BIOREFINERY VALUE CHAIN OUTPUTS

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ABLC	Advanced Bioeconomy Leadership Conference
AHB	Advanced Hardwood Biofuels Northwest
ALDC	Alternative Fuels Data Center
BANR	Bioenergy Alliance Network of the Rockies
1,4-BDO	1,4-butanediol
BR	biorefineries
CA	cellulose acetate
CAA	Clean Air Act
CAPs	Coordinated Agricultural Projects
CenUSA	CenUSA Bioenergy
EIA	Energy Information Administration
EPA	Environmental Protection Agency
EPP	Environmental Preferred Products
GHG	greenhouse gas
1,6-HDO	1,6- hexanediol
HMD	hexamethylenediamine
IBSS	Southeast Partnership for Integrated Biomass Supply Systems
NABC&E	National Advanced Biofuel Conference & Expo
NARA	Northwest Advanced Renewable Alliance
NBB	National Biodiesel Board
NEWBio	The Northeast Woody/Warm-season Biomass Consortium
NIFA	National Institute of Food and Agriculture
PA	polyamides
PAC	powered activated carbon
1,3-PDO	1,3-propanediol
PET	polyethylene terephthalate
PHAs	polyhydroxyalkanoates
PLA	polylactic acid
RFA	Renewable Fuels Association
SUBI	Sustainable Bioproduct Initiative
USDA	U.S. Department of Agriculture
WFC	word frequency count

EXECUTIVE SUMMARY

This NARA EPP Task 4 report consists of four subtask reports:

- Subtask 4.1: Review of the U.S. Biofuels Industry
- Subtask 4.2: Commercialization Factors for the U.S. Cellulosic Biofuels Industry
- Subtask 4.3: Review of the U.S. Bio-based Chemicals Industry
- Subtask 4.4: Opportunities for Lignin Valorization

An examination of bioproduct polymers indicates projected high growth markets. To better understand the impact of this market opportunity on the US biorefinery industry, the NARA EPP team developed a unique approach to examine biorefinery value chain outputs. This study characterized the structure of the US biofuels industry (n=414 biorefineries) and the US bio-based chemicals industry (n=35 companies). This study has also examined the cellulosic biofuel biorefineries regarding commercialization factors. The top three drivers for the commercialization of cellulosic biofuels were ***government policies***, ***added value from non-fuel co-products***, and ***carbon emission reduction***; the top three barriers to the commercialization of cellulosic biofuels were ***competition vs. petroleum-based fuels***, ***policy uncertainty***, and ***high production costs***. Examination of perceptions of academic researchers and industrial experts on the development and scale-up of cellulosic biofuels provides many insights related to policy, investment, economies, and cellulosic biofuels logistics. Additionally, our work presents a sequential process for examining potential lignin valorization. First, a short list of high-opportunity lignin products was developed from the literature. Several low-hanging product opportunities were identified, from which, lignin-based powdered activated carbon (PAC) for the sequestration of mercury from power plant flue gas was selected for further examination due, in part, to lignin's similarity to lignite coal. Next, an analysis of the web-based written content of PAC suppliers' promotional materials was performed to assess the attributes on which PAC products are sold and purchased. Finally, potential electric generating power plant buyers/users of lignin-based PAC for mercury sequestration were surveyed to examine the importance of 16 PAC product and service attributes, identify potential entry barriers for a new PAC product, and assess the market opportunity for lignin-based PAC. The top three product and service attributes for buyers/users of PAC for mercury mitigation were *Product Reliability, Product Effectiveness,* and *Proven Product Performance*; the top three barriers to entry for a new lignin-based PAC include *Title V Permitting, Operational Impacts,* and *Compliance with Regulations.* Buyers/Users are undecided about trial testing a lignin-based PAC product, but would be more likely to purchase from an existing vendor rather than a new vendor. As a whole, these activities provide strategic insights into the potential value chain outputs for U.S. biorefineries.

INTRODUCTION

Fossil fuels have long been the predominant source of liquid fuels, chemicals, and energy (Amidon et al., 2008; Naik, Goud, Rout, & Dalai, 2010). However, fossil fuel reserves are not infinite or sustainable from an economic and environmental point of view (Kamm, Kamm, Gruber, & Kromus, 2005). Concerns regarding global climate change, volatile oil prices, and resource depletion have collectively motivated research into sustainable and renewable alternatives (Fernando, Adhikari, Chandrapal, & Murali, 2006; Zaimes, Vora, Chopra, Landis, & Khanna, 2015). Liquid biofuels from renewable carbon sources are at the forefront of these developments as they contribute to maintaining national energy security, improving rural economic development, and reducing carbon emissions (Balan, Chiaramonti, & Kumar, 2013; Cherubini, 2010; Gegg, Budd, & Ison, 2014).

Growth of The U.S. Biofuels Industry

In the United States, corn-grain ethanol and biodiesel have served as the major substitute fuels for petroleum-based gasoline and diesel over the past few decades. Today, these two first generation biofuels account for over 90 percent of the total renewable biofuels within the United States (Environmental Protection Agency, 2015). The U.S. corn-grain ethanol industry, with the production volume growth at an annual rate of 67 percent from 1991 to 2015 (Renewable Fuels Association, 2016b) (Figure VCO-Intro.1), has also reshaped corn farming by reducing government support for cropping subsidies while raising farmers' incomes (Renewable Fuels Association, 2014). The production of 14.8 billion gallons of ethanol supported 85,967 direct jobs in the renewable fuel and agricultural industries (Renewable Fuels Association, 2016a). Meanwhile, corn ethanol blends in gasoline (typically, up to 10%) improve the octane number and add oxygen content to meet the U.S. Clean Air Act (CAA) (Urbanchuk, 2010). Similarly, the U.S. biodiesel industry (Figure VCO-Intro.2) has aided in the development of the rural economy by providing over 60,000 jobs nationwide (National Biodiesel Board, 2015b). Biodiesel also contributes to the U.S. CAA with 52 percent lower GHG emissions compared to petroleum-based diesel (Energy Efficiency & Renewable Energy, 2015).

Despite the benefits of first generation corn-grain ethanol, the "food-versus-fuel" and ethanol "blend wall" arguments continue to constrain the industry (Table VCO-Intro.1). The "food-versus-fuel" debate has lasted for more than a decade and includes controversy over food security (Carter & Miller, 2012; Ziegler, 2008) and food price inflation (Ahmed, 2008; Ajanovic, 2011; Bardhan, Gupta, Gorman, & Haider, 2015; Cuesta, 2014). The ethanol "blend wall" also constrains the growth of the U.S. corn ethanol industry due to the E10 (10%) blend limit (Figure VCO-Intro.3), the infrastructure requirements for higher blend options and consumer acceptance for higher biofuel blends (Energy Information Administration, 2011). In addition to the food-fuel issue, biodiesel fuels also face challenges related to environmental, economic and social impacts, for example, NOx emission, distribution and infrastructure modifications, and land use change (Bomb, 2005; Castanheira, Grisoli, Freire, Pecora, & Coelho, 2014; Rabago, 2008). As a result, interest in developing new biofuels from non-food based lignocellulosic feedstocks has grown (Brown & Brown, 2013; Mohr & Raman, 2013; Solomon, Barnes, & Halvorsen, 2007).

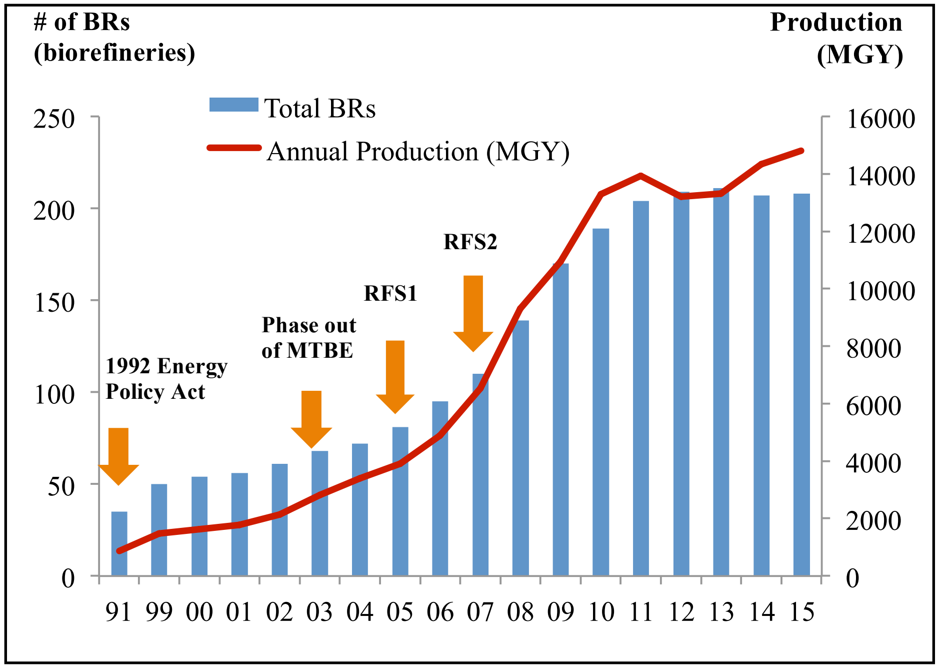

Figure VCO-Intro.1. Growth of the U.S. corn-grain ethanol industry (# of biorefineries and production) from 1991 – 2015 (Renewable Fuels Association, 2015, 2016)

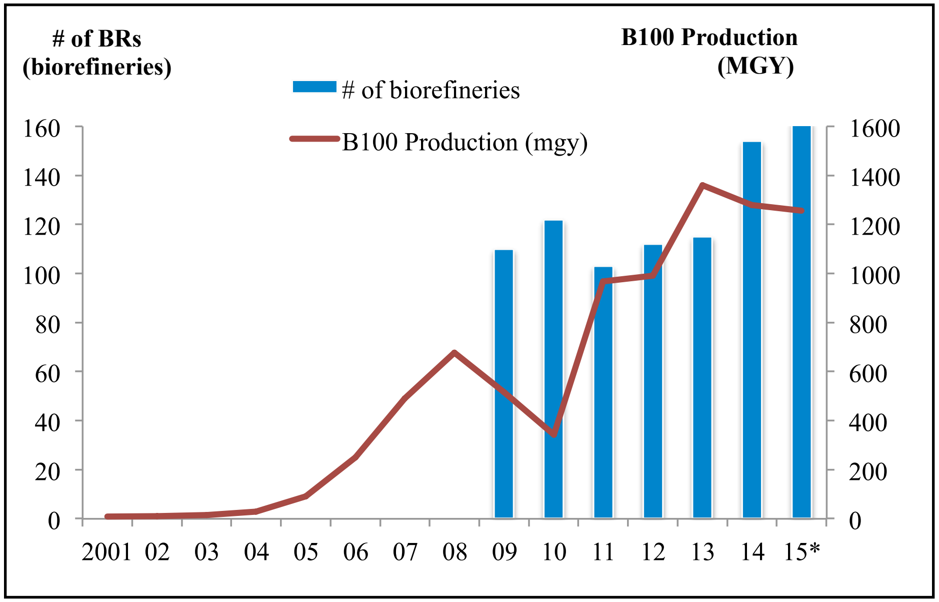

Figure VCO-Intro.2. Growth of the U.S. biodiesel industry (# of biorefineries and capacity) from 2001 to 2015 (Energy Information Administration, 2016b) *(*The production volume of 2015 is predicted by the first 11 months of 2015)*

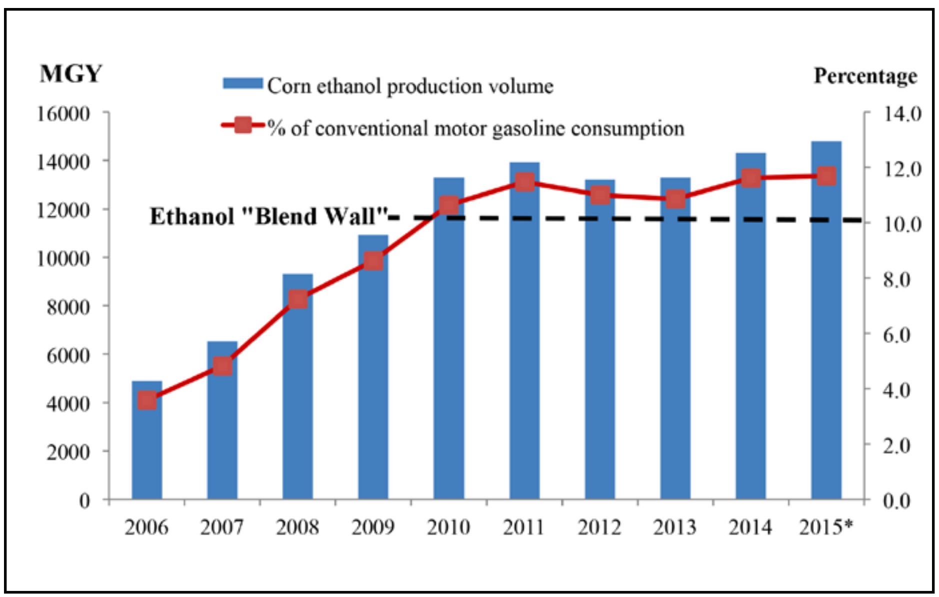

Figure VCO-Intro.3. Annual U.S. ethanol production volumes from 2006 to 2015 and their corresponding percentage of the conventional motor gasoline consumption *(*2015 fuel ethanol consumption data is based on the prediction from EIA)* (Chen, Smith, & Wolcott, 2016; Energy Information Administration, 2016b, 2016c)

Compared to first generation biofuels, second generation cellulosic alcohols (ethanol and butanol) avoid the food-fuel controversy while benefiting from lower lifecycle GHG emissions (Balan, Chiaramonti, & Kumar, 2013; FitzPatrick, Champagne, Cunningham, & Whitney, 2010). However, cellulosic biofuels have yet to become widely commercialized (Balan et al., 2013; FitzPatrick et al., 2010). Meanwhile, KiOR's November 2014 bankruptcy and Cobalt's June 2015 asset auction signal the challenges faced by cellulosic biofuel startups seeking scaled production.

Integrated Biorefineries

Facing these issues, several researchers have suggested a short-to-medium term strategy for the scale-up of the U.S. cellulosic biofuels industry; that is, to integrate the production of bio-based chemicals with cellulosic biofuels (Bozell, 2008; Bozell & Petersen, 2010; Cherubini, 2010; Cherubini & Strømman, 2011; FitzPatrick et al., 2010). This integrated biorefinery scenario can provide a diversified value stream outputs, and contribute to effective utilization of feedstock fractions, improvement of financial performance and mitigation of potential risks (Bozell, 2008; Bozell & Petersen, 2010; FitzPatrick et al., 2010). A techno-market assessment of selected bio-based polymers, which was initiated in January 2013, has been completed by Year 3 for the NARA project. Major research efforts have been focused on the bioplastics industry, including the global market and growth trend for the overall bioplastics industry (Figure VCO-Intro.4).

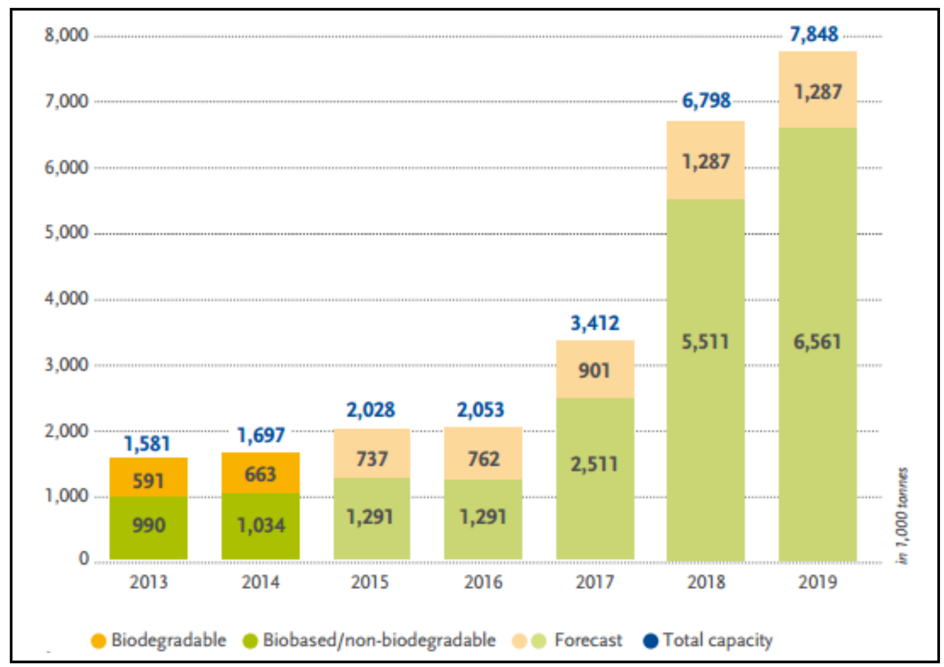

Figure VCO-Intro.4. Global Production Capacity of Bioplastics. Adapted from Bioplastics facts and figures [Infographic]. Institute for Bioplastics and Biocomposites, nova-Institute (2015). Retrieved from http://docs.european-bioplastics.org/2016/publications/EUBP_facts_and_figures.pdf

Lignin Valorization

Lignin was discovered in 1838 by Anselme Payen when wood reacted in an acidic then alkaline solution, resulted in an insoluble residue (McCarthy & Islam, 2000). Since then, over 10,000 scientific papers have been published on lignin, each contributing to a puzzle that remains incomplete today (Zakzeski et al., 2010).

Lignin constitutes 15 percent to 40 percent dry weight of lignocellulosic feedstock resulting in a large waste stream (Ragauskas et al., 2014). Lignin, an established byproduct of pulp mills, has traditionally been burned for combined heat and power. However, in second generation biorefineries, approximately 60 percent more lignin is generated than is needed to meet plant energy needs through combustion (Sannigrahi et al., 2010). As a result, research efforts are accelerating to identify viable opportunities for lignin valorization.

Globally, approximately 50 million tons of lignin are produced annually, while lignin-derived products represent 1 percent to 2 percent of the world's lignin production and the remaining 98 percent is burned for energy or landfilled (Gargulak and Lebo 1999; Lora and Glasser 2002; Mansouri and Salvadó, 2006; Vishtal and Kraslawski, 2011; Smolarski, 2012). Energy captures the most market volume, although it offers the lowest value-added opportunity (Higson & Smith, 2014). Current lignin products can be segmented into several categories: binding agents, rheology control, dispersing agents, emulsion stabilizers, and retardants (Gargulak & Lebo, 1999; Smolarski, 2012) (Figure VCO-Intro.5). Concrete additives are a value-added application for lignin waste to reduce water usage in concrete and retard concrete setting time (Gargulak & Lebo, 1999; Smolarski, 2012). Vanillin is a unique value-added product from lignin that is exclusively manufactured by Borregaard as a flavoring agent (Borregaard, 2015). The lignin product market has grown from $2 million in 1960 to $180 million in 1984 (Tillman, 1985) to $730 million in 2014 (Frost & Sullivan, 2014), excluding energy.

Markets for potential lignin-based products vary in terms of volume and value, creating different strategic opportunities for biorefineries to add value to lignin (Figure VCO-Intro.5). Whereas lignin-based phenol and carbon fiber are poised to capture the largest market potential, factors such as cost of production and viable chemical pathways to products limit commercial feasibility (Kleinert & Barth, 2008; Ragauskas et al., 2014).

An alternative potential market with lower volume and value potential is lignin-based benzene, toluene and xylene (BTX), which requires a depolymerization of lignin followed by separation, of which there are technology limitations (Cherubini & Strømman, 2011; Strassberger et al., 2014). Powdered Activated Carbon (PAC) is another potential market due to lignin's high carbon content, abundant supply and the changing regulatory landscape for electric generating power plants (Ragan & Megonnell, 2011; Suhas et al., 2007; Anonymous, 2013; Anonymous, 2015).

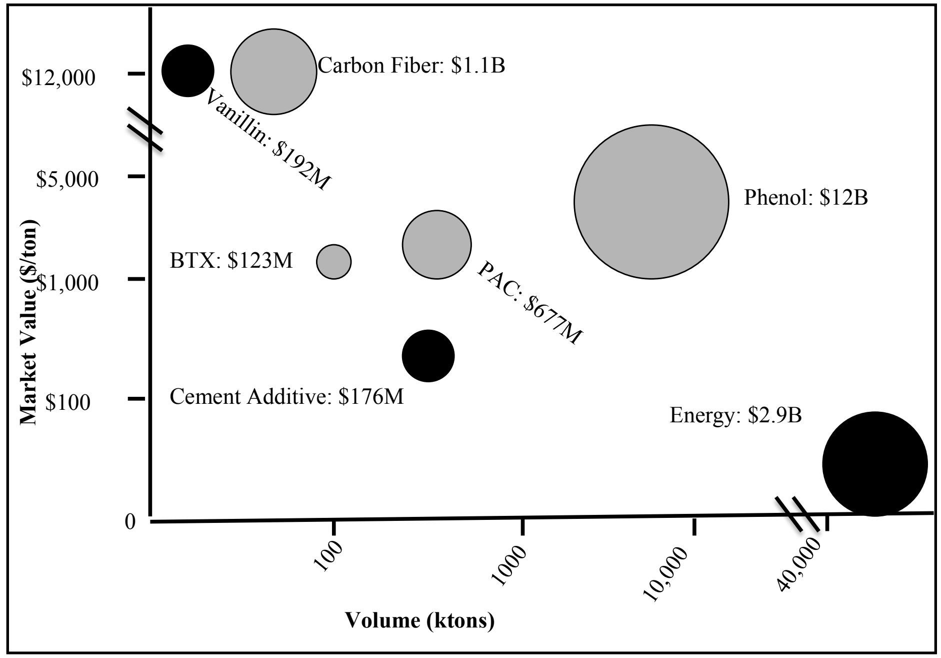

Figure VCO-Intro.5. Depiction of lignin products based on volume and value from literature (Downing, 2014; Higson & Smith, 2014; Anonymous, 2015; Smolarski, 2012). *[NOTE: The diameter of the circle represents the total market value of the product. Gray circles represent potential markets for lignin products, while black circles represent lignin products currently on the market]*

PAC for removing mercury from power plant flue gas streams is traditionally manufactured from lignite coal due to the coal's ability to generate proper PAC structure. Lignin is a precursor to lignite coal through a three step geochemical process that transforms lignin into lignite coal. This process is known as coalification, which includes; microbiological degradation of cellulose; the conversion of lignin into humic substances; and the condensation of the humic substances into coal molecules (Miller, 2011). The lignin molecule is estimated to experience a dehydroxylation process, a cleavage of the Β-O-4 ether bond, and a demethylation process to coalify lignin into lignite coal (Hatcher & Clifford, 1997). Due to the similarities between lignin and lignite coal, lignin has potential as a feedstock for the production of powdered activated carbon for mercury sequestration (Figure VCO-Intro.6).

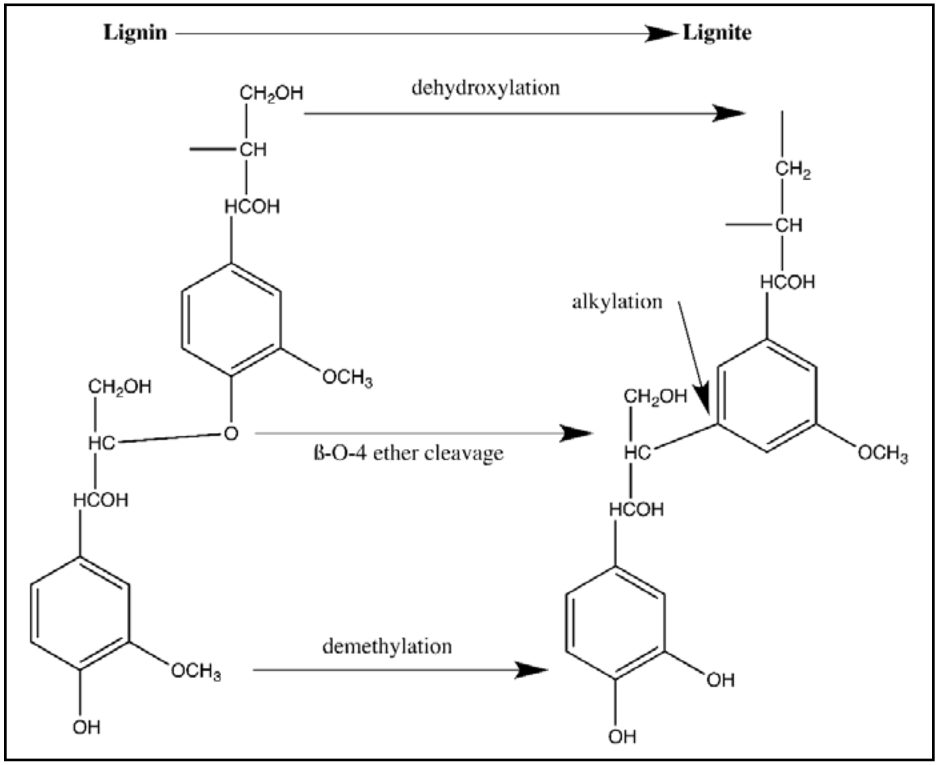

Figure VCO-Intro.6. Proposed coalification process from lignin to lignite coal. Adapted from "The organic geochemistry of coal: from plant materials to coal," by Hatcher, P.G. & Clifford, D.J., 1997, *Organic Geochemistry*, 27(5–6), p. 255.

Market Drivers

In December 2011, the EPA signed the MATS rule under the Clean Air Act Section 111 and 112 requiring coal-fired power plants over 25 MW to reduce their toxic emissions by April 2016 (EPA, 2012). The MATS called for existing and new power plants to cut mercury emissions by 91% from 2010 levels with a cost to power plants estimated at approximately $9.6 billion per year (EPA, 2012; Ray, 2015). The MATS were brought to the U.S. Court of Appeals for the D.C. Circuit on April 2014, where the ruling was upheld in a 2-1 decision (Larson, 2015). On November 25, 2014 the Supreme Court of the United States (SCOTUS) agreed to hear the case by consolidating three cases (Michigan, et al. v. EPA, Utility Air Regulatory Group v. EPA et al., and National Mining Assoc. v. EPA, et al.) focused on the limited question of: "whether the EPA unreasonably refused to consider costs in determining whether it is appropriate to regulate hazardous air pollutants emitted by electric utilities" (Reitenbach, 2014).

In March 2015, the SCOTUS over-ruled the MATS due to the EPA's lack of consideration of the costs associated with MATS implementation (Neuhauser, 2015). As a result, the EPA proposed supplemental cost of MATS data in November 2015, suggesting that the costs of the MATS "does not alter the EPA's previous determination that it is appropriate to regulate air toxics, including mercury, from power plants" (EPA, 2015). A date to readdress the SCOTUS ruling on MATS has yet to be released. Regardless, the U.S. Energy Information Administration (EIA) has reported that 77 percent of the nation's coal-fired power fleet has or will have met the emission regulations by installing emission controls by 2016 (Frazier, 2016; P. Gray et al., 2015).

Powdered Activated Carbon (PAC) for Mercury Sequestration

The combustion of coal feedstock in power plants releases mercury emissions into the biosphere where it is transformed into methylmercury, a neurotoxin (Bowen & Irwin, 2007; Chang, 1977; Hu et al., 2013). The U.S. contains three main coal-producing regions: Western Region (approx. 53%), Appalachian Region (approx. 27.4%) and Interior Region (approx. 18.6%) (EIA, 2016). Mercury emissions are a function of both the mercury content and calorific value (BTUs) of the coal, which varies by coal-producing region (Toole-O'Neil et al., 1999). The Appalachian region generally has the highest mercury content (ppm) and the Western Region the lowest. (Tewalt., et al. 2001; Toole-O'Neil et al., 1999)

Mitigating mercury from power plants can be achieved through various mechanisms including: controls for particulate matter, sulfur dioxide and nitrogen oxides (Strivastava, 2010); the reinjection of partially combusted coal, known as The Thief Process (Granite et al., 2007); and, the most effective mechanism, activated carbon injection systems (ACI) where the mercury contaminated PAC is disposed of safely in landfills or used as a concrete amendment (Gray, 2013; Sjostrom et al., 2010; Sjostrom, 2014; Zykov et al., 2014).

Lignin-based Powdered Activated Carbon (PAC)

Lignin is approximately 60 percent carbon and has a structure similar to bituminous coal, thus providing an opportunity as a renewable high carbon feedstock for the manufacture of carbon fiber and activated carbon (Kadla et al., 2002; Norberg, 2012; Ragan & Megonnell, 2011; Ragauskas et al., 2014; Suhas et al., 2007). Activated carbon has been produced from high carbon content materials such as hardwoods, coconut shells, fruit stones, coals and synthetic macromolecular systems (Marsh & Reinoso, 2006). Activated carbon is used in liquid phase and gas phase applications (Marsh & Reinoso, 2006) and may be used in various forms including powdered, granulated, and extruded activated carbon (Cabot, 2014).

Scientists have developed lignin-based PAC products through physical and chemical activation pathways (Ragan & Megonnell, 2011; Suhas et al., 2007). Lignin-based PAC has been studied for its use in liquid phase applications (Fu et al., 2013); however, in laboratory settings, NARA researchers have successfully applied lignin-based PAC in a gas phase application to sequester mercury from power plant flue gas streams (I. Dallmeyer, personal communication, November 10, 2015). Various performance-based, market-entry issues including, but not limited to PAC porosity and mercury capture rates are currently under investigation (I. Dallmeyer, personal communication, October 15, 2015).

TASK 1: REVIEW OF THE U.S. BIOFUELS INDUSTRY

OBJECTIVE

The overall goal of this task is to present a comprehensive review of the U.S. biofuels industry.

METHODOLOGY

A wide variety of secondary information sources regarding bioenergy, biofuel, and biorefinery have been selected and critically assessed. Those information sources are obtained from government organizations, industrial associations, magazines, and academic journals as listed in Table VCO-1.1.

RESULTS

Over 90% of U.S. ethanol biorefineries use corn grain as feedstock; the remaining use sorghum, cheese whey or waste beer (O'Brien, 2010; Renewable Fuels Association, 2015). Figure VCO- 1.1 illustrates the 208 U.S. corn-grain ethanol biorefineries in 2015 with the heaviest concentrations in the Midwestern corn-belt of Iowa (n=40), Nebraska (n=25), Minnesota (n=21), South Dakota (n=15) and Illinois (n=14).

Table VCO-1.1. Secondary information sources

Government organizations	U.S. *Department of Agriculture* (DOA) Forest Products Laboratory; U.S. *Department of Energy* (DOE) National Renewable Energy Laboratory (NREL) and Bioenergy Technologies Office (BTO); and U.S. *Energy Information Administration* (EIA)
Industrial organizations	*Renewable Fuels Association* (RFA) and *National Biodiesel Board* (NBB)
Journals & websites	*Ethanol Producer Magazine, Biofuels, Bioproducts and Biorefining,* and *BiofuelsDigest.com*

Biodiesel is defined under the standard of ASTM D6751 as "a fuel comprised of mono-alkyl esters of long-chain fatty acids", and can be produced from vegetable oilseeds (such as rapeseed, sunflower, olive, and soybean), animal fats (such as poultry, tallow, and white grease) or recycled restaurant grease (e.g. yellow grease) (Alternative Fuels Data Center, 2014; Energy Information Administration, 2016b; Lai, 2014). Among all biodiesel feedstocks, vegetable oilseeds were the major biodiesel feedstock, accounting for approximately 71 percent of the U.S. total in 2015 (Energy Information Administration, 2016b). That year, soybean oil was the largest feedstock accounting for 52 percent of the total, followed by recycled grease (14.3%), animal fats (13.4%), corn oil (11%), canola oil (8%), and other (1.3%) (Energy Information Administration, 2016b). Figure VCO-1.2 4 shows the locations of the identified 162 U.S. biodiesel biorefineries in 2015 (Biodiesel Magazine, 2015; Lane, 2013a; National Biodiesel Board, 2015a).

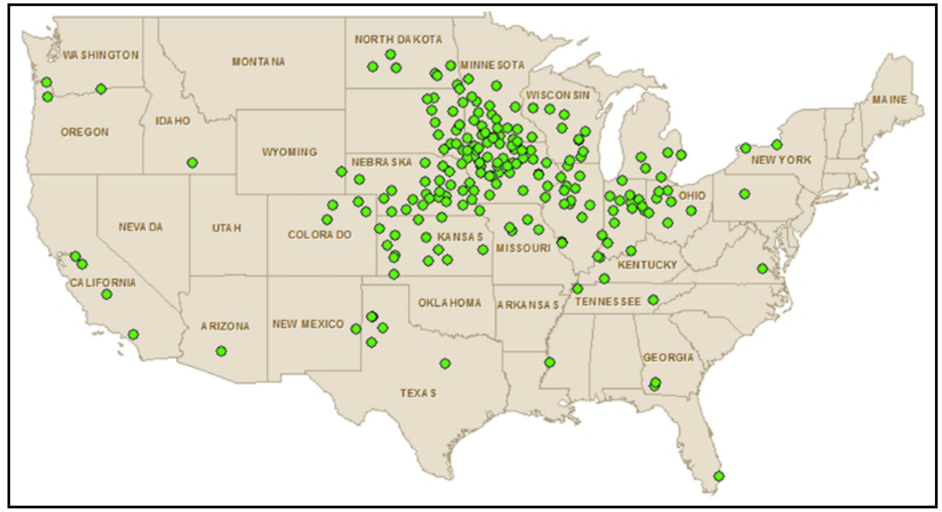

Figure VCO-1.1. U.S. corn-grain ethanol biorefineries (n=208) by location in 2015. Adapted from "Ethanol Biorefinery Locations", *Renewable Fuels Association*, 2015. Retrieved from http://www.ethanolrfa.org/resources/biorefinery-locations/.

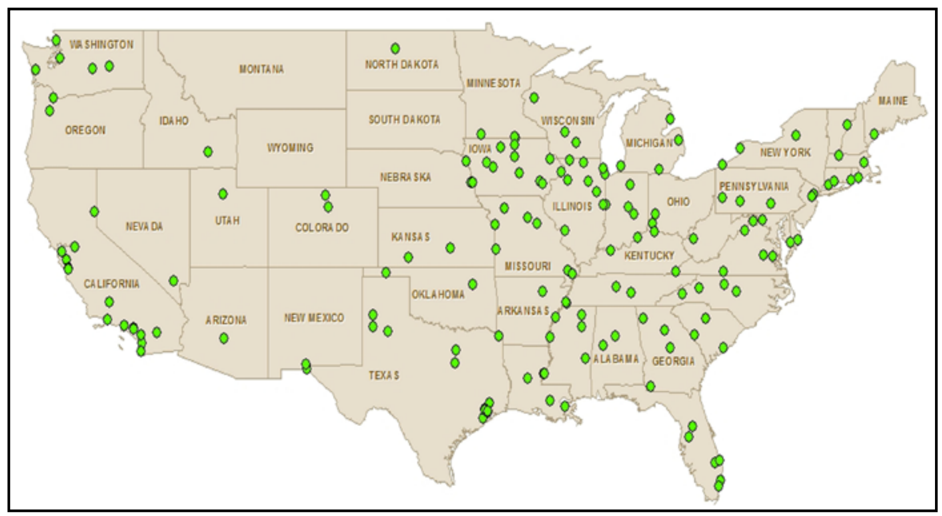

Figure VCO-1.2. U.S. biodiesel biorefineries (n=162) by location in 2015 (Adapted from (Biodiesel Magazine, 2015; Lane, 2013a; National Biodiesel Board, 2015a))

A wide variety of agricultural biomass can be used as raw materials to produce cellulosic alcohols including short rotation forestry crops (poplar, willow), perennial grasses (miscanthus, switchgrass), agricultural, forest and mill residues, and municipal solid waste (MSW) (Pacini, Sanches-Pereira, Durleva, Kane, & Bhutani, 2014; Sims, Taylor, Saddler, & Mabee, 2008). Compared to petroleum-based fuels and corn-grain ethanol, cellulosic alcohols benefit from their reliance on non-food based feedstocks, less competition on land use, and lower lifecycle GHG emissions (Balan, Chiaramonti, & Kumar, 2013; FitzPatrick, Champagne, Cunningham, & Whitney, 2010; Pacini et al., 2014).

Cellulosic alcohols may be produced in either "bolt-on" and "stand-alone" biorefineries. "Bolt-on" facilities are added to or co-located with existing corn-grain ethanol biorefineries to leverage existing corn-grain ethanol facilities. These "bolt-on" cellulosic biorefineries can share feedstock and distribution supply chains and lower capital costs to reduce investment risk (Morrison, Witcover, Parker & Fulton, 2016; Lane, 2014). Currently, eleven U.S. "bolt on" cellulosic biofuel biorefineries are in start-up mode (Table VCO-1.2) with two having launched commercial-scale production: POET-DSM "Project Liberty" (Sept. 3, 2014) and Quad County Corn Processors (July 1, 2014) (Fuels America, 2014).

Table VCO-1.2. "Bolt-on" cellulosic alcohol biorefineries in U.S. as of January 2016 (n=11)

Companies	Location	Product	Capacity (gallons/year)	Citations
Abengoa	York, NE	Ethanol	20,000	(Piersol, 2011)
ACE ethanol	Stanley, WI	Ethanol	Up to 3.6 million	(Lane, 2013b)
ADM	Decatur, IL	Ethanol	25,800	(Lane, 2013a)
Aemetis	Keyes, CA	Ethanol	NA	(Aemetis, 2012)
Flint Hills	Fairbank, IA	Ethanol	NA	(Business Wire, 2012)
Front Range	Windsor, CO	Ethanol	Up to 3.6 million	(Sweetwater Energy, 2013)
Gevo	Luverne, MN	Iso-butanol	0.6~1.2 million	(Gevo, 2015)
ICM	St. Joseph, MO	Ethanol	NA	(ICM, 2012)
Pacific Ethanol	Boardman, OR	Ethanol	Up to 3.6 million	(Pacific Ethanol, 2013)
POET-DSM	Emmetsburg, IA	Ethanol	25 million	(POET-DSM, 2014)
Quad-County Corn Processors	Galva, IA	Ethanol	2 million	(Advanced Ethanol Council, 2015; Quad County, 2015)

In addition, sixteen U.S. "stand-alone" cellulosic alcohol biorefineries have been identified with three having successfully launched commercial scale production: Abengoa Bioenergy 25 MGY in Hugoton, KS (Oct. 19, 2014); DuPont 30 MGY in Nevada, IA (Oct. 30, 2015); and INEOS Bio 8 MGY in Vero Beach, FL (July 31, 2013) (Fuels America, 2014; DuPont, 2015b; INEOS, 2013). Fifteen biorefineries produce cellulosic ethanol as the major product; Butamax focuses on the production of n-butanol (Table VCO-1.3).

Table VCO-1.3. "Stand-alone" cellulosic alcohol biorefineries in U.S. as of January 2016 (n=16)

Company	Location	Feedstock	Products	Capacity (MGY)	Citations
Abengoa	Hugoton, KS	Corn stover, switchgrass	Ethanol	25	(Abengoa, 2014)
American Process	Alpena, MI Thomaston, GA	Sugarcane bagasse Non-food based biomass, woodchips	Ethanol, acetic acid Ethanol, succinic acid, BDO	0.7 Up to 0.3	(Advanced Ethanol Council, 2013) (American Process, 2015)
Beta Renewables	Clinton, NC	Energy grasses	Ethanol, lignin	20	(Advanced Ethanol Council, 2013) (Beta Renewables, 2013)
Bluefire Renewable	Fulton, MS Anaheim, CA	Municipal solid waste (MSW)	Ethanol	19 200 lbs/day	(Advanced Ethanol Council, 2013) (Blue Fire Renewables, 2015)
Butamax	Wilmington, DE	Woody Biomass	n-butanol	NA	(Butamax, 2013)
Canergy	Imperial Valley, CA	Energy cane	Ethanol	25 (Canergy, 2015)	(Canergy, 2015)
Coskata	Madison, PA	Woody chips, MSW	Ethanol, ethylene	NA	(Coskata, 2015)
DuPont Biofuel Solutions	Nevada, IA	Corn cob	Ethanol	30	(Dupont, 2015b)
Enerkem	Pontotoc, MS	MSW	Ethanol and methanol	10	(Advanced Ethanol Council, 2013)
Fiberight	Blairstown, IA	MSW	Ethanol	6	(Advanced Ethanol Council, 2013) (Fiberight, 2015)
INEOS	Vero Beach, FL	Vegetative and wood waste	Ethanol	8	(INEOS, 2013)
Mascoma	Kinross, MI	Hardwood	Ethanol & biochemicals	20	(Balan, Chiaramonti, & Kumar, 2013)
Mendota Bioenergy	Five Points, CA	Energy beets	Ethanol	15	(Mendota Bioenergy, 2015)
ZeaChem	Boardman, OR	Energy woods	Ethanol & biochemicals	0.25 25	(ZeaChem, 2012) (Balan et al., 2013) (Brown & Brown, 2013)

The U.S. biofuels industry has also witnessed considerable progress of the non-food based hydrocarbon biofuels, which are drop-in replacements for gasoline, diesel, and jet fuel (Savage, 2011). Drop-in hydrocarbon biofuels are chemically similar to petroleum-based fuels and therefore are fully compatible with existing infrastructure, i.e., no need for engine modifications and drop-in biofuels may use existing petroleum distribution systems (Alternative Fuels Data Center, 2016). As of January 2016, seventeen companies are currently or proposing to use second generation (lignocellulsoic) and third generation (algal) feedstock for the production of various end products (Table VCO-1.4).

Table VCO-1.4. Drop-in hydrocarbon biofuels start-ups as of January 2016 (n=17)

Company	Location	Products	Citations
		Lignocellulosic biomass	
Amyris	Emeryville, CA	Renewable diesel from farnesene	(Amyris, 2016)
Cool Planet	Alexandria, LA	Renewable jet fuels & gasoline	(CoolPlanet, 2015)
Emerald Biofuels	Chicago, IL	Renewable diesel	(Emerald, 2015)
Envergent (UOP & Ensyn)	Kapolei, HI	Green diesel & jet fuel	(Envergent, 2015)
Fulcrum BioEnergy	Storey County, NV	SPK jet fuel or renewable diesel	(Fulcrum, 2015)
Haldor Topsoe Inc.	Pasadena, TX	Dimethyl ether, renewable gasoline	(Topsoe, 2015)
LanzaTech	Soperton, GA	Drop-in jet fuel via Alcohol-to-Jet (ATJ)	(LanzaTech, 2015)
Maverick Synfuels	Brooksville, FL	Renewable diesel/jet fuel via Methanol-to-Olefins (MTO)	(Maverick, 2015)
Red Rock Biofuels	Fort Collins, CO	Drop-in jet, diesel and naphtha fuels	(RedRock, 2015)
Sundrop Fuels	Longmont, CO	Green gasoline	(Sundropfuels, 2015)
SynTerra Energy	CA & OH	Synthetic diesel fuel	(SynTerra, 2012)
Terrabon, Inc.	Bryan, TX	Renewable gasoline & chemicals	(Terrabon, 2008)
Virent	Madison, WI	Renewable diesel, jet fuel & gasoline	(Virent, 2015)
		Algae	
Algenol	Fort Myers, FL	Renewable diesel, gasoline and jet fuel	(Algenol, 2016)
Joule Unlimited	Hobbs, NM	Sunflow-D (diesel)	(Jouleunlimited, 2014)
Sapphire Energy	Columbus, NM	Gasoline from omega oils	(Bardhan, Gupta, Gorman, & Haider, 2015; Sapphire, 2014)
Solazyme	Peoria, IL	Soladiesel, Solajet	(Bardhan et al., 2015; Solazyme, 2014)

Conclusion

Future biofuel conversion technologies and resultant final products are difficult to predict; however, a fully drop-in, sustainable and energy dense biomass-based liquid fuel at price parity with petro-based fuels is the ultimate goal to address societal needs around climate change and energy security (Babcock, Marette, & Tréguer, 2011). In particular, specific biofuel pathways will be driven by a favorable value proposition vis-à-vis petro-fuels in terms of overall economics and proven environmental benefits without perceived negative impacts on performance. This paper provides an up-to-date critical review for researchers and policymakers to better understand the structure of existing U.S. biorefineries and to benchmark future opportunities for the U.S. bioeconomy.

TASK 2: COMMERCIALIZATION FACTORS FOR THE U.S. CELLULOS BIOFUELS INDUSTRY

OBJECTIVE

The OVERALL objective is to examine, understand and quantify the perceived drivers for and barriers to the commercialization of the U.S. cellulosic biofuels industry among academic researchers and industrial experts.

METHODOLOGY

Data were collected via quantitative surveys between July and November 2015. The sample population for this study was obtained from the registration lists of the 2015 annual meetings of seven U.S. Department of Agriculture (USDA) Coordinated Agricultural Projects (CAPs) (Table VCO-2.1) (National Institute of Food and Agriculture (NIFA), 2015). These CAPs contain significant science-based expertise in research, education, and extension, as well as expertise gained from collaboration with key stakeholders and industrial partners. As a result, these seven programs represent a unique set of knowledge and experience on all aspects of biorefinery supply chains. To balance industrial expert group representation, attendees to the following two industrial conferences were added to our population: the 2015 National Advanced Biofuel Conference & Expo (NABC&E) and the 12th Advanced Bioeconomy Leadership Conference (ABLC) (Table VCO-2.1). These two conferences represent the U.S. biofuels and bio-based chemicals industries. In this sense, the samples analyzed in the paper are non-probability convenience samples.

The semi-structured survey instrument consisted of RATING questions designed to examine the importance of the drivers for and the degree of barriers to the commercialization of the U.S. cellulosic biofuels industry. Because of the emphasis of impediments to economy of scale by policymakers and academic researchers, this study's authors purposefully included a RANKING question to delineate the top three barriers in a meaningful and interpretable way (Dillman, Smith, & Christian, 2014). In other words, RANKING forced differences, which may not have been produced in the RATING question.

The procedure of administering the quantitative surveys includes several steps. Initially, a paper-based survey was administered at each venue. Later, a three-email follow-up strategy was deployed via an online-based survey to increase response rates. The first email included an embedded URL link to a SurveyMonkey® website, followed by two reminder emails at one-week intervals sent to all non-respondents (Dillman, Smith, & Christian, 2014). Data collection efforts resulted in 274 respondents (Table VCO-2.2), and the overall response rate was approximately 40%. The graduate students participating in this study represented young, relatively inexperienced professionals and future energy issues decision makers (Halder, et al., 2012); professors were typically research focused, often on specific bioenergy related issues; and industrial experts were the most experienced group and, arguably possess a bigger picture of the U.S. biofuels industry, but perhaps not as much expertise on a single focused issue compared to academic researchers.

Table VCO-2.1. The Seven USDA Coordinated Agricultural Projects (CAPs) (NIFA, 2015) and Two Industrial Conferences

CAPs	Lead University	2015 Annual Meeting Date & Location	Academic researchers	Industrial experts
Advanced Hardwood Biofuels Northwest (AHB)	U of Washington	Sept. 10, Seattle, WA	82	14
Bioenergy Alliance Network of the Rockies (BANR)	Colorado State U	Oct. 14, Missoula, MT	63	6
CenUSA Bioenergy	Iowa State U	July 28-29, Madison, WI	57	8
Southeast Partnership for Integrated Biomass Supply Systems (IBSS)	U of Tennessee	Aug. 10, Auburn, AL	74	6
Northwest Advanced Renewable Alliance (NARA)	Washington State U	Sept. 15, Spokane, WA	98	22
The Northeast Woody/Warm-season Biomass Consortium (NEWBio)	Pennsylvania State U	Aug. 3-5, Morgantown, WV	83	6
Sustainable Bioproduct Initiative (SUBI)	Louisiana State U	Oct. 21, Baton Rouge, LA	54	5
		Total:	**511**	**67**
Industrial Conferences	**Organizer**	**Dates & Location**	Academic researchers	Industrial experts
National Advanced Biofuel Conference & Expo (NABC&E)	BBI International	Oct. 26-28, Omaha, NE	-	40
The 12th Advanced Bioeconomy Leadership Conference (ABLC)	Biofuels Digest	Nov. 2-5, San Francisco, CA	-	60
		Total:		**100**

Overall, these three groups of participants collectively represent a broad array of U.S. biofuels research and development perspectives.

Table VCO-2.2. Participants' Profile of Quantitative Surveys

Participants of Quantitative Surveys	Study Participants (n)	Average Research Experience (years)
Graduate students	90	2.53
Professors	129	8.63
Industrial experts	55[1]	11.45

[1] The 55 industrial experts included 27 from the USDA CAP Annual Meetings and 28 industrial conference attendees.

RESULTS

Drivers for the commercialization of the U.S. cellulosic biofuels industry

As illustrated in Table VCO-2.3, this study's 268 academic researchers and industrial experts rated ***government policies*** significantly higher than any other cellulosic biofuel scale-up driver, with an overall mean value of 4.63. Overall, ***added value from non-fuel co-products*** and ***carbon emission reduction*** were the second and third most important drivers, respectively. Interestingly, ***food-vs.-fuel debate*** was the lowest rated scale-up driver by our three expert groups, which is not surprising given the public's skepticism regarding the impact on food security in the U.S. (Carus & Dammer, 2013).

Table VCO-2.3. The mean value of importance[1] of drivers for the scale-up of the U.S. cellulosic biofuels industry and significant differences of perceived drivers among three participant categories: graduate students (Grad), professors (Prof), and industrial experts (Industry).

Scale-up DRIVERS	Overall (n=268)	Grad (n=87)	Prof (n=126)	Industry (n=55)	Significance[2]	Multiple-Comparisons[3]
	Mean value					
1. Government policies	**4.63**	4.54	4.66	4.71	0.237	
2. Added value from non-fuel co-products	**4.26**	4.17	4.34	4.20	0.318	
3. Carbon emission reduction	**4.15**	4.22	4.20	3.96	0.284	
4. Volatile oil prices	**4.08**	4.08	4.09	4.06	0.974	
5. Dependence on fossil fuels	**3.99**	4.18	4.01	3.64	**0.004**	Grad, Prof>Industry
6. Rural economic development	**3.90**	3.91	3.85	3.98	0.641	
7. Energy security	**3.85**	4.14	3.73	3.69	**0.004**	Grad >Prof, Industry
8. Food-vs.-fuel debate	**3.19**	3.39	3.21	2.84	**0.017**	Grad> Industry
Multiple-Comparisons[2]	**1>2-8; 1-7>8**	1-7>8	1>3-8; 1-7>8	1>3-8; 1-7>8;	-	-

[1] Importance was measured using a 5-point Likert-scale, from 1=not important at all to 2=somewhat unimportant to 3=neither important nor unimportant to 4=somewhat important to 5=very important.
[2] Based on parametric analysis of variance (ANOVA) test, bold = significant at the 0.05 level.
[3] Based on Tukey's HSD (honest significant difference) test with 95% conference interval.

Significant differences between mean values of importance of drivers for the three participant categories were found at the 0.05 significance level for 3 out of the 8 drivers identified in this study (Table VCO-2.3). Graduate students and professors rated ***dependence on fossil fuels*** significantly higher than the industrial respondents. Additionally, graduate students rated ***food-vs.-fuel debate*** and ***energy security*** as significantly more important drivers to cellulosic biofuel scale up as compared to industry.

Comparing the three respondent groups, industrial experts clearly view potential cellulosic industry scale-up barriers differently vs. the other two groups (Table VCO-2.4). Industry views ***policy uncertainty*** and ***capital availability*** as significantly higher barriers and ***high production costs***, ***competition vs. petro-fuels***, and ***competition vs. corn-grain ethanol*** as significantly lower barriers compared to CAP researchers. These findings underscore the importance of examining issues from multiple perspectives.

Table VCO-2.4. The mean value of the degree1 of barriers to the scale-up of the U.S. cellulosic biofuels industry and significant differences of perceived barriers among three participant categories: graduate students (Grad), professors (Prof), and industrial experts (Industry).

Scale-up BARRIERS	Overall (n=264)	Grad (n=88)	Prof (n=121)	Industry (n=55)	Significance[2]	Multiple-Comparisons[3]
	Mean value					
1. High production costs	**4.19**	4.36	4.14	4.04	**0.041**	Grad>Industry
2. Policy uncertainty	**4.17**	4.05	4.12	4.45	**0.019**	Industry>Grad, Prof
3. Competition vs. petro-fuels	**4.15**	4.28	4.18	3.86	**0.034**	Grad>Industry
4. Feedstock costs	**3.86**	3.91	3.88	3.73	0.502	
5. Capital availability	**3.74**	3.57	3.74	4.02	**0.037**	Industry>Grad
6. Technology availability	**3.54**	3.53	3.60	3.40	0.443	
7. Cellulosic biofuels logistics	**3.50**	3.55	3.55	3.29	0.165	
8. Consistent feedstock supply	**3.34**	3.38	3.33	3.29	0.889	
9. Competition vs. corn-grain ethanol	**2.94**	3.23	2.85	2.69	**0.003**	Grad>Prof, Industry
Multiple-Comparisons[2]	**1-3>4-9; 1-8>9**	1-3>5-9;	1-3>5-9; 1-8>9	2>1, 3-9; 1-8>9	-	-

[1] Degree was measured using a 5-point Likert-scale, from 1=not a barrier to 2=low barrier to 3=moderate barrier to 4=high barrier to 5=very high barrier.
[2] Based on parametric analysis of variance (ANOVA) test, bold = significant at the 0.05 level.
[3] Based on Tukey's HSD (honest significant difference) test with 95% conference interval.

Ranking of barriers to the commercialization of cellulosic biofuels

A follow-up RANKING question was designed to supplement and possibly confirm the RATING scale responses to better delineate potential barriers to the scale-up of the U.S. cellulosic biofuels industry (Dillman et al., 2014). Participants were asked to indicate the top three barriers by using the pull-down menu of the 9 barriers listed in previous rating question. The responses were given a value weighting of 3 points for the "#1 commercialization barrier", 2 points for the "#2 commercialization barrier" and 1 point for the "#3 commercialization barrier" (Figure VCO-2.1).

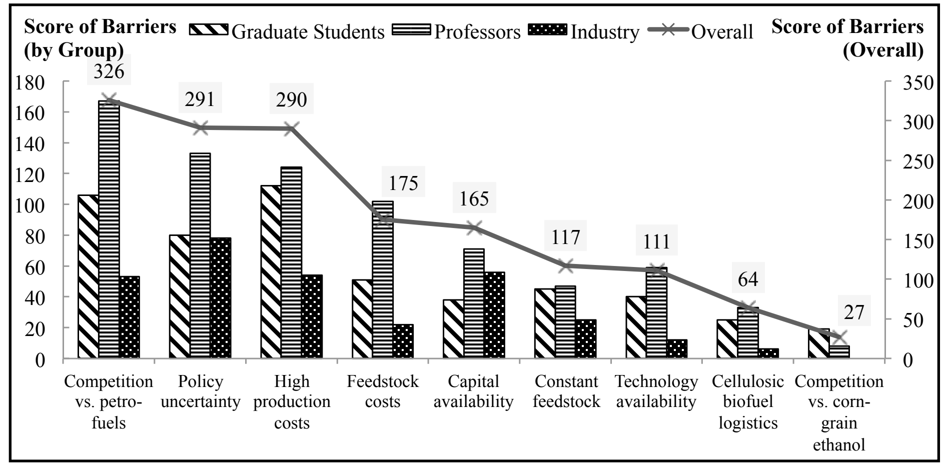

Figure VCO-2.1. Top 3 highest scale-up barrier ranked by survey participants [n=261]

Interestingly, the three highest RATED barriers to the commercialization of cellulosic biofuels (Table VCO-2.1) were also identified as the highest RANKED barriers in Table VCO-2.4. However, ***competition vs. petro-fuels*** was, by far, the #1 ranked *"commercialization barrier"* with an overall score of 326, followed by ***policy uncertainty*** (291), and ***high production costs*** (290).

Conclusion

By understanding how academic researchers and industrial experts perceive cellulosic biofuels commercialization, policy makers can increase the effectiveness of programs designed to encourage adoption and diffusion of cellulosic biofuels in the U.S. liquid transportation fuels market.

TASK 3: REVIEW OF THE U.S. BIO-BASED CHEMICALS INDUSTRY

OBJECTIVE

The overall goal of this subtask is to present a comprehensive review of the U.S. bio-based chemicals industry.

METHODOLOGY/RESULTS/CONCLUSION

This section identified existing and proposed projects in the U.S. bio-based chemicals industry through company websites and secondary reports (e.g. Nova Institute). As of June 2016, thirty-five companies producing twenty bio-based chemicals were identified (Table VCO-3.1). These renewable chemical building blocks are organized by their carbon number, i.e. C3 to C*n*. The microbial production of platform chemicals from carbohydrates has been the major conversion technique as shown in Table VCO-3.1.

These thirty-five companies may be categorized into three major groups, including "Chemical Giants", "Biochemical Start-Ups", and "Agricultural Giants".

Table VCO-3.1. U.S. bio-based chemical companies and their products (June 2016)

	Bio-based Chemicals	Companies (n=35)	Headquarters	Conversion Technique
C3	Acrylic acid	Blue Marble Biomaterials	Missoula, MT	Polyculture fermentation system
		Cargill, Incorporated	Wayzata, MN	Acquired OPXBIO's EDGE™ bioengineering technology
		SGA Polymers, LLC	South Charleston, WV	Converts lactic acid from carbohydrates into acrylic acid
	Lactic acid	Blue Marble Biomaterials	Missoula, MT	Polyculture fermentation system
		DuPont Industrial Biosciences	Itasca, IL	DuPont™ GENECOR® fermentation system
		GlycosBio Biotechnologies Inc.	Houston, TX	Metabolic engineering and fermentation
		Myriant Corporation	Woburn, MA	Single step, anaerobic fermentation with engineered microorganisms and catalytic upgrading
	1,3-Propanediol (PDO)	DuPont Tate & Lyle Bio Products Company, LLC	Loudon, TN	Convert corn glucose to Bio-PDO™ via fermentation
C4	n-Butanol & isobutanol	Butamax Advanced Biofuels LLC	Wilmington, DE	*Butamax*™ technology is designed to convert the sugars from various biomass feedstocks, including corn and sugarcane, into biobutanol using existing biofuel production facilities
		Gevo Inc.	Englewood, CO	Production of isobutanol by using an integrated strategy of biological and chemical
		Working Bugs, LLC	East Lansing, MI	Fermentation processes
	Succinic acid & 1,4-butanediol (BDO)	BioAmber Inc.	Plymouth, MN	Industrial biotechnology and chemical catalysis
		Genomatica, Inc.	San Diego, CA	Integrated biotechnology platform
		Myriant Corporation	Woburn, MA	Single step, anaerobic fermentation with engineered microorganisms and catalytic upgrading
	Furans	Micromidas Inc.	West Sacramento, CA	Use a non-fermentation, non-gasification, chemical-only process
C5	Isoprene	GlycosBio Biotechnologies Inc.	Houston, TX	Metabolic engineering and fermentation
		Yulex Corporation	Chandler, AZ	Purifying process to remove over 99.9% of natural rubber harmful impurities
	Levulinic acids	Segetis	Golden Valley, MN	Thermochemical conversion
C6	1,6-hexanediol (1,6-HDO)	Rennovia Inc.	Santa Clara, CA	Chemical catalytic process technology
	Adipic acid	Rennovia Inc.	Santa Clara, CA	Chemical catalytic process technology
		Verdezyne Inc.	Carlsbad, CA	Fermentation
	Glucaric acid	Rennovia Inc.	Santa Clara, CA	Chemical catalytic process technology
		Rivertop Renewables, Inc.	Missoula, MT	*Novel Chemistry*™ approach produces glucaric acid and other chemicals for consumer and industrial applications
	Hexamethylenediamine (HMD)	Rennovia Inc.	Santa Clara, CA	Chemical catalytic process technology
	Benzene	Anellotech Inc.	Pearl River, NY	Thermo Catalytic Biomass Conversion (Bio-TCAT™) to produce a mixture of benzene, toluene, and xylenes (bio-BTX)
Cn	Cellulose & Cellulose acetate (CA)	Celanese Acetate LLC	Dallas, TX	Cellulose acetate is derived from cellulose by deconstructing wood pulp into a purified fluffy white cellulose
		Eastman Chemical Company	Kingsport, TN	
		Innovia Films	Atlanta, GA	
		Rotuba Extruders	Linden, NJ	
	Polyamides (PA)	Arizona Chemical Company, LLC	Jacksonville, FL	Convert benzene to polyamide 6 and 6,6, via cyclohexane
		Arkema	King of Prussia, PA	
	Polyethylene terephthalate (PET)	Toray Plastic (America), Inc.	North Kingstown, RI	A polymer built up from the monomers mono-ethylene glycol (MEG) and purified terephthalic acid (PTA)
	Polyhydroxyalkanoates (PHAs)	Meredian Holdings Groups (MHG)	Bainbridge, GA	A group of microbial polyesters produced directly by fermentation
		Metabolix Inc.	Lowell, MA	
		Newlight Technologies LLC	Costa Mesa, CA	
	Polylactic acid (PLA)	Corbion	Lenexa, KS	Corn or other raw materials are fermented to produce lactic acid, which is then polymerized to make polylactic acid (PLA)
		NatureWorks LLC	Minnetonka, MN	
		PolyOne Corporation	Avon Lake, OH	
	Starch blends	StarchTech Inc.	Minneapolis, MN	Thermoplastic starch along with (modified) renewable polymers is used to produce starch blends
		Teknor Apex	Pawtucket, RI	
		Trellis Bioplastics	Seymour, IN	

OBJECTIVE

This subtask provides a roadmap to identify and assess value-added markets for industrial products through an examination of lignin-based products. One value-added lignin product with potential, powdered activated carbon (PAC), is used to further demonstrate a process for examining market opportunities for biorefinery lignin waste streams.

METHODOLOGY

This research deployed a multi-phase process including: a PAC vendor content analysis; and survey techniques (Figure VCO-4.1). A thorough literature review identified potential lignin-based value-added products. Powdered activated carbon (PAC) was selected as an appropriate “low-hanging” opportunity for biorefinery waste lignin and, as such, was used in subsequent research phases. Phase I then analyzed web-based content of PAC vendors’ promotional marketing literature tailored to power plant buyers/users for their PAC products. And, Phase II incorporated the Phase I results into an exploratory e-survey of select PAC buyers/users in the U.S. power generation industry.

<table>
<tr><td colspan="2">Problem:
Value-Added Applications for Biorefinery Waste Lignin</td></tr>
<tr><td>Phase I:
PAC Vendor Content Analysis</td><td>Phase II:
PAC Buyer/User Survey</td></tr>
<tr><td><u>Objective:</u>
Assess the criteria on which PAC is currently promoted by vendors</td><td><u>Objective</u>:
Explore attributes on which lignin-based PAC for mercury sequestration from electric generation power plant flue gas is purchased, examine barriers to entry and market opportunity</td></tr>
<tr><td colspan="2">Implications:
• The process may be applied to investigate other value-added opportunities
• Lignin has a potential market application as PAC for mercury sequestration from electric generating power plant flue gas</td></tr>
</table>

Figure VCO-4.1. Multi-phase process for new lignin product-market opportunity research.

Phase I: PAC Vendor Content Analysis

In 2015, nine firms supplied PAC for mercury sequestration to U.S. coal-fired power plants, 8 of which were used in the Vendor Content Analysis due to a lack of PAC specific promotional marketing material from one of the vendor websites. The population was identified through activated carbon market research reports (Table VCO-4.1) (Freedonia, 2013; Kahn, 2014; Marketsandmarkets.com, 2012; PR Newswire, 2013; Anonymous, 2013).

Table VCO-4.1. PAC Vendors analyzed in the vendor content analysis (n=8)
*not included in vendor content analysis

PAC Vendor	Print Media Access
ADA Carbon Solutions	www.ada-cs.com
Albemarle Corporation	www.albemarle.com
Babcock Power Inc.	www.babcockpower.com
Cabot Carbon	www.cabotcorp.com
Calgon Carbon	www.calgoncarbon.com
Carbotech AC GMBH	Carbotech.de/?lang=en
Donau Chemie	www.donau-carbon.com/?lang=en-US
Jacobi Carbon	www.jacobi.net
CECA *	www.cecachemicals.com

This task used a summative content analysis (Hsieh & Shannon, 2005) to identify and quantify specific terminology using a word frequency count (WFC) applied to the promotional marketing materials of eight U.S. PAC suppliers. The WFC and text interpretation were categorized using a priori coding (Stemler, 2001). Content analysis media included all material related directly to mercury sequestration from flue gas streams from the company websites, product brochures, and product tech sheets of eight U.S. PAC supplying companies.

Research suggests that industrial purchases are made on a set of value dimensions relating to product and service benefits or attributes (Ulaga & Eggert, 2005). The PAC vendor content analysis provided a systematic process to identify and code terminology into two mutually exclusive categories, product attributes and service attributes. A WFC was performed using MAXQDA software, identifying individual attributes mentioned most often, which were assumed to reflect high importance (Stemler, 2001). The attribute was then evaluated in the context of the document and sentenced to validate its importance to the analysis. Moreover, phrases and text were interpreted to code inferred attributes into individual attributes (Table VCO-4.2). The counted words and phrases were coded by individual attributes that best reflected the meaning of the word or phrase.

Table VCO-4.2. Examples of attribute assignment to PAC suppliers' web-based content

Print Media Content	Attribute Interpretation
"...tailored to meet your needs."	*Customizable Product*
"...customized solutions..."	*Customizable* Product
"Reduced mercury emissions"	*Product Effectiveness*
"...effective in removing many flue gas contaminants."	*Product Effectiveness*
"...plant-tested and proven..."	*Proven Product Performance*
"...90% mercury removal was easily attainable with..."	*Proven Product Performance*
"...supply assurance..."	*Reliable Delivery*
"...an undisturbed supply of..."	*Reliable Delivery*
"Our Advanced Performance Guarantee..."	*Product Guarantee*
"We can guarantee..."	*Product Guarantee*

Phase II: PAC Buyer/User Survey

Buyers/users of PAC, that is, electric generating power plants with ACI systems, assessed the importance of the Phase I product and service attributes, identified barriers to market entry, and evaluated market opportunity via an e-survey.

The Energy Information Administration (EIA) publishes an annually updated database from EIA Form-860, which includes all buyers/users of PAC from U.S. power plants currently operating an activated carbon injection (ACI) system, or proposing to operate an ACI system. In 2014, 173 electric generating power plants using 356 ACI units were identified (EIA, 2015a). The population for this study is all U.S. electric generating power plants currently operating or proposed to operate an ACI system included in a 2011 EPA online database (n = 98) (EPA, 2011). The 2011 EPA database included the most current available contact information for U.S. electric generating power plants (n=98) with ACI units delineated (n=261). As shown in Figure VCO-4.2, U.S. power plants are located throughout the U.S. with concentrations along the upper Atlantic coast, and the upper Midwest.

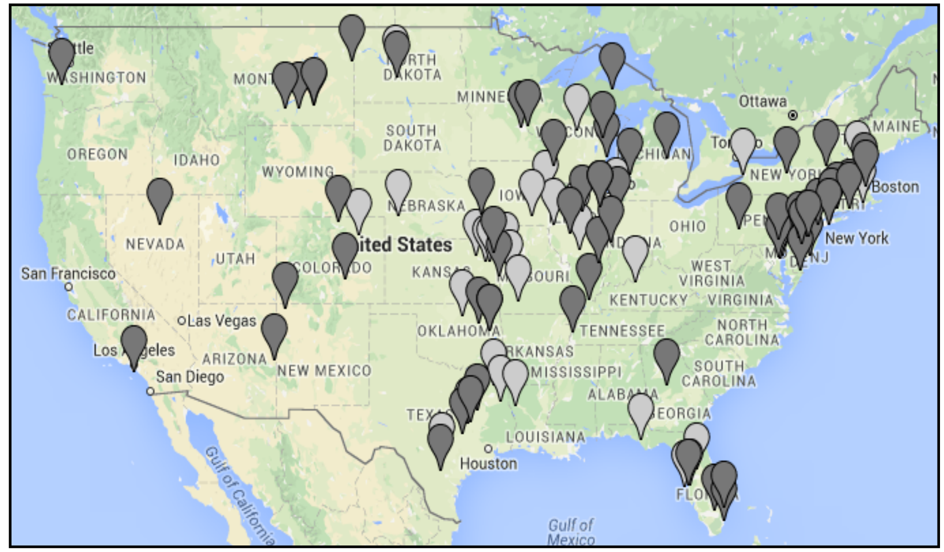

Figure VCO-4.2. Map of all U.S. power plants included in the EPA online database (2011) (n=98) delineating the contacted power plants (dark nodes; n=64) and the unreachable power plants (light nodes; n=34) (EIA, 2011).

The e-survey used SurveyMonkey (2015) and the data collection procedures were adapted from Don Dillman's Guiding Principles for Mail and Internet Surveys (2012). First, three electric generating power plants were contacted by phone and sent a pretest e-survey to discern question ambiguity and sensitive information. From the pretest, a modified and reduced, 5-question survey was emailed as a link via SurveyMonkey (2015) to all remaining electric generating power plants (n=95) along with a cover letter explaining the purpose of the study and the confidentiality of responses. Follow-up efforts included 3 reminder emails at 1-week intervals.

The overall response rate was 26.6 percent (17/64) after adjusting for unreachable power plants (n=34) due to erroneous contact information in the EPA (2011) online database. The adjusted population for this exploratory study included 64 electric generating power plants with valid contact information from the EPA's most current available database (EPA, 2011). Of the 17 participants, 4 are located in the upper Atlantic coast region, 1 in Florida, 7 in the upper mid-west, and 5 in the western U.S.

Results

Phase I: PAC Vendor Content Analysis - PAC suppliers utilize promotional marketing materials; product brochures, company websites, and product technical sheets to market products towards customers for the application of mercury sequestration from power plant flue gas. The print media consisted of 163 pages with 486 word frequency counts (WFCs); product attributes received 408 WFCs and service attributes 78 WFCs.

Product and Service Attributes

Following compilation of the product and service attribute word frequency count (WFC), individual attributes were tallied based on frequency. Overall, vendors of PAC convey a general message to buyers/users that their products will meet customer needs through product attributes. Based on WFCs, the top three attributes conveyed by vendors about their products were *Concrete Friendly* (WFC = 76), *Product Effectiveness* (WFC = 60) and *Product Reliability* (WFC = 44) (Table VCO-4.3). The service attributes most frequently mentioned were *Reliable Delivery* (WFC = 39) and *ACI Installations* (WFC = 18) (Table VCO-4.3). Analysis of the product and service attributes from the promotional marketing material provides insight into vendors' product positioning and communication strategies.

Table VCO-4.3. Word Frequency Count of 13 product and service attributes identified in the content analysis of PAC vendors' promotional marketing materials

9 Product Attributes	Word Frequency Count (WFC)
Concrete Friendly	76
Product Effectiveness	60
Product Reliability	44
Density	41
Product Efficiency	41
Ignition Temperature	39
Injection Rate	38
Proven Product Performance	35
Customizable Product	32
Total (Product Attributes)	408
4 Service Attributes	**Word Frequency Count (WFC)**
Reliable Delivery	39
ACI Installations	18
On-Site Support	12
Product Guarantee	10
Total (Service Attributes)	78
Total (13 Product & Service Attributes)	486

Phase II: PAC Buyer/User Survey

Powdered Activated Carbon (PAC) Product and Service attributes

In addition to the 13 product and service attributes derived from the content analysis of vendors' promotional materials, *Just-in-Time Delivery, Vendor Managed Inventory*, *List of Usage References* and *Delivered Price* were added from the pretest results and listed in Figure VCO-4.3 without word frequency counts (WFCs).

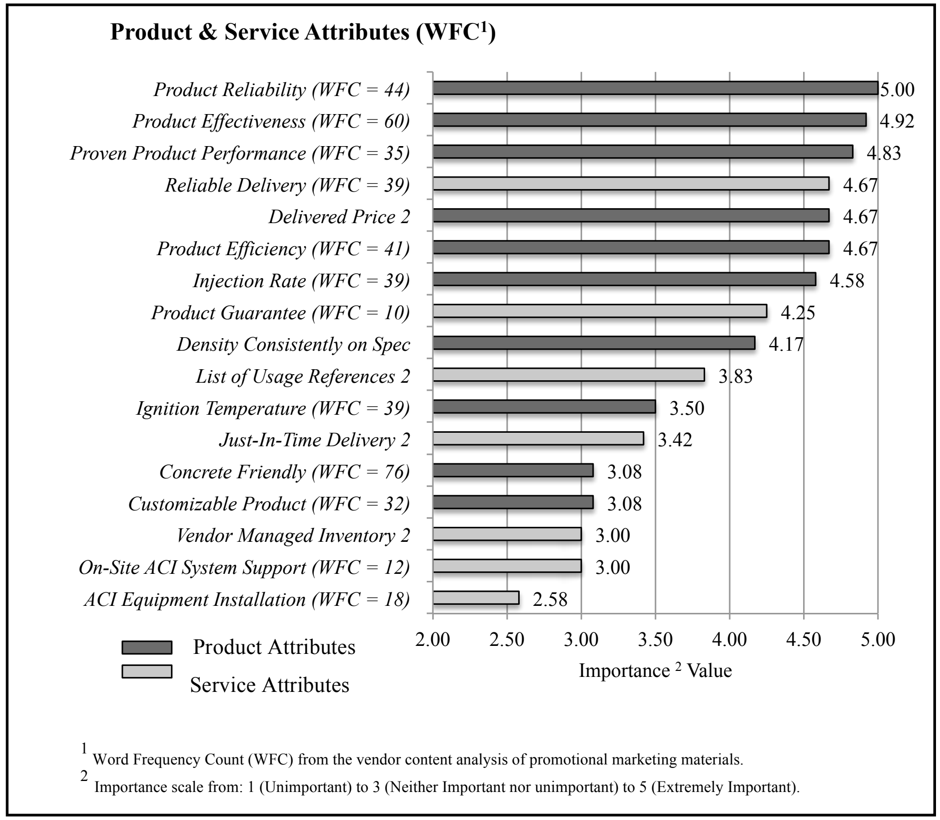

Figure VCO-4.3. Product and service attribute ratings by PAC buyers/users from U.S. electric generating power plants (n=17). **Question:** [on a 5-point scale from 1=unimportant to 3=neither important nor unimportant to 5=extremely important] **How IMPORTANT to your plant are the following PRODUCT and SERVICE attributes in the purchase of your powdered activated carbon product?**

Product Reliability was rated as the most important attribute by buyers/users of PAC (mean = 5), followed by Product Effectiveness, Proven Performance, Reliable Delivery, Delivered Price, and Product Efficiency (Figure VCO-4.3). The least important attribute was ACI Equipment Installation (mean = 2.58). The highest rated service attribute was Reliable Delivery (mean = 4.67), followed by Product Guarantee (mean = 4.25) and List of Usage References (mean = 3.83). The 10 product attributes (overall mean = 4.25) were, as a whole, rated higher than the 7 service attributes (mean = 3.53). Interestingly, PAC buyers/users rated Product Reliability, Effectiveness and Performance higher than Delivered Price, suggesting opportunities to differentiate products on performance attributes.

Barriers to Entry

Another issue addressed in the e-survey to PAC buyers at U.S. electric generating power plants concerned potential entry barriers for a new, lignin-based PAC product. Specifically, respondents were asked to list (un-aided) in rank-order the top three barriers to their purchase of a new lignin-based PAC. The buyer/user entry barrier responses were given a value weighting of 5 points for the largest barrier, 3 points for the second largest barrier and 1 point for the third largest barrier (Figure VCO-4.4). The barriers to entry were addressed as follows:

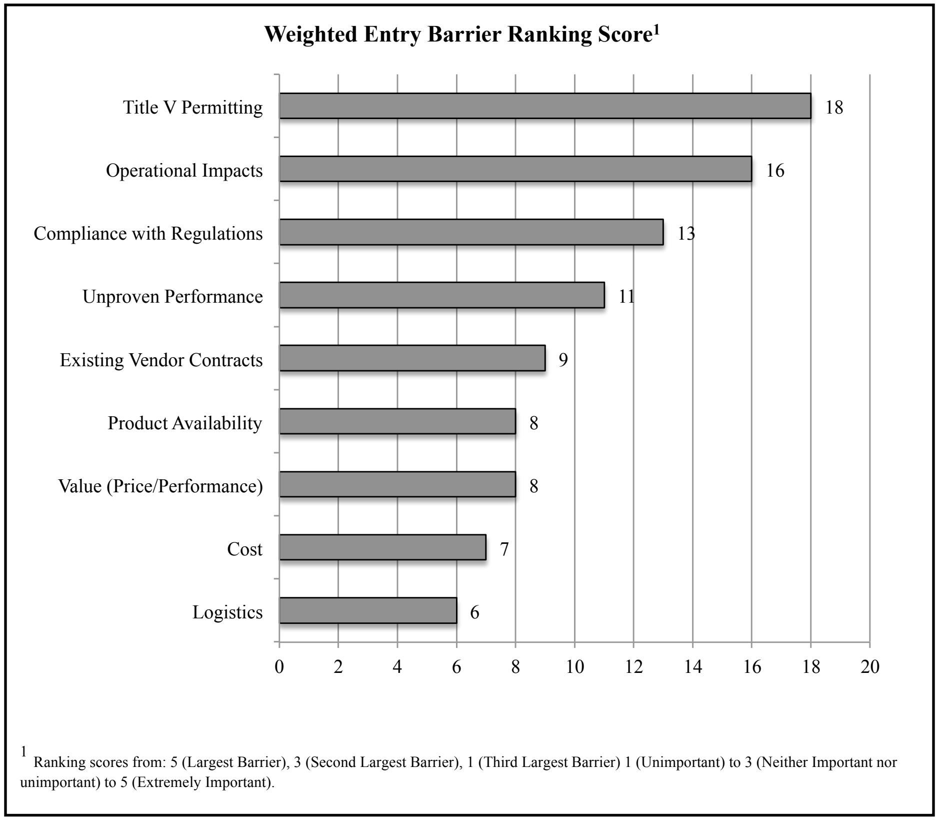

Figure VCO-4.4. Barriers to entry for a new lignin-based PAC product (n=13). Question: [on a 5-point scale from 1=extremely unlikely to 3=neither unlikely nor likely to 5=extremely likely] Please indicate the top 3 barriers to a new lignin-based PAC product for your power plant.

Title V Permits (weighted score = 18), such as a permit required for any physical plant change or change in the methods of plant operation, and *Operational Impacts* (weighted score = 16), that is, any impact on plant operations such as, down-time, or equipment change-over, represent the top two barriers to market entry for a lignin-based PAC, followed by *Compliance with Regulations* (weighted score = 13), specifically, compliance with mercury emission regulations, and *Unproven Performance* (weighted score = 11), that is, a product not yet tested on a full scale power plant (Fig. 20). Additional entry barriers to a new lignin-based PAC products mentioned by PAC buyer/users include: *Existing Vendor Contracts* (weighted score = 9), *Product Availability* (score = 8), *Cost* (weighted score = 7) and *Logistics* (transportation and distribution concerns) (weighted score = 6).

Opportunities for Substitution

Finally, the e-survey asked PAC buyers/users to indicate the likelihood that their power plant would test trial a new lignin-based PAC and their likeliness of purchasing a new lignin-based PAC from an existing vendor or a new vendor. The 13 respondents who answered the previous "…barriers to a new lignin-based PAC product for your power plant" (entry barriers) question were asked the following two questions:

> ***Question:*** *[on a 5-point scale from 1=extremely unlikely to 3=neither unlikely nor likely to 5=extremely likely]* ***Please indicate how LIKELY your plant is to consider a trial test for proof-of-concept of a lignin-based PAC, assuming similar price and performance as your current product?***
>
> ***Question:*** *[on a 5-point scale from 1=extremely unlikely to 3=neither unlikely nor likely to 5=extremely likely]* ***If the trial test proved lignin-based PAC to be a comparable product, how LIKELY is your plant to purchase lignin-based PAC from an Existing Vendor, or a New Vendor?***

Buyers/Users of PAC rated the likelihood of trial testing a new lignin-based PAC for proof-of-concept as 2.47 (5-point scale) with a standard devation of 1.19 (n=13) (Figure VCO-4.5). Respondents then indicated a somewhat stronger likelihood of purchasing a lignin-based PAC from an existing vendor at 3.00 with a standard devation of 1.00 (n=13) and 2.92 (n=13) from a new vendor with a standard devation

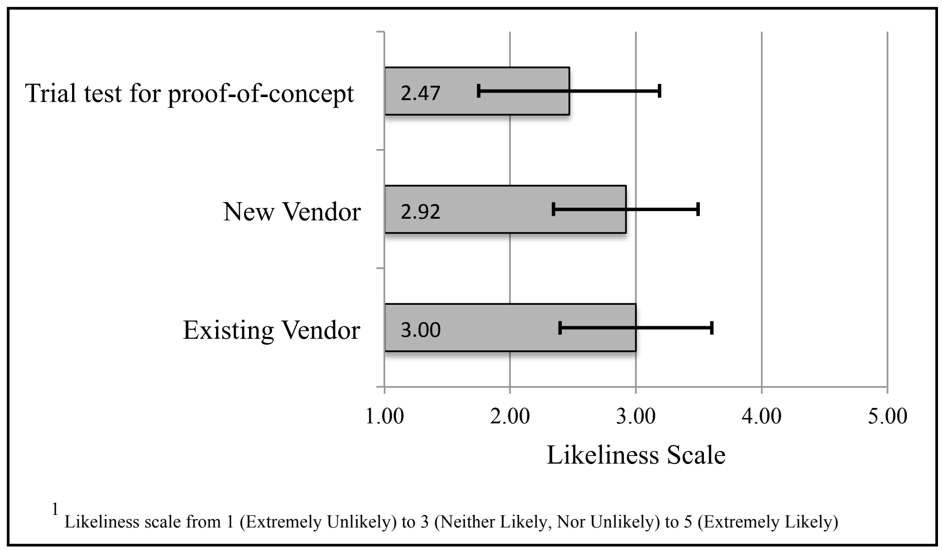

Figure VCO-4.5. PAC buyers/users' likeliness to consider purchasing lignin-based PAC from a new or existing vendor (n=13) of 0.95.

Conclusion

This research provides insights to the PAC producing industry, biorefineries, and the pulp industry regarding the introduction of a lignin-based PAC as a value-added option for mercury sequestration from power plant flue gas streams. Policy makers may better understand the impact and reaction of new rules on electric generating power plants and peripheral industries. Lastly, this work illustrates a framework for exploring value-added business-to-business product-market opportunities and, specifically, opportunities for lignin valorization with a particular application to lignin-based PAC for mercury sequestration from electric generating power plant flue gas.

NARA OUTPUTS

PUBLICATIONS

Cline, Stephen P. 2016. *Lignin as a biorefinery co-product market opportunity*. Master of Science Thesis, The Pennsylvania State University. May. 98 pp.

Chen, M., P. Smith, and M. Wolcott. 2016. *U.S. Biofuels Industry: A Critical Review of Opportunities and Challenges*. BioProducts Business 1(4):42-59.

PRESENTATIONS

Chen, M., P. Smith and M. Wolcott. 2015. Toward the Integrated Production of Cellulosic Biofuels and Biochemcials: Lessons Learned from the U.S. Corn & Cellulosic Ethanol Industries. Oral Presentation at the Year 4, NARA Annual Meeting, Spokane, WA. Sept. 15-17.

Chen, M. 2014. Evolving Structure of U.S. Biorefineries & Market Opportunity of Renewable Chemicals. Oral Presentation at the Year 3, NARA Annual Meeting, Seattle, WA. Sept. 15-17.

Cline, S.P. and P.M. Smith. 2014. NARA EPP Co-Product Market Opportunity: Lignin-Based Activated Carbon. Presentation at the NARA Annual Meeting. Sept. 15-17 in Seattle, WA.

POSTERS

Chen, M., and P. Smith. 2016. Perceived Drivers and Barriers for the U.S. Cellulosic Biofuels Industry by Bioenergy Experts. Poster presentation at Northwest Wood-Based Biofuels + Co-Products Conference, Seattle, WA. May 3-4.

Chen, M., and P. Smith. 2016. Expert Elicitation on Commercialization Factors for U.S. Integrated Cellulosic Biorefineries. Poster presentation at Northwest Wood-Based Biofuels + Co-Products Conference, Seattle, WA. May 3-4.

Cline, S.P. and P.M. Smith. 2016. Opportunities for lignin valorization: an exploratory process. Poster presentation at the NARA 2nd Northwest Wood-based Biofuels + Co-Products Conference, Seattle, WA. May 3-4.

Chen, M., and P. Smith. 2015. Expert Elicitation on the Integrated Production of 2nd Gen (Cellulosic) Biofuels & Biochemicals. Poster presentation at the Year 4, NARA Annual Meeting, Spokane, WA. Sept. 15-17.

Wolpart, M., P. Smith, S. Cline, and W. Shi. 2015. Screening of Value-Added Market Opportunities for Lignin. NARA Summer Undergraduate Research Experience (SURE) program poster session, Washington State University, Pullman, WA. July 30.

Chen, M. and P. Smith. 2014. Evolving Structure of the U.S. Biorefinery Industry. Poster presentation at the Year 3, NARA Annual Meeting, Seattle, WA. Sept. 15-17.

Chen, M., P. Smith, and P. Venugopal. 2014. Market Opportunities and Challenges Facing the Economically Viable Production of Renewable Chemicals in U.S. Biorefineries. Poster presentation at the Year 3, NARA Annual Meeting, Seattle, WA. Sept. 15-17.

Cline, S.P. and P.M. Smith. 2014. The Lignin-Based Activated Carbon Market Opportunity. Poster presentation at the NARA Annual Meeting. Sept. 15-17 in Seattle, WA.

P. Venugopal, P. Smith, and Chen, M. 2014. Potential Technology Pathways for the Production of Alternative Jet Fuel. Poster presentation at NARA-SURE, Washington State University, Pullman, WSU. July 31.

Chen, M., S. Cline, and P. Smith. 2013. Preliminary Market Opportunity for Biorefinery Intermediates (Lignin). Poster presentation at the Year 2, Northwest Advanced Renewables Alliance (NARA) Annual Meeting, Corvallis, OR. Sept. 10.

Chen, M. and P. Smith. 2013. Preliminary Market Opportunity for Biorefinery Co-Products (BioPlastics). Poster presentation at the Year 2, NARA Annual Meeting, Corvallis, OR. Sept. 10.

NARA OUTCOMES

No NARA outcomes were determined at the time of this report.

FUTURE DEVELOPMENT

The analysis of the primary data of integrated biofuels and biochemical production and strategic buyer-seller relationships in channels is in progress. The final report for these topics will be available in late September 2016.

Whereas the process described in this report may be applied to multiple emerging lignin-based products across a wide array of industrial applications, this work addresses a single lignin valorization market opportunity, lignin-based powdered activated carbon (PAC). Results may be considered as exploratory due to the relatively small population size of 64 electric generating power plants with usable contact information and a limited response of 17 surveys. The findings, however, may lay the groundwork for future work exploring market opportunities for other lignin-based products and in other business-to-business markets.

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