Chapter 6

Perceptions on Internal and External Factors Impacting the U.S. Nonfood Advanced Biofuel Industry

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/64611

Abstract

The goal of this chapter is to introduce and discuss internal and external barriers impacting the nonfood advanced biofuel industry in the United States. Since 2005 when the EPAct was created, 59 cellulosic biofuel projects have been attempted in the U.S. with little commercial success. An initial list of internal and external barriers was extracted from secondary sources using qualitative analysis techniques such as grounded theory. Once the list was validated, a survey was sent to the biofuel industry members to gain more knowledge and clarification on the initial list of barriers. Statistical analysis revealed differences in perceptions from industry members when barriers were compared by project status, technology, and type of project. In addition, barriers for marketing and distribution of advanced biofuel's coproducts and by-products were identified and ranked by industry members, academicians, and other stakeholders.

Keywords: biofuel, cellulosic biofuel, internal and external barriers, coproducts, by-products

1. Introduction

The development of an environmental bioeconomy is necessary in the U.S. to reduce fossil fuel energy dependency. The term energy is classified into three main categories: fossil, nuclear, and renewable. The main fossil fuels are petroleum, coal, natural gas, and nuclear material. They are currently nonrenewable and contribute to the accumulation of greenhouse gases (GHGs), one of the causes of climate change. Fossil fuels, namely, petroleum for transportation fuel, are being consumed at an increasing rate from diminishing finite reserves. One model estimates that, at the current usage rates, fossil fuel reserves of oil, coal, and gas will last approximately 35, 107, and 137 years, respectively [1]. Other researchers have estimated that fossil fuel depletion will occur between the years 2100 and 2200 [2].

There are three primary methods to create liquid advanced biofuel (AB) and its coproducts: direct microbial conversion (DMC-biochemical), simultaneous saccharification and fermentation (SSF-thermochemical), or a hybrid of these techniques [3]. These two main approaches are further broken down into six secondary options for developing cellulosic biofuel: (1) catalytic pyrolysis and hydrotreating to hydrocarbons; (2) gasification and Fischer-Tropsch synthesis to hydrocarbons; (3) gasification and methanol-to-gasoline synthesis; (4) dilute acid hydrolysis, fermentation to acetic acid, and chemical synthesis to ethanol; (5) enzymatic hydrolysis to ethanol; and (6) consolidated bioprocessing (single-step enzyme production, hydrolysis, and fermentation) to biofuel [3].

Liquid biofuel is one such renewable energy source. Biofuel is a fuel additive capable of increasing octane levels by blending it into the U.S. fuel supply, or can be used as a fuel in internal combustion engines [4]. The total renewable biofuel sector is currently diversified into first (1G)-, second (2G)-, and third (3G)-generation lignocellulosic biomass forms of energy. For example, 1G is derived from corn and sugarcane, 2G advanced biofuel is derived from wood, grasses, municipal wastes, and crop residues, and 3G is derived from algae. Biomass is considered as living or nonliving agricultural vegetation such as wood and grass crops. In this case, biomass is typically differentiated by dedicated wood and grass energy crops, and unmerchantable timber and forest waste. Lignocellulosic feedstock's price currently ranges from $50 to 80/ton of biomass [5]. These feedstocks could be from unmerchantable timber, forest thinnings (slash), sawdust, waste paper, mill residues, paper mill sludge, grasses, and grass variety residues. All biomass feedstock differs in moisture content and may have different costs. Dedicated energy crops are considered for energy use only. In this study, dedicated energy crops are categorized and differentiated as herbaceous crops (grasses) and wood-based crops. Herbaceous grass crops are harvested annually, with only the roots surviving the nongrowth cold seasons (e.g., switchgrass, *Miscanthus*). Wood-based crops, including fast-growing trees such as poplar, are harvested on a 3- to 12-year rotation cycle; harvest rotation cycles for slower growing trees may be as long as 25 years.

For this study, nonfood lignocellulosic biomass consisted specifically of biomass from wood and from grass varieties for the current purpose of substituting fossil petroleum-based fuels with renewable biofuel. Advanced biofuel is a contemporary liquid fuel for transportation produced primarily from cellulose and hemicellulose of renewable lignocellulosic biomass. It is derived from lignocellulose, which consists of three major components: cellulose, hemicellulose, and lignin. The cellulose and hemicellulose portions are the desired components for producing the highest value-added biofuel coproducts. Lignocellulosic biofuel currently has the greatest potential for energy, being the most abundant and rapidly renewable resource produced by photosynthesis [6]. The lignin portion typically becomes a process by-product, but recently was considered a coproduct when blended as filler for wood products.

This study presents results on an investigation conducted between 2014 and 2016 related to the status of AB projects in the U.S. market. It was found that the majority of AB projects never achieved a commercialization stage. Therefore, the research team was interested in learning more about the barriers and factors that have prevented the AB industry to reach commercial state, including impact not only on the AB production itself but also in coproducts and by-products of the AB industry.

2. Factors affecting the advanced biofuel industry

2.1. Biofuel policy

There are a multitude of government policies using a push-type strategy to bring the bioeconomy technology to the marketplace. The Environmental Protection Agency (EPA), U.S. Department of Agriculture (USDA), Energy Information Administration (EIA), Department of Energy (DOE), and Department of Defense (DOD) have jointly developed these policies to drive the bioeconomy. According to Reidy [7], the major goals and policy incentive's objectives driving the bioeconomy marketplace are the following:

1. **To reduce GHG emissions and sequester carbon**
   - Advanced carbon capture and storage (DOE Grants for R+D)
   - Federal Transit Administration (FTA) investments in GHG and energy reduction (Tigger) (DOT Grants)
2. **To achieve greater energy efficiency**
   - Efficient clean fossil energy systems (DOE Grants)
   - Integrated biorefineries grants program (DOE Grants)
   - Advanced marine and hydrokinetic grant program (DOE Grants)
   - Clean energy fund (DOE Grants)
   - Clean diesel grant program (EPA Grants)
3. **To integrate rural programs into efforts to increase energy security**
   - Transportation fuel and biofuels: Rural Energy for America Program (REAP)
4. **To stimulate economic growth and development**
   - Federal Transit Administration (FTA) Clean Fuels (DOT Grants)
5. **To obtain economically feasible conversion technologies**
   - Clean coal-to-liquid or gaseous fuel technologies grant program (NSF Grants)

Six main policies were created in the United States to bolster, develop, and implement the four incentives driving the bioeconomy. Sequentially, they are: (1) Clean Air Act 1970—through current amendments [8], (2) Energy Policy Act of 2005 (EPAct) [9, 10], (3) Advanced Energy Initiative 2006 [11], (4) Renewable Fuels Standards (RFS) of Energy Independence and Security Act of 2007 (EISA) [12–14]), (5) California Low Carbon Fuel Standard (LCFS) [15], and (6) Food, Conservation, and Energy Act of 2008 [16].

As of 2015, there were six policies driving the inception of advanced biofuels, and EISA carried the most focus toward developing biofuel projects while removing market share from the fossil industry. There are a host of incentives for industry development of advanced biofuels (AB), such as the 2005 EPAct creating the Renewable Fuel Standard, and its modification with 2007 EISA, and new components of RFS2: Renewable Volume Obligations (RVO), Renewable Identification Number (RIN), and Code of Federal Regulations (CFR). These policies provided production tax credits and research and development (R+D) funding to promote the RFS concept of replacing 35 billion gallons of fossil fuel with drop-in biofuel blends. The policy subsidies and incentives were the drivers leading to advanced biofuel (AB) project attempts from 2005 to 2015.

Biofuel projects are divided into three generations by feedstock type: first generation is ethanol —corn and sugarcane; second generation (2G) is advanced biofuel—wood, grass, and crop residues; and third generation (3G) is algae and butanol. Those feedstocks are in the $50–80 p/ton range. This chapter is focused on 2G wood and grass advanced biofuel. Wood and grass feedstock (lignocellulose) is typically separated by its major components in order of value: cellulose, hemicellulose, and lignin.

2.2. Advanced biofuel project status

The U.S. total renewable biofuels (TRFs) projects are classified as pilot with costs ranging $9 million or less, demonstration project costs ranging $100 million or less, or commercial projects costs ranging $100–500 million [17–19]. These three project types are further divided into five operational status categories: cancelled, shutdown, under construction, planning, and operating. Cancelled projects are considered terminal. Shutdown projects were stopped and put on hold, but potentially could be restarted at a later time. Under construction projects are currently being built, and planning projects are in the research and development phase, prior to construction. For operating projects, construction was completed and attempts at biofuel production have begun. References [18] and [19] provided the only accessible publication covering a large portion of wood-based biofuel projects, separated by location, type, and status, from their Forisk-Wood Bioenergy U.S. (WBUS) database. They indicated 36 cancelled projects, 4 shutdown projects, and 12 projects in planning or construction stages, stating that 75% have failed to advance [18, 19].

Currently, few advanced biofuel projects are producing biofuel, with none reaching sustainable commercial production economies of scale where biofuel project size to produce commercial-level biofuel was greater than costs. Some documents in the literature identified barriers, but the authors only focused on broad categories. The most inclusive documents provided a partial list of wood-based biofuel projects by type and status [18, 19]. In examining literature on barriers to advanced biofuel projects, the following 10 main barriers were determined: (1) high capital risks, (2) Organization of the Petroleum Exporting Countries

http://dx.doi.org/10.5772/64611

(OPEC)-based price distortions, (3) constrained blending markets, (4) policy fluctuations, (5) financing, (6) production costs, (7) global financial situation, (8) economic hurdles, (9) efficiency, effectiveness, and scaling technology, and (10) too many technology paths.

2.3. Factors impacting the advanced biofuel industry

Prior to 2005 EPAct, the corn ethanol industry was preestablished to close in 40 years, moving away from utilizing government subsidizes and close to achieving commercial production economies of scale. This subsidized preestablishment was the first barrier to advanced biofuel and 3G biofuel technologies. The EPAct led to a second barrier: different subsidy and expectation levels among the renewable fuel types. The EPAct created the RFS that forced the fossil fuel industry to relinquish approximately 10% yearly of the production output over the next 17 years until 2022. This created another barrier: a line drawn in the sand between OPEC-backed fossil fuel companies and government support of the emerging bioeconomy. Additionally, methyl tertiary butyl ether (MTBE) was increasingly being banned for environmental and health-related concerns, but fossil fuel companies needed the MTBE to increase the octane content of diesel and gasoline. MTBE was able to be transported in fossil fuel's current infrastructure, but biofuel has to be transported separately to the refinery and was more expensive. This was a third blow to the fossil fuel industry: reduction of their monopoly with market share percentage loss over time, MTBE could become banned with potential lawsuits, and unable to maximize delivery economies of scale without expensive upgrades to infrastructure for ethanol. These led to initial fossil infrastructure upgrades and supporting biofuel as a lubricant and octane enhancer with the 2005 EPAct.

The 2007 Energy Independence and Security Act and its modified RFS (EISA-RFS2) brought more specificity, policy incentive type drivers, and, subsequently, more barriers. The fossil fuel industry opposed the new RFS-2 and, to date, mounts continual media attacks to repeal the RFS. By 2007, the steady decline of fossil fuel consumption should have triggered more concern with the near-term potential for constrained blending markets. In 2012, the blend wall arrived; the advanced biofuel projects saturated market demand, with nowhere to put their fuel for blending above their mandate since D6 (RIN code for renewable fuel based on corn ethanol) by itself was filling more fuel capacity than available. The blend wall led to the next major barrier: political involvement in an attempt to create demand. The government was forced to balance the fallout of subsidizing and building an industry with diminishing room to put their products as they strive to meet mandated production economies of scale.

Lack of infrastructure and lack of factual knowledge are the main barriers to the public not having enough flex fuel vehicles and ethanol pumps to maintain low gas prices. The main barrier to all groups is time. Transportation fuel stations are willing to upgrade infrastructure [20] when the vehicles have upgraded technology. Republicans will not budge until the demand increases. Democrats cannot increase the infrastructure demand until they have control of the House and Senate. The vehicle demand will not increase until the vehicle infrastructure for higher blends is affordable. Advanced biofuel projects will have to receive subsidies until that happens. The public would not support another tax (i.e., carbon tax), while petroleum and gas prices are low [21]. Therefore, time is the overarching barrier with certainty, in an uncertain climate.

The knowledge gaps from the broad barrier categories are not precise enough to fully aid in developing an industry. Furthermore, 75% of AB projects have been lost since inception [18, 19]. No articles were found analyzing if AB location, status, or technology type was a barrier. The Renewable Fuel Standard (RFS) appears to work for some and not for others. Examining the barriers across multiple bioeconomy groups, such as academia, government, biofuel publishers, advanced biofuel projects, and the remainder of the bioeconomy, was pivotal to determine a progression of barriers and how the level of understanding changes when moving outwards from the proprietary inner workings of companies to the broader bioeconomy. No consolidated lists were found of coproducts and by-products from 2G AB companies. The focus was mainly placed on their funding and technology issues, as if they are not utilizing their secondary products.

Therefore, this study was deemed necessary due to the perceived advanced biofuel investment risk, investment potential in the bioeconomy, infrastructure need, and 75% loss of projects in less than 8 years. Additionally, a simplified understanding of internal and external barriers across and within industry stakeholders groups and market and distribution barriers of their products was needed to drive faster return on investment from reducing risk, as conditioned bioeconomy reinforcement. Determination of these knowledge gaps in a singular document will more quickly aid in bioeconomy collaboration maximizing the RFS-2 potential.

3. Methods

This research was conducted in two phases. Phase one identified all wood and grass (nonfood) AB projects that have been attempted by their status, location, feedstock, and technology type in the U.S. During phase two, a survey was conducted requesting industry members to rank internal and external barriers for the AB industry. In addition, industry members, academicians, government representatives, and other stakeholders were also asked to rank marketability and distribution barriers of biofuel's coproducts and by-products. After compiling survey responses, interviews with a selected group of industry members were conducted to discuss and gain more insights on the specific barriers.

The geographical location, operational status, and demographics information for each project were determined by examining secondary sources of information such as technical reports, peer-reviewed papers, trade journals, and newspapers. These were based on the biofuel industry terminology used in the Wood Bioenergy U.S. database according to Forisk Consulting [22] along with acquired secondary sourced data from the literature review. The data were used to individually classify and code categories directly associated with advanced biofuel projects as follows: type (pilot, demonstration, and commercial), operational status (cancelled, shutdown, operating, planning, and under construction), demographic (project, name, and location), feedstock type used, and contact information.

http://dx.doi.org/10.5772/64611

Grounded theory was used to examine peer-reviewed papers, industry reports, technical reports, trade journals, and newspapers to detect barriers impacting the AB industry. The goal of the grounded theory analytical technique is to classify and categorize information based on higher level categories. The technique starts with an initial open coding involving labeling, data segmentation, conceptualizing, and developing categories. Higher level grouping and categorization includes axial coding to analyze the most significant and frequent data from the initial coding, thus relating categories to subcategories [23]. Following the extraction of barriers, a list of the most common by-products, and coproducts were also extracted from secondary sources.

The outputs of grounded theory (list of barriers) were used to design a questionnaire to have biofuel industry members provide their perceptions on the list of barriers impacting the AB industry separated by internal, external, and marketing and distribution of coproducts and by-products. In addition, discussions with a sample of the biofuel industry experts were conducted to clarify survey results and gain additional insights. Industry members were chosen by direct requests from the projects identified in the first phase. The survey included Likert-type questions, open-ended questions, and close-ended questions. The Likert-scale questions were developed for nine different constructs that were identified during the literature review. A scale from 1 to 5 was used, where 1 was strongly disagree and 5 was strongly agree.

4. Results

4.1. Project status

A total of 59 AB projects were identified and classified by project status (**Figure 1**). The geographical distribution visually indicated that there was a relationship by region and project status for the Eastern part of the U.S. and in Mississippi. The geographic location analysis indicated that most of the advanced biofuel projects are located in the Eastern region, but the proportion rates of projects when comparing the Eastern and the Western regions does not show any significant difference between regions. Mississippi seems to have state policies designed to attract the industry. Other projects seem to be uniformly scattered in the Eastern region. In total, 19 projects were cancelled or shutdown. Of the 59 projects started since 2007, only 13 are operating in 2015.

A contingency table analysis indicated that the majority of projects have been started in the Eastern region ($n = 41$, 82%). Given that there could be a relationship between the regions and the status of projects, a test was conducted to test if the proportion of status of projects was the same for both regions. The results of the Chi-square test indicated that there was no significant relationship between regions and status of projects ($p = 0.3260$).

There are five stages of technology development for advanced biofuel projects (**Figure 2**). Each stage is representative of the feasibility of planning, financial constraints, proving conceptual design, and intellectual rights. Finally, repeat the success. The average pilot plant typically costs $10 million or less, the average demonstration plant cost is less than $100 million, and a commercial plant cost varies from $100 to $500 million. **Figure 2** shows the number of individual projects by technology status achieved from 2005 to current.

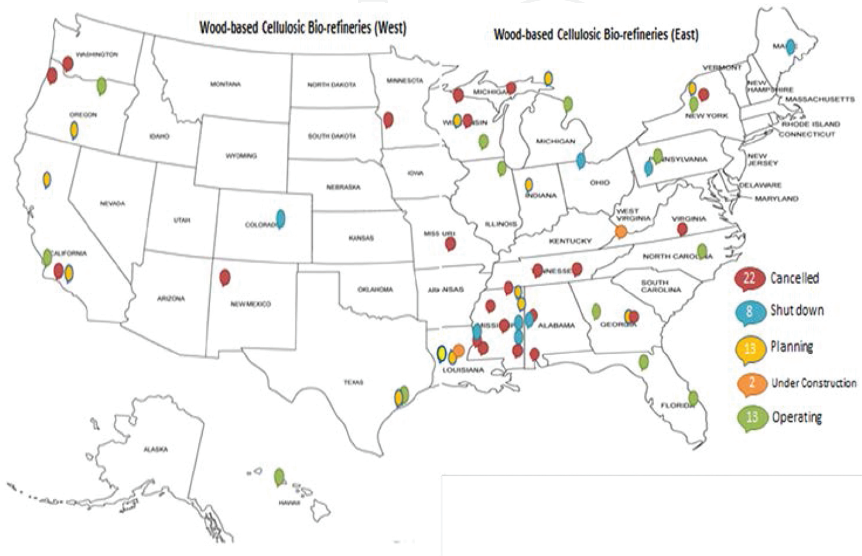

Figure 1. Map of all advanced biofuel projects since 2005 (Withers [23]).

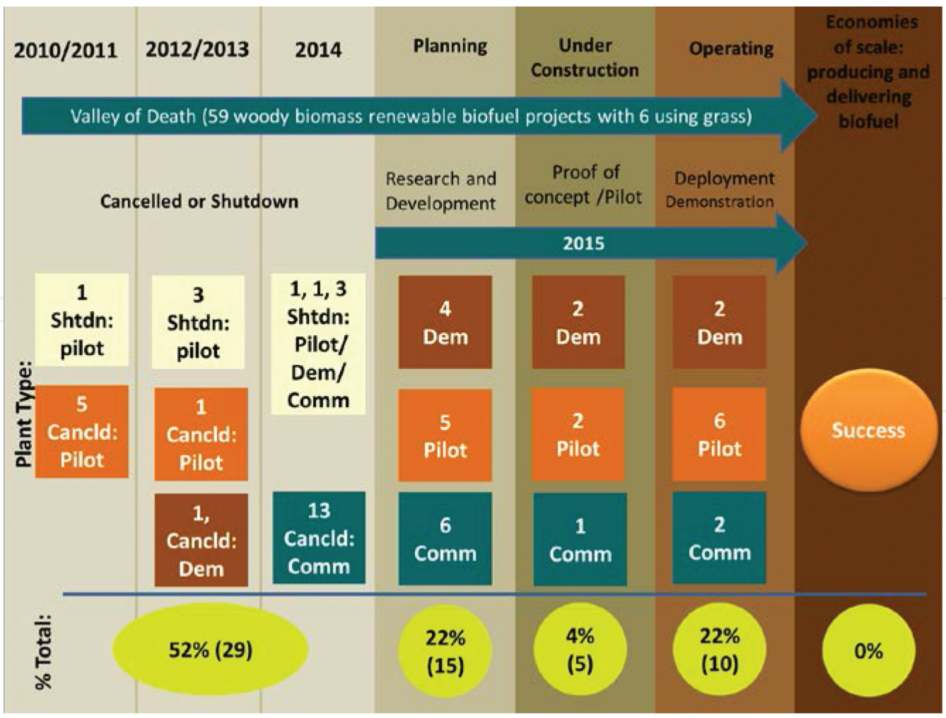

Figure 2. Project stages of technology development and percentage status where Shtdn = shutdown, Cancld = canceled, Dem = demonstration, and Comm = commercial (Withers 2016 [23]).

4.2. Perception of industry members on internal and external barriers

4.2.1. Internal barriers

A total of 16 industry members participated in the initial survey. Participants generally agreed that internal barriers include technology yield per ton (56%), technology conversion (50%), and lack of continuous project growth (44%). Participants did not view the following categories as barriers: coproducts marketing (69%), coproducts distribution (56%), by-products marketing (63%), by-products distribution (63%), strategy (56%), management (50%), and product development (44%).

Table 1 shows the median responses on internal barriers by project type, project status, and project technology. All participants had to indicate project type, project status, and technology type. Each of these categories was further divided in subcategories as shown in **Table 1**. Responses across project status are very similar and do not show a clear distinction between the subcategories. In the case of the category project type, it seems that industry members classified as pilot have a higher perception on barriers than the ones identified as open and closed. Also, in the technology type category, industry members classified as biochemical seem to have a stronger perception of internal barriers than the other technology types.

Median	TYPE			STATUS		TECHNOLOGY			
INTERNAL BARRIERS	Commercial	Demonstration	Pilot	Closed	Open	Planning	Biochemical	Hybrid	Thermochemical
Product development	2	2.5	4	2.5	3.5	2.5	4	3	2
Byproducts marketing	2	2	3	2.5	2	2	4	3	2
Byproducts distribution	2	2.5	3	2.5	2	2	4	2	2
Co-products marketing	2	2	3	2.5	2	2	4	2	2
Co-products distribution	2	2.5	3	2.5	2.5	2	4	2	2
Continuous project growth	3	3.5	4	3.5	3.5	3	4.5	3	3
Management	2	2.5	3	2	2.5	2.5	2.5	3	2
Strategy	2	2.5	4	3	2.5	2	3.5	2	2
Technology conversion rate	2	3.5	4	4	3.5	2.5	4	2	4
Technology high titer and yield per ton	3	3.5	4	4	3.5	3.5	4	4	4

Table 1. Median values of internal barriers by type, status, and technology.

A contingency analysis was conducted to compare the differences within each category or group. It was found that there were no differences within type (commercial, demonstration, and pilot) and status (closed, open, and planning). However, the contingency analysis by the technology group (biochemical, hybrid, and thermochemical) yielded a significant difference on internal barriers by-products distribution and coproducts marketing on the biochemical technology type. Given that the number of counts by cells was less than five in some cases, a Fisher's exact test was then performed on these categories; the Fisher's test determined that by-products distribution (p = 0.074) and coproducts marketing (p = 0.028) were significant barriers for a significance level of 0.1.

4.2.2. External barriers

In the case of external barriers, biofuel industry members agreed that funding (100%), renewable volume obligation (75%), EPA pathway process (75%), and RFS and RINs (56%) were external barriers. Noticeable uncertainty was placed in DOE pathway process and waiver credits. The categories of competitors, energy costs, suppliers, and third-party relationships yielded fairly similar disagreement.

The sample was also divided in categories, similar to the internal barriers analysis. The median responses on external barriers by project type, project status, and technology type were also examined (**Table 2**). Overall, the data show that industry members in all categories have a higher perception of external barriers than internal barriers. A contingency analysis was performed to compare the subcategories by project type, project status, and technology type to determine if the differences within each subcategory were significant. It was found that there were no differences in the category project status (closed, open, and planning are the same) on the perception of barriers. However, significant differences were found in the project type and technology type categories. By project type, differences were found on the perception of barriers competitors (demonstration and pilot different than commercial) and energy costs (pilot different than commercial and demonstration). And differences were found on the perceptions of barriers competitors (biochemical is different), energy costs (biochemical and hybrid different), and third-party relationships (biochemical is different to the other two). In all cases, an exact Fisher's test was conducted with a significance level of 0.1.

4.3. Marketability and distribution barriers for coproducts and by-products from advanced biofuel industries

In this part of the study, a ranking and classification of barriers impacting the marketability and distribution of lignocellulosic biofuel's coproducts and by-products were conducted. Coproducts and by-products are an important component of the AB industry business model. Without the proper marketing and commercialization strategies, coproducts and by-products cannot be commercialized. As it is today, AB industry needs to have revenue from its coproducts and by-products in order to remain competitive.

The advanced biofuel production process yields by-products and further processing generates subsequent coproducts. The list showed in **Table 3** was obtained through research from secondary sources. Combining or improving by-products can lead to desired coproducts. Unused by-products increase expenses [25], since they require disposal; as a result, increasing the value from by-products and coproducts could help sustain a biofuel project [26]. Vivekanandhan [26] suggests that many of the biofuel industry small-scale projects do not generally collect coproducts due to high opex (ongoing) costs foregoing added profit potential, while the opposite is true for commercial scale projects. The coproducts and by-products are more valuable to reduce energy costs when burned for biofuel projects are placed in landfill as waste [28]. Therefore, understanding harmful by-product waste streams is economically and environmentally beneficial when planning scaling projects to reduce harmful impact [25, 29]. According to Doherty et al. [29] and Gellerstedt et al. [30] providing value-added coproducts may lead to improved biorefinery financial success, and some coproducts could actually be more valuable than the biofuel itself [25].

Median	TYPE			STATUS			TECHNOLOGY		
EXTERNAL BARRIERS	Commercial	Demonstration	Pilot	Closed	Open	Planning	Biochemical	Hybrid	Thermochemical
Competitors	2	3	3	2	2	2	4.5	1	2
Funding	5	5	5	5	5	5	5	5	5
Suppliers	2	2.5	4	2	3	2.5	4	3	2
DOE pathway process	3	4	4	4.5	3.5	3	4	3	4
EPA pathway process	4	5	4	3.5	4.5	4.5	5	4	4
USDA pathway processes	4	3.5	4	4	3.5	3.5	4	3	4
Production tax credits	4	4	4	3.5	4	3.5	4	4	4
Renewable fuel policy standards	3	5	4	3	4	5	5	2	5
Waiver credits	3	4	4	3.5	3.5	4	4.5	4	4
Renewable volume obligation	5	5	4	3.5	5	5	5	4	5
Renewable identification numbers	3	4.5	5	3.5	4	4	5	2	4
Energy costs	2	2	5	4	4	2	3.5	4	2
3rd party relationships	3	3	3	3.5	2.5	3	4	3	2

Table 2. External median quantiles by type, status, and technology.

Product	Source	Process	Market	Examples of producing companies
		Gases and fuels		
Syngas	Biomass of lignin	Gasification	Production of ethanol, methanol, dimethyl ether, olefins, propanol and butanol [25, 34–36]	
Hydrogen	Lignin	Gasification	Fuel cells, industrial uses [25]	
Carbon dioxide	Sugars	Fermentation	Industrial uses, beverage, dry ice [25]	Lanza Tech
Carbon monoxide				Lanza Tech
Synthetic gasoline and diesel		Biochemical/ thermochemical/ hybrid	Liquid fuels	Joule, Sundrop, Envergent, Abengoa, Fiberight, Ensyn

Product	Source	Process	Market	Examples of producing companies
Jet fuel		Biochemical/ thermochemical/ hybrid		Envergent, Frontline, GEVO, Fulcrum, Byogy, Vertimass, Virent, Lanza Tech
Methane		Biochemical		Enerkem, Intrexon, Calysta, Siluria, Oberon, Kiverdi, Mango materials, Industrial microbes
Lignin	Lignin	Hydrolysis	Fuel for heat and electricity, fertilizer, wood adhesive, color additive, reinforcing filler, animal feed, yeast production [25, 37, 27]	Renmatix
Naphtha		Distillation	Fuel source solvent	Joule
		Organic acids		
Succinic acid	Glucose	Fermentation in high CO_2	Food additive, plasticism surfactants, detergents, solvents, textiles, and pharmaceuticals [29]	Myriant, Riverdia, BioAmber, Novozymes, DSM
Lactic acid polylactic acid	Glucose	Fermentation	Food and beverages, textiles [25]	Invista, Plaxica, Lanza Tech, IOC, Nature Works, Calysta, Direvo, Purac, Leaf Technologies, Myriant
Acetic acid	Glucose	Fermentation	Food additive and industrial chemicals, resins, and alcohols [25]	Zeachem, American Process
Fumaric acid	Glucose	Fermentation	Food additive, production of resins and alcohols [25]	Novozymes, Myriant
Oleic acid				
Acrylic acid				Myriant
Adipic acid				Renovia, Verdezyne
Levulinic acid				GFB Biochemical, Mercurious
		Alcohols		
n-buterol	Glucose	Fermentation	Liquid fuel, food additive, solvent [25]	
Xylitol	Xylose	Hydrogenation	Sweetener [25]	ZuChem, Xylitol, Taurus

http://dx.doi.org/10.5772/64611

Product	Source	Process	Market	Examples of producing companies
Sorbitol				joule
Arabinitol				
Aromatic compounds				
Xylose, arabinose		Dehydration	Solvent, pesticides, resins, liquid fuel [25]	Taurus, DuPont
Benzene, toluene, xylene	Lignin	Catalysis	Solvents, pesticides, resins, liquid fuel [25]	Virent, GEVO, Avantium
Olefins		Pyrolysis	Production of polyethylene [25]	SABIC, Byogy, INEOS
Biobenzene		Catalytic	Food and beverage packaging, textiles, automobiles, detergents, construction materials, and paints and coatings [38]	Virent, Anellotech's
Macromolecules				
Cellulose nanofibers	Cellulose	Chemical-mech treatment	Structural composites, plastics, films [25]	
Polyhydroxyalkanoate	Lignin	Fermentation	Biodegradable plastic use in films, packaging, fibers, coatings, foams, and medical [25]	
Lignosulfonates	Lignin	Sulfonation	Dispersants, emulsifiers, binders, sequestrants, adhesives, fillers, dust prevention [25]	
Carbon fiber	Lignin	Melt spinning	Reinforcement for automotive plastics [25]	BETO
High purity lignin	Lignin		Coatings, emulsifiers, gels, antimicrobial products [25]	
Other products				
Cellulose nanofibers	Cellulose	Hydrolysis	Animal feed [25]	
Protein	Protein		Animal feed [25]	Cargill, Calysta, Valicor
Biochar	Lignin	Combustion	Fuel, soil additive and carbon sequestration [25]	Cool planet, Mercurious
Betulinol	Forest residues		Antioxidant [29]	
Propanediol (PDO)	Sugars	Fermentation	Deicing fluids, engine coolants, heat transfer fluids, polyurethanes, solar thermal,	DuPont, Joule

Product	Source	Process	Market	Examples of producing companies
			unsaturated polyester resins, [39]	
Butanediol, biobutadiene	Dextrose or sucrose	Fermentation	Plastics, solvents, electronic chemicals, and elastic fibers [40]	Joule, Myriant, Genomatica
N butanol	Sugars	Fermentation	solvents, glycol ethers, acetate, acrylate [41]	Green Biologics, DuPont, GEVO
Polyethylene terephthalate (PET)	Isobutanol	biochemical	Films and bottles for packaging, fibers for nonwovens, textiles, automotive resin.	Anellotech's, GEVO, Joule
Farnesene	plant sugars	Fermentation	Solvents, emollients, vitamins [42]	Amyris, Intrexon, Chromatin
Polyamides	Syngas	Fermentation	Precursor for specialty plastics [43]	Arkema, Avantium, Genomatica, DuPont, Terryl
5c and 6c sugars				GeoSyn fuels, Sweetwater Energy, Kakira, San Martinho, Cascades, Buriram, Applied Biorefinery
Omega 3's and 7's				Solarvest, Nature Works, Lanza Tech, IOC, Calysta, KD-Pharma, BioProcess Algae, Cellana
		Waxes		
Furfural	Pentose and hexoses	Hydrolysis	Food additive in vanilla, resins [44, 45]	Chempolis, DuPont, Glucan Biorenewables, Mercurious
Suberin	Forest residues		Fatty acid [29]	

Table 3. List of potential coproducts and by-products from AB industry.

Many initial biofuel projects as in early in 2005, did not focus on these secondary products, but instead focused on more pressing technology and funding issues. Forty-two percent of all projects included in this study are pilot and demonstration plants designed for testing purposes, with reduced focus on secondary outputs. The commercial facilities are realizing

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the value of their coproducts and are restrategizing. For example, Virent Biogasoline, a commercial biofuel company impacted by the blend wall, changed its website to list available quantities of various coproducts they produce. Discussing survey results with the industry indicated there are at least 44 coproducts produced, nearly twice the number identified from the literature. This increase was based on companies currently stymied by blend-wall limitations that reduce demand to fund production economies of scale. These limitations drive stakeholders to consider new markets beyond biofuel to meet shareholder financial expectations. Advanced biofuel companies are currently focused on shifting to platform technologies, targeting higher value coproducts and the available funding arena [32, 33].

In addition to the perception of AB industry members, perceptions of other AB industry stakeholders such as academicians, government representatives, and journalists are included to rank AB's barriers for by-product and coproducts. Altogether, a total of 44 responses were obtained from all stakeholders. Out of the 44 responses, 28 respondents provided usable data to this section, identifying barriers to coproduct marketability (N = 27) and distribution (N = 28), as well as by-product marketability (N = 28) and distribution (N = 22), see **Tables 4** and **5**. Cost, financing, and public awareness were the main barriers across the four classifications. There are many similarities of response between the four categories of coproducts and by-products marketability and distribution barriers, such as infrastructure, fossil industry control, public perception, and policy. Some responses are very similar to the internal and external barriers analyzed in the previous section; however, many are unique to this study, such as sole source risk, heated rail car shortage, and flooding a niche market.

The perceived need of coproducts and by-products' infrastructure to support the already subsidized industry was not expected. Nor did the industry expect to be stymied by the blend wall, the fossil fuel industry buying cellulosic waiver credits (CWCs) and lobbying against them, politics, or a slowly developing infrastructure. It would seem the advanced biofuel industry initially did not examine the end-user market demand and capabilities for additional by-products and coproducts. The survey results indicated that by-product and coproducts infrastructure are a niche market and saturated in the short term, since the industry was already shifting toward platform technologies. According to, there was a 9% growth in premium renewable biochemicals in 2015, which implies that the shift to platform technology would potentially become a barrier, as well, in a niche market. Reidy [32] stated the industry is moving to produce and sell premium products. Selling premium products would imply the niche market barrier may only affect those in competition with advanced biofuels that already produce nonrenewable premium chemicals, such as the fossil fuel industry. The shift in this industry to compete at a multiproduct platform level other than biofuel in new markets was an attempt to avoid sole source risk and maximize by-products potential and funding. Rural economic development was one of the three primary objectives established by the government. The survey results indicated that some projects face lack of heated distribution channels from declining rural rail systems. In the short term, premium coproducts, such as waxes, will have to be developed to offset the cost of changing perceived risk to increase demand for the revitalization of the heated rural rail infrastructure.

Coproducts marketability		Coproducts distribution	
Main barrier	**Secondary barrier**	**Main barrier**	**Secondary barrier**
Biointegrity of supply chain	Access to capital	Competition and distribution restriction	Access to capital
Consumer awareness of larger societal benefits	Available volume	Cost	Available volume
Cost	Lack of benefit to producers	Financial support	Competition
Finding high credit-worthy third party for off-take	Limited market and competition from non-renewable sources	Flooding a niche market	Consumer demand
GMO	Not being focused	GMO isolation	Controlled by oil companies
Government uncertainty	Obligated parties	Government uncertainty	Misinformation about the need for the industry as a whole
I did not know that enough co-products produced to be impeded	Perception of cost and efficacy	Immature supply chain infrastructure	Obligated parties
Lack of clear end user demand	Poor policy	Lack of clear end user demand	Product purity
Lack of incentives	Public ignorance	Limited volume	Requires heated tankers or rail cars for shipment
Low identified uses	Quality	Market fragmentation	Small markets
Oversupply	Separation of water	No infrastructure	Market fragmentation
Process economics	Sole source risk	Oil industry	
Public awareness		Poor policy	
Public perception		Requires additional fractionation—no local fractionators	
Quality of F-T wax for use as a wax		Scale match or biointegrity of chemicals	
Specifications		Unavailability	
Technology		Unclear markets breeds unclear distribution channels	

Table 4. Coproducts marketability and distribution barriers.

By-products marketability		By-products distribution	
Main barrier	**Secondary barrier**	**Main barrier**	**Secondary barrier**
Cost	Conditioning and transportation to markets	Controlled by oil companies	Consumer demand
Financing	Controlled by oil companies	Cost	Lack of balance sheets
GMO	Distance to market	Financing	Lack of benefit to producers

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By-products marketability		By-products distribution	
Main barrier	**Secondary barrier**	**Main barrier**	**Secondary barrier**
High value product development	Investment	Flooding a niche market	Lack of product knowledge by customers
I did not know that enough by-products produced to be impeded	Lack of balance sheets	GMO isolation	Lack of true public education
Lack of awareness among public	Lack of benefit to producers	Lack of awareness among public	Low volume
Lack of clear end user demand	Limited markets	Logistics	Unfamiliarity
Lack of incentives	No perceived need	Market demand	
Low identified uses	Not being Focused	Marketing	
Low volume	Poor Policy	No infrastructure	
Low value wood ash		No local markets for ash	
No infrastructure		Oil industry	
Oversupply		Production technology	
Price		Transport cost	
Quality		Unclear markets breeds unclear distribution channels	
Specifications			
Technology			
Value proposition			

Table 5. By-products marketability and distribution barriers.

5. Conclusions

The barrier analysis indicated the perspectives on barriers to production of advanced biofuel are different by project type, status, and technology. The barrier impact changed across time and type of project. The closed projects faced the same barriers; however, fewer barriers than the current projects now that the blend wall is a permanent factor. Discussions with bioeconomy industry representatives about the implications of the blend wall led to an improved RFS model and improved understanding of the system.

Overall, timing is the main barrier to advanced biofuel projects. If the decline in fuel consumption was realized by all parties, the advanced biofuel group may not currently exist. However, the outcome of timing has created the realization that the remaining advanced biofuel projects are now rapidly moving to become advanced biochemical platform technology companies, quickly and annually claiming market share of global premium coproducts. They are well poised to either blend higher levels of biofuel and/or premium coproducts, dependent upon the full spectrum of petroleum barrel price and demand. Additionally, they are unifying their efforts to become a household lifestyle premium brand. Will the petroleum industry realize its marketing myopia and grow with the bioeconomy global brand, or will it inadvertently continue as the increasingly undesired environmentally unfriendly brand? A review of the literature did not distinguish any lists of barriers to the marketability and distribution of coproducts and by-products. However, through the survey and interviews in this study, an extensive list of barriers was developed, including 27 coproducts marketability and 28 coproducts distribution barriers, and 28 by-products marketability and 22 by-products distribution barriers. The main barriers were cost, funding, fossil industry control of market, and public awareness

To move the bioeconomy forward faster, developing an incremental greenhouse gas (GHG) carbon tax is needed on an incremental level to fund the developing infrastructure, public education, and factual perception to bolster the demand for biofuel and biochemicals. The funding is privately earmarked, ready, and in bearish stance, awaiting public demand. The information compiled in this study can aid the biofuel industry and the bioeconomy in future pursuits; it can provide guidance to inform R+D to reduce costs and improve perceived risk, increasing investment viability.

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