MARKET OPPORTUNITY FOR LIGNOCELLULOSIC BIOMASS

Background Paper: Multi-tier Market Reference Framework

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ABOUT THE PAPER

Having a portfolio of potential uses of biomass along the multiple tiers of its supply chain is vital to surmount the challenges associated with the development and commercialization of purpose-grown energy crop and bioenergy industries. However, extant literature discussing markets for biomass generally does not expressively distinguish different types of biomass products, by whom they are produced, and to whom they are sold. Therefore, it remains ambiguous where in the biomass supply chain the discussed market opportunities lie. We attempt to address this gap in this paper.

The paper discusses a *multi-tier market framework* and investigates biomass products and their uses at different stages along the supply chain. The premises for this framework are threefold. First, biomass products range widely in forms—from raw organic materials, intermediate biomass, refined biomass, to semi-finished, biomass-derived products, to name a few. Second, different biomass products generally render themselves to be traded in different markets. And, third, a wide range of biomass product reflects multiple tiers of biomass business players, each offering different biomass-based products and facing different competitors.

The relevance of the multi-tier market framework is further underscored by the various biomass markets to be funded through *the Agriculture Act of 2014* for the next five years, and the extended definition of bio-based products in *the 2008 Farm Bill*. Notable among biomass markets to be funded under *the Agriculture Act of 2014* for the next five years are: biomass crop assistance; bioenergy for advanced biofuels; biorefinery, renewable chemical and bio-based product manufacturing assistance; and bio-based markets (BBI International 2014). As to be discussed in this paper, these markets mirror different tiers of a biomass supply chain—ranging from tier-1 markets (biomass crop assistance); tier-2 markets (bioenergy for advanced biofuels); tier-2 and tier-3 markets (biorefinery, renewable chemical, and bio-based product manufacturing assistance); to tier-3 and tier-4 markets (bio-based markets). Similarly, the definition of bio-based products in *the 2008 Farm Bill* that extends from that in *the 2002 Farm Bill* to include bio-based intermediate ingredients or feedstocks

(Darby 2012a) implicates the distinction among different forms of biomass-based products.[1]

It should be emphasized at the outset that the multi-tier market framework presented in this paper illustrates a simplified, linear sequential relationship along the multiple tiers of a biomass supply chain to provide *a generic framework*. Having a generic framework is particularly useful for case-by-case market identification and analysis, depending on a company's product portfolio and business strategy. This is because in the real business world, supply chain relationships are not always linear. Suppliers of different supply chain tiers may find themselves serving the same markets under a number of circumstances. For instance, different biomass products may be required by the same buyers; buyers may choose to bypass middle-tier suppliers (e.g. buy direct); or biomass suppliers may choose to extend to downstream markets by expanding their products offered. Thus, users and suppliers—both within and outside the dedicate energy spaces—not only differ, but can also shift across different market tiers (e.g. moving upstream or downstream). Together, these conditions define opportunities and competitive landscape in individual markets that differ to different players.

Our hope is that the multi-tier biomass market framework discussed herein will provide the basis and common language for various entities in biomass supply chains in forming a systematic view of biomass market opportunities not only in the existing energy markets, but also in emerging non-energy markets.

[1] Defined by *the 2002 Farm Bill*, bio-based products are commercial or industrial products (other than food or feed) that are composed in whole, or in significant part, of biological products, renewable agricultural materials (including plant, animal, and marine materials), or forestry materials. *The 2008 Farm Bill* added bio-based intermediate ingredients or feedstocks to the definition.

INTRODUCTION

The past few years have witnessed the rapid development of plant biomass-based energy, such as heat and power, and biomass-based fuels such as bioethanol and biodiesel. The basis of development constitutes both the supply sources of plant biomass and refining technologies. Table 1 provides a summary of plant biomass category and corresponding examples.

Table 1 / Plant Biomass Categories

Plant Biomass Category	Examples
Sugar-based biomass	Sugar cane, sugar beet, sweet sorghum
Starch-based biomass	Corn grain, wheat
Oil-based biomass/oleaginous crops	Rapeseed, sunflower seed, soybean, palm, jatropha, camelina, and cynara
Woody lignocellulosic biomass	Willow, poplar, eucalyptus
Non-woody lignocellulosic biomass	Reed canary grass, miscanthus, switchgrass, giant reed
Algal biomass/microalgae biomass	Algae, various aquatic organisms e.g. lipid microalgae

Among these different biomass categories, lignocellulosic biomass raw materials have been more seriously considered as alternatives to food-based biomass (sugar- and starch-based biomass) used in the 1st generation (1G) refining technologies. The bioenergy industry and governments now focus on the 2nd generation (2G) refining technologies that rely on lignocellulosic biomass as raw materials. While the 3rd (3G) and 4th generation (4G) technologies, mostly found in algae-based companies, began to emerge, it is conceded that these more advanced technologies do not imply a superior commercial viability in terms of feedstock cost, the capital expense, and operating expense of the technology. In fact, some of the best early-stage candidates for commercial-scale operations are 2G companies (Biofuels Digest 2010).

Despite the high expectations of 2G bioenergy, one of the key issues shared by all bioenergy sectors remains whether or not the supply of biomass can be guaranteed in the long term (IFP Energies nouvelles 2011). Large-scale production of high yielding energy crops that can supply sustainable amounts of low-cost biomass feedstocks is widely accepted and promoted as a means to mitigate the supply issues. However, purpose-grown biomass or energy crops are not the one and only source of lignocellulosic biomass raw materials. Other sources of note, competing with purpose-grown biomass, are non-food terrestrial plants (e.g. woody plants like trees and bushes, and non-woody plants like grass and oleaginous crop), agricultural waste (e.g. stover, straw, sugarcane bagasse, stalks, leaves, chaff, and husks), and forestry biomass (e.g. logging residues and forest clearing/thinning).

The prospect of energy crops as long-term, low-cost biomass sources for the bioenergy industry is made complicated by the commercial marketplace of biomass that still faces a number of challenges. On the demand side, many bioenergy companies are still in pilot and demonstration stage, and are not able to generate revenue through commercial sales of their products or services (Son 2013), thus creating *price and demand uncertainties* for cellulosic energy crops. On the supply side, farmers growing cellulosic energy crops are faced with *production uncertainties* that are inherent in agriculture, and made more prominent by the relative novelty of specific energy crop production techniques. In other words, *revenue uncertainties* for energy crop growers remain exorbitant (Song, Zhao, and Swinton 2011). Consequently, there is a growing interest in exploring market opportunities for biomass beyond the energy markets to enhance the development and commercialization of both the energy crop and bioenergy industries.

The rest of the paper is organized by beginning with an overview of lignocellulosic biomass conversion pathways to identify key "*juncture*" products produced from lignocellulosic biomass. They are termed as such for their roles as major feedstocks used in the production of a wide variety of refined biomass materials, intermediates, and finished products. Markets for these juncture products and others produced in subsequent tiers of biomass supply chains are then identified, a summary of which listed by NAICS codes is provided in the Appendix.

OVERVIEW OF LIGNOCELLULOSIC BIOMASS CONVERSION PATHWAYS

Lignocellulosic biomass is primarily composed of three biopolymers: celluloses, hemicelluloses,[2] and lignin. Both cellulose and hemicellulose compounds are carbohydrate polymers (polymers of sugars) that are potential sources of fermentable sugars or sugar raw materials (glucose). Lignin is an aromatic polymer that can be used for the production of chemicals, and combined heat and power. Cellulosic biopolymers are the most abundant and considered the most valuable components of lignocelluloses that are used for the production of various bio-based products (Harmsen et al. 2010; Varanasi et al. 2013).

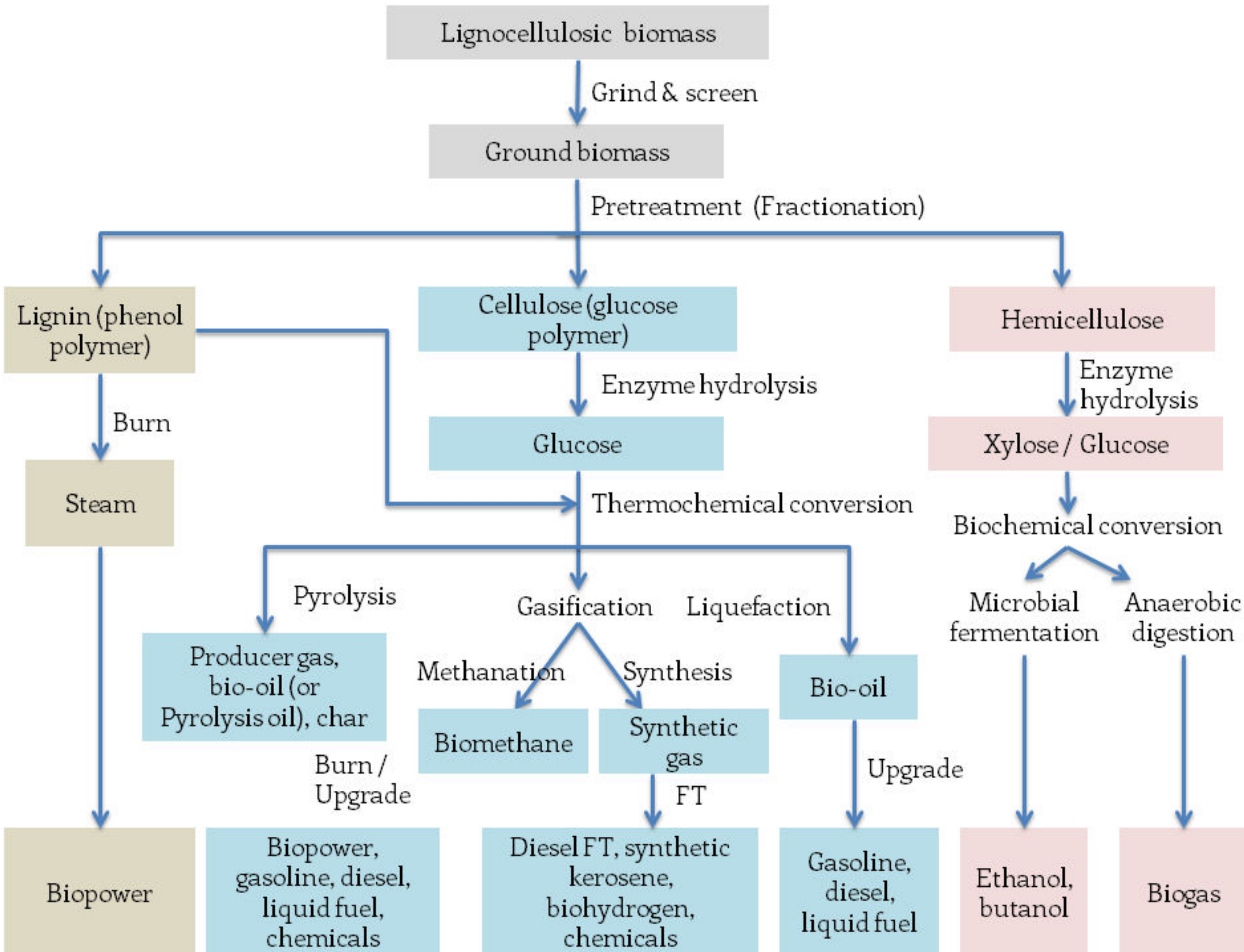
Simplified conversion pathways commonly employed at the time of this writing (2G technologies) to produce an array of bio-based outputs are depicted in Figure 1. Key "*juncture*" products derived from the three lignocellulosic biopolymers are pyrolysis oil (bio-oil), synthetic gas (syngas), biogas (producer gas), and glucose (fermentable sugar).

- **Bio-oil** can be produced using fast pyrolysis process. Bio-oil contains a wide range of organic chemicals, mostly oxygenates (alcohols, aldehydes, and acids) (The Essential Chemical Industry Online 2013).
- **Biogas,** a mixture of methane and carbon dioxide, can be produced from biomass with high moisture content using anaerobic digestion, a biological process. Thus, biogas is effectively the same as landfill gas, which is produced by the anaerobic decomposition of organic material in landfill sites. High-moisture raw biomass is suitable for the anaerobic digestion process. Examples of commonly used biomass are: (1) solid and liquid animal manure, (2) agricultural plant waste, (3) waste from agricultural products processing industry e.g. food processing waste, (4) algae, and

[2] The term *hemicelluloses* is a collective term representing a family of polysaccharides such as arabino-xylans, gluco-mannans, galactans, and others that are found in the plant cell wall and have different composition and structure depending on their sources and the extraction methods (Harmsen et al. 2010).

(5) organic components in town waste, waste waters, and landfills (Malik and Mohapatra 2013; Tong, Wang, and Olson 2013).

Figure 1 / Simplified Lignocellulosic Biomass Conversion Pathways



Note: *Products and materials resulting from different pretreatment processes and conversion pathways differ in terms of properties and qualities, thus affecting corresponding market opportunities.*

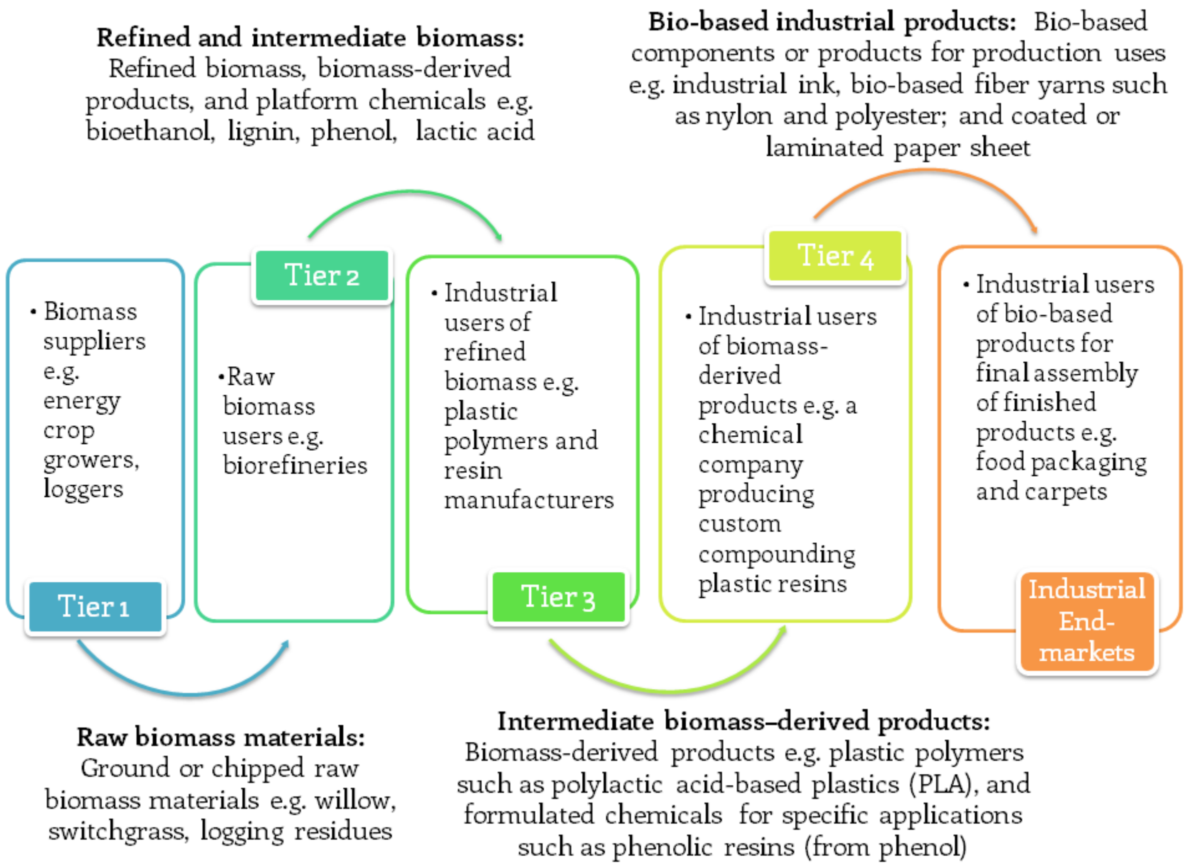
Source: Discerned from Alonso, Bond, and Dumesic (2010); Chaturvedi and Verma (2013); Chung (2013); CRIP-Biorefinery (2009); Fuente-Hernández et al. (2013); Kamm and Kamm (2004); and Wettstein et al. (2012)

- **Producer gas** (also known as **bio-based fuel gas**) is a mixture of combustible gases (principally carbon monoxide and hydrogen), noncombustible gases (mainly nitrogen and carbon dioxide), and typically a range of hydrocarbons such as methane (Enggcyclopedia 2012). Biomass (e.g. wood, algae, bagasse, sawdust, coconut shell) can be converted into a producer gas through the pyrolysis and gasification process (without the synthesis process) (Ashton and Cassidy 2007; Enggcyclopedia 2012).
- **Synthetic gas (syngas)** is a mixture of combustible gases, carbon monoxide, and hydrogen, with possibility of having carbon dioxide content sometimes. It is distinguished from producer gas that also contains significant amounts of noncombustible gases (e.g. nitrogen and carbon dioxide). Syngas can be made from producer gas by heating the thermal cracking or catalytic reforming (Enggcyclopedia 2012; Malik and Mohapatra 2013; Tong, Wang, and Olson 2013).
- **Glucose (fermentable sugar).** Fermentable sugar is obtained from the cellulose and hemicelluloses (xylose) fractions of lignocellulosic biomass, such as straw and grasses, as opposed to glucose obtained from traditional crops like sugar cane or beets, and cereal crops such as wheat (Alonso, Wettsteina, and Dumesic 2012; Skibar 2009).

OVERVIEW OF MULTI-TIER MARKET FRAMEWORK

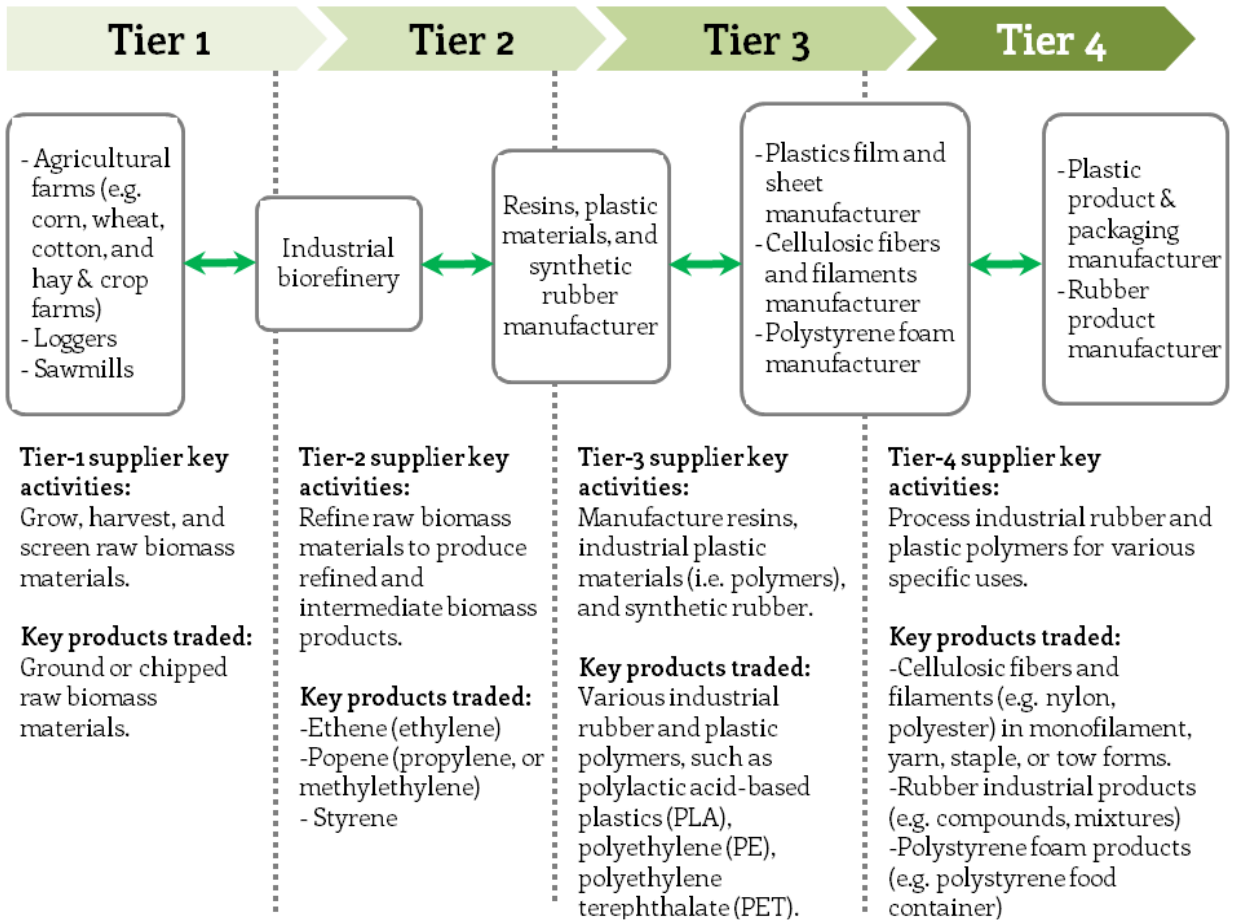
In the proceeding sections, we summarize the various sources of raw biomass feedstocks (see Table 1), and provide an overview of key outputs produced by biorefineries via different conversion pathways (see Figure 1). To provide foundation for further discussion of multi-tier markets for biomass, a *macro-scenario* of multi-tier biomass markets is depicted in Figure 2. Using markets associated with rubber- and polymer-based products as a case in point, a simplified path of four-tier markets is illustrated in Figure 3.

Figure 2 / Simplified Macro-scenario of Multi-tier Biomass Markets



- **Tier 1: Raw biomass materials.** The first tier entails markets for raw biomass materials (e.g. ground or chipped biomass). Suppliers in the tier-1 markets are, for example, farmers, forest loggers, and sawmills. The biorefinery industry falls within tier-1 buyer market.
- **Tier 2: Refined and intermediate biomass.** The second-tier markets involve industrial markets of refined biomass finished products such as bioethanol, biodiesel, and synthetic kerosene. Also traded in the tier-2 markets are intermediate biomass and coproducts that biorefineries produced. Notably, they are biomass produced after pretreatment (to release lignin, celluloses, and hemicelluloses), and platform chemicals such as ethane, lactic acid, and phenol that are derived from the juncture biomass products (e.g. glucose, syngas, bio-oil). The chemical industry, pharmaceutical industry, and food producers are examples of tier-2 buyer markets.

Figure 3 / Simplified Example of Multi-tier Rubber and Polymer Markets for Biomass



- **Tier 3: Intermediate biomass–derived products.** The third-tier markets encompass industrial markets of intermediate biomass–derived products, notably those derived from aromatic intermediates and olefin- and alcohol-based intermediates. The plastic and resin manufacturers and composite materials manufacturers are examples of tier-3 suppliers. They purchase intermediate biomass and formulate them to produce products for a wide range of specific applications. Tier-3 buyer markets are, for instance, textile mills, cardboard box and container manufacturers, and fertilizer manufacturers.
- **Tier 4: Bio-based industrial products.** The forth-tier markets entail industrial end-markets of bio-based products such as bio-based plastics, textile fibers, and customized resins. Among examples of tier-4 buyer markets are apparel knitting

mills, and manufacturers of rubber products (e.g. doormats, rubber bands, and rubber gloves), auto parts, and plastic products and packaging (e.g. food and beverage packaging, and plastic sheets and bags).

DISCUSSION OF MULTI-TIER MARKETS FOR LIGNOCELLULOSIC BIOMASS

Tier 1: Markets for Raw Biomass Materials

Tier-1 markets consist of suppliers of *raw biomass materials* such as energy crops, agricultural residues, forestry biomass (e.g. logging residues and forest thinning), and urban wood wastes (e.g. demolition wastes, pallets and packaging, furniture). Thus, energy crops compete not only with other alternative energy sources (e.g. wind, solar, hydropower), but also with other sources of lignocellulosic biomass. Demand for raw biomass materials is created by entities that procure raw biomass materials in their natural form for their operations. These entities can be in energy market sectors as well as non-energy market sectors.

Energy markets

Bioheat and biopower markets

Three of the most immediate markets for raw biomass materials are for: (1) a power plant designed specifically to operate on 100-percent biomass feedstock, (2) electrical utilities to co-fire biomass with fossil fuels (mostly coal but also natural gas) in the same power plant (IEA-ETSAP and IRENA 2013), and (3) combined heat and power (CHP), or cogeneration, to directly burn biomass to produce renewable electricity (Smolker 2008).

According to *Biomass Magazine* data as of February 2014 shown in Appendix 1, there are about 180 biomass–power plants in operation in the United States with the total capacity of 5,909 million megawatts (MW). These plants are owned and operated by a wide range of stakeholders, varying from industrial users (e.g. pulp and paper mills and lumber companies), to utilities, independent power producers, and small-scale community users (e.g. institutional users) (DOE/EERE 2010).

Dedicated biomass–power plant market segment

New biopower plants grew sharply from the early 1980s to the early 1990s, and have remained relatively steady over the last decade. The majority of the existing biopower plants are designed specifically to operate on 100-percent biomass feedstock. They are generally small in capacity (typically 20–50 MW vs. 100–1,500 MW of coal-fired power plants), and use direct firing system,[3] which has limited energy efficiency (in the low 20% range) (DOE/EERE 2010; IEA-ETSAP and IRENA 2013).

Cofiring plant market segment

Cofiring of biomass with coal is gaining increased attention from both utilities and regulatory stakeholders owing to a number of advantages compared to dedicated power plants burning 100-percent biomass. First, there is lower risk of biomass supply disruption because the plant can burn coal (or gas) if biomass is not available.

Second, cofiring is regarded as the "low-hanging-fruit" opportunity to reduce GHG emissions from existing coal-fired power plants. A high biomass share is favorable due to associated lower GHG emissions. Depending on the plant set up and the chosen cofiring technology,[4] substitution of 20 percent of coal is currently feasible and more than 50 percent is technically achievable. However, high biomass shares involve technical issues, such as securing sufficient biomass, as well as potential combustion problems, such as slagging, fouling (which reduces heat transfer), and corrosion. Today, the usual biomass share is below 5 percent, with only about a

[3] **Direct firing** involves the combustion of biomass feedstocks to produce steam, which is then used with a turbine and generator to produce electricity (DOE/EERE 2010).

[4] Three major cofiring technologies include: (1) **direct cofiring,** using a single boiler with either common or separate burners. It is the simplest, cheapest, and most widespread approach; (2) **indirect cofiring,** in which a gasifier converts solid biomass into a gaseous fuel; and (3) **parallel cofiring,** in which a separate boiler is used for biomass, and its steam generation is then mixed with steam from conventional boilers (IEA-ETSAP and IRENA 2013).

dozen cofire plants worldwide exceeding 10 percent on a continuous basis (DOE/EERE 2010; IEA-ETSAP and IRENA 2013).

Third, investment costs for retrofitting a coal-fired power plant for cofiring are lower than those for 100-percent biomass plants. The investment cost for retrofitting a coal-fired power plant for cofiring is in the range of USD430–500/kW for **co-feed** plants, USD 760–900/kW for **separate feed plants,** and USD 3,000–4,000/kW for **indirect cofiring.** In all three cases, associated investment costs are significantly lower than those of dedicated 100-percent biomass power plants (IEA-ETSAP and IRENA 2013).

Finally, cofiring also enables power generation from biomass with the high efficiency achieved in modern, large-size coal-fired power plants, which is much higher than the efficiency of dedicated, 100-percent biomass power plants (Energy Global 2013; IEA-ETSAP and IRENA 2013). The net electric efficiency of a cofired coal-biomass power plant ranges from 36 percent to 44 percent, depending on plant technology, size, quality, and share of biomass (IEA-ETSAP and IRENA 2013).

<u>Combined heat and power (CHP) market segment</u>

In relation to the foregoing two market segments, the total energy efficiency can be increased even further if biomass cofiring takes place in CHP plants. As of 2013, some 230 CHP plants worldwide use cofiring, mostly in northern Europe and the United States, with a capacity of 50–700 MWe (IEA-ETSAP and IRENA 2013).

Gauging from Appendix 1, out of 180 biomass power plants currently in operation in the United States, only 26 are CHP plants, with total capacity of 961.6 million MW, or about 16 percent of total biopower capacity in operations. CHP plants are also small in size, mostly around 7.5 million MW. More than 80 percent of these CHP plants are located on-site at over 3,700 industrial and commercial facilities around the country (U.S. Department of Energy and U.S. EPA 2012).

CHP capacity additions in the United States during 2006–12 have been sluggish, and its roles in wider U.S. energy markets remain limited. Most of the current CHP capacity in the United States was added in the period of the 1980s to 2005. Capacity additions from about 2006 to 2012 were only a small fraction of what they had been in the previous 20 years owing to a host of factors, including: (1) increasing deregulation of utilities, (2) open access to electricity transportation by utilities, (3) a revision of the Public Utility Regulatory Policies Act (PURPA) to limit mandatory purchase provisions in regions with competitive power markets, and (4) a period of very volatile and high natural gas prices, due to a large extent caused to disruption of gas supplies by Hurricanes Katrina and Rita (Quinn, James, and Whitake 2013).

Moreover, CHP represent approximately 8 percent of power generation in the United States, which compared unfavorably to over 30 percent in countries such as Denmark, Finland, and the Netherlands (U.S. Department of Energy and U.S. EPA 2012). Nevertheless, given that the Obama Administration is supporting a new challenge to achieve 40 gigawatts (GW) of new, cost-effective industrial CHP in the United States by 2020,[5] CHP's uses and potential role as a clean energy source for the future is encouraging (U.S. Department of Energy and U.S. EPA 2012).

Overall, widespread deployment of biopower faces a number of market barriers, chief among which are feedstock cost and supply uncertainties, and varying policies and incentives (DOE/EERE 2010). In the United States, Renewable Energy Portfolio Standards (RPS) and green pricing programs are currently enacted by more than half of all U.S. states. Given the lack of federal RPS, however, the state-level RPS applicability and the levels of support vary from state to state, resulting in the lack of expansive definition for biomass, the lack of nationally consistent incentives (e.g., tax parity) for biopower, and uncertain policy environment for investors (DOE/EERE 2010).

Biorefinery markets

In addition to direct burning of biomass, raw biomass materials are sourced by biorefineries who produce different types of solid (e.g. biochar), gaseous (e.g. biosyngas), and liquid (e.g. bio-oil) outputs from raw biomass materials. These outputs can then be used in the production of biopower, a host of biomaterials and biochemicals, and advanced liquid biofuel such as cellulosic ethanol and biomass-to-

[5] An additional 40 GW of CHP capacity (approximately 50% increase) is estimated to save 1 Quad of energy (equivalent to 1% of total U.S. annual energy consumption), reduce CO_2 by 150 million metric tons annually (equivalent to the emissions of over 25 million cars), and save energy users $10 billion a year relative to their existing energy sources (U.S. Department of Energy and U.S. EPA 2012).

liquids (BtL) diesel (also known as Fischer-Tropsch diesel). Thus, a biorefinery can be considered as a renewable mirror of a petroleum refinery in which a variety of fuels, chemicals, and power are produced.

In recent years, new biorefinery construction in the United States has declined, with new facility commissions dropping from a 2008–2009 high of 30 facilities to fewer than 10 facilities in 2012. However, in 2013, advanced biofuel industry is gaining ground as KiOR, Ineos Bio, and other emerging companies commenced commercial production (Lawrence 2013). In fact, the United States leads the world in the advanced biofuel industry, accounting for an estimated 67 percent of global ventures in advanced biofuel (Market Watch 2014). Among different advanced biofuel, **biodiesel** continues to lead advanced biorefinery scale-up, accounting for over 50 percent of new biorefinery capacity built in 2013 (Lawrence 2013).

Fuel pellet markets

Pellet mills use raw biomass materials to produce pellets of several types and grades as "*fuels*" for electric power plants, homes, and non-residential uses (e.g. industrial). Fuel pellet products and torrefied pellet products are used for burning in light industrial appliances and pellet furnaces (Rodden 2011).

It should be noted that depending on raw biomass materials used (e.g. sawdust, wood chips, rice straws, wheat straws, cotton stalks, corn stalks, switchgrass), markets for pelletized biomass can also be found in non-energy markets such as animal feed pellets, animal bedding pellets, and mulch pellets (see discussion in non-energy market sections). However, it is **wood-pellet markets** that are growing significantly. To put in perspective, out of 80.9 million green tons (MGT) of wood expected to be consumed by viable projects in the United States by 2023, according to Forisk Consulting, wood pellet production is expected to hold the largest share at 34.2 MGT (Baker 2014).

Pelletized biomass is also used as *densified feedstock for biorefinery*, thus, illustrating same-tier trades between pellet mills and biorefinery plants. However, biorefineries are not among the primary markets of pellet plants in the United States today. Currently, two primary markets for U.S. pellet plants are domestic U.S. home heating and export markets for electricity and cogeneration. Export markets, in particular, have gained traction in recent years, due in large part to aggressive emissions policy in the European Union (EU), notably the United Kingdom. As of November 2013, the United States had exported 2.5 million tons of wood pellets compared to 1.75 million tons exported over the same period in 2012, according to the U.S. Department of Agriculture's Foreign Agricultural Service (FAS). Total wood-pellet exports are expected to triple between 2013 and 2018 (Baker 2014).

Not surprisingly, most recent investments in pellet mills are intent on exports. These export-oriented pellet mills are 100-percent focused on sourcing the raw material, operating the wood pellet production plant, and handling the logistics for transporting pellets from the United States to Europe (van Tilburg 2013). These export-oriented projects[6] are also larger than their domestic-oriented counterparts. Based on recent projects, a typical pellet production facility has an output of 500,000 metric tons per year (van Tilburg 2013), and consumes hundreds of thousands to over

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[6] Examples of export-oriented pellet projects are as follows (van Tilburg 2013; Wood Bioenergy 2013):

- The Atlanta-headquartered **Enova Energy Group** is developing three wood pellet projects in Georgia and South Carolina, each with a capacity of 450,000 metric tons per year for exports to Europe through the Port of Savannah.
- **Fram Renewable Fuels** invested $91 million in Hazelhurst, Georgia, to produce 500,000 metric tons of wood pellets for European export and is reportedly planning a second facility. Combined with its existing plant near Baxley, Georgia, Fram will produce more than 900,000 metric tons annually upon the start up of the new facility in 2014.
- **German Pellets** is building two U.S. pellet plants—one in Woodville, TX, with a production capacity of 500,000 metric tons, and the other in Urania, LA, with an expected production capacity of 1 million metric tons per year. The entire output will be exported to Europe.
- **Enviva** invested $120 million of corporate borrowing on new pellet mills at Courtland, Virginia, and Northampton County, North Carolina, as well as the increased storage capacity at its Chesapeake Port terminal, Virginia, to 100,000 metric tons. The combined capacity will push Enviva production to more than 1.5 million metric tons annually.
- Companies targeting **torrefied pellets** are: (1) **New Biomass** in Quitman, Mississippi, making its first torrefied pellet shipment in early 2012; (2) **Vega Biofuels** is moving ahead with a pellet plant in Cordele, Georgia, announced in 2012; and (3) **Thermogen Industries** is constructing a torrefied pellet plant in Millinocket, Maine, scheduled to begin production in 2013.

1 million tons of wood per year (vs. the typical 50–200 thousand tons of wood per year for domestic-oriented mills) (Baker 2014).

Non-energy markets

Paper and paperboard markets

Paperboard (sometimes referred to as "*cardboard*" as a generic term for any heavy-paper-pulp-based board) is made from fibrous materials that comes mainly from two sources: virgin sources (mainly wood), and recycled paper products (also called "*paper stock*" in the paper industry) (EPA 2013). Paperboard mills turn these materials into various paperboard varieties, including unbleached and bleached packaging paperboard, coated paperboard, industrial converting paperboard, and recycled paperboard (Hoopes 2013).

Wood chips from residues from logging activities, sawmills, furniture manufacturers, and other sources are dominated virgin sources used by paper mills,[7] who are, therefore, buyers in these tier-1 biomass material markets. However, uses of recycled paper and paperboard products, which accounted for about 70 million tons (or 28%) of all materials in the U.S. municipal waste stream in 2011, have been on the rise. According to the American Forest and Paper Association (AF&PA), an organization representing U.S. forest, paper, and wood products industry, nearly 80 percent of America's paper mills are designed to use paper collected in recycling programs, and depend on paper recycling as a source of production raw materials (EPA 2013). As part of its sustainability initiative – *Better Practices, Better Planet 2020* – AF&PA realized the second-highest recovery rate for paper in 2012 at 65.1 percent, and

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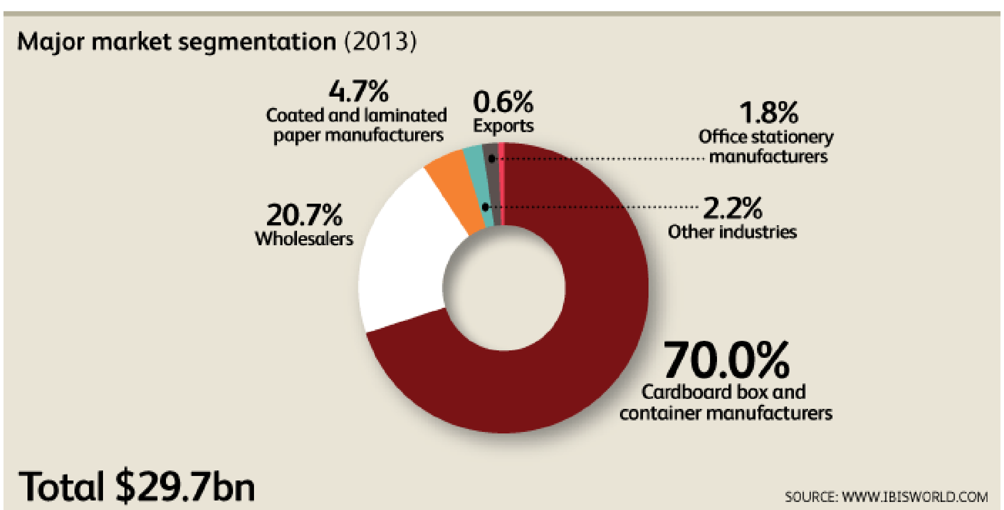
[7] There exist three basic types of paper mills, which differ in their processes based on the source of fiber used and the end product produced, including: (1) **pulp mills** that make pulp, a mixture of cellulose fibers and water used as the basis of all paper products, (2) **recycled paper processing mills** that use recovered waste paper as their feedstock to produce new paper products made entirely of recovered fiber (i.e. 100% recycled content) or from a blend of recovered and virgin fiber), and (3) **hybrid mills** that use both recycled and virgin fiber to make paper. These mills are typically set up to process virgin wood into pulp and incorporate recovered fiber by purchasing bales of recycled pulp which are added to the wood pulp (EPA 2012).

is well on its way to achieve its goal of exceeding 70 percent paper recovery for recycling by 2020 (AF&PA 2012).

While today fibers for paper and paperboard production comes mainly from the two sources discussed above (wood and recycled paper products); over the centuries, paper has been made from a wide variety of feedstock, such as cotton, wheat straw, sugar cane waste, flax, bamboo, and other plant products. The literature shows that **miscanthus** can be used as a raw material for the production of paper or cardboard. Miscanthus enables countries with insufficient forest resources for domestic production of paper and cardboard raw materials (Cradle Crops 2011).

The prospect of biomass entering this market is favored by the truly domestic nature of the U.S. paperboard mills industry. Less than 2 percent of paperboard purchased in the United States originates from overseas, mainly because paperboard is not cost-effective to transport. Paperboard mills sold their products to cardboard box and container manufacturers, and a range of consumer and industrial product producers for further processing (Hoopes 2013). Figure 4 depicts paperboard market size and major market segments in 2013.

Figure 4 / U.S. Paperboard Industry Size and Major Market Segments



Source: Hoopes (2013)

More than two-thirds of all paperboard is converted into cardboard boxes and containers, with a much smaller proportion delegated for other products. Paperboard mills sell directly to cardboard box manufacturers, bypassing the wholesaler. This trend of wholesale bypass stems is due to long-standing relationships between mills and converters, and the intermediate nature of the products that do not require the marketing and advertising typically done by wholesalers. Nonetheless, wholesalers do sell paperboard to smaller converters that do not have the power or relationships to buy directly from mills. Wholesalers purchase an estimated 20.7 percent of products produced by paperboard mills in 2013 (Hoopes 2013).

Composite material markets for natural wood fiber

Many natural materials, including wood and grasses, can be manufactured into composites that can be categorized into two categories: (1) **thermoset composites** (e.g. particle board and fiberboard such as medium-density fiberboard, high-density fiberboard, cardboard, and hardboard), and (2) **thermoplastic composites** (e.g. wood-plastic composite [WPC]) (BioSUCCEED n.d.). The majority of biocomposites are currently used in the automotive, construction, furniture, and packaging industries (Johansson et al. 2012).

<u>Thermoset composite market segment</u>

In the thermoset composite market segment, wood is increasingly combined with other materials to meet manufacturing demands of various **engineered wood** (also called **wood-based composite materials, composite wood, manmade wood,** or **manufactured board**). Raw woody biomass materials can be broken down into smaller elements, such as flakes, chips, particles, fiber, and cellulose to either remove defects (e.g. knots, cracks, etc.) or redistribute them to increase uniformity, depending on intended products. For instance, the breakdown of *forest biomass* can include large timbers, dimensional lumber, very thick laminates for *glued-laminated beams*, thin veneers for *plywood,* strands for *strandboard*, flakes for *flakeboard,* chips for *chipboard*, particles for *particleboard*, and fibers for *fiberboard* (Rowell 2007).

In North America, production and use of **particleboard** (or low-density fiberboard) and **medium-density fiberboard**[8] have grown dramatically, replacing more and more solid wood lumber and plywood products (Green Seal 2001). Medium-density fiberboard, in particular, has become one of the most popular wood-based composite materials due to its advantages and favorable machining properties (e.g. static bending, internal bond, and screw holding). Medium-density fiberboard, heavily used in the furniture industry, is also used widely in kitchen cabinets, door parts, moulding, millwork, and laminate flooring (Iqbal, Kyazze, and Keshavarz 2013).

While particleboard and medium-density fiberboard products are currently manufactured primarily from wood residues from production of lumber and plywood, there is the opportunity to use agricultural residues like straw residues of grain crop (e.g. rice, wheat, soy) as raw materials. An added advantage of **straw biomass** is that although processing straw into particleboard and medium-density fiberboard is similar to processing wood residues, breaking straw into fibers requires less processing and less drying, therefore less energy use. In terms of properties of **strawboard** (e.g. internal bond strength, resistance to rupture, moisture resistance, and screw-holding strength), it is found that they are equal to or better than wood-based particleboard and medium-density fiberboard (Green Seal 2001).

<u>Thermoplastic composite market segment: Polymer</u>

There are many different types of fibers that can be used to reinforce polymer matrix composites for specific end-applications. The most common are *carbon fibers* and *fiberglass*. In recent years, among the possible alternatives, the development of **fiber reinforced polymer composites (FRPs)** using lignocellulosic materials in the place of synthetic fiber materials (e.g. glass and carbon fibers) receives a great deal of research effort (Iqbal, Kyazze, and Keshavarz 2013). These lignocellulosic-based FRPs can be derived from plant fibers from crops (e.g. cotton, flax or hemp), recycled wood, waste paper, and crop processing byproducts (Johansson et al. 2012). Lignocellulosic-based FRPs possesses a number of advantages and favorable machining properties

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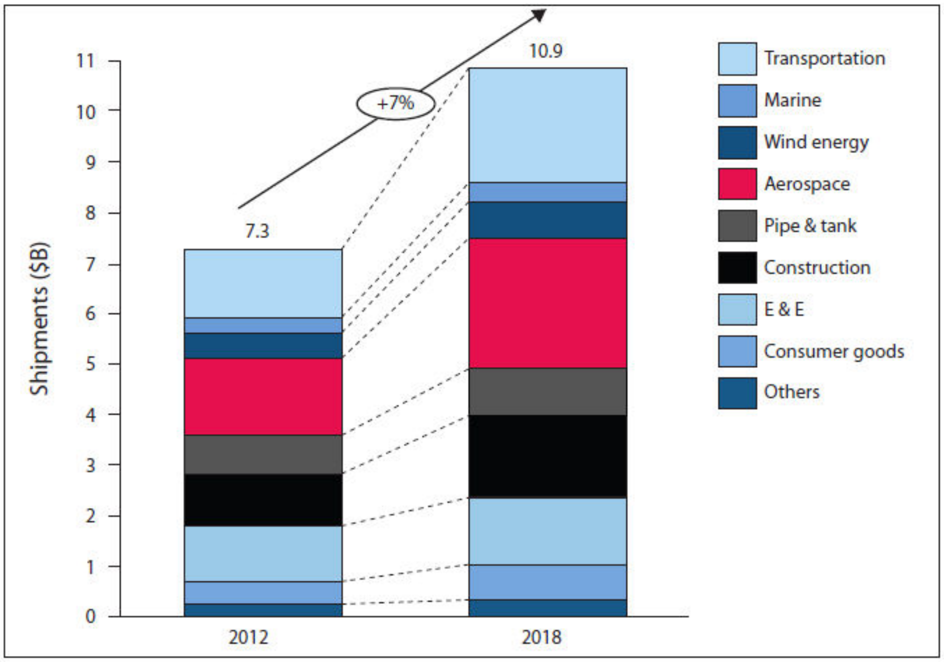
[8] Distinguished from the third type of fiberboard (in terms of density), namely hardboard (or high-density fiberboard) (www.doityourself.com).

compared to synthetic fiber counterparts. Synthetic fibers are brittle and are often broken into smaller fragments, while lignocellulosic fibers are flexible and offer a high ability for surface modification. They also present fewer health problems such as skin irritations and respiratory disease, which are associated with most synthetic fibers (Iqbal, Kyazze, and Keshavarz 2013).

A notable product, **wood-plastic composites** (also referred to as **natural fiber polymer composites**)—used in, for example, motor vehicle plastic parts manufacturing—have gained popularity due to their superior outdoor durability (Pelaez-Samaniego 2013). Wood-plastic composites make use of woody raw materials in various forms, although commonly in the form of *wood flour (fine particles)*. Their formulations include additives (e.g. lubricants, inorganic fillers, colorants, UV stabilizers, biocides and fire retardants), and thermoplastic resins such as polyethylene (PE) and Polyethylene terephthalate (PET) (BioSUCCEED n.d.). Notably, uses of thermoplastic resins indicate additional market opportunities for biomass in this market segment (see tier-2 markets for bio-based resins such as bio-PE and bio-PET).

Overall, the commercial opportunity for biomass in this market is encouraging both in terms of market size and potential growth. The United State has the highest composites consumption per capita in the world, suggesting a sizable market with industry revenue estimated at US$7.3 billion in 2012. Even so, there are still many application areas—including transportation (especially lightweight vehicles) and construction—where composites penetration is less than 2 percent, and there are significant opportunities for growth. A compound annual growth rate (CAGR) for the North American composite materials market is projected to be around 7 percent to reach $10.9 billion in 2018. Notable growth drivers are strong recovery in the transportation and construction markets, and continued double-digit growth in the wind energy and aerospace markets (Jacob 2013) (see Figure 5).

Figure 5 / North American Composite Materials Market Size and Projected Growth

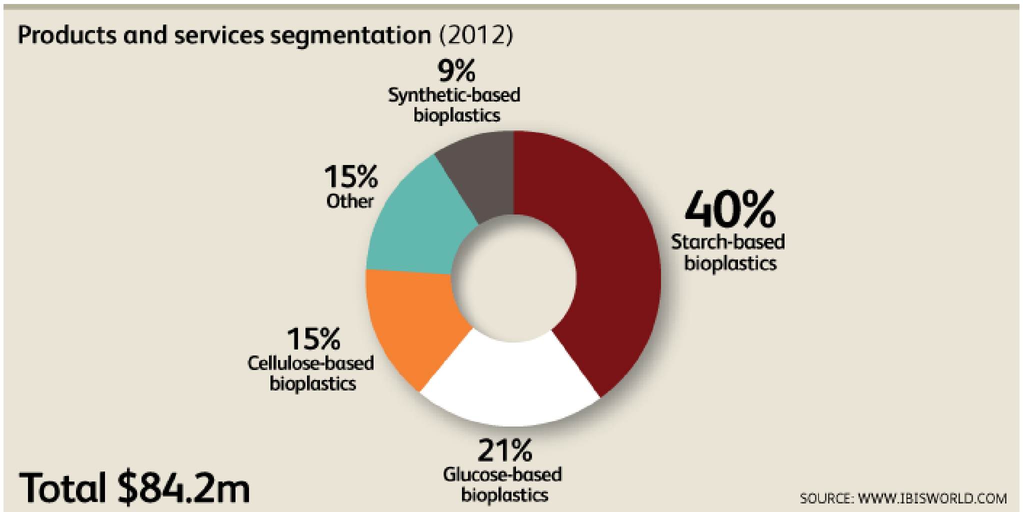


Source: Jacob (2013)

Industrial polymer and plastic material markets for raw biomass materials

Currently, most industrial polymers and plastics are produced from nonrenewable oil- or gas-based resources. The growing interest in bio-based polymer and plastic materials from renewable sources provides market opportunities for biomass. As shown in Figure 6, the majority of biopolymers are manufactured using **starch** and **cellulose**. The current major sources of starch are maize, potatoes, and cassava. Other potential sources include arrowroot, barley, some varieties of liana, millet, oats, rice, sago, sorghum, sweet potato, taro, and wheat. Cellulose, a polymer of glucose and an integral plant cell structural component, has been used to make plastic for nearly 140 years. Common cellulose sources include wood, cotton and hemp (The British Plastics Federation n.d.). In terms of applications, *starch-based bioplastics* are primarily used to manufacture food-service ware. *Glucose-based bioplastics* derived from polylactides (lactic acid polymers or PLA) are water resistant and are used to manufacture cold drinks, cups and bottles, food packaging film and containers, carpets and clothing. PLA can also be used to manufacture CDs and electronics casings. Applications of *cellulose-based bioplastics* include packaging for CDs, confectionary, and cigarettes (Jose 2012).

Figure 6 / Products and Segments of the U.S. Bioplastic Manufacturing Industry



Source: Jose (2012)

Given a variety of biomass feedstock, bio-based polymers and plastic can be grouped according to their origin into three main categories as follows (Johansson et al. 2012):

- Polymers **directly extracted from natural materials.** Examples are starch-based bioplastics manufactured from raw starch; proteins; lipids; and polysaccharides and lignin from biomass crops, either woody species (e.g., pine, poplar, spruce, eucalyptus, willow) or grasses (e.g., sugarcane, sorghum, miscanthus, switchgrass, corn stover) (Johansson et al. 2012; Ten and Vermerris 2013). It should be noted that in procuring production inputs in this category, polymer and plastic material manufacturers may extract starch and cellulose from raw biomass materials themselves, thus engaging with tier-1 suppliers. Or, they may purchase extracted biomass products (e.g. starch, cellulose, lignin) as feedstocks from suppliers further downstream like biorefineries and milling companies (The British Plastics Federation n.d.). In the latter case, market opportunities exist in tier-2 markets (see discussion of industrial polymer and plastic markets for refined and intermediate biomass). Thus, this category constitutes **tier-1 and tier-2 biomass markets**.

- Polymers produced by **"classical" chemical synthesis from renewable bio-derived monomers**. Examples are starch-based bioplastics manufactured from modified starch (e.g. thermoplastic starch, or TPS); glucose-based bioplastics derived from polylactides from lactic acid (e.g. PLA), which is in turn made from lactose (or milk sugar) obtained from sugar beet, potatoes and wheat. Bio-PE is also an example in this category (Johansson et al. 2012). This category constitutes **tier-2 biomass markets** (see next section).
- Polymers produced by **microorganisms or genetically transformed by bacteria.** This category includes polyhydroxyalkanoates (PHAs). This category also constitutes **tier-2 biomass markets** (see next section).

The bioplastic manufacturing industry has experienced steady growth in the past five years to 2012. Adding to the steady growth, opportunities for biomass in this market are facilitated by the development of a new generation of bio-based polymers (e.g. polylactides and polyhydroxyalkanoates) that is progressing rapidly. With such development, firms in this industry are able to use technology that converts bio-based polymers into bioplastics more effectively, thereby reducing the manufacturing cost and allowing them to be more cost competitive against petroleum-based competitors (Jose 2012).

Nevertheless, since firms also compete on product quality, the lack of reliable industry standards for biodegradability creates uncertainties in terms of the technical properties of the product, consistency, and reliability (Jose 2012). For instance, the Federal Trade Commission's **Green Guide** gives a broad definition of biodegradability for manufacturers to use in regards to advertising, but it does not touch on manufacturing requirements or standards. The U.S. Department of Agriculture adopted a broad set of standards for biodegrading and composting in 2011 as a backbone for its **certified bio-based product label.** The label has made inroads into measuring claims of biodegradability, but the industry still has a ways to go (Jose 2012).

Animal bedding markets

There is an existing market for raw biomass materials as bedding for livestock, notably **wood-based beddings** (e.g. wood chips, wood pellets, wood shavings, sawdust), and **hay/straw-based bedding.** Energy-crop biomass materials can be price competitive and offer a number of quality advantages compared to conventional straw (the dry stalks of cereal crops such as barley, oats, rice, rye, and wheat). Conventional straw used for animal bedding is, in general, of poorer quality than their most common uses for feed/forage, and do not have a high level of absorbency (Widrick 2011). **Switchgrass straw** has more consistent quality compared to conventional straw because switchgrass straw is generally not sprayed, while it is unknown how much chemical pesticide and herbicide is used on conventional straw (OSCIA 2012).

Grass and straw from biomass can be pelletized for **absorbent pellet markets**, also used as animal bedding. *Pelletized straw bedding* makes a good alternative to wood-, straw-, paper- or clay-based beddings. It is very absorbent; low dust; creates a soft, springy and non-slip surface; and permits selective removal of waste-contaminated bedding. Pelletized biomass sold by the bag for bedding is considerably more valuable than the energy value of the grass for combustion (Cornell University Cooperative Extension 2011). Grass and straw pellets from biomass share a concern with those from conventional agricultural materials when using for bedding in that animals may attempt to eat the materials. To prevent animals from consuming their bedding materials, some pelleting operations in Europe mix lavender with pelletized biomass to ensure the material is unpalatable bedding for animals (Cornell University Cooperative Extension 2011).

Livestock feed/forage markets

Lignocellulosic **agricultural crop residues** (e.g. rice straw, wheat straw, and corn stalks) can be good alternatives in rations for livestock and in the situation of forage shortages. However, they should not be fed without properly supplemented with higher quality feedstuffs because they do not provide enough energy and protein to meet an animal's requirements (Redden 2012).

The prospect in this market may be limited for **dedicated energy crops** such as switchgrass, for reasons not different from those of agricultural crop residues. Energy crops are not suitable for livestock feeds/forages primarily because the ideal composition of energy crops is essentially the opposite of ideal nutrient content for feeds/forages. Energy crops should be as high as possible in fiber content (the structural components of the cell wall, including cellulose, hemicelluloses, and lignin), and as low as possible in crude protein (CP) (the nonstructural parts of the plant tissue such as protein, sugar, and starch) (Cornell University Cooperative Extension 2011). In contrast, high-protein forages are generally deemed to be high-quality forages, while fiber content of forages is inversely related to forage quality (Weiss, Eastridge, and Underwood n.d.).

Nevertheless, **switchgrass** offers a unique value if used as forage in that it can be grown on marginal land that is not suitable for higher value hay, and other feed or food crops. A study conducted in 2011 showed that when switchgrass is harvested at a leafy stage, it has acceptable digestibility and protein that growing steers need. UK researchers found that producers could take an early cutting of switchgrass for hay and harvest it in late fall for a biomass crop without a significant yield loss, which is promising if a market develops (Pratt 2013). It should be noted, however, that while **green switchgrass** has been fed as hay or grazing grass for beef cattle, its potential as forage for other animals (e.g. horses, sheep, and goats) may be limited. This is due to chemical compounds produced by switchgrass called *saponins* that can cause health problems in non-ruminant animals (Caddel et al. n.d.). Another opportunity in this market is the use of **dry switchgrass** as a *non-nutritive* bulking agent by adding to animal feed—similar to other agricultural residues such as rice straw, corn stalks, grass hay, and wheat straw (e.g. hammer-milled to produce a powder suitable for bulking).

Mulch markets

Ground and screened biomass fibers (e.g. wood, paper, corn stover, and straw) can be used as **organic mulch**[9] (Coye-Huhn 2013; OSCIA 2012). Organic mulch is available in various forms and properties. Commercial **bark mulches** (generally the byproducts of milled fir, pine, redwood, and spruce logs) have been adopted for landscape use in three grade standards based on particle size, including *bark chunks* (decorative bark), *bark granules* (soil conditioner), and *shredded bark*. Among the most desirable characteristics of bark mulches are their excellent resistance to compaction and blowing in the wind, their ornamental attractiveness, and their availability (Rakow 2013).

Another common type of organic mulch, **wood chip mulches** are derived from many different hardwood and softwood species and are available in various colors. Wood chips are one of the best performers in terms of moisture retention, temperature moderation, and weed control. They are considered to be slow decomposers, as their tissues are rich in lignin, suberin, tannins, and other decomposition-resistant, natural compounds. Thus, wood chips supply nutrients slowly to the system, while absorbing significant amounts of water that is slowly released to the soil (Chalker-Scott 2007). However, wood chip mulches generally have a high carbon-to-nitrogen ratio. This property means that, in the process of decomposing, they may temporarily reduce the supply of soil nitrogen for plant uptake. This loss can be compensated for by adding nitrogen fertilizer to mulched plants (Rakow 2013).

Straw mulches (e.g. from wheat, timothy, oats, rye, or barley) are lightweight, normally sold in compressed bales, and, like wood chips, are available in various colors. However, because they have an unkempt look, they are commonly used as winter mulches around tree or shrub roots, and as summer mulches in vegetable gardens and strawberry plantings (Rakow 2013). They are biodegradable and neutral in pHs, and have good moisture retention and weed controlling properties, although they are more likely to be contaminated with weed seeds (Williams n.d.).

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[9] As opposed to **inorganic mulches** such as gravel, pebbles, black plastic, and landscape fabrics.

Liquid hydroseeding mulches (sometimes also called **hydraulic mulch seeding,** or **hydraseeding**) containing fiber is another new arena that offers market opportunities for raw biomass materials. A distinction should be noted between **hydromulching** and **hydroseeding.** The former, hydromulching is the application of hydraulic mulch and surface stabilizers for the primary purpose of erosion control; while the latter, hydroseeding has dual objectives of soil stabilization and seed germination and plant growth (Roadside Revegetation. n.d.). We discuss hydromulching in the next section on erosion-control product markets.

Hydroseeding is used when other seeding methods are impractical, typically on steeper sites where ground based seeders are limited (Roadside Revegetation. n.d.). Mixed into slurry using water, plant seeds, and ground biomass fibers, hydroseeding mulch is sprayed onto exposed dirt. As the liquid dries, the fibers and seeds form a blanket that covers the dirt, providing a growing environment that spurs rapid development by the seeds (Lemke 2008). Hence, hydroseeding has the advantage over other seeding methods owing to its one-pass operation of applying soil amendments, fertilizers, soil stabilizers, and seeds together in one operation. In addition, seeds that are used in hydroseeding operations do not have to be as clean (e.g. free of straw, awns, chaff) as those for other seeding methods, thus reducing costs and time associated with seed cleaning operations (Roadside Revegetation. n.d.).

Commercial hydroseeding mulches are derived from **wood fiber, recycled paper (wood cellulose), sterilized grass straw,** or a combination of the three. **Wood-fiber mulches** are manufactured from wood chips thermally treated by a steam and high pressure shredding process; **wood-cellulose mulches** are made from waste paper materials such as recycled newspaper and cardboard (Roadside Revegetation. n.d.). Wood-fiber mulches are generally considered to offer better holding capabilities on steep slopes than wood-cellulose mulches, which have shorter fibers, making it compacted much easier when they are applied. However, wood fiber is slightly more expensive than recycled paper, and some hydroseeding machines cannot use 100-percent wood-fiber mulches. **Blended mulches** (e.g. wood fiber mixed with recycled paper or straw) are an effort to improve the characteristics of recycled paper. Wood-paper blend is available in the market in varying ratios, of which a blend of 70 percent wood and 30 percent paper is the most common (others are wood-paper blends of 50-50, 80-20 and 90-10). In fact, some users consider wood-paper blends to offer the best advantages of paper and wood (International Association of HydroSeeding Professionals n.d.; Roadside Revegetation. n.d.).

A notable trend to watch for raw biomass materials competing in mulch markets is the strong demand for colored mulch that results in a thriving and lucrative business in most parts of the United States. In fact, the **color-enriched mulch** market continues to provide strong, double-digit growth over the last five years even during the challenging economic times (Thompson 2011). Not surprisingly, mulch manufacturers are turning more and more to colored mulches to improve their bottom line. The longevity of the colored mulches (vs. most natural materials) is one of its biggest selling points, even though it may be 30–40 percent more expensive. Mulch manufacturers are expanding not only the range of color, but also mulch attributes so that it has other applications other than just aesthetics. Those attributes might include retardant chemicals for insects, and fertilizer and weed-killing attributes (Heller 2011).

Erosion-control product markets

A range of erosion-control products are used for erosion and sediment control, such as to stabilize and protect disturbed soil from raindrop impact and surface erosion, conserve soil moisture, and decrease compaction and soil crusting. They are also used to protect seeds from predators, reduce seed and soil loss, and aid in the establishment of vegetation (strawbale.com 2013).

Raw biomass materials can be used in erosion-control product markets in the form of straw bales, or as materials for products such as fiber rolls, erosion control blankets, and coir logs. **Straw bales** have historically been used for erosion and sediment control as, for instance, check dams, inlet protection, outlet protection, and perimeter control. Their generally low moisture content reduces the issues of decomposition and mold growth (strawbale.com 2013). However, many applications of straw bales for erosion and sediment control have proven ineffective. Straw bales do not work well in areas with heavy rain or on sites with large drainage areas or steep slopes because they cannot be properly staked into the surface. They are also very impermeable, making them prone to fall apart and wash away over time as water runs between and under straw bales (US EPA 2010).

Alternatively, erosion-control products such as fiber rolls, erosion control blankets, and coir logs have become the industry standard. **Erosion control blankets** are usually woven from materials with lots of ridges and obstructions to slow down the speed at which water moves across the surface. They can be made from natural materials (e.g. straw fiber, coconut fiber, aspen fiber, and jute), and synthetic materials like polypropylene (plastic). Common *natural* erosion-control blanket products range from lightweight straw blankets to heavier, slower degrading coconut blankets which can be pure coconut fiber or straw/coconut fiber blends.[10]

Fiber rolls are the other type of erosion control device, usually made from the same materials used in erosion control blankets. The materials are rolled into large diameter "logs" and are usually incased in some kind of netting sewing into the desired shape. The three major materials used in fiber rolls are coconut fiber, rice wattle, and wheat wattle (Sutton and Williams 2007).

Silt socks—a filter fabric sock filled with organic material—may be used for erosion control as an alternative to a traditional sediment and erosion control tool such as a silt fence or straw bale barrier. In the Northeast United States, it is not uncommon to use wood chips or compost as organic fill materials. Silt socks are flexible, making them especially useful on steep or rocky slopes where installation of other erosion control tools is not feasible. They also offer an affordable alternative to silt fence. To wit, in most places in Pennsylvania, developers would typically pay from $7.50 to $10 a linear foot for super silt fence to be installed on jobs; whereas a 24-inch compost filter sock is available at about $8–$8.50 per foot. Another factor to consider in terms of affordability, the cost of removal at the end of the job, also favors silt sock. It typically requires a backhoe or a skid-steer or a couple of guys to rip the super silt fence out at the end of a job; while with compost filter sock, a laborer with a utility knife is suffice to complete the task (Brzozowski 2011).

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[10] **Straw-fiber rolls** are suitable for temporary uses. They are flat by nature and do not naturally form an interlocking matrix so after the netting material degrades, straw remains are blown on the soil surface. **Coconut rolls and straw/coconut products** (typically 70-percent straw and 30-percent coconut fibers by weight) are suitable for extended uses.

In addition, **hydromulching** is typically conducted on multi-year construction projects, when surface soils need to be temporarily stabilized for soil erosion or dust abatement (Roadside Revegetation. n.d.). **High performance mulches** such as bonded fiber matrix (BFM) and flexible growth media (FGM) are now available as alternatives to erosion control blankets. Unlike erosion control blankets, these high performance products bond directly to the soil surface, hold in place better, and require less surface preparation (thus less labor needed) (International Association of HydroSeeding Professionals n.d.).

Appendix 2 provides an outline of key suppliers, products traded, and customers in teir-1 markets (with corresponding NAICS code).

Tier 2: Markets for Refined and Intermediate Biomass

Tier-2 markets consist of suppliers of refined biomass and intermediate coproducts from primary manufacturing streams that can be further processed for a wide range of applications. Referring to Figure 1 and discussion of juncture biomass products derived from lignocellulosic biomass, **refined biomass** are those appearing in the bottom boxes of Figure 1. **Intermediate biomass coproducts** are all other biomass outputs along the conversion pathways, notably the juncture biomass products discussed previously.

Biorefineries, the main biomass suppliers in tier-2 markets, can covert the juncture biomass products for a wide range of markets. Moreover, biorefineries with biochemical conversion technologies (not thermochemical pathways) also produce waste stream as coproducts of their industrial processing, including most of the **lignin**,[11] a portion of the **cellulose** (approximately 5%) that is resistant to deconstruction, **monomeric sugars** that cannot be converted microbially, **compounds formed from the monomeric sugars** during processing (e.g., furfural, HMF), and

[11] There are two principal categories of lignin: **sulphur-bearing lignin** and **sulphur-free lignin.** It is the sulphur-bearing lignin that has to date been commercialized (e.g. lignosulphonates – world annual production of 500,000 tons, and Kraft lignin – under 100,000 tons). Due to the lack of suitable industrial processes, the sulphur-free lignin has yet to become commercialized (The International Lignin Institute 2013).

various extractives (Varanasi et al. 2013). The physical and chemical characteristics of these waste materials give them great potential for a wide range of biotechnical applications (Iqbal, Kyazze, and Keshavarz 2013) as further discussed as follows.

Energy markets

Bioheat and biopower markets

Intermediate biomass coproducts can be further processed to produce heat and power.

- **Bio-oil.** While it cannot be directly used as a transport fuel because acids can harm the engine, bio-oil can be used as a fuel for large stationary engines and turbines such as those used to generate electricity (The Essential Chemical Industry Online 2013).
- **Biogas.** Methane in biogas is a flammable gas, chemically identical to the main constituent of natural gas, and can be used as a fuel for heat and/or electricity generation (The BIOMASS Energy Centre 2011).
- **Producer gas / bio-based fuel gas.** Producer gas contains a relatively low energy density—with the heating value varying from 4.5 MJ/m3 to 6 MJ/m3, depending upon its constituents—making it most suitable for combustion to produce thermal energy (Ashton and Cassidy 2007; Enggcyclopedia 2012). It can be burned as a fuel gas such as in a boiler for heat or in an internal combustion gas engine for electricity generation or combined heat and power (CHP) (The BIOMASS Energy Centre 2011).
- **Synthetic gas.** Syngas can be burned to fuel equipment like fired boilers and direct-fired dryers, or used as a replacement for natural gas as a fuel in power generation using integrated gasification combined cycle (IGCC) (Ashton and Cassidy 2007; Enggcyclopedia 2012).
- **Lignin.** Biomass contains about 15–25 percent lignin by mass. Most of the current biorefining strategies for lignin fall into two categories. One involves the burning of lignin to produce waste heat and/or electricity within biorefinery plants. The

other involves the production of lignin in a form suitable for burning for residential heating (U.S. Department of Energy National Laboratory 2012; Varanasi et al. 2013).

Transportation fuel markets: cellulosic ethanol, advanced biofuels, and fuel-cell power

Biorefineries produce various refined biomass that can be used as transportation fuels, key of which are cellulosic ethanol, advanced biofuel, and fuel-cell power.

<u>Cellulosic ethanol</u>

Markets for cellulosic liquid biofuel for internal combustion engine vehicles include bioalcohol such as bioethanol and biobutanol, and oils such as biodiesel. In the United States, much emphasis is on cellulosic ethanol, although the mainstream arrival of second-generation cellulosic ethanol is only now emerging. Two basic types of ethanol-from-cellulose (EFC) processes—biochemical and thermochemical (and possibly a bio- and thermochemical hybrid)—emerged in the United States. The most common is acid hydrolysis (Badger 2002). While a number of pilot-scale cellulosic feedstock plants are coming on stream, only a few are commencing commercial production of cellulosic bioethanol, notably: Coskata (Warrenville, IL); Enerkem (Pontotoc, MS); and Ineos New Planet Bioenergy (Vero Beach, FL), a joint venture between Ineos Bio and New Planet Energy (League City, TX) (Scott 2011).

<u>Advanced biofuels</u>

Markets for advanced biofuel (also called alternative drop-in biofuel) for internal combustion engine vehicles are bioalcohol such as *biobutanol* as a gasoline substitute, *synthetic diesel* as a diesel substitute, and *synthetic kerosene* as a jet fuel substitute. Alternative drop-in biofuel have gained increasing interests in the United States. One attraction of drop-in biofuel compared to cellulosic biofuel is that drop-in biofuel could replace conventional fossil fuels directly, rather than having to be blended into conventional fuels as mandated by the governments. Thus, while demand for cellulosic biofuels that are used as blending components (e.g. E10, E85, B20) depends to a large extent on government blending mandates, demand for drop-in fuels may be less susceptible to changing political caprice (The Economist 2013).

Another important advantage of drop-in biofuel in relation to cellulosic biofuel is the infrastructure compatibility. Unlike cellulosic biofuel, drop-in biofuel is substantially similar to their petroleum-based gasoline, diesel, or jet fuel counterparts in that they could be distributed through the existing pipelines and other infrastructure. They can also be used to power the engines of current cars and trucks without any modifications. The current focus of U.S. government research is aimed at replacing diesel and jet fuel, which typically fuels vehicles that are not good candidates for electrification (U.S. Department of Energy 2012).

Potential technology pathways to produce alternative drop-in biofuel include upgrading of synthetic gas (CO and H2) from gasification, and pyrolysis or liquefaction of biomass to bio-oil. In the former pathway, following clean-up to remove any impurities such as tars, **syngas** can be used to produce (via Fischer-Tropsch synthesis) synthetic natural gas (SNG) or liquid biofuel such as synthetic diesel and synthetic kerosene (used as jet fuel) (The BIOMASS Energy Centre 2011). It can also be directly used in place of gasoline in vehicles with a filtering and cooling treatment. Synthetic diesel gave performance characteristics comparable to those of petroleum fuels. Hence, they may be considered as diesel fuel substitutes, or internal combustion (I.C.) engine fuel, commonly used for mobile propulsion in portable machinery and vehicles (automobiles, trucks, motorcycles, boats, and in a wide variety of aircraft and locomotives) (Malik and Mohapatra 2013; Tong, Wang, and Olson 2013). In the latter pathway, the pyrolysis of biomass produces various bio-based solid, liquid, and gaseous products (see Figure 1). **Pyrolysis liquid,**[12] after distillation and further hydrogenation, can be readily stored and transported, and can be used either as a renewable liquid fuel or in chemical production (Balat 2011; The Essential Chemical Industry Online 2013).

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[12] Also referred to in the literature by terms, such as pyrolysis oil, bio-oil, biocrude oil, biofuel oil, wood liquid, wood oil, liquid smoke, wood distillates, pyroligneous tar, and pyroligneous acid (Balat 2011).

Fuel-cell power

In the fuel-cell / plug-in electric vehicle market, there is an emerging interest in **hydrogen** as an alternative transportation fuel owing to its ability to power fuel cells in zero-emission, high efficiency electric vehicles.[13] It is a cleaner source of power for electric vehicles than electricity produced from coal (the most carbon-intensive fuel for electricity generation) that accounts for as much as 40 percent of electricity generated in the United States (Kiger and Lavelle 2013).

On the supply side of hydrogen, steam reforming of methane (natural gas) currently accounts for the majority of the hydrogen produced in the United States (U.S. Department of Energy 2013). Alternatively, two thermochemical processes can be used to produce hydrogen from biomass—gasification followed by reforming of the **syngas,** and fast pyrolysis followed by reforming of the carbohydrate fraction of the **bio-oil** (Kleperis et al. 2011). Renewable supply market competition for plug-in, electric-powered vehicles is from wind, solar, and other non-carbon-burning electric generation methods. In terms of demand, almost all of hydrogen produced in the United States is used for refining petroleum, treating metals, producing fertilizer, and processing foods. In the transportation fuel market, most of the few currently operating hydrogen fueling stations are in California (U.S. Department of Energy 2013).

Nonenergy markets

Pulp markets

In this market, biorefineries compete against traditional pulp mills. Pretreatment technologies can provide competitive edges compared to traditional pulp mills in that the quality and value of mills' pulp is directly related to the size and thickness of the wood chip used. In contrast, certain pretreatment processes are used in cellulose production to allow biorefineries to use several different types of biofiber as raw material (e.g. traditional sawdust, and renewable resources such as sugarcane, perennial grass, and wheat straw). Furthermore, pretreatment processes can be

[13] Electric vehicles are two to three times more efficient than internal-combustion-engine vehicles (U.S. Department of Energy 2013).

adjusted to produce different desired results for end-product uses, such as packaging materials and paper products (e.g. diaper pads, feminine care pads, tissue paper) (Pure Lignin Environmental Technology 2009; Tong, Wang, and Olson 2013).

Feed markets

First-generation biorefineries, corn ethanol producers, are familiar suppliers in this market. They produce feed proteins during ethanol production called *dried distiller's grain (DDG)*, a medium protein feed (\$0.09–\$0.10/lb) that is a byproduct of corn starch fermentation (Kozak 2011). For cellulosic biorefineries, the quantities and economic value of **high-protein feed** that could be produced from advanced biofuel nonfood or agricultural residues may offer a potential market opportunity. It is a more promising avenue for lignocellulosic agricultural residues than animal feed stuff direct feed or with partial treatment discussed in tier-1 market section (Iqbal, Kyazze, and Keshavarz 2013).

The market opportunities differ, however, depending on the technology used. Feed enzymes can be produced by *solid-state fermentation*, using cellulosic-based materials. For instance, in the integrated bioprocessing of sweet sorghum, the extracted partially digested and enzyme enriched pulp is a valuable feed ingredient in animal feed rations (Iqbal, Kyazze, and Keshavarz 2013). *Thermochemical conversion* processes will **not** retain plant biomass proteins for uses as animal feed or feed ingredients. On the other hand, the use of *benign pretreatment*, the critical step for the retention of plant amino acids in *biochemical technology*, can retain plant proteins and produce biofuel sugars (Kozak 2011). Biorefineries also produce **sweet liquor** that can be fermented into protein as pure as soy or fish protein, for which the current market is primarily in cattle feed and pet food. It can also be used in the production of nontoxic adhesives as well as in fertilizers (Pure Lignin Environmental Technology 2009).

Biochar markets: soil amendment, livestock & poultry farming, construction sector

Biochar markets are growing quickly. There are many different technologies to make biochar. For biorefineries, bioenergy and biochar can be coproduced from thermal treatment of biomass feedstocks by pyrolysis or gasification systems. A wide range of lignocellulosic biomass materials can be used to produce biochar, such as wood chips, tree bark, paper mill sludge, energy crops such as switchgrass, and crop residues (both field residues and processing residues such as nut shells, fruit pits, bagasse, etc.) (International Biochar Initiative 2014).

Biochar has a wide range of uses, thus there are many potential markets for biochar (see further discussion below). However, despite its benefits, the lack of market awareness of biochar benefits is reported as a number-one barrier to biochar market expansion, according to the *Worldwide Biochar Project survey* conducted by the International Biochar Initiative (IBI) during May–June 2013 (Tomlinson 2013).

Soil amendment

According to the *Worldwide Biochar Project survey*, the top-three uses of biochar are soil amendment for sale, garden/subsistence farming, and land remediation (Tomlinson 2013). While the composition of biochar (the amount of carbon, nitrogen, potassium, calcium, etc.) depends on the feedstock used, and the duration and temperature of pyrolysis (International Biochar Initiative 2014), the benefits of biochar are quite tangible and far-reaching. Its benefits as soil amendment include reduced leaching of nitrogen into ground water, increased cation-exchange capacity, moderating of soil acidity, increased water retention, and increased number of beneficial soil microbes (Tomlinson 2013). Using biochar will increase the soil's water holding capacity, meaning less runoff and less frequent watering. Biochar also increases aeration and slows the loss of nutrients (NPK), thus reducing the need for chemical fertilizers. Biochar also acts to increase the cation-exchange capacity (CEC) of the soil, which makes it easier for plants to actually take up the nutrients present in the soil (Gonzalez 2012).

Livestock and poultry farming

Biochar can be used in various applications in animal farming. In fact, some 90 percent of the biochar used in Europe goes into animal farming (Schmidt 2012). Its applications include the following:

- **Silage agent and feed additive/supplement.** In using biochar in silage, only biochar registered as food additives and produced by licensed feed manufacturers may be used. Biochar, and in particular biochar bokashi, is also used as a feed supplement. Biochar promotes digestion and improves feed efficiency, in particular energy absorption via the feed (Schmidt 2012).
- **Litter additive.** Biochar has a very high water holding capacity and can absorb up to five times its own weight of water. Biochar adsorbs very efficiently both organic molecules (e.g. amino acids, fatty acids, proteins, and urea), and mineral compounds (e.g. ammonium, ammonia, and nitrate). Used in litter, biochar locks in moisture, and organic and inorganic nitrogen compounds. The nitrogen adsorption and the continuous drying of the litter deprive the microbial pathogens of their nutrient base and reduce toxic emissions of ammonia. The biochar should, depending on the type of litter, be mixed 5–10 percent by volume with the usual litter (Schmidt 2012).
- **Manure composting.** Biochar can be used to improve manure quality. With the aforementioned effects of biochar for storing moisture and nutrients, it can be used to help manure better degraded microbiologically. Carbon and nitrogen losses are also significantly reduced, thus improving the fertilizer quality of the manure (Schmidt 2012).

<u>The construction sectors: biochar-mud plaster</u>

Two properties of biochar—namely its extremely low thermal conductivity and its ability to absorb water up to six times its weight—make it a suitable material for *insulating buildings and regulating humidity.* Biochar can be added to sand at a ratio of up to 50 percent to create *indoor plasters* with excellent insulation and breathing properties, able to maintain humidity levels in a room at 45–70 percent in both summer and winter. Such **biochar-mud plaster** also adsorbs smells and toxins, and can be recycled (if the houses were demolished) as a valuable *compost additive.* Biochar is also a very efficient *absorber of electromagnetic radiation*, meaning that biochar-mud plaster is very good at preventing "electro smog." Applied to the outside walls of a building by jet-spray technique at thicknesses of up to 20 cm, biochar can be used as a *substitute for styrofoam.* Companies such as Casadobe (Germany) are developing a range of biochar-mud plasters for this market (Schmidt 2012).

Sorptive media markets

Switchgrass biochar produced by fast pyrolysis and a **corn-stover biochar** from a slow pyrolysis process are residues from bioenergy production and the corn industry, respectively. For many years biochar has been used primarily for the purposes of carbon sequestration and to improve soil fertility. One potential avenue to add value to biochar is to use it as **sorptive media for toxic materials.** Biochar has been shown to be an effective sorbent for toxic compounds such as heavy metals and pesticides. Future work will involve looking into altering the pyrolysis processing method to significantly lower ash content (less than 5%). This may also improve sorptive quality by increasing the carbon: ash ratio (Peterson et al. 2013).

Food manufacturing markets

Pyrolysis oil, a complex, combustible mixture, can be used as a fuel for diesel transportation and stationary turbine and diesel power (see discussion on tier-2 energy markets). Compounds that are first extracted from bio-oil during the fast pyrolysis process (the remainder is either upgraded to fuel, or reformed to syngas) can be used as food additives to infuse "smoked," "roasted," or "grilled" flavors (Ashton and Cassidy 2007). In addition, food producers in the food, beverage, and tobacco manufacturing sector use a number of refined biomass products to modify the nutritional value of foods or to extend shelf life (Son 2013).

Industrial polymer / plastic markets for refined biomass

The majority of **bio-based polymers and plastics** are currently manufactured using starch as a feedstock. As noted earlier in tier-1 market section, cellulose-based plastics are usually made from chemically modified cellulose, the most common of which is cellulose acetate used in packaging film. Lignin, a complex compound found in woody plants, is also used to manufacture bio-based plastics and for coating. These intermediate biomass feedstocks can vary in quality depending on the biomass raw material sources and the method of extraction and purification used by biorefineries and milling companies (The British Plastics Federation n.d.).

Polymeric material and resin markets show promises to the extent that biorefineries look into entering these markets. Important thermoplastic resins are as the followings (BioSUCCEED n.d.):

- **Polyolefins**. *Polyethylene (PE)* that includes high density (HDPE) and low density (LDPE); *Polypropylene (PP)* used in many food storage applications (e.g. Tupperware), and *Polystyrene (PS).*
- **Polyesters.** *Polyethylene terephthalate (PET), polyethylene oxide (PEO)*, and *natural polyesters (PLA, PHA, PHB)* that are biodegradable and have similar processing properties as polyolefins.
- **Polyvinyl chloride (PVC).** PVC is a formulation that can be tailored for a wide range of processing conditions and properties, notably in windows, doors, and siding.

Currently, producing bio-based polymers using bacteria to ferment sugars into polymers remains more expensive than using fossil fuel-based inputs. Active research is undergoing to tap plants to produce polymers instead of sugars to make bio-based polymers more competitive. The **plant-to-polymer** endeavor requires high-tech genetic engineering. Multiple research efforts aim to genetically engineer plant such as switchgrass, camelina, and sugarcane to produce and store in its tissues the key compound called *polyhydroxyalkanoate (PHA).* Provided successful genetic engineering, the still unsolved challenge of efficiently extracting *polyhydroxybutyrate (PHB)*, a PHA polymer belonging to the polyesters class, needs to be addressed to reduce the production costs to be as low as, or lower than, oil-based counterparts (Barber 2013).

Industrial markets for lignosulfonate (byproduct lignin)

<u>Multi-polarity related products</u>

Lignosulfonates—byproduct lignin, which differ from *natural lignin (or native lignin)* present in plant tissues (Ten and Vermerris 2013)—contains both hydrophilic and hydrophobic groups. Specific treatments can strengthen either characteristic for particular applications as in emulsions, dispersants, and sequestrates (The International Lignin Institute 2013).

- **Lignin as a dispersant.** Lignosulfonate prevents the clumping and settling of undissolved particles in suspensions. By attaching to the particle surface, it keeps the particle from being attracted to other particles and reduces the amount of water needed to use the product effectively. The dispersing property makes lignosulfonate useful in products such as cement mixes, leather tanning, clay bricks and tiles, ceramics, concrete admixtures, dyes and pigments, gypsum board, oil well drilling mud, pesticides and insecticides, electrolytes, and paper sizing (Pure Lignin Environmental Technology 2009; The International Lignin Institute 2013).
- **Lignin as an emulsifier.** Lignosulfonate stabilizes emulsions of immiscible liquids (e.g. oil and water), making them highly resistant to breaking. Lignosulfonates are at work as emulsifiers in products such as pesticides, asphalt emulsions, pigments and dyes, wax emulsions, bitumen, vitamins, and micronutrients (Pure Lignin Environmental Technology 2009; The International Lignin Institute 2013).
- **Lignin as a sequestrant.** Lignosulfonates can tie up metal ions, preventing them from reacting with other compounds and becoming insoluble. Metal ions sequestered with lignosulfonates stay dissolved in solution, keeping them available to plants and preventing scaly deposits in water systems. As a result, they are used in multi-polarity products such as micronutrient systems, cleaning compounds, and water treatments for boilers and cooling systems (Pure Lignin Environmental Technology 2009).
- **Lignin in other multi-polarity products**. Other multi-polarity products using lignin are complexing agents, flocculating, heavy metal binders, ion exchanging, water softening, protein coagulants, destabilization of oil emulsions, corrosion protection, anti-scaling, metal cleaners, and grinding aids (The International Lignin Institute 2013).

Additive of filler to enhance composites

Another potential for waste lignin is the development of other **high-strength lignin fillers for composite materials** (U.S. Department of Energy National Laboratory 2012). Waste lignin can be *used in a composite* with a compostable plastic such as Polylactic Acid (PLA) or as a true *lignin-PLA copolymer.* However, a composite of untreated lignin in combination with commercial PLA suffered some strength loss, suggesting poor compatibility between the two polymers. To overcome this issue, research shows that exposing lignin to an oxidative treatment (introduction of polar groups) improves compatibility between these two polymers considerably, resulting in a composite with higher strength properties than PLA by itself. As copolymer, incorporating lignin even in low concentrations into a PLA-lignin copolymer reduced the overall molecular weight of the polymer without significantly affecting melting points (Tschirner and Ramaswamy 2011).[14]

Lignin as a chemical binder

Lignosulfonates are a very effective and economical adhesive, acting as a binding agent or "glue" in pellets or compressed materials. This binding ability makes it a useful component of various products, including biodegradable plastic, coal briquettes, plywood and particle board, ceramics, animal feed pellets, carbon black, fiberglass insulation, fertilizers and herbicides linoleum paste, dust suppressants, and soil stabilizers (Pure Lignin Environmental Technology 2009).

Lignin in agriculture

Lignin and lignin-derived products play an important role in the formation of soils and in plant and animal nutrition. Examples are soil rehabilitation, slow release fertilizers, fertilizer encapsulation, composting aid, manure treatment, humus

[14] In this market, biorefineries compete with pulp and paper mills that also produce lignin as byproducts. Unlike **natural or native lignin** (present in plant tissues), **lignosulfonates** (byproducts from the production of wood pulp using sulfite pulping) are water soluble due to the presence of sulfonate groups. The presence of both hydrophilic and hydrophobic domains in lignosulfonates enables them to be mixed with different kinds of polymers to enhance thermochemical and mechanical characteristics (Ten and Vermerris 2013).

improvement, soil stabilization, insecticides, granulation, and pelletizing (The International Lignin Institute 2013).

Lignin as active substances

Specially prepared lignin is suitable as an *active substance* (active pharmaceutical ingredient) with antioxidant, antibacterial, and antiviral properties. These qualities have already been explored and could play an important role in the future. Examples are antibacterial effects, HIV inhibition, digestion regulation, antioxidants, growth stimulators, oxygen scavengers, and hydrogel (The International Lignin Institute 2013).

Nanotube production

Carbon nanotubes with the fullerene structure have many uses, including the smart delivery of therapeutic agents to target cells in humans and animals. One of the challenges associated with carbon nanotubes are their chemical inertness and sharp, needle-like shape that can mimic asbestos. The production of nanotubes derived from lignin, such as *flexible nanotubes* or *nanowires*, may overcome some of these challenges. These lignin-derived nanotubes could be easily functionalized due to the presence of many reactive groups, and whose optical and physical properties could be tailored depending on the monomers employed in the polymerization reaction (Ten and Vermerris 2013).

Basic chemical markets

In 2004, the U.S. DOE released a report identifying 12 “basic” or “platform” chemicals that could be produced from sugars, most through microbial fermentation. These building blocks were of interest because they could be converted into various high-value, bio-based chemicals and materials (Ebert 2007). Bio-based chemicals are expected to increase their share of overall chemical production to 9 percent from the current 1 percent by 2020 (De Guzman 2011).

The products of the chemical industry can be divided into three categories: basic chemicals, specialty chemicals, and consumer chemicals. Tier-2 biomass markets are primarily those for *basic chemicals* that are produced in large quantities, and mainly sold within the chemical industry and to other industries before becoming products for the general consumer.[15] Major basic chemicals include organic compounds that are *building blocks* such as **ethene** (also known as **ethylene**), **propene** (also known as **propylene** or **methylethylene**), **ethanoic acid (acetic acid), butadiene, benzene,** and **succinic acid** (Ebert 2007; The Essential Chemical Industry Online 2013). These potential markets are elaborated as follows.

<u>Basic chemicals from pyrolysis oil (bio-oil)</u>
Pyrolysis oil (or bio-oil) can be reduced catalytically to hydrocarbons that can then be cracked, in a similar way to the cracking of gas oil, to yield a gas containing alkanes, alkenes, and a naphtha-like liquid. These outputs can then be steam cracked to yield **ethene, propene,** and **buta-1,3-diene,** all of which are major feedstocks for a variety of important chemicals (The Essential Chemical Industry Online 2013).

- **Ethene (ethylene)** is the most important organic chemical, by tonnage, that is manufactured. It is the building block for a vast range of chemicals, the principal uses of which are to produce polymers and other useful chemical compounds (The Essential Chemical Industry Online 2013). It is the key building block in the production of *polyethylene* (polyethylene accounts for 50% of all U.S. ethylene production), *ethylene oxide* (10% of ethylene production), and its range of derivatives (such as ethylene glycol). It also is used to produce vinyl acetate, polyvinyl chloride, polyester fiber and film, and a range of alcohols and solvents. An estimated 60 percent of total U.S. ethylene production capacity uses liquefied natural gas, with a further 38 percent derived using naphtha. Over the five years to 2013, demand for ethylene has fluctuated in line with downstream demand, namely ethylene-based chemicals used in plastic production (Kaicher 2013).

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[15] For example, **ethanoic acid (acetic acid)** is sold to producers of **esters,** much of which, in turn, is sold to producers of paints that are then sold to the consumer. As another example, huge quantities of **ethene** are transported as a gas by pipeline around Europe and sold to companies making **poly(ethene)** and other polymers that are then sold to manufacturers of plastic components before being bought by the actual consumer (The Essential Chemical Industry Online 2013).

- **Succinic acid.** Succinic acid is a bulk chemical with a global production rate of between 30,000 and 50,000 tons annually. The market is expected to grow at a compound annual growth rate of 18.7 percent from 2011 to 2016. Industrially, succinic acid has been conventionally made through the catalytic hydrogenation of maleic acid or its anhydride, both of which are derived from *benzene* or *butane* (Higson 2013; Jenkins 2010). **Biomass-derived succinic acid** could serve as an attractive replacement for *maleic anhydride*[16] (a petroleum-derived substance to which succinic acid has a similar chemical structure), and a platform chemical for the synthesis of a multitude of compounds (Ebert 2007). So far, biosuccinic acid is being produced only at a small scale (Coons 2010). Biosuccinic acid production is of particular interest in the biotechnology industry because of technology development, as well as current and potential new applications that can be derived from the product. In terms of production, bio-oil could be fractionized into an organic phase and aqueous phase parts. The former phase bio-oil can be easily upgraded to transport fuel; while the latter phase bio-oil (AP-bio-oil) is of low value. Research studies show that AP-bio-oil can be used by E. coli for cell growth and succinic acid production (Wang et al. 2013). Microorganism performance for biosuccinic acid production is improving and demonstration plants have been built. Major chemical companies investing in biosuccinic acid commercialization include: Netherlands-based DSM in a joint venture with French starch derivatives producer Roquette; Germany-based BASF in collaboration with Dutch lactic acid producer Purac; and Japan-based Mitsubishi Chemical. US-based renewable chemical companies in this field include BioAmber (formerly DNP Green Technology) and Myriant Technologies (De Guzman 2011). In terms of applications, succinic acid and its derivatives are most widely used as food ingredients or as precursors to active pharmaceutical ingredients or pharmaceutical additives. Succinic acid also has a wide range of industrial applications, although they are limited by its prices (Higson 2013). In industrial application, there is a growing interest among chemical-using

[16] **Maleic anhydride** provides a chemical feedstock for food and pharmaceutical products, surfactants and detergents, plastics, clothing fibers, and biodegradable solvents (Ebert 2007).

industries in natural solvents. Biosuccinic acid can be converted into *pyrrolidinones*, materials that can address a large solvent market (Skibar 2009). Furthermore, succinic acid is currently considered one of the **key platform chemicals** used directly in preparation of *biodegradable polymers* such as polybutylene succinate and polyamides, and as a **raw material** to synthesize *compounds in the C4 family*, including 1,4-butanediol (BDO), tetrahydrofuran, N-methyl pyrolidinone, 2-pyrrolidinone and γ-butyrolactone (Wang et al. 2013). In particular, BDO, which is widely used in a range of applications, including engineering plastics and spandex, caught attention of major players in BDO market such as BASF and Mitsubishi that have a keen interest in the development in biosuccinic acid production (De Guzman 2011).

- **Phenolic resin (phenol-formaldehyde resin)**. Pyrolysis oil produced from biomass is currently used to make **renewable phenolic resins** without requiring further purification (Chemical Industry Education Centre n.d.). Phenolic resins are the oldest commercially manufactured synthetic polymer (Global Phenolic Resins Association n.d.). Basic types of phenolic resin include *novolacs* and *resols*, which are distinguished from each other by their aldehyde to phenol ratios. The original use of phenolic resins is in moulding powder formulations based mostly on novolacs that could be produced in batch processes without the need for substantial technical innovation. However, the role of phenolic resins has become more specialized, particularly in applications where heat resistant binders are required. It is made available in the market in a range of geometries, typically phenolic sheets, tubes, rods, profiles, slabs, and specific shapes and blocks. It is also available as foam, which is typically used in insulation applications. While there are still significant uses of phenolic resins within moulding powders for items such as cookware, they became widely used as reinforcing agents for rubber; as binders for refractory equipment, grinding wheels, and friction materials; and in adhesives and paint formulations (particularly in the areas of can coating and printing inks) (ThomasNet 2014).

Basic chemicals from gasified biomass

The basic building blocks of petroleum-based chemicals can be produced indirectly from the synthetic gas of biomass gasification; from syngas fermentation products such as **ethanol, sorbitol, methanol, amines,** and **succinic acid** (Tong, Wang, and Olson 2013); and/or from coproducts from primary industrial processing stream, notably **lignin** and **cellulose.** Applications of these building block chemicals range widely from solvents, pharmaceuticals, chemical intermediates, phenols, adhesives, furfural, fatty acids, dyes and pigments, carbon black and paints, detergents, to cosmetics (Ahmed, Nasri, and Hamza 2012).

- **Propylene.** Propylene is the second most important olefin product, after ethylene (Gay, Pope, and Wharton 2011). Biomass-derived syngas can be used to produce propylene through processes such as via a syngas-to-dimethyl ether (DME) route and via a methanol-to-olefins route. Currently, the main source of propylene comes as a coproduct during the production of ethylene through steam cracking of liquid petroleum-based feeds, such as naphtha and gas oil (Gay, Pope, and Wharton 2011; Kaicher 2013). In 2010, the global production of propylene was 184 billion pounds, and it is estimated that demand for propylene will continue to grow at a rate of 6 percent per year. In the meantime, many chemical plants have switched from using *steam crackers* to *ethane crackers* to generate ethylene because ethane cracking has much higher ethylene selectivity. However, ethane cracking does not produce any propylene. With steam crackers going offline or being switched to ethane crackers, the production of propylene has declined. Propylene production capacity is not enough to keep pace with demand, causing propylene prices to skyrocket. From December 2010 to January 2011, the price of propylene increased by 15 percent, and in February, it increased by another 25 percent to reach a record high of $0.805/lb for polymer grade propylene.[17] Propylene is a primary petrochemical precursor, with nearly two-thirds of all propylene being

[17] Propylene is sold in three different grades: (1) **polymer grade** propylene requires a purity of at least 99.5 percent, (2) **chemical grade** propylene requires a purity of 93 percent, and (3) **refinery grade** propylene requires a purity of 70 percent. Although global demand and production totals do not distinguish between purities, there is a significant price differential between the three grades (Gay, Pope, and Wharton 2011).

used to produce **polypropylene** (Gay, Pope, and Wharton 2011). Polypropylene, in turn, has numerous end users, including plastics, packaging materials, packaging film, beverage containers, personal care products (including cosmetics), carpet fibers, and molded plastic parts used for numerous household and automotive items (Kaicher 2013). Other major uses include production of propylene oxide, acrylonitrile, and alcohols (Gay, Pope, and Wharton 2011).

- **Methanol.** Though much of today's methanol comes largely from catalytic reforming of natural gas, a great and growing amount of methanol is being made from renewable and sustainable resources. As the most basic alcohol, methanol has the distinct advantage of polygeneration whereby methanol can be made from any resource that can be converted first into synthesis gas, including biomass, agricultural and timber waste, solid municipal waste, landfill gas, and industrial waste. Syngas can be catalytically synthesized to *biomethanol* (sometimes referred to as *wood alcohol*), through various technologies that offer a spectrum of possibilities most suitable for different desired applications. An alcohol that is water soluble and biodegradable, methanol is used in the cleanup of sensitive waterways and aquifers through wastewater denitrification. Nearly 200 wastewater treatment facilities across the United States are currently using methanol in their denitrification process (Methanol Institute 2011). It should be noted, however, that methanol—either made from natural gas, or from renewable and sustainable resources—is highly toxic.

- **Anhydrous ammonia used in fertilizer production.** The fertilizer manufacturing industry produces a range of products—typically made from three key nutrients, namely phosphorus, nitrogen, and potassium—that serve many different markets. Opportunities for biomass in this market are for the production of **anhydrous ammonia** that currently uses natural gas as the main feedstock (Khedr 2013). Syngas can be used to produce anhydrous ammonia (Markets and Markets 2013), in place of natural gas, which is the major cost component of making ammonia, accounting for 75–90 percent of the total cost of production (Khedr 2013). Anhydrous ammonia serves as a *directly applied nitrogen fertilizer product* and is the *basis for making other nitrogen-based fertilizer products*. It is also used in the production of trending *high-analysis (high phosphorus content) fertilizers* such as diammonium phosphate (DAP) and mono-ammonium phosphate (MAP). In fact, DAP is one of the most widely used phosphate fertilizers and can be used on all types of soil for fertilizing field, garden, orchard, and flower garden crops and plants. They are often applied to fields in the spring or fall as a primary source of phosphate nutrients and a secondary source of nitrogen (Khedr 2013; Kruchkin 2013b).

- **Acetic acid (or ethanoic acid).** Acetic acid, an important petrochemical that is currently produced from methane (or coal), can be produced by syngas fermentation. Its uses include foodstuffs, solvents, and fungicides. It is a key component in the production of pharmaceuticals like aspirin. **Esters** derived from the acid are used to produce *vinyl acetate* used in paints, glues, and wallboard; and *cellulose acetate* used mainly for rayon and photographic films. Vinegar is 4 to 8 percent acetic acid by volume (Ashton and Cassidy 2007).

Basic chemicals from bioethanol

Bioethanol can be dehydrated to produce ethane (gaseous hydrocarbon) that can be converted to ethylene and hydrogen by pyrolysis or cracking (The Essential Chemical Industry Online 2013).

Basic chemicals from sugar derived from solid biomass

- **Lactic acid.** Lactic acid is an important and versatile chemical that can be produced from renewable resources such as biomass by microorganism fermentation (Okano et al. 2010). Demand for lactic acid is linked to the food, pharmaceutical, and polymers industries, the most interesting of which is *polylactic acid (PLA) plastics* (Chemical Engineering 2011). Cellulose can be converted into glucose by acid digestion. The **glucose** will oxidize to produce lactic acid. The low-cost raw materials, lactic acid competes as a **direct substitute for petrochemical lactic acid,** and take advantage of its own unique properties. Lactic acid forms lactide, and lactide, in turn, can form polymers. These *lactide polymers* make transparent films and strong fibers, and are biodegradable. Research and development for lactide polymers will tailor new products to meet requirements for specific end uses in direct competition to petrochemical polymers (The Global Hemp 1993).

- **Levulinic acid**. Levulinic can be produced from **xylose** (by first transforming to furfural, thus furfuryl alcohol, then levulinic acid) and **glucose** (by first transforming to Hydroxymethylfurfural (HMF), then levulinic acid) (Alonso, Wettsteina, and Dumesic 2012). Levulinic acid is a highly versatile chemical intermediate with great potential as a basic platform chemical. It can be made from different precursors made from biomass such as **fructose, glucose, sucrose, starch,** and **cellulose.** Levulinic acid can be can be used as solvent, antifreeze, food flavoring agent, intermediate for pharmaceuticals, and for plasticizers synthesis. However, in spite of its great potential as a basic platform chemical, levulinic acid has never been produced in significant volume (Galletti et al. 2012).
- **Xylitol.** Two valuable biochemicals that can be fermented from sugars derived from lignocellulosic biomass are xylitol and ethanol (Vajzovic 2012). Sugar alcohol, xylitol is considered to be a platform chemical because of its functional versatility. Xylitol has applications and potential for at least three types of industries, namely: (1) *food* (for dietary, especially in confectioneries and chewing gums as a zero-calorie sweetener), (2) *odontological* (for its anticariogenicity, tooth rehardening and remineralization properties), and (3) *pharmaceutical* (for its tooth-friendly nature, capability of preventing otitis, ear, and upper-respiratory infections, and its uses as a sweetener or excipient in syrups, tonics, and vitamin formulations). Because of its proven marketable applications in food and pharmacological industries, it is an attractive candidate for biomass products. Currently, xylitol is manufactured at the industrial level by a chemical hydrogenation of the five-carbon sugar D-xylose, using chemical process that is deemed laborious, and cost- and energy-intensive. Alternative raw materials and production processes, thus, have been sought (Prakasham, Rao, and Hobbs 2009). Xylitol can be extracted by microbial fermentation from fibrous material such as corn husks, sugar cane bagasse (sugar industry wastes), corn stover, corn fiber, wheat straw, and switchgrass (Iqbal, Kyazze, and Keshavarz 2013; Prakasham, Rao,

and Hobbs 2009). Compared with **glucose** (fermentable sugar), which can be readily fermented by well studied yeast and bacterial strains, **xylose** (wood sugar, a carbohydrate component of biomass) is more difficult to ferment because of a lack of industrially suitable microorganism able to rapidly and efficiently metabolize xylose in presence of six carbon sugars. The need for a microorganism that can utilize all the sugars present in lignocellulosic biomass and to tolerate the inhibitory compounds generated during biomass pretreatment is, therefore, apparent (Vajzovic 2012).

- **Para-xylene (p-xylene).** P-xylene—primarily used as a basic raw material in the manufacture of **terephthalic acid (TPA),** a monomer used in the formation of polymers such as *poly(ethylene terephthalate) (PET)*—has been among the most sought-after targets in recent biochemical development (Coons 2012). PET polymers are among the most commonly used plastics in packaging, particularly in the food and beverage industry (widely used for water because of its non-breakage properties as well as carbonated beverages because of good carbon dioxide barrier properties). PET polymers are also used to produce fiber fabrics for curtains, upholstery, clothing; and films for x-rays, magnetic tapes, photographic film, and electrical insulation (Chevron Phillips 2014). The plastics industry currently produces p-xylene from petroleum. There has been increasing interest in developing PET packaging from biomass by transforming glucose (via multiple steps) into p-xylene. The biomass-derived p-xylene can be mixed with petroleum-based plastics with little difference on end products (Science Daily 2012).

<u>Basic chemicals from lignin</u>

Today, the manufacturers of phenol and related chemicals operate on a large scale using petroleum as an input. For biorefineries, commercial production of cellulosic biomass-derived sugars at the scale needed to serve the biofuel and renewable chemical industries will generate an enormous amount of lignin (Gotro 2013). Lignin's native structure suggests that it could play a central role as a new chemical feedstock, particularly in the formation of supra-molecular materials and aromatic chemicals. This renders lignin potentials as a substitution for products currently based on petrochemical substances in several areas. It is important to note, however, that the physical and chemical properties of lignin differ depending on the extraction method. Market opportunities, thus, vary depending on the quality of lignin produced. For example, new and broader markets in medicine and food require high quality lignin (Nimani 2011).

Liquid oil that can be produced by pyrolysis of lignin are: **phenols** (phenol, catechol, guaiacol, syringol, cresols); **aldehydes** (vanillin, syringaldehyde); and **aliphatics** (methane, ethane, branched alkanes) (Nimani 2011). Thus, it is a potential renewable source for many *low molecular weight chemicals* like benzene, phenol, guaiacol, vanillic acid, methanol, acetic acid, and dimethyl sulfoxide (DMSO). These lignin products are considered "value-added" chemicals that could substantially impact the profit margins of a lignocellulosic biorefinery, but significant technological hurdles remain before they can be fully realized (Varanasi et al. 2013).

- **Phenol (or carbolic acid) and its derivatives.** It has been demonstrated that controlled pyrolysis of lignin can yield significant amounts of a number of *phenolic chemicals* that are important precursors to many applications by downstream users. This market offers a higher-value option for lignin (as opposed to current uses by burning for its fuel value) (Gotro 2013). The three major uses for phenols as feedstocks are found in the manufacture of *phenolic resins*, *bisphenol A*, and *caprolactam* (International Labour Organization 2007).[18] Note that, like some petrochemical companies, biorefineries may offer products of multiple value-

[18] Other notable uses for phenol are:
- **Phenylamine (Aniline)** is used as an antioxidant in rubber manufacture, and as an intermediate in herbicides, dyes and pigments, and pharmaceuticals. It is used to make isocyanates for the production of polyurethanes, with a wide range of uses from paints and adhesives to expanded foam cushions (Chemical Industry Education Centre n.d.).
- **Alkylphenols** are compounds used in the manufacture of surfactants, detergents, emulsifiers, insecticide, and plastics (Chemical Industry Education Centre n.d.).
- **Chloro-phenols** are used in medical antiseptics and bactericides such as TCP and Dettol. They are also used in fungicides for timber preservation, as additives to inhibit microbial growth in many products, and used to manufacture a range of pesticides (Chemical Industry Education Centre n.d.).
- **Salicylic acid** is a precursor to the production of aspirin, used in teas as a pain reliever and fever reducer, and used to treat acne and warts (Mackay et al. 2009).

added stages. For example, they may offer phenol along with any of the three products discussed below.

- **Phenolic resins (phenol-formaldehyde resin)**. As previously discussed (see discussion on phenolic resins produced from pyrolysis oil), biorefineries can compete in this market either as suppliers of phenol to producers of phenolic resins, or as suppliers of phenolic resins. However, the phenolic resin industry has become more diversified in terms of resin type and formulation, making it less attractive for phenol producers to forward integrate into resin manufacture business (Global Phenolic Resins Association n.d.). This is particular the case for biorefineries because, like most large-volume, commercially important polymers, it is unclear which technology will be the winner for production of renewable phenolic resins (Gotro 2013).
- **Bisphenol A (BPA)** is a chemical produced in large quantities for use as a precursor primarily in the production of *polycarbonate plastics* and *epoxy resins.* Polycarbonate plastics have many applications including use in some food and drink packaging (e.g. water and infant bottles), compact discs, impact-resistant safety equipment, and medical devices. Epoxy resins are used as lacquers to coat metal products such as food cans, bottle tops, and water supply pipes (National Institute of Environmental Health Sciences 2010).
- **Caprolactam (capro)** is mainly used to make *Nylon 6* (a type of resin) and *engineering plastics*, accounting for about 68 percent and 32 percent of global demand, respectively. Users of phenol may offer products like Nylon 6 (formulated for specific manufacturing application needs) along with its feedstock, Caprolactam. Nylon 6 resin are used extensively in textiles, carpets and industrial yarns, with tire-cord being a large and growing market, especially in China. Nylon resins are also the basis of engineering plastics, used in electronic and electrical components and automobiles, and oriented polyamide films used widely in food packaging (ICIS 2010).

Specialty chemical markets

Specialty chemicals are manufactured on the basis of their performance or function. They can be single-chemical entities or formulations whose composition influences the performance and processing of the end product. Specialty chemical manufacturing is sometimes referred to as "*custom*" or "*fine*" chemical manufacturing. The term specialty chemical is based on use, and fine chemical is based on purity, yet they are both considered a part of specialty chemical manufacturing (Society of Chemical Manufacturers and Affiliates 2014).[19]

Specialty chemicals differ from commodity chemicals in that each one may have only one or two uses, whereas commodities may have dozens of different applications for each chemical. While commodity chemicals make up most of the production volume (by weight) in the global marketplace, specialty chemicals make up most of the diversity (number of different, high-value chemicals) in commerce at any given time. In addition, in contrast to the production of commodity chemicals, specialty manufacturing requires that the raw materials, processes, and operating conditions and equipment change on a regular basis to respond to the needs of customers. They are, thus, produced in relatively small volumes for specific end uses (Society of Chemical Manufacturers and Affiliates 2014).

In 2012, the global specialty chemicals market had total revenues of $773 billion, representing a compound annual growth rate (CAGR) of 2.1 percent between 2008 and 2012. The fine chemicals segment was the most lucrative segment in 2012, with total revenues of $218.9 billion, equivalent to 28.3 percent of the market's overall value. The market is forecast to accelerate, and is expected to reach a value of $996 billion by the end of 2017 (MarketLine 2013). The world's top-five specialty chemicals

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[19] Examples of **specialty** chemicals are active ingredients in biocide formulations, as additives for plastics (e.g. as a UV stabilizer) and coatings, or as active ingredients in cosmetics and toiletries. Larger markets for **fine** chemicals include agrochemicals, dyes, and flavors and fragrances. Agrochemicals, and flavors and fragrances each represent some 8 percent of the value of the total market. The pharmaceuticals industry, however, has long been the largest market for fine chemicals, and is likely to account for more than 70 percent of the fine chemicals market by 2014. The massive market share of pharmaceuticals means that the trends and developments in the pharmaceutical market largely determine what is happening in the fine chemicals industry (Ramakers 2010).

segments in 2012 were *specialty polymers*, *industrial and institutional (I&I) cleaners*, *construction chemicals*, *electronic chemicals*, and *flavors and fragrances*. These segments had a market share of about 36 percent of total annual specialty chemicals sales (HIS 2013).

Specialty chemical manufacturers produce organic chemicals that are used in thousands of products vital to consumers and U.S. industry (Society of Chemical Manufacturers and Affiliates 2014). Several important specialty chemicals that are produced from woody biomass are **enzymes, 3-HP, butanol,** and **glycerin** (Ashton and Cassidy 2007).

- **Industrial enzymes.** Enzyme production is a growing field of biotechnology and has become a central part of the modern biotechnology industry. **Ligninolytic enzymes, cellulases,** and **hemicellulases** are important industrial enzymes with numerous applications for various industries, including chemicals, fuel, food, brewery and wine, animal feed additives, textile and laundry, pulp and paper, and agriculture (Iqbal, Kyazze, and Keshavarz 2013).[20] Expectations are that enzyme sales will increase 10 percent annually as new markets and needs emerge. Over the past five years, growth in the industrial enzyme market has started to accelerate as advances in technology have opened new markets to the traditional players (Son 2013). A range of different lignocellulosic materials that have successfully been adopted for the production of different enzymes with industrial importance are sugar cane bagasse, orange peel waste, corn cobs, corn stover, rice straw, peanut shells, newspaper, wheat straw, banana stalk, rice bran, wheat bran, apple pomace, oil palm empty fruit bunch fiber, beech tree leaves, and eucalyptus residue (Iqbal, Kyazze, and Keshavarz 2013).
- **3-hydroxypropionate (3HP)** is perhaps the most well known intermediate chemical produced by lignocellulosic fermentation behind lactic acid. 3HP is an

[20] Enzyme-derived products have replaced water-polluting phosphate detergents and allowed wash waters to be cooler. They are used to coagulate milk proteins for cheese production, as sweeteners for sodas, and in lactose-free milk. **Xylanase enzymes** are beginning to replace chlorine in the pulp and paper industry and **cellulase** in the textile industry (Ashton and Cassidy 2007).

important compound in the chemical industry, and the *polymerized 3HP* can be used as a bioplastic. With the addition of chemical processing, 3-HP is transformed into a variety of marketable chemicals such as *1,3-Propanediol (PDO)*, *acrylic acid*, *acrylonitrile*, and *acrylamide*. When transformed into acrylic acid, the polymer is used in coating, adhesive, superabsorbent, and detergent. In addition, it is used to make acrylic fibers for carpets and clothing, pipes, furniture, automobiles, nitrile rubber, and the resin in latex (Ashton and Cassidy 2007).

Plastic and resin manufacturing industry

One of the largest buyers of petrochemicals in the U.S. markets is the Plastic and Resin Manufacturing industry (Kaicher 2013). This industry is composed of establishments that primarily manufacture **resins, plastic materials** (i.e. polymers), and **synthetic rubber** (Windle 2013). This industry purchases **ethylene** and **propylene** to produce polypropylene, a highly demanded plastic used for packaging film, carpet fibers and numerous household appliances (Kaicher 2013).

Recall that the basic/platform chemical inputs used by this industry are among chemical products discussed thus far in this tier-2 market section where biorefineries convert biomass to monomers for polymers using biological or thermochemical approaches (Manzer 2010). For example, polymers are among the principal uses of ethene (ethylene) in this industry. Ethene is synthesized to produce *acetic acid* that is, in turn, used in the production of *polyethylene terephthalate (PET)*, a thermoforming polymer commonly used for food and beverage containers (Ashton and Cassidy 2007). Other important **ethene-based products** are: (1) poly(ethene), (2) ethylbenzene and hence phenylethene and poly(phenylethene), and (3) chloroethene (vinyl chloride), hence poly(chloroethene), i.e. poly(vinylchloride) (The Essential Chemical Industry Online 2013).

Appendix 3 outlines key suppliers, products traded, and customers in teir-2 markets (with corresponding NAICS code).

Tier 3: Markets for Intermediate Biomass-derived Outputs

In the tier-2 market section, we describe the opportunities for biorefineries using lignocellulosic biomass to produce a range of products (e.g. *cellulose fermentation* to acids and alcohols, and *lignin conversion* to aromatic chemicals). Industrial users of these products as their production inputs (tier-2 buyers discussed previously) constitute teir-3 suppliers. A chemical company using sugar-, oil-, or lignin-based chemicals as simple intermediates in their traditional chemical processing is an example of tier-3 suppliers (Skibar 2009).

Tier-3 market opportunities lie mainly in **chemical** and **polymer markets**[21] as applications of bio-based chemicals and polymers are adopted within a wide range of industrial sectors discussed thus far (e.g. textiles, cosmetics, health care, detergents, food and feed, pulp and paper, bioremediation, biosensors) (Ahmed, Nasri, and Hamza 2012; Son 2013). The markets most likely to exploit a bio-based platform and specialty chemicals as production inputs are discussed as follows.

Fertilizer manufacturing industry

Studies have shown that up to 70 percent of conventionally applied fertilizer goes unutilized by plants and becomes a contaminant of surface and ground (drinking) water. **Controlled-release fertilizers,** capable of delivering plant nutrients in a controlled manner over time, are the most promising fertilizer technology. However, controlled-release fertilizers currently command a 3–10 times of price premium over traditional fertilizers, making them too expensive for most crop applications. Therefore, new technology is needed to make controlled-release fertilizers cost competitive with conventional fertilization strategies. A new controlled-release fertilizer system which uses a biodegradable polymer matrix made from renewable resources is being explored.[22] **Xylaric acid** from xylose (wood sugar supplied by tier-2

[21] All tier-2 energy markets are **industrial end-markets.** Their subsequent wholesale, distribution, and retail markets are beyond the scope of this paper.

[22] As part of a project awarded by the Small Business Innovation Research (SBIR) program, US Department of Agriculture (Kiely and Smith 2010).

suppliers) can be used by fertilizer manufacturers as the basis for controlled-release fertilizer systems (Kiely and Smith 2010).

The residue of the lactic acid fermentation process to produce polylactic acid includes nutrients such as phosphorus, nitrogen, and potassium. These nutrients are to be recovered as a potential resource for **recycled fertilizer** (Nagare et al. 2012).

Biopharmaceutical and nutritional product manufacturing industry

As discussed earlier, the pharmaceuticals industry has been and is expected to continue to be the largest market for fine chemicals. Some segments of the pharmaceuticals market are showing annual growth rates that are well above the general average, among which are **high potency drugs** and **biopharmaceuticals.** Currently the market for biotechnology drugs is estimated to be similar in size to the market for high potency drugs. Together, they are set to grow to some 30 percent of the total pharmaceuticals market in 2014. Moreover, during the past few years, an increasing number of large pharmaceuticals companies have announced plans to outsource more of their manufacturing to the fine chemicals industry. Many of the large, fine-chemical companies have invested in biotechnology (mostly in *fermentation*), either through acquisitions or self-funded R&D and commercial plants. The relatively high investment needed to be able to use *mammalian cell technology* has kept all but a very few of them away from that technology. The increased outsourcing and continuing growth of the pharmaceutical markets will provide further growth options for the fine chemicals industry (Ramakers 2010), and high-value product market opportunities for biorefineries.

Dye and pigment manufacturing industry

Although the industry comprises a mere 1 percent of the chemical sector's revenue in the United States, the industry manufactures colorant products[23] that are key

[23] Colorants can be either dyes or pigments. **Dyes** are soluble colored organic compounds that are usually applied to textiles. They are designed to bond strongly to the polymer molecules that make up the textile fiber. **Pigments** are insoluble compounds used in paints, printing

chemical intermediate products used in many industries to impart color on products such as clothes, paints, plastics, photographs, prints, and ceramics. Thus, growth in manufacturing sectors (tier-4 markets), including coatings, ink, textiles and fibers, paper and personal care products, has a direct bearing on industry demand (Turk 2013).

While the industry is expected to expand over the five years to 2018, growth rates will vary among particular product segments. For example, **synthetic dyes** are expected to grow less than 1 percent annually. This trend can be attributed to high-input commodity prices, such as historically high crude oil prices, causing carbon-based synthetic dyes to be relatively more expensive in comparison to other industry products. Similarly, demand will remain relatively flat for **commodity pigments** used in ink manufacturing. Commodity pigments are very saturated and consist of the strongest tinting colorants, which causes them to be expensive (Turk 2013).

In contrast, demand is growing for colorants used in novel applications and are termed **functional (high technology)** as they are produced in small volumes compared to compounds used for dyeing textiles, and developed for specific purposes. Examples are liquid crystal displays (now have largely replaced the traditional display technologies e.g. calculators), laser dyes (applications includes communication technology and microsurgery), ink jet printing (now having a great impact on high volume industrial printing for packaging, textiles, wall coverings, and advertising displays), and photodynamic therapy (a treatment for cancer that uses a combination of laser light, a photosensitizing compound (the dye) and molecular oxygen) (The Essential Chemical Industry Online 2013).

The synthetic fiber industry

One of notable industrial customers of plastic and resin manufacturers (see tier-2 market discussion) is the synthetic fiber manufacturing industry. Companies in this

inks, ceramics and plastics. Most pigments used are also organic compounds (The Essential Chemical Industry Online 2013).

industry manufacture artificial and synthetic fibers[24] and filaments in the form of monofilament, filament yarn, staple or tow. The industry is divided into two product groupings, **noncellulosic fibers** and **cellulosic fibers.** Key cellulosic organic fibers and filaments include **rayon** and **acetate.** Noncellulosic fibers and filaments include **acrylic, nylon, polyester** and **spandex.** Noncellulosic fibers account for about 90 percent of industry revenue, while cellulosic fibers account for less than 10 percent of industry revenue. Noncellulosic fibers consist of fibers that are formed by the polymerization and subsequent fiber formation of synthetic organic chemicals and refined petroleum products. Cellulosic fibers (also called natural fibers, plant fibers, vegetable fibers, or lignocellulosic fibers), on the other hand, may be derived from natural sources, such as wood pulp (tier-2 biomass products) (Davies 2013). Forestry-derived fibers, in particular, have already been strongly industrialized over the past century with different processes developed to fractionate the fibers such as kraft pulping, sulfite pulping, and mechanical pulping from different tree species (Johansson et al. 2012).

The polystyrene foam manufacturing industry

The polystyrene foam manufacturing industry is another key buyer of petrochemical intermediates (thus potential bio-based alternatives). The industry purchases **styrene** to make **expanded polystyrene**, which is used to manufacture polystyrene foam goods (tier-4 markets), such as insulation and single-use cups, lids and plates. This industry also reduced its purchases of petrochemicals, when the housing crisis and economic recession hit with a decline in sales to food retailers and the construction industry (Kaicher 2013).

[24] Products are considered **artificial fibers** when manufactured from organic polymer, which is derived from natural raw materials, mainly cellulose obtained from wood pulp and cotton. But, it may still be considered **synthetic** if they are chemically (rather than mechanically) manipulated during the manufacturing process (Davies 2013).

The plastic material / polymer manufacturing industry

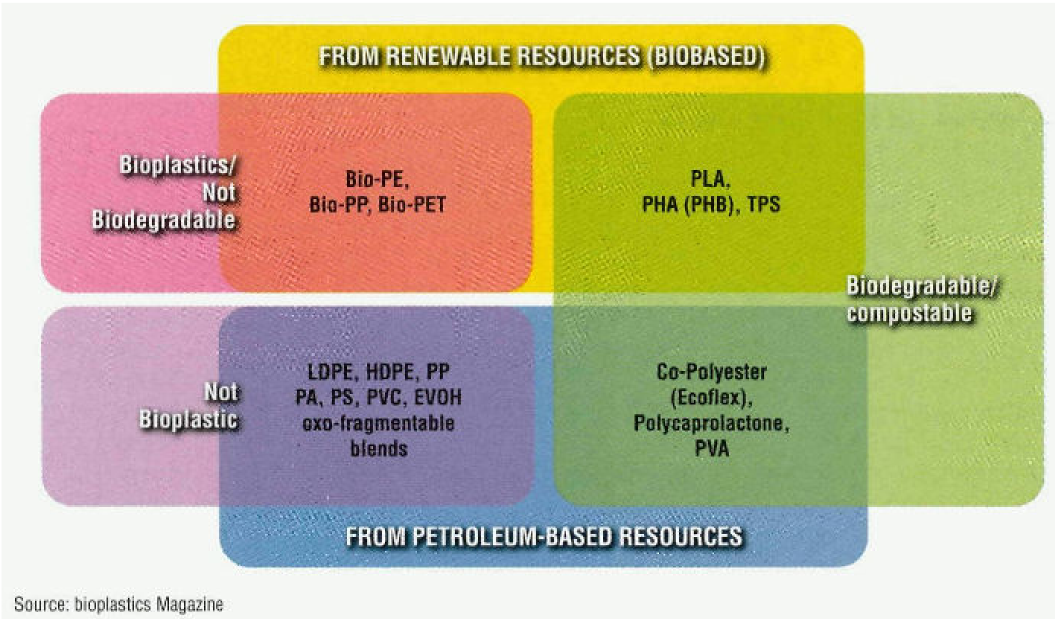
Companies in the plastic and resin manufacturing industry produce biopolymers (using tier-2 intermediate biomass as inputs) that can provide an alternative to a number of petroleum-derived polymers such as polyolefins and polyesters (Queiroz and Collares-Queiro 2009; Ten and Vermerris 2013). In addition, biopolymers can enable the development of novel applications, especially as biocompatible compounds, sometimes with properties that exceed those of synthetic polymers made from petroleum (Ten and Vermerris 2013). This emerging sector is deemed to be the first industrial sector to address the use of renewable chemicals (Skibar 2009) with a proliferation of players and projects in polylactic acid or polylactide (PLA) and the succinic acid/BDO value chains (Cascone and Burke 2010).

Bioplastics contain biopolymers in various percentages (Queiroz and Collares-Queiro 2009), and consist of either **biodegradable** plastics (i.e., plastics produced from fossil materials) or **bio-based** plastics (i.e., plastics synthesized from biomass or renewable resources). Plastics that biodegrade can be made from either petroleum-based or renewable bio-based resources. And nonbiodegradable plastics can be made from renewable resources (Tokiwa et al. 2009). Figure 7 depicts bioplastic classification according to bio-based content and biodegradability.

<u>Bio-based, biodegradable plastics</u>

In this category, **polylactic acid-based plastics (PLA)** (polymerized from lactic acid obtained from dextrose) is currently and is projected to continue to be one of the most common *bio-based, degradable* plastics (Newes et al. 2012). PLA is now manufactured in both commodity and specialty grades (e.g. medical) worldwide. The largest share of world production is held by NatureWorks Inc., a company wholly owned by Cargill and located in the US mid-west, which has PLA manufacturing and sales as its main business activity (Johansson et al. 2012). Niche markets such as food packaging (tier-4 industrial end market) are already served by PLA (Skibar 2009). However, high brittleness and the cost of PLA are the major issues determining the penetration rate of PLA in wider packaging applications (Chemical Engineering 2011).

Figure 7 / Bioplastic Classifications According to Bio-based Content and Biodegradability



Source: (Darby 2012b)

Polyhydroxyalkanoates (PHAs) is another important product in this category produced by microorganisms or genetically transformed by bacteria. Commercially, these principally consist of **polyhydroxybutyrate (PHB)** and copolymers of hydroxybutyrate and hydroxyvalerate (PHBV) (Johansson et al. 2012). PHAs (PHBs) are not only biodegradable, but also possess features such as insoluble in water, nontoxic, biocompatible, piezoelectric, thermoplastic, and/or elastomeric. These features make them suitable for several applications. Current end uses for PHAs (PHBs) include various injection-molded products, such as bathroom accessories (soap dishes, pump dispensers) and pens (Chemical Engineering 2011); in the packaging industry; lower volume-higher value uses in medicine (e.g., drug delivery, implants) (Johansson et al. 2012); in agriculture; in food industry; as raw materials for the production of enantiomerically pure chemicals; and for the production of paints (Andreeßen and Steinbüchel 2010).

While PLA and PHB are both biodegradable thermoplastics, PHB is slightly more biodegradable than PLA. A more important advantage of PHB is that PHB-based plastics have a wider range of properties. PLA can be processed in a number of different ways, including injection molding, film forming, and blow molding, but its poor impact strength and heat resistance mean that it is unsuitable for many applications. For this reason, PLA has mainly been confined to food packaging. PHB, on the other hand, can be used for a much wider range of applications, ranging from stiff packaging to highly elastic materials for coatings. The reason for this is that many bacteria naturally produce PHB in the form of a copolymer, with different strains of bacteria producing different copolymers with different properties (Evans 2010).

<u>Bio-based, nonbiodegradable plastics</u>

Bio-PE, Bio-PP, Bio-PET will be considered drop-in replacements for petroleum-based plastics, as the products are identical in their chemical structure and physical properties. Hence, products made from these bio-based, nonbiodegradable plastics must be recycled, landfilled or incinerated like their traditional plastics counterparts (Darby 2012b; Johansson et al. 2012).

In this category, **bio-PE** has gained rapid market acceptance and is produced in large volume since 2010. This growth is expected to fuel bio-based versions of PP, polyvinyl chloride (PVC) and partial bio-based polyethylene terephthalate (PET). They are currently made primarily from sugar cane (Darby 2012b).

Appendix 4 outlines key suppliers, products traded, and customers in teir-3 markets (with corresponding NAICS code).

Tier 4: Industrial End-markets for Bio-based Products

Industrial end-markets of bio-based products span a broad spectrum of manufacturing industries, examples of which are provided in Appendix 5. Many of tier-4 industrial end-markets are consumer-driven markets, among which **packaging** (e.g. packaging films, and bags and food service disposables) are growing in importance for the bioplastic industry as compostables are becoming more commonly used (Darby 2012b; Green 2011). Today's packaging industry relies strongly on the use of petroleum-derived plastic materials (Johansson et al. 2012). Although a significant percentage of production of bio-based plastics PLA is directed towards spun fibers (e.g. for textiles), there is no doubt that packaging has been a prime targeted market that can vary by sectors (Johansson et al. 2012). We discuss this high potential market further below.

Food and beverage packaging sector

In Western Europe, the largest market sector is food and beverage packaging, which accounts for almost 60 percent of the bioplastic market's total value (Johansson et al. 2012). PLA has also been used in blow-moulding processes to manufacture such new items as non-carbonated beverage bottles (e.g. water) (Johansson et al. 2012). Improvements in PLA-based products are continuing, whether through the use of additives (e.g. plasticizers, impact modifiers) or through new formulations. A heat-resistant PLA formulation for use in, for example, ready-to-eat meals trays, is also now available. Despite these commercial advances, there is still a considerable need for cost-effective methods to enhance PLA properties, especially in terms of higher gas and water vapor barrier properties, reduced brittleness, increased thermal stability (higher Tg) and, in the context of natural fiber-reinforced biocomposites, improved fiber/matrix surface compatibility (Johansson et al. 2012).

Big name users in this sector are: (1) **Pepsi,** in 2013, plans to debut bio-degradable PET bottles for its various fizz drinks (Docksai 2012; Financial Express 2011); (2) In May 2009, **Coca-Cola** began packaging some of its sodas into "plant bottles" that were 30-percent bio-based polyethylene, a bioplastic synthesized from sugarcane (Docksai 2012); and (3) **Frito-Lay** tried selling all flavors of its SunChips in degradable bags but, after consumers complained the stiff bag was too noisy, the plant-based package is only used for the original flavor. However, Frito-Lay continues to work on an improved eco-friendly package (Green 2011).

In addition to food manufacturers, other notable downstream customers are institutional and commercial sector, and food service and catering sector. While, composting and compostable products have made inroads primarily in the former sector thus far, it is the latter (food service and catering) that is a significant market force that will shape bioplastics production development over the next several years. Distributors of food service packaging now have full lines of compostable items available in greater quantity and diversity to supply the increasing food waste recycling and zero waste programs (Darby 2012b).

Plastic film, sheet, and bag manufacturing sector

One of the primary reasons for bio-plastics market growth, according to AURI study, is large retailers, such as Target and Walmart that are demanding bioplastic packaging. **Target**'s website promotes its 'green commitment' stating it tries to source packaging that is recyclable, biodegradable, made with renewable resources, or manufactured with sustainable practices. **Walmart** is using corn-based PLA in vegetable and fruit trays and bags (Green 2011).

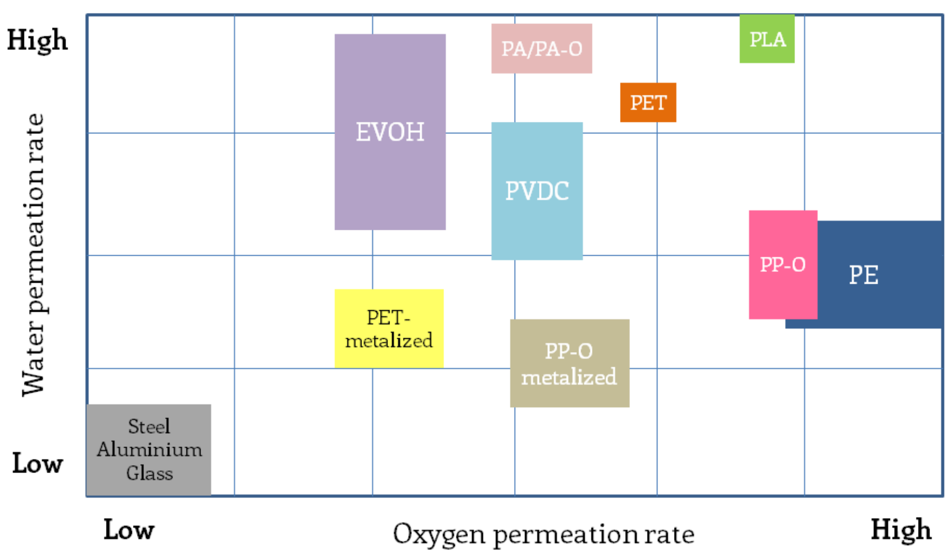
Emerging with the trend to use bioplastics in food packaging is advancing development of **barrier bioplastic systems** (Omnexus 2007). Typically, barrier coatings are based on oil-derived polymers, and often consist of multilayers or coated films designed to be impervious to gas and moisture migration. Traditional multilayer packaging films are neither recyclable nor compostable. They are comprised of multiple layers of traditional plastics and adhesives needed to provide the barriers, colorful print and necessary adhesives that bond all the layers together. These various materials are not easily separated for disposal, making recycling problematic, and the chemicals those layers are made from cannot be composted (Rosato n.d.). Thus, recyclable barrier coatings will be of greatest value in the manufacture of a number of important products, especially for packaging. Renewable biopolymer coatings can act as gas and solute barriers and complement paper, as well as other types of packaging, by minimizing food quality deterioration and extending the shelf life of degradable products (Johansson et al. 2012). Certain environmental friendly materials are now in used. Commonly used layered barrier film materials are listed below. Their relative performance is depicted in Figure 8 (Rosato n.d.).

- **PP (polypropylene):** Mechanical properties and water vapor barrier
- **PE (polyethylene):** Sealing/water vapor barrier
- **mLLDPE (metallocene catalyzed linear low density polyethylene):** Good optical and mechanical properties
- **Polyamide (nylon):** Aroma/O_2 barrier with stiffness

- **EVOH (ethylene vinyl alcohol):** High O_2 barrier; providing excellent barrier properties to gas and water vapor. It is also environmentally friendly and clear. However, it is not suitable for high-temperature processes
- **EVA (ethylene vinyl acetate):** Good for sealing
- **PLA (polylactic acid):** Biodegradability.

A notable trend in the packaging industry is a move toward **light-weight packaging** built up from a "monomaterial" structure, as opposed to extrusion-coated and waxed products, has evolved (Johansson et al. 2012). A case in point, in rigid high barrier packaging, the trend is toward mono-layer PET bottles, away from co-injection/stretch blow-molded and coated PET containers (Omnexus 2007). Thus, for the bio-based plastic alternatives to find wide industrial acceptance, it would be desirable to reduce the required amount of coating weight. Coating renewable polymers onto a paper or paperboard supporting substrate is generally advantageous when compared to *self-supporting bioplastic materials* because sufficient mechanical strength is easily achieved through the paperboard, which itself is bio-based, recyclable, and biodegradable (Johansson et al. 2012).

Figure 8 / Relative Permeation Rates of Commonly Used Layered Film Barrier Coating Materials



Source: Adapted from Rosato (n.d.)

APPENDIX

Appendix 1 / Biomass Power Plants in Operation in the United States

Note:

- **Source.** *Biomass Magazine*, "Biomass Plants" last modified on February 17, 2014.
- **Total number of plants.** 180, 26 of which are CHP plants.
- **Total capacity in millions.** 5,909 MW, CHP 961.6 MW (16% of total)
- **CHP plant capacity in million MW.** Average 36.98, Max 116.9, Min 1.2, Mode 7.5
- **Dedicated 100-percent biomass plant capacity in million MW.** Average 32.13, Max 128.9, Min 1.6, Mode 40

Company	Plant	State	Feedstock	Capacity	CHP
Ameresco, Inc.	Savannah River Site Biomass Cogeneration Facility	South Carolina	Logging residue	20	Yes
Arlington County/ City of Alexandria	Covanta Alexandria/Arlington	Virginia	MSW	23	No
Aspen Power LLC	Aspen Biomass Power Plant	Texas	Urban wood waste, logging & mill residue	44	No
Avista Corp.	Kettle Falls Generating Station	Washington	Mill & logging residue	43	No
Biomass One LP	Biomass One	Oregon	Woody biomass	30	No
Boise Cascade LLC	Medford Operation	Oregon	Mill residue	11	No
Bridgewater Power Co LP	Bridgewater Power LP	New Hampshire	Woody biomass	15	No
Burlington Electric Department	Joseph C McNeil Generating Station	Vermont	Whole chipped trees	59.5	No

Company	Plant	State	Feedstock	Capacity	CHP
Burney Forest Products	Burney Forest Power	California	Logging & mill residue	31	No
Casella Waste Systems Inc	Maine Energy Recovery Company	Maine	MSW	22	No
City & County of Honolulu	Covanta Honolulu Resource Recovery Venture	Hawaii	MSW	57	No
City of Long Beach	Covanta Long Beach Renewable Energy	California	MSW	36	No
City of Perham	Perham Resource Recovery Facility	Minnesota	MSW	4.5	No
City of Spokane	Wheelabrator Spokane, Inc.	Washington	MSW	26	No
City of Tampa	Wheelabrator McKay Bay Inc.	Florida	MSW	22	No
CMS Energy	Craven County Wood Energy	North Carolina	Mill residue	50	No
CMS Energy	Genesee Power Station LP	Michigan	Wood waste & animal bedding	40	No
CMS Energy	Grayling Generating Station	Michigan	Mill residue & TDF	38	No
Collins Company	Collins Pine Company	California	Woody biomass	12	No
Connecticut Resources Recovery Authority	Covanta SECONN	Connecticut	MSW	18	No
Connecticut Resources Recovery Authority	Mid-Conn. Resource Recovery Facility	Connecticut	MSW	68	No

Company	Plant	State	Feedstock	Capacity	CHP
Connecticut Resources Recovery Authority	Wheelabrator Bridgeport, L.P.	Connecticut	MSW	67	No
Covanta Energy Corporation	Covanta Babylon Inc.	New York	MSW	17	No
Covanta Energy Corporation	Covanta Bristol Inc.	Connecticut	MSW	16.3	No
Covanta Energy Corporation	Covanta Delano	California	Logging & mill residue	58	No
Covanta Energy Corporation	Covanta Delaware Valley LP	Pennsylvania	MSW	80	No
Covanta Energy Corporation	Covanta Essex Company	New Jersey	MSW	65	No
Covanta Energy Corporation	Covanta Fairfax Inc. (I-95 Energy)	Virginia	MSW	80	No
Covanta Energy Corporation	Covanta Haverhill Inc.	Massachusetts	MSW	49	No
Covanta Energy Corporation	Covanta Hempstead Company	New York	MSW	80	No
Covanta Energy Corporation	Covanta Hennepin Energy Resource Co. LP	Minnesota	MSW	40	No
Covanta Energy Corporation	Covanta Huntington LP	New York	MSW	25	No
Covanta Energy Corporation	Covanta Indianapolis Inc.	Indiana	MSW	7	No
Covanta Energy Corporation	Covanta Jonesboro Power Station	Maine	Logging & mill residue	24.5	No
Covanta Energy Corporation	Covanta Lake Inc.	Florida	MSW	15	No
Covanta Energy Corporation	Covanta Marion Inc.	Oregon	MSW	13	No
Covanta Energy Corporation	Covanta Mendota	California	Orchard residue	25	No

Company	Plant	State	Feedstock	Capacity	CHP
Covanta Energy Corporation	Covanta Niagara Company	New York	MSW	30	No
Covanta Energy Corporation	Covanta Onondaga LP	New York	MSW	40	No
Covanta Energy Corporation	Covanta Pacific Oroville Power	California	Forest residue, ag waste, urban waste	17	Yes
Covanta Energy Corporation	Covanta Pacific Ultrapower Chinese Station	California	MSW	19.8	No
Covanta Energy Corporation	Covanta Pittsfield, Inc.	Massachusetts	MSW	4	No
Covanta Energy Corporation	Covanta Plymouth Renewable Energy Ltd.	Pennsylvania	MSW	32	No
Covanta Energy Corporation	Covanta Projects of Wallingford LP	Connecticut	MSW	11	No
Covanta Energy Corporation	Covanta SEMASS, L.P.	Massachusetts	MSW	54	No
Covanta Energy Corporation	Covanta Springfield LLC	Massachusetts	MSW	9	No
Covanta Energy Corporation	Covanta Stanislaus Inc.	California	MSW	22.5	No
Covanta Energy Corporation	Covanta Warren Energy Resource Co. LP	New Jersey	MSW	14	No
Covanta Energy Corporation	Covanta WBH LLC	Oklahoma	MSW	17	No
Covanta Energy Corporation	Covanta West Enfield	Maine	Forest & mill residue	25	No
D.R. Johnson Lumber Company	Riddle Facility	Oregon	Woody biomass	7.5	Yes
Dairyland Power Cooperative	DTE Stoneman Station	Wisconsin	Woody biomass	40	Yes
Dominion Virginia Power	Pittsylvania Power Station	Virginia	Logging residue	83	No

Company	Plant	State	Feedstock	Capacity	CHP
DTE Energy Services	Woodland Biomass Power, Ltd.	California	Woody biomass	28	No
Dutchess County Resource Recovery Agency	Covanta Hudson Valley Renewable Energy LLC	New York	MSW	9	No
Eastern Connecticut Resource Recovery Authority	Wheelabrator Lisbon Inc.	Connecticut	MSW	15	No
Ecomaine	Ecomaine	Maine	MSW	14	No
Energy Investor Funds	Greater Detroit Resource Recovery Facility	Michigan	MSW	68	No
Enpower Corp.	Wadham Energy, LP	California	Rice hulls	26.5	No
Ever-Green Energy, LLC	St. Paul Cogeneration, LLC	Minnesota	Urban tree waste	37	No
Evergreen BioPower LLC	Evergreen Biopower LLC	Oregon	Mill residue	10	No
EWP Renewable Corp.	DG Whitefield LLC	New Hampshire	Woody biomass	19	Yes
EWP Renewable Corp.	Fairhaven Power	California	Woody biomass	18.8	No
EWP Renewable Corp.	Springfield Power, LLC	New Hampshire	Whole Tree chips, round wood	19	No
Florida Crystals	New Hope Power Co.	Florida	Baggasse	128.9	No
Fortistar	Hillman Power LLC	Michigan	Wood waste & TDF	20	No
Foster Wheeler Corp.	Camden Resource Recovery Facility	New Jersey	MSW	35	No
GDF Suez Energy North America, Inc.	Pinetree Power - Bethlehem	New Hampshire	Logging residue	16.2	No
GDF Suez Energy North America, Inc.	Pinetree Power - Tamworth	New Hampshire	Woody biomass	25	No

Company	Plant	State	Feedstock	Capacity	CHP
GDF Suez Energy North America, Inc.	Pinetree Power - Westminster	Massachusetts	Woody biomass	17	No
GDF Suez Energy North America, Inc.	Ryegate Power Station	Vermont	Whole tree chips	20.5	No
Grays Harbor Paper LP	Grays Harbor Paper LP	Washington	Mill residue	14	Yes
Great River Energy	Elk River Energy Recovery Station	Minnesota	MSW	29	No
Greenleaf Power, LLC	Desert View	California	Ag residue and urban wood waste	48	No
Greenleaf Power, LLC	Eel River Plant	California	Logging & mill residue	28	No
Greenleaf Power, LLC	HL Power Company	California	Mill & logging residue	36.2	No
Harrisburg Authority	Covanta Harrisburg Inc.	Pennsylvania	MSW	22	No
Hawaiian Commercial and Sugar Co Ltd	Hawaiian Commercial and Sugar Puunene Mill	Hawaii	Baggasse	46.1	Yes
Hillsborough County Solid Waste Department	Covanta Hillsborough Inc.	Florida	MSW	47	No
Hoge Lumber Co	Hoge Lumber	Ohio	Mill residue	3.7	No
Homeland Renewable Energy Inc.	Fibrominn Biomass Power Plant	Minnesota	Poultry litter	55	No
Indeck Energy Services, Inc.	Indeck Energy - Alexandria LLC	New Hampshire	Wood waste	16	No
Islip Resource Recovery Agency	Covanta MacArthur Renewable Energy Inc.	New York	MSW	12	No

Company	Plant	State	Feedstock	Capacity	CHP
Jackson County Solid Waste Authority	Jackson County Resource Recovery	Michigan	MSW	3.6	No
Kent County	Covanta Kent Inc.	Michigan	MSW	18	No
Kimberly-Clark Corp	Everett Cogen	Washington	Mill residue	42	No
Koppers, Inc.	Koppers Susquehanna Plant	Pennsylvania	Railroad ties	7.5	No
L'Anse Warden Electric Company	L'Anse Warden	Michigan	Wood waste	20	No
Lancaster County Solid Waste Authority	Covanta Lancaster Inc.	Pennsylvania	MSW	36	No
Lee County Solid Waste Authority	Covanta Lee Inc.	Florida	MSW	57	No
London Economics	Ampersand Chowcilla Biomass, LLC	California	Woody biomass	10.5	No
London Economics	Merced Power, LLC	California	Woody biomass	10.5	No
Longview Fibre Paper & Packaging Inc.	Longview Fibre	Washington	Mill residue	55	Yes
Los Angeles County	Commerce Refuse-to-Energy Facility	California	MSW	12	No
Macpherson Energy Corporation	Mt. Poso Cogeneration Company, LLC	California	Orchard residue	44	Yes
Maryland Environmental Service	Eastern Correctional Institute	Maryland	Woody biomass	3.8	Yes
Miami-Dade County	Covanta Dade Renewable Energy	Florida	MSW	77	No
Miami-Dade County	Miami-Dade County Resource Recovery Facility	Florida	MSW	77	No
Mid-Maine Waste Action Corp.	MMWAC Resource Recovery Facililty	Maine	MSW	3.6	No

Company	Plant	State	Feedstock	Capacity	CHP
Minnesota Power	Hibbard Energy Center	Minnesota	Wood waste & coal	72.8	Yes
Minnesota Power	Rapids Energy Center	Minnesota	Logging & mill residue	26.5	Yes
Multitrade Biomass Holdings	Rabun Gap Cogen Facility	Georgia	Logging & mill residue	20	No
Multitrade Biomass Holdings	Telogia Power	Florida	Ag, logging & mill residue	14	No
NewPage Holding Corporation	Mead Coated Board	Alabama	Mill residue	87.5	Yes
North American Power Group	Rio Bravo Fresno	California	Woody biomass	28	No
North American Power Group	Rio Bravo Rocklin	California	Woody biomass	28	No
Northeast Maryland Wast Disposal Authority	Covanta Montgomery Inc.	Maryland	MSW	55	No
Northeast Maryland Waste Disposal Authority	Wheelabrator Baltimore, L.P.	Maryland	MSW	64.5	No
Olmsted County Environmental Resources	Olmsted Waste-To-Energy Facility	Minnesota	MSW	9.6	No
Oswego County Solid Waste Authority	Oswego County Energy Recovery Facility	New York	MSW	3.6	No
Pasco County	Covanta Pasco, Inc.	Florida	MSW	31.2	No
Patriarch Partners, LLC	Old Town Fuel & Fiber	Maine	Mill residue	28.5	No
Permeate Refining Inc.	Permeate Refining Cedar Rapids	Iowa	Ag residue	7.5	Yes

Company	Plant	State	Feedstock	Capacity	CHP
Pinellas County Utilities	Pinellas County Resource Recovery Facility	Florida	MSW	75	No
PSNH - Public Service of New Hampshire	Schiller Station	New Hampshire	Whole chipped trees	50	Yes
ReEnergy Holdings LLC	ReEnergy Ashland	Maine	Woody biomass	40	No
ReEnergy Holdings LLC	ReEnergy Chateaugay	New York	Woody biomass	20	No
ReEnergy Holdings LLC	ReEnergy Fort Fairfield	Maine	Woody biomass	36	No
ReEnergy Holdings LLC	ReEnergy Livermore Falls	Maine	Woody biomass	40	No
ReEnergy Holdings LLC	ReEnergy Lyonsdale	New York	Whole tree chips	21	No
ReEnergy Holdings LLC	ReEnergy Stratton Energy	Maine	Woody biomass	50	No
Rio Grande Valley Sugar Growers, Inc.	Rio Grande Valley Sugar Growers	Texas	Baggasse	23.5	Yes
Riverstone Holdings	Coastal Carolina Clean Power	North Carolina	Woody biomass	44.1	No
Robbins Lumber Inc.	Robbins Lumber	Maine	Mill residue	1.2	Yes
Rollcast Energy, Inc.	Cadillac Renewable Energy	Michigan	Logging residue	44	No
Rollcast Energy, Inc.	Piedmont Green Power	Georgia	Woody biomass	60.5	No
Roseburg Forest Products	Dillard Complex	Oregon	Woody biomass	51.5	No
Sappi Fine Paper North America	S D Warren Westbrook	Maine	Mill residue	62.5	Yes
Sappi Fine Paper North America	Somerset Plant	Maine	Mill residue	116.9	Yes

Company	Plant	State	Feedstock	Capacity	CHP
Sauder Woodworking Co.	Sauder Power Plant	Ohio	Mill waste from furniture making	7	Yes
SDS Lumber Co.	SDS Lumber Gorge Energy Division	Washington	Logging & mill residue	10	No
Seneca Sawmill Company	Seneca Sustainable Energy	Oregon	Mill residue	19.8	Yes
SET PERC Investment LLC	Penobscot Energy Recovery	Maine	MSW & woody biomass	25	No
Shakopee Mdewakanton Sioux Community	Koda Energy LLC	Minnesota	Ag residue	23.4	Yes
Sierra Pacific Industries	Sierra Pacific - Aberdeen	Washington	Logging & mill residue	18	No
Sierra Pacific Industries	Sierra Pacific - Anderson	California	Logging & mill residue	4	No
Sierra Pacific Industries	Sierra Pacific - Burlington	Washington	Logging & mill residue	28	No
Sierra Pacific Industries	Sierra Pacific - Burney	California	Logging & mill residue	20	No
Sierra Pacific Industries	Sierra Pacific - Lincoln	California	Woody biomass	19.2	No
Sierra Pacific Industries	Sierra Pacific - Quincy	California	Mill residue	27.5	No
Sierra Pacific Industries	Sierra Pacific - Sonora	California	Logging & mill residue	7.5	No
Sierra Power Corporation	Sierra Power Cogen	California	Ag, logging & mill residue	7.5	No

Company	Plant	State	Feedstock	Capacity	CHP
Simpson Tacoma Kraft Co LLC	Simpson Tacoma Kraft Biomass	Washington	Mill residue	64	Yes
Smurfit-Stone Container Corp.	Stone Container Panama City Mill	Florida	Paper mill waste	34	No
Snider Industries Inc.	Snider Industries	Texas	Woody biomass	5	No
Snowflake Power, LLC	Snowflake Power, LLC	Arizona	Logging & mill residue	27	No
Solid Waste Authority of Palm Beach	Palm Beach Renewable Energy	Florida	MSW	62.3	No
Southern Power Company	Nacogdoches Power LLC	Texas	Logging residue	100	No
SP Newsprint Company	SP Newsprint - Newberg Cogen	Oregon	Logging & mill residue	55.3	No
Stimson Lumber Company	Plummer Cogen	Idaho	Wood waste	6	Yes
Suez Energy North America, Inc.	Viking Energy of Lincoln, Inc.	Michigan	Wood waste	16	No
Suez Energy North America, Inc.	Viking Energy of McBain	Michigan	Wood waste & TDF	18	No
Tamarack Energy, Inc.	Tamarack Energy Partnership	Idaho	wood waste	6.2	No
The Powell Group	Agrilectric Power Partners Ltd	Louisiana	Rice hulls	12.1	No
Thermagen Power Group, LLC	Fox Valley Clean Energy Center	Wisconsin	Mill residue	7	No
Union County Utilities Authority	Covanta Union Inc.	New Jersey	MSW	44	No
United States Sugar Corp	Clewiston Sugar House	Florida	Baggasse	70.6	Yes
US Renewables Group	Niagara Generation, LLC	New York	Woody biomass	56	Yes
US Renewables Group	Thermal Energy Dev Partnership LP	California	Woody biomass	21.5	No

Company	Plant	State	Feedstock	Capacity	CHP
Warm Springs Forest Products Industries	Warm Springs Forest Products	Oregon	Mill residue	9	No
Wasatch Integrated Waste Management District	Wasatch Integrated Energy Recovery	Utah	MSW	1.6	No
Wheelabrator Technologies, Inc.	Wheelabrator Claremont Company, L.P.	New Hampshire	MSW	5	No
Wheelabrator Technologies, Inc.	Wheelabrator Concord Company, L.P.	New Hampshire	MSW	14	No
Wheelabrator Technologies, Inc.	Wheelabrator Falls, Inc.	Pennsylvania	MSW	53.3	No
Wheelabrator Technologies, Inc.	Wheelabrator Gloucester Company, L.P.	New Jersey	MSW	14	No
Wheelabrator Technologies, Inc.	Wheelabrator Hudson Falls LLC	New York	MSW	15	No
Wheelabrator Technologies, Inc.	Wheelabrator Millbury Inc.	Massachusetts	MSW	46	No
Wheelabrator Technologies, Inc.	Wheelabrator North Andover, Inc.	Massachusetts	MSW	40	No
Wheelabrator Technologies, Inc.	Wheelabrator North Broward, Inc.	Florida	MSW	68	No
Wheelabrator Technologies, Inc.	Wheelabrator Portsmouth	Virginia	MSW	60	No
Wheelabrator Technologies, Inc.	Wheelabrator Ridge Energy, Inc.	Florida	Wood waste & TDF	50	No
Wheelabrator Technologies, Inc.	Wheelabrator Saugus, Inc.	Massachusetts	MSW	38	No
Wheelabrator Technologies, Inc.	Wheelabrator Shasta Energy Co., Inc.	California	Logging, mill & ag residue	63.7	No
Wheelabrator Technologies, Inc.	Wheelabrator South Broward, Inc.	Florida	MSW	66	No

Company	Plant	State	Feedstock	Capacity	CHP
Wheelabrator Technologies, Inc.	Wheelabrator Westchester LP	New York	MSW	59.7	No
Xcel Energy	Bay Front Power Plant	Wisconsin	Woody biomass	40	No
Xcel Energy	French Island Generating Plant	Wisconsin	Wood waste	30.4	No
Xcel Energy	Red Wing	Minnesota	MSW	20	No
Xcel Energy	Wilmarth Generating Station	Minnesota	MSW	25	No
York County Solid Waste Authority	Covanta York Renewable Energy LLC	Pennsylvania	MSW	36.5	No

Appendix 2 / Tier-1 Raw Biomass Material Markets

Tier-1 Markets		
	Tier-1 Suppliers	1. Corn farms (11115) 2. Wheat, barley & sorghum farms (11117) 3. Fruit & nut farms (11135) 4. Cotton farms (11192) 5. Hay & crop farms (11199) 6. Logging (11331) 7. Sawmills & wood production (32111) *Note: The emergence of the biomass sector may give rise to new categories of suppliers.*
	Products traded	Raw biomass materials (ground or chipped): 1. Woody lignocellulosic biomass (e.g. willow, poplar, eucalyptus) 2. Non-woody lignocellulosic biomass (e.g. reed canary grass, miscanthus, switchgrass, giant reed)
	Tier-1 Customers	**Energy market customers** 1. Biomass electric power generation (221117): Co-fire power plant, and combined heat and power (CHP) plant) 2. Industrial biorefineries: Cyclic crude, intermediate, and gum and wood chemical manufacturing (325194); all other basic organic chemical manufacturing (325199) 3. All other miscellaneous wood product manufacturing (321999): Wood pellets, briquettes **Non-energy market customers** 1. Pulp mills (322110) 2. Paperboard mills (322130) 3. Reconstituted wood product manufacturing (321219): Engineered wood, composite materials such as particleboard, fiberboard, medium density fiberboard 4. Agriculture (11), including: a. Animal bedding markets b. Livestock feed/forage markets 5. All other miscellaneous wood product manufacturing (321999): Wood mulch markets 6. Basic chemical manufacturing (3251)

	Tier-1 Customers *(continued)*	7. Erosion-control material markets, customers may include: a. Landscaping services (561730) b. Administration of conservation programs (924120) c. Construction sectors (236): Commercial and institutional building construction (236220); industrial building construction (236210); housing, apartment & condominium construction (236117)

Appendix 3 / Tier-2 Refined and Intermediate Biomass Markets

Tier-2 Markets	**Tier-2 suppliers**	**Energy market suppliers** Industrial biorefineries **Non-energy market suppliers** See tier-1 non-energy market customers
	Products traded	**Energy products** 1. Bioheat and biopower (produced from bio-oil, biogas, producer gas/bio-based fuel gas, syngas, and lignin) 2. Transportation biofuel a. **Cellulosic liquid biofuels:** bioalcohols (e.g. bioethanol and biobutanol), and oils (e.g. biodiesel) b. **Advanced biofuels:** bioalcohols such as biobutanol/gasoline substitute, synthetic diesel/diesel substitutes, and synthetic kerosene/jet fuel substitute c. **Fuel-cell power:** hydrogen (produced by reforming syngas and bio-oil) **Non-energy products** 1. Pulp 2. Biochar 3. Lignin 4. Basic/platform industrial chemicals, commonly traded examples are: a. Acyclic (i.e., aliphatic) hydrocarbons such as ethene (ethylene), propene (propylene, or methylethylene), and butylenes b. Cyclic aromatic hydrocarbons such as benzene, toluene, styrene, para-xylene (p-xylene) c. 3-hydroxybutyrolactone (3-HBL) d. 3-Hydroxypropionic acid (3-HPA) e. Acetic acid (ethanoic acid) f. Butanediol (butylene glycol) g. Butadiene (Buta-1,3-diene) h. Glycerin (e.g. glycerol) i. Lactic acid j. Levulinic acid k. Methyl alcohol (e.g. methanol)

	Products traded *(continued)*	l. Phenol (carbolic acid) and/or phenolic resins (formulated from phenol) m. Succinic acid n. Xylose and/or xylitol (converted from xylose) 5. Specialty chemicals, for example: a. Industrial enzymes (e.g. ligninolytic enzymes, cellulases, and hemicellulases) b. 3-hydroxypropionate (3HP)
	Tier-2 customers	**Energy market customers** 1. Electric power generation (biomass, 221117) 2. Petroleum and petroleum products bulk stations and terminals (424710) 3. Petroleum and petroleum products merchant wholesalers (424720) **Non-energy market customers** 1. Agricultures (11) 2. Nursery and tree production (111421) 3. Sewage treatment facilities (22132) 4. Construction sectors (236) 5. Animal feeds, supplements, concentrates and premixes manufacturing (except cats, dogs) (311119) 6. Seasoning, sauce and condiment production (31194) (e.g. flavoring extracts/emulsions/liquid flavors/colorings) 7. Reconstituted wood product manufacturing (321219) (e.g. engineered wood, composite materials such as particleboard, fiberboard, medium density fiberboard) 8. Paper mills (322121) 9. Paperboard mills (322130) 10. Industrial chemical manufacture ring (325) 11. Dye & pigment manufacturing (32513) 12. Plastic & resin manufacturing (32521): Manufacturers of resins, plastic materials (i.e. polymers) and synthetic rubber (e.g. thermosetting resins, thermoplastic resins, and synthetic rubber) 13. Fertilizer manufacturing (32531) 14. Pharmaceutical manufacturing (32541a-c): Brand-name pharmaceutical, generic pharmaceutical, and vitamin & supplement

Appendix 4 / Tier-3 Biomass-derived Industrial Input Markets

Tier-3 Markets		
	Tier-3 suppliers	**Energy market suppliers** 1. Electric power generation (biomass, 221117) 2. Petroleum and petroleum products bulk stations and terminals (424710) 3. Petroleum and petroleum products merchant wholesalers (424720) **Non-energy market suppliers** See tier-2 customers
	Products traded	**Energy products** See tier-2 products **Non-energy products (mainly industrial chemicals, plastics and polymers):** Examples are: 1. Formulated chemicals (e.g. expanded polystyrene; Xylaric acid formulated from xylose (tier-2 refined biomass input)) 2. Various plastic polymers (e.g. polylactic acid-based plastics (PLA), polyhydroxyalkanoates (PHAs)/ polyhydroxybutyrate (PHB), Bio-PE, Bio-PP, Bio-PET) 3. Biopharmaceutical ingredients 4. Commodity and/or functional (high tech) colorants
	Tier-3 customers	**Energy market customers** 1. Electric power distribution systems (221122) (including electric power brokers) 2. Industrial and commercial buyers (e.g. trucking companies, manufacturing facilities, real estate) 3. Gasoline service stations (4471) **Non-energy market customers** (examples) 1. Textile Mills (31310): Manufacturers of woven and nonwoven fabrics & yarn) 2. Reconstituted wood product manufacturing (321219) (e.g. engineered wood, composite materials) 3. Cardboard box & container manufacturing (32221)

	Tier-3 customers *(continued)*	4. Coated & laminated paper manufacturing (32222) (e.g. coated or laminated paper and packaging, multiwall bags and laminated aluminum foil for flexible packaging; also purchase raw materials, such as paper and paperboard, and process them with plastic, clay, latex and metal to create industry products) 5. Cellulosic fibers and filaments manufacturing (325220): Manufacturers of rayon, acetate, nylon, polyolefin, polyester, and PET fibers and filaments in the form of yarn, staple, or tow 6. Fertilizer Manufacturing (32531) 7. Pharmaceutical manufacturing (32541a-c): Brand-name pharmaceutical, generic pharmaceutical, and vitamin & supplement 8. Adhesive manufacturing (32552) (excluding asphalt, dental and gypsum-based adhesives) 9. Industrial ink manufacturing (32591): Sold to commercial printers, newspaper and magazine printers, office supplies wholesalers and screen printers. 10. Chemical product manufacturing (32599): Manufacturers of custom compounding plastic resins and manufacturing toners, toner cartridges, photographic chemicals and sensitized photographic film, paper and plates. 11. Unlaminated plastics film and sheet (except Packaging) manufacturing (326113): Converting plastics resins into plastics film and unlaminated sheet (except packaging). 12. Laminated plastics plate, sheet (except packaging), and shape manufacturing (326130) 13. Polystyrene foam manufacturing (32614) 14. Medical instrument & supply manufacturing (33911a)

Appendix 5 / Tier-4 Bio-based Products Industrial End-markets

<table>
<tr><th rowspan="3">Tier-4 Markets</th><th></th><th></th></tr>
<tr><td>Tier-4 suppliers</td><td>Energy market suppliers
1. Electric power distribution systems (221122) (including electric power brokers)
2. Gasoline service stations (4471)

Non-energy market suppliers
See tier-3 customers</td></tr>
<tr><td>Products traded</td><td>Energy products
See tier-3 products

Non-energy products
1. Various cellulosic fibers and filaments (e.g. rayon, acetate, acrylic, nylon, polyester, spandex) in the form of monofilament, filament yarn, staple, or tow; or texturized cellulosic fibers & filament products (e.g. curtains and linens, textile bags and canvas)
2. Various adhesives (e.g. synthetic resin and rubber adhesives, structural sealants, nonstructural caulking components, natural-based glues and adhesives)
3. Various pigments and dyes (e.g. color, lead, chrome, metallic, zinc-based pigments, disperse, vat, and direct dyes)
4. Various ink products (e.g. lithographic and offset printing inks, flexographic printing inks, gravure printing inks, screen process ink, and textile printing ink)
5. Various rubber products (e.g. automotive rubber parts, rubber compounds and mixtures, industrial rubber products, other rubber products for mechanical uses)
6. Various polystyrene foam products (e.g. Polystyrene foam, polystyrene building insulation, polystyrene food container, polystyrene insulation)
7. Various chemical products (e.g. custom compounding resins, photographic chemicals, toners and toner cartridges, and sensitized film, paper, cloth and sensitized plates)</td></tr>
</table>

	Tier-4 customers	**Energy market customers** Consumers **Non-energy market customers** 1. Construction sectors (236) 2. Paint manufacturing (2551) 3. Carpet & rug mills (31411): Manufacture and finish carpets and rugs for the domestic, commercial and industrial sectors) 4. Hosiery mills (31511) 5. Apparel knitting mills (31519) 6. Shoe & footwear manufacturing (31621) 7. Sanitary paper product manufacturing (32229a) 8. Industrial printing (32311) (e.g. commercial lithographic printing, digital printing, flexographic printing, screen printing, gravure printing) 9. Soap & cleaning compound manufacturing (32561) (e.g. household soaps and detergents, commercial soaps and detergents, surface active agents, and polishes and other sanitation goods) 10. Cosmetic and beauty product manufacturing (32562) 11. Rubber product manufacturing (32629) (e.g. automotive parts, doormats, rubber bands and rubber gloves) 12. Automotive manufacturing (3363) (e.g. auto parts manufacturers, automobile interior manufacturers) 13. Aircraft parts manufacturing (3364) 14. Athletic & sporting goods manufacturing (33992a) 15. Plastic product & packaging manufacturing (e.g. food and beverage packaging companies; plastic film, sheet, and bag manufacturers; plastic bottle manufacturers) 16. Various food and beverage manufacturing (311 & 312)

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