/h = 2884\ kg\ algae/h$$

$$2884\ kg\ algae/h * 27\%\ starch = \frac{513\ \ kg\ starch/h}{70\%\ starch} = 1112\ kg\ corn\ displaced/h$$

Another opportunity to enhance algae biomass productivity is through the introduction of co-digestion of other wastes. This could be implemented by using animal wastes from nearby cattle lots, as an existing relationship is already in place for DDGS and other feed products distribution or through the use of high strength wastewater treatment at the novel biorefinery. The objective is to determine if the introduction of co-digestion can increase the biomass concentration of *Chlorella sorokiniana* to be able to have a significant impact (5%) on corn use.

Several studies have been done analyzing the ability of microalgal species to cultivate on the digested effluent from industrial wastewaters. Wastewaters and their high nutrient content are a possible solution to obtain nutrients for algae cultivation at a low cost, many studies have investigated the possibility of coupling biofuel production with wastewater treatment (Koller et al., 2012; Oswald, Gotaas, Golueke, Kellen, & Gloyna, 1957). Xia and Murphy (2015) evaluated the ability of several microalgal species for their efficient removal of nutrients from digestate while producing high-value biomass that can be used for the production of biochemicals and biofuels. This was tested on different digestate medium from agricultural and industrial wastes. The research was able to achieve a biomass productivity of 0.03-0.67 g algae L^{-1} day^{-1} and 0.4-4.8 g/L digestate, by using diluted digestate. Based on the upper scale concentration of (4.8 g/L) and the 3.99% of corn remaining to be displaced to reach the 5% displacement goal.

$$3.99\% \times \frac{27\%\ starch\ (algae)}{70\%\ starch\ (corn)} \times 110{,}000\ kg\ algae/h = 1693\ kg\ algae/h$$

$$= 1112\ kg\ corn\ displaced/h$$

$$\frac{1693\ kg\ algae/h}{4.8\frac{g}{L\times d}} = 3.53\times 10^{5}\ L\ digestate/h$$

The biomass productivity for the co-mingled digestion is low and therefore the plant would require a very significant amount of digestate in order to achieve the 5% displacement.

Therefore, the co-digestion of other wastes, including agricultural wastes, will not have a significant impact on the algae production. Achieving a significant displacement of corn (5%) through the use of algal cultivation on digestate appears to be unlikely based on the current data. New research should focus on increasing the biomass productivity on the algae, as this could lead to further corn displacement.

Removal of Algae Cultivation

Due to the low biomass productivity of the microalgae cultivation an alternative method for thin stillage treatment was proposed where the thin stillage digestate was directly reused as process water, opposed to the further treatment proposed in this study. This would allow the novel biorefinery to negate many of the capital intensive and operational costs for additional processing including algae cultivation and aerobic treatment. It also benefits from simplifying the process; the traditional corn-ethanol process has very little downtime and a biological process like algae cultivation can have stability issues like bacterial infections which impact productivity.

Other novel biorefineries were approached through an integrated ethanol-methane fermentation system where thin stillage was treated by anaerobic digestion and then directly reused to make mash for the following ethanol fermentation (K. Wang et al., 2013). The anaerobic digestion was able to achieve a 98% total chemical oxygen demand (TCOD) removal at laboratory scale and 97% at pilot scale, during a hydraulic retention time of 22.9 days. However, this was only able to be achieved via thermophilic AD, while mesophilic was only able to achieve a TCOD removal of 56.4%. Research by Sayedin et al., (2018) was able to achieve TCOD removal of 94-97% while utilizing mesophilic digestion. This allows for digestion to take place under controlled parameters and without external heating, while also maximizing biogas production.

Ethanol production was not influenced by recycling anaerobic digestion effluent at laboratory and pilot scale (K. Wang et al., 2013). The distillers' dried grains with solubles produced in the proposed system exhibited higher quality than traditional because of increased protein concentration and decreased salts concentration. This novel process, like the current study, was also able to improve the net energy ratio for the corn-ethanol process. Further, as hypothesized for the current study, the digestate was able to be utilized as the sole nitrogen source for the ethanol fermentation, negating the need for external urea use. When the anaerobic digestion effluent was recycled, ammonium in the effluent replaced the urea as nitrogen source for ethanol fermentation (K. Wang et al., 2013).

This research suggests that the corn ethanol process can be improved through the incorporation of anaerobic digestion without the requirement for additional treatment through the use of algal cultivation. Currently, the additional treatment for the novel biorefinery only nets a displacement of 0.32 kg of corn/mmbtu. This only reduces costs by $0.05/mmbtu and will have a minimal impact on lifecycle impacts through this displacement. By removing the additional processing, much of the additional capital costs can be removed while still maintaining the value-added products of struvite precipitation, biogas production and the additional corn oil removal. The assessment of the novel biorefinery with and without algae cultivation should be explored to determine the effect on ethanol production.

10.4 Allocation Methods

The co-product credit system can have a major impact on how the process impacts are distributed across the products. This report analyzed the two systems using the system expansion method, but comparisons with other methods can help demonstrate transparency in the process. Chapter 6.4 identifies how the system expansion, physical allocation and economic allocation would weigh the environmental impacts from the process. Physical allocation was chosen as the secondary co-product credit system and it allocates the impacts based on the weight of each product produced.

Table 0-2: Co-product weightings when using the physical allocation method

	Volume (kg/mmbtu)		**Allocation**	
Product	**IGPC**	**Novel**	**IGPC**	**Novel**
Ethanol	39.1	39.1	38%	40.3%
DDG(S)	48.27	36.4	46.9%	37.5%
Corn Oil	1.25	2.73	1.2%	2.8%
Carbon Dioxide	14.26	14.26	13.9%	14.7%
Nitrogen fertilizer	-	2.83	-	2.3%
Phosphate fertilizer	-	2.83	-	2.3%

The openLCA process for physical allocation is the same, except the products are no longer used to negate the impacts of the avoided products they displace. The impacts for the system get divided based on the percentage contribution for ethanol. The impacts from both processes while using physical allocation is lower than using system expansion. This is because ethanol in the IGPC and the novel process only bears 38% and 40%, respectively, of the overall impacts from the process. This also helps indicate why the LCA results for many of the impact categories are slightly higher for the novel process than IGPC; in the novel process, ethanol takes a slightly higher burden than at IGPC Ethanol. The results in Table 11-3 indicate that the co-product credit method makes a large impact on the LCA results. However, ISO 14040 and 14044 recommend avoiding allocation whenever possible through subdivision of processes or by expanding the system boundaries to include the functions associated with the coproducts (Pereira et al., 2019). For this reason, system expansion was used as the main analysis in this study.

Table 0-3: Life cycle impact results comparing system expansion to physical allocation

	System Expansion		**Physical Allocation**		
Name	**IGPC**	**Novel**	**IGPC**	**Novel**	**Unit**
Global warming	42.12	31.59	33.12	31.61	kg CO2 eq
Land use	0.43	-1.84	-.30	.32	m^2a crop eq
Fossil resource scarcity	8.65	0.78	5.63	4.24	kg oil eq
Marine eutrophication	0.10	0.10	0.16	.17	kg N eq
Freshwater eutrophication	0.01	0.01	0.03	0.03	kg P eq
Terrestrial acidification	0.56	0.54	0.40	.42	kg SO2 eq
Water consumption	1.17	0.68	0.54	.66	m^3