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# Supply Chains for Emerging Renewable Polymers: Analysis of Interactive Sectors and Complementary Assets

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## Abstract

Revitalized interest in biobased or renewable ingredients in manufacturing has emerged in recent years due to rising real petroleum prices, concerns regarding environmental impacts of crude oil, and national security issues related to petroleum resources. This research analyzes the complexities of renewable supply chains. In particular, polymers manufactured from renewable feedstocks will augment various industrial markets, such as plant material used as a renewable ingredient in paint manufacture, partially substituting for crude oil derivative ingredients. The analysis defines polymer industrial supply chains and estimates the market opportunity for renewable polymers. A section of the analysis is devoted to complementary assets as a new product development bridge to supply chain issues.

**Keywords:** supply chains, renewables, economics of biobased industrial markets, complementary assets

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## Emerging Biobased Industrial Markets

For several decades, plastics derived from fossil fuels have grown at a faster rate than any other group of bulk materials (Crank et al. 2005; Weizer 2006). Although the first plastics were developed from polymers derived from renewable materials (Stevens 2002), petroleum-based polymers are cheaper and consequently dominate industrial markets. Although most polymer markets are expanding, growth in specific polymer products is expected to be quite variable in the future, ranging from a negative 8.9% annually to an increase of 71% over the next several years, Table 1.

**Table 1**. Estimated growth in the polymer industry by product, various authors

| Product | Growth Rate | Reference |
|---|---|---|
| Co-polyester | 7.31% CAGR over 2006-2013 to reach 28 million by 2013 | GIA |
| Starch | 6.44% CAGR over 2006-2013 to reach 17 million by 2013 | GIA |
| Starch | 11.9% GAGR from 2005-2010 starting with 8 tonnes in 2005 | Platt |
| Others (Lignin, soybean, water-soluble, polycaprolactone) | 5.62% CAGR over 2006-2013 to reach 3 million by 2013 | GIA |
| PLA | 11.06% CAGR over 2006-2013 starting with 18 million pounds in 2006 | GIA |
| PLA | 18.7% CAGR over 2005-2010 starting with 9.6 tonnes in 2005 | Platt |
| PLA | 71% CAGR from 2005-2010 starting with 0.1 tonnes in 2005 | Platt |
| Synthetics | 18.4% CAGR from 2005-2010 starting with 3.6 tonnes in 2005 | Platt |
| Chlorine | -8.9% drop in output in 2008 from 2007 | Stork |
| Sulfuric Acid | -1.8% drop in 2008 from 2007 | Stork |
| Ammonia | -6.9% drop in 2008 from 2007 | Stork |
| Propylene | -7.7% decline in output in 2008 from 2007 | Stork |
| Ethylene | -8.4% drop in output in 2008 from 2007 | Stork |

Interest in biobased or renewable polymers has emerged in recent years due to rising real petroleum prices, concerns regarding environmental impacts from crude oil, and national security issues related to petroleum resources (Crank et al. 2005). With advances in technology, renewable polymers are increasingly competitive with petroleum-based polymers in cost and performance and may offer additional advantages. Specifically, renewable polymers are often biodegradable and not toxic to produce (Paster, Pellegrino, and Carole 2003).

The economic prospects for promoting renewable polymers are great. The market size for biodegradable polymers generated from renewable natural sources, such as plant and animal biomass, is growing significantly (GIA 2006). With consumption of renewable polymers projected to increase over the next five years by 22 percent annually in the U.S. (Pira 2006), a strategic economic growth opportunity arises from the emerging linkages between the polymer processing sector and the agricultural sector.

There are several key trends driving the demand for renewable polymers. Renewable materials help mitigate the effects of increasing demand for oil and volatility in supply and price (Conway and Duncan 2006; Paster et al. 2003). Rapid technological progress opens many prospective industrial markets based on renewable polymers. Biotechnology and plant breeding continue to produce crops with higher yields and desirable plant composition for bioproduct applications. Further plant improvements, combined with advances in chemistry, engineering, and manufacturing, will further enhance efficiency by lowering relative costs compared with petroleum-based counterparts (Paster et al. 2003; Perlack et al. 2005).

Concomitant with these technological advances is considerable growth in consumer preference for “environmentally-friendly” and sustainable products. As a result, more U.S. businesses, including major retailers such as Walmart, are adopting policies that promote environmental and social responsibility. These policies may require suppliers to innovate by introducing more sustainable materials, especially in product packaging (Brody 2006). Industry members, who produce products marketed by major retailers, are pursuing strategies to integrate the use of renewable materials into their product lines to enhance their market position (FPA 2006).

In the United States, for example, the Federal Biobased Products Preferred Procurement Program (USDA 2007) now requires federal agencies to purchase renewable products (made from plant or animal sources) in designated categories. This opens potentially large markets for vendors of renewable products and services, further stimulating demand. In addition, compliance costs for petroleum-based industries are escalating. New national environmental policies or international agreements (such as the Kyoto Agreement) may internalize costs of pollution and greenhouse gas emissions. Current costs associated with environmental regulation are significant for petroleum-based industries (Deloitte 2005). Another demand factor is rapidly escalating disposal cost for solid waste disposal. Renewable products can be removed from the solid waste stream and composted, rather than deposited in landfills. This effectively reduces costs and provides environmentally favorable alternatives (GIA 2006).

Emerging technologies related to a renewable polymer production from natural sources, such as plants, animals, and microorganisms, have opened substantial economic opportunities and potentials within the chemical, agricultural, and polymer clusters[1] over the past few years. What is currently not known is the magnitude of the economic impact of this emerging renewable polymer cluster and the promise of future market opportunities for renewable polymers. The research reported herein focuses on precise definition of the emerging renewable polymer supply chain. The goal of the applied research is to provide an economic assessment of the market opportunity for renewable polymers.

## Polymer Supply Chains

While this analysis focuses on polymers it is important to include petroleum and chemicals in a supply chain context to capture the economic complexity of biobased industrial markets. Polymers represent a significant subset of the chemical industry but the basic chemicals industry supplies the specialized chemicals (such as polymers) to industrial markets (Deloitte 2005).

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[1] A business cluster is a geographic concentration of interdependent businesses, suppliers, and associated institutions in a particular economic sector. Clusters enhance the efficiency and/or productivity of all firms within the cluster so they may compete on a more sustainable basis within global markets.

### *Polymers Defined*

Analysis of the chemical and polymer industrial markets requires careful definition. Polymers are substances consisting of molecules with a large molecular mass made of repeating structural units, also called monomers, and connected by covalent chemical bonds (PolymerOhio 2008). There are four classes of polymers: thermoplastics, thermosets, fibers, and films and coatings (Carlsson 2002). Some well-known examples of polymers include plastics, DNA, and proteins (GIA 2006). A polymer consists of various chemical compounds composed of monomers linked together. Some polymers occur naturally while others are artificially created, but polymers are used widely in industrial markets for plastic, glass, concrete, and rubber. Synthetic polymer industrial markets include automobiles, computers, planes, buildings, eyeglasses, and paints. Polymers are the newest addition to the bulk materials arena, having only been used for five to seven decades, but in substantial amounts (Crank et al. 2005). There are several different types of polymers used: polyester, polysaccharides, polyurethanes, and polyamides (Crank et al. 2005). The majority of feedstocks used to make polymers are derived from oil, a finite resource. With volatile prices that the petroleum market experiences, it is important to understand the economic linkages between conventional polymer production and crude oil. Conventional polymer production utilizes crude oil in three ways: as a raw material or feedstock, as a source of energy during polymer manufacturing, and as a fuel source in transporting finished polymer products (Task Force Report 2008).

### *Renewable Polymers*

Renewable polymers (sometimes referred to as ‘biopolymers’ or ‘bioplastics’) are substances derived from biomass such as a living plant, animal, or ecosystem, which has the ability to regenerate itself (GIA 2006). Renewable polymers are derived from biomass feedstocks such as corn, potatoes, wheat and soybeans. A biopolymer is a macromolecule formed in a living organism such as starch or proteins. Biobased polymers include co-polyester-based, polylactic acid, starch-based, soybean-based, lignin-based (from wood), water-soluble and polycaprolactone (GIA 2006; Platt 2006), Table 2.

The term “renewable polymers” is used throughout this research as opposed to other popular expressions such as “biopolymers”, “bioplastics”, and “bioproducts”. The majority of feedstocks for plastics today are derived from crude oil. A source is renewable if it can be replenished at a rate comparable or faster than its rate of consumption; thus, it has a sustainable yield (USDOE 2007). Polymers made from biomass’ monomers are known as renewable polymers, which can be replaced by growing more biomass and repeating the extraction process.

### *Biodegradable Complexities*

The terms “bioplastics”, “biopolymers”, and “bioproducts” regularly confuse the public because they tend to associate “bio” with the definition of “biodegradable”. These terms can be confusing since petroleum-based polymers can be biodegradable and plant-derived (renewable) polymers can be non-degradable (NNFCC 2007). This is why the term “renewable” more accurately reflects the characteristics of biobased polymers.

**Table 2.** Most important types of bio-based polymer groups

| **Bio-based polymer group** | **Type of polymer** | **Structure/Production method** |
|---|---|---|
| Starch polymers | Polysaccharides | Modified natural polymer |
| Polylactic acid (PLA) | Polyester | Bio-based monomer (lactic acid) by fermentation, followed by polymerization |
| Other polyesters from bio-based intermediates<br>1. Polytrimethyleneterphthalate (PTT)<br>2. Olybutyleneterephthalate (PBT)<br>3. Polybutylene succinate (PBS) | Polyester | 1. Bio-based 1,3-propanediol by fermentation plus petrochemical terephthalic acid (or DMT)<br>2. Bio-based 1,4-butanediol by fermentation plus petrochemical terephthalic acid<br>3. Bio-based succinic acid by fermentation plus petrochemical terephthalic acid |
| Polyhydroxyalkanoates (PHAs) | Polyester | Direct production of polymer by fermentation or in a crop |
| Polyurethanes (PURs) | Polyurethanes | Bio-based polyol by fermentation or chemical purification plus petrochemical isocyanate |
| Nylon<br>1. Nylon 6<br>2. Nylon 66<br>3. Nylon 69 | Polyamide | 1. Bio-based caprolactam by fermentation<br>2. Bio-based adipic acid by fermentation<br>3. Bio-based monomer obtained from a conventional chemical transformation from oleic acid via azelaic acid |
| Cellulose polymers | Polysaccharides | a)Modified natural polymer<br>b)Bacterial cellulose by fermentation |

**Source:** Adapted from Crank et al. (2005)

Biodegradable refers to a material that biodegrades by microorganisms (bacteria, fungi, and algae) found in the environment and will eventually biodegrade completely into carbon dioxide or water. The American Society for Testing and Materials standard ASTM-6400-04 specifies the criteria for biodegradability of plastic, which requires 60% biodegradation within 180 days (ASTM 2008). Compostable polymers are plastics that degrade by biological processes during composting to yield carbon dioxide, water, and inorganic compounds and biomass at a rate consistent with other compostable materials and leave no toxic residue. Polymers can be either biodegradable or not. In addition, biodegradable polymers can be manufactured completely from petroleum-based resources (Crank et al. 2005).

## Economic Analysis of Polymer Industrial Supply Chain

An input-output (I-O) economic model consists of a set of linear equations where each equation explains the distribution of an industry's production throughout other industries representing the rest of the economy (Blair and Miller 1985). The I-O model was developed by Wassily Leontief in the late 1930s and is a well-established method that has been widely used to analyze changes in interindustry activity (Blair and Miller 1985).

The I-O model captures what each business or sector purchases from every other sector to produce a dollar's worth of goods or services. The I-O model is used to capture the economy-wide interdependencies so as to analyze demand changes (Lee and Schluter 1993). The model captures industry interdependencies since each industry employs the outputs of other industries as its raw materials or as factors of production. Uncovering these interdependencies can show how much of each industry's output is used by other industries in the economy. Economic measures the I-O model provided for each sector are total employment, estimates of the direct purchases per dollar of output, income, contribution to gross domestic product (GDP), and the total dollar value of output. In this application, the I-O model is useful in developing the precise details of the interdependencies inherent in an industrial polymer supply chain.

## The Chemical, Polymer, and Petroleum Cluster Industrial Supply Chain

### *Scope of the Supply Chain*

To illustrate the magnitude of the polymer industrial supply chain, an input-output model that precisely defines the polymer supply chain is estimated for 2007, Table 3. The table is constructed so that the total polymer supply chain is accounted for in the top portion. The supply chain consists of five sector components, listed by the degree of value add the sector represents in the total industrial supply chain. The five components are 1) petroleum and natural gas extraction, 2) chemical manufacturing, 3) polymer manufacturing, 4) mold and equipment manufacturing related to polymer production, and 5) chemical and polymer wholesale distribution. These five sectors, each composed of numerous industries, represent the industrial supply chain for polymers. Consequently, the industrial supply chain for renewable polymers is embedded within the supply chain defined in Table 3.

Since there is focus on polymers and renewable polymers in this research, detailing the polymer sector as defined in Table 3 is useful. The polymer sector is comprised of five manufacturing subsectors: 1) coated and laminated packaging, paper, and plastics film, 2) plastics material and resin, synthetic rubber, and organic fibers, 3) paints, coatings, and adhesives, 4) plastic products, and 5) rubber products. The most economically important subsector in most studies is plastic product manufacturing. The primary feedstocks for this sector come mostly from the chemical manufacturing sector consisting of four manufacturing subsectors: 1) petroleum and coal products, 2) basic chemicals, 3) soap, cleaning compounds, and toilet preparations, and 4) chemical products and preparations. Similarly, the primary feedstocks for the chemical manufacturing sector are purchased from the petroleum and natural gas extraction sector.

**Table 3.** United States Polymer Supply Chain: Output, Gross Domestic Product, Income and Employment, 2007[a]

| | Total Output | Gross Domestic Product (GDP) | Income | Employment |
|---|---|---|---|---|
| | ***$ Thousands*** | ***$ Thousands*** | ***$ Thousands*** | ***Person Years*** |
| ***Polymers, Chemicals, and Petroleum Cluster*** | | | | |
| **Petroleum and Natural Gas Extraction** | **542,595.5** | **271,523.9** | **247,448.5** | **783,594** |
| Oil and Gas Extraction | 278,448.1 | 161,763.3 | 145,877.9 | 368,451 |
| Support Activities for Mining | 137,401.4 | 65,944.8 | 64,425.8 | 306,243 |
| Natural Gas Distribution | 126,746.0 | 43,815.8 | 37,144.8 | 108,900 |
| **Chemicals** | **975,457.9** | **199,105.0** | **192,988.7** | **465,877** |
| Petroleum and Coal Products Manufacturing | 598,362.6 | 106,336.8 | 103,592.0 | 111,593 |
| Basic Chemical Manufacturing | 220,611.2 | 41,160.4 | 38,404.0 | 148,368 |
| Soap, Cleaning Compound, and Toilet Preparation Manufacturing | 105,192.5 | 38,537.1 | 38,226.7 | 106,455 |
| Other Chemical Product and Preparation Manufacturing | 51,291.6 | 13,070.7 | 12,766.0 | 99,461 |
| **Polymers** | **409,717.2** | **103,967.3** | **100,448.7** | **981,867** |
| Coated and Laminated Packaging Paper and Plastics Film Mfg | 19,713.0 | 4,780.8 | 4,705.1 | 47,746 |
| Plastics Material and Resin, Synthetic Rubber, and Organic Fiber Mfg | 133,432.3 | 22,179.3 | 20,819.0 | 105,763 |
| Paint, Coating, and Adhesive Manufacturing | 39,164.8 | 9,258.7 | 9,066.7 | 63,507 |
| Plastics Product Manufacturing | 171,738.1 | 53,029.3 | 52,034.5 | 618,661 |
| Rubber Product Manufacturing | 45,669.0 | 14,719.2 | 13,823.4 | 146,190 |
| **Mold and Equipment Manufacturing Related to Polymer Production** | **21,470.6** | **7,961.8** | **7,741.8** | **111,837** |
| Plastics and Rubber Industry Machinery | 4,688.9 | 1,531.0 | 1,480.5 | 17,853 |
| Industrial Mold Manufacturing | 5,621.3 | 2,686.2 | 2,637.9 | 39,953 |
| Boat Building | 11,160.4 | 3,744.6 | 3,623.4 | 54,031 |
| **Chemical and Polymer Distribution (Wholesale)** | **144,491.8** | **97,325.9** | **76,327.7** | **1,405,976** |
| **Total Polymers, Chemicals, and Petroleum Cluster** | **2,093,733.0** | **679,883.9** | **624,955.4** | **3,749,151** |

**Table 3.** *Cont.* United States Polymer Supply Chain: Output, Gross Domestic Product, Income and Employment, 2007[b]

|  | **Total Output** | **Gross State Product (GSP)** | **Income** | **Employment** |
|---|---|---|---|---|
|  | ***$ Thousands*** | ***$ Thousands*** | ***$ Thousands*** | ***Person Years*** |
| ***General Manufacturing & Service Sectors*** |  |  |  |  |
| Farm Inputs, Equipment & Professional Services | 153,349.6 | 57,042.1 | 1,581.4 | 1,269,932 |
| Farming | 412,492.5 | 168,779.2 | 3,156.4 | 3,101,493 |
| Food Processing | 761,694.1 | 132,360.0 | 4,999.6 | 1,628,260 |
| Wood Processing | 365,450.1 | 103,025.8 | 3,792.2 | 1,400,406 |
| Food Services | 579,681.6 | 281,631.9 | 8,566.2 | 10,560,608 |
| Mining | 50,004.3 | 29,300.8 | 299.2 | 119,279 |
| Stone, Clay & Glass | 157,337.2 | 66,720.3 | 3,592.5 | 581,330 |
| Metal Industries | 631,549.2 | 188,779.8 | 17,125.2 | 1,754,911 |
| Construction | 1,623,849.5 | 690,847.0 | 19,236.8 | 11,364,947 |
| Textiles, Apparel, Accessories, Yarn & Leath | 159,544.5 | 36,039.5 | 588.2 | 678,758 |
| Machinery, Equipment & General Manufacturing | 689,542.7 | 245,806.1 | 13,091.5 | 2,653,416 |
| Motor Vehicles, Allied Equipment & Services | 666,379.3 | 183,218.7 | 13,563.7 | 2,814,053 |
| Transportation & Communication | 886,622.6 | 387,687.5 | 16,481.3 | 5,193,896 |
| Computer & Electronic Products | 769,322.4 | 341,368.3 | 7,999.3 | 3,723,557 |
| Publishing & Information Technologies | 1,014,941.2 | 538,742.7 | 13,059.4 | 3,416,372 |
| Wholesale & Retail Trade | 2,355,366.0 | 1,586,513.3 | 43,918.4 | 24,534,532 |
| Business, Professional & Personal Services | 3,206,556.0 | 1,969,766.5 | 62,537.4 | 22,892,686 |
| Financial, Legal, & Real Estate | 3,636,687.3 | 2,328,950.3 | 51,346.3 | 18,167,928 |
| Leisure Activities & Entertainment | 810,840.2 | 428,173.8 | 6,357.6 | 6,975,940 |
| Health Care & Social Assistance | 1,819,678.9 | 1,081,789.1 | 39,726.4 | 18,233,684 |
| Electricity, Gas & Sanitary | 484,965.6 | 313,837.9 | 7,721.4 | 1,005,386 |
| Education Services | 794,942.1 | 701,171.9 | 22,681.6 | 13,360,840 |
| Government, Military, & Non-Profit | 1,478,660.6 | 1,266,163.8 | 36,640.5 | 17,456,938 |
| **Total of Manufacturing & Service Sectors** | **23,509,457.5** | **13,127,716.3** | **398,062.7** | **172,889,152** |
| **Total U.S. Economy** | **25,603,190.5** | **13,807,600.2** | **1,023,018.1** | **176,638,303** |

**Note:** The wholesaling sector is one sector in the input-output model but is disaggregated. *County Business Patterns 2006* is used to estimate the percentage of payroll and employment in the polymer, chemical and petroleum cluster. The percentage of payroll (6.54) is used to estimate the proportion of PCP cluster output, GCP, and income.

The percentage of employment (6.42) is used to estimate PCP cluster employment. [a] Includes diverse service items such as advertising, cleaning, hair salons, and funerals

**Source:** Computed

### *Size of the Supply Chain*

The input-output model is designed to estimate the industrial supply chain for polymers in the United States. The estimated model provides a summary of the entire United States economy by sector and the corresponding numbers for the value of output, gross state product, income and the number of persons employed by each sector, Table 3. The model consists of 39 sectors with a total gross domestic product (GDP) for 2007 of $13.8 trillion. Total economic output for the entire economy in 2007 was $25.6 trillion, with total employment of almost 177 million. The chemical, polymer, and petroleum supply chain's share of total GDP is $679.9 billion, or about 5% of total GDP. This translates into the supply chain generating about $4.92 of each $100 of U.S. total GDP. This lends a quantitative perspective to the importance of this industrial supply chain to the national economy.

More specifically to the polymer sector of the supply chain. The polymer sector accounts for $104.0 billion of the cluster's total GDP of $679.9 billion, or about 15%. The industrial supply chain cluster GDP of $679.9 billion is divided among its five components. The largest component of the cluster's GDP comes from the petroleum and natural gas extraction sector that accounts for $271.5 billion, a share of 40%. The chemical sector's $199.1 billion GDP is about 29% share for the entire supply chain. This contribution consists of over $106 billion from both the petroleum and coal products manufacturing, a 53% share of the total chemicals manufacturing GDP contribution. Another $41.2 billion of GDP is accounted for by the basic chemical manufacturing subsector. Soap, cleaning compounds, and toilet preparation manufacturing subsector adds another $38.5 billion to GDP while the chemical products and preparation manufacturing contributes $13.1 billion.

The largest segment of the polymer manufacturing sector is plastics product manufacturing subsector, representing $53.0 billion in GDP, or over half the total GDP for the entire polymer sector. The next most significant subsector of the polymer sector is plastics material and resin, synthetic rubber, and organic fiber manufacturing which contributes about $22.2 billion to GDP for the entire polymer sector, or over one-fifth of the polymer total.

The chemical and polymer cluster contributes 1.45 million jobs to the United States economy. The polymer sector of this cluster represents the largest share, contributing nearly 982 million jobs, or about one in four jobs in the total industrial supply chain cluster. The chemical and polymer distribution sector contributes the most to employment, accounting for over 1.4 million jobs. This accounts for about 37 in every 100 jobs for the entire supply chain.

## Industrial Market Trends for Renewable Polymers

### *Types of Renewable Polymers*

Polymers made from renewable feedstocks are emerging and facilitate cleaner production of a broad array of chemicals. There are three primary types of renewable polymers: starch, polylactide acid (PLA), and biopolymer poly-3-hydroxybutyrate (PHB).

Starch and starch blends account for about 80% of the renewable polymer market. Pure starch compounds can absorb humidity and is used for drug capsules in the pharmaceutical sector. Polylactide acid (PLA) is a transparent plastic made from natural resources, such as corn. It not only resembles conventional petrochemical mass plastics in its characteristics but also does not require specialized processing equipment. PLA and PLA-blends generally are shipped as granulates and are used in the plastic processing industry for the production of foil, moulds, tins, cups, bottles and other food and non-food packaging. The biopolymer poly-3-hydroxybutyrate (PHB) is a polyester produced from renewable feedstocks. Its characteristics are similar to those of the petrochemical-produced plastic polypropylene. The South American sugar industry has decided to expand PHB production to an industrial scale (Biomass Research and Development Technical Advisory Committee, 2008). PHB produces transparent film at a melting point higher than 130 degrees Celsius yet is biodegradable without residue.

### *Trends in the Renewable Markets*

Biobased products are slowly penetrating markets in the United States. The American Chemistry Council (2009) forecasted that in 2005 the U.S. chemical industry would increase 5% to $700 billion. However, they estimated that overall, chemical industry production would fall 1.5% in 2008 and this trend would continue through 2009, falling again 1.5% compared with a 2007 growth. The National Petroleum and Refiners Association estimated that the U.S. chemical industry output declined by 3.2% in 2008 from 2007 (Storck 2006) predicting that production of virtually all major petrochemicals would decline in 2008 after a rise in 2007 (O'Reilly 2009). Industry sales rose by 2.4% compound annual growth rate (CAGR) and production increased by 2.6% CAGR during the 1998-2007 period, Table 1. Some longer-term studies suggest dramatic renewable chemical and polymer growth from 2020-2050 (Patel, et al., 2006).

Global demand for renewable polymers, which include plastic resins that are biodegradable or derived from plant-based sources, is forecasted to reach 890,000 metric tons in 2013 (SPI). Primary drivers for this four-fold increase over 2008 levels include the development of bio-based feedstocks for commodity plastic resins, enhanced restrictions on the use of certain plastic products such as plastic bags, and enhanced demand for environmentally-sustainable products. Bioplastics are expected to become more cost-competitive with petroleum-based resins in the intermediate term. Biodegradable plastics, such as starch-based resins, polylactic acid and degradable polyesters, accounted for almost 90% of the bioplastics 2008 market.

Nonbiodegradable plant-based plastics are anticipated to be the primary driver of bioplastics demand. Demand for non-biodegradable plant-based plastics is forecasted to increase from just 23,000 metric tons in 2008 to nearly 600,000 metric tons in 2013.

Western Europe is the largest renewable polymer producer, accounting for about 40 percent of world demand in 2008. Renewable polymer sales in the region benefit from strong consumer demand for biodegradable and plant-based products, a regulatory environment that favors bioplastics over petroleum resins, and an extensive infrastructure for composting. However, future increases are forecasted to be relatively more rapid however in the Asia/Pacific region, equaling West European market production levels by 2013. China is expected to open over 100,000 metric tons of new renewable polymer capacity by 2013.

### *The BREW Project*

In 2006, several universities and research institutions in the EU collaborated to produce the “BREW Project”, which estimates the growth opportunities for biobased chemicals in Europe (Patel, et al. 2006). This research identifies three scenarios for the growth of the biobased chemicals industry in Europe applied to a specific set of biobased chemicals and their petrochemical counterparts. Growth rates for the biobased chemicals industry are applied to volumes of tonnage of each biobased chemical (Patel, et al. 2006). The growth rates used in the “BREW Project” are a result of primary data collection that codified expert opinion. Because the “BREW Project” employed expert opinion and is recent (2006), it is considered an important global reference in forecasting the dynamics of renewable polymer industrial markets.

### *Future Renewable Chemical and Polymer Industrial Markets*

Emerging technologies related to renewable polymer production from natural sources, such as plants, animals, and microorganisms, have opened substantial economic opportunities and potentials within the chemical, agricultural, and polymer clusters of the state over the past few years. What is currently not known is the magnitude of the economic impact of this emerging renewable chemical and polymer cluster and the promise of future market opportunities for renewable polymers. This knowledge is critical to stakeholders within the renewable polymer cluster if private sector firms make the investment necessary to become leading producers of innovative renewable products and materials.

The BREW report utilizes a CAGR of 1-3% to construct all its scenarios for the future. Considering additional industry reports within the United States, the 1-3% annual growth rate seems reasonable. Growth rates and technical substitution potentials for the renewable chemical and polymer cluster depend on several factors. These factors include crude oil prices, alternative feedstock prices, and biotechnology development (Sporleder 2005). For example, renewable industrial markets will be slow to emerge if 1) global crude oil prices are sustained at relatively historic low levels, 2) alternative feedstock prices are higher than crude oil prices, and 3) minimal biotechnology innovation related to renewable polymer advancement occurs.

## Individual Firm Innovation Strategy and Complementary Assets

From the viewpoint of senior managers, the innovation strategy for a firm in the chemical/polymer industrial supply chain is important to the future competitiveness and sustainability of the firm. Innovation in agricultural biotechnology has been rapid and encourages and facilitates designer genes from various germplasm sources to become renewable polymer ingredients in a wide array of applications never before possible. Hence, the individual firm strategy relative to innovation is a vital aspect of how firms will develop and participate in emerging renewable polymer future supply chains. The problem can be captured in the first-mover theory that isolates key factors regarding managerial decision-making about renewable polymers.

### *First-mover Strategy*

Pioneer firms are first-movers that attempt to gain advantages over rivals from being first with an innovative product or service in a market. These first-mover advantages may include strong image and reputation, brand loyalty, technological leadership, and being in an advantageous position relative to the 'learning curve' involved in managing a specific product or process innovation.

Three advantages may be realized by pioneer firms: 1) the preemption of rivals, 2) the imposition of switching costs on buyers, and 3) the benefit that accrues from being seen by customers as a technological leader compared to rival firms (Sporleder et al. 2008). Second-mover or follower firms have the advantage of lower costs through less expensive imitation of first-mover products (or processes) and the resolution of market or technological uncertainties faced by first-movers. Taken together, market pioneers deploy innovative products or processes with high initial costs and risks, but yield high potential returns. This also implies that second-movers or followers experience lower costs because imitation is less expensive than innovation. How do firms decide to engage in first-mover compared to second-mover strategies for new product development (NPD)? What factors influence this decision? What role might the supply chain play in making this decision? These questions are key to the success of innovation in renewable polymers. One useful construct for better understanding the linkage between supply chain issues and firm innovation strategy is complementary assets.

### *Complementary Assets as Bridge from Firms to Supply Chains*

Capture and sustainability of first-mover advantages are related to complementary assets (Teece 1986). Commercialization of innovation requires linking with complementary assets such as marketing expertise, brands, and logistics and supply chain networks, all in support of the innovation.

In general, a firm's competitive advantage is a function of the unique organizational skills that determine how it combines and orchestrates assets over time. The degree of innovativeness of a new product is related to whether the new product can be produced and marketed by existing complementary assets available to the firm. When an innovation requires new capabilities, it may create intrafirm conflicts. The more disruptive the innovation is from a customer's view, the more the portfolio of existing assets needs to be changed. Hence, the probability of innovation adoption declines for any time t or the rate of adoption slows (i.e. slower diffusion). This is because the customer may not want to acquire or build complementary assets to make innovation adoption feasible, as in the case of B2B or industrial markets.

The strength of appropriability regimes also may influence the sustainability of economic rents to innovators. Appropriability refers to the ability of various stakeholders to retain the economic rents generated from the commercialization of an innovation. Weak appropriability regimes imply that stakeholders will have difficulty in capturing sustainable economic rents from their innovation. Economic rents from commercializing an innovation potentially are shared among the innovator, customers buying the innovation, suppliers to the innovation, and second-movers or followers. Commercializing innovation by firms that lack complementary assets, or in the event that only 'generic' general-purpose assets are required, leads to weak appropriability.

What is the most appropriate characterization of chemical/polymer supply chains regarding appropriability? What specific implications does this have for supply chain coordination and the potential for sustainable rent capture from innovation in renewable polymers aimed at industrial markets? These questions need systematic analysis to better understand this emerging area of renewable polymers.

## Conclusions

The objective of this research was to precisely define the polymer industrial supply chain in the context of value added industries. The research is only a beginning at analyzing emerging industrial supply chains that link renewable germplasm from agriculture to manufacturing sectors. The input-output model provides inter-industry linkages among various sectors and industries that form the total U.S. economy. The model is designed to maintain significant detail in the chemical and polymer cluster. This facilitates estimates of the economic importance of this entire cluster, along with the industries of the general manufacturing and services sectors. The economic measures of importance provided are output, gross domestic product, income, and employment.

The input-output analysis indicated that in 2007 the chemical and polymer cluster output accounted for about 5% of total gross domestic product. United Sates GDP was $13.8 trillion with about $679.9 billion accounted for by the polymer industrial supply chain. The chemical and polymer industrial supply chain cluster contributes $4.92 of each $100 of United States GDP.

Four manufacturing and one distribution sector defines the chemical/polymer industrial supply chain. These include: 1) petroleum and natural gas extraction, 2) chemicals manufacturing, 3) polymer manufacturing, 4) mold and equipment manufacturing related to polymer production, and 5) chemical and polymer wholesale distribution. The polymer manufacturing sector includes five subsectors: 1) coated and laminated packaging, paper, and plastics film, 2) plastics material and resin, synthetic rubber, and organic fibers, 3) paints, coatings, and adhesives, 4) plastic products, and 5) rubber products. The polymer sector contributes about 15% of the total GDP contribution accounted for by the entire industrial supply chain. The largest subsector within the polymer sector is plastics products manufacturing, which accounts for over half of the total GDP contribution by the polymer sector. Three-fourths of the contribution from the polymer sector comes from plastics products manufacturing, and plastics material and resins and synthetic rubber manufacturing.

Individual firm strategy relative to innovation is a vital aspect of how firms will develop and participate in emerging renewable polymer supply chains. The strength of appropriability regimes within emerging chemical/polymer supply chains will influence sustainable rent capture for firms within the chain. Weak appropriability regimes imply that stakeholders will have difficulty in capturing sustainable economic rents from their innovation. Economic rents from commercializing an innovation may be shared among the innovator, customers buying the innovation, suppliers to the innovation, and second-movers or followers. These issues will be resolved over time as dynamic supply chains for renewables emerge globally.

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