A Distributed Model Of Oilseed Biorefining, Via Integrated Industrial Ecology Exchanges

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Biographical Sketch

Jeremy C. Ferrell was born in Oakland, California March 4th, 1976. He was raised in Raleigh, North Carolina where he attended primary and secondary schools and was influenced by his father's interest in renewable energy, having had a small wind turbine and solar thermal panels on the family's home. He received his Bachelor of Science degree in Natural Resource Ecosystem Assessment from North Carolina State University in 1999. He worked for the National Parks Service at Grand Canyon before serving as a Peace Corps volunteer in rural eastern Paraguay from 2000 to 2003. In 2004 he continued work in agroforestry development in Paraguay with GTZ where he was exposed to vegetable oil as a diesel fuel substitute in a permaculture course in Brazil and began to research agroforestry systems with mbokaya palm as a biofuel feedstock. Upon returning to the US, Jeremy entered a Master's program at Appalachian State University's Appropriate Technology program and took on a leadership role in an innovative closed-loop biodiesel project. Jeremy completed his Masters in 2007 and continued working on grant-funded biofuel projects through Appalachian Energy Center.

Jeremy joined North Carolina A&T State University in 2009 to pursue a Ph.D. in Energy and Environmental Systems. He set out to use the emerging EcoComplex Biorefinery facility that he managed for the empirical side of his research. Jeremy continued to work at the EcoComplex throughout his time as a student. While a student, Jeremy participated as a Fulbright Fellow for the first Biofuels Technology Short Course in Sao Paulo, Brazil. He also won an award for the FOCUSS ADM Biofuels Business Idea Competition. He is a member of the International Society of Industrial Ecology.

After completing his Ph.D. degree, Jeremy intends to pursue a teaching career in academia and continue to research renewable energy and sustainable technologies.

Dedication

I would like to dedicate the fruits of this long journey to my supportive family and especially to my wife Katie, who shares my fiery passion for sustainability, and for her tireless support, understanding, and love throughout.

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Abbreviations

gCO_2-eq/MJ	Grams of carbon dioxide equivalent per megajoule
$	Dollar
°C	Degrees Celsius
°F	Degrees Fahrenheit
ac	Acre
ASTM D6751	American Society for Testing and Materials standard for biodiesel
B2	Blend of 2% biodiesel and 98% petroleum diesel
B20	Blend of 20% biodiesel and 80% petroleum diesel
bu	Bushel
C&D	Construction and Demolition
CARB	California Air Resources Board
CI	Carbon Intensity value
CO_2	Carbon dioxide
D4 RIN	Biomass-based diesel Renewable Identification Number
EDA	Economic Development Agreement
EIP	Eco-Industrial Park
ELCA	Energy Life Cycle Assessment
EN 14214	European quality standard for automotive FAME
EPA	Environmental Protection Agency
EPAct	Energy Policy Act
EROI	Energy Return on Investment
FAME	Fatty acid methyl ester

FER	Fossil Energy Ratio
FFA	Free fatty acid
FIE	Fertilizer-induced emissions
g	Gram
GHG	Greenhouse Gas Emissions
GJ	Gigajoule
GMO	Genetically Modified Organism
GREET	Greenhouse gases, regulated emissions, and energy use in transportation
GWP	Global Warming Potential
H20	Water
H3PO4	Phosphoric acid
Ha	Hectare
hr	Hour
HVAC	Heating, ventilation, and air conditioning
IE	Industrial Ecology
ILUC	Indirect Land-use Change
IPCC	Intergovernmental Panel on Climate Change
IS	Industrial Symbiosis
ISO	International Organization for Standardization
IX	Ion exchange
k	Degrees Kelvin
K3PO4	Potassium phosphate
kg	kilogram

km	kilometer
KOH	Potassium hydroxide
kW	Kilowatt
kWh	Kilowatt hour
kW_{th}	Kilowatt thermal
l	Liter
Lbs	Pounds
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LEED	Leadership in Energy and Environmental Design
LFG	Landfill Gas
LFGTE	Landfill Gas to Energy
LPM	Liters per minute
LPY	Liters per year
M	Million
m^3	Cubic meter
MA	Mass Allocation
MeOH	Methanol
MIF	Material Input Flow
min	Minute
MIU	Moisture, impurities, unsaponifiables
MJ/hr	Megajoules per hour
MMbd	Million barrels per day

MMBtu	Million British Thermal Units
mol	Mole
MSW	Municipal Solid Waste
MW	Megawatt
MWe	Megawatt electricity
MWh	Megawatt hour
N_2	Nitrogen
N_2O	Nitrous Oxide
NBB	National Biodiesel Board
NC	North Carolina
NCDA	North Carolina Department of Agriculture
NCDENR	North Carolina Department of Environment and Natural Resources
NCGA	North Carolina General Assembly
NER	Net Energy Ratio
NOx	Nitrogen oxides
O_2	Oxygen
Pa	Pascal
ppm	Parts per million
PSI	Pounds per square inch
RBD	Refined, Bleach, Deodorized
RFS	Renewable Fuel Standard
RIN	Renewable Identification Number
scfm	Standard cubic feet per minute

UCO	Used Cooking Oil
ULSD	Ultra low sulfur diesel
yr	Year

Abstract

As the demand for direct petroleum substitutes increases, biorefineries are poised to become centers for conversion of biomass into fuels, energy, and biomaterials. A distributed model offers reduced transportation, tailored process technology to available feedstock, and increased local resilience. Oilseeds are capable of producing a wide variety of useful products additive to food, feed, and fuel needs. Biodiesel manufacturing technology lends itself to smaller-scale distributed facilities able to process diverse feedstocks and meet demand of critical diesel fuel for basic municipal services, safety, sanitation, infrastructure repair, and food production. Integrating biodiesel refining facilities as tenants of eco-industrial parks presents a novel approach for synergistic energy and material exchanges whereby environmental and economic metrics can be significantly improved upon compared to stand alone models.

This research is based on the Catawba County NC EcoComplex and the oilseed crushing and biodiesel processing facilities (capacity-433 tons biodiesel per year) located within. Technical and environmental analyses of the biorefinery components as well as agronomic and economic models are presented. The life cycle assessment for the two optimal biodiesel feedstocks, soybeans and used cooking oil, resulted in fossil energy ratios of 7.19 and 12.1 with carbon intensity values of 12.51 gCO_2-eq/MJ and 7.93 gCO_2-eq/MJ, respectively within the industrial ecology system. Economic modeling resulted in a biodiesel conversion cost of \$1.43 per liter of fuel produced with used cooking oil, requiring a subsidy of \$0.58 per liter to reach the break-even point. As subsidies continue significant fluctuation, metrics other than operating costs are required to justify small-scale biofuel projects.

CHAPTER 1

Introduction

Fossil fuels have given rise to modern industry, industrialized nations, and are the driver of today's society characterized by mobility, high material consumption, and high quality of life. They account for 82% of total energy use in the United States and 86% of global energy use (EIA, 2013; IEA, 2011). This resource powering the modern age is inherently non-renewable and subject to increasing scarcity and depleting reserves exacerbated by insatiable demand. The extraction and use of fossil fuels have resulted in the unprecedented and unevenly distributed accumulation of wealth and technological advancement. This achievement has compromised political, societal, economic systems, and the biosphere through pollution and emissions to air, water, and soil that threaten the planet's ability to provide essential ecosystem services for our very own species. This makes Amory Lovins (2011), a leader in sustainable energy, ponder, "What if we could make energy do our work without working our undoing?" (p. 232). Rethinking energy and navigating the impending transition to a new energy matrix that includes smart utilization, efficiency, and renewables to dramatically reduce fossil fuel usage is one of the concurrent unparalleled challenges of the 21st century. Adapting to a changing global climate and providing resources for a growing human population are inextricably linked with energy use, availability, and demand.

Of the energy sectors, transportation is particularly reliant on fossil fuels whereby 95% of the US demand is met by petroleum based liquid fuels (EIA, 2013). Petroleum derived liquids exemplify desirable fuel attributes such as high energy density and ease of transport and storage. Virtually all infrastructure related to the end use of liquid fuels is based on three petroleum derived fuels: gasoline, kerosene, and diesel. Therefore any competitive alternative must have the ability to “drop-in” to current infrastructure. According to the Energy Information Administration, in 2013 the United States consumed 18.7 million barrels per day of petroleum fuels and 0.95 MMbd of renewable biofuels (0.87 ethanol and 0.083 biodiesel). Additionally, petroleum is the platform upon which the polymer chemical industry was founded and responsible for the plastics industry, the third largest industry in the United States with over 16,200 manufacturing facilities employing over 800,000 workers (Plastics-Industry-Trade-Association, 2014). Global plastics consumption is on the order of 170 million tons annually with economic value of $560 billion (Biron, 2007). The myriad of commodity products used in everyday life, from bottles to packaging to product moldings, makes one realize the ubiquitous yet precious value of this resource.

Biomass is the only piece of the renewables matrix that can directly replace petroleum by producing energy and biobased products, such as bioplastics, and polymers. Biomass is currently responsible for over half of U.S. renewable energy consumption, and represents 2.1% of the total energy supply (EIA, 2013). The emerging biobased economy, whose three pillars include bioenergy, biofuels, and biomaterials, is poised for substantial growth. Worldwide consumption of biofuels in the transportation sector is forecasted to increase from a current level of 6% of the liquid fuels market to roughly 8% by 2022 with a corresponding production increase from 122 to 193 billion liters per year of drop-in fuels (Shepard & Gartner, 2014).

Interest in biofuels, first piqued by the oil embargos of the 1970s, then propelled by policy and mandates in the name of energy security, environmental benefit, and economic development, has evolved into a significant player in the energy sector. The past decade has been a time of unprecedented funding and investment in research and development in the larger biomass energy arena. Principal areas have been second generation feedstocks and technologies that avoid the contentious issues of land-use change and competition with food. Advancements in the associated biomaterials sector have also been developed during this period, built primarily upon polylactic acid polymers from conversion of corn starch.

Trends in the transportation sector suggest that light duty personal transportation will move towards increased fuel economy and electrification, while heavy-duty engines, the workhorses of the industrial economy, will continue to rely on liquid fuels (IEA, 2013). Though questions regarding long-term viability of the internal combustion engine persist, renewable diesel fuel represents a promising bridge technology. Petroleum diesel is the energetic backbone of industrial agriculture, transport, and heavy-duty applications. Diesel powered equipment is fundamental to food production, construction of the built environment, infrastructure maintenance, and transportation of goods in both short and long haul via truck, rail, and ship. Securing this energy source is paramount for any nation's security.

The amount of "critical" diesel fuel (i.e. fuel needs for basic municipal services, sanitation, safety vehicles, infrastructure repair, and food production) can be achieved through biorenewable feedstocks (Knothe, Krahl, & Gerpen, 2005). The development of second generation technologies will ultimately increase the pathways to renewable diesel from cellulosic materials, algae and genetically modified bacteria and yeast that convert sucrose to a diesel compatible hydrocarbon (Lipp, 2008). Significant market penetration for these emerging technologies remains in a nebulous time frame; however, the National Biodiesel Board has stated its ambitious goal of supplying 10% of the US diesel fuel mix with biodiesel by 2022 (NBB, 2013a). Feedstocks to provide this fuel are expected to become increasingly diverse.

1.1 Proposed Solution: Distributed Biorefineries

As the demand for direct petroleum substitutes increases, biorefineries are poised to become distributed centers for conversion of biomass into fuels, energy, and bioproducts. A distributed model offers many advantages such as reducing transportation cost of raw materials, tailoring process technology to available feedstock, and supplying local demand. This decentralized approach is contrary to concentrated production, such as conventional petroleum refineries, which offer incredible economies of scale but are costly to build, maintain, and offer little resilience in a rapidly transforming energy economy. Biodiesel manufacturing in particular lends itself to smaller-scale distributed facilities. Its technical process is simpler, reactions take place at atmospheric pressures with low quality thermal energy input, and it has the ability to handle diverse feedstocks including common wastes such as used cooking oils and trap grease. Integrating biodiesel refining facilities as tenants of eco-industrial parks (EIPs) presents a novel approach to realizing the potential for synergistic energy and material flows whereby environmental and economic metrics can be optimized and significantly improved upon compared to stand alone models.

Oilseed biorefining, integrated farm to fuel systems, and the biodiesel production chain exemplify symbiotic relationships within an EIP. Oilseed crops are grown on non-traditional agronomic buffer lands irrigated with re-use water and fertilizer produced on-site, then extracted to produce vegetable oil and protein meal, a valuable feed commodity. Vegetable oil, raw, semi-refined, or recycled as used cooking oil, is transesterified to produce biodiesel and glycerin while utilizing non-fossil based electricity and waste process heat from a co-generation plant. Biodiesel is consumed in heavy duty engines while the crude glycerin is refined into fertilizers, technical grade glycerol, or burned in micro-turbines for power generation. Waste is minimized and the process is additive to food, feed, and energy systems while mitigating carbon emissions. Producing biofuels is manufacturing that creates jobs throughout the supply chain from plant operators to farmers. Municipal landfill sites offer many advantages for co-locating biorefineries including: good infrastructure (roads, power, and water), fuel demand for heavy mobile equipment, and biogas production that can be developed as an economical energy source for process heat.

Though biodiesel manufacturing has become established and economically viable as an independent entity, it has not been sufficiently developed in regard to producing high-value low-volume products in addition to low-value high-volume fuels. Additionally, biodiesel manufacturing has not been proven at a smaller-scale (less than 500,000 liters per year) or incorporated into eco-industrial parks to lower operating costs and gain environmental advantage. This is in part due to the nature of the endeavor. There are still a relatively small number of biodiesel facilities, and an even smaller number of eco-industrial parks. Finally, economics as the preeminent metric of evaluation may likely preclude the concept of regional biorefineries from taking root.

1.2 Study Site: The NC EcoComplex

The EcoComplex and Resource Recovery Facility of Catawba County, North Carolina is developing an eco-industrial park that synergistically co-locates private and public partners to employ industrial symbiosis by combining industry, waste management, energy production, and university research. The EcoComplex is a 326 hectare site centered on the Blackburn Landfill with 2.4 million metric tons of waste in place that serves the 156,000 county residents, receiving 484 tons/day of MSW and 80 tons of construction wastes per day. Anchoring the EIP are three GE-Jenbacher co-generation units each with 1MWe capacity that convert landfill gas into electricity and heat. Existing components include a municipal solid waste (MSW) landfill, a construction and demolition (C&D) landfill, a recycling center, a landfill gas fueled electrical generation facility, the Catawba County-Appalachian State University Biodiesel Research, Development, and Production Facility with capacity of 490,000 liters per year, a 4-ton per day Crop Processing and Oilseed Crush Facility, a high tech dimensional lumber facility, and a pallet recycling facility.

The biodiesel facility and crush facility are collectively considered the oilseed biorefinery system. The biorefinery was conceptualized as an integral component of the EIP for three principal reasons: 1) utilize buffer lands to grow biodiesel feedstock, 2) use waste thermal input from the co-gen facility for process heat, and 3) provide fuel for the landfill operations.

1.3 Dissertation Objectives

The overarching goal of this dissertation research is quantify, analyze, and interpret the components of oilseed biorefining using tools and methods offered by the multidisciplinary approach of industrial ecology. The context for conducting this research is the backdrop of industrial ecology exchanges, primarily heat and material flows through the integrated system. Economic systems (capital, investment, and business studies) as well as policy, engineering, and legal elements will be presented to develop a holistic systems approach as they pertain to the core disciplines of Industrial Ecology. The following questions address the technical, environmental, and economic feasibility of the proposed system.

1. What are the technical bottlenecks and their pathways to optimization within biodiesel production from a mixed feedstock?

2. What improvements are made in Life Cycle Assessment (LCA) through this integrated model compared to conventional means (quantified in GHG emissions, Net Energy Ratio, and Fossil Energy Ratio)?
3. After developing an economic model for biomass utilization at the EcoComplex Biodiesel facility, what are the key variables, and their pathways to optimization based on economic sensitivity analysis?

1.4 Organization of the Dissertation

This dissertation consists of eight chapters. Chapter two is the review of literature presenting background of key components of the interdisciplinary research area. Chapter three introduces the Catawba County NC EcoComplex, the study site, source of data, and inspiration for this dissertation. Background and a historical perspective are presented as well as future endeavors for this developing EIP. Chapter four outlines the material and energy balance of the oilseed biorefinery within the given system boundary. A life cycle inventory (LCI) is created for the biorefinery system. These flows are analyzed for technical bottlenecks and incongruities of the system. Key recommendations are listed for improvements of the system. Chapter five presents the life cycle assessment (LCA) of the system defined both in terms of energy balance and greenhouse gases. The most common feedstocks currently used for biodiesel production (soybean, canola, sunflower, and used cooking oil) are compared. Chapter six delivers an economic analysis for each piece of the integrated biorefinery. Recommendations are included for pathways to improve current economic projections. Chapter seven compiles an overall synthesis of results and discussion and finally, chapter eights provides conclusions and recommendations for future work.

CHAPTER 2

Literature Review

2.1 Industrial Ecology

The term industrial ecology produces a spontaneous reaction in some, insisting that it is a contradiction in terms, an oxymoron like deafening silence or freezer burn. How can industrial be attributed to any natural system that examines the relationships of organisms to one another and their physical surroundings? It is this perspective that separates the biosphere from the technosphere as mutually independent. On a planet with finite resources one realizes that the industrial system is located within the bounds of the natural earth system. Industrial ecology explores this perspective to ask how industrial systems can resemble an ecosystem in terms of materials, energy, and information flows where there is no concept of waste and organisms exist in homeostasis. This thinking has been manifest intuitively for some time. Forces that have shaped human evolution: colonialism, the industrial revolution, fossil fuel use, and the internet, further the evolving concept of how humans use technology to interact with their environment. Population growth and the progression of people living in urban areas concentrate energy and material flows, accelerating the industrial aspect of human civilization and the imperative for these systems to reduce impacts to the environment.

2.1.1 IE Principles. The premise for Industrial Ecology (IE) is based upon the synergetic relationships found in natural ecosystems where the flow of energy and materials are efficiently optimized. IE uses the idea of a *roundput*, where the recycling of matter and cascading of energy are in accordance with natural ecosystem behavior (Korhonen, 2004). In nature, these interactions are the results of millions of years of evolution and the formation of biological niches. In relation to modern industries this has also been coined, waste equals food, where all materials are either technical or biological nutrients that flow back into the making of new products (McDonough & Braungart, 2002).

In industrial ecology, symbiotic and collaborative possibilities of interacting firms (industries) are offered by their geographic proximity (M. R. Chertow, 2000). Eco-industrial parks (EIPs) are the product of synergetic interaction that looks to optimize local economies while decreasing negative environmental externalities. The concept of industrial metabolism captures the essence of an eco-industrial park, and is studied through analysis of material and energy flows (Deschenes & Chertow, 2004).

Industrial symbiosis (IS) is a defining aspect of applied industrial ecology and the assessment of eco-parks. Relationships that describe IS can be categorized in five principal ways (Graedel & Allenby, 2010). Category 1 is through waste exchanges such as an automobile scrap yard that recovers and sells useful parts and prepares the bulk material for recycling. Second is within a facility, firm, or organization where materials or products are exchanged within given boundaries of a single organization. A modern petrochemical complex practices this type of exchange. The third category is among co-located firms in a defined industrial area where firms organize themselves in close proximity to exchange energy, water, materials, or services. An example is a brewery whose byproducts of spent grain and yeast are used as inputs for mushroom, pig, fish, and vegetable farming. The fourth category is described as among firms not co-located. Kalundborg Denmark’s EIP contains firms that exchange steam, fly ash, and water over a 3 km radius. The industrial park was not planned for IS, however the economic advantage offered through material exchange was highly motivating. Lastly, the fifth category is among firms organized across a broader region which covers a broader spatial range. This category is the most difficult to realize and would likely require active management.

Drivers for incentivizing industrial ecosystems vary widely though likely include financial opportunities that make good business sense. Lower input costs, lower operating costs, and increased revenues are strong motivators to engage in material and energy exchanges with other firms. Other drivers include resource scarcity, most commonly water, reduced liability from potentially harmful or toxic byproducts, staff mobility where highly trained employees may offer expertise to partnering firms or businesses, and a focus on sustainability as a means for distinction or to achieve internal goals or mandates. Barriers to implementing IE systems are also many. Exchanges and joint approaches may cause excessive and unplanned costs. The dependence on other firms that have separate administrations and management systems to provide material inputs adds risk and liability in the case where one firm fails or increases its costs. Information is another barrier whereby the firms involved share a lack of understanding of the process inputs and outputs of potential symbiosis. Firms that are interested in IS may not have an appropriate technical pairing where inputs and outputs simply to not match. Regulation may prevent exchanges in some cases, in particular when dealing with hazardous materials. Finally, motivation is a significant barrier. Committing to collaborative and symbiotic relationships is largely outside the norm for traditional business and is requisite to achieve high levels of industrial symbiosis (Gibbs & Deutz, 2007).

2.1.2 Applying Ecology to Industrial Systems. Industrial activities have long been congregated in centers based on practical factors including infrastructure, roads, utilities, access to urban areas, and local natural resources. Early industrial parks developed organically without extensive planning, because of simple efficiencies gained by co-location of industrial activity to access available resources. An early well-documented site is Prestongrange, Scotland. The site located at East Lothian near Edinburgh, UK on the Firth of Forth Bay, was blessed with surface coal seams that were first extracted by Monks to evaporate sea water to produce salt for trade to peoples of the interior. This activity began in the 14th century and gradually transitioned to glass works by the 17th century, to brick works and pottery by the 18th and 19th centuries with extensive coal mining (Cressey, Johnson, Haggarty, Turnbull, & Willmott, 2012). Prestongrange was later home to one of the Cornish Beam engines used for water pumping as mines were built for continued coal extraction. Though this site was common to many different industrial activities that did overlap, they were not necessarily practicing mutualism. Prestongrange represents the early age of the industrial revolution and similar sites can be found around the globe. The evolution necessary to advance industrial activities to become more technically, economically, and environmentally efficient by incorporating ecological based relationships developed in the 20th century.

Eco-Industrial Parks have three guiding principles: (a) reducing and minimizing energy requirements, (b) using industrial wastes as inputs, and (c) the development of a diverse and resilient system (Frosch & Gallopoulos, 1989). EIPs operate at micro, meso, and macro-levels where the clustering of firms offers unique opportunities for value adding. In the seminal work "Industrial Symbiosis: Literature and Taxonomy," M. R. Chertow (2000) gives the following succinct definition of an eco-industrial park:

> An EIP is defined as "a community of manufacturing and service businesses located together on a common property. Member businesses seek enhanced environmental, economic, and social performance through collaboration in managing environmental and resource issues. By working together, the community of businesses seeks a collective benefit that is greater than the sum of individual benefits each company would realize by only optimizing its individual performance. The goal of an EIP is to improve the

> economic performance of the participating companies while minimizing their environmental impacts. Components of this approach include green design of park infrastructure and plants (new or retrofitted); cleaner production, pollution prevention; energy efficiency; and intercompany partnering. An EIP also seeks benefits for neighboring communities to assure that the net impact of its development is positive." (p. 320).

Eco-Industrial Parks can be a new industrial model that reconcile the three dimensions of sustainable development: social, economic, and environmental (Elabras Veiga & Magrini, 2009). The World Environment & Development Conference of 1992 (ECO 92 in Rio de Janeiro) helped to define the three "E's" of sustainability: environmental integrity, social equity, and economic efficiency. This has also been translated into the "triple bottom line" approach now common in the entrepreneurial sector of the green economy.

Though the potential for industrial ecology and eco-industrial parks represents a potential breakthrough for sustainable development, there is little evidence and empirical data on what has been done. This is commonly referred to as the *Implementation Gap* (Gibbs & Deutz, 2007). This gap also refers to the relatively well developed theory and essentially underdeveloped practice of industrial ecology.

Appendix A lists Eco-Industrial Parks commonly referred to in the literature. EIPs are listed by location, date, characteristics and firms present, and exchanges that take place. Many of these parks were originally listed on President's Council on Sustainable Development under President Clinton's initiative for eco-industrial park development. The Kalundborg Denmark eco-industrial park was the first to create a model of industrial symbiosis, receiving international recognition in 1990 (Chertow, 1998). The firms involved are an oil refinery, power station, gypsum board facility, pharmaceutical plant, and the City of Kalundborg. By sharing and recycling water, overall water usage declined by 25% and waste process heat was piped to 5,000 district homes, fish farms in greenhouses, and neighboring businesses. Additionally, a cement manufacturer uses byproducts from the power plant's coal burners and the plant's scrubbers produce gypsum wall board. This landmark case led to clear economic efficiencies as well as environmental, personal, and equipment benefits such as reduced maintenance.

The well documented success of Kalundborg gave rise to the promotion of EIPs to implement closed-loop systems that produce compatible outputs and inputs for interacting firms. Kalundborg has inspired planners and designers to rethink and redesign industrial and manufacturing activities worldwide.

2.1.3 Eco-Industrial Parks. Since the 1970s EIPs have been designed and developed across a spectrum of firms from high-tech manufacturing to waste management, to farming and agricultural systems. The Intervale Center in Burlington VT consists of a 1.6 hectare (4 acre) site centered on a 60MW biomass gasification co-generation unit. Heat is supplied to bioshelter greenhouses for food production and water purification from ecological machines (Chertow & Lombardi, 2005). A commercial composting operation diverts organic wastes from landfilling to produce soil amendment for the farming operations. Exchanges include wastes, heat, and technology transfer. The Civano Industrial Eco-Park in Tucson AZ co-locates firms in the electronics industry including makers of photovoltaics, electric vehicles, and circuit boards. The goals of symbiosis are to exchange water and material inputs while reducing transportation and increase each firms competitiveness (Spitzer, 1997).

The Rutgers EcoComplex Environmental Research and Extension Center is an EIP located at a former landfill site for the greater New York City metro area in northeast New

Jersey. This site is centered on a landfill gas to energy project, a 250kW micro-turbine. Waste heat from the micro-turbine is supplied to greenhouses that support aquaculture and vermi-compost components. The site also contains on-going research efforts supported by Rutgers University including small-scale landfill gas cleaning system, a fuel cell, and algae to biofuel work. The Rutgers EcoComplex is also a small business incubator to foment start-ups focused on alternative energy innovations (Rutgers-EcoComplex, 2013).

ReVenture Park is an EIP in planning stages near Charlotte, NC to redevelop an abandoned Brownfield industrial property containing retired facilities and discarded equipment. The site occupies a former 260 hectare superfund site along the Catawba River that was home to an extensive textile dye manufacturing facility with over 46,000m^2 of existing industrial space. Planned components of ReVenture incorporate waste to energy, solar photovoltaic, wastewater treatment and reuse facility, greenhouses, in-vessel composting, a recycling center, and an incubator space with research and classrooms facilities (Marks, 2011).

The idea of incorporating biomass energy and biorefining facilities into EIPs follows a logical progression in the path toward distributed biorenewable energy systems and sustainable resource management. It also provides an opportunity to improve economic and environmental efficiencies. While biomass energy plants often employ principles of IE, such as sugar cane-based ethanol facilities in Brazil that use spent cane stalks (bagasse) for process heat, the author is unaware of commercial scale biofuels production incorporated into an eco-industrial park at present time.

2.2 Biorefining

The term biorefinery was established in the 1990s as a facility that integrates biomass conversion processes and equipment to co-produce fuels, power and chemicals from diverse biomass sources. The term biomass refers to any organic matter that is available on a renewable basis (excluding old-growth forests) that include dedicated energy crops and trees, grains and cereals, agricultural residues, wood and wood residues, animal wastes, aquatic plants, and other waste material. These raw materials are ultimately derived from photosynthesis where worldwide terrestrial biosynthesis is estimated at 170 billion tons annually (Kamm, Gruber, & Kamm, 2006). The basic compounds are carbohydrates, mainly in the form of cellulose, starch, and saccharose, lignin, oils, and proteins. The US Department of Energy uses the following 1997 definition, “a biorefinery is an overall concept of a processing plant where biomass feedstocks are converted and extracted into a spectrum of valuable products.” The US National Renewable Energy Lab (NREL, 2009) defines a biorefinery as “a facility that integrates biomass conversion processes and equipment to produce fuels, power, and chemicals from biomass.” The biorefinery concept is analogous to today’s petroleum refineries, which produce multiple fuels and products from petroleum oil.

The history of biorefining actually predates petroleum oil refineries as 19th century scientists, primarily German chemists, discovered starch hydrolysis, wood saccharification, furfural, lactic acid, lipids, and the basis of industrial chemicals and extraction technologies (Kamm, et al., 2006). It was not until post WWII that cheap petroleum became the feedstock of choice for industrial production of fuels, and chemicals. An example of a modern biorefinery is the wet-milling of corn whose products include corn oil, corn gluten, feed and meal, ethanol, and high fructose corn syrup. Another example is the Austrian Green Biorefinery, primarily based on grass feedstocks. This example takes a broader and more holistic approach to incorporating bioenergy crops in the landscape. Biorefining systems within proper land management utilization can result in the following benefits: water cycle regulation, tourism and attractive landscapes, job creation in rural areas (Kromus et al., 2004).

In essence biorefineries are tasked with taking on the role of the traditional petroleum refinery to provide energy and materials while being held accountable to sustainability metrics including life cycle assessment, minimizing environmental impact though green chemistry, providing jobs and acknowledging equity and maintaining economic viability. This is a significant challenge in the face rising demand for energy, fuels, and chemicals coupled with dwindling cheap energy to construct these facilities. Biorefineries will likely look different than their predecessors, utilizing a range of feedstocks, showing diversity in size and scale, and providing products to more localized markets. Cherubini (2010) adds that biorefineries of the future should strive to produce at least one high-value chemical/material (such as soap stock and fertilizers) besides low-value high-volume products (transport fuels). This dual strategy produces favorable economics whereby the high volume products cover operating costs and the high value products result in profits. It is likely that the majority of future biorefineries will focus on lignocellulosic feedstocks, as they cheapest and most widely available source of raw material that reduce direct competition with food systems.

2.2.1 Biorefinery Process Technologies. Processes used in biorefining are classified by type of feedstock and the technology deployed. The following categories of biorefineries have been determined according to their functions: fast pyrolysis, gasification, sugar, energy crops, oilseed, and forest/lignocellulosic (Demirbas, 2009). The biomass conversion system has two primary conversion process branches, thermochemical and biochemical. Thermochemical process use high heat and pressure to transform solid biomass feedstocks into liquids (liquefaction), gases (gasification), and solid biochar which can be used as a high value solid amendment. Once biomass is converted into a liquid or gas, further refinement, reaction, or separation is accomplished through catalyzed synthesis such as Fischer-Tropsch or distillation. Thermochemical conversion technologies typically require significant investment in infrastructure. Biochemical conversion processes occur at lower temperatures, pressures, and reaction rates and typically require less infrastructure investment than thermochemical processes. The most common transportation biofuels, ethanol and biodiesel, are examples of biochemical processes. Figure 1 illustrates these two primary routes for processing biomass with associated feedstocks and technologies.

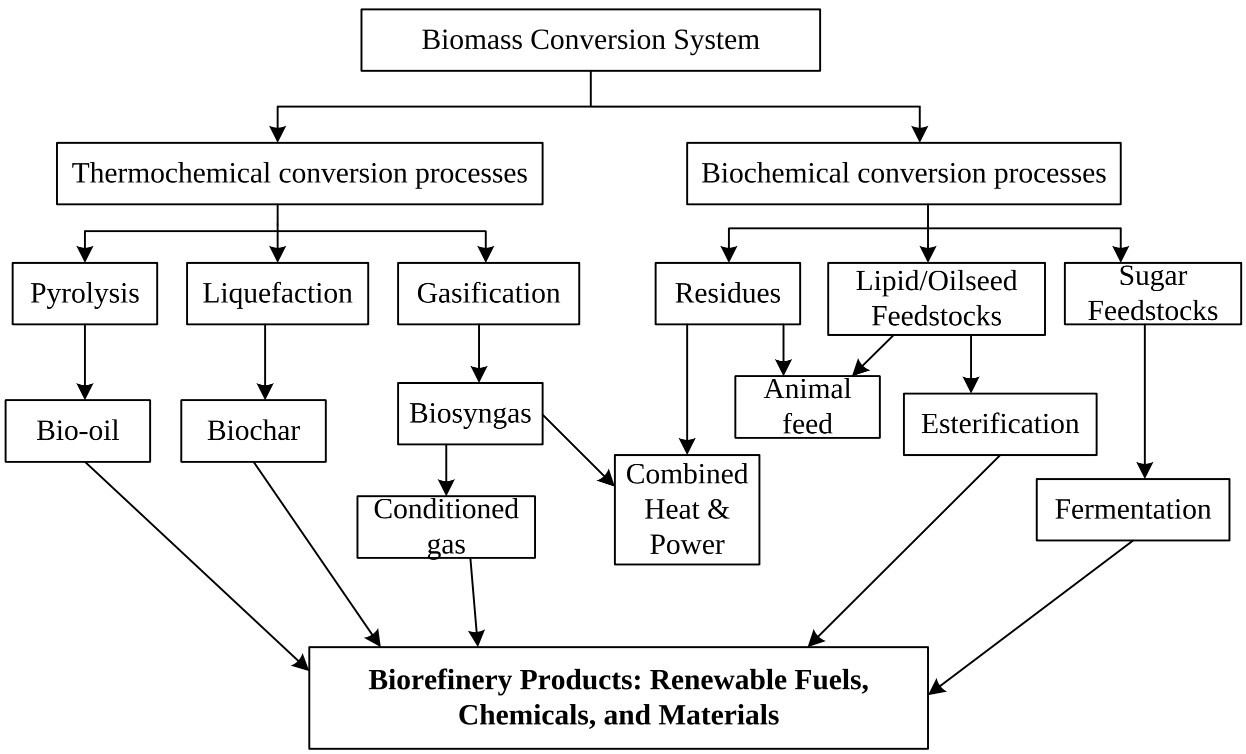


Figure 1. Concept Diagram of a Biorefinery System (adapted from Demirbas, 2009).

2.2.2 Oilseed Biorefining. The raw materials for the oilseed biorefinery are plant oils, fruits, seeds, and oil crops. Grain production and oil extraction, both mature technologies, can be reinvented by their incorporation into biorefining systems. Feedcake or meal, the primary co-product of oil extraction, is a high quality protein source used extensively in livestock feed. The oil compound of interest is the carbon chain rich triglyceride which comprises greater than 95% of the oil by mass. The remainder is a mixture of phosphatides, sterols, and antioxidants (tocopherols). Refinement of food oils results in gums, lecithin, and sterols that can be used in additives, and nutraceuticals. Non-food uses of vegetable oils include soaps, cosmetics, lubricants, greases, motor oils, paints, fatty alcohols for detergents, electrical transformer fluids, and methyl/ethyl ester solvents and engine fuels (M. K. Gupta, 2008). Biodiesel is an ester based engine fuel that has been commercialized and resulted in an industry that consumes large volumes of triglycerides, primarily vegetable oils and animal fats. See Figure 2 for oilseed biorefinery concept with processes and outputs.

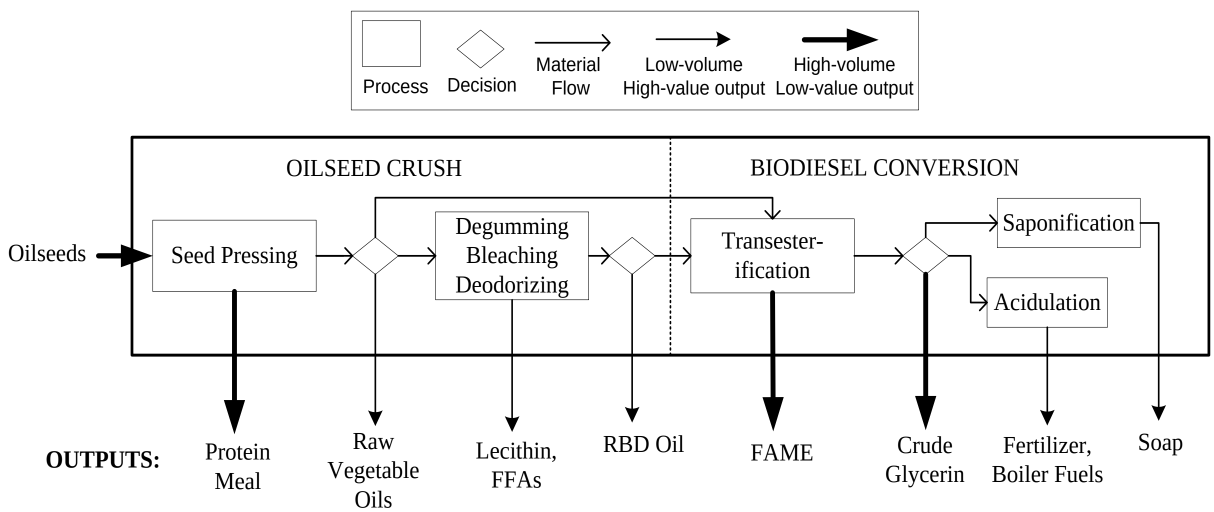
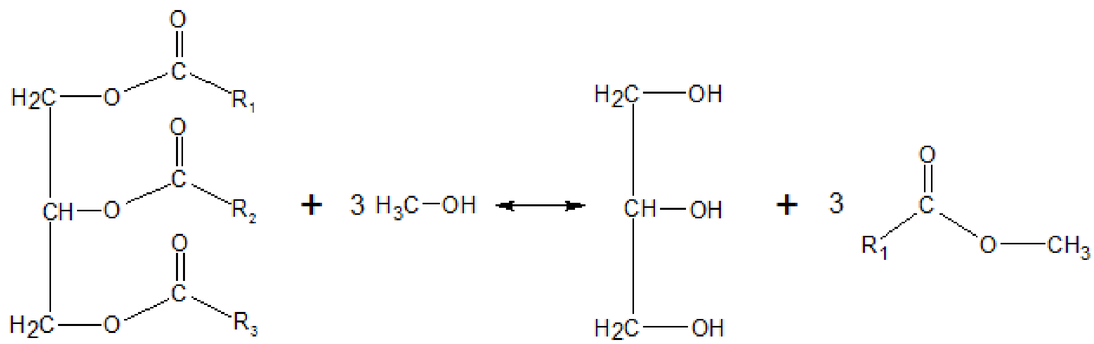


Figure 2. Oilseed Biorefinery Concept with Processes and Outputs.

Industrial oilseed processing led to the development of process steps to ensure consistent oil quality and stability as a packaged food. These steps were developed in the mid-20th century by large companies such as Archer Daniels, Midland, and Cargill, who were already in the process of integrating their crushing operations with oil refining. With research and development from academic institutions and consumer goods companies like Proctor and Gamble, oil refining was standardized along with associated analytical parameters. Modern refining produces a final vegetable oil product, known as RBD, which consists of three principal steps, (a) refining, (b) bleaching, and (c) deodorizing. Each step is responsible for the removal of undesirable components from the crude oil so that the processed oil provides satisfactory results in all applications of the oil.

2.2.2.1. Tranesterification of Vegetable Oils. Transesterification describes a class of organic reactions where one ester is transformed into another. This process is relevant in several industrial processes including production of PET (polyethylene terephthalate) which involves a step where dimethyl terephthalate is transesterified with ethylene glycol in the presence of a zinc catalyst (Schuchardt, Sercheli, & Vargas, 1998). Biodiesel is also produced by transesterification, reacting a triglyceride with a monohydric alcohol in the presence of a strong base catalyst either sodium or potassium hydroxide. The alcohol typically used in industry is methanol due to cost, though ethanol, propanol, and butanol have been used (J.V. Gerpen, 2005; Knothe et al, 2005). To shift this equilibrium reaction towards a high yield of fatty acid methyl esters (FAME), 100% excess alcohol with a 6:1 molar ratio is required (Drown, Harper, & Frame, 2001; Mittelbach, 2006). A high yield of FAME, greater than 90%, allows for phase separation from the glycerol formed (Y. Zhang, Dube, McLean, & Kates, 2003a). The process sequence consists of three reversible reactions whereby diglycerides and monoglycerides are formed as intermediates. Other transesterification catalysis methods include strong acids, lipases, heterogeneous catalyst, and enzymes; though these techniques have yet to be fully commercialized.

Biodiesel quality specifications are defined by country where ASTM D6751 is used in the United States and EN 14214 is used in Europe (Appendix B and C respectively). These standards reflect a minimum quality for fuel performance and long-term use. These standards are continually updated to track changes in feedstocks and process technology.



Triglyceride 3 x Methanol Glycerol 3 x FAME

Figure 3. The transesterification reaction with triglycerides and methanol combine to produce fatty acid methyl esters and glycerol in the presence of a catalyst.

Fatty acid methyl esters are most commonly thought of as a fuel; however they do have applications as an environmentally friendly industrial solvent, and as a medium for site bioremediation of crude petroleum spills (Fernandez-Alvarez, Vila, Garrido-Fernandez, Grifoll, & Lema, 2006; Wildes, 2002). Additionally, FAME can be further synthesized into many useful chemicals such as fatty alcohols, alkanolamides, polyamides, and sucrose polyesters. Examples of products include non-ionic surfactants, emulsifying, thickening, and plastifying agents, lubricants, and cosmetics (Schuchardt et al., 1998; Yan et al., 2014).

In the process of forming esters from triglycerides, glycerol is liberated as the main co-product at approximately 14% by mass of the fuel output. This material coming off the biodiesel process is a mixture of monoglycerides, diglycerides, and triglycerides as well as soaps, and excess methanol. It is commonly referred to as crude glycerin or glycerin bottoms as an unrefined product. Producing a high quality potassium phosphate fertilizer from crude glycerin has been reported by acidulation with phosphoric acid (Javani, Hasheminejad, Tahvildari, &

Tabatabaei, 2012). Refined glycerol however represents the widest diversity of potential uses as a chemical feedstock. Glycerol can be synthesized to produce a myriad of chemical building blocks such as propanediol, glycols, dichloropropanol, rhamnolipids, succinicacid, propionicacid, glycerol ethers, and glycerol carbonates (Ragauskas et al., 2006). The conversion of glycerol to propanediol, propanol, and lower chain alcohols with sulfated catalysts or microorganisms for use as a gasoline fuel additive, has been studied. Mixtures of glycerol derived alcohols and gasoline have resulted in high octane fuel blends, greater than 100, due to the additive's property as an oxygenate (Fernando, Adhikari, Kota, & Bandi, 2007). This glycerol based blend stock, potentially derived from the oilseed biorefinery can be incorporated as additives into petroleum fuels to further reduce pollutants and GHG emissions (Chen, Wang, Shuai, & Chen, 2008).

2.2.2.1.1 Biodiesel Advantages and Disadvantages. Biodiesel as a fuel offers important advantages over petroleum such as lubricity (Bhatnagar, Kaul, Chhibber, & Gupta, 2006). With removal of sulfur containing compounds from diesel fuel consumed in the United States, increased engine wear and reduced life has become a concern for engine manufacturers. Lubricity of soybean-based biodiesel has produced wear scar length values of 129µm (micrometer) compared to 651 µm for Ultra Low Sulfur Diesel without lubricity additives (Knothe & Steidley, 2005). Even low level blends of soy methyl esters in ULSD has shown lubricity improvements from 551 µm to 212 µm for B2 and to 171 µm for B20 (Moser, Cermak, & Isbell, 2008). Exhaust emissions from biodiesel combustion have also shown to be less toxic than petroleum diesel of those regulated by the US Code of Federal Regulations. Particulates, total hydro carbons, and carbon monoxide from biodiesel combustion have resulted in a reduction of 48%, 77%, and 48% respectively compared to conventional diesel (McCormick, 2007). Nitrous oxide emissions have shown increases, up to 12% compared to petroleum diesel (Graboski & McCormick, 1998). This is an acute concern due to the potency of nitrous oxides as a greenhouse gas and toxicity implications urban areas. Studies have shown that low level blends of biodiesel, less than 20%, have had produced no increase in NOx with a diesel engine equipped with an exhaust gas circulation (Williams, McCormick, Hayes, Ireland, & Fang, 2006). Other technological advancements in diesel emission controls including, selective catalyst reduction, diesel oxidative catalysts, and diesel particulate filters may further help address the NOx issue (Hanks, 2013).

2.3 Biodiesel: Historical Background, Policy, and State of Commercialization

The technology for manufacturing biodiesel is relevant to both developed and developing countries and to some extent is scale independent. Developing production capacity is justified as a means to address the following: energy security, environmental concerns, foreign exchange savings, and socioeconomic issues related to the rural sector. In general possible benefits of a developed biofuels sector are energy security, economics, and environment, as shown in Table 1.

Table 1

Major Benefits of Biofuels (adapted from Demirbas, 2009)

Economic Impacts:	Fuel Diversity, investment in manufacturing, job creation, agricultural development, reduce dependency on petroleum
Environmental Impacts:	Greenhouse gas reductions, reduce air pollution, biodegradability, higher combustion efficiency, carbon sequestration
Energy Security:	Domestic production, supply and ready reliability, domestic distribution , reduce use of fossil fuels, renewability

2.3.1 Historical Context of Biodiesel. Vegetable oil-based engine fuels have been around for over a century. It was Rudolf Diesel’s peanut oil-powered engine at the 1900 Paris Exposition that brought his idea of locally produced feedstock to power internal combustion to the rest of the world. Within a few short years, Diesel engines were being manufactured throughout the industrialized world in applications ranging from the automobile to locomotion to ocean liners. The idea that colonies and lesser developed countries could provide motor fuel through their own agricultural products was revolutionary. Diesel who published many articles and abstracts writes (1912) in a prescient tone, "the fact that fat oils from vegetable sources can be used may seem insignificant today, but such oils may perhaps become in course of time of the same importance as some natural mineral oils and the tar products are now" (p. 397). Later in the 20th century, vegetable oil-based fuels were used during WWII as emergency fuels by various nations when normal supplies of petroleum-based fuels were disrupted. Brazil utilized cottonseed oil, and the Japanese battleship Yamato is reported to have used refined, food-grade soybean oil as bunker fuel (Pahl, 2005). After the war, steady supplies of cheap petroleum were again made available and virtually all research on vegetable-based fuels ceased.

Monoalkyl esters of oils and fats, later to be known as biodiesel, were first noted prior to World War II when the Belgian patent 422.877 was granted to G. Chavanne of the University of Brussels in 1937 for creating ethyl esters of palm oil. This fuel was tested on an urban bus in 1938 with satisfactory performance reported (Knothe, 2001). In 1939 J. Walton wrote about the potential fuel value from vegetable oils and the necessary chemical reaction to split off the glycerides and utilize the residual fatty acid. This chemical process, transesterification, would take large branched triglyercides and an alcohol and transform them into smaller straight-chained molecules. This product would be similar to diesel fuel having a reduction in kinematic viscosity by an order of magnitude (Quick, 1989). After the 1940s literature on fuels from agricultural sources were sparse until the late 1970s. Research and development that led to the eventual commercialization of biodiesel began in earnest in the 1980s.

2.3.2 US Policy Background. There have been several major policy milestones to advance biodiesel adoption over the past few decades. In 1992, the Energy Policy Act (EPAct) was passed by Congress to reduce U.S. dependence on imported petroleum by requiring a certain percentage of government fleet vehicles to use alternative fuels (Pahl, 2005). The legislation had dramatic effect on the use of biofuels, especially in government vehicles. An executive order by President Clinton, issued in 1999, called for the increased use of farm products, including agriculturally based ethanol and biodiesel. In December 2001, the American Society for Testing and Materials (ASTM) published a standard for biodiesel as a blend stock. The standard, D-6751, has helped to move the biodiesel industry and achieve a new level of legitimacy. There are notable advancements being made at the state level regarding biofuels. In 2002, Minnesota became the first state to impose a B2 mandate for biodiesel, two percent biodiesel mixed with petroleum diesel. This is in part due to the fact that Minnesota is a large producer of soybeans and the law helps its internal economy. However, this law acted as an agent of change and set an important precedent for other states to follow suit despite lack of federal support. The demand created by this mandate is on the magnitude of 16 million gallons of biodiesel annually, securing a market and giving impetus for production. Illinois, also a producer of soy, was another state in the vanguard of biofuels legislation. In 2003, the Governor of Illinois signed a bill that gives a partial tax exemption to biofuels. The legislation was designed to give biofuels a competitive price and boost the state's economy (Pahl, 2005). After the failed energy bill of 2003, Republican Senator from Iowa and biofuels supporter Chuck Grassley introduced a tax credit for biodiesel at 1 penny per percentage point of biodiesel blended with petroleum. The legislation passed in 2005 and the tax credit stands at nearly one dollar per gallon for biodiesel. This subsidy, known as the fuel tax credit or blenders' credit, would expire at the end of 2009 and

2011 only to be retroactively instated mid-year 2012. While giving the industry a huge boost, the swinging pendulum of the fuel tax credit also has made for a highly uncertain investment climate (Kotrba, 2013b). The tax credit would be the principal subsidy until the Renewable Fuel Standard mandated specific volume of biofuels and created a market place for Renewable Identification Numbers (RINS) whereby obligated parties would be required to purchase them according to a percentage of their overall petroleum business transactions.

The Energy Policy Act of 2005 established the Renewable Fuel Standard Program (RFS) to incentivize and encourage the blending of renewable fuels into the nation's motor vehicle fuel. The bill established a timeline for increases in renewable fuel production, whereby 11.1 billion gallons of renewable fuel would be blended into energy supplies by 2009. The US EPA was chosen to oversee the program and given authority to make changes in rulemaking going forward as the program unfolded. In 2007 the Energy Independence and Security Act expanded the RFS, calling for a target of 36 billion gallons of renewable fuel by 2022 (EPA, 2014). The RFS2 was created, representing a 320% increase over the bill passed only two years before. This version also capped corn-based ethanol at 15 billion gallons and mandated that the remaining 21 billion gallons come from advanced biofuels including a sub-category for biomass-based diesel starting at one billion gallons (Schnepf & Yacobucci, 2013). The RFS2 introduced the first greenhouse gas regulatory system for US transportation fuels. The system used a life cycle assessment framework based on their upstream and downstream emissions to rank a fuel's overall environmental performance. The chosen metric was global warming potential, also referred to as carbon intensity value expressed as grams of carbon dioxide equivalent per unit energy of fuel. A biofuel could be compared directly to the LCA of petroleum diesel to show percent reduction or increase (Venkatesh, Jaramillo, Griffin, & Matthews, 2010).

At present time, winter of 2014, the US biodiesel industry growth is jeopardized once again by the direction of policy. In November 2013, the EPA proposed to reduce the current advanced biofuel mandate from 3.75 to 2.2 billion ethanol-equivalent gallons, and hold constant the biomass-based diesel volume requirement. This creates a negative production incentive because of the annual roll-over ability to sell RINS from a previous year and if instated has a projected impact to contract the industry from 1.28 billion to 700 million gallons in 2014. There are numerous factors influencing this decision including a concerted effort by both the petroleum lobby and environmental groups to dismantle the RFS, RIN fraud cases, and the scaling back of mandates in Europe (Kotrba, 2013b). Even with consistent $100/barrel petroleum, the US biofuels industry remains dependent on policy decisions and subsidies for continued growth and development.

2.3.3 State of Commercialization. Biodiesel technology is well suited to distributed manufacturing that function at various scales. The US biodiesel industry has depicted this evolution unfolding over the last decade while continuing to diversify feedstocks. There are commercial producers are all 50 states except Colorado, Wyoming, Montana, and Alaska. The industry is trending toward smaller-scale plants, where in 2013 72% of all US biodiesel plants had a production capacity of less than 68,000 tons or 20 million gallons per year (NBB, 2013b).

In 2013 the US Biodiesel Industry produced a record 1.28 billion gallons (4.36 million tons) to stay directly on tract with the RFS2 mandates (see Figure 4). While the majority of biodiesel is produced from soybeans, canola, palm, sunflower, cottonseed, and peanuts, feedstocks continue to diversify over time. In 2013 soybean oil at 53% was still the predominant feedstock, though down from 59% only two years before. Yellow grease, which is rendered used cooking oil from restaurants, rose from 7% to 10% in the same time period (EIA, 2013).

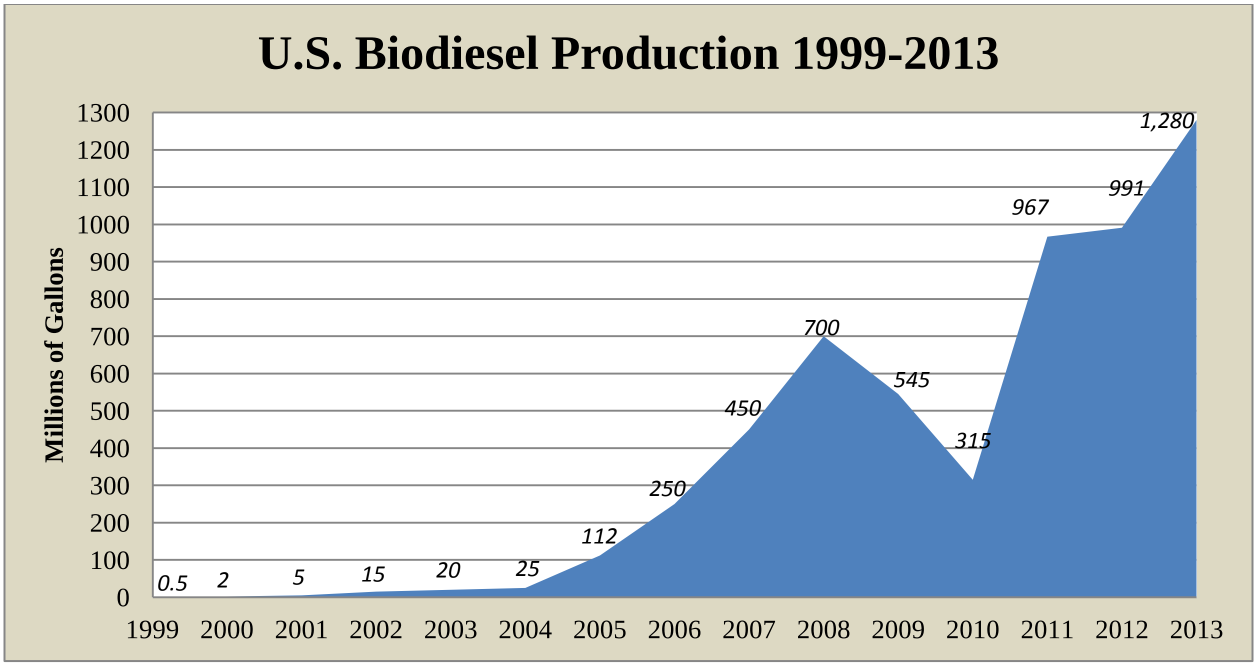


Figure 4. United States Biodiesel production in millions of gallons since the industry inception (EIA, 2013; NBB, 2013b).

The dramatic rise, fall, and subsequent rise of US biodiesel production over the past 14 years can be explained by specific events. From 1999 to 2004, the industry developed to utilize soybean oil from excess production, providing additional markets for soybean farmers. Production was concentrated in the Midwest and the fuel was widely known as soydiesel. The dollar per gallon fuel tax credit went in effect in 2005, combined with a dramatic rise in petroleum, up to $150/barrel in 2008, to further substantiate investment in capacity building. The first lapse of the tax credit and the great recession sent production crashing with many smaller plants and those dependent on single feedstocks declaring bankruptcy. The RFS2 mandated RIN program passed in 2007 was finally rolled out in 2010 and the industry has strongly rebounded.

Little (2014) cites Joe Jobe, the CEO of the National Biodiesel Board who summarized the necessity of government support in the following statement at the 2014 National Biodiesel

Conference, “Biodiesel’s story is an example of how effective government policy can be to jump start a fledgling industry. That is the same story of nearly every new industry that involves technological development. Strong government policy support along with a unique spirit of innovation, entrepreneurship, and risk-taking are the primary reasons that so many major modern industries had their start in America” (p.22).

2.3.3.1 State of the Art. Technological advancement is the frontier for the biodiesel industry to compete directly without subsidies. While base-catalyzed transesterification plants have paved the way for commercialization thus far, they cannot convert FFAs to biodiesel, rather to soaps which results in yield loss and must be removed. Where feedstock cost represents 70-85% of production cost, process advancements that afford access to lower cost and diverse feedstocks are most promising. In a review of the biotechnological preparation of biodiesel, Yan et al. (2014) lists the following influential and promising technologies: enzyme and lipases catalysts, ultrasonication and microwave assisted reactions, and supercritical reactions. The commonality across these process techniques is the tolerance of water and FFAs in the starting material.

Lipases used in biodiesel production are from a diverse group of enzymes mainly obtained from bacteria, yeast, and filamentous fungi that serve to hydrolyze lipids at the glycerol backbone to liberate energy rich free fatty acids (Tan, Lu, Nie, Deng, & Wang, 2010). The merits of enzymatic processing are their ability to work at lower temperatures (35°C) and ability to convert both triglycerides and free fatty acids to biodiesel. The glycerol co-product is also at 80% purity after methanol and water removal, thus increasing its value. This process is currently being commercialized by Viesel Fuel of Stuart Florida, in collaboration with enzyme manufacturer Novozymes, and equipment builder Tactical Fabrication to produce 5 million gallons of enzymatic biodiesel per year. Start-up testing has shown that enzymes can be recovered and reuse a minimum of eight times (Hobden, 2013). Ultrasonication and microwave assisted treatments have shown compatibility with enzyme based processing to enhance reaction rates and reduce overall energy inputs (Nogueira et al., 2010).

Tranesterification in super critical fluids increases reaction rates due to higher diffusion and does not require a catalyst. Supercritical methanol has long been studied, however presents many practical obstacles when scaled-up. Supercritical CO_2 appears to be a promising fluid as it is non-toxic, non-flammable, cheap, and has mild critical properties (Rathore & Madras, 2007). Supercritical CO_2 can also be used in conjunction with enzymatic processing for increased efficiency. Patriot Fuels, Biodiesel LLC in Annawan Illinois is commercializing a 5 million gallon per year facility based on supercritical technologies. The plant, located next to an ethanol refinery plans to use distillers' corn oil as its primary feedstock. The capital expense is estimated at 15% increase over a standard base catalyzed plant, though paying back the difference in less than a year once operational. Operations at Patriot Fuels are anticipated for third quarter 2014 (Kotrba, 2013a).

2.4 Critiques of Biofuels

The burgeoning biofuels industry backed by the political promise of more jobs, a cleaner environment, and greater autonomy from imported oil has been met by outspoken criticism in an ongoing debate regarding the expansion of biofuel production. Critics cite the following key issues with biofuels: using of first generation biofuels (food crops) causes an increase in food prices, they have marginal energy balances compared to the fuels they replace, and they have poor overall environmental performance from overuse of agrochemicals and the effect of indirect land use change (Taylor, 2008). Smolker (2012) describes biofuels and bioenergy as a disaster for biodiversity, health, and human rights. They represent a threat to ecosystems, wildlife, human health, and the climate. Biofuels add to the commoditization of natural resources, forest, grassland, and cropland. Where biofuels once portrayed the image as a silver bullet to the energy problem their reputation has become tarnished by the perception of over promise and under delivery. Almost immediately after all G8+5 countries, except Russia, implemented aggressive biofuel targets and mandates, public concerns were voiced related to rising food prices reinforced by several influential studies stating that biofuels may aggravate net GHG emissions rather than reduce them (Lee, Clark, & Devereaux, 2008).

2.4.1 Food vs. Fuel. The first issue to gain widespread attention was the “food vs. fuel” discussion. The notion that diverting land from food to energy production may be deleterious for food security in developing countries only became apparent when developed countries began mandating biofuel blends and creating markets for these fuels. The issue boiled into mainstream media in 2007 when Jean Zeigler, United Nations special reporter on the Right to Food referred to the conversion of crops such as corn, sugar cane, soybean, cassava, wheat, and vegetable oils into automobile fuels as a “crime against humanity.” This comment was made in light of the fact that the United Nations estimated that more than 1 billion people were living with chronic malnourishment. Zeigler who had been a UN expert on the right to food since 2000 called for a five year moratorium on biofuel production to develop new technologies to address these issues and prevent further impact on the world’s rural poor and malnourished (Lederer, 2007). Searchinger (2011) adds that the demand for biofuels nearly doubles the challenge of producing more food. Additionally, the U.S. soy and corn industries, which form the basis of biofuels production, typically use genetically modified (GMO) varieties that are planted on large mechanized tracts of land. While genetic improvement has led to greater yields and ease of cultivation, the loss of genetic material from traditional varieties cannot be overstated. This trend is happening worldwide with the expansion of multi-national corporations into the developing countries (FAO, 2008).

2.4.2 Indirect Land-Use Change (ILUC). Indirect land use change is another contentious issue in the debate of biofuels. It is described as the phenomena where grasslands or forest are converted to cropland due to market forces, resulting in the release of carbon and sacrificing ongoing carbon storage (Fargione, 2008; Searchinger, 2010). Palm and soybean, two primary global oil crops, have been strongly linked to tropical deforestation. In the developing world land clearing is most commonly achieved through biomass burning, augmenting emissions of CO_2 and N_2O. Indonesian palm oil based biodiesel has been the poster child of the anti-biofuel establishment and primary example of indirect land-use change. Increase demand for vegetable oils, largely due to mandates in Europe and the US for biodiesel, led to farmers to plant oil palm as a new cash crop. This has led to rapid deforestation of tropical rainforest and land clearing in parts of Indonesia's most diverse tropical forests, resulting in losses of species diversity and habitat. It has been estimated that 98 percent of the primary forest on Borneo and Sumatra could be cut and replaced with palm oil monocultures by 2022 under current market conditions (Smolker, 2012). As petroleum prices increase, the demand for biofuels will increase, furthering the pressure on agricultural supply for raw materials. The German Association for Plant Oils calculates that 3.6 million km^2 of oil palm would be required to substitute for today's global crude oil demand. This is equivalent to 12% of the African land mass or 2.6% of the earth's land surface. However, only 14 million km^2 are available for agriculture, according to the Food and Agriculture Organization of the United Nations (FAO, 2013).

Land use change is not restricted to food based crops. It is applied to any crop grown on good agricultural land. Second generation biofuels such as energy grasses or fast growing trees receive the same scrutiny for occupying otherwise food producing farmland. The complexity of the issue is illustrated by soybeans grown for animal feed. Soybeans are primarily grown for protein meal, approximately 80% by weight of the seed, to be used in animal feeding operations. The byproduct of crushing soybeans is soybean oil which is edible oil. The increase in demand for meat from rapidly developing countries such as India and China has a potential three-fold increase on agricultural land required leading to further expansion and land use conversion (Gerbens-Leenes & Nonhebel, 2002). Biofuels manufactured from crop residues, wastes, and byproducts are the only exemptions for land use effects.

ILUC has been extensively discussed and quantified in peer reviewed literature. A wide range of reported values exist but conservative estimates can add 50 to 60 gCO_2-eq/MJ to the baseline of direct emissions making most crop-based biofuel higher than petroleum diesel (R. Edwards, Mulligan, & Marelli, 2010). For soybean-based biodiesel, this means a doubling or tripling of the overall environmental impact, thus negating any environmental benefit related to global warming potential. California Air Resources Board estimate Soybean biodiesel has an ILUC value of 62 gCO2-eq/MJ (CARB, 2014). This is largely from linkage to deforestation in tropical countries as edible oil demand increases. Quantifying this value depends on the crop and where in the world it is being grown. For example, palm oil grown in Indonesia is more pronounced than rapeseed grown in Europe. In terms of policy making, ILUC is generally considered too diffuse and subjective to be included in net emissions assessments and is not currently used by the US EPA as part of the RFS2 biofuel mandate (Mathews & Tan, 2009).

2.4.3 Energy Balance. Energy return on energy invested (EROI) or energy balance is an concept borrowed from ecology that applies to an organism's requirement to engage in activities that produce surplus energy that promote growth and fecundity (Odum, 1971). When applied to energy technologies, the balance is a ratio of the output energy (return) divided by the total energy invested to make the fuel. The result is a measure of overall efficiency where the break-even is 1:1. Fossil fuels, in particular early petroleum extraction, have had enormous energy balances as much as 100:1 (Hall, Balogh, & Murphy, 2009). As these resources become increasingly difficult to mine and extract, the ratio comes down quickly. The idea of a minimum energy balance is a discussion likely to intensify as society looks to replace fossil fuels with renewables. Hall et al (2009) argues a minimum energy balance of 3.0 to be considered a renewable energy source and therefore lower the fossil fuel subsidy required. Since EROI values are unit-less they can be compared against other technologies. Wind turbines have reported a average energy balance value of 18 while solar photovoltaics have a reported range of 3-10 with an average of 6.6 (A. K. Gupta & Hall, 2011). The used cooking oil biodiesel feedstock presented in chapter 5 manufactured within the industrial ecology context ranks at the high end of biodiesel fuels, with an EROI of 12:1.

One of the strongest critics of biofuels is David Pimentel of Cornell University, who published an energy balance study of corn-based ethanol. This study showed a net loss in fossil energy of ethanol due to agricultural inputs and energy requirements for processing. Pimentel (2008) concludes that ethanol is not a renewable fuel because of high costs in terms of production and subsidies, and said production causes serious environmental damage. This landmark study lends itself to further critique and analysis of biofuels that are produced through agricultural means.

CHAPTER 3

The Catawba County NC EcoComplex: County Government Led EIP Development using Municipal Biomass Resources for Clean Energy Production[1]

3.1 Abstract

The Catawba County North Carolina, USA EcoComplex and Resource Recovery Facility is an ecological-industrial park (EIP) whose mission is synergistic waste and resource management, renewable energy production, and local economic development through public and private partnerships. The EcoComplex is a 326 hectare site centered on the Blackburn Landfill with 2.4 million metric tons of waste in place and serves the 156,000 county residents, receiving 484 tons/day of MSW and 80 tons of construction wastes per day. The site hosts a grid-tied 3MWe landfill gas to energy project (LFGTE) using three GE-Jenbacher spark-ignition engines, a biodiesel facility with 490,000 LPY capacity, and a crop processing facility that provides feedstock utilizing buffer lands on-site to grow oilseed crops.

This chapter details the existing and impending biomass energy systems, applications of industrial symbiosis, and the use of public and private partnerships to leverage this municipal landfill as a hub for clean energy development.

3.2 Introduction

In transitioning towards a low-carbon energy economy, industrial societies must rise above their expectations with an evolutionary leap in re-thinking energy and waste. Fueling economic growth with fossil fuels has proved unequivocally short sighted, and threatens our planet's ability to provide ecosystem services and sustain a suitable habitat for our species. The

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[1] Parts of this chapter were adapted from: Ferrell, J., & Shahbazi, A. (2013). County Government Led EIP Development using Municipal Biomass Resources for Clean Energy Production, a case study of the Catawba County North Carolina EcoComplex. *Progress in Industrial Ecology*. (Submitted).

demonstrable scientific evidence of climate change due to the combustion products of these fuels is clear (IPCC, 2013). Continued linear, cradle to grave, industrial manufacturing is an equally untenable practice in a resource constrained world.

The transition to a new energy matrix that includes smart utilization, conservation, and renewables will be a landscape-changing endeavor, and will likely be an engine of future economic growth. Biomass is the only piece of the renewables matrix that can directly replace petroleum by producing energy, fuels, and biobased products, such as bioplastics and polymers. Biomass is currently responsible for over half of current U.S. renewable energy consumption, and represents 2.1% of the total energy supply (EIA, 2012). The emerging biobased economy, whose three pillars include bioenergy, biofuels, and bioproducts, is poised for substantial growth.

Waste management is also positioned for rapid transformation, as landfills become increasingly regulated at state and federal levels, and more difficult to construct and permit. Existing landfills and transfer stations will be forced to increase operating efficiency on less land while serving greater populations. Resource recovery and waste to energy projects are imperative.

3.2.1 Industrial Ecology. The foundation of the North Carolina EcoComplex is Industrial Ecology (IE), based upon the synergetic relationships found in natural ecosystems, where the flow of energy and materials are efficiently optimized. Eco-Industrial Parks (EIPs) are the application of IE whereby firms in close proximity mutually benefit through exchanges such as heat, materials, water, and byproducts. Industrial symbiosis results in enhanced environmental, economic, and social gains, wherein the community of businesses attain a collective benefit that is greater than the sum of individual benefits each company would realize by only optimizing its individual performance (M. R. Chertow, 2000).

Though the potential for eco-industrial parks represents a logical step for sustainable development, there is little evidence or empirical data on what has been achieved, a situation referred to as the Implementation Gap (Gibbs & Deutz, 2007). This gap represents a challenge to conduct research and report findings of applied industrial ecology. Eco-Industrial Parks have three guiding principles: (a) reduce and minimize energy requirements, (b) use industrial wastes as inputs, and (c) development diverse and resilient systems. Eco-Industrial Parks can be a new industrial model that reconciles the social, economic, and environmental dimensions of sustainable development (Elabras Veiga & Magrini, 2009).

3.2.2 NC EcoComplex. Catawba County's EcoComplex is a renewable energy industrial park employing industrial ecology symbiosis that combines industry, waste management, energy production, and university research. The EcoComplex consists of a municipal solid waste (MSW) landfill, a construction and demolition (C&D) landfill, a recycling center, a landfill gas fueled electrical generation facility, the Catawba County-Appalachian State University Biodiesel Research and Production Facility, Gregory Wood Products (a high tech dimensional lumber facility), and PalletOne (a pallet recycling facility). The County's EcoComplex incorporates shared, mutually beneficial relationships between industry byproducts and required manufacturing resources.

The inspiration for this EIP came from the Rutgers, New Jersey Agricultural Experiment Station. The Rutgers EcoComplex integrates government, academia, and private sector partners to function as a hub for education and outreach for industrial ecology research as well as a business incubator for emerging technology companies (Rutgers-EcoComplex, 2013).

3.2.2.1 Striving toward Zero Waste. An additional driving force for EIP development resulted from waste reduction goals codified in N.C. General Statute 130A-309.09A (NCGA, 1983). These ideas were incorporated in NC Senate Bill 111 in 1989 (NCGA) that required each county and municipality to develop a comprehensive solid waste management program to reduce waste disposal by 30% over 20 years. Many counties, including Catawba have gone beyond these waste reduction goals and developed zero waste initiatives. Baseline levels for total waste disposed (MSW and Construction and Demolition waste combined) for Catawba County in 1990 were 1.14 metric tons/capita/year (NCDENR, 2013). Since 1990 the County has actively reduced waste through curbside collection and installing convenience centers in rural areas where citizens separate recyclables from waste. The EcoComplex recycling center also separates concrete, asphalt, tires, roofing shingles, and wood and yard waste, which are ground and composted or consumed directly by industry as manufacturing goods. Due to these active measures in waste reduction, the fiscal year 2010-2011 numbers showed 0.85 metric tons of waste disposal per capita, in-line with the reduction goals, and ahead of the state average of 0.89 metric tons per capita. Additionally, Catawba County had the highest per capita recycling rate in North Carolina, at 331 kilograms recovered per person (0.33 metric tons per capita) for fiscal years 2010-2011, of which the EcoComplex recovery activities represents 27% of this total (Catawba-County, 2012; NCDENR, 2013). Catawba County has ranked in the top five counties for per capita recycling for the past eight years. This has been largely credited to diverting wood waste and pallets into composting operations and alternative day cover (used during landfilling operations) at the EcoComplex. Where is Catawba County on its path toward zero waste? After rising to a per capita waste tonnage high of 1.34 in 1998, the past 15 years have shown an overall decline of 68%. This decline can be attributed in part to improved recycling and EcoComplex recovery activities coming on-line. Though encouraging, Catawba County still relies on landfilling as its primary strategy for solid waste management and zero waste is an evolving process, governed by policy, economics, technology, and human behavior.

The fundamental goal of the EcoComplex is to promote economic development in Catawba County through the use the county's solid waste streams by making waste streams into commodities, and employing the County's MSW and C&D landfills as resource recovery facilities for capturing and converting solid waste into commodities or green energy. The system is also designed to recover and employ all usable byproducts from EcoComplex entities' waste streams, either as a source of energy or as a manufacturing feedstock. Landfill gas and other bio-gases are and will be used to produce electricity and heat energy. The proposed Wood Gasification Energy Facility will use woody waste from EcoComplex entities to generate renewable energy in the form of electricity, steam, heat, and CO_2. Catawba County's EcoComplex business structure promotes waste reduction and economic development through byproduct/resource management and employing predominantly green and renewable energy. Since inception, the EcoComplex has generated approximately 150 jobs, while reducing the County's per capita waste disposal rate by nearly 30% (Catawba-County, 2012; B. Edwards & Chandler, 2009). The EcoComplex IE Chart in Figure 5 demonstrates the closed-loop potential for heat and materials flow through the EcoComplex. Co-generation facilities use biomass to produce energy, heat, and co-product streams.

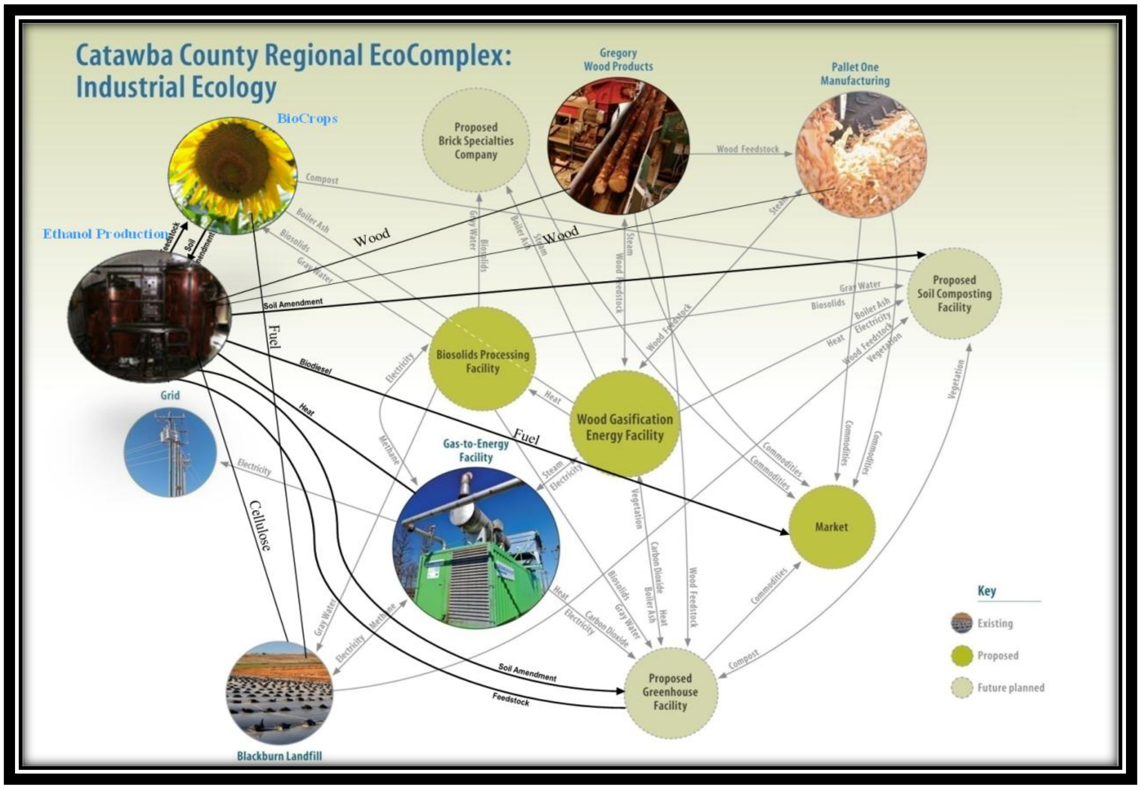

Figure 5. EcoComplex IE Chart (Courtesy of Catawba County Utilities and Engineering).

3.2.2.2 Public & Private Partnerships. Public-private partnerships are a cornerstone of development at the EcoComplex. Eco-park development began with a landfill gas-to-energy project, installing 3MWe by partnering with Jenbacher to establish a testing site in 1999. To date, electricity production has surpassed 125MWh, with total utility sales reaching $5.1M. The success of this installation has helped to keep landfill operating costs stable, operating with no tax dollars, and also helped to leverage political support from county commissioners to endorse further IE projects (B. Edwards, 2010). Catawba County negotiated two economic development agreements that provided local incentives to incentivize industry to expand in the County. Gregory Wood Products and a Pallet One located new operations on adjacent sites to the landfill. These contracts agreed on land transfer and utility connection in exchange for capital investments, guaranteed employment, and first right of refusal for wood waste produced (Catawba-County-Government-EDA, 2003).

Partnering with Appalachian State University in 2007, the EcoComplex supported the development of a biodiesel research, development, and production facility by constructing a 700 m^2 dedicated building, and agreeing to use waste heat from the GE-Jenbacher engines for building and process heat. This facility is charged with providing the county with a biodiesel fuel from feedstocks grown in part on adjacent agricultural lands (landfill buffer areas) while serving as a research and testing center for North Carolina's biodiesel industry. The facility is modular in nature to facilitate change in feedstock and process technologies to further the development of a decentralized fuel production model that relies heavily on local feedstocks and fuel markets (Ramsdell, 2007). Additionally, the facility houses a drive-on dynamometer that is used for combustion emissions analysis and research in conjunction with an on-road test vehicle. Funding for equipment and operations came through state and federal grants totaling $1.4M.

Catawba County worked with local engineering firms to design a LEED certified building. With preliminary designs drawings completed, the County's Utilities and Engineering Department proposed the facility to the County Commission where the project was approved and financed by borrowing $1.6M from the landfill post-closure fund. This fund, generated through solid waste tipping fees, is designed to maintain environmental compliance of the site upon closure. This municipal landfill is expected to operate until 2080, providing adequate time to recover costs through leasing the facility and anticipated fuel savings.

3.3 Biomass Energy Resources & Facilities

The system boundary for biomass inputs entering the EcoComplex are defined by feedstock. Municipal solid waste (MSW) is currently collected from Catawba County exclusively. Oilseed crops are grown on buffer areas around the landfill as well as nearby agricultural lands within Catawba County, per contract agreements with local farmers. Wood fuel, the byproduct from Gregory Wood Products and Pallet One, are generated on-site. However, raw materials to support the lumber mill are transported from a five-state, 322 kilometer radius. Biosolids originate from nine municipal wastewater treatment plants in Catawba County. Feedstock for a second generation cellulosic ethanol production includes perennial grasses grown as alternative landfill cap and micro-algae that utilizes waste water, waste heat, and combustion carbon dioxide for waste water remediation and biomass production. Annual carbon dioxide reductions listed below in Table 2 are compared to the conventional energy source these alternatives replace such as coal-based electricity, petroleum diesel, etc.

Table 2

Biomass Energy Potential

Feedstock	Process	Energy Type	Net Energy (MWe)	Net Heat (GJ)	Annual Energy (MWh)	Annual CO_2 Reduction (metric tons) (EPA, 2013)
MSW	Anaerobic Digestion	Landfill Gas	2.3	8.53	19,710	13,906
Oils & Fats	Trans-esterification	Biodiesel	490,000 liters/year	N/A	4,545	3,207
Wood fuel	Gasification	Syngas	1.9	7.05	14,979	10,568
Cellulose-materials	Cellulosic Ethanol	Ethanol	302,000 liters/year	N/A	1,758	1,240
Multi-feed Digester	Anaerobic Digestion	Methane	1.0	3.71	7,884	5,562
		TOTALS	**5.2**	**18.3**	**47,847**	**33,757**

3.3.1 Landfill Gas to Energy. Anchoring the EcoComplex are three GE-Jenbacher co-generation units with combined capacity of 3MW that convert landfill gas into electricity and heat. Landfill gas is produced at a rate of 31,680-34,560 liters per minute, naturally evolved from the 502 metric tons of municipal solid waste buried daily for 23 years. Gas production is dynamic with regular fluctuations depending on climactic conditions. Gas composition is typically 39-40% carbon dioxide, 50-53% methane, less than 1% oxygen, and the balance of the gas consists of gases such as hydrogen sulfide and nitrogen (Beebe, 2013). The Jenbachers are 20 cylinders, 1450 horse-power spark ignition engines with attached generator sets that meter power directly onto the electric grid (see Figure 6). These engines burn landfill gas directly. There is no pre-filtration of the landfill gas other than a gas cooler that reduces moisture. Impurities in the gas stream, such as siloxanes, are directly combusted, which leads to coking of pistons and valves and down time for routine decoking procedures every 3,000-5,000 hours. Engine life is estimated at 60,000 hours before blocks are sent off for refurbishment. Catawba County has a performance contract with Nixon Energy to manage engine service and optimize up-time and efficiency. Average net electricity production, discounting down-time, is 2.3MW.

Figure 6. Jenbacher Engine 2 with installed heat exchanger.

3.3.2 Biodiesel & Crop Processing. Surrounding the active landfill is approximately 61 hectares of agricultural land dedicated to bioenergy crop production. This land contributes toward growing of oilseed and biomass feedstock. All lands in this buffer are dedicated to the landfill process, and will ultimately be developed for soil removal or the construction of new cells over the next 60 years, the landfill's anticipated useful life. It is in this window that bioenergy crops are viable.

University research and Catawba County Cooperative Extension have developed crop rotation models to maximize oilseed production for biodiesel feedstock, while maintaining soil and plant health. An example is a three-year period transitioning winter canola, summer soybeans, winter cover crop, summer sunflower, winter wheat, and summer corn. One hectare over this three year period produces roughly 2,245 liters of vegetable oil, 2.4 tons of protein meal, commodity crops for outright sale (corn & wheat), and crop residue.

The Biodiesel Research, Development, and Production Facility, operated by partner Appalachian State University has a nameplate capacity of 490,000 liters per year. At 85% conversion of oil to methyl esters and an average oil production of 748 liters per hectare, 770 hectares of land dedicated to oilseed production are required. Achieving this production goal will require engaging the local agricultural community, and potentially acquiring waste commodity streams such as used cooking oil and brown grease. Mandating and/or incentivizing county-wide collection of used cooking oil is being considered.

To further integrate renewable fuel production in 2012, the Catawba County EcoComplex funded the construction of the on-site Crop Processing Station (see Figure 7 and Figure 8). This project, valued at $800,000, was also financed through the landfill post-closure fund. This facility includes grain handling, storage, drying, and oilseed pressing to provide biodiesel feedstock oil. Catawba County is currently working with private and public partners to develop a vegetable oil leasing program where oil will be refined to food-grade, leased to local restaurants, then returned as biodiesel feedstock.

Figure 7. Biodiesel Facility Process Line.

Figure 8. Crop Processing Facility.

3.3.3 Industrial Symbiosis. The Biodiesel Research, Development, and Production Facility represents the potential of enhanced environmental and economic performance through on-site integration. Off-road diesel equipment to maintain landfill operations consumes roughly 284,000 liters of diesel fuel per year. The 61 hectares of oilseed crops grown on buffer areas add value to under-utilized lands, and when processed into biodiesel and blended with petroleum diesel, can account for 12% of the total fuel consumed.

The facility is located adjacent to the landfill gas generators, where a combined heat and power system was retrofitted to provide process heat and building heat. A liquid-to-liquid heat exchanger, rated at 211,000 MJ/hr, was installed on the jacket coolant loop of one engine. Hot water at 79°C is circulated at 300 LPM to a 9,500 liter thermal storage tank for process operations, and to forced air unit heaters for building heat, when necessary. This heat recovery system had an installed cost of $21,700, thus avoiding the cost of a comparable-sized natural gas boiler ($10,000) and incremental costs of natural gas inflating at 1%. The system has a 3 year payback period, net present value of $120,000 at year 20, and a 40% internal rate of return based on avoided fuel costs.

3.4 Impending and Developing Components

Impending energy production components include biomass gasification of wood fuel, anaerobic digestion of biosolids, and pilot-scale cellulosic ethanol production with university partners. Developing components include those aimed at growing cellulosic feedstocks for ethanol as part of an alternative landfill cap, micro algae production using wastewater from biosolids and combustion gas, a commercial greenhouse facility, a scrap tire recycling and product manufacturing center, a plastic product manufacturing facility, and additional university research facilities/partnerships. Implementing an alternative landfill cap with a perennial bioenergy crop does present concerns related to compliance. State and federal regulations require a vegetative barrier to prevent excessive soil erosion and degradation of the cap and liner. Permitting for alternative landfill caps could be achieved through research and development solicitations, in conjunction with robust erosion control measures during crop establishment.

3.4.1 Wood Fuel Gasification. This future facility plans to use cleaned wood waste, or wood fuel from EcoComplex entities to generate electricity, heat, steam, and CO_2. The proposed facility will employ Nexterra gasification technology, coupled with GE-Jenbacher internal combustion engines. The facility will handle 13,000-18,000 dry metric tons of biomass per year generated from Gregory Wood Products, Pallet One, and potentially segregated and cleaned wood from the construction and demolition waste stream. Electricity output is estimated at 1.9 MW. Waste heat from this facility is currently being analyzed as a means for drying lumber or biosolids.

3.4.2 Bio-Solids (Sludge) and Organic Waste Processing. This facility is designed to replace the existing privately run regional sludge management and composting facility. A multi-feed digestion system is designed to process wastewater sludge, trap grease, agricultural, food, restaurant and cafeteria wastes, and byproducts from the existing biodiesel facility, as well as from the future ethanol and algae facilities. Wastewater sludge and other organics will be brought to this facility which will anaerobically digest waste, produce methane and increase the power and heat output of the GE-Jenbacher co-generation internal combustion engines in conjunction with landfill gas flows. This facility intends to handle wastewater sludge and other organics from Catawba County and the Unifour region (Alexander, Burke, Caldwell, and Catawba Counties) for approximately twenty years.

3.4.3 Cellulosic Ethanol. Perennial grasses such as switchgrass have the potential to serve as an alternative landfill cap while producing feedstock for fuels. Cellulosic ethanol from switchgrass has surpassed yields of 3,700 liters per hectare (Schmer, Vogel, Mitchel, & Perrin, 2007). As landfill cap increases in area at the EcoComplex, alternative perennials such as switchgrass become increasingly attractive. With approximately 81 hectares of alternative landfill cap growing switchgrass, 300,000 liters of cellulosic ethanol per year could be produced. Though this scale is typically too small for commercial viability of an anhydrous product, it provides value for modeling, demonstration, research, and as a feedstock for advanced biodiesel processing.

3.4.4 Algae. Incorporating algae into wastewater remediation while enhancing the CO_2 content with combustion exhaust gas from co-generation units, is a viable long-term endeavor for biomass production at the EcoComplex. An algae system of this nature can provide multiple benefits: production of animal feed, biodiesel and ethanol, algae biomass for anaerobic digestion, reduction of nutrient loading in wastewater, and sequestration of carbon (Lundquist, 2008). Anaerobic digestion is the simplest pathway for energy production and dovetails with the planned biosolids management facility. A combined pond/photo-bioreactor system could feasibly produce sufficient algae biomass to match methane and energy production of the biosolids multi-feed digester component.

3.5 Discussion

All aforementioned bioenergy processes have associated byproduct streams, the added value of which is essential for economic viability. Byproduct examples include protein meal, glycerol, wood ash, biosolids wastewater, ethanol wash, and residual algae.

Oilseeds grown on buffer areas of the EcoComplex are crushed to extract oil. Typical oil content is 20-30% by weight of the seed. The remainder is protein meal or feed-meal, primarily used as animal feed. An assay on canola meal by NCDA shows 35% protein content, which is comparable to soybean meal (NCDA, 2008). Protein meal can also be used as a soil amendment, fertilizer, and as biomaterials feedstock. Glycerol is the byproduct from transesterification of triglycerides with methanol, produced at approximately 10% by volume per liter of biodiesel.

Glycerol has myriad uses including: dust control, animal feed, soap stock, and chemical feedstock for industrial or technical grades. Wood ash from gasification can be used in compost or soil amendment. Biosolids wastewater can serve as fertilizer, make-up water in the landfill to control gas flows, and as nutrient-rich irrigation water. Wash or residual water after distillation of ethanol can be used for digester feed, fertilizer, or a compost amendment. Algae residue can be used for animal feed, digester feed, fertilizer, and potentially in food supplements.

Zero waste goals and overall waste reduction measures are expected to continue as tipping fees increase and landfill siting and operations become increasingly expensive. Waste-to-energy technologies are responding to this economic opportunity and developing on numerous platforms, including gasification, incineration, and refuse derived fuels. Waste characterization studies by EPA (2009) estimate paper and paperboard, plastic, and wood at 28.2%, 12.3%, and 6.5% respectively, of total landfilled MSW. These discards are the primary feedstocks for future MSW-to-energy processes and refuse derived fuels. Zero waste is a development in progress, and waste characterization studies are of paramount importance in effectively quantifying and explaining reductions over time, as economic conditions change. The limitations of zero waste include materials that cannot be recycled or composted into soil amendments.

Future directions for the EcoComplex encompass resource recovery and renewable energy production, as well as food systems development with research and production greenhouses, nurseries, and value-added foods. Contributing toward regional bioproductivity (defined as the footprint necessary to provide goods and services for a community or region) is a realistic endeavor for this EIP.

3.6 Conclusion

The Catawba County EcoComplex is an evolving eco-industrial park led by municipal government striving towards zero waste. While waste reduction continues as a primary driver, renewable energy from municipal biomass has become a focus for EIP development moving forward.

Biomass energy systems are dictated by regionalism. Deriving feedstock from a tighter radius will become increasingly cost effective. Methods of biomass utilization fluctuate regularly. For example, biosolids can be digested to produce methane for energy, or they can be composted to produce soil amendment. Both methods produce commodities with varying economic value. Robust technologies that facilitate operation, management, and system longevity are highly desirable. Well defined systems are paramount, as these systems becoming increasingly integrated and complex.

The establishment of a financially successful landfill gas-to-energy project laid the foundation for on-going political support. The ability to develop public and private partnerships is the key driving factor to cultivate future projects. University partnerships continue to show promise, as the EcoComplex demonstrates leadership as a regional model and unique case study. A creative financing using landfill post-closure fund has enabled Catawba County to fund capital intensive buildings and equipment. All landfills are required to maintain a post-closure fund, thus representing a potential source of funds for future waste/biomass-to-energy systems and zero waste initiatives. Such projects will likely delay closure. Prolonging landfill life span will allow for less constrained payback periods. Local governments and municipal landfills are potential leaders for developing successful eco-industrial parks based on biomass and waste resources for clean energy development.

CHAPTER 4

Material and Energy Flow Analysis of the EcoComplex Oilseed Biorefinery

4.1 Abstract

Material and energy flows for processes associated with the NC EcoComplex Biorefinery were analyzed through a mixed methods approach which included primary data from the biodiesel and crush facilities as well as secondary data from literature review for agricultural production of oilseed crops. The results of this data are to establish a baseline for biodiesel manufactured at the Catawba County EcoComplex and are valuable in assessing technical bottlenecks and process inefficiencies through the system. This baseline data gives the life cycle inventory (LCI), which are used as the primary inputs for conducting life cycle assessment (LCA).

Technical bottlenecks discussed include fertilizer use in agriculture and the ability to produce plant nutrients through byproducts of crush and conversion in symbiosis with existing waste and resource management industrial ecology systems. The scale factor of the crush facility and potentially the technology selected, present an incompatibility with the scale of the biodiesel facility. For biodiesel production capacity to be realized, additional feedstocks must be sourced. The conversion step points to three potential bottlenecks: feedstock preparation, methanol recovery, and thermal loads for expanded production.

4.2 Introduction

This chapter details the movement of materials and energy through the oilseed biorefinery by examining the three fundamental operations involved in processing raw materials, primarily oilseeds, into finished products and biodiesel fuel. These operations consisting of agriculture, oilseed crush, and biodiesel conversion are analyzed to give material and energy flows of biodiesel manufactured within an eco-industrial park which intends to enhance overall efficiency through geographic proximity and materials and energy reuse and recovery. The results are data used in analysis of technical bottlenecks and process inefficiencies through the system as well as to establish a baseline for energy and material flows for biodiesel manufactured at the Catawba County EcoComplex. This baseline data produces the life cycle inventory (LCI), which are used as the primary inputs for conducting life cycle assessment (LCA). LCA is used to determine greenhouse gases emitted and global warming potential throughout production steps and serve as a comparison against conventional petroleum diesel as well as other alternative fuels. The LCI also provides energy usage data throughout the process and is used to calculate Fossil Energy Ratio (FER) defined as the ratio of energy output of one unit of biodiesel divided by the associated fossil energy required to make that unit. This is also commonly referred Energy Return on Investment (EROI) and is used to assess the renewability of a given technology or process. LCA of this system is presented in chapter 5.

4.3 Materials and Methods

Materials and energy inputs for each process include both primary data from plant operation and secondary data from literature. The landfill gas to energy system has been in place for 13 years with detailed records of gas flows, average conditions, and power outputs. This data was provided by the Catawba County. Agricultural inputs were compiled from crop budgets and compared with field trials on-site. Both crush and conversion data are experimental, based on start-up of those facilities and extrapolated for operation under production capacity.

4.3.1 System Boundaries. The goal of the EcoComplex system is to take advantage of geographic proximity for all inputs and outputs of the production system. Farmland is the critical piece of this system since agricultural commodities can be transported large distances relatively inexpensively. Catawba county and the surrounding counties still maintain an agricultural character and is home to the last large-scale piedmont grain farming before moving west into the foothills of the Blue Ridge Mountains. The system boundary for regional farms to supply oilseed for biodiesel feedstock is defined as an 80km (50 miles) radius. The landfill gas to energy facility which provides thermal energy to the biodiesel facility and the manufacturing processes of crush and conversion are co-located on the EcoComplex site where transportation is negligible. Chemical inputs included in the inventory are fertilizers and chemical applications in agriculture and process chemicals in conversion. The inputs for production of capital goods such as process equipment and buildings are excluded as they do not affect operating costs, the focus of this research.

4.3.2 Landfill Gas to Energy. The landfill anchors the EcoComplex and its waste is the primary material flow into the system. At present, 484 metric tons/day of municipal solid waste (533 tons/day) are buried at the Catawba County Blackburn landfill Monday through Friday, and a half day Saturday. This waste stream which contains roughly 25% organic materials, evolves into landfill gas with constituent parts 50% methane, 50% carbon dioxide, and trace components such as hydrogen sulfide (Beebe, 2013; EPA, 2009). A thorough waste characterization has not been performed at the EcoComplex. This gas flows (at averaged annual conditions) at rate of 1200 scfm (34.5 cubic meters/minute) at 67°F (18.3°C) at a pressure of 15 psi (103,425 Pa) into a manifold that supplies fuel to three GE-Jenbacher generator sets equipped with 20 cylinder 1500 horse power spark ignition engines. Combustion products from the landfill gas assuming complete combustion, stoichiometric air supply and fuel supply as 50% methane are per the following equation: $CH_4 + 2\,O_2 + 3.76\,N_2 \rightarrow CO_2 + 2\,H_2O + 3.76\,N_2$

Converting volume into mass and mass flow rates, the ideal gas law is used with the observed parameters listed in Table 3. Anaerobic digestion and gas production of the landfill system is dynamic, depending on moisture levels from recent rain events, barometric pressure, ambient temperature, and other climatic conditions such as snow cover. Table 3 and Table 4 present estimates of average mass flow rates, representing typical landfill gas conditions.

Table 3

Landfill Gas Conversion to Mass

Flow rate of LFG	1200	scfm
Methane content	50%	
Methane gas flow	600	scfm
Methane gas flow	16.99	m3/min
Pressure	103,425	Pa
Temperature	291.48	k
R constant	8.3145	m3*Pa/(mol-K)
Moles of Methane	724.93	(at 600 scfm)

Table 4

Landfill Gas Mass Flows

Reactants	Molecular wt (g/mole)	Grams/min	Kg/hr
Methane	16	11,599	696
Oxygen	32	23,198	1,392
Products			
Carbon Dioxide	44	31,897	1,914
Water	18	13,049	783
CO2 from LFG	44	31,897	1,914

The energy density of methane is 55.6 MJ/kg (DOE, 2013) which results in instantaneous flow rate of 10.75MJ/second. Average combined electrical output of the three GE-Jenbacher generator sets is 3MW (see Figure 9). The electrical conversion efficiency is calculated at 27.9%, with the remainder thermal energy dissipated primarily to exhaust flow and the jacket water radiator cooling system at 60% and 40% respectively (Beebe, 2013). Resultant waste thermal energy equals 2.15MJ (7.3 MMBtus/hr) in the exhaust and 1.43 MJ (4.9 MMBtus/hr) in the jacket water for each generator set.

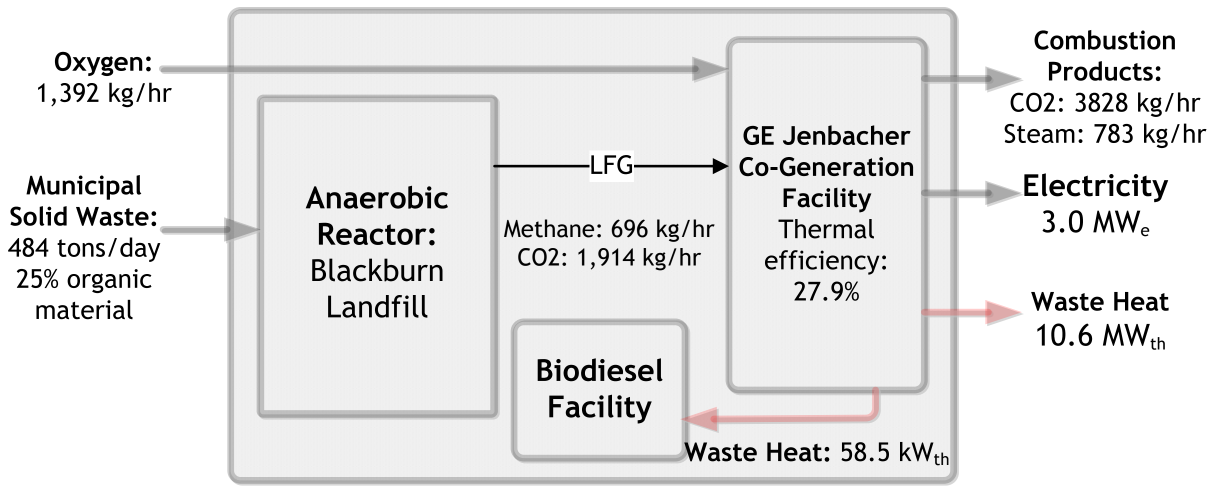

Figure 9. Energy & Material Flows of Landfill Gas to Energy System.

Two important feedstocks for driving further IE developments are the available waste heat and the carbon dioxide produced from combustion and from the landfill gas itself. The heat recovery application is designed to provide the Biodiesel facility process and building heat for an operating capacity of 490,000 liters per year.

4.3.3 Agriculture: Farming & Oilseed Production. Farming operations for growing oilseeds to support the EcoComplex Crush Facility are analyzed for material inputs and outputs, illustrated in Table 5. Crop enterprise budgets for canola, sunflower, and soybeans were compiled including data from two crops grown at the EcoComplex, fall 2011 canola and summer

2012 soybeans (see Appendix E). Primary inputs are seed, fertilizers (nitrogen, phosphorous, potash), lime, chemical applications including herbicides, insecticides, fungicides, and direct energy inputs (diesel consumed in farming operations for tilling, planting, spraying, and combining). Output is the harvested seed that is combined. This analysis does not consider the organic material, stover, produced by the plant as it is left in the field to recycle nutrients. All farming methods used in this analysis can be characterized as “conventional“ and do use a more complex “integrated farming systems“ approach to reduce chemical and energy usage.

Canola is a trademark term which signifies “Canada Oil Low Aid,” is a cultivar of European rapeseed and bred for low acidity and palatability as an edible oilseed crop for cool climates (Callihan, Brennan, Miller, Brown, & Morre, 2000). Canola has been introduced in the Southeastern US as a winter crop, typically planted in the fall six weeks before a killing frost. Significant work has been invested to select seed varieties and develop management practices for raising canola across the Southeast. This paper cites the enterprise budget in the “North Carolina Production Guide” for associated farming inputs (George, Tungate, & Hobbs, 2008).

Sunflowers are primarily grown in the Midwestern and Great Plains states. Sunflower as an oil crop has not been significantly developed for North Carolina. Therefore, crop budgets from Nebraska and Kansas were selected as comparables to give a representative average for both inputs and seed yield.

Soybeans are the dominant oilseed crop in commodity US agriculture and have been the focus of continual genetic improvement and associated management practices such as no-till (Pradhan et al., 2009). Genetically engineered soybeans became commercially available in the US during the 1990s and quickly advanced in the marketplace where they accounted for 75% in 2002 and 93% in 2012 of the US soybean crop planted (USDA-ERS, 2013). This rapid trend has had profound effects on the use of chemical applications, in particular herbicide usage. Soybean system inputs are from the USDA-Economic Research Service 2006 data for average across North Carolina.

Table 5

Material and Energy Flows per Hectare by Oilseed Crop

Materials (per Hectare)	Canola(1)	Sunflower (2)	Soybeans (3)
Seed (kg)	3.4	5.6	57.3
Fertilizers			
Nitrogen (kg)	179.6	60.6	23.4
Phosphate (kg)	67.4	16.8	49.4
Potash (kg)	146.0	16.8	94.2
Lime (kg)	741.0	741.0	741.0
Chemical Application			
Herbicides (kg)	1.2	6.7	1.8
Insecticides (kg)	1.0	0.3	1.7
Fungicide (kg)	1.7	0.0	0.2
Direct Energy Use			
Diesel Fuel (liters)	39.3	39.3	39.3
Outputs			
Seed (kg)	2,807	1,639	2,699

1 (George, et al., 2008), 2 (UNL, 2013), 3 (USDA-ARMS, 2013)

4.3.3.1 Oilseed Crush. The Crop Processing and Crush Facility consists or grain handling, cleaning, and storage equipment as well as a 4 ton oilseed crush capacity, and four KK40 oilseed presses working in parallel. The oilseed press technology is cold extrusion, designed to produce high quality vegetable oils for use in food or fuel applications. The equipment is capable of handling a diverse variety of oilseeds including the common row crops considered in this study; canola, sunflower, and soybeans. The rate of processing for each seed is distinct, primarily dependent on inherent oil content and seed hardness factor. The overall pressing speed is a result of these two primary variables and has been observed experimentally to be a fraction of the nominal capacity whereby canola equals 75%, sunflower at 67%, and soybeans at 50%. These significant differences explain the variation in material throughput by oilseed type.

4.3.3.1.1 Crush Process. Oilseeds are harvested mechanically, combined in the field at the appropriate point in the life cycle where the seeds have reached maturity and have a relatively low moisture content (~12%) to promote processing and storage. Conditions during harvest depend on numerous agricultural practices that influence the presence of non-seed particles, or foreign material, that enters the harvested seed. This material includes chaff, weed seeds, rocks, and soil. Figure 10 presents material and energy flows at the Crush Facility. The air screen cleaner facilitates the removal of this undesirable material by using two sets of screens, differential in size to the seed, and forced air to sort foreign material from the seed. The foreign material removed from a well-managed field has been observed at 0.5% by weight of the incoming seed. Once the seed is cleaned it moves to the dryer. The dryer uses propane and forced air to reduced moisture content to levels adequate for long-term storage, typically up to one year. Moisture loss has been observed at 1% by weight of incoming seed. Dried seed moves to the dry bin where it is stored and augured to the seed presses. Oil extraction efficiency is the weight of the oil pressed divided by the starting weigh of seed expressed as a percent. Canola is 28%, sunflower is 20%, and soybeans are 10.5%. Oilseed meal, also referred to as protein meal or grain meal, is the principal product of oilseed pressing and the balance by weight after oil extraction. Protein meal is at the proper moisture content for storage after pressing and transported to local feed mills by truck. The pressed oil contains small particles from the seed coating and is cleaned by a plate and frame style filter press. A filter aid, diatomaceous earth, is added to increase surface area between frames. The oil is pumped through the filter where the solids and sediments, known as foots, are trapped in the filter. These sediments represent 2% of the starting oil by weight. Filtered oil is equal to the starting oil weight minus the sediment loss.

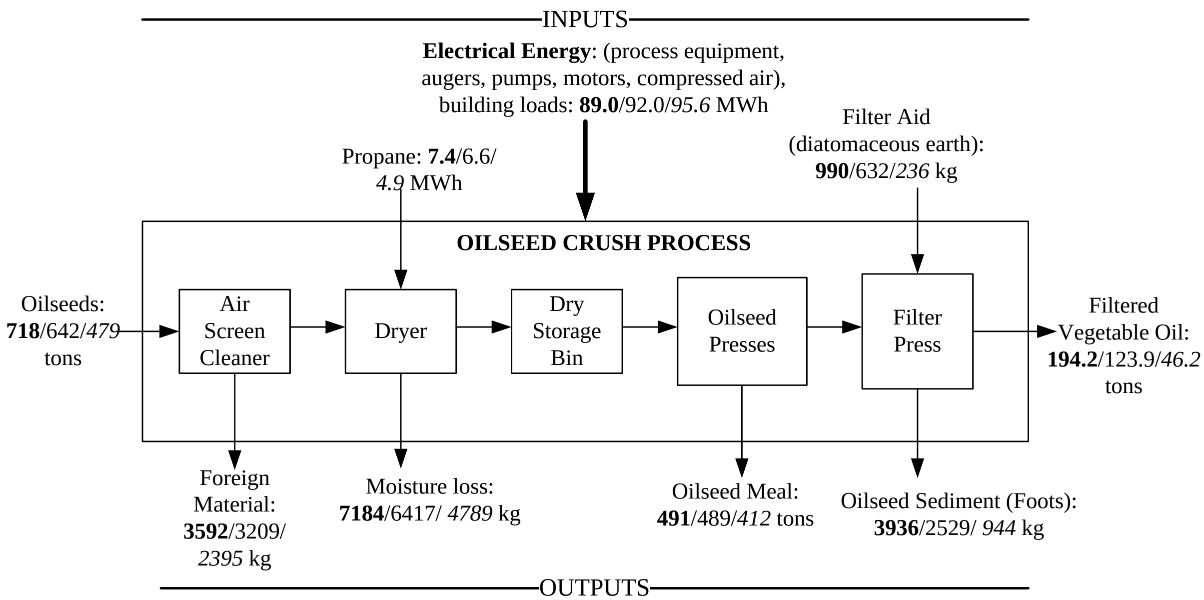

Figure 10. Annual Material and Energy Flows through Crush Facility operating at 250 days/year by Oilseed Type (**Canola**, Sunflower, *Soybeans*).

Electrical energy use in the facility was determined by load assessment for each piece of equipment throughout the process for each of the three oilseeds. Hours of operation for each piece of equipment were determined by dividing the overall mass by the flow rate by equipment (Appendix F). Operating hours were multiplied by motor specification, typically full load amps, to give kilowatt-hours. Other electrical loads such as lighting exhaust fans, and seasonal building heaters were estimated based on operating schedule and added to the equipment electrical usage.

4.3.4 Biodiesel Conversion. The EcoComplex Biodiesel Facility houses a multi-feedstock process that is able to convert a variety of oils and fats into fatty acid methyl esters

(FAME). Common feedstocks include raw seed oils such as canola, sunflower and soybeans processed on-site, used cooking oils recycled from restaurants, and animal fats rendered from large scale processing plants. The primary conversion step is transesterification, a base catalyzed reaction where potassium hydroxide is added to methanol and reacted with feedstock oil under moderate temperatures (60°C) for 1-2 hours. Methanol is used at a 6:1 molar ratio with the feedstock oil, 20% by volume of oil, and potassium hydroxide (KOH) is used at a ratio of 14.83 grams per liter of feedstock oil (Mittelbach, 2006). KOH can be reduced to as little as 9 grams per liter for virgin vegetable oils or feedstocks that have been pretreated. This is an emulsion reaction requiring shear mixing or vigorous agitation to ensure complete reaction defined by and measured in the European Biodiesel Standard (EN 14214) as a minimum of 96.5% methyl ester content and indirectly by the US Biodiesel Standard (ASTM D6751) as less than 0.24% bound glycerin by mass (see Appendix B and C). Important reactions in the conversion process are listed below:

1. Transesterification: capable of achieving desired conversion to FAME with alkali catalyst, KOH with feedstock oil containing up to 5% free fatty acids.

   OIL + 3 MeOH (KOH CATALYST) ⟶ 3 FAME + GLYCEROL 95% conversion of OIL

2. Saponification: Additional catalyst must be added to compensate for catalyst lost to soap formation.

   FATTY ACID + POTASSIUM HYDROXIDE ⟶ POTASSIUM SOAP + WATER

3. Water treatment/Catalyst Removal: Adding phosphoric acid to waste water to form a potassium salt. This does liberate FFAs which are miscible with the FAME phase. This material is added to incoming feedstock oil.

3 KOH + H3PO4 ⟶ K3PO4 + 3 WATER   100% conversion of KOH

4. Acid Esterification: Technique applied to high FFA feedstocks to convert free fatty acids directly to FAME. This requires materials handling of highly corrosive sulfuric acid and creates water which complicates the base catalyzed reaction.

   FATTY ACID + METHANOL (SULFURIC ACID CATALYST) ⟶ FAME + WATER

4.3.4.1 Feedstock Preparation. Due to the multi-feedstock nature of the plant, infrastructure to handle different types of oils and their associated properties was developed. The two most critical characteristics of incoming feedstock oil are free fatty percentage (FFA %) and moisture, impurities and unsaponifiables, expressed as MIU. This MIU term includes solids such as food particles from a fryer or seed coatings and hulls from oilseed extraction. Table 6 lists common feedstock oils processed at the plant gate.

Table 6

Feedstock Oils at Plant Gate

Oil Type	FFA %	MIU %
Refined vegetable oil	<0.05	<0.05
Used cooking oil	3-7	2-8
Crushed unrefined oilseeds (canola, sunflower, soy)	0.5-1.5	<0.5
Commodity Yellow Grease	1-3	< 1.0
Animal Fats and Tallow	5-12	<0.5

FFA and moisture are the two most significant parameters for oil quality that effect use of expendable chemicals principally potassium hydroxide, downstream processing including washing, and overall yield or conversion ratio.

4.3.4.1.1 FFA%. Free fatty acids interfere directly with methyl ester conversion by forming a soap with the catalyst, a sodium or potassium salt. This translates into direct yield loss, creates water that can hydrolyze triglycerides and form more soap, creates difficulties in ester and glycerol separation, and further complicates the downstream purification process. These soaps must be removed from the fuel per EN14538 which states the potassium/sodium combined cannot exceed 5 ppm. Water washing and ion exchange resin filtration are unit operations designed for soap removal as well as other impurities. Van Gerpen (2005) suggests that FFA levels under 0.5% can be ignored, levels between 0.5-2% can be reacted by additional catalyst, and recommends that any feedstock oil with FFA value over 2% be subject to a pretreatment such as acid catalysis followed by alkali catalysis. Practical experience from North Carolina biodiesel producers show that feedstock oil can be reacted with higher FFA values (2-5%), however with the trade-off of decreased yields due to saponification and loss to soaps.

4.3.4.1.2 MIU%. Moisture, impurities, and unsaponifiables are primarily an issue with used cooking oil and yellow grease. Specifically these are fryer and food oils that become contaminated with water, food particles, cleaning products and soaps and are often allowed to degrade in collection vessels that increase overall FFA percentage. The range of 2-8% MIU describes the variable nature of handling this material and the fact that has been traditionally treated as a "waste" product for the restaurant. Only in recent years has it become a sought after commodity and generates a revenue stream for the restaurant.

The two primary methods to achieve consistent feedstock quality are (a) to blend low quality oils with higher quality oils, and (b) to pre-treat low quality oils with an acid esterification process to lower FFAs prior to base catalyzed transesterification (see Figure 10). The first method is preferred and only requires storage capacity, while the latter step involves additional unit operations and material inputs, which also involves handling of highly corrosive sulfuric acid.

A standard process has been developed for the EcoComplex Biodiesel Facility based on start-up production from August 2011 through November 2013 where 15 batches (average batch size of 1850 liters) were converted to fatty acid methyl esters in accordance with ASTM D6751. Appendix D lists the standard unit operations used in the EcoComplex biodiesel process. A process flow diagram of the facility’s capabilities is found in Appendix G. During this period feedstock consisted of both high quality raw vegetable oils and lower quality used cooking oils at 46% and 54% by volume respectively. The average quality of this blended feedstock oil, was found to have a FFA (free fatty acid) value of 2.80%, and moisture content of 2,273 ppm. Average yield during this start-up period was found to be 85%, where from 100 liters of starting oil, 85 liters becomes finished fuel. The 15 liters of feedstock oil not converted is lost along the process, in conversion to soap, in the crude glycerin phase separation, to waste water, during feedstock settling and solids removal, etc. These values are used as the baseline for materials and energy flows per batch.

Energy usage during conversion was determined by load assessment for equipment throughout the process. Hours of use for each piece of equipment were determined based on observation during the plant start-up period. Operating hours were multiplied by motor specification, full load amps, to give kilowatt-hours. Other electrical loads such as general building use was estimated using electric billing cycles during a period after the building was commissioned and before start-up batch production (Appendix H and I). Thermal energy inputs were calculated for the waste heat recovery system and measured experimentally to calculate heat exchanger efficiency and estimate thermal energy requirements for each unit operation (Appendix J).

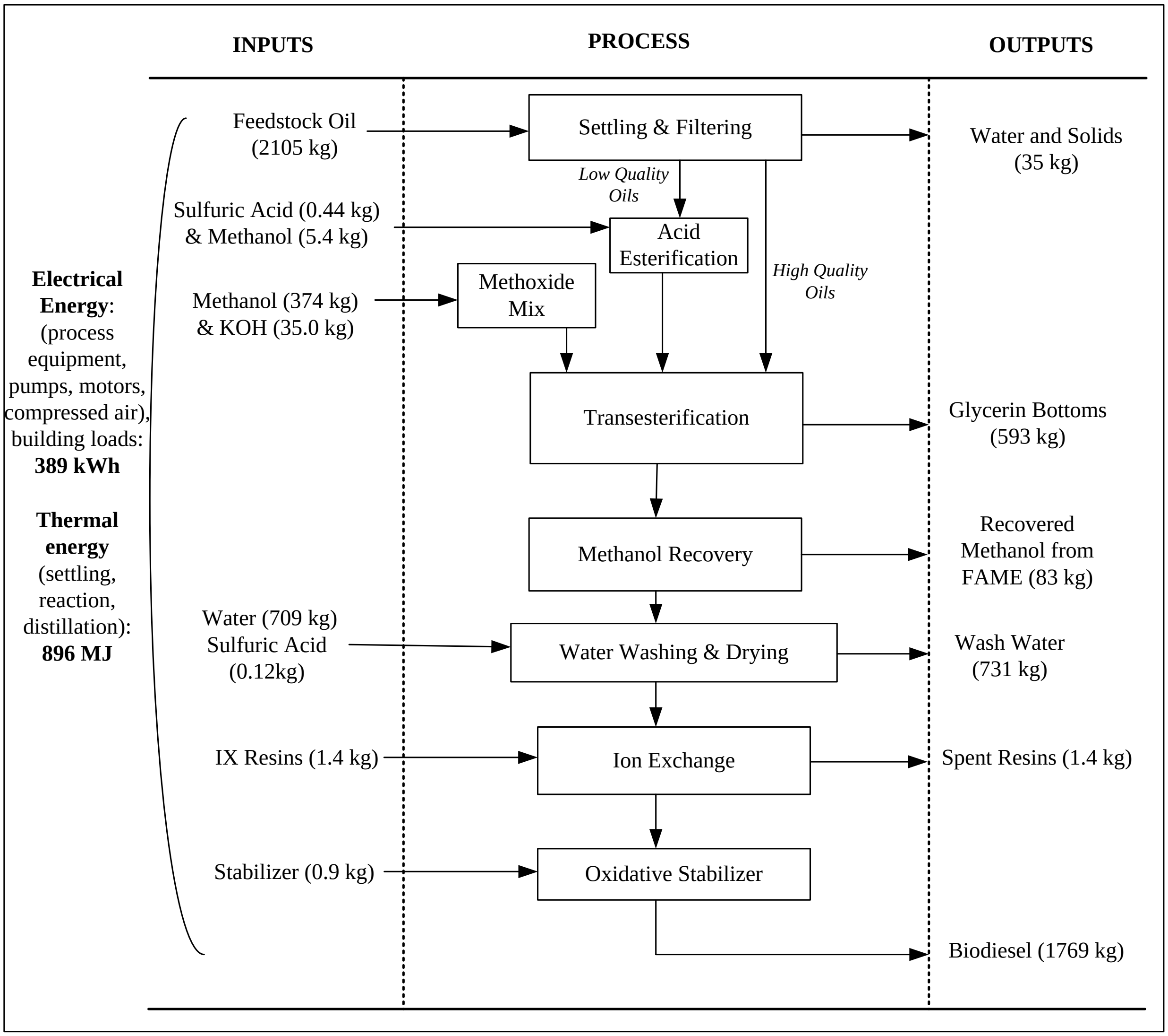

Figure 11. Material and Energy Flows through EcoComplex Biodiesel Facility per 2,365 liter Batch (625 gallons).

4.4 Results and Discussion

Annualized material flows for the three processes are listed in Table 7. Agricultural flows are scaled to meet the crush facility production capacity operating 250 days per year. Therefore seed output and ultimately land required is based on crushing rate for each oilseed.

Table 7

Agriculture Material Flows Per Year

Category	Canola	Sunflower	Soybeans
Hectares farmed	256	392	177
Seed input (kg/yr)	862	2,199	10,162
Fertilizers			
Nitrogen (kg/yr)	45,952	23,745	4,144
Phosphate (kg/yr)	17,232	6,596	8,767
Potash (kg/yr)	37,336	6,596	16,717
Lime (kg/yr)	189,552	290,219	131,506
Chemical Application			
Herbicides (kg/yr)	316	2,628	311
Insecticides (kg/yr)	258	119	297
Fungicide (kg/yr)	431		27
Energy Use			
Diesel Fuel (liters/yr)	10,044	15,379	6,968
Outputs			
Seed (kg/yr)	718,487	641,848	478,991

Fertilizer applications account for the most significant material input in oilseed farming. Crop budgets are formulated to maximize yield and are typically prescribed on economic returns only. For example, applying excess nitrogen to canola before the massive growth bolting stage does not account for embodied energy or emissions to the environment. Crop budgets also represent average conditions and have inherent limitations in regards to accuracy.

Canola is considered a “heavy feeder” requiring the greatest fertilizer input for each macro nutrient, illustrated in Figure 12. Soybeans on the other hand benefit from biological nitrogen fixation where on average 50-60% of total nitrogen uptake comes through this means (Salvagiotti et al., 2008). There is a clear need for the development of an integrated farming system approach that includes conservation tillage, selection of disease resistant cultivars, target use of nitrogen, and increased biodiversity through rotation (Alluvione, Moretti, Sacco, & Grignani, 2011).

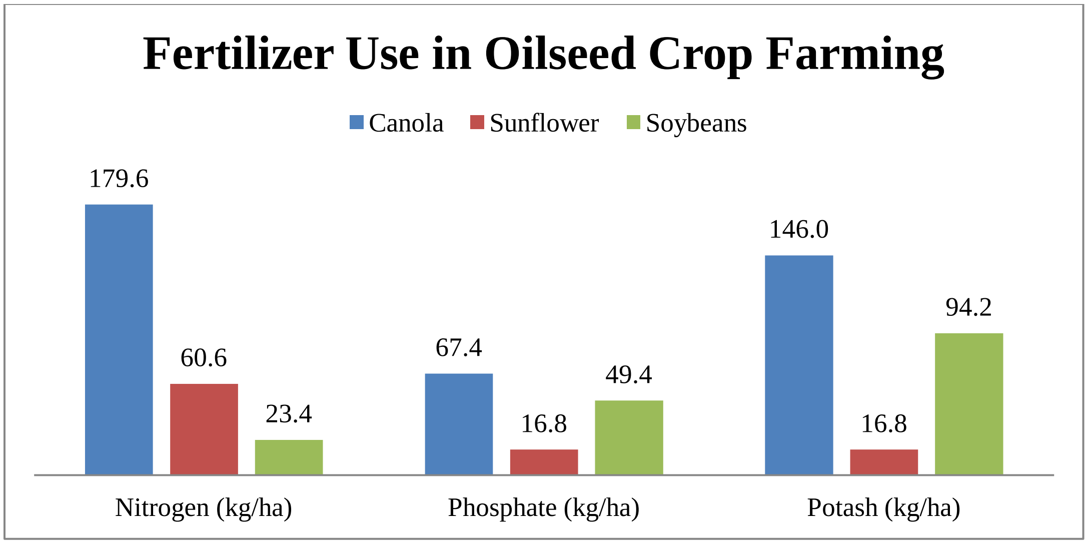

Figure 12. Macro-nutrient inputs based on Crop Budgets for Oilseed crops.

Incorporating elements of industrial ecology to produce soil amendments is well defined in the scope and long term objectives of the EcoComplex. In addition to yard waste and wood scraps that are composted, byproducts from the biorefinery could be added to a digester, either anaerobic or aerobic. These byproducts include both sources of nitrogen (seed meal which ranges from 25-35% protein content) and carbon sources in the forms of solids and sediment from feedstock preparation and crude glycerin bottoms (NCDA, 2013b; Sadano, Toshimitsu, Kohda, Nakano, & Yano, 2010). The refining of crude glycerin using phosphoric acid produces a separation of the crude glycerin emulsion results in the formation free fatty acids, technical grade glycerol at 85% purity, and a potassium salt, potassium phosphate. This salt is water soluble and provides two important macro-nutrients (Javani et al., 2012). Important decision making criteria to incorporate this utilization of byproducts include effect on labor and production scheduling and life cycle assessment.

The bottleneck for crushing is clearly scale. At current capacity this facility can only provide 36%, 23%, and 8% of the feedstock oil to meet the capacity of the biodiesel facility for canola, sunflower, and soybeans respectively. A minimum three-fold scale-up would be required to match the oil outputs for canola. This would also maximize the physical space of the building. Economic analysis would be needed before capital investments and facility expansion were made.

Table 8

Crush Facility Material Flows Per Year

Category	Canola	Sunflower	Soybeans
Oilseeds (kg/yr)	718,487	641,848	478,991
Foreign Material (kg/yr)	3,592	3,209	2,395
Moisture loss (kg/yr)	7,184	6,417	4,789
Protein Meal (kg/yr)	491,152	489,341	412,360
Filter media (kg/yr)	990	632	236
Oilseed foots (kg/yr)	3,936	2,539	944
Propane (kWh/yr)	7,423	6,631	4,949
Electricity (kWh/yr)	89,644	92,409	95,754
Filtered Vegetable Oil (l/yr)	194,196	123,916	46,237
Filtered Vegetable Oil (kg/yr)	179,437	114,498	42,723

Biodiesel conversion flows are scaled for an annual production capacity of 502,695 liters per year whereby 250-2,365 liter batches of feedstock oil are reacted with an average conversion yield of 85% (see Table 9). This is performed with the labor of one shift working 250 days per year. The biodiesel conversion step is not constrained by lack of vegetable seed oil feedstock from the crushing step; however, switching to a lower quality feedstock requires increased processing to achieve the same yield. Feedstock preparation is therefore the defining bottleneck of conversion. This is a formidable challenge to the biodiesel industry and has led to the wide spread efforts to develop alternative upstream technologies for feedstock pretreatment. Solid catalyst and enzymes are both techniques that afford the ability to treat low quality oils and potentially produce a higher value glycerin byproduct (Burton, Fan, & Austic, 2010). At present, these are not cost effective at scale and are continue in the development phase.

Methanol recovered from distillation is another important process step that presents trade-offs. Methanol recovery is not required for fuel to meet ASTM specification as both water washing and ion exchange filtration remove excess methanol. However, methanol removed from the FAME phase post reaction, facilitates downstream purification and reduces material input for process water and ion exchange resins as well as energy inputs. The recovered methanol can be recycled for use in subsequent batches, though it contains water from the saponification reaction concurrent during transesterification. Although recovered methanol is 94-95% pure (technical grade is 99.5%), the presence of this water promotes further oil degradation, soap formation, and yield loss (J.V. Gerpen, Pruszko, Clements, Shanks, & Knothe, 2006). Recovered methanol in the EcoComplex process model is blended into new methanol at a 20% ratio. Methanol rectification and drying techniques such as use of molecular sieves are good options for improving purity especially if crude glycerin is processed.

Table 9

Biodiesel conversion material flows per year

Batches per year	250
Batch size (kg)	2,105
Feedstock Oil (kg/yr)	526,250
KOH (kg/yr)	8,750
Methanol (kg/yr)	93,525
Sulfuric Acid (kg/yr)	111
Process Water (kg/yr)	177,375
IX Resins (kg/yr)	355
Oxidative Stabilizer (kg/yr)	228
Waste Water & Solids (kg/yr)	8,875
Glycerin Bottoms (kg/yr)	148,200
Recovered methanol (kg/yr)	20,775
Wash Water (kg/yr)	182,696
Biodiesel (kg/yr)	442,250
Electricity (kWh/yr)	97,120
Thermal Energy (MJ/year)	390,000

4.4.1 Energy Analysis.

4.4.1.1 Crush Facility. Energy used in crushing was averaged for all three oilseeds as their energetic inputs are similar, presented in Figure 13. The seed presses are responsible for 78% of the total crush energy for they operate continuously, though with relatively low power requirements. The remainder of the energy loads is intermittent, such as compressed air for oil pumping and augers for material handling and grain cleaning. Drying energy in the form of propane is the second largest operation, consuming 7% of total crush energy. Exhaust fans and unit heaters along with lighting are background usage associated with building energy and have a combined consumption of 9%. Grain handling, cleaning, air compressor usage, and meal handling sum the balance of 5%.

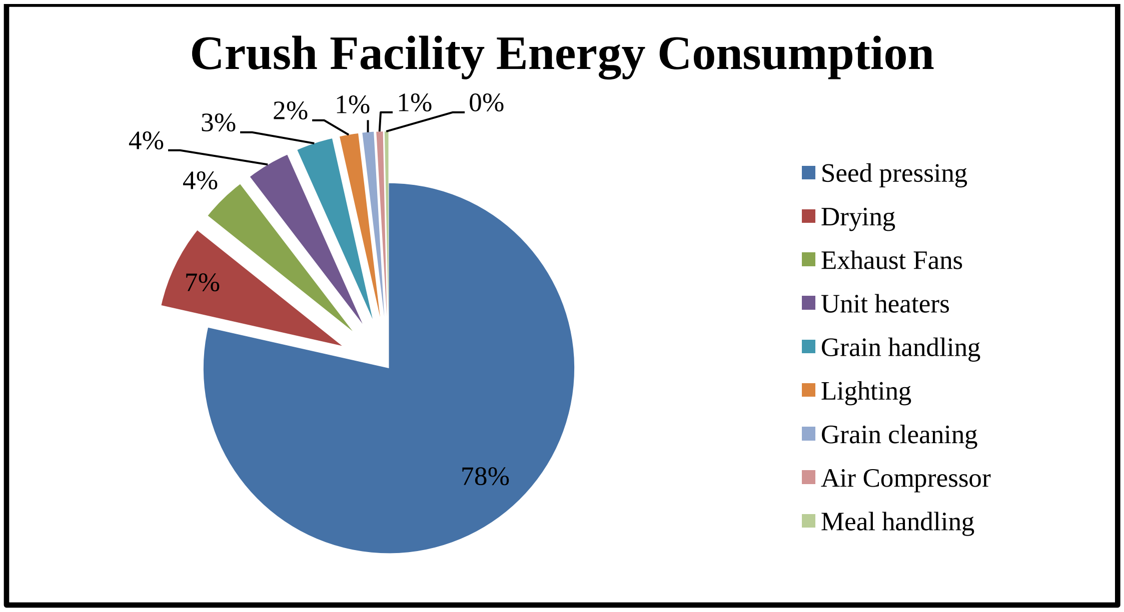

Figure 13. Crush Facility Energy Use.

4.4.1.2 Biodiesel Facility. Energy use for biodiesel conversion was itemized for each operation, see Figure 14. Building energy usage at 31% is the largest item and consists of loads including: exhaust fans, lighting, HVAC, lab equipment, and office equipment. The vacuum venturi is powered by compressed air and is used for pulling vacuum during flash drying, distillation, and as a safety mechanism to exhaust vapors when filling tanks. It accounts for 19% of the total energy consumed. Heat distribution pumping energy is 15% of the total and is pumping energy to move heat transfer fluid from a storage tank inside the facility to the heat exchanger located on the landfill gas generator and from the storage tank to each heated tank in the process. Ion exchange pumping energy accounts for 10% which uses compressed air to move washed and dried fuel through a fluidized bed of ion exchange resins. The reactor pump and agitator are used in conjunction for flash drying, transesterification, and methanol recovery. Compressed air loads where converted to electrical energy by calculated compressed air volume for each device and multiplying it by a power factor for industrial compressors (Schmidt & Kissock, 2002). Compressed air loads comprise over a quarter of total energy, 27%, which include the vacuum venturi, ion exchange pump, methoxide mix pump.

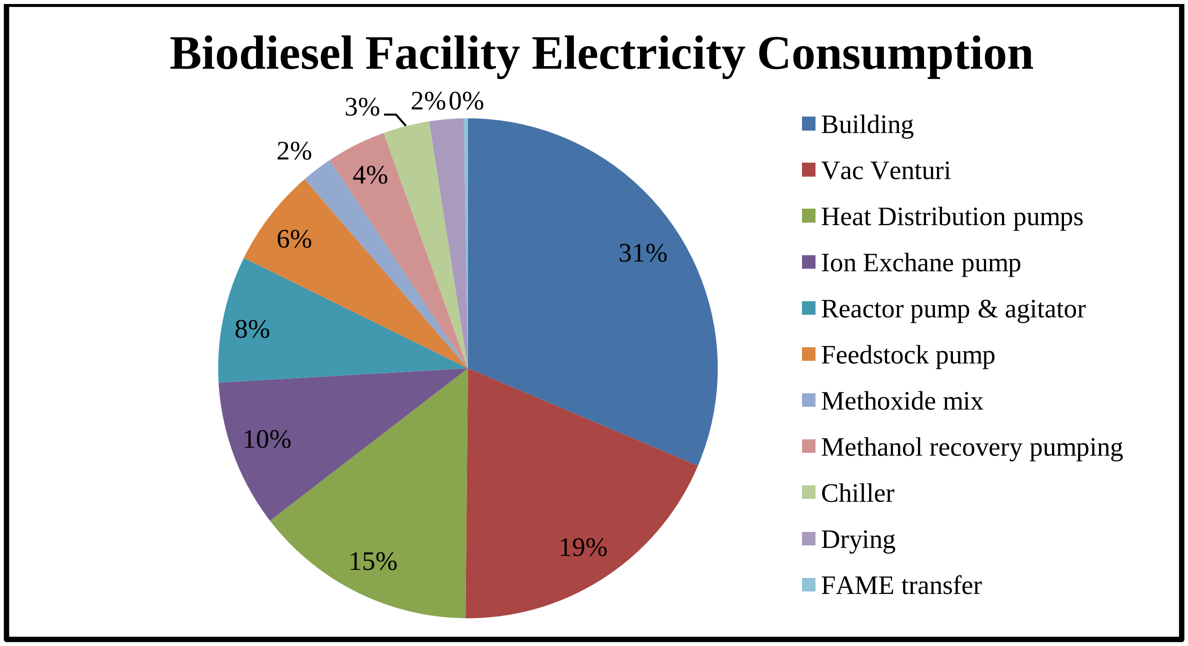

Figure 14. Biodiesel Facility Electricity use by category.

Thermal energy inputs were calculated for each unit operation of biodiesel conversion by measuring mass flow rate of the heat transfer fluid over time, given a heat exchanger's efficiency factor (see Figure 15). Heating energy required for conversion is spread out over several unit processes, though distillation for methanol recovery from FAME post reaction uses one quarter of the total. With the absorption chiller added to this (concurrent process), the total is 38%. This is due to the latent heat of methanol and required phase change for boiling and condensation. Feedstock settling is the second largest load as it requires high temperatures to assist with particle removal and viscosity reduction as the oil is pumped through canister filters. Transesterification and feedstock vacuum drying require similar heating while the remainder of the processes are relatively minor loads.

Thermal energy is provided to the biodiesel facility from waste heat off the jacket water of one LFGTE engine. The absorption chiller, which uses propane, is the only exception. The heat recovery system was designed to substitute a 200,000 Btu/hr (58.5 kW) boiler to supply low quality heat (water at 76°C) for process heating loads. A 2,500 gallon (9,462 l) storage tank was added to allow addition heating capacity for simultaneous high thermal load processes such as distillation and feedstock settling. Maximum on-demand heating load, where all process tanks are being heated is calculated at 46kW. Developing future capabilities such as glycerin distillation and methanol rectification, both requiring high thermal inputs, running simultaneously with other operations will likely surpass the supply heat system capacity. Additional heat supply or process scheduling should be analyzed as these new capabilities are considered.

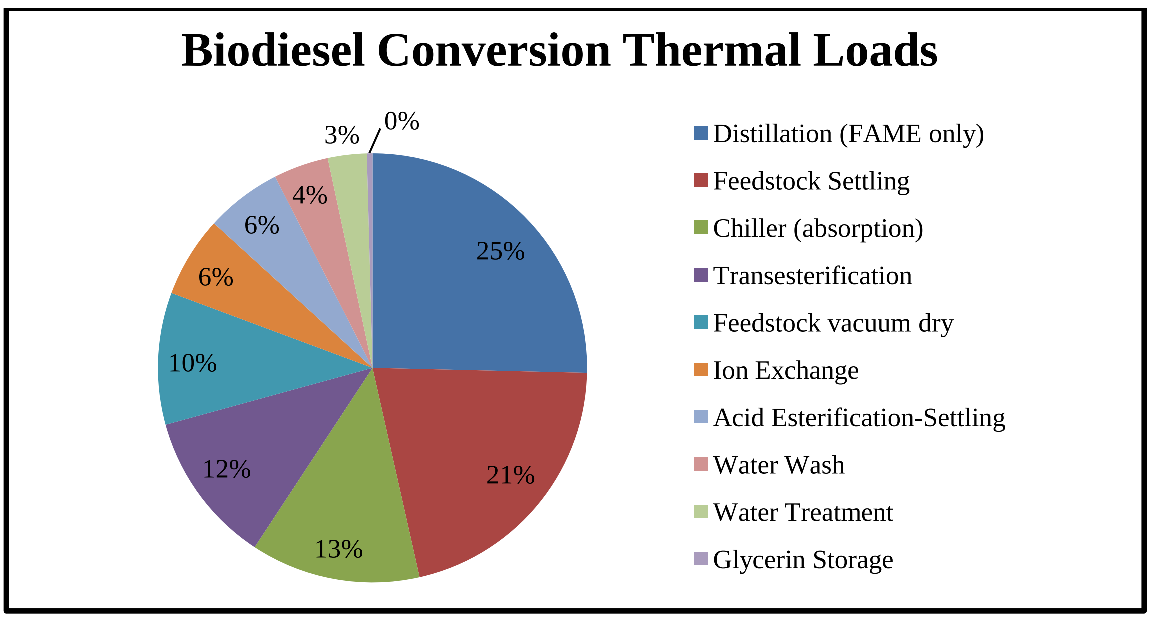

Figure 15. Thermal Loads for Biodiesel Conversion by Unit Operation.

4.5 Conclusion

The life cycle inventory for each process associated with the NC EcoComplex Biorefinery was determined through a mixed methods approach which included primary data from the biodiesel and crush facilities as well as secondary data from literature review for agricultural production of oilseed crops. The material and energy flows discussed in this chapter points to distinct bottlenecks of the EcoComplex oilseed biorefinery. These bottlenecks include fertilizer use in agriculture and the ability to produce plant nutrients through byproducts of crush and conversion in symbiosis with existing waste and resource management industrial ecology systems. The scale factor of the crush facility and potentially the technology selected, present an incompatibility with the scale of the biodiesel facility. For biodiesel production capacity to be realized, additional feedstocks must be sourced. The conversion step points to three potential bottlenecks: feedstock preparation, methanol recovery, and thermal loads for expanded production.

CHAPTER 5

Energy & Greenhouse Gas Life Cycle Assessment of Multi-Feedstock Biodiesel Production within the EcoComplex Industrial Ecology System

5.1 Abstract

The role of biofuels as a renewable energy source for the 21st century is subject of considerable debate. To play a significant role in the evolving energy mix, biofuels must accept an unprecedented degree of scrutiny that fully addresses potential economic, societal, and environmental benefits. The task of confronting these concerns while achieving a high level of transparency is complex. Life Cycle Assessment (LCA) methodology has become the standard framework for sustainability assessments of biofuels with regards to energy use and environmental performance.

A cradle to grave LCA was conducted for canola, soy, sunflower, and used cooking oil (UCO) biodiesel feedstocks within a conventional process system and the EcoComplex Industrial Ecology (IE) system which uses non-fossil based electricity and process heat in crush and conversion steps. LCA results of energy balance and carbon intensity analysis show a large range by feedstock type where UCO clearly benefits from its classification as a secondary-use or waste product. The agriculture step is costly both in terms of energy equivalents and embodied emissions primarily attributable to nitrogen fertilizer. Removing the agricultural as well as crushing steps consolidates UCO feedstock impacts to the conversion step which is significantly affected by implementation of applied industrial ecology. The IE system for UCO feedstock resulted in a carbon intensity value of 7.93 gCO_2-eq/MJ, a 57% reduction compared to the conventional system, and a fossil energy ratio (FER) of 12.24:1. Soybean based biodiesel

resulted in the most environmentally benign of the oilseed crops with a carbon intensity value of 12.51 gCO_2-eq/MJ and FER of 7.19 within the IE system.

5.2 Introduction

The role of biofuels as a renewable energy source for the 21st century is subject of considerable debate. To play a significant role in the evolving energy mix, biofuels must accept an unprecedented degree of scrutiny that fully addresses potential economic, societal, and environmental benefits. The task of confronting these concerns while achieving a high level of transparency is complex. Biofuels are located at the nexus of ever changing global petroleum and agricultural markets affected by myriad policies. Energy security, foreign relations, and socioeconomic issues related to rural sector development are primary reasons for subsidizing biofuels growth and the setting of targets and goals for further market penetration.

The potential environmental benefits of displacing petroleum with biofuels continue as a principal driving force to justify biofuel development. As of 2005, the Kyoto Protocol to the United Nations Framework Convention on Climate Change has legally binding targets for signatory and ratifying countries (European Union and Australia). These countries face the great challenge of reducing greenhouse gas emissions. Biofuels represent a commercially available technology and deployable tool to address emissions in the transportation sector and to a lesser degree in electricity generation (Sanz Requena et al., 2011). The concept of "carbon neutral" has historically applied to biofuels where CO_2 from combustion is sequestered by subsequent biomass crops over time, maintaining net biogenic carbon at steady state (Rabl et al., 2007). Biofuel, specifically biodiesel compared to petroleum diesel, combustion has been shown to decrease other emissions including hydrocarbons, carbon monoxide, particulates, and sulfur oxides (Dorado, Ballesteros, Arnal, Gomez, & Lopez, 2003; He et al., 2009; Sheehan, Camobreco, Duffield, Graboski, & Shapouri, 1998). While methods for determining direct emissions from combustion and material processing life cycle stages have been well developed, agricultural emissions are less understood and have significant variation due to location specific factors that affect plant growth and biomass accumulation in soils.

5.2.1 Emissions from Crop Agriculture. Dedicated biomass energy production requires arable land and the use of fertilizers and chemical applications that can cause contamination of soil and water resources (Alluvione et al., 2011). Carbon dioxide and nitrous oxide are the primary emissions associated with crop agriculture. Mechanical soil preparation or tillage oxidizes soil carbon causing its release to the atmosphere as carbon dioxide. An equilibrium occurs in most soil systems over time where carbon sequestration equals carbon released during tillage and is not further discussed here other than the notion that continuous no-till agricultural may serve as a carbon sink (Sundermeier, Islam, Raut, Reeder, & Dick, 2011).

Soil emissions from fertilizer applications include nitrous oxide and ammonia volatilization, as well as nitrate and phosphate leaching; both contribute toward GHG production and lead to acidification and eutrophication through deposition (Brentrup, Kusters, Lammel, & Kuhlmann, 2000; Caffrey & Veal, 2013). Smith and Searchinger (2012) propose that current biofuel emission models inadequately handle fertilizer impacts and therefore underestimate the ultimate emissions released to the environment. Soil emissions from agriculture are an important aspect of total emissions accounting and are controversial as they prove difficult to quantify. Additionally, the ability of plants to efficiently sequester nutrients supplied through fertilizer inputs varies by soil type, soil moisture, growth stage of plant, climactic conditions, fertilizer type, crop type, and management system. These variables range widely by geography and are ultimately site specific.

Nitrous oxides (N_2O) are soil emissions released due to volatilization of nitrogen in excess of plant uptake. This results from naturally occurring soil microbial processes, largely anaerobic denitrification and aerobic nitrification (Henault, Grossel, Mary, Roussel, & Leonard, 2012). This is a powerful greenhouse gas with an emissions factor 298 times that of carbon dioxide, accounting for 8% of the anthropogenic global warming potential (Lesschen, Velthof, de Vries, & Kros, 2011). Of this eight percent, over half is estimated as emissions from agricultural soils. The IPCC has been involved in providing direction for the quantifying of nitrogen oxides resulting from agriculture, in particular commodity crops with heavy fertilization applications. Stehfest and Bouwman (2006) developed a system to calculate a fertilizer-induced emission (FIE) indicator based on the observed linear relationship between N_2O and N application rates. The FIE was originally estimated at 0.91% with high uncertainty, whereby 0.91% of the nitrogen applied is directly lost as nitrous oxides. The greatest contributing factors affecting nitrous oxide formation were determined to be animal manures versus synthetic nitrogen source, soil pH, and soil texture. The resultant FIEs ranged from 0.0% to 10.8% with an average of 1.1% and a standard deviation of 1.7% (Flechard et al., 2007). The IPCC (2013) has set the baseline emission factor in its guidelines at 1%. This means that nitrous oxide emissions are equal to 1% of the total mass of nitrogen applied.

Indirect land use change (ILUC) is another contentious issue in the life cycle debate of biofuels. It is described as the phenomena where grasslands or forest are converted to cropland due to market forces, resulting in the release of carbon and sacrificing ongoing carbon storage (Fargione, 2008; Searchinger, 2010). Palm and soybeans, two primary oilseed crops, have been strongly linked to tropical deforestation. In the developing world land clearing is most commonly achieved through biomass burning, augmenting emissions of CO_2 and N_2O. ILUC therefore challenges the "carbon neutral" conceptual framework where sequestration credit minus combustion debit equals zero. The lack of identifying specific carbon stocks of biomass production over time may produce a greater carbon footprint such as the case of a forest being converted for crop production. Alternatively, land-use change may have a meritorious effect increasing carbon sequestration in the case of a fallow or degraded field converted to a soil building, cellulosic, or low-input high diversity grass crop (Johnson, 2009; Tilman, Jason, & Lehman, 2006).

5.2.2 Life Cycle Assessment. Life Cycle Assessment (LCA) methodology has become the standard framework for sustainability assessments of biofuels with regards to energy and environmental performance. LCA uses quantitative assessments of material and energy flows, wastes, and emissions for each associated process in the biofuel production life cycle. LCA interpretation provides insight into high impact areas and identifies opportunities for environmental improvement. International standards for LCA procedures and methods (ISO 14040 and 14044) were first developed in 1997 and updated in 2006 to specify the distinct phases of analysis: goal and scope definition, inventory, impact assessment, and interpretation (Finkbeiner, Inaba, Tan, Christiansen, & Klüppel, 2006; Sauer, 2012). The life cycle for transportation fuels are commonly described as *well to wheel* for the entire life cycle and *well to pump* and *pump to wheel* as subsets. However, the exacting process for biofuels in particular continues to evolve on account of feedstock type, conversion technologies, system boundaries, and reference energy systems (Cherubini et al., 2009). Allocation methods for co-products such as soybean meal and glycerin have also been shown to have significant effects on outcomes (Huo, Wang, Bloyd, & Putsche, 2008). Finally, the concept of substitution's effects on GHGs has been brought to the attention of LCA methodology. Diverting by-products such as used cooking oil or poultry fat to biodiesel instead of its original use (animal feed or cosmetics) may ultimately eliminate the benefits of biodiesel production because the original intended use will be forced to find a substitute that incurs environmental costs elsewhere (Jørgensen, Bikker, & Herrmann, 2012).

Energy life cycle assessment or ELCA is a component of LCA commonly used for assessing and comparing renewable energy sources. Energy balance, often referred to as energy return on energy invested (EROI), involves the accounting of total production energy used and the type of energy used (fossil or renewable). When the total production energy is divided by the energy contained in the resulting unit of biofuel, the outcome is net energy ratio (NER), a measurement of process efficiency (Morris, 2005). The second type of energy balance used in ELCAs is fossil energy ratio (FER). FER is equal to the renewable energy output divided by the fossil energy input. FER addresses renewability of the biofuel, how much it relies on fossil or petroleum derived energy sources for its production. FER is an important tool for comparing different biofuels and the manufacturing systems within which they are produced. Renewability along with environmental, economic, and social metrics creates a holistic view upon which to assess the potential benefits of biofuels.

5.2.3 Biodiesel LCAs. Sheehan et al. (1998) produced the first comprehensive life cycle inventory and LCA for soybean biodiesel in the US. The inventory and assumptions made in this paper were developed by a large stake holders group, subject to several peer reviews, and have been touted as the baseline for soybean biodiesel. The key findings state that FER for soybean-based biodiesel yields 3.2 units of fuel product energy for every unit of fossil energy consumed in its life cycle. Soy-biodiesel reduces direct emissions of CO_2 by 78.45% compared to petroleum diesel. Finally, substituting 100% biodiesel for petroleum diesel reduces the life cycle consumption of petroleum by 95%. In 2009, Pradhan et al. updated the Sheehan life cycle inventory with 2002 data for soybean production. The original study had been based on 1990 agricultural data. An FER of 4.56 was reported and the change was cited as a function of increase in soybean yields and improved extraction and conversion efficiencies. In 2011 the study was revisited again to include 2006 data. The FER analysis increased to 5.54 and again was attributed the improved soybean yields as well as increasingly energy-efficient technologies in crush and conversion plants.

Biodiesel GHG studies use global warming potential (GWP) as the reference unit for comparing different feedstocks and processes. This is expressed in grams CO_2-eq/MJ where all emissions have been classified according to their impact category and multiplied by a characterization factor to convert the emission to the reference unit. For example the emissions factor for N_2O is 298, therefore 6 grams of nitrous oxide converts to 1788 grams of CO_2 equivalent for global warming potential (GWP). These factors are determined by two widely accepted methods, Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) from US EPA in the United States and CML from Leiden University's Institute of Environmental Sciences in Europe (Margni & Curran, 2012). This metric is also referred to as *Carbon Intensity* value (CI) and used to compare biofuels across feedstocks and technologies. CI value of a particular biofuel is commonly expressed as a percent reduction compared to the petroleum fuel being substituted. This has become the baseline metric used in policy formation such as EPA RFS2.

California Air Resources Board (CARB) has evaluated carbon intensity values of numerous biofuels for policy guidance of the Low Carbon Fuels Standard (LCFS), a market-based cap and trade approach to lowering emissions from transportation fuels in California.

Direct emissions without ILUC from two approved biodiesel pathways, soybeans and used cooking oil, resulted in 21.35 and 11.86 gCO_2-eq/MJ respectively (CARB, 2014). US EPA specifies that biomass-based diesel fuel (biodiesel) must reduce carbon intensity by at least 50% compared to 2005 petroleum diesel emissions to be considered for subsidy under the Renewable Fuel Standard. Current feedstock types complying with this requirement include soybeans, biogenic waste oils/fats/greases, non-food grade corn oil, oil from annual cover crops, algal oil, and canola oil (EPA, 2011). An analysis of European oilseed-rape biodiesel direct emissions by the UK Department of Transport (2008) showed a range of carbon intensities from 45.4 to 59.5 gCO_2-eq/MJ depending on country of origin. The European Commission's Joint Research Centre published analyses of direct emissions for other oilseed based feedstocks, sunflower and palm oil, which resulted in a reduction of carbon intensity of 51% and 19% respectively (Rothengatter, Hayashi, & Schade, 2011).

Soybean-based biodiesel represents the majority of the US biodiesel market and has been the focus of LCA studies in the United States. LCA studies based on waste oils such as used cooking oil from smaller producers have received less attention due to their relatively small percentage of the overall market share. One exception is an LCA which used plant data from a small-scale producer that used waste vegetable oils exclusively, North Carolina based Piedmont Biofuels (Daystar, 2012). This study reported an energy balance of 7.85 and net global warming potential or CI value of 3.76 gCO_2-eq/MJ based on primary data from plant operations. This resulted in an overall greenhouse gas emissions reduction of 96% compared to petroleum diesel life cycle for a no-feedstock burden scenario, where emissions from feedstock production were not considered.

The goal of this chapter is to conduct an LCA to determine the energy balance and the direct greenhouse gas emissions associated with the production of biodiesel from multi-feedstock sources including unrefined soy, sunflower, and canola oils as well as used cooking oil at the Catawba County NC EcoComplex. The results of this LCA are to serve for 1) internal use by providing a baseline whereby changes in process will be measured and compared and to identify opportunities for reducing current environmental impact and 2) external use to make comparisons against other fuels and manufacturing facilities. Interpretation and discussion of the results are focused on effects of manufacturing within an eco-industrial park.

5.3 Methods

5.3.1 Scope. This assessment is on a cradle to grave basis, from the production of raw materials used in biodiesel manufacturing to the end of life use in a diesel engine. This includes the following life cycle stages or unit processes for unrefined vegetable oils: agriculture/feedstock production, oilseed crushing, transportation, biodiesel conversion, and combustion. Used cooking oil (UCO) feedstock includes transportation for material collection; however, feedstock production is not included as the material is considered a waste product to the food service industry. It is assumed that collection of used cooking oil does not significantly impact the demand for yellow grease; therefore commodity substitution effects are not considered. Indirect effects such as land use change have potentially large impacts on assessments but are also highly controversial. ILUC is often considered too diffuse and subjective to be included in LCA rulemaking (Mathews & Tan, 2009). The effects of indirect land use change are discussed however they are kept separate from baseline emissions in this study. Local agricultural production is assumed to use historic lands, not recently converted from forests, with steady state carbon stocks. Therefore biogenic carbon emitted from combustion is assumed neutral on balance negated by sequestration from crop production and is not quantified in this greenhouse gas inventory. The fertilizer induced emission factor used in this study is the IPCC baseline of 1% of nitrogen fertilizer applied. All crop production is rain-fed without need for irrigation.

5.3.2 Allocation. A mass-based allocation system was chosen throughout the agriculture, grain transport, crush, and conversion portions of the life cycle. This is the preferred methodology of dividing or partitioning process input and output flows defined in ISO 14044 section 4.3.4.2 (Sauer, 2012). For example, canola oil extraction is 28% by mass of the starting seed. Therefore the amount of fertilizer and farming inputs used in the agricultural production phase is reported as the mass-based oil fraction, 28% of the total. The crush phase also uses mass-based methodology, where the balance of the seed, the meal co-product, is not considered. This applies to energy inputs as well. For example, the electric input for crushing canola seeds is also reported as a fraction of the total, only accounting for the oil portion. The conversion phase uses mass allocation by the yield factor. This study uses a yield at the conversion step of 85%, where 85% of the incoming oil is converted to biodiesel. The 15% not converted is lost along the process, as non-reacted material, in conversion to soap, in the crude glycerin phase separation, et cetera.

5.3.3 Functional Unit. The functional LCA unit chosen for energy and material flows is one metric ton of biodiesel. The energy density unit is expressed in MJ/kg unless otherwise stated. Net greenhouse gas emissions, or carbon intensity value, are reported in grams of CO_2 equivalent per MJ. An energy basis is used for GHG comparisons to nullify the effect of different energy densities of biodiesel and petroleum diesel on emissions per unit mass.

5.3.4 System Boundaries. The subsystems used in the inventory are illustrated in Figure 16. Inputs entering the system are listed above each associated process. The outputs of each process are emissions from the production of inputs, combustion from activities related to the process, and from soil in the case of agriculture. Mass out-flows occur at the crush and conversion steps, where oilseed meal and glycerin leave the system. Transportation is involved in all steps within the boundary. Feedstock production is defined as origin from regional farms within 50km. Used cooking oil collection is defined as within 160km. The crush and conversion facilities are co-located at the EcoComplex. Transport of final fuel to end-use bulk tanks is 65km, all consumed within Catawba County.

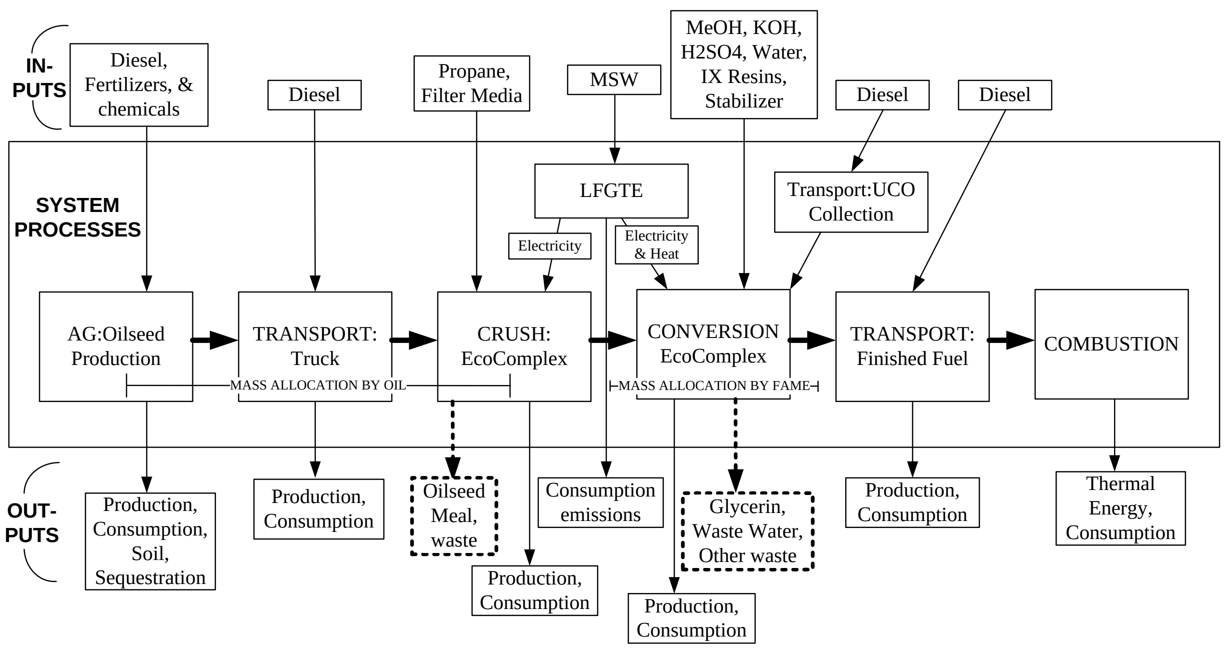

Figure 16. Cradle to Grave System Boundaries for Oilseed and Used Cooking Oil feedstock. Mass outputs are denoted with bold dashed lines.

The system boundary includes the landfill gas to energy (LFGTE) project located at the EcoComplex. This facility generates on average 3MW of power from the combustion of landfill gas derived from organics in municipal solid waste (MSW). This facility provides thermal energy for the biodiesel conversion step. It also provides electricity to the crush and conversion facilities by virtue of co-location despite the “buy all, sell all” contractual arrangement for electricity consumption and generation on-site.

Transportation for agriculture inputs and process chemicals are included in the life-cycle energy equivalents found in Table 11. All direct and indirect energy inputs such as electricity and waste heating from landfill gas co-generation are included. The inputs for production of capital goods such as process equipment and buildings are excluded. Chemical inputs from the inventory include fertilizers and chemical applications in agriculture and process chemicals in conversion.

5.3.5 Life Cycle Inventory. An LCI and associated data for the EcoComplex Crush and Biodiesel facilities, operating at capacity, is presented in Chapter 4. Agricultural inputs required to satisfy crush facility capacity are also described in Chapter 4. Tables 10 and 11 illustrate material and energy inputs per ton of biodiesel (880 liters).

It is important to note the used cooking oil only has materials and energy inputs at the conversion phase. This study deals with this material as a by-product and therefore is considered to have no feedstock burden. Energy for transport is included in Table 11 which is the sum of (a) crop transport, moving oilseeds from local farms to the crush facility, (b) collection of used cooking oil from restaurants, and (c) transport of finished fuel to pump stations for distribution.

Table 10

Direct Material Inputs by Life Cycle Category Per Ton of Biodiesel (Based on Chapter 4 LCI Data)

Feedstock	Canola	Sunflower	Soybeans	UCO
Material Input by Category		kg input/ton FAME		
Agriculture				
Nitrogen	74.2	42.9	10.0	
Phosphate	27.8	11.9	21.2	
Potash	60.3	11.9	40.5	
Lime	0.3	0.5	0.3	
Herbicides	0.5	4.8	0.8	
Insecticides	0.4	0.2	0.7	
Fungicides	0.7	0.0	0.1	
Crush				
Filter Media	5.7	5.7	5.7	
Conversion				
KOH	19.8	19.8	19.8	20.4
Methanol	211.5	211.5	211.5	218.0
Sulfuric Acid	0.25	0.25	0.25	0.26
Process Water	401.1	401.1	401.1	413.5
IX Resins	0.80	0.80	0.80	0.83
Oxidative Stabilizer	0.51	0.51	0.51	0.53

Table 11

Direct Energy Inputs by Life Cycle Category (Based on Chapter 4 LCI Data)

Energy Input	Category	Unit	Canola	Sunflower	Soybeans	UCO
Diesel	AG	l/ton FAME	16.23	27.81	16.89	
Diesel	Transport	l/ton FAME	9.92	12.17	20.06	11.35
Propane	Crush	l/ton FAME	5.41	7.59	15.2	
Electricity	Crush	kWh/ton FAME	144.8	167.1	232.0	
Electricity	Conversion	kWh/ton FAME	185.7	185.7	185.7	191.4
Thermal heat	Conversion	MJ/ton FAME	506.5	506.5	506.5	522.2
Total Energy	All Steps	MJ/ton FAME	3,179	4,027	4,284	1,799

5.3.6 Energy Life Cycle. Energy consumed over the life cycle of a fuel is defined by its system boundary. A cradle to grave (well to wheel) approach is used for this study. Net energy ratio is the ratio of total energy of combustion using low heating value, divided by the sum of energy from each life cycle stage. The fossil energy ratio uses the same formula, however only accounting energy inputs from fossil sources. In this study, FER is calculated with the five conditions referred to as the industrial ecology (IE) system, found in Table 12.

Table 12

Industrial Ecology System Conditions

1) B20 in diesel powered agricultural equipment
2) B20 in diesel powered transportation equipment
3) Electricity used in crush and conversion is non-fossil biogenic carbon coming from landfill gas
4) Thermal energy used in conversion is derived from LFGTE heat recovery
5) 20% methanol recycle in conversion

Net and fossil energy ratios are calculated from the life cycle inventory which uses primary plant data from the crush and conversion steps as well as secondary data from literature for the agriculture step. Transport energy inputs were calculated using the Argonne National Lab's GREET model (Argonne-National-Laboratory, 2013). Below is the equation for NER, Net Energy Ratio.

$$NER = \frac{Energy\ of\ biodiesel\ combustion\,(lhv)}{(E(ag) + E(crush) + E(conversion) + E(transport))}$$

This equation states that NER is equal to the energy value of biodiesel (lower heating value), divided by the sum of energetic inputs from each step, agriculture, crush, conversion, and transport.

5.3.7 GHG Accounting Procedure. Net environmental impact data emission factors were collected from the following sources: GaBi, a commercial LCA software that conducts assessments based on ISO 14040/44, Argonne National Laboratory's GREET model, and references from the LCA literature (Appendix K; IKP/PE, 2013). This includes direct emissions from production of raw material inputs, processes in the agriculture, crush, transport, and conversion stages, as well as fertilizer induced nitrous oxides emissions from soils. All data were characterized per the 100 year GWP value to produce the GHG functional unit of grams of CO_2-eq (GWP) and allocated on a mass basis per kilogram of biodiesel. Material input flows for each life cycle stage and mass allocation value per unit of FAME were developed in the LCI. Finally, GWP per mass was divided by the energy density per kg of biodiesel resulting in gCO_2-eq /MJ, the carbon intensity metric. Overall emissions reduction expressed as percentages compare the biofuel's CI value to that of US refined ultra-low sulfur diesel with a baseline value of 94.71 g CO_2-eq/MJ (CARB, 2014). The *Industrial Ecology System* models CI values of the various feedstocks by using the parameters outlined in Table 12.

One additional condition is that a negative value was assigned to process heat for the conversion step. The IE system uses waste heat otherwise rejected to the environment; no other fuel or heating source is required. Therefore a negative value is assigned. The Carbon Intensity equation by feedstock type is listed below. MIF equals Material Input Flows, MA equals the Mass Allocation value, and EF equals the Emissions Factor.

$$CI(feedstock) = \frac{\sum(Ag + Crush + Conversion + Transport)(MIF * MA * EF)}{Energy\ Density}$$

5.3.8 Energy & GHG Conversion Factors. Material and fuel inputs were converted to their energy and greenhouse gas life cycle equivalents based on literature and databases found in the GaBi software package (see Table 13). Fossil fuel inputs (fuels and methanol) are subject to an embedded energy and life cycle efficiency surcharge, where the lower heating value is divided by an efficiency factor to yield a net fossil energy ratio (Pradhan et al., 2011).

Diesel, propane, methanol, and electricity are subject to following efficiencies respectively: 84.3%, 89.8%, 67.7%, and 32.5%. The electricity efficiency factor is clearly significant, dependent upon the fossil fuel used in its generation (Spath, Mann, & Kerr, 1999). The value for coal-based generation is given here as it the predominant power source in the region of study.

Table 13

Life-Cycle Energy Equivalents and GHG emissions factors by Input

INPUT	Life-Cycle Energy Equivalent	units	Reference	GHG emission factor	unit	Reference
Material						
Seed	4.7	MJ/kg	a			
Nitrogen	51.5	MJ/kg	b	6.67	kgCO2-eq/kg	g
Phosphate	9.2	MJ/kg	b	0.393	kgCO2-eq/kg	h
Potash	6.0	MJ/kg	b	0.46	kgCO2-eq/kg	g
Lime	0.1	MJ/kg	c	0.117	kgCO2-eq/kg	h
Herbicides	319.0	MJ/kg	b	5.41	kgCO2-eq/kg	i
Pesticides	325.0	MJ/kg	b	5.41	kgCO2-eq/kg	i
Fungicide	319.0	MJ/kg	b	5.41	kgCO2-eq/kg	i
Methanol	33.5	MJ/kg	d	1.95	kgCO2-eq/kg	j
KOH	1.5	MJ/kg	a	1.19	kgCO2-eq/kg	j
Sulfuric Acid	1.7	MJ/kg	a	1.95	kgCO2-eq/kg	j
Water	0.00036	MJ/kg	h	0.000086	kgCO2-eq/kg	h
Fuel						
Diesel	42.5	MJ/L	a,e	3.67	kgCO2-eq/kg	a
Propane	26.4	MJ/L	a,e	0.307	kgCO2-eq/MJ	h
Electricity	7.4	MJ/kWh	f	0.674	kgCO2-eq/kWh	h

a) (Sheehan, et al., 1998), b) (Hill, Nelson, Tilman, Polasky, & Tiffany, 2006), c) (Graboski, 2002), d) (Wang & Huang, 1999), e) (Huo, et al., 2008), f) (EIA, 2010), g) (Kumar, Singh, Nanoti, & Garg, 2012), h) GaBi: (IKP/PE, 2013), i) (Woods et al., 2008), j) (IPCC, 2006)

5.4 Results and Discussion

LCA results of energy balance and carbon intensity analysis show a large range by feedstock type where UCO clearly benefits from its classification as a secondary-use or waste product. The agriculture step is costly both in terms of energy equivalents and embodied emissions. Removing the agricultural as well as crushing steps transfer UCO feedstock impacts to the conversion step which is significantly affected by implementation of applied industrial ecology.

5.4.1 Energy LCA. The net energy required per unit of biodiesel produced for each of the four feedstocks analyzed is found in Figure 17. Agriculture is the largest factor influencing energy requirements by oilseed. This step accounts for 44%, 32%, and 21% of the net energy inputs for canola, sunflower, and soybeans respectively. The nitrogen fertilizer is the most significant source of embodied energy for the agriculture step especially in canola (a heavy nitrogen feeder) where it accounts for 3/4 of the total agricultural energy input. The energy input for conversion is very similar across all feedstocks accounting for 5.4 MJ/kg, with UCO having a 5% increase due to additional process inputs and unit operations to handle higher FFA and moisture impurities. The conversion step's relative percentage of the total varies from 49% for canola, 58% for sunflower, 63% for soybeans, and 93% for UCO. Crushing energy is relatively minor energy impact for canola (4%) and sunflower (6%), with soybeans at 9% due the slower rates of pressing and the use of heating collars to facilitate oil extraction. Grain and finished fuel transport are also minor impacts accounting for 2-3% of total energy inputs.

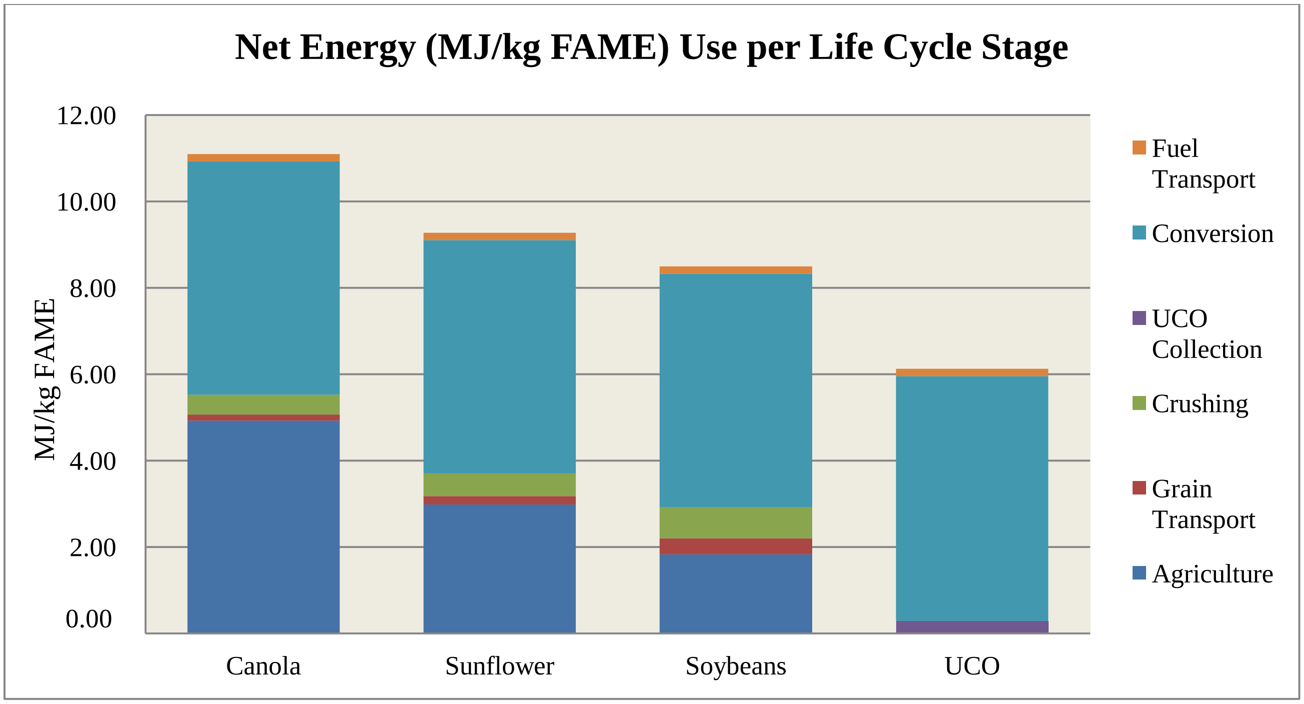

Figure 17. Net Energy Inputs by Feedstock Type.

Net electricity usage is located in the crush and conversion steps. Electricity is of particular concern because of its inherent high life cycle surcharge. For the crush step, electricity use is 0.42, 0.47, and 0.66 MJ/kg FAME for canola, sunflower, and soybeans respectively. Electricity input for crushing is the primary energy input accounting for 88% of the total energy used in this step. For conversion, net electricity use was 2.05 MJ/kg FAME for all feedstocks accounting for 38% of the total for that process step. The balance of energy input for conversion is predominantly methanol. Net electricity usage results in the following percentages of total energy input, canola: 22%, sunflower: 27%, soybeans: 32%, and UCO: 34%.

5.4.1.1 NER & FER Values. Energy ratios are the sum of inputs from all life cycle stages divided by the energy value per unit of resultant fuel. This analysis finds FER ratios to be higher than NER ratios for all feedstocks due to the implementation of industrial ecology system (see Figure 18). Of the oilseed feedstocks, soybeans show the highest potential for both process efficiency and overall renewability, or the greater autonomy from petroleum throughout its lifecycle. Although soybeans contain the least amount of oil, the mass-based allocation methods show greatest favorability by both metrics. This is due in kind to lower relative fertilizer requirements, specifically nitrogen where soybeans benefit from the symbiotic association with nitrogen fixing bacteria. Soybean based biodiesel is the industry standard in the United States with a FER bench mark of 5.54 by Pradhan et al. in 2011. This study shows a 29% improvement upon this benchmark due to the use of non-fossil based electricity on-site (from landfill gas) and non-fossil thermal heat (waste heat recovery). Used cooking oil results in the lowest amount of energy required and also is most impacted by the IE system with a near doubling of FER.

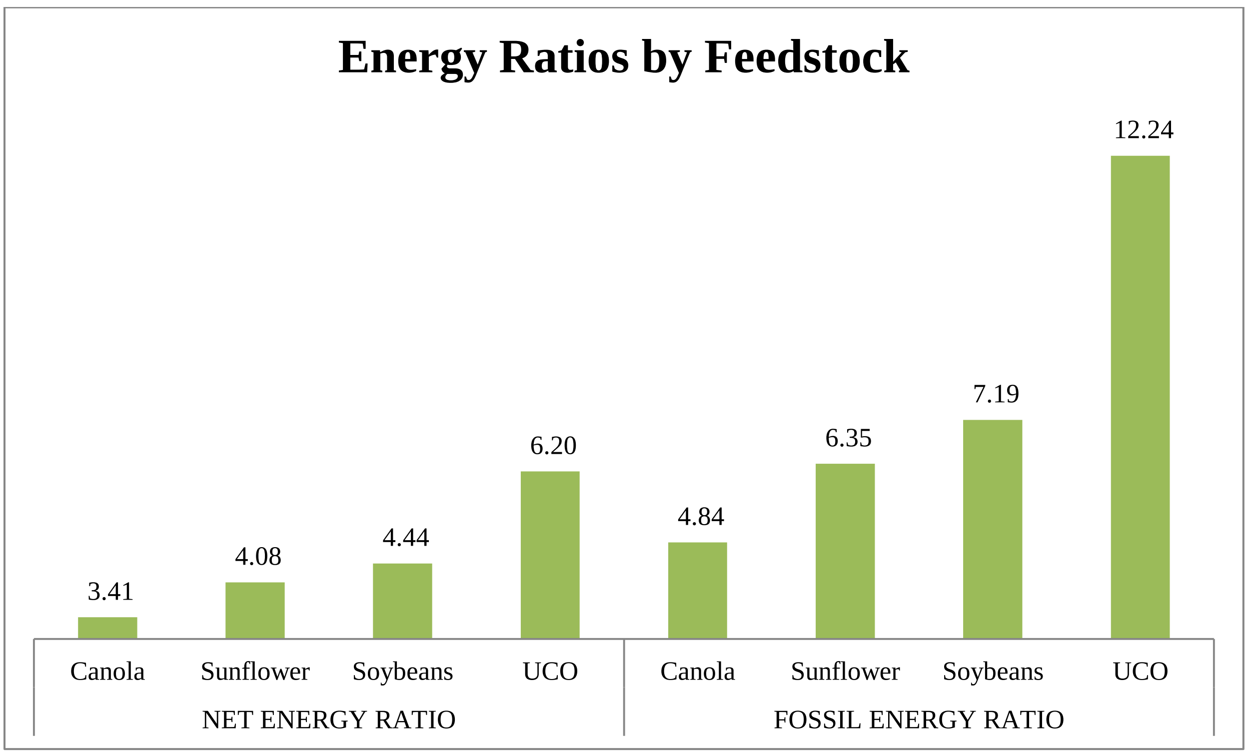

Figure 18. NER and FER by Feedstock Type.

5.4.2 GHG LCA: Carbon Intensity Value. Results of CI values by feedstock are analogous to the energy balances in general trends and the reduced environmental impact moving from canola to UCO feedstocks. The agricultural impact is large from the oilseeds resulting from the production of nitrogen fertilizer and fertilizer induced nitrous oxide soil emissions. Figure 19 compares the feedstocks in the two systems, conventional and industrial ecology with reductions due to aforementioned conditions. The gains made in the IE system are from changes in the crush and conversion steps as agricultural impacts are little affected by change in primary energy.

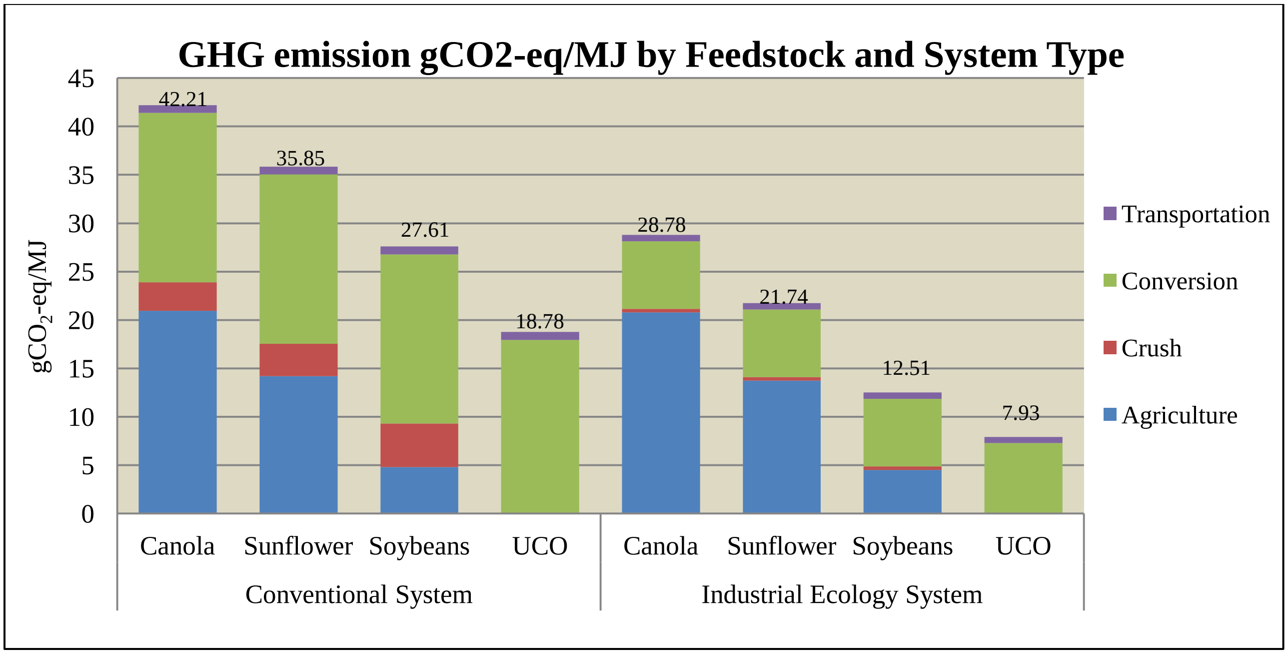

Figure 19. Carbon Intensity values in gCO2-eq/MJ by feedstock and system.

Canola feedstock showed the highest GHG intensity due to the nitrogen fertilizer effect. The crush phase showed significant reduction in the IE system as electricity, the primary input, was discounted from on-site generation. Transportation remains constant across systems with only a small emissions reduction from the use of B20 biodiesel in the IE system. Soybean biodiesel resulted in CI values of 27.6 in the conventional system and 12.5 in the IE system, a reduction of 55%. The literature from CARB (2014) lists Midwestern produced soybean FAME at 21.13, in between the two systems of this study. This may be in part due to higher average yields in for soybean harvest than compared to North Carolina production. All feedstocks achieved an emissions reduction of greater than 50% to comply with US EPA biomass diesel category under RFS2.

5.4.2.1 High Impact Parameters on CI. Primary factors contributing to the CI value are nitrogen fertilizer, methanol, electricity, and thermal energy in conversion. Diesel in transport and KOH catalyst make minor contributions. The balance of all other parameters have a combined range from 1% (UCO both systems) to 11% for soybean (IE system). These high impact parameters outlined in Table 14 provide insight into the impact hierarchy by parameter.

Table 14

Percent of CI Contribution for Each Parameter by Feedstock and System Type

Parameter	Life Cycle Stage	Conventional System				Industrial Ecology System			
		Canola	Sunflower	Soybeans	UCO	Canola	Sunflower	Soybeans	UCO
N-Fertilizer	Ag.	45%	30%	9%	0%	66%	50%	20%	0%
Methanol	Conversion	26%	30%	40%	59%	30%	40%	70%	113%
Electricity	Crush	6%	8%	15%	0%	0%	0%	0%	0%
Electricity	Conversion	8%	9%	12%	19%	0%	0%	0%	0%
Thermal	Conversion	6%	7%	9%	14%	-9%	-12%	-20%	-33%
Diesel	Transport	4%	9%	8%	4%	5%	11%	14%	8%
KOH	Conversion	2%	2%	2%	4%	2%	3%	5%	8%

5.4.2.2 Nitrogen Fertilizer and Methanol Recycle Sensitivities. Nitrogen fertilizer contributes to CI of oilseed feedstocks through direct emissions from manufacturing inputs and transportation of finished materials as well as from soil emissions that release nitrous oxides after application on crops. Figure 20 illustrates the sensitivity of carbon intensity by changes in the application of nitrogen fertilizers. Canola has the greatest response where a 10% reduction of fertilizer use translates into the lowering of CI value by 1.89 or 2%. Soybeans are the least responsive to change with sunflower showing a moderate response. These results are intuitive in relation to the fertilizer inputs for each oilseed.

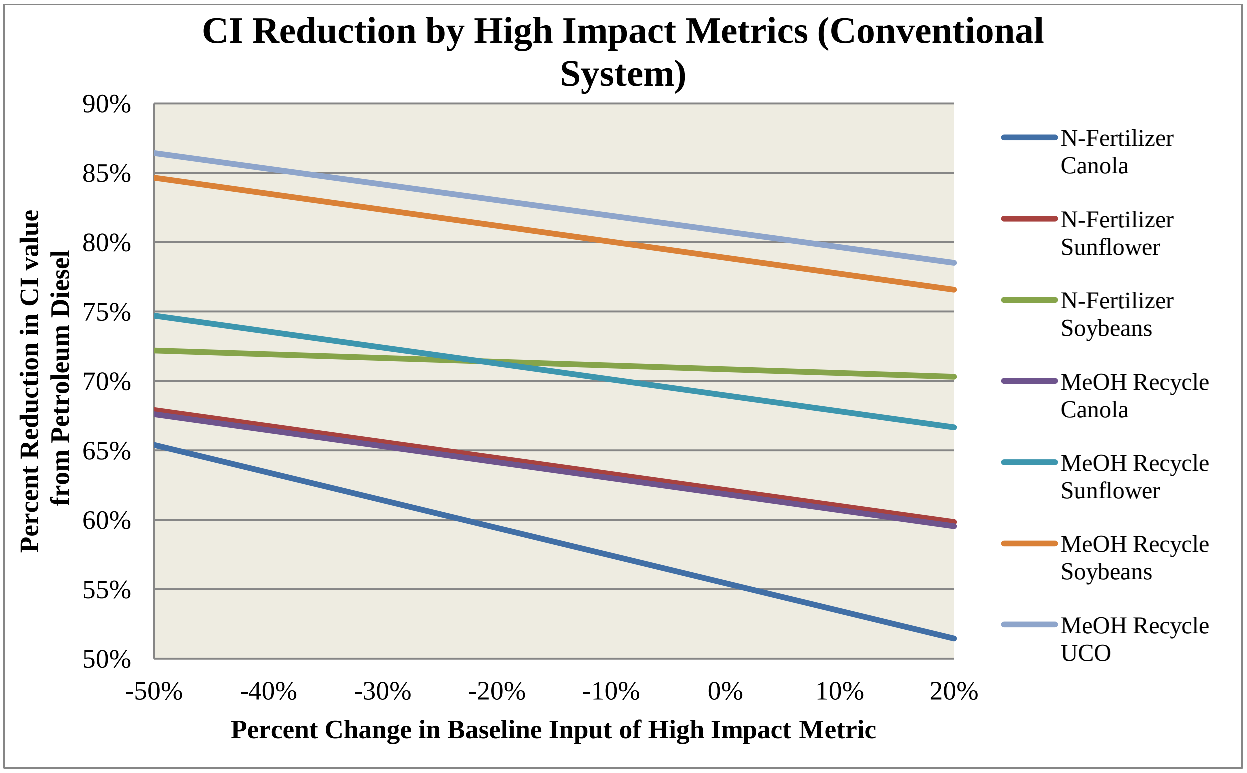

Figure 20. Sensitivity of CI reduction to changes in baseline value of High Impact Metrics.

The ability to reduce fertilizers without significantly affecting yield is dependent on soil type and fertility, land use history, climate, and numerous site specific variables. Crop yields are directly affected by nutrient availability and recommendations have generally quantified applications so that fertilizers are not the limiting factor for plant growth. Reducing fertilizer input may result in the lowering of CI value for the resultant biofuel; however the lower crop yield would also produce a higher indirect land-use effect. Integrated farming or low-input systems that practice minimal tillage and balanced crop rotation is one tool for addressing fertilizer reductions (Alluvione et al., 2011). Additionally, the raw organic materials delivered daily to the EcoComplex as municipal solid waste could be separated to provide compost or digester feedstocks that products include fertilizers and soil amendments. Emissions from these processes require further analysis but would arguably produce lower emissions as their primary input materials are considered waste.

Methanol is a primary reactant in the conversion step, added in excess of stoichiometric requirements to ensure complete reaction and a reduced reaction time. A doubling of the consumed methanol is a well-established baseline for biodiesel conversion. This means that the excess methanol, distributed between biodiesel and glycerol phases, is available and can be recovered. Implementing a 10% recycle and reuse of this costly environmental input result in a reduction of the CI value by 1.1 for the oilseed feedstocks and 1.07 for UCO feedstock.

5.4.2.3 ILUC Effect on CI Value. While models for quantifying the effect of indirect land-use change are in a nascent stage of development, the overwhelming voice of the scientific community has insisted that ILUC be considered in policy making decisions. Crop, country where grown, type of biofuel, market for crop and biofuel, and time accounting period are all significant factors that determine ILUC value. The US EPA Renewable Fuel Standard 2 program has published an ILUC value for soybean biodiesel of 32 gCO_2-eq/MJ (EPA, 2010). This value does not currently enter into pathway determination, the process of deciding which fuels are capable of receiving subsidies, but has been offered to show the agency's commitment to address this specific concern. Figure 21 shows EPA's ILUC value added to the direct emissions baseline for each oilseed crop. UCO-based biodiesel is unaffected by land use considerations.

All oilseed crops still fall below the petroleum diesel CI value however the percent reduction from this baseline is significantly affected. Soybean-based biodiesel manufactured within the IE system (53% reduction) is the only oilseed-based biodiesel to meet the 50% emission reduction target that is mandated by RFS2 for the biomass-diesel classification, further illustrated in Figure 22. It is this level of scrutiny that may have large implications in the direction and development of future biofuel policies. This topic is especially salient considering that EPA has tended to downplay the potential impact of ILUC on biofuels emissions compared to other agencies such CARB and the European Commission's Renewable Energy Directive.

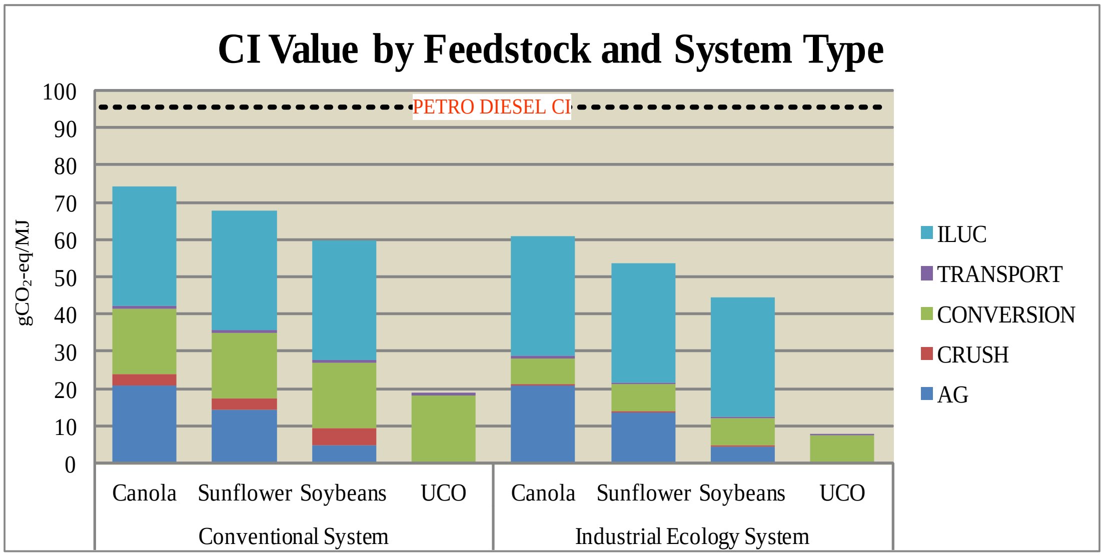

Figure 21. CI Values by Feedstock and System Type with the inclusion of ILUC.

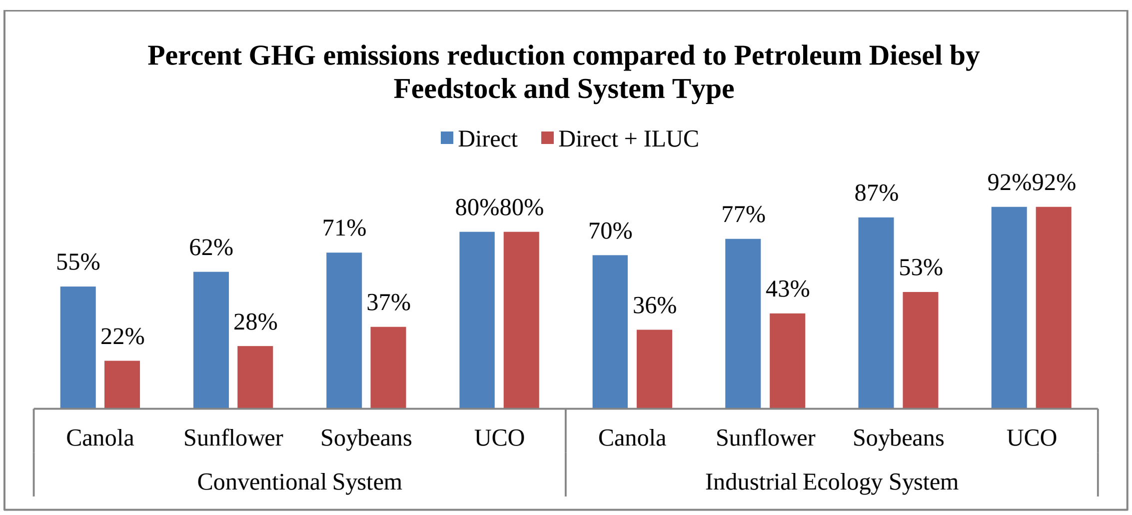

Figure 22. Carbon Intensity Comparison with ILUC across feedstocks and system types.

5.5 Conclusion

The energy and GHG LCA provides a straightforward perspective on the associated environmental impacts of each life cycle stage for the feedstocks presented in both conventional and IE system frameworks. Clearly, UCO-based biodiesel is the most environmentally benign, with a net energy balance of 6.20 and fossil energy balance of 12.24. UCO achieves a reduction in carbon intensity of 80% compared to petroleum diesel fuel in the conventional system and 92% reduction when ascribed to the conditions of the IE system employed at the Catawba County EcoComplex. Soybean-based biodiesel poses the least environmental impact of the oilseed feedstocks, primarily due to the fact that soybeans require minimal nitrogen fertilizer compared to other oilseed crops. Soybeans produced an NER of 4.44, an FER of 7.19 and CI reductions of 71% and 87% for conventional and IE systems respectively. Comparing UCO and soybean GHG results, there is an interesting counter intuitive cross-over where producing biodiesel from soybeans within the IE system is more environmentally advantageous than producing UCO-biodiesel in a conventional system.

LCA is also a powerful tool in quantifying high impact parameters by feedstock type and system. The highest impact areas are nitrogen fertilizers, methanol use, electricity, and thermal process heat. Each of these areas can be mitigated through applied industry ecology.

5.5.1 Recommendations.

5.5.1.1 Agriculture & Feedstock Production. Reducing the amount of fossil-derived nitrogen fertilizer applied should be the top priority for the production of canola and sunflower crops. It should be noted that fertilizer uptake by plants is highly variable. This can be achieved through a combination of integrated farming practices and local recycling of organic waste materials through composting and anaerobic digestion. The latter requires separation of organics and capital investment to make value added products. The price of these biogenic fertilizers may be cost prohibitive under current conditions. Indirect land-use change is a real phenomenon under intensive scientific review in the field of climate change research. Traditional non-agronomic lands that do not impart this heavy environmental burden must be considered. Potential lands include, municipal buffer lands, spray and brown fields, utility and highway right-of-ways. The Freeway to Fuels Program at Utah State University estimates that 10 million acres of non-agricultural lands (4.05 million hectares) suitable for transportation fuel feedstock exist in the United States (Hanks, 2013). Though perennial cellulosic feedstocks may be better suited and more practical options, these lands will be become increasingly attractive when confronted by effects of land-use change.

5.5.1.2 Conversion: Methanol Recovery. Methanol is a costly component of the CI value and can be recycled and reused with recovery systems at the conversion step. This is particularly important in addressing the crude glycerol phase where the majority of excess methanol is contained. Methanol recovery is process energy intensive and the source of heating and cooling energy inputs should be considered with the goal of improving LCA outcomes.

5.5.1.3 Renewable Energy Integrated Production Facilities**.** Incorporating renewable energy in the manufacturing process itself benefits both energy and GHG aspects of the LCA. By reducing the subsidy of fossil energy through crush and conversion steps, the overall biofuel process is more robust and has a significantly better energy balance that is more competitive with conventional petroleum diesel. Using off-spec fuel or feedstock oil is common in biodiesel facilities and is a biogenic source of process heating. Solar thermal or waste heat is even more advantageous in CI accounting. Finally electricity production from on-site generators or photovoltaics where viable is has significant effects on LCA outcomes and addresses the inefficiency issue of electricity, in particular coal-based electricity.

5.5.1.4 Producer Specific LCAs. Due to the multitude of site induced variables that effects LCA, it is plausible to think in terms of producer specific assessments based on feedstock, technology, and on-site factors. Specific energy balances and GHG emissions may help a biofuel producer to distinguish their product in the marketplace. Third party certification companies such as Roundtable for Sustainable Biomaterials have entered into this space to rate biomaterials on their promise of improved sustainability (RSB, 2014). Their services evaluate products, supply chains, and create certification for individual producers. As GHG emission LCAs on the producer level may become common and offer economic advantages.

CHAPTER 6

Economic Analysis of the EcoComplex Civic-Scale Farm to Fuel Biodiesel Plant[2]

6.1 Abstract

Biofuels manufacturing integrates numerous sectors (agriculture, transport logistics, recycled and waste materials, and processing plants) that hold the promise of economic development, especially in rural agricultural and former manufacturing areas. While the concentration of biodiesel production began in the North American Midwest, diverse scales have developed based on regional feedstocks. This chapter addresses a gap in economic analysis of civic-scale biodiesel production, whereby a local municipality leads the development a renewable fuel project to support local farmers, hedge against high petroleum prices, value independence, and diversify their energy mix.

This chapter uses budgeting analysis to examine the economics of operating an integrated oilseed crush and biodiesel plant, with fuel production capacity of 490,000 liters per year. This plant is part of the Catawba County North Carolina EcoComplex, a municipal government led eco-industrial park based on synergetic waste management and biomass to energy projects. The corn-canola-soybean-fallow rotation is found to be the most profitable crop rotation for oilseed production. Due to the high value of protein meal, soybeans showed the greatest sensitivity to increased crush capacity, though not viable as a biodiesel feedstock at 12 tons/day. Current operating conditions result in a biodiesel conversion cost of $1.43 per liter of fuel produced using least valuable commodity feedstock, yellow grease. Break-even requires a subsidy of $0.58 per liter to bring down the net biodiesel cost, matching the avoided cost of

[2] Parts of this chapter were adapted from: Ferrell, J. (2013). Economic Analysis of a Civic-Scale Farm to Fuel Biodiesel Plant, a case study of the Catawba NC EcoComplex. *Biomass and Bioenergy.* (Submitted).

petroleum diesel. As subsidies continue significant fluctuation, metrics other than operating costs are required to justify civic-scale biofuel projects.

6.2 Introduction

The US biodiesel industry has evolved in the North American Midwest as a means to provide additional markets for soybean oil (Demirbas, 2007). The average plant size in Iowa, the biodiesel industry's top producing state, has a capacity of 95 million liters per year (NBB, 2013b). The North Carolina biodiesel industry in contrast, has been built on using lower quality feedstocks such as animal tallow and used cooking oils collected from restaurants. The average biodiesel plant in North Carolina produces 1.1 million liters per year (Smit, 2013). Feedstock availability and cost, up to 88% of total estimated production costs have driven many NC biodiesel producers to develop oil rendering capabilities (Haas, McAloon, Yee, & Foglia, 2006). Blue Ridge Biofuels, an Asheville NC biodiesel company, collects used cooking oil from over 500 restaurants helping to control feedstock costs, scale production to available feedstock supply, and reduce the impact of fluctuating commodity markets (Eaton, 2013).

There are large-scale oilseed processing plants in North Carolina's industrial agriculture zone but the costs of these refined, bleached and deodorized vegetable oils, are typically out of reach for smaller scale biodiesel plants (Morrone, Stuart, McHenry, & Buckley, 2009). There are few known and documented examples of civic-scale or small-scale integrated oilseed crush and biodiesel production facilities. Civic-scale is considered small-scale, however with leadership from local government that develops a renewable fuel project to support local farmers, hedge against high petroleum prices, value independence, diversify their energy mix, and provide outreach and educational opportunities.

Bender (1999) concluded during early development of the biodiesel industry in the United States and Europe that community-scale farmer cooperatives for biodiesel were only profitable with government subsidies and that using waste oil feedstocks resulted in lower production costs. There are current examples of small-scale farm-to-fuel operations where farmers grow and process oilseed crops to produce biodiesel for on-farm use, though not analyzed for economic viability. Small-scale and farm-scale biofuels projects have been presented as a positive contributor to renewable energy production and rural development, as well as an exception to allow for conversion of first generation feedstocks to biofuels (Grau, Bernat, Antoni, Jordi-Roger, & Rita, 2010; Han, Mol, Lu, & Zhang, 2008).

The objective of this chapter is to examine the economic viability of operating a small-scale integrated oilseed crush and biodiesel plant under current conditions, and address pathways and technologies going forward to improve viability.

6.2.1 Catawba County NC EcoComplex. The Catawba County EcoComplex and Resource Recovery Facility is an ecological-industrial park (EIP) whose mission is synergistic waste and resource management, renewable energy production, and local economic development through public and private partnerships working in close geographic proximity (Mackie, 2007). The EcoComplex is an 326 hectare acre site centered on the Blackburn Landfill with 2.0 million metric tons of waste in place and serves the 156,000 county residents (B. Edwards, 2009, 2010). The site hosts a grid-tied 3MW landfill gas to energy (LFGTE) facility using three GE-Jenbacher spark-ignition engines, an oilseed crush facility and a biodiesel research and production facility operated by Appalachian State University. Biodiesel production is vertically integrated at the EcoComplex in three ways 1) by utilizing 61 hectares of on-site buffer lands to grow high yielding oilseed crops for biodiesel feedstock 2) by incorporating waste heat recovery from the

LFGTE facility for process and building heat of the biodiesel facility and 3) by providing biodiesel fuel for on-site landfill operations. Initial funding for the biodiesel and crush facilities were provided through grants and landfill post-closure funds.

The EcoComplex civic model of distributed renewable energy production represents a new scale for biofuel manufacturing. While this model offers many benefits to local municipalities as a potential fuel source for basic services (waste management, police and safety, infrastructure repair), the overall economic viability of such an integrated system is uncertain. The scale offered by these facilities, though sufficient to supply the biofuel blend needs at the Catawba EcoComplex and surrounding areas, is still only a fraction of the capacity found in most established industrial plants (Y. Zhang, Dube, McLean, & Kates, 2003b).

The rest of the chapter is organized as follows. The materials and methods section outlines the three operations of the farm to fuel project: farming, crushing, and conversion. An economic model is constructed for each operation based on data from start-up plant operations and agricultural and commodities markets. The effect of current subsidies on conversion costs is also located here. Sensitivity analyses of crop yield, crop rotation, crush metrics, and conversion metrics are included in the results section. The discussion section concludes by addressing the influence of subsidies, and future trends and technologies.

6.3 Materials and Methods

The first step in economic analysis is to separate the three distinct operations that are vertically integrated at the Catawba County EcoComplex. The supply chain of raw materials from farming to crushing, and finally to biodiesel conversion is closely managed to optimize transportation logistics via geographic proximity. However, the biodiesel feedstocks as well as products of farming and crushing (oilseeds, vegetable oil, and meal) are commodities that can enter or leave the system via local markets at any point. Isolating each operation allowed for standalone analysis of economic viability. Models of the EcoComplex farming, crushing and conversion were created for the purpose of making projections and to be used in decision making to choose an optimal portfolio of feedstocks. Each model evaluates the profits, which are equal to revenues minus costs, given the current technology and year 2013 prices. The integration of the three models also allows for the assessment of the EcoComplex profitability.

Figure 23 depicts suitable feedstocks for biodiesel production and their flow through the crop processing and biodiesel facilities located at the Catawba County EcoComplex. The diamonds indicate a decision where a material can flow one of two ways. Farmed oilseed crops can move to the Crush Facility or can be sold to the grain market. Vegetable oil produced in the Crush Facility can move to the Biodiesel Facility or be sold to the food-grade vegetable oil market.

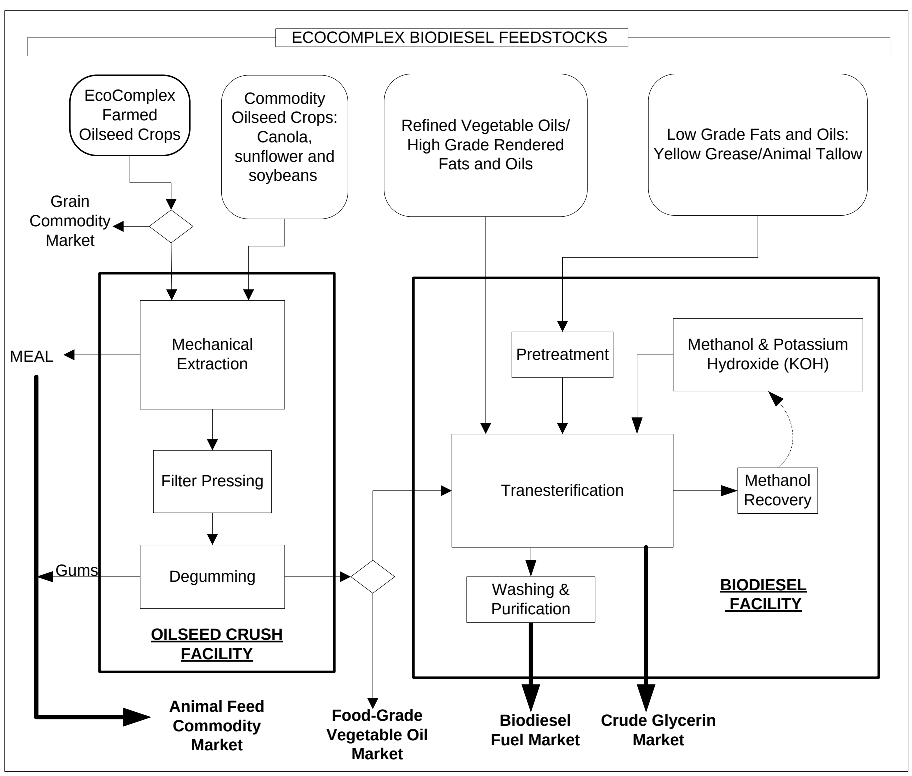

Figure 23. Material flow for biodiesel production process.

6.3.1 Farming & Agronomics for EcoComplex Oilseed Crops. The 61 hectares of agricultural buffer land surrounding the landfill are the starting point for biodiesel feedstock. Farming operations of this buffer land are managed by Catawba County to produce oilseed and commodity crops. This land has historically been planted using two conventional crop rotations for the piedmont of North Carolina (a) corn-wheat-soy-fallow, and (b) soy-wheat. To optimize for oilseed production, canola can be substituted for wheat in the conventional rotation to produce a third rotation: (c) corn-canola-soy-fallow.

A fourth rotation was developed in conjunction with local cooperative agriculture extension agents to include high yielding oilseed crops (canola and sunflower). This rotation also introduces a winter cover crop to promote soil fertility and weed control, increases time between canola plantings to reduce pathogens, and allows sufficient planting and harvesting windows suited to the agricultural calendar for the piedmont of North Carolina. Table 15 lists vegetable oil and meal yields by rotation assuming average yields under best farming practices and an extraction efficiency of 75% of total oil (USDA, 2013)

Table 15

Vegetable Oil and Meal Yields by Rotation

Rotation	**Average Vegetable Oil liters/hectare/year *(gallons/acre/year)***	**Average Oilseed Meal kg/hectare/year *(Lbs/acre/year)***
1) Corn-Wheat-Soybeans-Fallow	178 *(19)*	1067 *(950)*
2) Soy-Wheat	355 *(38)*	2133 *(1900)*
3) Corn-Canola-Soy-Fallow	617 *(66)*	1976 *(1760)*
4) Soybeans-Winter Cover Crop-Sunflower-Wheat-Corn-Canola	580 *(62)*	1671 *(1488)*

Figure 24 depicts this fourth potential crop rotation that occurs over three years, transitioning from winter canola, to summer soybeans in year one, winter cover crop of rye and vetch to summer sunflower in year two, and finally winter wheat to summer corn in year three. One hectare over this three-year period can be expected to produce 1740 liters of vegetable oil, 2.0 tons of protein meal, commodity crops for sale (wheat and corn), and residual stover. This production estimate is based on average yields under best farming practices with mechanical extrusion crush technology. These four crop rotations are analyzed in the model.

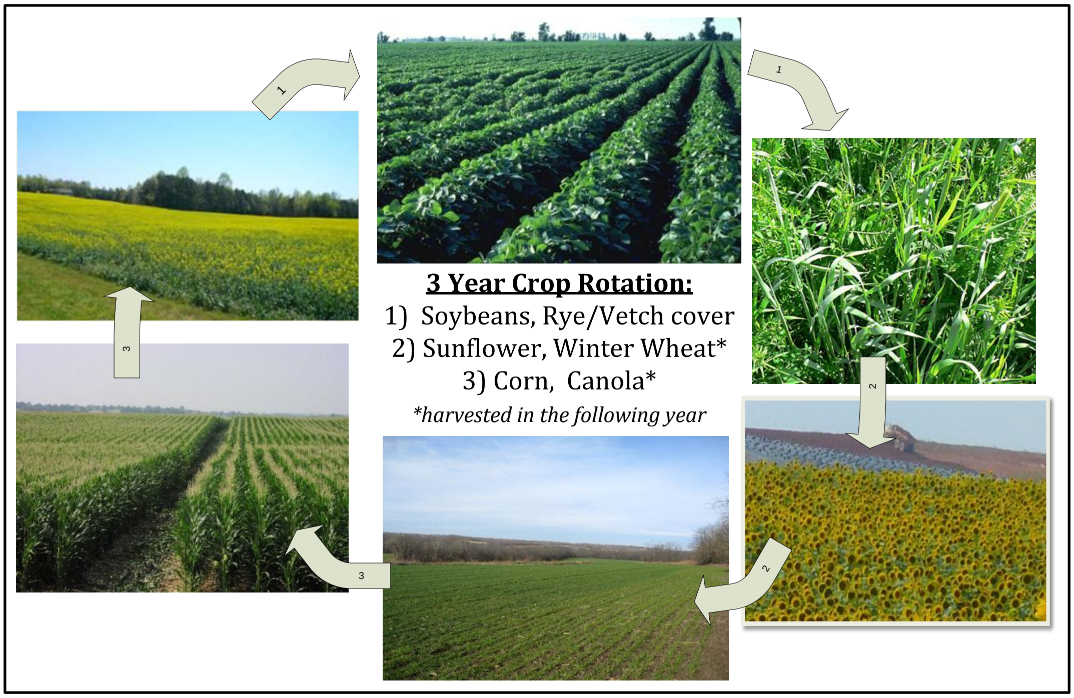

Figure 24. Proposed 3-Year Crop Rotation.

Data used for the agronomic modeling consists of enterprise budgets for each crop that includes all farming costs on a per hectare basis, yields based on averages for the region of study, and commodity value by crop. The winter cover crop is used as a soil builder and is not harvested. Cover crops are incorporated into the soil to add organic material, sequester carbon, and improve fertility over time.

Table 16

Agronomic Data

Crop	Farming Cost/ Ha *(Acre)*	Estimated Yield kg/ ha[15] (*bu/ac*)	Commodity Price $/ kg (*$/bu*)
Canola	$736.00 [a] (*298.00*)	2807 (*50*)	$0.55 [a] (*12.50*)
Soybeans	$671.00 [b] (*272.00*)	2695 (*40*)	$0.50 [c] (*13.75*)
Winter Cover Crop	$371.00 [b] (*150.00*)	n/a	n/a
Sunflower	$622.00 [d] (*252.00*)	1661 (*51*)	$0.43 [d] (*5.66*)
Wheat	$581.00 [b] (*235.10*)	3705 (*55*)	$0.18 [e] (*5.01*)
Corn	$865.00 [b] (*350.00*)	6287 (*100*)	$0.19 [e] (*4.92*)

a: (George, et al., 2008; PennState, 2011), b: (NCSU, 2012), c: (PFL, 2013), d: (UNL, 2013), e: (NCDA, 2013a)

6.3.2 Crop Processing, Crushing, and Conversion Crushing Costs.

6.3.2.1 Crop Processing and Crush Facility. This facility is designed to receive, clean, dry, store, and press oilseed crops. Once oilseeds have reached the dry storage silo, they are transferred by auger to a bank of four Kern Kraft (KK40) mechanical extrusion presses working in parallel with combined capacity of 4 tons/day. Each press is rated at 40 kg/hour, or approximately one ton per day run in continuous fashion.

6.3.2.2 Oil and Meal Production. Each oilseed has an inherent percentage of extractable oil. Total oil content by weight has been widely reported for the following crops: canola 40-45%, oilseed sunflower 30-35%, and soybean at 18-22% (USDA, 2013). The limits to practical oil extraction using mechanical extruders varies by equipment, but has a general maximum, approximately 90% of total oil, while the remainder is bound in the meal fraction. Based on using KK40 cold pressing equipment, the following extractable oil contents (weight of oil /weight of seed) have been determined experimentally: canola at 28%, sunflower at 20%, and soybeans at 10.5%. The balance is considered grain meal, which has a typical base commodity value as an animal feed protein source. Oilseed meal is blended with other grains to produce a feed ration with desired protein, fat, carbohydrate content. Oilseed meal is a valued protein source, particularly soybean meal with 44% to 48% protein concentration, which accounts for 63% of all protein sources used in animal feeds in the U.S. (Cromwell, 1999). Since there are no established commodity markets for canola and sunflower meal in North Carolina, values have been calculated based on their protein as a ratio of the protein content of soybean meal, the feed industry standard as illustrated in Table 17. Meal samples of canola, sunflower, and soy were sent to the North Carolina Department of Agriculture for analysis, including protein concentration (NCDA, 2013a).

Table 17

Determination of Meal Value Based on Protein Concentration

Meal Type	**% Protein by mass**	**Commodity Value of Protein Meal per kg (*$/lb*)**
Soybean	48%	$0.55 (PFL, 2013) (*0.25*)
Canola	30%	$0.35 (*0.35*)
Sunflower	22%	$0.26 (*0.12*)

6.3.2.3 Crushing Costs. Table 18 lists the crushing costs associated with the three oilseeds considered on a per liter and per kilogram basis, the latter can be used for direct comparisons to commodity pricing. These costs are observed costs based on utility bills and labor during initial crush operations.

Table 18

Crush Facility Oil Costs by Oilseed

Oilseed	**Canola**	**Sunflower**	**Soybean**
Land Area Ha (*Ac*)	455 (*1124*)	559 (*1382*)	298 (*736*)
Oil Production liters/year (*gal/yr*)	395,660 (*104,533*)	282,615 (*74,667*)	111,279 (*29,400*)
Costs	Cost per liter oil ($/gallon)	Cost per liter oil ($/gallon)	Cost per liter oil ($/gallon)
Feedstock (oilseeds)	$1.79 (6.79)	$1.95 (7.41)	$4.38 (16.59)
Variable	$0.05 (0.20)	$0.09 (0.37)	$0.22 (0.85)
Fixed	$0.21 (0.80)	$0.29 (1.11)	$0.75 (2.83)
Total	$2.05 (7.78)	$2.35 (8.89)	$5.36 (20.27)
Revenue (meal)	$0.75 (2.84)	$0.86 (3.28)	$4.04 (15.29)
Total Cost	$1.31 (4.94)	$1.48 (5.61)	$1.31 (4.97)
Oil Cost per kg ($/lb)	$1.43 (0.65)	$1.63 (0.74)	$1.45 (0.66)

Feedstock costs are calculated by dividing the weight of one liter of oil by the oil extraction efficiency, and then multiplied by the commodity value per given weight. Variable costs include filter aid used in the filter pressing step at $0.0023/l, propane used for seed drying at $0.0026/l and electricity at $0.12/kWh for grain handling, pressing, and degumming operations (motors, discharge augers, air compressor, process heat, and lighting). Electricity cost is estimated at $6.50 per day ($0.048 per liter oil) for each press in continuous operation for canola and sunflower. Soybeans required additional electricity due to electric heating collars that elevate seed crush temperature and facilitate higher extraction efficiencies. Fixed costs include labor, building rent, and equipment maintenance which are summed together and divided by the oil production in gallons per year. Labor is for one full-time operator/general facility manager ($25/hr including fringe benefits) which covers supervision of crush and degumming operations and material handling of seed, oil, and meal and one half-time operator assistant at $15/hr. Building rent is estimated at $12,000 per year. Insurance is $2,062 per year, calculated at 0.5% of capital costs (Haas et al., 2006). Capital costs for all process equipment, which includes presses, degumming skid, filter press, pumps, seed cleaners, silos, dryer, augers, hopper bins, and dump truck, totals $412,500. Equipment maintenance is $4,125 per year, calculated at 1% of total capital costs. Revenue is the weight of oilseed meal produced per liter of oil, multiplied by the its commodity value in $/weight. Total cost is the revenue minus the total of feedstock, variable and fixed costs. Oil cost per kilogram is the total cost divided by 0.913 kg, the average weight of one liter of vegetable oil. Oil production is calculated by operating the crush facility at full capacity, 350 days per year, with a crush capacity of 4 tons per day, where soybeans operate at 75% of crush capacity due to observed slower pressing speeds.

6.3.2.4 Biodiesel Conversion Costs. The Biodiesel Facility is capable of converting a variety of fats and oils into fuel. In addition to the vegetable oil derived from on-site farming and pressing operations, there are several other suitable commodity options including lower quality feedstocks: yellow grease and rendered tallow, and higher quality feedstocks: RBD vegetable oils, and high grade rendered fats and oils. In general the less expensive, lower quality feedstocks have greater impurities that reduce conversion yield and increase processing costs for base-catalyzed transesterification (Knothe et al., 2005).

Table 19 lists conversion costs based on three common commodity biodiesel feedstocks from cheapest- lowest quality to most expensive-highest quality. Conversion yield is a percentage of starting feedstock that is converted into biodiesel and is directly affected by impurities such as moisture, sediments, and free fatty acids that once reacted become soaps to further reduce yield and increase purification costs. Conversion yields are estimates based on start-up production and are consistent with published literature. Feedstock cost is calculated multiplying the commodity value by the feedstock oil density (0.89 kg/l yellow grease, 0.90 kg/l choice white grease, and .91 kg/l RBD soy), then divided by the conversion yield. Variable costs include direct material inputs. Methanol and potassium hydroxide are primary reactants and are purchased as commodities with current pricing of $0.53/l and $1.94/kg respectively (Chemsolv, 2012). Methanol is used at a ratio of 22% by volume of feedstock oil (J.V. Gerpen et al., 2006). Potassium hydroxide is used at approximately a ratio of 20.42 grams per liter of feedstock oil (Y. Zhang et al., 2003a). Operating supplies include ion exchange resins and oxidative stabilizer, both at a cost of $0.0079 per liter. Lab expendables for in-house testing contribute $0.0053/liter. Electricity for motors, air compressor, lighting, and general building consumption contribute $0.06 per liter based on a utility cost of $0.11/kWh. Process heat is provided via a waste heat recovery system from the adjacent landfill gas generator and is accounted for in electricity usage for pumping energy. Fixed costs include labor, building rent, insurance, equipment maintenance, fuel quality testing, and RIN (renewable identification number) compliance which are summed together and divided by the biodiesel production in gallons per year. Labor includes two full-time positions, general manager at $30/hr and production manager $25/hr including fringe, one half-time lab manager at $20/hr, and one 1/4 time intern at $12.50/hr. Building rent is $12,000 per year. Insurance is $1,500 per year, at 0.5% of capital costs. Equipment maintenance is $3,000 per year, at 1% of capital cost. Fuel quality testing, to ensure ASTM specifications, is estimated at $4,500 per year and RIN compliance is estimated at $3,500 per year. Revenue is the sale of crude glycerin or glycerin bottoms, produced at a rate of 0.24 kilograms per liter biodiesel

(Knothe et al., 2005). Glycerin value is a function of its composition with current pricing between $0.09-$0.13 per kilogram. Total cost is the revenue minus the sum of feedstock, variable, and fixed costs. All costs were observed from plant start-up operations and have been extrapolated to the plant operating at capacity.

This facility operates using a base-catalyzed transesterification process with batch size of 1,960 liters of finished fuel, whereby plant operators working one 40 hour per week shift, process 5 batches per week, 50 weeks per year. Conversion costs are based on the output of 490,000 liters of biodiesel per year.

Table 19

Conversion Costs by Commodity Feedstock

Commodity Feedstock	**Yellow Grease**	**White Grease**	**RBD Soy**
Oil Cost per kg[(PFL, 2013)] **(*$/lb*)**	$0.75 (*0.34*)	$0.86 (*0.39*)	$0.99 (*0.45*)
Conversion Yield	80%	85%	90%
Costs	Cost per liter of biodiesel (*$/gal*)		
Feedstock	$0.83 (*3.16*)	$0.91 (*3.44*)	$0.96 (*3.63*)
Variable	$0.28 (*1.06*)	$0.27 (*1.01*)	$0.26 (*0.97*)
Fixed	$0.34 (*1.29*)	$0.34 (*1.29*)	$0.34 (*1.29*)
Total	$1.46 (*5.51*)	$1.52 (*5.74*)	$1.56 (*5.89*)
Revenue (Glycerin)	$0.02 (*0.08*)	$0.02 (*0.10*)	$0.03 (*0.12*)
Total Conversion Cost	$1.43 (*5.43*)	$1.49 (*5.64*)	$1.52 (*5.77*)

6.3.2.5 Subsidies and Conversion Cost Summary. At present there are two subsidies that allow for competitive biodiesel manufacturing in the United States. The first is the Federal Fuel Tax Credit, a production tax credit valued at $1.00 per gallon ($3.79/liter) of biodiesel produced.

This tax credit was valid for 2013, approved during the passage of the American Taxpayer Relief Act of 2012 and housed under the Internal Revenue Service (Congress, 2012; EPA, 2013).

The second is the RIN Credit (Renewable Identification Number) defined by the Environmental Protection Agency's RFS2 Program (Renewable Fuel Standard). The associated biodiesel RIN is classified D4, biomass-based diesel RIN, and is valued at 1.5 RINs by volume (EPA, 2013). At the time of this writing the D4 RIN is worth $0.32 for each liter of biodiesel (PFL, 2013).

Table 20 summarizes the conversion costs for the three commodity feedstocks above with the same production capacity. Net conversion cost is the total cost plus the RIN and fuel tax credit subsidies. The fuel tax credit is not available to government entities but may be accessible by purchasing petroleum diesel through obligated parties that can utilize the tax credit and transfer savings to the purchased diesel fuel. Diesel bulk cost is the cost to Catawba County in purchasing petroleum diesel fuel in bulk without road taxes. Net profit is the difference between diesel bulk cost and net conversion cost, or the bottom line of all factors that influence conversion costs.

Table 20

Conversion Cost Summary including Subsidies

Commodity Feedstock	**Yellow Grease**	**White Grease**	**RBD Soy**
	Values per liter of biodiesel ($/gal)		
Total Conversion Cost	$1.43 (*5.43*)	$1.49 (*5.64*)	$1.52 (*5.77*)
RIN	$0.31 (*1.20*)	$0.31 (*1.20*)	$0.31 (*1.20*)
Fuel Tax Credit	$0.26 (*1.00*)	$0.26 (*1.00*)	$0.26 (*1.00*)
Net Conversion Cost	$0.85 (*3.23*)	$0.91 (*3.44*)	$0.94 (*3.57*)
Diesel Bulk Cost	$0.86 (*3.25*)	$0.86 (*3.25*)	$0.86 (*3.25*)
Net Profit	$0.005 (*0.02*)	$-0.05 (-*0.19*)	$-0.08 (-*0.32*)

6.4 Results

Standalone analysis of each operation indicates that crushing and conversion are not optimized under current conditions to create an economically viable integrated system. With the goal of producing biofuels, it would be most economical to sell all crops and buy the cheapest biodiesel feedstock, yellow grease, whereby the sale of grain subsidizes the biodiesel conversion process. The following sensitivity analyses of farming, crushing, and conversion look at key variables to determine optimal viability scenarios.

6.4.1 Net Farming Profit vs. Crop Rotation. This scenario compares the four proposed crop rotations on an annual basis whereby net farming profit is equal to the commodity grain value minus the farming costs, assuming average yields per Table 15. This is the farmer perspective that addresses the best way to utilize farm land, or buffer land in the case of the EcoComplex. Figure 25 shows rotation 3, corn-canola-soy-fallow to be the optimal rotation with averaged annual profit at $151.05 per hectare. This rotation is also the highest vegetable oil producer at 617 liters per hectare per year. Canola currently enjoys a high commodity price and helps to drive the overall profit of rotation 3. The 3-year oilseed rotation, rotation 4, shows the lowest net profit largely due to the addition of a winter cover crop with a farming cost of $60.70 per hectare. There is no harvest associated with this cover crop, as its sole purpose is to provide soil coverage and prevent erosion, fix nitrogen, and increase organic soil carbon.

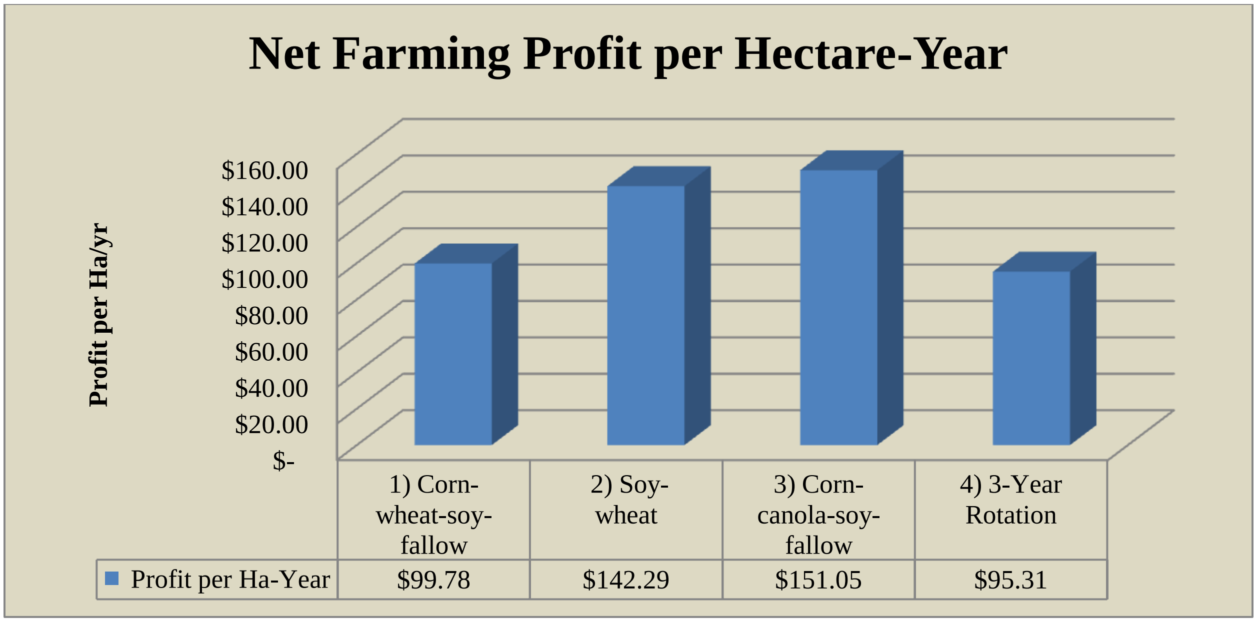

Figure 25. Net Farming Profit vs. Crop Rotation.

6.4.2 Sensitivity of Net Farming Profit to Yield. This analysis examines yield, the principal farming variable, across all the crops listed in the proposed rotations. Net farming profit is the estimated yield multiplied by yield factor, by grain commodity minus the farming cost (referred to in Table 16). Yield represents one of the largest farming risks accounting for soil fertility, pricing of key inputs such as fertilizer, lime, spray, and general knowledge of planting, management, and harvest for each crop.

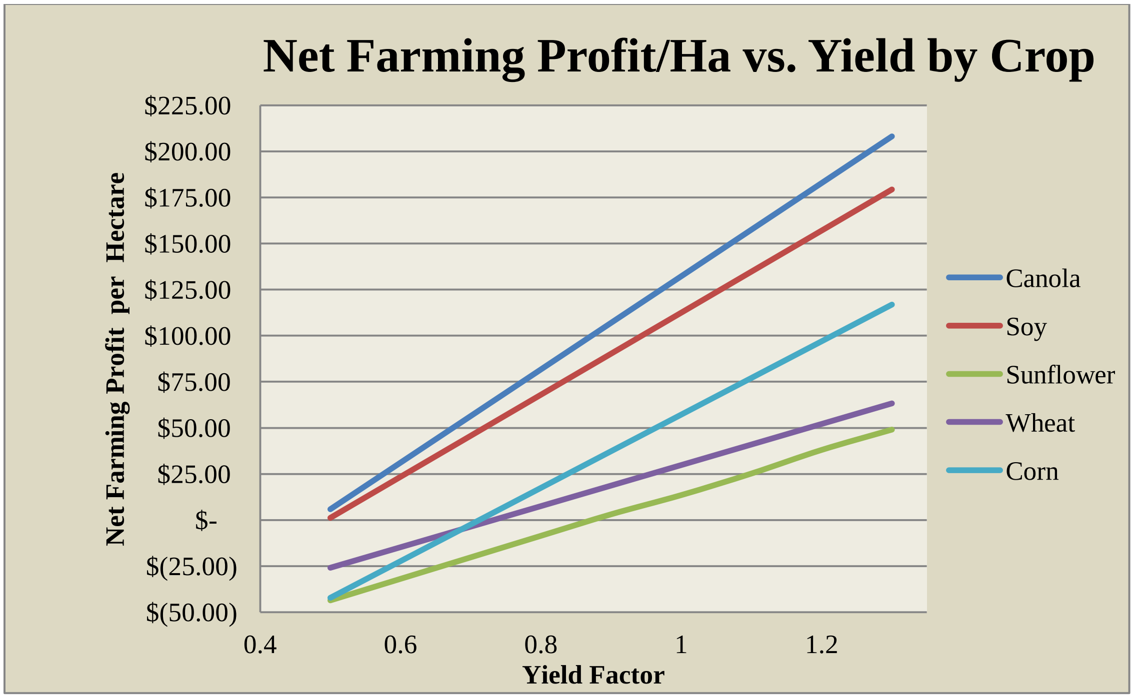

Figure 26. Net Farming Profit vs. Crop Yield.

Results from this analysis show canola and soybeans to be the most responsive to yield, where a 10% increase in yield over the baseline enterprise crop budget represents a 16% increase in farming profit. At a 50% yield, both canola and soybeans are still above break-even, minimizing overall risk. Corn has a similar slope to canola and soybeans with a shifted origin while wheat and sunflowers are the least responsive to change in yield. This sensitivity further supports why crop rotation 3, corn-canola-soy-fallow, is the optimal rotation in terms of net profit and risk minimization by yield.

6.4.3 Crush Facility Sensitivity. The key variables related to the cost of producing vegetable oil are oil extraction efficiency and crush capacity. Figure 27 shows the effect of oil extraction efficiency on production cost. This analysis models the current installed capacity of 4 tons/day while holding all other variables constant. Sunflower and canola, with the highest inherent oil content, are the most sensitive to the increase in extraction efficiency. Every 1% increase in extraction efficiency of canola or sunflower oil results in a $0.018 reduction in the cost per kilogram of that oil. Soybeans show a decrease in cost of $0.0066 per kilogram of oil for each percent increase in extraction efficiency.

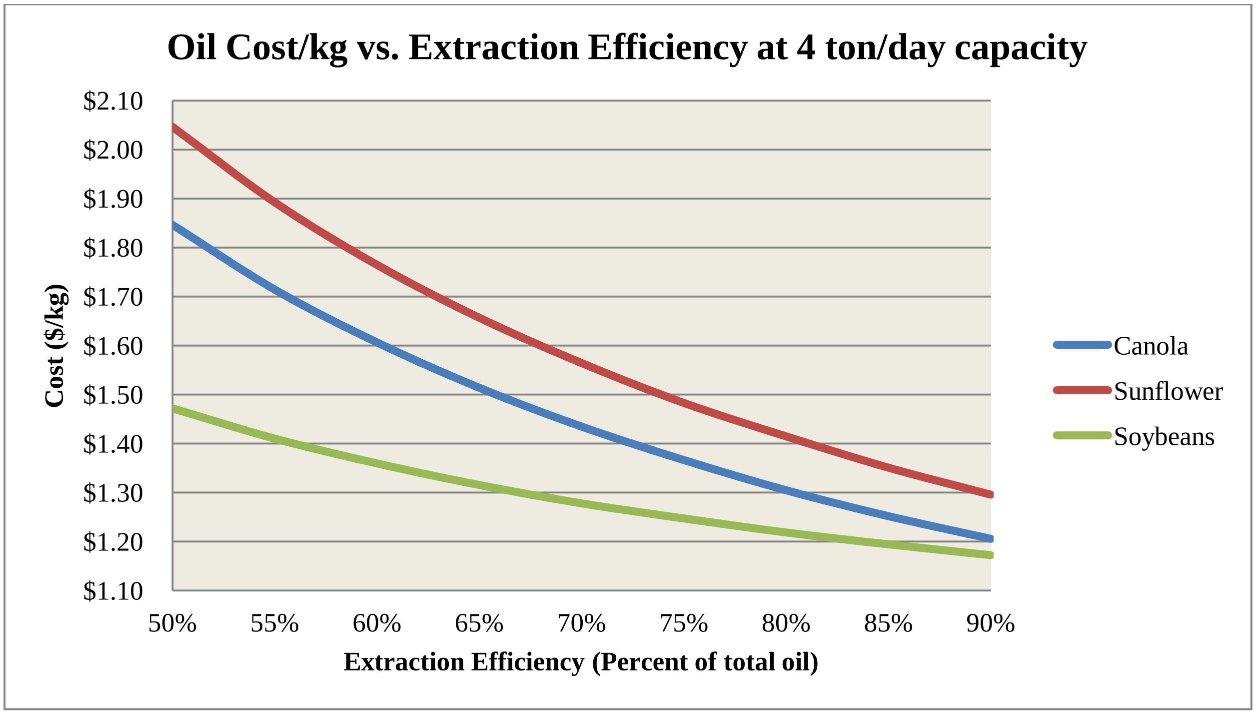

Figure 27. Sensitivity of Oil Cost to Extraction Efficiency.

Crush capacity's effect on oil cost is show in Figure 28. Soybeans are the most sensitive to an increase in capacity holding all other variables constant, include labor. The crush cost of soybeans surpasses sunflower at 3 tons/day and canola at 4 tons/day. At 12 tons/day, the maximum capacity of the EcoComplex Crush Facility due to footprint and space limitations, the crush cost is $0.90 per kilogram. This is competitive with RBD soybean at ($0.99/kg) and approaches the cost of the next cheapest biodiesel feedstock, white grease at $0.86/kg.

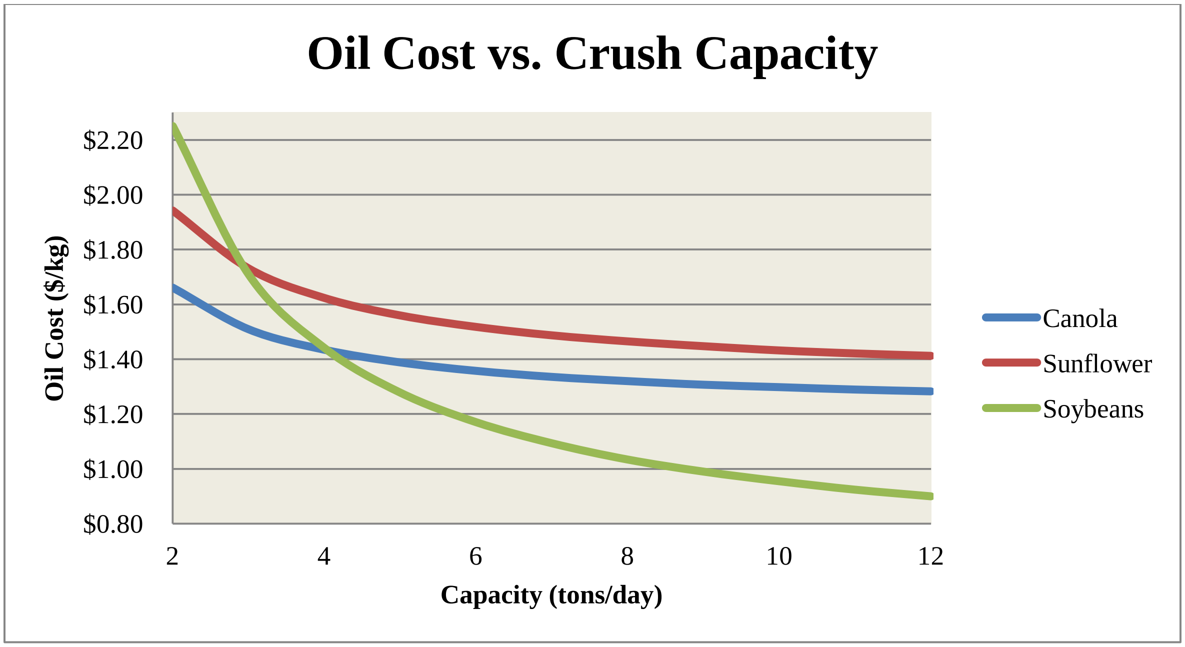

Figure 28. Sensitivity of Oil Cost to Crush Capacity.

6.4.4 Sensitivity of Biodiesel Conversion Cost to Production Metrics. This scenario examines key production costs (yellow grease, labor, methanol, and yield) by changing their value plus/minus 10% of the baseline cost. These variables were modeled by setting production volume to 490,000 liters per year biodiesel using the cheapest commodity feedstock yellow grease with pricing of $0.75 per kilogram.

Yield, the ratio of finished biodiesel divided by starting feedstock oil, and feedstock cost (yellow grease) have same magnitude of slope and are the most significant of the four metrics. For every 1% increase in yield, total conversion cost per gallon is reduced by $0.0022/liter, where as a 1% increase in feedstock cost results in total conversion cost increase of $0.0022/liter. For labor, each percent increase results in a $0.00077/liter increase in conversion cost. Finally, methanol increases the conversion cost by $0.00039/liter for each percent increase in price.

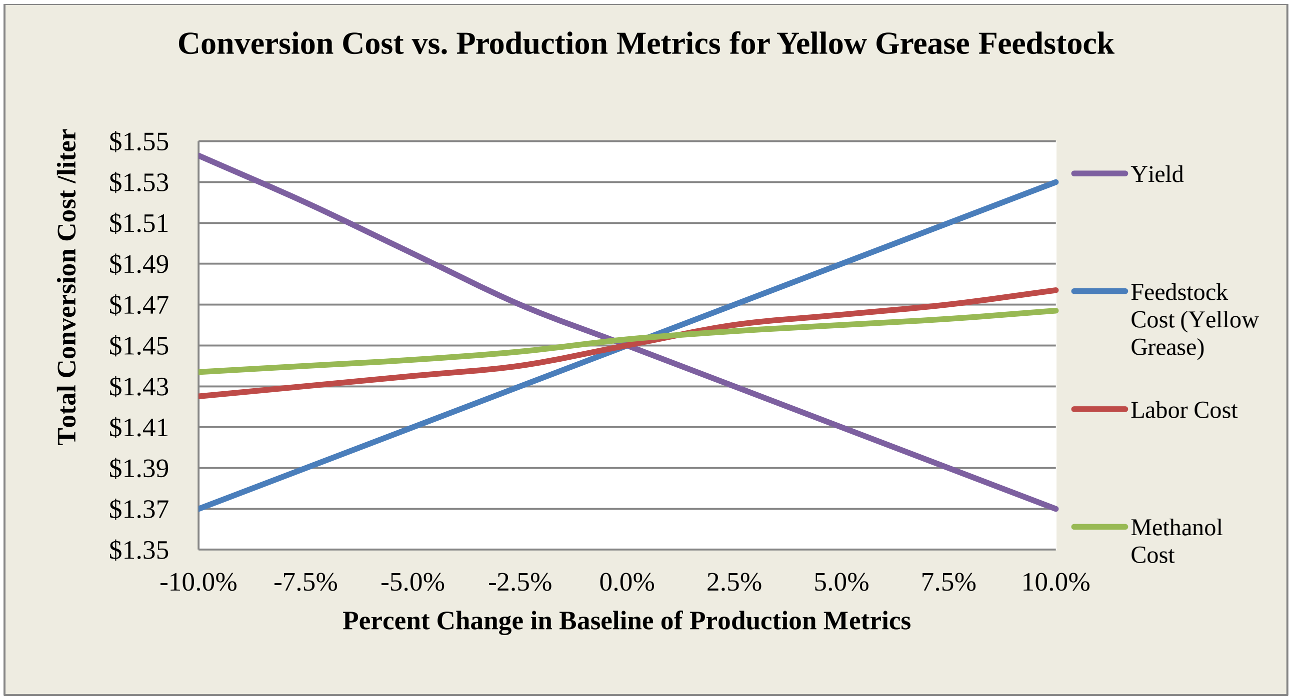

Figure 29. Sensitivity of Biodiesel Conversion Costs to Production Metrics.

6.4.5 Net Profit vs. Subsidies. Break even for biodiesel conversion at the facility's capacity of 490,000 liters per year using the cheapest feedstock of yellow grease with all conversion metrics at the baseline of zero, requires a subsidy of $0.58 per liter. This requires D4 RIN values of $0.21 or $0.38, with and without the fuel tax credit.

6.5 Discussion and Conclusion

The agronomic and economic modeling provides a clear view of the economic challenges to operating small-scale crush and biodiesel plants. The present study found that consistent federal government subsidies are paramount to encourage sustained growth of the US biodiesel industry, particularly at the small-scale. This has been problematic over the past several years with the lapse and subsequent start-up of the fuel tax credit and with cases of RIN fraud that have undermined its value and led to questioning the validity of the EPA's Renewable Fuels Standard program.

6.5.1 Limitations of Study. This analysis is limited to the Catawba County NC EcoComplex Crop Processing and Biodiesel Facilities and the equipment utilized within. These facilities are in start-up phase of production with only preliminary production data. Operating costs are based on measurements during start-up and supplemented by literature review. All commodity inputs (feedstocks, chemicals, products, RIN) were cited in 2013 and provide a snapshot of current market conditions during this time. This analysis is based on government owned civic-scale project, therefore depreciation and taxes are not calculated.

6.5.2 Recommendations.

6.5.2.1 Oilseed Crops & Crushing. *Camelina sativa* is an alternative oilseed crop and biodiesel feedstock that may add flexibility to the crop rotation and increase overall oil production per hectare. Camelina has a very rapid growth cycle, in as little as 70 days to maturity in late winter, giving possibility of replacing a fallow period with an oilseed crop. Although it produces half the yield of canola, it also requires half the fertilizer input (Ciubota-Rosie, Ruiz, Ramos, & Perez, 2013; Zubr, 1997). Lack of familiarity with farm management and unknown commodity pricing are barriers for camelina development as an oil crop. Capacity is the other significant variable for the crush facility as there is room for expansion to 10-12 tons per day in the current building footprint. The capital requirement for additional equipment, payback period, and the overall impact on cost of oil production need further analysis.

6.5.2.2 Conversion. Though methanol cost was the least sensitive to conversion cost, it is also the simplest variable to change by increasing storage capacity and purchasing in bulk. The current model uses the purchased price of methanol for a short truck load instead of a full tanker truck load. Extrapolating the reduction in total conversion cost by decreasing the methanol purchase price by 25%, from \$0.53 to \$0.39 per liter, would result in a \$0.04/liter decrease in total conversion cost and payback the investment of a larger tank and piping in less than one year.

6.5.3 Future Trends and Technology. Field to Fryer to Fuel or F3 is a program being conducted by a NC economic development group to promote a concept to expand used cooking oil conversion to biodiesel (AdvantageWest, 2013)**.** The North Carolina biodiesel industry has largely been built on used cooking oil. Many NC biodiesel companies have used cooking oil collection, servicing restaurants to access lower cost feedstock. This model has proven to be resilient allowing these companies to weather the periods of inadequate subsidy, while many commodity oil dependent biodiesel manufactures were forced to close their doors. At this juncture the concept of oil leasing was born. Vegetable oil could be owned by the biodiesel company and leased to a restaurant to reduce collection cost and take advantage of the margin on food-grade oil. This takes additional coordination to procure and distribute the food-grade oil and may indeed give rise to a new business entity. Connecting agriculture and local food markets is facilitated by the distributed scale and the equipment found in small crushing plants, such as the EcoComplex. Small-scale crushing produces mechanically extracted cold-pressed oil with inherently low phosphorous levels suitable for upgrading to food quality. The increased margin for edible oil tied back into local biodiesel producers has the potential to create a new business niche and expand the concept of locally made and locally grown fuels.

Technology and process improvements continue to develop around co-products that support the possibility of the oilseed biorefinery. These value-added co-products include glycerin soap manufacturing and nutraceutical fractionation to produce hydroxypropyl methycellulose (HPMC) a carbohydrate polymer used in natural products potentially made from grain meal and glycerol (L. Zhang et al., 2013). Soap manufacturing provides a higher value use of crude biodiesel glycerin while the nutraceutical uses oilseed meal and crude glycerin. Process technology advancements include reusable catalysts such as heterogeneous zeolites and commercially produced enzymes that stand to produce a higher value glycerin stream while utilizing lower quality oils therefore improving biodiesel production economics, scale independent (Burton, 2009; Hasheminejad, Tabatabaei, Mansourpanah, Far, & Javani, 2011).

Creative programs and partnerships along with technology and efficiency improvements combine to give reason for optimism in the arena of small and civic-scale biofuel endeavors. And while current economic viability is marginal at best, the emerging bio-based economy is poised for near-term growth at all scales that warrant continued investment in the development of distributed models.

CHAPTER 7

Synthesis of Results and Discussion

The Catawba County EcoComplex is an evolving eco-industrial park led by municipal government striving towards zero waste. While waste reduction has been the original motivation, renewable energy from municipal biomass has become the tangible focus for EIP development going forward. The establishment of a financially successful landfill gas-to-energy project laid the foundation for on-going political support. The ability to develop public and private partnerships is a driving factor to cultivate future projects. University partnerships continue to show promise, as the EcoComplex demonstrates leadership as a regional model and unique case study. Creative financing using landfill post-closure funds have enabled Catawba County to fund capital intensive buildings and equipment. All regulated landfills are required to maintain a post-closure fund, thus representing a potential source of funds for future waste/biomass-to-energy systems and zero waste initiatives; however, with the expectation that projects will generate revenue to repay the fund. Projects that further convert the waste stream to resources will likely prolong landfill life span thus allowing for less constrained payback periods. Local governments and municipal landfills are well positioned to be leaders for developing successful eco-industrial parks based on biomass and waste resources for clean energy development.

The biorefinery system, which includes 61 hectares of buffer lands, a 4-ton/day oilseed crushing facility and biodiesel conversion (490,000 liters per year) facility, is integrated into the EcoComplex via for three fundamental reasons: (a) utilize buffer lands to grow oilseed feedstock, (b) use waste thermal input from the landfill gas to energy facility for process heat, and (c) provide fuel for the heavy equipment in landfill operations. The biorefinery within the

EIP system was analyzed for technical bottlenecks, environmental performance through LCA, and economic assessment based on four biodiesel feedstocks: unrefined oils from soybean, canola, sunflower, and used cooking oil.

7.1 Technical Bottlenecks

The bottleneck for oilseed crushing is scale. At current capacity, operating 250 days per year, this facility can only provide 36%, 23%, and 8% of the feedstock oil to meet the capacity of the biodiesel facility for canola, sunflower, and soybeans respectively. A minimum three-fold scale-up would be required to match the oil outputs for canola. This would also maximize the physical space of the building. Economic analysis would be needed before capital investments and facility expansion were made.

The conversion step points to three potential bottlenecks: feedstock preparation, methanol recovery, and thermal loads for expanded production. Utilizing a cheaper feedstock equates to higher impurities mainly in the form of moisture and free fatty acids which in turn requires more unit operations (flash drying, esterification) and associated labor and material inputs. Methanol recovered from distillation is another important process step that presents trade-offs. Methanol recovery is not required to for fuel to meet ASTM D6751 specification as both water washing and ion exchange filtration remove excess methanol. However, methanol removed from the FAME phase post reaction, facilitates downstream purification and reduces material input for process water and ion exchange resins as well as energy inputs. The recovered methanol can be recycled for use in subsequent batches, though it contains water from the saponification reaction concurrent during transesterification. Although recovered methanol is 93-95% purity (technical grade is 99.5%), the presence of this water promotes further oil degradation, soap formation, and yield loss. Methanol recovery from the crude glycerin phase is not currently planned for in facility operations because it occupies the reactor vessel creating a bottleneck for batch production and requires additional heating inputs beyond the 58.5 kW (200,000 btu/hr) provided by the heat recovery unit.

7.2 Environmental Performance & LCA Results

The energy and GHG LCA provides a straightforward perspective on the associated environmental impacts of each life cycle stage for the feedstocks presented in both conventional and IE system frameworks. UCO-based biodiesel is the most environmentally benign, with a net energy balance of 6.20 and fossil energy balance of 12.24. UCO achieves a reduction in carbon intensity of 80% compared to petroleum diesel fuel in the conventional system and 92% reduction when ascribed to the conditions of the IE system employed at the Catawba County EcoComplex. Soybean-based biodiesel poses the least environmental impact of the oilseed feedstocks, primarily due to the fact that soybeans require minimal nitrogen fertilizer compared to other oilseed crops. Soybeans produced a NER of 4.44, an FER of 7.19 and CI reductions of 71% and 87% for conventional and IE systems respectively. Comparing UCO and soybean GHG results, there is an interesting counter intuitive cross-over where producing biodiesel from soybeans within the IE system is more environmentally advantageous than producing UCO-biodiesel in a conventional system.

Canola feedstock showed the highest GHG intensity due to the nitrogen fertilizer effect. The crush phase showed significant reduction in the IE system as electricity, the primary input, was discounted from on-site generation. Transportation remains constant across systems with only a small emissions reduction from the use of B20 biodiesel in the IE system. Soybean biodiesel resulted in CI values of 27.6 gCO_2-eq/MJ in the conventional system and 12.5 in the IE system, a reduction of 55%. The literature from CARB lists Midwestern produced soybean

FAME at 21.13, in between the two systems of this study. This may be in part due to higher average yields in for soybean harvest than compared to North Carolina production. All feedstocks achieved an emissions reduction of greater than 50% to comply with US EPA biomass diesel category under RFS2. Primary factors contributing to the CI value are nitrogen fertilizer, methanol, electricity, and thermal energy in conversion. Diesel in transport and KOH catalyst make minor contributions.

7.3 Economic Analysis

Standalone budget analysis of each operation indicates that crushing and conversion are not optimized under current conditions to create an economically viable integrated system. With the goal of producing biofuels, it would be most economical to sell all crops and buy the cheapest biodiesel feedstock, yellow grease, whereby the sale of grain subsidizes the biodiesel conversion process. This conclusion could be supported by chemical simulation software such as ASPEN to model the conversion portion of the life cycle.

The corn-canola-soybean-fallow rotation is found to be the most profitable crop rotation for oilseed production rotation with averaged annual profit at $151.05 per hectare. This rotation is also the highest vegetable oil producer at 617 liters per hectare per year. Canola and soybeans are the most responsive to change in yield, where a 10% increase in yield over the baseline enterprise crop budget represents a 16% increase in farming profit. At a 50% yield, both canola and soybeans are still above break-even, minimizing overall risk. Due to the high value of protein meal, soybeans showed the greatest sensitivity to increased crush capacity, though not viable as a biodiesel feedstock at 12 tons/day for this scale production facility.

Current operating conditions result in a biodiesel conversion cost of $1.43 per liter of fuel produced using least valuable commodity feedstock, yellow grease. Production metrics in the order of greatest sensitivities are yield, feedstock cost, labor cost, and finally methanol cost. Break-even requires a subsidy of $0.58 per liter to bring down the net biodiesel cost, matching the avoided cost of petroleum diesel. This requires D4 RIN values of $0.21 or $0.38, with and without the fuel tax credit. The agronomic and economic modeling provides a clear view of the economic challenges to operating small-scale crush and biodiesel plants. As subsidies continue significant fluctuation, metrics other than operating costs are required to justify civic-scale biofuel projects.

CHAPTER 8

Conclusions and Recommendations for Future Work

Use waste first then biomass energy crops for biorefinery inputs. Biofuels are at their best when they utilize waste resources as principal material inputs and conversely at their worst when they use food crops and lands that compete with food production. Used cooking oils, trap and brown greases should be the baseline of biodiesel production. Second generation feedstocks such as yeasts, bacteria, and algae that offer multiple functions, i.e. bioremediation, will likely be the future of high environmentally performing biodiesel fuels. Over the past decade the scientific community has engaged in a rigorous debate on the issue of indirect land use change associated with the increase in global demand for grains. While land use change, either direct or indirect, is not currently quantified in biofuels policy, its effect is weighing in, resulting in many governments in Europe and now the United States to scale back policies that incentivize growth in the sector. Economic sustainability for the US biofuels sector is dependent on federal government subsidies for all but the largest producers. The promise of biodiesel and the environmental advantage is not based on consolidation or a single feedstock, but in multiple agricultural products and waste streams suited to an increasingly local scale and regional community.

Improve technologies to diversify feedstocks, process low-quality low-cost materials, and produce higher value co-product streams. There are many promising technologies on the near horizon that may prove disruptive to the industry. Enzymatic catalysis which can combine esterification and transesterification in one process is currently being commercialized. Since the enzymes need water to operate, high moisture feedstocks are not a barrier, nor are high concentrations of free fatty acids, both of which cause significant yield loss and increased unit operations. Enzymes may also use ethanol as the monohydric alcohol, instead of fossil-based methanol, for the prospect of a truly renewable biofuel. Additionally, wet methanol recovered from both biodiesel and glycerin phases could be recycled completely without costly rectification systems.

Work on integrated farming systems for bioenergy crops. Nitrogen is the largest factor for GHGs in the agricultural production step (with an emissions factor of 6.7 compared to 0.393 for phosphorous and 0.46 for potassium). This is due to the costly manufacturing step and in application, where it is estimated that 1% of the mass of nitrogen fertilizer is emitted by conversion directly to nitrous oxide gases Potentially another third is lost to leaching though water movement in soil. Crop budgets are not formulated to minimize nitrogen loss, but to maximize opportunity for plant uptake. A multitude of factors determine plant uptake efficiency including soil pH, texture, and soil carbon. Integrated farming systems represents an approach to increase the efficiency of plant uptake by nurturing a support system that includes high levels of stable carbon, such as biochar, and a diverse soil biotic community enhanced through crop rotation, reduced herbicide and pesticide applications, and no-till practices. Biochar applications associated with bioenergy crops is an area in need of long-term studies. Nitrogen fixing crops that have evolved with biological nitrogen fixation should be among those first considered as the primary biomass energy crop, or at least incorporated into crop rotation.

Producing soil amendments and fertilizers is well defined in the scope of a biorefinery and certainly at the EcoComplex. In addition to yard waste and wood scraps that are composted, byproducts from the biorefinery could be added in a digester either anaerobic or aerobic. These byproducts include both sources of nitrogen (seed meal which ranges from 25-35% protein content) and carbon sources in the forms of solids and sediment from feedstock preparation and crude glycerin bottoms. The refining of crude glycerin using phosphoric acid produces a separation of the crude glycerin emulsion which results in the formation free fatty acids, technical grade glycerol at 85% purity, and a potassium salt, potassium phosphate. This salt is water soluble and provides two important macro-nutrients. Important decision making criteria to incorporate this utilization of byproducts include effects on labor, production and scheduling, economic analysis, and life cycle assessment.

Work to incorporate various levels of applied industrial ecology. EIPs struggle with the implementation gap. The barriers for executing industrial symbiosis across multiple firms are numerous. However, levels of applied industrial ecology can be incorporated within the boundaries of one firm, and a biorefinery provides an exceptional opportunity. Renewable energy systems incorporated for heat and electricity offer tremendous potential reductions in GHG emissions at the conversion phase. This accounts for a 60% reduction in the case of the EcoComplex compared to conventional means. Investing in solar thermal, biofuel-powered boilers or photovoltaics can also make substantial environmental contributions at the producer level.

Develop producer specific LCAs. With the confluence of climate change science, advanced by the IPCC, sophisticated modeling software including open source packages, and real time data streams, it has become possible to create LCAs for individual producers. Accounting systems that have imbedded allocation and emissions factors only require mass inputs. These are simple to tract as they are also the primary economic metric. As the science of LCA progresses it will become increasingly likely that a value of carbon will come into the bottom line economic calculation either through cap and trade, carbon tax, or other means. Therefore, specific LCAs on the producer scale will not only distinguish a product on the market place but offer a quantified economic advantage. Developing widely accepting independently verified methods for producer specific LCAs is an upcoming area for the biofuels sector.

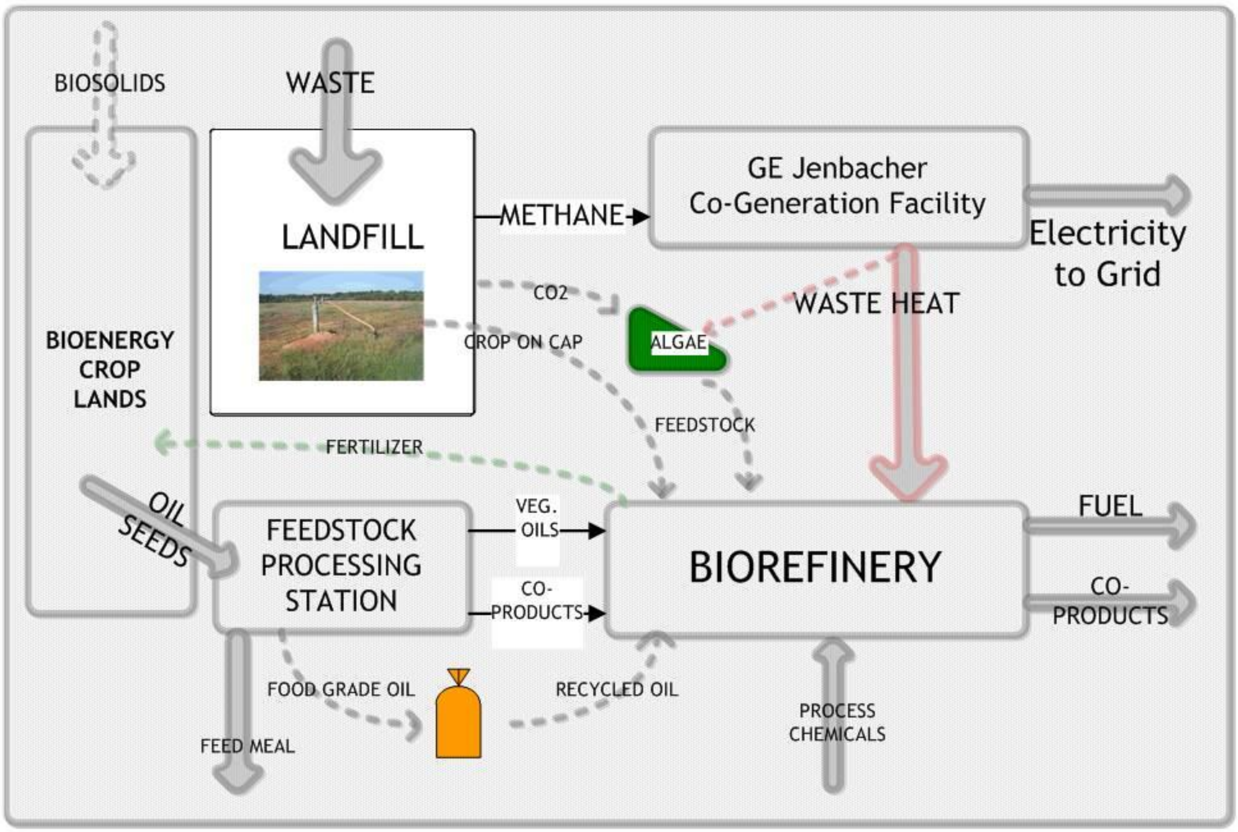

Figure 30. Oilseed Biorefinery within the EcoComplex (future components with dashed lines).

This dissertation is dedicated to improving the overall sustainability, both economic and environmental, of the Catawba County NC EcoComplex and others that envision a decentralized and distributed energy future that is fundamentally regenerative and builds resilience in local communities. Figure 30 illustrates reasonable future endeavors for this biorefinery. This work represents a baseline for what can be expected at this project and how improvements and efficiencies can be measured. While the system in place has much work to be optimized and reach its full potential, this research helps to establish the foundation for future endeavors of which we all must strive towards.

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Appendix A

Eco-Industrial Parks Based on Literature

EIP -location	Date Established	Characteristics & Firms	Exchanges	Citation
Kalundborg, Denmark	1970-1990	Coal Power Plant, wall-board plan, Cement, Novozymes & Novo Nordisk, Fertilizer production, fish farm, Kalundborg waste water treatment plant	waste water, fuel, information, nutrients	(Tudor, 2007;Chertow, 2000)
PRTEC - Puerto Rico Techno-Economic Corridor	Under development	Information technologies, medical device manufacturing, electronic manufacturing, recycling of cardboard, metal alloys, isopropanol	Wastes, technology transfer	(Deschenes & Chertow, 2004)
Burnside EIP Halifax, Nova Scotia, Canada	Under development	2500 acres, 1500 businesses, 1800 people employed working toward improving environmental performance and profitable partnerships.	Energy, information	(Spitzer, 1997; Chertow, 2000)
Monfort Boys Town-Biosystem Suva, Fiji		Utilizes spent grain from breweries as substrate to grow mushrooms, fed to pigs, pig waste to anaerobic digester, treated waste to fish ponds. Biosystem model	Nutrient cascade	(Chertow, 2000)
Fairfield, Baltimore MD	1990s - developing	60 operating companies in heavy industry, Brownfields site development 1300 acres zoned industrial, mass commuting options	Intermodal materials, waste streams	(Spitzer, 1997)
Intervale Food Center Burlington, VT	1990s	4 Acre site: 60MW Biomass gasification co-gen unit, living systems & bioshelters, urban agriculture. Goals are energy supply, food production, water purification waste disposal, and commercial composting. Formerly Riverside Eco-Park.	Wastes, technology transfer	(Spitzer, 1997; Chertow, 2000)
Port of Cape Charles Eastville, VA	Under development	Mixed residential, commercial, and industrial uses	Water recovery, recycling,	(Spitzer, 1997)
Civano Industrial Eco-Park	Under development	Core businesses: makers of PVs, electric vehicles, circuit boards, steel fabricators,	Water, resources	(Spitzer, 1997)

Eco-Industrial Parks Based on Literature

(Cont.)

EIP -location	Date Established	Characteristics & Firms	Exchanges	Citation
Tucson, AZ		design firms, renewable construction. Goals to reduce transportation, increase competitiveness, share resources		
Londonderry, New Hampshire	1990s	100 acre site with 720MW combined-cycle gas power plant, waste water from nearby sewage treatment plant for cooling towers	Water, heat	(Chertow, 2000)
EcoComplex, Newton NC	1990s - developing	Landfill gas to energy 3 MW with power purchase agreement. Sawmill and pallet manufacturers. Biodiesel plant with ,feedstock processing station under construction, biosolids, greenhouses, bricks and pottery.	Heat, steam, by-products	(Edwards, 2009)
Rutgers EcoComplex, New Jersey	1990s-Developing	250kW micro-turbine, co-gen, 1 acre greenhouses, aquaculture, desalination, compost	heat, nutrients, water	(Goldstein, 2004)

Appendix B

ASTM D6751 Specification of Biodiesel from 2012, Courtesy of National Biodiesel Board

BIODIESEL

TM by the National Biodiesel Board

SPECIFICATION FOR BIODIESEL (B100) – ASTM 6751-12

*Biodiesel (B100) and the petroleum diesel must meet their respective ASTM specifications before blending.

Property	ASTM Method	No. 1-B	No. 2-B	Units
Calcium & Magnesium, combined	EN 14538	5 max	5 max	ppm (µg/g)
Flash Point (closed cup)	D 93	93 min	93 min	°C
Monoglycerides	D 6584	0.4 max	N/A	mass %
1. Methanol Content***	EN 14110	0.2 max	0.2 max	mass %
2. Flash Point***	D93	130 min	130 min	°C
Water & Sediment	D 2709	0.05 max	0.05 max	% vol.
Kinematic Viscosity, 40 C	D 445	1.9 – 6.0	1.9 – 6.0	mm^2/sec.
Sulfated Ash	D 874	0.02 max	0.02 max	% mass
Sulfur				
S 15 Grade	D 5453	0.0015 max	0.0015 max	% mass (ppm)
S 500 Grade	D 5453	0.05 max	0.05 max	% mass (ppm)
Copper Strip Corrosion	D 130	No. 3 max	No. 3 max	N/A
Cetane	D 613	47 min	47 min	N/A
Cloud Point	D 2500	Report	Report	°C
Carbon Residue 100% sample	D 4530*	0.05 max	0.05 max	% mass
Acid Number	D 664	0.5 max	0.5 max	mg KOH/g
Free Glycerin	D 6584	0.020 max	0.020 max	% mass
Total Glycerin	D 6584	0.240 max	0.240 max	% mass
Phosphorus Content	D 4951	0.001 max	0.001 max	% mass
Distillation	D 1160	360 max	360 max	°C
Sodium/Potassium, combined	EN 14538	5 max	5 max	ppm (µg/g)
Oxidation Stability	EN 15751	3 min	3 min	hours
Cold Soak Filtration	D 7501	200 max	360** max	seconds

BOLD = BQ-9000 Critical Specification Testing Once Production Process Under Control

* The carbon residue shall be run on the 100% sample.

** 200 seconds maximum for use in temperatures at or below -12°C

*** Either parameter is to be met

\# A considerable amount of experience exists in the US with a 20% blend of biodiesel with 80% diesel fuel (B20). Although biodiesel (B100) can be used, blends of over 20% biodiesel with diesel fuel should be evaluated on a case-by-case basis until further experience is available.

Appendix C

EN 14214 European Standard of Biodiesel from 2008, courtesy of European Committee for Standardization (CEN, 2008)

Table 1 — Generally applicable requirements and test methods

Property	Unit	Limits		Test method [a] (See Clause 2)
		minimum	**maximum**	
FAME content [a]	% (*m/m*)	96,5 [b]	–	EN 14103
Density at 15 °C [c]	kg/m^3	860	900	EN ISO 3675 EN ISO 12185
Viscosity at 40 °C [d]	mm^2/s	3,50	5,00	EN ISO 3104
Flash point	°C	101	–	EN ISO 2719 [e] EN ISO 3679 [f]
Sulfur content	mg/kg	–	10,0	EN ISO 20846 EN ISO 20884
Carbon residue (on 10 % distillation residue) [g]	% (*m/m*)	–	0,30	EN ISO 10370
Cetane number [h]	–	51,0	–	EN ISO 5165
Sulfated ash content	% (*m/m*)	–	0,02	ISO 3987
Water content	mg/kg	–	500	EN ISO 12937
Total contamination	mg/kg	–	24	EN 12662
Copper strip corrosion (3 h at 50 °C)	rating	class 1		EN ISO 2160
Oxidation stability, 110 °C	hours	6,0	–	prEN 15751 [i] EN 14112
Acid value	mg KOH/g	–	0,50	EN 14104
Iodine value	g iodine/100 g	–	120	EN 14111
Linolenic acid methyl ester	% (*m/m*)	–	12,0	EN 14103
Polyunsaturated (≥ 4 double bonds) methyl esters	% (*m/m*)	–	1	[k]
Methanol content	% (*m/m*)	–	0,20	EN 14110
Monoglyceride content	% (*m/m*)	–	0,80	EN 14105
Diglyceride content	% (*m/m*)	–	0,20	EN 14105
Triglyceride content [a]	% (*m/m*)	–	0,20	EN 14105
Free glycerol	% (*m/m*)	–	0,02	EN 14105 [i] EN 14106
Total glycerol	% (*m/m*)	–	0,25	EN 14105
Group I metals (Na+K)	mg/kg	–	5,0	EN 14108 [i] EN 14109 EN 14538
Group II metals (Ca+Mg)	mg/kg		5,0	EN 14538
Phosphorus content	mg/kg	–	4,0	EN 14107

[a] See 5.6.1.

[b] The addition of non-FAME components other than additives is not allowed, see 5.2. When C17-methyl esters naturally appear in FAME this can result in a lower measured fatty acid methyl ester content. In this situation reference should be made for verification to a modified determination procedure [4], until a modified method is established within CEN.

[c] Density may be measured by EN ISO 3675 over a range of temperatures from 20 °C to 60 °C. Temperature correction shall be made according to the formula given in Annex C. See also 5.6.2.

[d] If CFPP is -20 °C or lower, the viscosity shall be measured at -20 °C. The measured value shall not exceed 48 mm^2/s. In this case, EN ISO 3104 is applicable without the precision data owing to non-Newtonian behaviour in a two-phase system.

[e] Procedure A to be applied. Only a flash point test apparatus equipped with a suitable detection device (thermal or ionization detection) shall be used. See also 5.6.2.

[f] A 2 ml sample and apparatus equipped with a thermal detection device shall be used.

[g] ASTM D 1160 shall be used to obtain the 10 % distillation residue. See also 5.3.4.

[h] See 5.6.3.

[i] See 5.6.2.

[k] A suitable test method is under development by CEN [3].

Appendix D

Standard Unit Operations Used in the EcoComplex Biodiesel Process

Unit	Purpose	Location
Course Filter WVO	Coarse filter 3/8” (9.5mm) incoming WVO feedstock oil to remove large solid particles to prevent lodging and fouling of piping.	Feedstock Settling tank, course canister filter.
Heated Filtering, Settling, and de-watering	Heat Oil to 140°F (60°C) and circulate through step canister filters (1/4”, 1/8”, 150 mesh), heat to 170°F (77°C) and settle. After 24 hours, drain off remaining water and sediment.	Feedstock Settling tank, fine canister filter.
Vacuum oil drying	To achieve moisture below 1500ppm and minimize soap formation during reaction. This is especially important for high FFA feedstocks.	Processor & Methanol Receiver tank
Acid Esterification	Pretreatment step to convert FFA in low quality oil to FAME and reduce overall FFA level.	Feedstock Treatment tank
Methoxide Mixing	Add potassium hydroxide to methanol per FFA%	Methoxide Mix tank
Transesterification	Oil reacts with methanol in the presence of potassium hydroxide catalyst to yield biodiesel and glycerol	Processor
Glycerin Removal	Gravity drain off glycerin byproduct, pump to bulk storage tank.	Processor & glycerin storage
Methanol Recovery	Recover excess methanol from FAME phase for reuse in future batch. This step also lowers flash point and reduces water use.	Processor & Methanol Receiver vessel
Water Washing	Remove impurities in FAME such as soaps, excess methanol and un-reacted materials. Process water usage is 30% of final fuel volume.	Wash Tank
Waste Water Treatment/Oil Recovery	Reduce biological oxygen demand of waste water and recover some usable feedstock oil	Water treatment tank
Drying	Remove excess soluble water after water wash. Dry down to 800ppm moisture	Wash Tank
Dry Wash- Ion Exchange	Pump FAME through fluidized bed of ion exchange resin bead. Another step to remove impurities in FAME such as soaps, excess methanol and un-reacted materials.	Wash Tank, Test tank
Oxidative Stabilizer & Fuel Testing	Add oxidative stabilizer to test tank, stir then take sample to lab for in-house testing	Test tank

Appendix E

Agricultural Inputs by Crop Budget

Material inputs/ Acre	**SOYBEANS**			**CANOLA**			**SUNFLOWER**	
REFERENCE:	NCSU (1)	USDA-ARMS (2)	2012 Eco-Complex	George et al. (3)	Penn State (4)	2011 Eco-Complex	UNL (5)	K-State (6)
Seed (lbs)	50	51	50	3	4	5	5	5
Nitrogen (lbs)		20.8	25	160	160	117	54	76
Phosphate (lbs)	65	44	30.8	60	88	111	15	30
Potash (lbs)	83	83.9	84	130	168	131	15	0
Lime (lbs)		660	600	660	1000	1500	660	500
Herbicides (lbs)	5.5	1.56	2.9	1.1		8.4	6.0	28.5
Pesticides (lbs)	0.1	1.489	0.5	0.9		0.2	0.27	0.05
Fungicide (lbs)		0.135		1.5				

1) (NCSU, 2012)
2) (USDA-ARMS, 2013)
3) (George, et al., 2008)
4)(PennState, 2011)
5) (UNL, 2013)
6) (K-State, 2007)

Appendix F

Crush Facility Electrical Load Assessment

ENERGY USAGE							**Energy Usage kWh**		
Process	Flow rate	unit	Hrs-Canola	Hrs-Sunflower	Hrs-Soy	Motor specs (kW)	Canola	Sunflower	Soybeans
Drag Conveyor C-101	1500	bushels/ hour	21.1	32.5	11.7	1.93	40.8	62.8	22.7
Bucket Elevator E-201	1500	bushels/ hour	21.1	32.5	11.7	1.50	31.7	48.8	17.6
Indented Cylinder Separator	175	bushels/ hour	0.0	278.8	0.0	2.76		769.6	-
Vibratory Conveyor C-201	250	bushels/ hour	126.7	195.2	70.4	0.69	87.4	134.7	48.6
Elevator E-202	500	bushels/ hour	63.4	97.6	35.2	1.50	95.0	146.4	52.8
Air Screen Separator	175	bushels/ hour	181.0	278.8	100.6	3.50	633.6	975.9	352.0
Clean Product Cleaner	300	bushels/ hour	105.6	162.6	58.7	1.15	121.4	187.0	67.5
Cyclone Dust Collector			181.0	278.8	100.6	0.68	122.2	188.2	67.9
Elevator 3	500		63.4	97.6	35.2	1.50	95.0	146.4	52.8
Dryer Feed Auger	500		63.4	97.6	35.2	1.15	72.9	112.2	40.5
Dryer Discharge Auger	500		63.4	97.6	35.2	1.15	72.9	112.2	40.5
Dryer (electrical)	200	bushels/ hour	158.4	244.0	88.0	2.00	316.8	487.9	176.0
Dryer propane							7,423.0	6,631.2	4,948.6
Elevator 4	500		63.4	97.6	35.2	1.50	95.0	146.4	52.8
Pressing Operations									
Dry storage conditioning fan			384.0	384.0	384.0	3.45	1,324.8	1,324.8	1,324.8

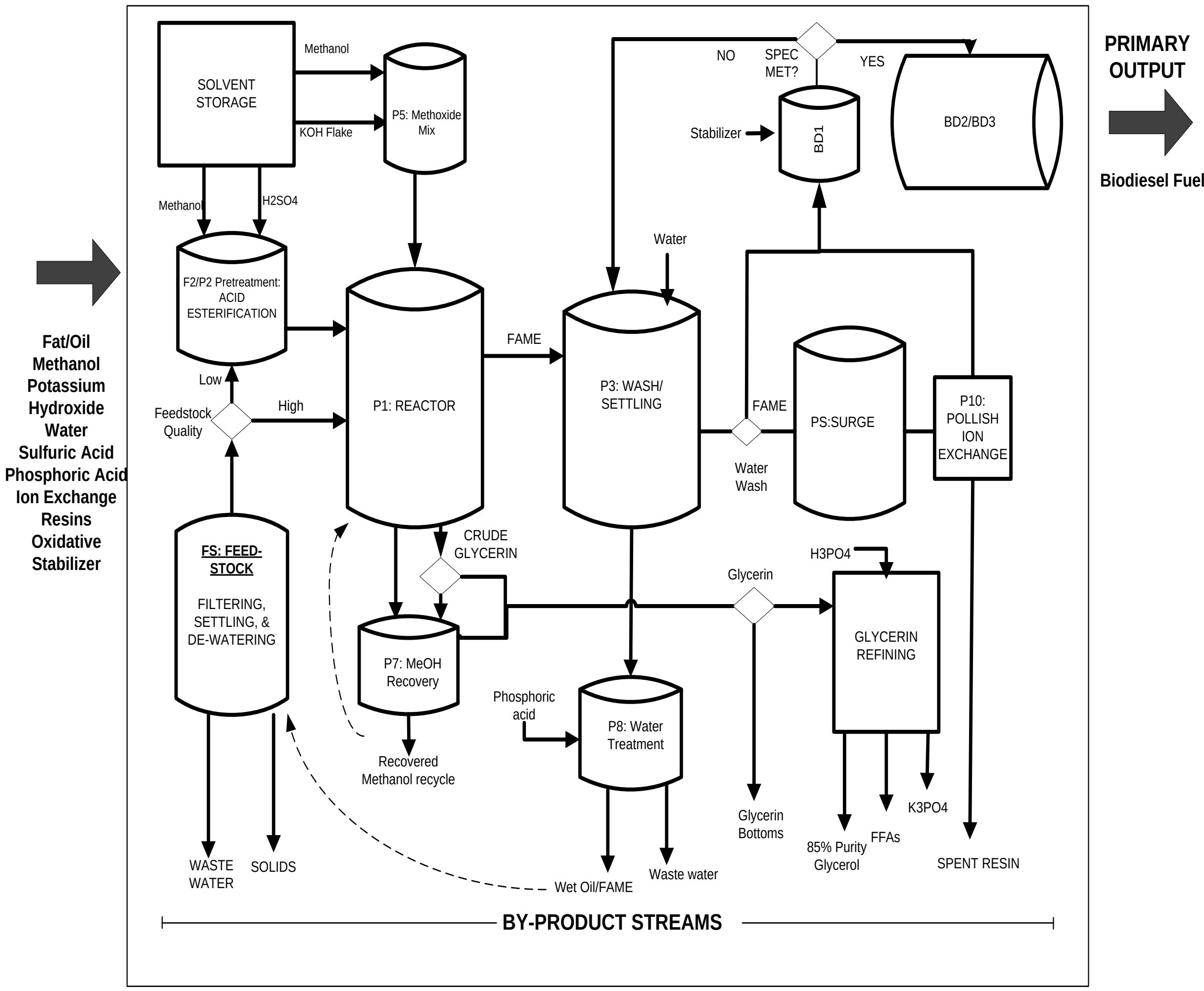
Crush Facility Electrical Load Assessment

(Cont.)

ENERGY USAGE								**Energy Usage kWh**	
Unload Auger with Sweep	250	bushels/ hour	126.7	195.2	70.4	1.15	145.7	224.5	81.0
Conveyor Auger	250	bushels/ hour	126.7	195.2	70.4	1.50	190.1	292.8	105.6
Leveling Auger	250	bushels/ hour	126.7	195.2	70.4	1.00	126.7	195.2	70.4
4 KK40 Oil Presses- Canola	264	lbs/hr	5910.0			11.68	69,052.4		
4 KK40 Oil Presses- Sunflower	236	lbs/hr		5910.0		11.68		69,052.4	
4 KK40 Oil Presses- Soy	176	lbs/hr			5910.0	11.68			69,052.4
4 KK40 heaters - soy					5910.0	2.00		-	11,820.0
Meal inclined discharge auger	200	bushels/ hour	108.3	107.9	90.9	1.50	162.4	161.8	136.4
Oil Press meal auger	200	bushels/ hour	108.3	108.3	90.9	1.50	162.4	162.4	136.4
Air Compressor							279.8	178.5	66.6
<u>Other Electrical Loads</u>									
Lighting			500	500	500	3.00	1,500.0	1,500.0	1,500.0
Exhaust fans			181.0	278.8	100.6	19.20	3,475.7	5,353.5	1,931.0
4 Unit Heaters (seasonally)			60	60	60	57.60	3,456.0	3,456.0	3,456.0
					TOTAL kWh/year	89,083.9	92,051.6	95,620.7	

Appendix G

Process Flow Diagram of Biodiesel Facility Conversion Process



Appendix H

Electric Load Analysis per 2,365 Liter Batch (625 Gallons)

Device	Compressed Air (scfm)	kW	hrs/batch	kWh/batch	
Feedstock Loading	551.5			3.7	
Feedstock circulating	2,205.9			14.6	
Feedstock Transfer		1.2	0.5	0.6	
Methoxide mix	900.0		1.0	6.0	
Process Pump		2.8	5.0	14.0	
Process Agitator		1.7	3.0	5.1	
Glycerin Transfer		2.8	0.1	0.3	
MeOH recovery		2.8	3.0	8.4	
P7 circ pump		1.0	3.0	3.0	
Chiller		0.8	4.0	3.2	
Chiller propane (equivalent)		10.6	3.0	31.8	
Chiller circ pump		0.1	24.0	2.2	
Chill water circ		1.2	3.0	3.5	
Vacuum Venturi	8,400.0		5.0	55.6	
Process Agitator		1.7	3.0	5.1	
Wash Pump transfer		2.8	0.3	1.0	
Dry loop		2.8	2.0	5.6	
IX pump	4,261.4		14.2	28.2	
Fill Rite Transfer		0.5	0.4	0.2	
Finish Fuel Transfer		1.1	0.5	0.6	
Heat Dist pump		1.0	24.0	23.5	
zone 1 pump		0.2	12.0	2.9	
zone 2 pump		1.2	12.0	13.8	
zone 3 pump		0.2	12.0	2.5	
Building (HVAC, lab, office, misc)				93.0	
			Total	328.5	kWh

Appendix I

Process Equipment Electrical Loads per 2,365 Liter Batch (625 gallons)

Compressed Air Loads (CA) Requirements/batch
1. Feedstock loading pump:17gpm,15 cfm @100psi (20min)
2. Methoxide mix pump:17gpm,15 cfm @100psi (40 min)
3. Vacuum venturi: full vacuum= 28cfm @ 80psi (300min)
4. Drying loop:10 cfm@80psi (120min)
5. Waste treatment circ:10cfm@80psi (30min)
6. Ion Exchange pump: 5cfm@80psi (600min)
7. Filter Press: 25 gpm, 20cfm@80psi (30min)
8. Methanol circ. pump:4 gpm,15cfm@80psi (120 min)
9. Crude glycerin pump:17gpm,15 cfm @100psi (20min)

3-Phase Loads & Full Load Amps (3Φ)
1. Reactor Pump: 208V, 13.5A
2. Reactor Agitator: 208 V, 8.2A
3. Wash/Dry Pump: 208V, 13.5A
4. Feedstock Pump: 208V, 5.98A
5. Glycerin Pump: 208V, 13.7A
6. Acid Esterification Pump: 208V, 14.4A
7. Heat Distribution Pump: 208V, 4.7A
8. Air Compressor: 460 V, 16A
9. Glycerin Tank Agitator: 208V, 13.6A

1-Phase 240V Loads (1Φ-240V)
1. Hot Water Circulation pump: 240V, 6A
2. Future Loads (Receptacles): 240V, 20A
3. Feedstock Loading (Receptacle): 240V, 20A
4. Centrifuge (Receptacle): 240V, 20A
5. 10kW Aux. Heater: 240V @ 42A
6. 10kW Aux. Heater: 240V @ 42A
7. LFG Chiller, 240V. 3.3A
8. Chill water circulation pump, 0.49A

1-Phase 120V Loads (1Φ-120V)
1. NIRS spec (receptacle): 120V, 20A
2. Ion Exchange pump (receptacle): 120V, 20A
3. Fill-Rite Transfer pump (receptacle): 120V, 20A
4. Zone 1 Pump1: 120V, 9.6A
5. Zone 2 Pump2: 120V, 2A
6. Zone 3 Pump3: 120V, 1.76A
7. Low Voltage Power Supply:120V, 2.6A
8. Low Voltage Power Supply: 120V, 2.6A
9. Waste water transfer pump (receptacle): 120V, 20A
10. Chill water 80 GPM circulation pump, 9.6A

Appendix J

Thermal Loads per 2,365 liter Batch

Tank(s)	Process	Volume (gal)	Starting Temp (F)	Desired Temp (F)	Thermal load (BTUs/batch)	Op. Time (hrs)	Btus/hr	Percent
P1	Distillation (FAME only)	550	95	150	215,531	3	71,844	25%
FS	Feedstock Settling	500	68	160	179,400	24	7,475	21%
	Chiller (absorption)				108,565	4	27,141	13%
P1	Transesterification	625	100	140	97,500	1.5	65,000	11%
P1	Feedstock vacuum dry	625	125	150	84,467	2	42,233	10%
PS	Ion Exchange	531	90	115	51,773	2	25,886	6%
F2	Acid Esterification-Settling	625	100	120	48,750	6	8,125	6%
P3	Water Wash	550	110	120	35,211	1	35,211	4%
P9	Water Treatment	212.4	75	105	24,851	3	8,284	2.9%
G1	Glycerin Storage	132.75	68	75	3,624	24	151	0.4%

Appendix K

GaBi Screenshot of Electricity Production Mix for Eastern United States