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WHY BIOBASED?

Opportunities in the Emerging Bioeconomy

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EXECUTIVE SUMMARY

This report explores the opportunities associated with the biobased economy (excluding fuel, food and feed). Much of the work relies upon prior literature. Some of the key findings include:

- Government policies and industry Business to Business sustainability programs are driving the biobased economy.
- Across the globe, nations are investing in Public/Private Partnerships to expand their biobased economy for domestic and international consumers.
- In the U.S., the United States Department of Agriculture (USDA) BioPreferred program and Federally-supported research continue to drive investment in research and development (R&D) and make available broader sets of biobased consumer products.
- While there is wealth of data and information regarding the economic impact of the bioeconomy in Europe and various nations, there is a lack of understanding and quantification of the economic benefits of the bioeconomy and specifically the non-fuel bioeconomy in the U.S.
- There are challenges facing the continued expansion of the bioeconomy. These include reliable availability of raw materials with increased climate and severe weather impacts, water availability, and stability of the markets.

The biobased economy is, in fact, growing, and it offers great potential for increased job creation in numerous sectors across the U.S.

- Continued investments are needed to establish a biobased infrastructure while ensuring that the economics of biobased feedstocks are competitive with existing, petroleum-based feedstocks.
- An economic impact model is required to study the potential impacts of the bioeconomy and policies that can encourage investment. Such a model should include many of the factors identified in this report and it should predict changes to a wide range of outcomes, for example, impacts on jobs, job creation, GDP, the environment, and national security.

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His research covers sustainable systems and production consumption systems of Earth resources using control theory and lifecycle modeling. Current areas of focus include risks and resiliency resulting from increased industrialization of terrestrial-based resources, rapid urbanization, and the interactions with environmental, economic, and social drivers. Dr. Golden received his Ph.D. in Engineering from the University of Cambridge, and his Master's degree in Environmental Engineering and Sustainable Development from a joint program of the Massachusetts Institute of Technology and the University of Cambridge. He also holds a Professional Mastery of Project Management Certificate from Stanford University, and he has a BA degree in Management.

In 2009, Dr. Golden was presented the Faculty Pioneer Award by the Aspen Institute for his leadership in the field of sustainability education & research, and he was named by Ethisphere as one of the 100 Most Influential People in Business Ethics. He was appointed to the UN Lifecycle Management Task Force, and he was named an AT&T Industrial Ecology Fellow. Dr. Golden is best known for founding and co-directing the Sustainability Consortium.

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GLOSSARY OF TERMS

PLA:	polylactic acid
PTT:	polytrimethylene terephthalate (from biobased 1,3-propanediol)
PHAs:	polyhydroxyalkanoates
PE:	polyethylene
PVC:	polyvinyl chloride
PBT:	polybutylene terephthalate
PBS:	polybutylene succinate
PET:	polyethylene terephthalate
PEIT:	polyethylene-co-isosorbide terephthalate polymer
PUR:	polyurethane

The greatest service which can be rendered any country is to add a useful plant to its culture - Thomas Jefferson (1800)

I. INTRODUCTION

Throughout human history, agriculture has been used for non-food purposes, including energy, clothing, shelter, medicines, and other everyday human needs. During the industrial revolution, people achieved great scientific and technological advances through the use of non-renewable resources, and the use of such resources has been and remains vital to the economy of the U.S. As an example, in the 1950s, the U.S. chemical and plastics industry was responsible for over 5 million U.S. jobs, and a $20B positive trade balance for the U.S. Jobs associated with the industry typically were among the highest paid in U.S. manufacturing (Landau and Arora, 1999).

The challenges of the twenty-first century have created new socioeconomic and resource challenges, including rapid population growth and urbanization, an expanding global middle class hungry for automobiles and modern technology, resource competition and scarcity, environmental protection and regulation, and more volatile economic cycles that impact all countries in the global economy. The emergence of these factors has served as the catalyst for the emergence of what is being termed the **Bioeconomy**. The Bioeconomy is characterized by a new generation of environmentally-friendly materials and products and economic opportunities for U.S.-based agriculture, chemical, and manufacturing sectors and their value chains, with far-reaching potential impacts on socioeconomic development and the resurgence of production in the U.S.

In this initial summary report we focused on Biobased Materials to the exclusion of Biobased fuels and energy sources. We examined the literature from governments, academia, and non-governmental organizations (NGOs) supplemented by a workshop and a survey to answer the following three primary questions:

1: What are the drivers and opportunities of the Bioeconomy?
2: Are there barriers and challenges to manage?
3: What gaps in knowledge must be addressed?

A. Defining the Bioeconomy

White House (2012). *"A bioeconomy is one based on the use of research and innovation in the biological sciences to create economic activity and public benefit."*

We define the Bioeconomy as:

The Bioeconomy is the global industrial transition of sustainably utilizing renewable aquatic and terrestrial resources in energy, intermediate, and final products for economic, environmental, social, and national security benefits.
Golden & Handfield, 2014

Organization for Economic Co-operation and Development (OECD 2009): *"From a broad economic perspective, the bioeconomy refers to the set of economic activities relating to the invention, development, production and use of biological products and processes. If it continues on course, the bioeconomy could make major socioeconomic contributions in OECD and non-OECD countries. These benefits are expected to improve health outcomes, boost the productivity of agriculture and industrial processes, and enhance environmental sustainability."*

The European Commission (2014): “*The Bioeconomy – encompassing the sustainable production of renewable resources from land, fisheries and aquaculture environments and their conversion into food, feed, fiber biobased products and bio-energy as well as the related public goods – is an important element of Europe’s reply to the challenges ahead. The Bioeconomy includes primary production, such as agriculture, forestry, fisheries and aquaculture, and industries using/processing biological resources, such as the food and pulp and paper industries and parts of the chemical, biotechnological and energy industries.*”

A 2012 release by the U.S. Biotechnology Industry Organization placed the national value of the Bioeconomy at $1.25 trillion. The European Commission (2014), estimated that the Bioeconomy is worth over $2.7 trillion, providing 20 million jobs and accounting for 9% of total employment in 2009.

B. Economic Value

Various studies have explored the global and domestic economic value of the bioeconomy. Biobased chemicals are expected to constitute over 10% of the chemical market by 2015 (OECD, 2009). Commercialized polymers, such as polylactic acid (PLA) and polyhydroxyalkanoates (PHAs), have already established strongholds in the market, with a per annum growth in the range of 10-30% (IEA Bioenergy). In 2012, PLA and starch-based polymers accounted for 47 and 41%, respectively, of total consumption of biodegradable materials (Michael Malveda and Kazuteru Yokose, 2012). Cargill and McKinsey & Company believe that there is potential to produce two-thirds of the total volume of chemicals from biobased material, representing over 50,000 products, a $1 T annual global market (Peter Nelson et al., 2010). Most of the growth will occur in specialty chemicals and polymers. Specialty chemicals alone, such as adhesives, surfactants, and solvents, would constitute 60% of the total value of all the biotech-based chemical production in 2025 (OECD, 2009). The global worldwide capacities of biobased plastics will increase to 3.45 million metric tons in 2020. Starch plastics would have a 38% share of global, biobased plastics capacity by 2020 (Li Shen et al., 2009). The market for industrial enzymes also will experience strong growth to 2015. Reiss et al. (2007) estimated that there would be 6.5% annual growth in the global enzyme market, with global sales of $7.4B in 2015.

C. Opportunities for the Rural Economy

The emerging bioeconomy has the potential to create unprecedented growth in the rural economy and create a higher level of self-sufficiency for farming and rural communities. In the current petroleum-based economy, many rural areas consume more energy than they produce. Consequently, rising energy costs have an adverse effect on the farming sector of the economy. However, the movement towards a bioeconomy can help rural areas exploit biomass materials to produce bioproducts and create an opportunity for continued economic growth. The conversion of lignocellulosic biomass is considered to provide maximum benefits to the rural economy. A recent study concluded that in a 98-county area in the Mid- South Mississippi Delta region, lignocellulosic feedstock processing utilizing 10% of cropland, 25% of idle lands, 25% of conservation reserve program land, and 15% of pasture land would support a biomass industry worth over $8B annually and create 50,000 jobs by 2030 in the study area alone (Tripp et al., 2009). However, the high cost of transporting biomass would necessitate the decentralization of biorefineries across rural areas. Local production of energy would simultaneously reduce the need to pay for the import of petroleum and the need to pay for the transportation of products to export destinations. By becoming bioenergy producers, manufacturers and companies that are the major consumers of processed energy would find rural areas more attractive than they did in the fossil fuel-based economy. Local businesses would have an advantage over urban centers to flourish since local transportation is always cheaper. Rural areas also are major sources of under-utilized agricultural material, such as crop residues, forest residues, and animal manure. Conversion of these materials to bioenergy would provide both economic and environmental benefits (Thomas G. Johnson and Ira Altman, 2014). If the cost of producing bioenergy becomes competitive with that of petroleum, rural economies will be positioned to realize significant benefits in the form of economic growth and potentially the resurgence of product manufacturing in America.

II. BIOBASED PRODUCTS

A. Chemicals

Biobased products are both commercial and industrial products that are composed in whole, or in significant part, of biological products or renewable domestic agricultural materials or forestry products (USDA, 2006). While much of the focus on the bioeconomy has been on biobased fuels and energy sources, we are focused on manufactured goods. However, one cannot simply exclude the energy and fuel sectors because both infrastructure and co-products are part of an integrated bioproducts system. Consider that 96% of all goods manufactured in the U.S. incorporate a chemical product, accounting for almost $3.6T of the U.S.'s GDP (Milken Institute, 2013). This provides unique opportunities to create a wide range of biobased chemicals that could improve the environmental performance of those products while also stimulating the U.S. economy. Shifting 20% of the current plastics produced in the U.S. into bioplastics could create about 104,000 jobs in the U.S. (Heinz and Pollin, 2011).

A1. Biopolymers – non-plastic specific

Biopolymers are partial replacements for petrochemical-derived materials. Biopolymers are macromolecules derived from plants, trees, bacteria, algae, or other sources, and they are long chains of molecules linked together by chemical bonds. Biopolymers occur naturally, and they can be produced through several different processes, such as the genetic modification of plants, starch conversion, or microbial conversion. The most commercially-available biopolymer, PLA, is produced from lactic acid through the fermentation of dextrose, which is extracted from a starch source material. Starch is a carbohydrate that consists of a large number of glucose units joined by glycosidic bonds. Starch is produced by most green plants as a means of storing energy. It is the most common carbohydrate in the human diet, and it is contained in large amounts in such staple foods as potatoes, wheat, corn, rice, and cassava.

Currently, most biopolymers are made in large biorefinery systems (Sustainable Biomaterials Collaborative, 2014). Biobased polymers may be divided into three main categories based on their origin and production. Category 1 includes those derived from polysaccharides, such as starch or chitin; category 2 includes those produced from classical chemical synthesis using renewable, biobased monomers (which includes PLA); and category 3 includes those produced by microorganisms or genetically-modified bacteria, such as PHAs (Mukherjee and Kao, 2011).

Many new biopolymers are being developed every year. For instance, a recent development was the production of nanocellulose particles from biomass in various ways (Ericksen and Washington, 2014). Potential applications of nanocellulose particles include recyclable electronics, biobased plastics, paper and packaging materials with improved surfaces, flexible cement, automotive and aircraft components, and protective armor. The Office of Science and Technology in the White House has projected that the economic growth associated with just one application – cellulose nanomaterials in the paper industry – could create as many as 425,000 jobs in the U.S. by 2020. The U.S. government is strongly urging investors to explore the development of this technology.

The global polyethylene terephthalate packaging market will be worth $60B by 2019 and account for almost 20 million tons. The question is: Will there still be room for lightweighting of materials beyond 2019?

Smithers Pira (2014), Environmental Leader (2014)

A2. Bioplastics[1]

In the past, plastics have been derived primarily from petrochemicals, but there is a significant expansion in the replacement of synthetics with biobased plastics. There are two general types of plastics, i.e., thermoplastics and thermoset plastics, also known as 'thermosets.' Thermosets melt and take the shape of the mold, and, after they have solidified, they maintain that shape. The chemical reaction is irreversible. Conversely, as presented in Table 1, thermoplastics do not undergo changes in their chemical composition when they are heated, so they can be molded again and again. Both types of plastics can be produced from renewable resources.

Bioplastics are plastics made in whole or in part of renewable resources. They include starch plastics, cellulosic polymers, PLA, polytrimethylene terephthalate (PTT) from biobased 1,3-propanediol (PDO), polyamides (nylon), polyhydroxyalkanoates (PHAs), polyethylene (PE), polyvinyl chloride (PVC) from biobased PE, other biobased

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[1] Adapted and partially sourced from Biochem, 2010

thermoplastics (polybutylene terephthalate (PBT)), polybutylene succinate (PBS), polyethylene terephthalate (PET), polyethylene-co-isosorbide terephthalate polymer (PEIT), polyesters based on PDO, polyurethane (PUR) from biobased polyols, and biobased thermosets. Globally, bioplastics make up nearly 300,000 metric tons of the plastics market. While this is a significant quantity, bioplastics account for less than 1% of the 181 million metric tons of synthetic plastics produced worldwide each year. While the bioplastic market is growing by 20–30% per year, this growth may not be sufficient to meet demand. For a few years, natural food purveyors, such as Newman's Own Organics and Wild Oats, have been using some PLA products, but the material got its biggest boost when Wal-Mart, the world's largest retailer, announced that it will sell some produce in PLA containers (Nampootheri, Nair, and John, 2010).

Thermoplastics	**Thermosets**	**Elastomers**
Polyethylene	Phenolics	Polyisoprene (natural rubber)
Polypropylene	Polyesters (unsaturated)	Polybutadiene (synthetic rubber)
Polyvinyl chloride	Epoxies	Polyurethane (foams, spandex)
Polystyrene	Polyurethanes	Ethylene-propylene-diene terpolymer (EDPM rubber)
Acrylonitrile butadiene styrene (ABS)		Polysiloxanes
Acrylics		
Celluloid		
Cellulose acetate		
Polyacetal		
Polyesters (PET, PBT)		
Polyamides (nylons)		

Table 1. Conventional polymers (2013): Source: Informa Economics (2006)

Bioplastics have been accepted in the market and sometimes may even bring premium prices. Braskem SA, a São Paulo-based petrochemical giant, sold out of its green polyethylene in three months, receiving a premium price for it (Verespej, 2011).

The following paragraphs provide information on some of the most common bioplastics. Newer and niche polymers have had more challenges gaining significant market share, and there is little evidence that they can attain a sustainable premium price.

Biobased Polymers		Average Biomass Content of Polymer
Cellulose Acetate	CA	50%
Polyamide	PA	Rising to 60%
Polybutylene Adipate Terephthalate	PBAT	Rising to 50%
Polybutylene Succinate	PBS	Rising to 80%
Polyethylene	PE	100%
Polyethylene Terephthalate	PET	Up to 35%
Polyhydroxy Alkanoates	PHAs	100%
Polylactic Acid	PLA	100%
Polypropylene	PP	100%
Polyvinyl Chloride	PVC	43%
Polyurethane	PUR	30%
Starch Blends (in plastic compounds)		40%

Table 2. Average biomass content of polymers

A2a. Polylactic acid (PLA)

As Table 2 shows, PLA is one of many biobased polymers. An important feature of starch produced by green plants is its potential enzymatic hydrolysis into glucose and subsequent fermentation into lactic acid. PLA can be obtained from this fermentation product via direct condensation or via its cyclic lactide form. PLA has been fabricated into fibers, films, and surgical implants and sutures. Currently, most PLA is produced by Natureworks® (Cargill-PTT Global Chemical), which produces 136,000 metric tons per year in its plant in Nebraska (Mooney, 2009). The advantageous properties of biobased PLA are that it is renewable, biodegradable, recyclable, compostable, biocompatible, and processable, and it saves energy. However, PLA has poor toughness, slow degradation, and hydrophobicity, and it lacks reactive side-chain groups (Rasal et al., 2010). The main concern with PLA is its price. On an industrial scale, producers are seeking a target manufacturing cost of lactic acid monomer to less than $0.8/kg because the selling price of PLA should decrease roughly by half from its present price of 2.2 $/kg.[2] According to the cost analysis, the base manufacturing cost of lactic acid was estimated to be 0.55 $/kg. There are several issues that must be addressed for the biotechnological production of lactic acid, such as the development of high-performance lactic acid-producing microorganisms and reducing costs of raw materials and fermentation processes (Nampootheri, Nair, and John, 2010).

A2b. Polyhydroxyalkanoates (PHAs) are linear polyesters produced in nature by bacterial fermentation of sugars or lipids. They are produced by the bacteria to store carbon and energy. PHAs can be used for the manufacture of films, coated paper, and compost bags; they also can be molded into bottles and razors (Mooney, 2009). Co-polymers of PHAs are more useful for industry, since they exhibit lower crystallinity and easy processability; also, the final products are very flexible.

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[2] This cost is for a 10^8 lb/yr plant in the midwestern U.S. with carbohydrate raw material priced at $0.06/lb. The cost can vary based on the raw material, technology, plant size and percentage change in capital investment. Technological and economic potential of polylactic acid and lactic acid derivatives is discussed in (Datta et al., 1995).

A2c. Plant oils are primarily triacylglycerides that can be used directly for the synthesis of a variety of polymers. For instance, they have been used in the synthesis of coatings, often avoiding additional costs and the time associated with the modification of the starting materials (Derksen et al., 1995). A wide range of polymerization methods have been investigated, including condensation, radical, cationic, and metathesis procedures. The scope, limitations, and possibility of utilizing these methods for polymer production from triacylglycerides were reviewed by Güner and co-workers (2006). The primary sources of oils are soybeans and Castor plants.

A2d. Fatty acids (FA) and fatty acid methyl esters (FAME) can be used directly or after functionalization as monomers for the synthesis of a variety of polymeric materials. The most important functionalization possibilities of the double bonds and the ester groups have been reviewed extensively in the literature (Biermann et al., 2001, 2007; Biermann and Metzger, 2004). There are encouraging carbohydrate-based and plant oil-based polymers that could substitute, at least partially, for the mineral oil-based materials that are currently in the market. Although some renewable polymeric materials already have been commercialized, others are still not economically feasible for large scale production (Türünç and Meier, 2012).

A3. Biolubricants (also see Biosynthetics). These can be either vegetable-based oils, such as rapeseed oils or synthetic esters manufactured from modified oils and mineral oil-based products. Example end product usage includes aviation, automotive, and marine applications, as well as power tool lubricants and drilling fluids.

A4. Biosolvents are soy methyl ester (soy oil esterified with methanol), lactate esters (fermentation-derived lactic acid reacted with methanol or ethanol), and D-limonene, which is extracted from citrus rinds. One of the primary benefits of biosolvents is that they do not emit volatile organic compounds (VOCs) that are of concern from the perspectives of workers' safety and adverse environmental impacts. Biosolvents primarily are used as degreasing agents for metals and textiles, and they also are used to strip household paint, to remove glue, and as diluents for paints and pesticides. They also are used as extraction solvents in perfumes and pharmaceuticals.

A5. Biosurfactants. Oleochemical surfactants generally are derived from plant oils, such as palm oil and coconut oil and from plant carbohydrates, such as sorbitol, sucrose, and glucose. These surfactants are used to make household detergents, personal care products, food processing products, textiles, coatings, pulp and paper products, agricultural chemicals, and industrial cleaners.

A6. Other Biosynthetics. Many research efforts and trials are being conducted to replace petrochemically-produced ingredients, such as isoprene that is used in manufacturing synthetic rubber, with renewable biomass, i.e., BioIsoprene™. Examples of biosynthetic end products include car tires, passenger car motor oils, marine lubricants, wind turbines, food grade lubricants, dielectric fluids, refrigeration coolants, and personal care products, such as skin-care and hair-care products and decorative cosmetics.

B. Co-Products

Co-Products will have an increasingly important role in the economic growth and profitability of biobased products. In part, this will likely follow the value chain development of the petroleum sector, which was able to obtain co-product benefits from over 6,000 petroleum-derived co-products, such as alkenes (olefins), lubricants, wax, sulfuric acid, bulk tar, asphalt, petroleum coke, paraffin wax, and aromatic petrochemicals that are used for production of hydrocarbon fuels and hydrocarbon chemicals (Sticklen, 2013).

B1. Biofuel co-products

In addition to the primary biobased feedstocks presented in Figure 1, co-products also can provide opportunities. Biofuels have provided an answer to our increasing demand for energy. However, the production of biofuels generates vast amounts of residues/wastes. These include vinasse, bagasse from sugarcane, sugar beet-based ethanol plants, and silage from corn-, cassava-, and sorghum-based ethanol plants, lignin from cellulose-based ethanol plants, and seed cakes and glycerol from biodiesel plants. To make biofuel economically competitive, it is imperative to reuse these co-products (Devin Takara et al., 2010). Recent research has enhanced this aspect of some of these methods. Bagasse, the fibrous residue generated by cane-based ethanol plants, can be used to produce heat/steam and electricity for in-plant use (Waclawovsky et al., 2010).

Similarly, bagasse produced from other sources, such as sorghum, also can be used for in-plant electricity production. Sorghum bagasse also can be used as animal feed. Wang and Hanna et al. (2009) determined that 107% and 75% of the heat and power cost associated with the conventional use of natural gas and grid electricity, respectively, can be attained by integrating the heat and power systems and utilizing corn stover and distiller grain in the ethanol plant.

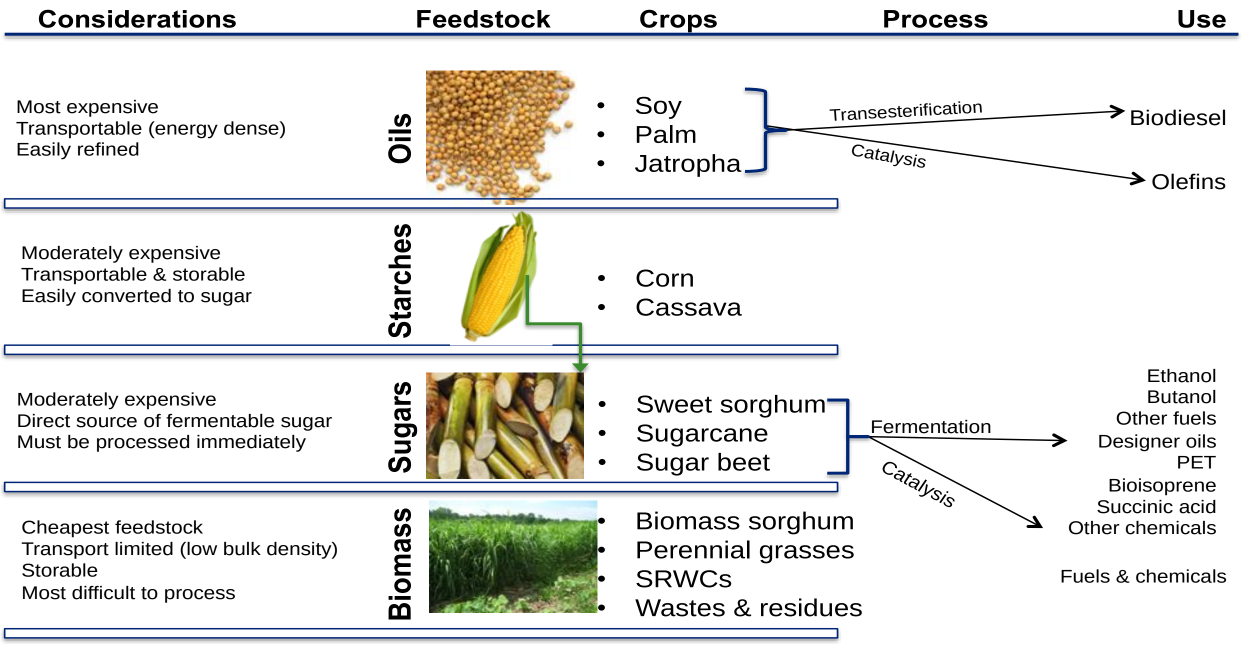

Figure 1. Considerations related to biobased feedstock: Adapted from A. Rath (2012)

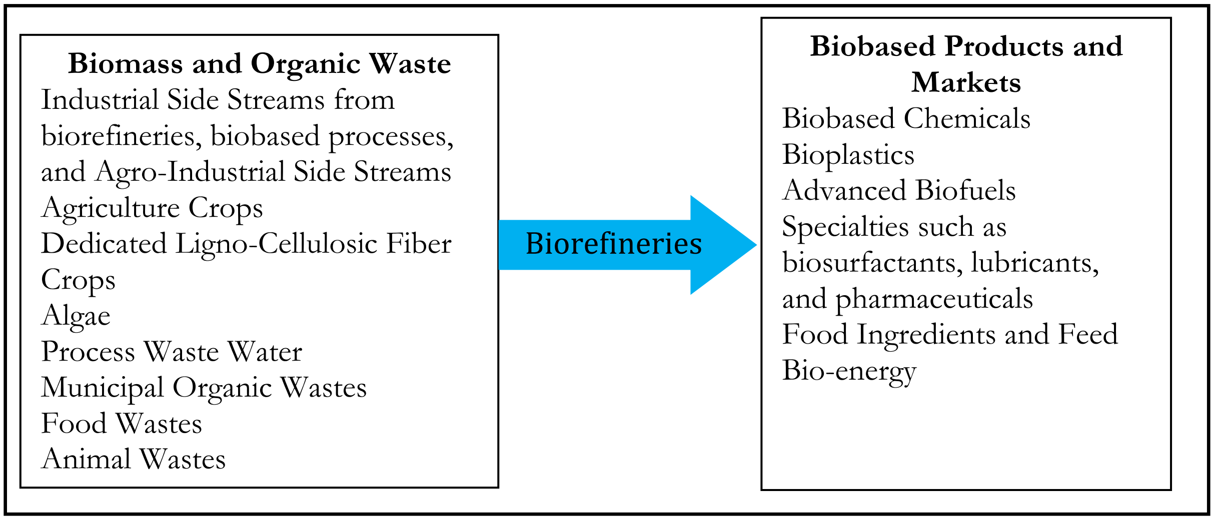

Figure 2. Biobased co-products: Adapted from Bridge (2002)

Vegetable oil-based and animal fat-based biodiesel contains esters that cannot be degraded by conventional wastewater treatment methods. Microbial fuel cells, which convert chemical energy to electrical energy, use microorganisms as catalysts to oxidize organic and inorganic matter and produce electrical energy (Logan et al., 2006). A recent study by Yujie Feng et al. demonstrated the use of microbial fuel cells to simultaneously treat biodiesel waste and generate electricity.

Third-generation biofuels derived from microalgae are also a source of several co-products that are useful commercially (Liam Brennan and Philip Owende, 2009). Microalgae biomass, such as Chlorella, is marketed as a food additive in health food markets because of its nutritional value. Algae biomass also is used as feed for animals and for the aquatic organisms in aquaculture. Microalgae are a rich source of polyunsaturated fatty acids (PUFAs), which have numerous health benefits. Currently, PUFAs are found only in fish and fish oil, which has an unpleasant taste and odor. Microalgae can be used as a potential PUFA resource in infant formulas and nutritional supplements.

C. Biopharmaceuticals

Biopharmaceuticals are not part of this evaluation due to the complexity of this sector, but they have a significant impact on the economy. According to Pharma (2013), the U.S. biopharmaceutical sector employs more than 810,000 workers, supports a total of nearly 3.4 million jobs across the country, and contributes nearly $790B in economic output on an annual basis when direct, indirect, and induced effects are considered. The U.S. biopharmaceutical sector accounts for the single largest share of R&D among all U.S. businesses, representing nearly 20% of all domestic, business-funded R&D according to data from the National Science Foundation. Biotech products, such as bioengineered vaccines and biologics, were 21% of the worldwide market for prescription and over the counter product sales in 2012, and, by 2018, they are projected to account for 25% of this $858B sector. Also, 51% of the sales of the top 100 products in 2018 will be biobased (Evaluate Pharm 2013).

D. Microorganisms and Enzymes

This broad category includes microorganisms, enzymes, and peptides. Enzymes are biologically produced proteins that catalyze chemical processes without being altered or destroyed themselves. Bioprocessing utilizes the ability of enzymes to catalyze chemical transformations to produce a variety of chemicals. Enzymes are used industrially to process foods, textiles, leather goods, pulp and paper, grains, and detergents. Enzymes typically are produced biologically by the fermentation of a carbohydrate substrate.

E. Inks and Dyes

Currently, over 90% of U.S. newspapers and 25% of commercial printers use soy-based ink toner for printers and copiers, ink for ballpoint pens, and lithographic inks that are UV curable. The market share for vegetable oil-based inks increased from 5% in 1989 to approximately 25% in 2002 (Freedonia Group, 2001; Informa Economics, Inc., 2006).

F. Consumer Products

While the listing of biobased products that are available to consumers is too extensive to present in its entirety, Table 3 provides some indication of the vast variety of such products.

HOUSEHOLD FURNISHINGS	**HOUSEHOLD SUPPLIES**	**PERSONAL CARE**	**AUTOMOTIVE SECTOR**	**CONSTRUCTION SECTOR**	**FOOD SECTOR**
Bedding and Bed Linens	Laundry Detergents	Apparel	Car Tires	Acoustic Panels	Food Containers at Sporting Events
Towels	Bathroom Tub and Tile Cleaners	Textiles	Soy - Based Foam for Automotive Seats	Structural Wall Panels	Food Containers at Restaurants
Tableware	Fertilizers	Footwear	Acoustical Products	Plastic Lumber	Water Bottles
Upholstery	Paint Strippers	Shampoo and Conditioners	Structural Foam	Interior Panels	Other Bioplastic Bottles
Soy Wax Candles	Hydraulic Fluids	Lip balms	Seat Cushions	Insulating Foams	Disposable Cutlery
Carpets	Mold and Mildew Removers	Cosmetics	Sunshades	Non-Food Disposable Containers	
Carpet Backing	Lubricants	Soap Bars for Algal Oils	Headrests	Concrete and Asphalt Release Fluids	
Furniture Protectors	Dry Erase Board Cleaner	Pet Shampoo	Headliners	Floor Strippers	
Soy - Based Foam for Household Furniture	Household Cleaning Solvents	Deodorants	Armrests	Wood and Concrete Sealers	
Computer Plastics	Soy Ink Toner Cartridges for Printers	Sun Care Products	Elastomers	Household Insulation	
Electronic Plastics	Household Paints	Shaving Products		Decorative Composites	
Lignin - Based Printed Wiring Boards	Stainless Steel and Glass Cleaners	Lotions		Mold and Trim	
Electronic Acoustic Foams	Drain and Septic Tank Cleaners	Moisturizers		Adhesives	
Wall Coverings	Floor Cleaners	Hand Cleaners		Films	
Window Coverings	Insecticides	Razors			
Natural Furniture	Wood Sealant and Waterproofing				
Biobased Polyurethane Refrigerator Insulators	Wood Stains				
Toys	Air Fresheners				
Cellulose - Based Batteries (in development)					

Table 3. Examples of consumer-related biobased products

While there is recent data and information regarding the economic impact of the bioeconomy in Europe and various other nations, more timely information is needed to document the benefits of the bioeconomy to the overall US economy.

III. OPPORTUNITIES

In general, many of the nations in the world anticipate long-term opportunity for the Bioeconomy, in part due to the growing pressure on food and water supplies, climate change mitigation, and healthcare, as well as the increased focus on more sustainable products and energy sources. In 2009, the Public Policy Forum (PPF) convened over 100 experts from Canada for a dialogue on the opportunities for Canada with regard to a Bioeconomy. They agreed that the opportunities were "significant," namely through the integration of biomaterials into manufacturing value chains (Lister, 2009). Similarly, the European Union (EU) and its 28 member countries have been among the most active national bodies exploring and advancing the concept of a Bioeconomy.

In a 2010 report prepared for the European Commission, a potential global bioplastics market of 4.5 metric tons was projected by 2020, up; from 0.75-1.5 metric tons in 2009. It has been estimated that the consumption of lubricants in the EU will increase by 3.6% by 2020, up from 0.15 metric tons in 2009 to 0.23 metric tons in 2020. Biosolvent use in the EU is expected to increase from 0.63 metric tons in 2008 to 1.1 metric tons by 2020. The production of biosurfactants is expected to reach 2.3 metric tons in the EU by 2020, up from 1.52 metric tons in 2008 (Biochem, 2010). The European Bioplastics Association has estimated that 42 of the 50 metric tons/year (85%) of polymer consumption in Western Europe could be bioplastics (van der Pol, 2011).

In addition, in 2013, the EU proposed that it partner with an industry consortium, including Unilever, Cargill, Solvay, Sappi, Stora Enso, Smurfit Kappa, and others, in a public-private partnership (PPP) to accelerate the deployment of biobased products. This led to an eventual $5B Biobased Industries Joint Technology Initiative to "convert R&D leadership into new products and new markets. It is about reaping the benefits of a global biobased market of $272.3B by 2020[3] (Biobased Industries Consortium, 2014).

A. Public Opinion

In 2011, the EU Commission conducted a public on-line survey to allow industry, academia, and the general public to comment on the future potential of the bioeconomy (EU Commission, 2012a, 2012b). The respondents identified the following three main advantages of a Bioeconomy for the EU:

1. **Strengthening R&D (63.5%)**
   - new integrated structures between researchers and research funders, further research and innovation excellence in Europe, European leadership through knowledge and technology transfer, and economic and employment stimulus to rural and regional development.

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[3] See fact sheet referenced for a comprehensive listing of the drivers and goals for the PPP.

2. **Securing a sufficient supply of food and biomass (56.9%)**

- contribution to global food security, new agricultural practices to avoid competition between food and non-food use of biomass, and improved animal health and welfare.

3. **Supporting biobased markets and the creation of economic growth and high-skill jobs (52.8%)**

- new business opportunities, higher potential for value creation through cascading use of biomass and reuse of materials, and EU global market leadership.

More than 3,000 companies in the U.S. either manufacture or distribute biobased products. Senator D. Stabenow, Chair, Senate Agriculture Committee, June 17, 2014 Hearing

B. Job Creation

There is very little literature regarding the economic and job creation opportunities of the Biobased economy in the U.S. Most literature refers to the USDA's report (2008) entitled "U.S. Biobased Products Market Potential and Projections Through 2025," which was based on data from 2006 and focused on biofuels, biobased chemicals, and biobased end products. Utilizing the USDA report, in part, as a platform, the U.S.-based Biotechnology Industry Organization (BIO) indicated that U.S.-based jobs for renewable chemicals and biobased products will increase from approximately 40,000 jobs in 2011 for the biochemical/product sector, which represents 3%-4% of chemical sales, to more than 237,000 jobs by 2025, which would represent approximately 20% of total chemical sales (Bio, 2012).

C. Economic impact

Around the world, over $400B worth of conventional manufacturing products are produced each year using biomass. The European Union estimates that the sectors that comprise the Bioeconomy account for 22 million jobs, which is approximately 9% of the EU's workforce (European Commission, 2012; European Bioplastics, 2012). Aided by the stabilization in glycerin prices, the biobased chemical sector achieved a market value of $3.6B in 2011.

By 2021, SBI Energy forecasts that the global market for biobased chemicals will have increased to $12.2B, accounting for 25.4 billion pounds of biobased chemical production at the end of the decade (SBI Energy, 2012). According to European Bioplastics (2013), global production of bioplastics is expected to increase by 500% by 2016.

It is anticipated that the transition of the bioeconomy will provide many environmental advantages. Bang et al. (2009) estimated that, by 2030, the use of biobased fuels and chemicals could prevent between 490 and 1,790 million metric tons of carbon dioxide from reaching the atmosphere every year. When utilized in place of fossil fuels, sugarcane-based and cellulosic ethanol can reduce greenhouse gas (GHG) emissions by more than 75%.

D. Price comparisons

A recent report by the Nova Institute (Dammer et al., 2013) stated that finding clear information on prices for biobased plastics was difficult because no database was available. The analysis provided in their report was based on information acquired from market experts. The comparison showed that, in general, the price of biobased plastics is higher than the price of fossil-based plastic. During the period of 2006-2009, the prices of PLA ranged between $2 and $3 per kg. PLA from GMO-free raw material cost even more: $4-6 per kg. NatureWorks LLC, headquartered in Minnesota, is the world's first large-scale producer of PLA (Li Shen et al., 2009). NatureWorks LLC supplies PLA to its large-volume customers at $2.60/kg ($1.2/lb).

NatureWorks views PLA prices moving towards commodity polymer prices. Studies suggest that, in the future, use of lignocelluloses from corn stover can help bring down the cost of producing PLA. It also is expected that large scale production of cellulosic ethanol would bring down the prices of the enzymes used in the fermentation process and help reduce the cost of producing PLA.

Even though they are more expensive than fossil-based alternatives, biobased plastics have become successful in the market. This willingness of consumers and investors to pay a higher price for biobased products, which is known as the 'green premium price,' depends on two factors: consumer preferences (e.g., biobased packaging for organic foods) and manufacturing image and marketing strategies (e.g., Coca Cola's biobased bottles). (Dammer et al., 2013).

Our 2020 goals include replacing 25% of petroleum-based raw materials with sustainably sourced renewable materials for our products and packaging. Procter & Gamble (2014)

IV. DRIVERS

In reviewing the literature, two specific entities seem to be driving the future of the Biobased economy (i.e., – national governments and sector-specific industrial associations). Much of the literature that has explored the implications of the global expansion of the Biobased economy has been prepared by academic researchers, non-governmental organizations (NGOs), and, to some extent, governmental agencies. In this brief overview report, we provide a summary of the information that the current literature is providing the community concerning the future of the Bioeconomy.

A. Governmental Drivers

Section 9002 of the Farm Security and Rural Investment Act (FSRIA) of 2002, Public Law 107-171 (U.S. Farm Bill, 2002) authorizes USDA to designate biobased products for federal preferred procurement. The U.S. Farm Bill requires federal agencies to purchase biobased products designated for preferred procurement under the BioPreferred program, except as provided by Federal Acquisition Regulation (FAR) Part 23.404(b). In general, federal agencies are required to give preference to items with the highest percentage of biobased content when purchases exceed $10,000 per fiscal year, as prescribed by 7 CFR 3201.3.

In addition to the preferred procurement program, the 2002 Farm Bill authorized USDA to implement a program to certify biobased products deemed eligible to display the "USDA Certified Biobased Product" label. The presence of the label indicates that the products have been tested to determine their biobased content and have met the established minimum content for the product category in which the product falls. The BioPreferred program was continued and strengthened under subsequent U.S. Farm Bills in 2008 and 2014.

In addition to expansion of the BioPreferred program, the 2014 U.S. Farm Bill provides loan guarantees for biorefinery projects and funds for biomass research and development.

Beyond the BioPreferred program, there are other governmental drivers meant to expand the Bioeconomy in the U.S. Executive Order 13514 (October 5, 2009), signed by President Obama, made it a requirement under section 2h that Federal agencies ensure that 95% of new contract actions, including tasks and delivery orders (excluding weapons), include biobased requirements (Federal Register, 2009).

On February 21, 2012, President Obama issued a Presidential Memo directing federal agencies to effectively execute federal procurement requirements for biobased products, including those requirements identified in Executive Order 13514 and prescribed in the Farm Bills.

Also, on April 26, 2012, President Obama announced the development of a National Bioeconomy Blueprint (White House, 2012). The overarching goal of the Blueprint is to "strengthen bioscience research as a major driver of American innovation and economic growth" through five strategic imperatives (White House, 2012):

1. Support R&D investments that will provide the foundation for the future bioeconomy.
2. Facilitate the transition of bioinventions from the research lab to the market, including an increased focus on translational and regulatory sciences.
3. Develop and reform regulations to reduce barriers, increase the speed and predictability of regulatory processes, and reduce costs while protecting human health and the environment.
4. Update training programs and align academic institutions' incentives with student training for national workforce needs.
5. Identify and support opportunities for the development of public-private partnerships and pre-competitive collaborations in which competitors pool their resources, knowledge, and expertise to learn from each other's successes and failures.

B. Industry Drivers

In addition to regulatory pressures, many firms are beginning to use biobased technologies, in part due to both private and institutional pressures and perceived competitive advantages in both costs and green marketing to consumers.

Two drivers of the growth of the Bioeconomy are exemplified by the launching of The Sustainability Consortium (TSC) and the Sustainable Apparel Coalition. Formed in 2009, the Walmart-led TSC now has over 150 of the world's largest retailers, brands, and manufacturers from various sectors that are using the strength of their combined purchasing power to drive their vast global supply chain to improve the environmental performance of the consumer products that are manufactured and sold around the globe. While smaller in number, the Sustainable Apparel Coalition (SAC) comprises a large segment of the global apparel, textile, and footwear industries. Both the TSC and SAC utilize Lifecycle modeling or Lifecycle-inspired approaches to quantify the impacts of the resources and manufacturing practices that are used. Both of these efforts have resulted in various projects among suppliers to utilize biobased feedstocks in lieu of non-renewable resources for various products, such as household cleaners, spandex, and plastics.

In addition, in 2012, five major firms, i.e., Nike, Procter & Gamble, Coca-Cola, Heinz, and Ford, formed a pre-competitive collaborative to accelerate the development of biobased products (P&G, 2012). In many ways, this resulted from the successful trials by each of the partner firms. One such highly visible example was Coca-Cola's launch in 2009 of biobased PET bottles. Marketed as Coke's "PlantBottle™", over 15 billion bottles have been sold in more than 25 countries. Coke is using a PET resin containing biobased monoethylene glycol (MEG), which comprises approximately 30% of the bottle (European Bioplastics, 2013). The firm has been able to point out to its customers and its competitors that its trial of the PlantBottle™ in 2010 eliminated almost 30,000 metric tons of carbon dioxide – an impact equivalent to reducing the combustion of oil by approximately 60,000 barrels (Coca-Cola, 2012). Another example is Ford's trial of soy seats in over one million vehicles, which reduced use of petroleum by one million pounds, while concurrently curbing carbon dioxide emissions by five million pounds annually (Ford, 2008). By 2010, over one million Ford vehicles contained soy foam products.

C. Consumer Drivers

A recent survey of consumers was conducted by Van Winkle et al. (2013) to determine 1) consumer awareness and perceptions of bioproducts and their labels, 2) the characteristics of current bio-product purchasers, and 3) consumers' willingness-to-pay for bioproducts. The results indicated that there was a mixed image of bioproducts and a high level of uncertainty regarding the benefits and risks of using agricultural products as an alternative to petroleum. The respondents cited pesticide use and food security as their primary concerns. Consumers' uncertain opinions of bioproducts are likely the result of a lack of exposure to information about bioproducts. In addition, the survey showed that, on average, consumers are willing to pay 10% more for household products and packaged goods made from biologically-derived plastic alternatives, although they did not feel strongly that bioproducts were of better quality than traditional products. This finding suggested that consumers are purchasing bioproducts for reasons other than quality.

The presence of the USDA Certified Biobased Product label is also believed to be a driver among consumers. While the labeling program has been existence for only three years, much progress has been made to educate consumers as to the meaning of the label and also to educate manufacturers of biobased products of the potential benefits of displaying the label on their products. As the labeling program is implemented, consumers will come to realize that the presence of the label provides assurance that the product has been evaluated and certified by USDA as having a significant biobased content.

D. Non-Government Organizations

Non-governmental organizations are also influencing the Bioeconomy, both in its future expansion as well as to identify and mitigate risks. In July 2011, Greenpeace launched its Detox Campaign (Greenpeace, 2014) targeting the global apparel sector and toxic wastewater discharges. One of the manufacturing stages that this impacts is in the coloring/dyeing of apparel using petroleum-based synthetic pigments and dyes.

E. Role of Shale Gas

Shale gas is expected to drive ethylene prices lower for the foreseeable future. The price of natural gas has decreased significantly since 2008. Shale gas is less useful than fossil oil in the production of many commercial chemicals because it has less of the aromatic compounds required for their manufacture. Aromatic compounds form a base material for many chemical applications, (e.g., aromatic phenol) which is used in the chemical industry to produce high-grade synthetics, such as polycarbonate. Estimates for shale gas replacement of other fossil fuels vary (Platts, 2013), but it generally is anticipated that it will place market pressure on aromatics (Biorizon, 2013). Furthermore, the market for aromatics is increasing by 5 to 10% annually. This also applies to biobased raw materials for which demand is increasing while the supply is decreasing. Overall, it is expected that there will be negative implications for biobased ethylene, propylene, and monoethylene glycol. Yet, benefits are expected for biobased n-butanol, isobutanol, paraxylene, adipic acid, butadiene, isoprene, 2,5-furandicarboxylic acid and farnesenes (ICIS, 2013). The relative benefits and disadvantages for different chemicals from economic and environmental standpoints are not yet fully known.

One of the challenges for the biobased economy is to achieve production efficiency that can compete with fossil-based products. New scale-efficient product supply chains have to be created, or current supply chains have to be amended to incorporate the biomass supply chain. These new supply chains are more complex in nature than existing ones. In some cases, reliability of supply and quality of biobased raw materials can cause producers and users to choose a less risky alternative. (EU Taskforce on Biobased Products, 2007; LEI, 2012)

V. SYSTEM IMPLICATIONS

While much of the literature that we have reviewed and summarized provides either commodity or product estimates for production and growth, there is a need for a more robust system analysis of the biobased economy. Much of the literature has focused on chemicals, fuels, and plastics, with less attention paid to many other sectors and sub-sectors, such as textiles, apparel, footwear, construction, automotive, household cleaners, packaging, and electronics. Very little work has been done to quantify the current growth and anticipated future growth of these segments of the market. Similarly, while our review identified various environmental and social impacts associated with the Bioeconomy, there is a need to more effectively “back-cast” the flows of primary resources from the final assembled product to the biological resources used to produce it, including the spatial distributions of those resources and the risks associated with U.S.-based companies’ ability to acquire the needed crop-based raw materials over the long term.

Figure 3 shows global trends in food, population, energy, and manufactured products are interrelated. As presented in this report, these trends have led to increased demand for biofeedstocks. These resources are subject to uncertainties, including climate change, the availability of water, changes in land use, and national security. The result is that the Bioeconomy faces various types of feedback from the system, including shifting resources, changing markets, and various unintended consequences.

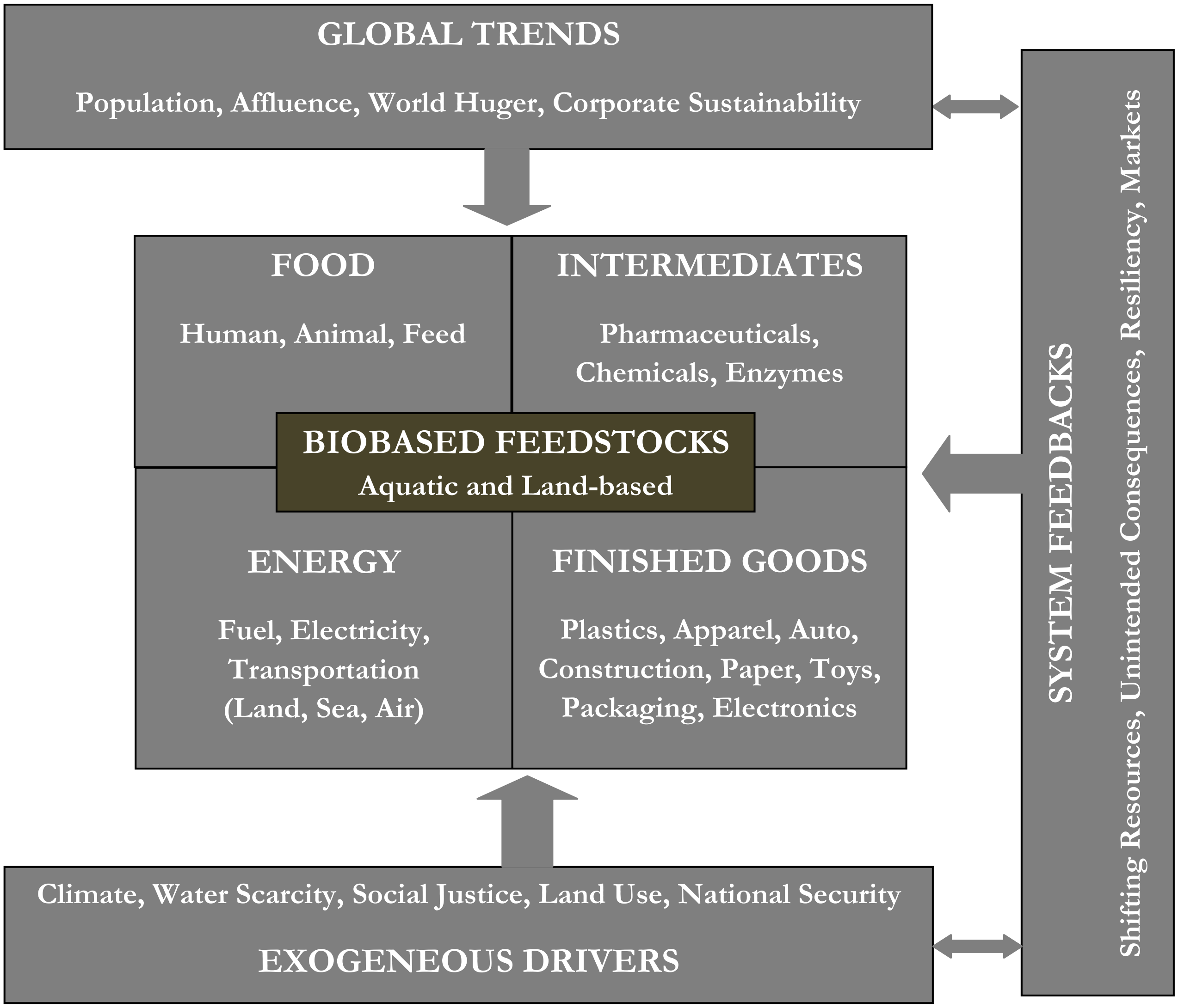

Figure 3. Interactions of the Bioeconomy system

Assessing the broad impacts of policy and technology choices is a formidable challenge, as exemplified in the lifecycle analysis of the implications of alternative energy and mobility technologies. Several research groups are using dynamic modeling techniques, including biocomplexity and system dynamics, to investigate the impacts of major shifts, such as climate change and the associated policy and technology responses, on ecological and human systems (Fiksel, 2006). O'Shea et al. (2012) pointed out the limitations of traditional lifecycle assessment (LCA) methods regarding ecological services, and they presented emerging developments to improve on LCA for resources and ecosystems.

Although, in principle, bioplastics seem to offer a viable solution for sustainable products for the future, there has been significant debate concerning the cradle-to-grave LCA of renewable feedstock-based polymers, and whether such polymers are beneficial or harmful to the environment (Vink et al., 2003; Patel et al., 2005; Tabone et al., 2010). Vink et al. (2003) provided an overview of applications of LCA to the production of PLA and provided insight into how PLA is used. Tabone et al. (2010) conducted a study in which they evaluated the efficacy of green design principles such as the "12 Principles of Green Chemistry" and the "12 Principles of Green Engineering" with respect to environmental impacts determined by using the LCA methodology. A case study of 12 polymers was presented, seven of which were derived from petroleum, four of which were derived from biological sources, and one of which was derived from both sources. The environmental impacts of the production of each polymer were assessed using LCA methodology standardized by the International Organization for Standardization (ISO). Each polymer also was assessed for its adherence to green design principles. The metrics included mass from renewable sources, biodegradability, percent recycled, feedstock that was transported the longest distance, price, lifecycle health hazards, and lifecycle energy use. A decision matrix was used to generate single value metrics for each polymer, evaluating either adherence to green design principles or environmental impacts during their lifecycles. The results from this study showed that there was a qualified positive correlation between adherence to green design principles and reduction of the environmental impacts of production. The qualification results from the differences in the production of biopolymers and petroleum polymers. While biopolymers rank highly in terms of green design, their production produces relatively large environmental impacts. The biopolymers were ranked 1, 2, 3, or 4 based on their green design metrics; however, they ranked in the middle of the LCA rankings. Polyolefins were ranked 1, 2, and 3 in the LCA rankings, whereas complex polymers, such as PET, PVC, and PC, were ranked at the bottom of both ranking systems.

Except for polymers, there is no consensus concerning the environmental benefits for the utilization of biobased products for their full lifecycle. This is due in large part to spatial variability, the technologies used, and the source of the biomaterial. A recent meta analysis of 44 lifecycle assessment studies by Weiss et al. (2012) identified that one metric ton (t) of biobased materials saves, relative to conventional materials, 55 ± 34 gigajoules of primary energy and 3 ± 1 t of carbon dioxide equivalents of greenhouse gases. However, as previously stated, spatial variability has implications for other environmental impacts. The report indicated that biobased materials may increase eutrophication by 5 ± 7 kilograms (kg) of phosphate equivalents/t and increase stratospheric ozone depletion. Their findings were inconclusive with regard to acidification in sulfur dioxide equivalents and in photochemical ozone formation savings in ethane equivalents.

One key consideration is the utilization of petroleum-based fertilizers and pesticides during the cultivation of industrial biomass. Also, gaps exist in the current literature with regard to land-use impacts, potential loss of biodiversity, depletion of carbon in the soil, soil erosion, deforestation, and greenhouse gas emissions from indirect changes in land use.

The future challenge is how best to invest in innovations for the biobased economy that foster an equitable allocation of value among shareholders, feedstock suppliers, biomass processors and converters, consumers, and the environment. An example of substitute products for the bioeconomy includes those made from ethylene (C_2H_4), a common chemical precursor. Although initially produced from ethanol, ethylene has been produced using crude oil-derived naphtha or natural gas liquids for many decades. It is the molecular building block for several important plastics, textiles, and chemicals. The global market for polyethylene, the largest volume derivative of ethylene exceeds 100 million metric tons per year, and it is used extensively in packaging and construction. Ethylene oxide is another derivative of ethylene, and it is used to make polyester materials, anti-freeze, and some industrial chemicals (Pellegrino, 2000). Over 3.2 million metric tons of ethylene oxide were produced in the U.S. in 1997.

The production of ethylene from biobased ethanol is reemerging. Notably, the Brazilian multi-national company, Braskem, is producing polyethylene from ethylene made from sugarcane. Thus, there is now commercially-available packaging film that is made from sugarcane. India Glycols is producing ethylene glycol for polyester production using ethanol derived from sugar beets, sugarcane, or corn. This ethylene glycol is used in the polyester for Coca-Cola's biobased soda bottle.

The United Nations Food and Agricultural Organization (Alexandratos and Bruinsma, 2012) estimated that between 2005 and 2050, the production of cereal and sugarcane-based biofuels will experience average annual growth rates of 2% and 2.6%, respectively, from 2012 levels.

Particularly for non-food feedstocks, the cost of distribution to a processing facility is often the significant driver in the overall economics of using biobased feedstocks to produce chemicals and fuels. Biobased feedstocks usually have low bulk densities and relatively low energy densities. Also, they often contain significant amounts of moisture. These factors lead to high distribution costs. Often the scale and siting of processing facilities are limited by the amount of feedstock that can be transported economically to the processing facilities. For grain and cellulosic ethanol facilities, the maximum economic distance that the feedstock can be transported for processing has been estimated at between 50 and 75 miles (Khosla, 2012).

Most often, however, the value of co-products associated with a given feedstock must be considered. In the production of ethanol from corn, the value of co-products, such as dried distillers grains with solubles (DDGS), has a considerable influence on the economics of the process. In sugarcane-based and cellulosic ethanol production, the value of electricity that can be generated from solid residues can be a significant factor in the economic viability of a facility. Similarly, when naphtha is processed (i.e., 'cracked') to produce various chemicals, several petrochemical building blocks are produced, principally ethylene, propylene, butane, butylenes, butadiene, benzene, toluene, and xylene. Propylene, which can be used to produce isobutanol, typically is 15% of the mass of the incoming naphtha. Therefore, the prices of the other co-products are important in determining the net cost of the naphtha raw material.

The use of ethanol made from corn, sugarcane, or sugar beets to produce ethylene adds greater complexity to the supply chain. Crops must be grown, harvested, and fermented; ethanol must be refined, transported, and converted, and additional costs are incurred for the conversion of ethanol to ethylene. If absolute traceability is desired, new polyethylene or ethylene oxide production capacity dedicated solely to biobased ethylene conversion may have to be built. This new capacity likely would not have the scale efficiencies of modern, world-scale polyethylene or ethylene oxide facilities.

Braskem (2013) first produced certified green, high-density polyethylene from sugarcane-based ethanol on a limited scale in June 2007, and, after market testing and qualifications, began the commercial production of this product in 2010.

VI. LOOKING TO THE FUTURE

The market for biobased products is growing because of the efforts of manufacturers, consumers, and government officials to promote the development and acceptance of these products as they become commercially viable. One of the main objectives of the efforts to increase the market share for biobased products is to reduce the U.S.'s dependence on foreign oil. However, the widespread use of such products also would help to rejuvenate the rural economy so that it is less dependent on government subsidies and also would help to create a self-sustaining sector that relies on domestic renewable resources.

Some of the many biobased products that are currently produced are bioplastics, biolubricants, biosolvents, bio-surfactants, and other biosynthetics. In addition, many biofuel co-products are emerging that can be produced from a variety of different sources of biomass.

Purchasing of biobased products continues to be supported through government mandates on procurement policies. However, sales of biobased products also are driven increasingly by U.S. consumers' preferences based on their growing awareness of the environmental impacts of their purchasing decisions. Surveys suggest that consumers want to buy "green," biobased products, but they continue to be more sensitive to prices than their European counterparts.

As the bioeconomy expands, challenges arise in the development of biobased products. One of these challenges is the uncertainty created by policy changes impacting current farming practices. Many companies are forging ahead with the integration of biobased products into their market and product development design strategies, however, confident that the challenges will be overcome, that consumers will become even more concerned with sustainability, and that the potential economic benefits are significant.

REFERENCES

Airbus, Airbus, Boeing, Embraer collaborate on aviation biofuel commercialization, (2012) (from http://www.airbus.com/presscentre/pressreleases/press-release-detail/detail/airbus-boeing-embraer-collaborate-on-aviation-biofuel-commercialisation/).

Biobased Industries Consortium (2014). FAQ Sheet http://biconsortium.eu/sites/default/files/downloads/BIC_BBI%20Fact%20Sheet_APRIL2014.pdf Accessed June 7, 2014

Biochem (2010). D2.3 – Report on the Assessment of the Biobased Products Market Potential for Innovation. Final Report September 30, 2010.

Bioeconomy, Biomass and Bioenergy 63(2014) 341e3 44

Braskem, Green Products, (2013) (from http://www.braskem.com.br/site.aspx/green-products-USA).

British Petroleum p.l.c., Energy Outlook 2030, London, 2013.

Coca-Cola, PlantBottle™: Frequently Asked Questions, (2012) (from http://www.coca-colacompany.com/stories/plantbottle-frequently-asked-questions).

D. Dupuy, Technological change and environmental policy: the diffusion of environmental technology, Growth and Change 28(1) (1997) 49-66.

D.R. Bohi, M.A. Toman, Economics of Energy Security, Kluwer Academic Publishers, Norwell, MA, 1996.

D2.3 – Report on the Assessment of the BiobasedBio (2012). New Opportunities: Renewable Chemicals and Biobased Products. Biotechnology Industry Organization. February 8, 2012 presentation. http://energyoutlook2012.naseo.org/presentations/Batchelor-Renewable_Chemicals_and-Biobased_Products.pdf Accessed June 7, 2014

Dammer, L., Carus, M., Raschka, A., Scholz, L. (2013): Market Developments of and Opportunities for biobased products and chemicals, nova- Institute for Ecology and Innovation, Germany

Doucin, M. (2013). The French Legislation on extra-financial reporting: built on consensus. Ambassador at large for Corporate Social Responsibility. https://www.globalreporting.org/SiteCollectionDocuments/GoFPara47PoliciesInitiatives-France.pdf Accessed June 19, 2014

E.T.H. Vink, K.R. Rábago, D.A. Glassner, P.R. Gruber, Applications of life cycle assessment to NatureWorks™ polylactide (PLA) production, Polymer Degradation and Stability 80(3) (2003) 403-419.

EIA, What drives crude oil prices?, (2013) (from http://www.eia.gov/finance/markets/spot_prices.cfm).

EPA, EPA Finalizes 2013 Renewable Fuel Standards, U.S. Environmental Protection Agency (2013).

Ericksen, Britt, and Washington, C, "Transforming Nanocellulose", CEN.ACS.ORG, June 14, 2014.

European Bioplastics, Global PlantBottle™ use continues to grow, European Bioplastics Bulletin (2013) (from http://en.european-bioplastics.org/blog/2013/06/21/global-plantbottle-use-continues-to-grow/).

European Commission (2012). Bioeconomy in Europe: state of play and future potential – Part 2. Summary of the position papers received in response of the European Commission's Public on-line consulation. ISBN 978-92-79-20653-5

European Commission (2012a). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Innovating for Sustainable Growth: A Bioeconomy for Europe. Brussels, 02 13 2012.

European Commission (2012b). Bioeconomy in Europe: state of play and future potential – Part 1. Report on the European Commission's Public on-line consultation. ISBN 978-92-79-20652-8

Evaluate Pharma (2013). World Preview 2013 Outlook to 2018. Returning to Growth. http://www.evaluategroup.com/public/reports/Evaluate-World-Preview-2013-Outlook-to-2018.aspx

Federal Register (2009). Presidential Documents. Executive Order 13514 as of October 5, 2009. Vol. 74. No. 194. Thursday October 8, 2009.

Ford, Lear earn accolades for innovative use of soy foam in seat cushions, (2008) from (http://world-wire.com/news/0812080001.html).

G. Warwick, Biofuels could account for 1% of all commercial jet fuel by 2015, says Boeing, Aviation Daily (2013).

Gevo, Gateway to renewable chemicals and hydrocarbon fuels, (2011).

Greenpeace (2014). http://www.greenpeace.org/international/en/campaigns/toxics/water/detox/

Heintz, J. and Pollin, R. (2011). The Economic Benefits of a Green Chemical Industry in the U.S.: Renewing Manufacturing Jobs While Protecting Health and the Environment. Political Economy Research Institute, Amherst, MA.

http://www.icis.com/resources/news/2013/06/07/9676331/market-outlook-shale-gas-impacts-biobased-chemicals/ Accessed June 7, 2014

ICIS, (2013). Market outlook: Shale gas impacts biobased chemicals. http://www.icis.com/resources/news/2013/06/07/9676331/market-outlook-shale-gas-impacts-biobased-chemicals/ Accessed June 7, 2014

IEA Bioenergy, Task 42 Biorefinery, Bio based chemicals value added products from Biorefineries

Informa Economics, The Emerging Biobased Economy: A multi-client study assessing the opportunities and potential of the emerging biobased economy, (2006).

J. Fiksel, Sustainability and resilience: toward a systems approach, Sustainability: Science, Practice, & Policy 2(2) (2006) 14-21.

J.K. Bang, A. Follér, M. Buttazzoni, Verdensnaturfonden, Industrial Biotechnology: More than Green Fuel in a Dirty Economy? WWF, Denmark, 2009.

J.L. Pellegrino, Energy environmental profile of the U.S. chemical industry, Columbia, MD, 2000.

J.S. Golden, K.J. Dooley, J.M. Anderies, B.H. Thompson, G. Gereffi, L. Pratson, Sustainable product indexing: navigating the challenge of ecolabeling, Ecology & Society 15(3) (2010) 1-7.

Jefferson, T. (1800). Memorandum of Services to My Country, after 2 September 1800 PTJ, 32:124. Polygraph copy at the Library of Congress. http://www.monticello.org/site/jefferson/useful-plant-quotation

K. van Dijken, Y. Prince, T.J. Wolters, M. Frey, G. Mussati, P. Kalff, O. Hansen, S. Kerndrup, B. Søndergård, E.L. Rodrigues, S. Meredith, Adoption of Environmental Innovations: The Dynamics of Innovation as Interplay between Business Competence, Environmental Orientation and Network Involvement, Kluwer Academic Publishers, The Netherlands, 1999.

Landau, R., & A. Arora (1999). Growing by Changing and Adapting to Changing Environments. Business Economics. Vol. 34 No. 4 ISSN: 0007-666X

LEI, (2012). Biobased supply chains. Risks and institutional arrangements. LEI Memorandum 12-036. LEI part of Wageningen UR, the Hague

LEI, (2012). BiobasedYujie Feng, Qiao Yang, Xin Wang, Yankun Liu, He Lee, Nanqi Ren,2010, Treatment of biodiesel production wastes with simultaneous electricity generation using a single-chamber microbial fuel cell, Y. Feng et al. / Bioresource Technology 102 (2011) 411–415

Li Shen, Juliane Haufe, Martin K.Patel, 2009, Product overview and market projection of emerging biobased plastics, Universiteit Utrecht

Liam Brennan, Philip Owende, 2009, Biofuels from microalgae—A review of technologies for production, processing, and extractions of biofuels and co-products, Renewable and Sustainable Energy Reviews 14 (2010) 557–577

Lister, M (2009). The future of the bioeconomy in Canada. Roundtable outcomes report. Public Policy Forum. June 2009.

Logan, B.E., Hamelers, B., Rozendal, R., Schrorder, U., Keller, J., Freguia, S., Aelterman, P., Verstraete, W., Rabaey, K., 2006. Microbial fuel cells: methodology and technology. Environ. Sci. Technol. 40, 5181–5192

M. Bustillo, Wal-Mart to assign new 'green' ratings, Wall Street Journal 2009.

M. Buttazzoni, GHG emission reductions with industrial biotechnology: assessing the opportunities, Denmark (2009).

M. Patel, C. Bastioli, L. Marini, D.-G.E. Würdinger, Life-cycle assessment of biobased polymers and natural fiber composites. Biopolymers Online (2005).

M. Wu, M. Mintz, M. Wang, S. Arora, Y. Chiu, Consumptive water use in the production of ethanol and petroleum gasoline - 2011 update, Center for Transportation Research (2011).

M.D. Tabone, J.J. Cregg, E.J. Beckman, A.E. Landis, Sustainability Metrics: Life Cycle Assessment and Green Design in Polymers, Environmental Science & Technology 44(21) (2010) 8264-8269.

Michael Malveda and Kazuteru Yokose, 2012, Biodegradable Polymers, http://chemical.ihs.com/CEH/Public/Reports/580.0280

Milken Institute. (2013). Unleashing the Power of the Bioeconomy. Financial Innovations Lab

Mooney, R. The second green revolution? Production of plant-based biodegradable Plastics, Biochem J 418 (2): 219 – 232.

Mukherjee T. and Kao, N. "PLA Based Biopolymer Reinforced with Natural Fibre: A Review" Journal of Polymer Environment (2011) 19:714–725.

Mundi, Commodity prices, (2013) (from http://www.indexmundi.com/).

N. Alexandratos, J. Bruinsma, World agriculture towards 2030/2050: the 2012 revision, FAO-ESA Working paper No. 12-03

N. Stauffer, Ethanol study shows biofuel benefits, TechTalk 51(15) 2007.

N.A. Ashford, C. Ayers, R.F. Stone, Using regulation to change the market for innovation, Harvard Environmental Law Review 9(2) (1985) 419-466.

OECD, 2009, The Bioeconomy to 2030, Designing a Policy Agenda, *www.oecd.org/publishing/corrigenda*

P&G, Five global companies demonstrate their strong commitment to sustainable innovation, 2012, (from http://news.pg.com/press-release/pg-corporate-announcements/coca-cola-ford-heinz-nike-and-procter-gamble-form-collabora)

Peter Nelson, Elizabeth Hood, and Randall Powell, 2010, The Bioeconomy: A New Era of Products Derived from Renewable Plant-Based Feedstock, Chapter-1, Plant Biomass Conversion, First Edition

Pharma (2013). 2013 Profile. http://www.phrma.org/sites/default/files/pdf/PhRMA%20Profile%202013.pdf accessed June 7, 2014

Platts (2013). The Shale revolution and its impacts on aromatics supply, pricing and trade flows.

R. Dobbs, J. Oppenheim, F. Thompson, M. Brinkman, M. Zornes, Resource Revolution: Meeting the world's energy, materials, food, and water needs, McKinsey Global Institute (2011).

R.L. Priem, M. Swink, A demand-side perspective on supply chain management, Journal of Supply Chain Management 48(2) (2012) 7-13.

Rasal RM , Janorkar AV , Hirt DE . 2010. Poly(lactic acid) modifications . Prog Polym Sci 35 (3): 338 – 356 .

Rath (2012). Presentation at the Biobased Feedstocks Supply Chain Risks and Rewards Conference. Hosted by Duke and Yal Universities. Washington DC 2012.

Ravasio, P. (2012). How can we stop water from becoming a fashion victim? The Guardian. 7 March 2012.

Reiss, T., et al., 2007, Consequences, Opportunities and Challenges of Modern Biotechnology for Europe, Task 2 Main Reports, Joint Research Centre Reference Reports, IPTS, Seville.

Report, February 2013. Santa Monica, CA: Milken Institute.

S. Rothenberg, S.C. Zyglidopoulos, Determinants of environmental innovation adoption in the printing industry: the importance of task environment, Business Strategy & the Environment 16(1) (2007) 39-49.

SBI Energy, The World Market for Biobased Chemicals, 2nd ed., 2012.

Sticklen, M., (2013). Co-Production of High-Value Recombinant Biobased Matter in Bioenergy Crops for Expediting the Cellulosic Biofuels Agenda. *Advances in Crop Science and Technology*. http://dx.doi.org/10.4172/2329-8863.1000e101

Sustainable Biomaterials Collaborative (2014). http://www.sustainablebiomaterials.org/index.php accessed June 7, 2014

T. O'Shea, J.S. Golden, L. Olander, Sustainability and earth resources: life cycle assessment modeling, Business Strategy and the Environment 22(7) (2012) 429-441.

T. Stecker, Algal biofuel sustainability review highlights concerns about water supply, Energy & Sustainability, (2012) (from http://www.scientificamerican.com/article.cfm?id=algal-biofuel-sustainability-review-hightlights-concerns-about-water-safety).

Thomas G. Johnson, Ira Altman, 2014, Rural development opportunities in the

Tripp, S., Nelson, P., & Powell, R. 2009. Regional Strategy for Biobased Products in the Mississippi Delta, Report by Battelle Technology Partnership Practice.

Tufekei, N., Sirvi, Nuket and I, Toroz (2007). Pollutants of Textile Industry Wastewater and Assessment of its Discharge Limits by Water Quality Standards. *Turkish Journal of Fisheries and Aquatic Sciences*. 7: 97-103

Türünç, O. and Meier, M. Biopolymers. Chapter in *Food and Industrial Bioproducts and Bioprocessing*, First Edition. Edited by Nurhan Turgut Dunford, 2012 John Wiley & Sons, Inc.

U.S. Biobased Products: Market Potential and Projections Through 2025. Office of the Chief Economist, Office of Energy Policy and New Uses, U.S. Department of Agriculture, February 2008.

U.S. Economic Impact of Advanced Biofuels Production: Perspectives to 2030, independent research carried out by bio-era (Bio Economic Research Associates), with financial support from the Industrial & Environmental section of the Biotechnology Industry Organization (BIO), February 2009

UNESCO, Facts and figures: managing water under uncertainty and risk, United Nations World Water Assessment Program (WWAP) (2012).

US Agriculture Act, 2014. file:///Users/handfield/Documents/SCRC/Duke%20Sustainability%20Initiative/AMEC/Literature%20Review/Farm%20Bill%2020134.pdf

US Energy Information Agency (2014). Independent Statistics and Analysis. http://www.eia.gov/dnav/ng/hist/rngwhhdd.htm Accessed June 3, 2014

US Navy, Great Green Fleet, (2012) (from http://greenfleet.dodlive.mil/files/2012/12/20121203_Great-Green-Fleet-Factsheet.pdf).

USDA, U.S. Biobased Products: Market Potential and Projections through 2025, (2008) (from www.USDA.gov/oce/reports/energy/BiobasedReport2008.pdf).

V. Khosla, Where Will Biofuels and Biomass Feedstocks Come From? (2012).

Van der Pol, H. (2011). Bioplastics – Market Pull for Biobased Chemicals in Europe. European Bioplastics http://www.sari-energy.org/PageFiles/What_We_Do/activities/worldbiofuelsmarkets/Presentations/BioBasedChemicalsCongress/Hans_van_der_Pol.pdf Accessed June 7, 2014

Van Winkle, Chrina, Zhang, Wei, Yuan, Yi, and Qian, Yifei, Bioproducts: Consumer Perceptions and Willingness to Pay", Duke Center for Sustainability, Working Paper, 2013.

Verespej, M. Biopolymers targeting commodity chemicals. Plastics News, 9/5/11, p. 13.

White House, Executive order 13514: federal leadership in environmental, energy, and economic performance, (2009) (from http://www.whitehouse.gov/administration/eop/ceq/sustainability)

White House, National Bioeconomy Blueprint, (2012) (from http://www.whitehouse.gov/sites/default/files/microsites/ostp/national_bioeconomy_blueprint_april_2012.pdf)

APPENDICES

APPENDIX 1 – TABLE OF PRIOR LITERATURE

Author	Title	Year Published	Literature Format	Benefits	Carbon Offset	Carbon Sequestration	Costs Markets	Economics	Efficacy	Environmental Sustainability	Fossil Fuel Replacement	Innovation	International	Job Creation	Markets	Obstacles/Limitations	Overview	Products	Public Health
N. Alexandratos, J. Bruinsma	World agriculture towards 2030/2050: the 2012 revision, FAO-ESA Working paper No. 12-03	2012	Working paper					X	X				X				X		
Procter & Gamble	Five global companies demonstrate their strong commitment to sustainable innovation	2012	from: http://news.pg.com/press-release/pg-corporate-announcements/coca-cola-ford-heinz-nike-and-procter-gamble-form-collabora	X		X	X					X		X		X	X	X	
Coca-Cola	PlantBottle™: Frequently Asked Questions, (2012)	2012	Coca-Cola, http://www.coca-colacompany.com/stories/plantbottle-frequently-asked-questions			X	X			X	X	X		X				X	
Ford Website	Ford, Lear earn accolades for innovative use of soy foam in seat cushions.	2008	http://worldwire.com/news/0812080001.html							X	X	X						X	
U.S. Navy		2012	http://greenfleet.dodlive.mil/files/2012/12/20121203_Great-Green-Fleet-Factsheet.pdf				X				X	X		X					

Author	Title	Year Published	Literature Format	Benefits	Carbon Offset	Carbon Sequestration	Costs Markets	Economics	Efficacy	Environmental Sustainability	Fossil Fuel Replacement	Innovation	International	Job Creation	Markets	Obstacles/Limitations	Overview	Products	Public Health
British Petroleum, p.l.c.	British Petroleum p.l.c., Energy Outlook 2030, London, 2013	2013	Energy Outlook publication	X	X			X	X		X		X				X		
SBI Energy	SBI Energy, The World Market for Biobased Chemicals, 2nd ed.	2012	Book	X	X		X	X	X	X							X	X	
Informa Economics, Inc.	A multi-client study assessing the opportunities and potential of the emerging biobased economy	2006	Report				X	X	X	X							X	X	
V. Khosla	Where Will Biofuels and Biomass Feedstocks Come From?	2012	White paper http://www.khoslaventures.com/wp-content/uploads/Where-will-Biofuels-and-Biomass-Feedstocks-Come-from-.pdf		X	X		X	X	X	X					X			
Bang et al.	By 2030 the use of biobased fuels and chemicals could prevent between 490 and 1,790 million metric tons of carbon dioxide from reaching the atmosphere every year.	2009	J. K. Bang, A. Follér, M. Buttazzoni, Verdensnaturfonden, Industrial Biotechnology: More than Green Fuel in a Dirty Economy? WWF, Denmark, 2009	X	X	X												X	X

Author	Title	Year Published	Literature Format	Benefits	Carbon Offset	Carbon Sequestration	Costs Markets	Economics	Efficacy	Environmental Sustainability	Fossil Fuel Replacement	Innovation	International	Job Creation	Markets	Obstacles/Limitations	Overview	Products	Public Health
White House Presidential Order 13514		2009	Presidential Order	X	X	X												X	X
White House	National Bioeconomy Blueprint	2012	White House Document: http://www.whitehouse.gov/sites/default/files/microsites/ostp/national_bioeconomy_blueprint_april_2012.pdf	X		X	X	X				X		X			X	X	
E. T. H. Vink, K. R. Rábago, D. A. Glassner, P. R. Gruber	Applications of lifecycle assessment to NatureWorks™ polylactide (PLA) production	2003	Polymer Degradation and Stability 80(3) (2003) 403-419		X	X	X			X	X							X	
M. Patel, C. Bastioli, L. Marini, D.-G.E. Würdinger	Lifecycle assessment of biobased polymers and natural fiber composites	2005	Biopolymers Online		X	X	X			X	X							X	
M. D. Tabone, J. J. Cregg, E. J. Beckman, A. E. Landis	Sustainability Metrics: Lifecycle Assessment and Green Design in Polymers	2010	Environmental Science & Technology 44(21) 8264-8269		X	X	X			X	X							X	
Environmental Protection Agency	EPA Finalizes 2013 Renewable Fuel Standards	2013	U.S. Environmental Protection Agency	X	X			X	X	X	X								X

Author	Title	Year Published	Literature Format	Benefits	Carbon Offset	Carbon Sequestration	Costs Markets	Economics	Efficacy	Environmental Sustainability	Fossil Fuel Replacement	Innovation	International	Job Creation	Markets	Obstacles/Limitations	Overview	Products	Public Health
Braskem	Green Products	2013	from http://www.braskem.com.br/site.aspx/green-products-USA	X		X	X					X		X			X	X	
N. Stauffer	Ethanol study shows biofuel benefits	2007	TechTalk 51(15).																
T. Groode	MIT ethanol analysis clarifies benefits of biofuel	2013	http://web.mit.edu/erc/spotlights/ethanol.html	X	X	X	X		X	X	X	X							
J. Fiksel	Sustainability and resilience: toward a systems approach	2006	X		X	X					X		X		X	X	X		
T. O'Shea, J. S. Golden, L. Olander	Sustainability and Earth resources: lifecycle assessment modeling	2012	Business Strategy and the Environment 22(7) 429-441			X	X	X											
European Bioplastics, Global	PlantBottle™ use continues to increase.	2013	http://en.european-bioplastics.org/blog/2013/06/21/global-plantbottle-use-continues-to-grow/			X	X	X	X	X	X								
M. Buttazzoni	GHG emission reductions with industrial biotechnology: assessing the opportunities	2009				X	X	X	X	X	X								
M. Wu, M. Mintz, M. Wang, S. Arora, Y. Chiu	Consumptive water use in the production of ethanol and	2011	Center for Transportation Research			X	X	X	X	X	X								

Author	**Title**	**Year Published**	**Literature Format**	**Benefits**	**Carbon Offset**	**Carbon Sequestration**	**Costs Markets**	**Economics**	**Efficacy**	**Environmental Sustainability**	**Fossil Fuel Replacement**	**Innovation**	**International**	**Job Creation**	**Markets**	**Obstacles/Limitations**	**Overview**	**Products**	**Public Health**
	petroleum gasoline																		
Airbus	Airbus, Boeing, Embraer collaborate on aviation biofuel commercialization	2012	http://www.airbus.com/presscentre/pressreleases/press-release-detail/detail/airbus-boeing-embraer-collaborate-on-aviation-biofuel-commercialisation/								X				X	X	X	X	
Warwick	Biofuels could account for 1% of all commercial jet fuel by 2015, says Boeing	2013	Aviation Daily								X				X	X	X	X	
Rasal, R. M., Janorkar, A. V., Hirt, D. E., 2010 .	Polylactic acid modifications	2010	Prog Polym Sci 35 (3): 338 – 356				X		X	X	X	X						X	
Türünç, O. and Meier, M.	Biopolymers	2012	Chapter in *Food and Industrial Bioproducts and Bioprocessing*, First Edition																
Mukherjee T. and Kao, N.	"PLA Based Biopolymer Reinforced with Natural Fibre: A Review"	2011	Journal of Polymer Environment 19:714–725				X		X	X	X	X						X	
Verespej, M.	Biopolymers targeting commodity	2011	Plastics News, 9/5/11, p. 13				X		X	X	X	X						X	

Author	Title	Year Published	Literature Format	Benefits	Carbon Offset	Carbon Sequestration	Costs Markets	Economics	Efficacy	Environmental Sustainability	Fossil Fuel Replacement	Innovation	International	Job Creation	Markets	Obstacles/Limitations	Overview	Products	Public Health
	chemicals.																		
Mooney, B. P., 2009	The second green revolution? Production of plant-based biodegradable Plastics	2009	Biochem J 418 (2): 219 – 232				X		X	X	X	X						X	
Van Winkle, Chrina, Zhang, Wei, Yuan, Yi, Qian, Yifei	Bioproducts: Consumers' Perceptions and Willingness to Pay	2013	Duke Center for Sustainability, Working Paper, 2013.			X									X	X	X	X	
A. Rath	Presentation at the Biobased Feedstocks Supply Chain Risks and Rewards Conference	2012	Conference. Hosted by Duke and Yale Universities. Washington, D.C.	X					X	X	X	X				X	X	X	