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U.S. Biofuels Industry: A Critical Review of Opportunities and Challenges

BIOPRODUCTS
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Abstract

Due to climate change concerns, governments and consumers are demanding higher environmental accountability for transportation fuels, particularly as related to carbon emissions. Additionally, the U.S. policymakers are seeking renewable alternatives to enhance energy security, reduce oil price volatility and increase rural economic development opportunities. Such factors present an emerging market opportunity for lignocellulosic materials to be used as biofuels. But this oppiortunity also has a number of associated challenges, particularly in terms of scaling up. This paper offers a comprehensive review of the emerging biofuels sector in the U.S. It begins with first generation corn-grain ethanol and biodiesel, today's most widely available biofuels within the U.S. The paper argues that further growth of these biofuels may be limited by the "blend wall", the "food-versus-fuel" debate, and land use change inssues. As a result, industrial, governmental and academic research interests have shifted to second and third generation biofuels produced from lignocellulosic biomass and algae to address GHG emissions, land use change, and the food-fuel issue. We outline that there are several limitations in scaling-up these hydrocarbon drop-in biofuels which include feedstock costs and availability, high production and capital costs, policy uncertainty, and various technical, environmental and social issues. Overall, this paper synthesizes the extant literature and draws on secondary sources to present a comprehensive and current inventory of existing U.S. biofuel players and a thorough review of the U.S. biofuels industry.

Keywords: biofuels, blend wall, food vs. fuel, renewable fuel standard (RFS), low carbon fuel standard (LCFS)

1.0 Introduction

Over the past century, the success of personal transportation in the form of automobiles powered by internal combustion engines has driven the worldwide success of oil (Brancheau, Wharton, & Kamalov, n.d.). In turn, the historical growth of the petroleum industry has led to these hydrocarbons supplying not only a bulk of the world's energy needs but also a vast majority of the building blocks for chemicals and materials. But according to the Energy Information Administration's (EIA) 2014 International Energy Outlook and Annual Energy Outlook 2015, liquid fuel supplies are uncertain beyond the year 2040 due to a variety of "above-ground" geopolitical issues leading to average oil price volatility of 30 percent per year over the past two decades (Energy Information Administration, 2014, 2015).

These supply and demand issues are exacerbated by the emission of greenhouse gases (GHGs) from the combustion of fossil fuels and the associated climate change effects. Fossil fuel recovery and use also introduces an array of other environmental issues, such as air and water pollution. To combat climate change, in March 2015, the U.S. submitted an Intended Nationally Determined Contribution (INDC) to the United Nations Framework Convention on Climate Change to cut net GHG emissions by 26-28 percent below 2005 levels by 2025 (The White House, 2015b). At the subsequent Paris climate conference (COP21) in November and December 2015, approximately 200 countries adopted the universal global climate deal to avoid dangerous climate

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change by limiting global warming to well below 2°C (European Commission, 2015). According to the 2016 Federal Activities Report on the Bioeconomy released on February 2016, the Biomass R&D Technical Advisory Committee has recommended "targeting a potential 30% penetration of biomass carbon into the U.S. transportation market by 2030" (The Biomass Research and Development (R&D) Board, 2016). And, in January 2016, the White House and Environmental Protection Agency (EPA) released the final Clean Power Plan to reduce carbon dioxide emissions by 32 percent from 2005 levels by 2030 (The White House, 2015a). Additional mechanisms to curb U.S. fossil fuel emissions include the 1970 Clean Air Act (CAA), Corporate Average Fuel Economy (CAFÉ) and the Renewable Fuel Standard (RFS).

In response to an increasing consumer awareness (Charles, Ryan, Ryan, & Oloruntoba, 2007), governments are demanding that renewable liquid fuels deliver economic benefits while mitigating several key negatives associated with petroleum products, including unreliable global supply, price volatility and GHG emissions (Gegg, Budd, & Ison, 2014; The Biomass Research and Development (R&D) Board, 2016). To economically migrate to bio-renewable feedstocks for liquid fuels and chemicals, some have envisioned what is termed, the bioeconomy. Golden & Handfield (2014) have defined the bioeconomy as:

> "…the global industrial transition of sustainably utilizing renewable aquatic and terrestrial resources in energy, intermediate, and final products for economic, environmental, social, and national security benefits." (p. 7)

The global bio-based economy has been initially based on first generation biofuels produced primarily from food crops, such as, grains, sugar cane and vegetable oils (Mohr & Raman, 2013). 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, 2015a). 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, 2016), has also reshaped corn farming by reducing government support for cropping subsidies while raising farmers' incomes (Renewable Fuels Association, 2014). 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 has aided in the development of the rural economy by providing over 60,000 jobs nationwide (National Biodiesel Board, 2015c). Biodiesel also contributes to the U.S. CAA with 52 percent lower GHG emissions compared to petroleum-based diesel (Energy Efficiency & Renewable Energy, 2015b).

Despite the benefits of first generation corn-grain ethanol, the "food-versus-fuel" and ethanol "blend wall" arguments continue to constrain the industry. 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, 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).

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, second generation cellulosic biofuels have yet to become widely commercialized in the US due to a variety of underlying issues (Balan et al., 2013; FitzPatrick et al., 2010). For instance, cellulosic alcohols face the same ethanol "blend wall" issue, plus strong price competition from existing corn-grain ethanol players. Additional barriers to the scale-up (commercialization) of the cellulosic biofuels industry are well documented and include feedstock costs and availability, high production costs, high capital requirements, policy uncertainty, and various technical, environmental and social issues (Balan et al., 2013; Brown & Brown, 2013; Cheng & Timilsina, 2011; Oltra, 2011; Pimentel & Patzek, 2005; Temesgen, Affleck, Poudel, Gray, & Sessions, 2015). Going forward, government, academic and industrial biofuel research efforts will include hydrocarbon biofuels recovered from lignocellulosic biomass and algae (Gegg et al., 2014; Regalbuto, 2009).

The **overall goal** of this paper is to present a comprehensive review of the U.S. biofuels industry. The specific objectives are to provide a historical perspective for the development of the U.S. biofuels industry and to examine barriers to the scale-up of second and third generation versions with future development considerations. This paper contributes to extant debates on the transition from first generation biofuels to cellulosic alcohols and drop-in advanced biofuels.

2.0 Historic perspective of U.S. first generation biofuels

2.1 Corn-Grain Ethanol

As shown in Fig. 1, ethanol production dates back nearly 9,000 years to alcoholic beverages consumed in China; later, first century AD Greeks distilled ethanol, allowing higher alcohol concentrations ("Ethanol history", 2010). Between 1824 and 1826, Samuel Morey invented the world's first internal combustion engine running on ethanol and turpentine ("Ethanol history", 2010). In 1896, Henry Ford built the first automobile to run on pure ethanol; however, the prohibition era in the U.S. (1919-1933) marked the end of ethanol and the rise of gasoline as an automobile fuel ("Ethanol history", 2010; Gustafson, 2010). The 1973 energy crises once again made ethanol fuel more interesting and the U.S. began exploring ways to encourage its corn-grain ethanol industry (Hoffman & Baker, 2010; Hughes, Gibbons, & Kohl, 2009; Nixon, 1973). Later, the U.S. corn-grain ethanol industry's growth was supported by the 1990 Clean Air Act (CAA) and the 1992 Energy Policy Act (EPAC). Using ethanol as an oxygenate helped control carbon monoxide emissions (Environmental Protection Agency, 2014), and the 1992 EPAC created a biofuels tax credit for the U.S. corn-grain ethanol industry (Lave, Burke, & Tyner, 2011). From 2003-2007, methyl tertiary butyl ether (MTBE) was phased out as a U.S. gasoline oxygenate (Lave et al., 2011; Lidderdale, 2000) and early in the 21st Century, the 2005 Energy Policy Act established the first Renewable Fuel Standard (RFS1) to further spur the biofuels industry while addressing oil price volatility, greenhouse gas (GHG) emissions, energy security, and rural economic development (Golden & Handfield, 2014; Schnepf & Yacobucci, 2013). In 2007, the Energy Independence and Security Act (EISA) expanded the reach of RFS1 (to RFS2) by mandating 36 billion gallons of biofuels to be blended into the U.S. fuel supply by 2022 (Schnepf & Yacobucci, 2013). The U.S. corn-grain ethanol industry's production grew from approximately 830 million gallons in 1991 to nearly 14.8 billion gallons in 2015, representing about 60 percent of the world's ethanol production (Fig. 2) (Renewable Fuels Association, 2015, 2016).

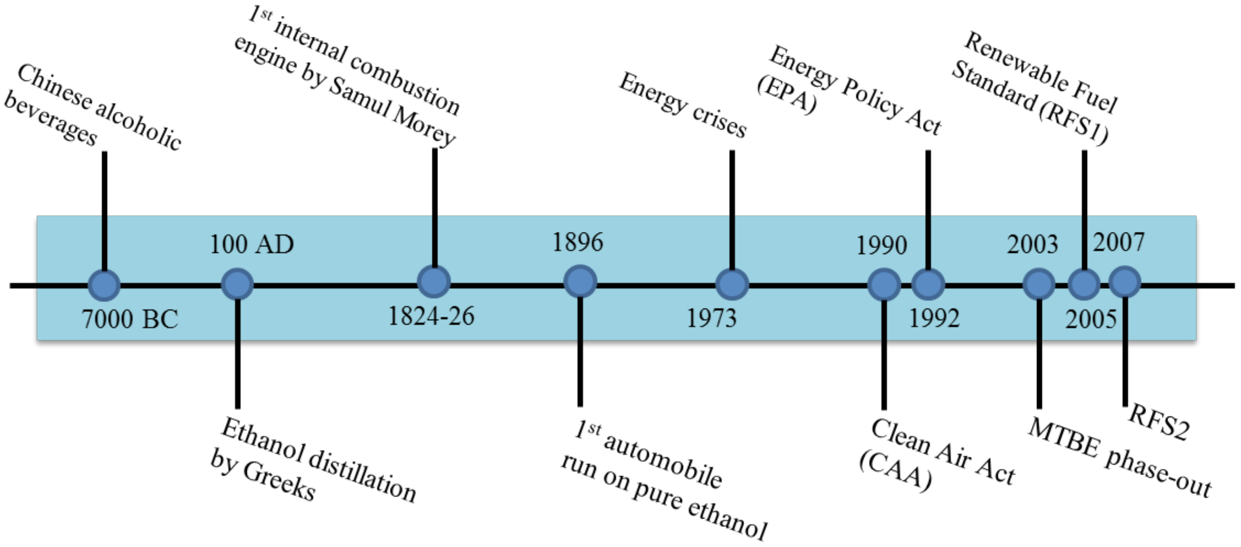

Figure 1. History of ethanol.

2.2 Biodiesel

The use of biofuels recovered from vegetable oils in diesel engines originated with the demonstration of the diesel engine by the German inventor Rudolph Diesel, at the World Exhibition in Paris in 1911 (Yusuf, Kamarudin, & Yaakub, 2011). Diesel envisioned widespread use of vegetable oils, such as hemp and peanut oil, for diesel engines; however, modern biodiesel, recovered by converting vegetable oils into fatty acid methyl esters, was not established in Europe until the late 1980s (Pacific Biodiesel, 2015). In the U.S., biodiesel was first manufactured in 1991 in Kansas City, Missouri (National Biodiesel Board, 2015a). Later, by 2002, biodiesel legislation in Minnesota required the inclusion of 2 percent soybean biodiesel into the majority of Minnesota's diesel pool (National Biodiesel Board, 2015a). Fig. 3 depicts the growth of the U.S. biodiesel industry from approximately 10 million gallons of 100% biodiesel (B100) in 2002 to 1.26 billion gallons in 2015 (Energy Information Administration, 2016a).

3.0 Current status of first generation biofuels in the US

3.1 Corn-Grain ethanol

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). Fig. 4 illustrates the 208 U.S. corn-grain ethanol biorefineries in 2015 with the heaviest concentrations

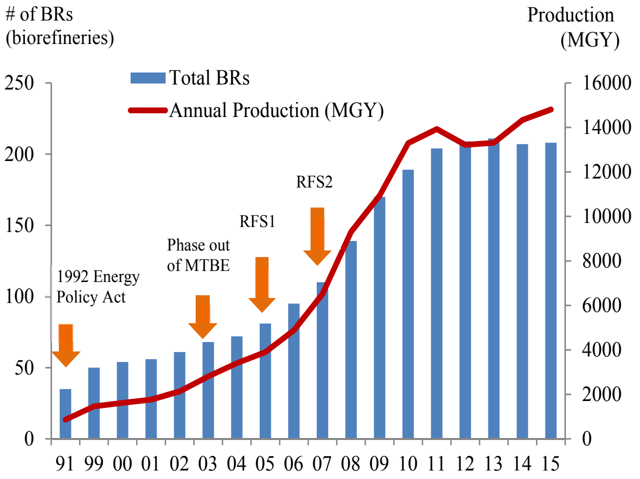

Figure 2. Growth of the U.S. corn-grain ethanol industry (# of biorefineries and production) from 1991 - 2015 (Renewable Fuels Association, 2015, 2016).

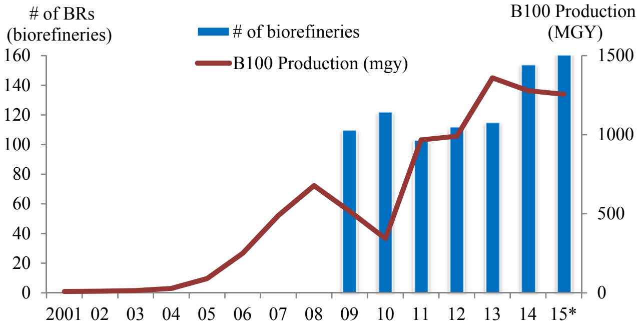

*Figure 3. Growth of the U.S. biodiesel industry (# of biorefineries and capacity) from 2001 to 2015 (Energy Information Administration, 2016b). (*The production volume of 2015 is predicted by the first 11 months of 2015)*

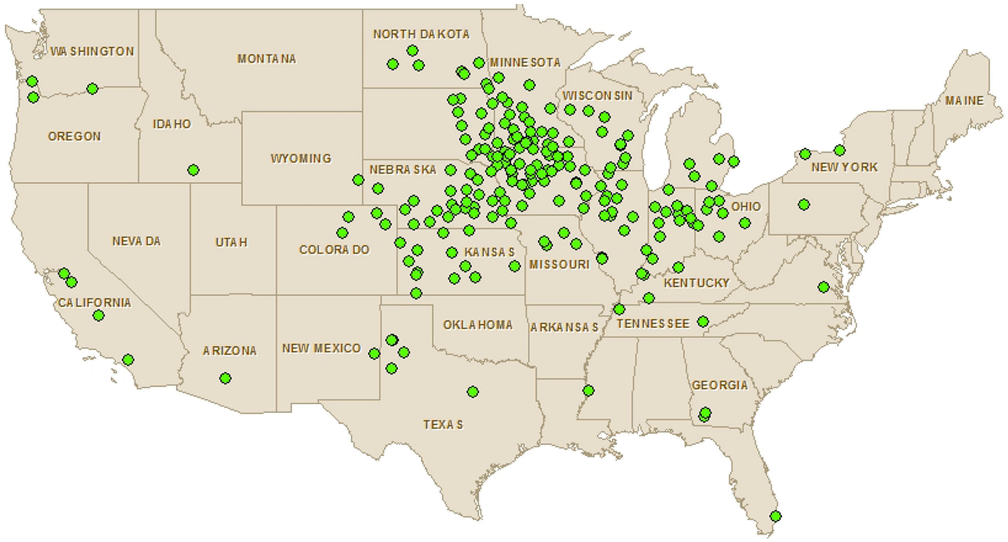

Fig. 4. U.S. corn-grain ethanol biorefineries (n=208) by location in 2015 (Adapted from (Renewable Fuels Association, 2015))

Table 1. The U.S. leading corn-grain ethanol producers by capacity in 2015 (Renewable Fuels Association, 2015)

Company	States	2015 Capacity (MGY)
Archer Daniels Midland (ADM)	IA, IL, MN, NE	1,762
POET LLC	IN, IA, MN, MI, MO, SD, OH	1,666
Valero Renewable Fuels	IA, IN, MN, NE, OH, SD, WI	1,300
Green Plains Renewable Energy	IA, IN, MI, MN,NE,TN,TX,VA	1,220
Flint Hills Resources LP	IA, NE	820
Cargill, Inc.	IA, NE	345
The Andersons Ethanol LLC	IA, IN, MI, OH	330
Abengoa Bioenergía Corp.	IL, IN, KS, NE, NM	323

in the Midwestern corn-belt of Iowa (n=40), Nebraska (n=25), Minnesota (n=21), South Dakota (n=15) and Illinois (n=14). The largest ethanol producers in 2015 were Archer Daniels Midland (ADM), POET, Valero Renewable Fuels, Green Plains Renewable Energy, and Flint Hill Resources (Table 1).

3.1.1 Conversion Technologies & Co-products. Corn-grain ethanol in the United States is produced in both wet and dry mills (Naik, Goud, Rout, & Dalai, 2010). Wet mills separate each component of the corn kernel into different fractions via steeping, de-germinating and separation (Fig. 5). A variety of products can be recovered in wet mills, including starch, gluten meal, gluten feed and oil. The starch derived from wet mills may be further processed into sweeteners (high-fructose corn syrup, HFCS) or ethanol (AMG, 2013). This diversified product portfolio allows producers to quickly adapt to changes in market conditions (Hoffman & Baker, 2010).

Compared to wet mills, dry mills are typically smaller, less expensive to build and produce a narrower product mix (Fig. 6). The primary co-products of dry mill are distillers' dried grains with solubles (DDGS) and/or corn oil (Fig. 6). Roughly one-third of every 56-pound bushel of grain that enters the ethanol process is converted to distillers' grains and corn oil, with approximately one-quarter of dry mill's gross revenue from the sale of these two co-products in 2013 (Renewable Fuels Association, 2014). As a result, the market share of ethanol dry mills increased from 30 to 89 percent from 1991 to 2009/10 (Hoffman & Baker, 2010; Urbanchuk, 2010).

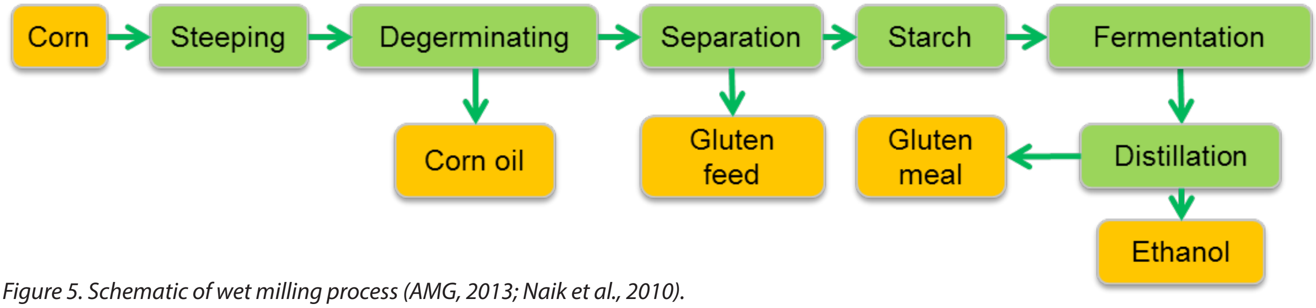

Figure 5. Schematic of wet milling process (AMG, 2013; Naik et al., 2010).

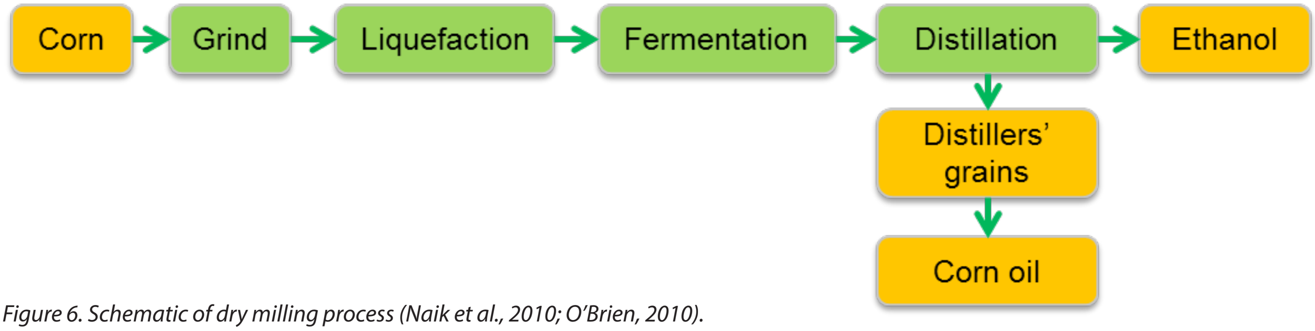

Figure 6. Schematic of dry milling process (Naik et al., 2010; O'Brien, 2010).

3.2 Biodiesel

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, 2016a; 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, 2016a). 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, 2016a). Fig. 7 shows the locations of the identified 162 U.S. biodiesel biorefineries in 2015 (Biodiesel Magazine, 2015; Lane, 2013a; National Biodiesel Board, 2015b).

3.2.1 Conversion Technologies & Co-products. Trans-esterification is the most widely used technology in biodiesel production (Fig. 8) (Moser, 2011). This trans-esterification reaction involves a triacylglycerol (TAG) reacting with short-chain monohydric alcohol with the presence of alkaline catalysts (such as NaOH, KOH, or related alkoxides) to form fatty acid alkyl esters (biodiesel) and glycerol (Fig. 8). The price of biodiesel depends largely on conversion technologies. In order to be cost-competitive against petro-diesel, research interests have been focused on the development of heterogeneous catalyst systems to increase conversion yields and to standardize biodiesel to enhance its marketability (Hanna, Isom, & Campbell, 2005; Santacesaria, Vicente, Di Serio, & Tesser, 2012).

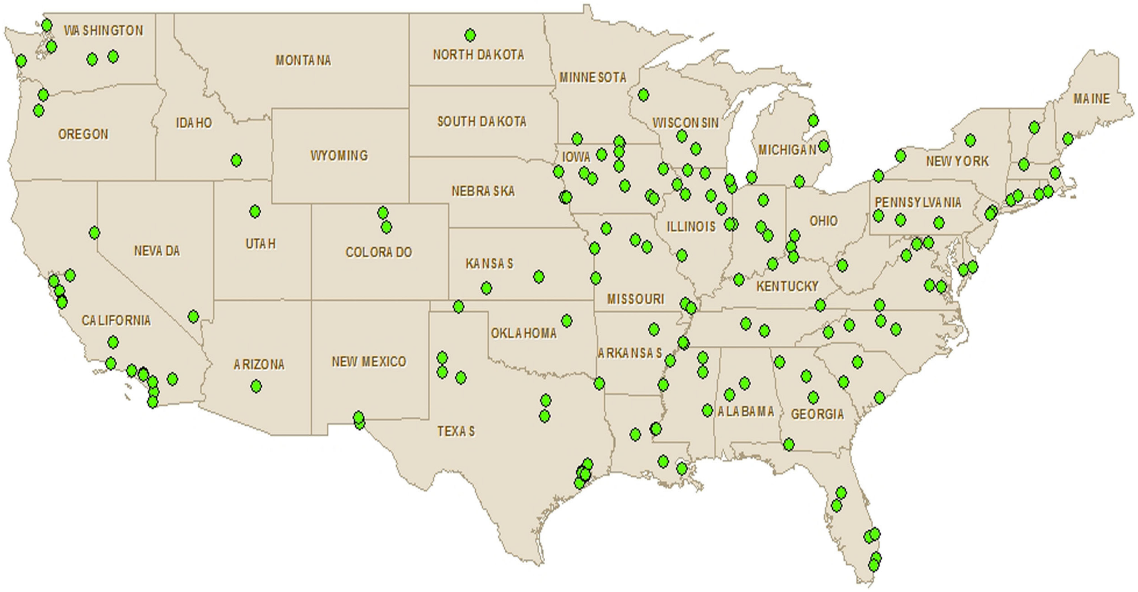

Figure 7. U.S. biodiesel biorefineries (n=162) by location in 2015 (Adapted from (Biodiesel Magazine, 2015; Lane, 2013a; National Biodiesel Board, 2015b))

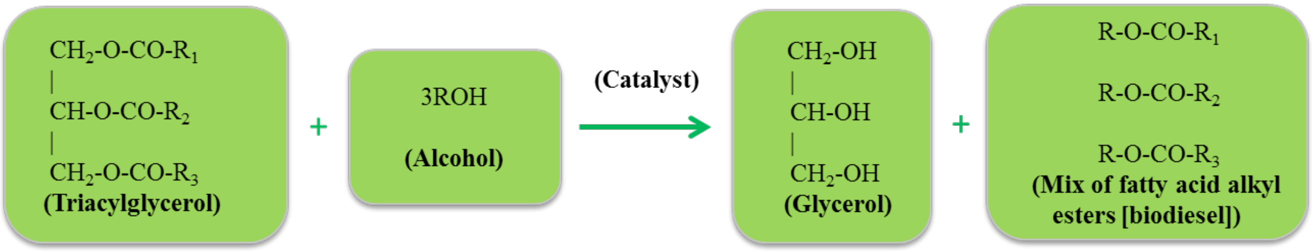

Figure 8. Production of fatty acid alkyl esters (biodiesel) via trans-esterification (Moser, 2011).

Glycerol, a co-product from biodiesel production, has a wide range of applications including personal care, pharmaceuticals, foods and beverages (Hanna et al., 2005; Sheela, 2014). According to Transparency Market Research (2013), the global demand for glycerol was around 2,000 kilotons in 2011 and is expected to reach 3,000 kilotons by 2018, worthing an estimated $2.1 billion (Sheela, 2014).

4.0 Challenges confronting U.S. first generation biofuels

4.1 Ethanol "Blend Wall"

Corn-grain ethanol in the U.S. is blended with gasoline, primarily as E10 (up to 10% ethanol blended with 90% unleaded gasoline). A key benefit of E10 is that it is compatible with existing vehicles and infrastructure, including fuel tanks and retail pumps (Schnepf & Yacobucci, 2013). Since 2010, the ethanol production volume has surpassed the capacity that can be blended with conventional motor gasoline at the 10% blend rate, commonly referred to as the ethanol "blend wall" (Fig. 9).

To address this demand dilemma, the EPA approved the sale of E15 (up to 15% ethanol blended with 85% unleaded gasoline) in 2010 for 2001 and newer vehicles, with the potential to increase the annual amount of ethanol sold by 50% (Renewable Fuels Association, 2013). In addition, the U.S. ethanol industry anticipates significant progress through the USDA's Biofuels Infrastructure Partnership program (October 2015), which will result in 4,880 pumps and 515 tanks installed throughout the U.S. over the next year in 1,486 stations to offer consumers E15 and higher blends (Buis, 2016). However, the adoption of higher blends is not a panacea as a lack of compatible fueling infrastructure and poor automaker and consumer acceptance of E15 or E85 for flex fuel vehicles (FFVs) remain (Antoni, Zverlov, & Schwarz, 2007; Energy Information Administration, 2011; Martin, 2013; NACS, 2013).

4.2 "Food-Versus-Fuel" Debate

The "food-versus-fuel" debate unfolded during the food crisis of 2007 and 2008 because most feedstocks currently used for first generation biofuels are directly or indirectly used for food production (Ajanovic, 2011; Babcock, 2012; Srinivasan, 2009). As a result, serious concerns remain regarding the preservation of the food security of the planet and increasing feedstock prices (Carter & Miller, 2012; Srinivasan, 2009; Ziegler, 2008). However, others contend that oil prices and export demand may be the driving influences of feedstock and food price inflation and that the impact of biofuels production on food security and price inflation are exaggerated (Schill, 2016). The Renewable Fuels Association (RFA) contends that corn ethanol production uses only the grain's starch component and returned an estimated 39 million metric tons of protein, minerals, fat and fiber to the animal feed market in 2014 (Renewable Fuels Association, 2014).

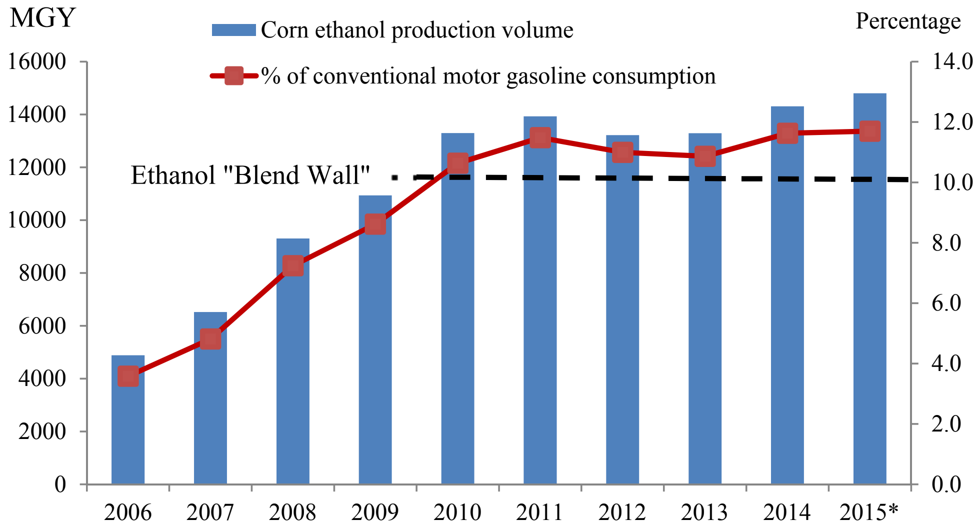

*Figure 9. Annual U.S. ethanol production volumes from 2006 to 2015 and their corresponding percentage of the conventional motor gasoline consumption (*2015 fuel ethanol consumption data is based on the prediction from EIA) (Energy Information Administration, 2016b, 2016c)*

At the Global Forum for Food and Agriculture (January 2015), Jose Graziano de Silva, director of the United Nations Food and Agriculture Organization (FAO), stated:

> "We need to move from the 'food versus fuel' debate to a 'food and fuel' debate. There is no question: food comes first. But biofuels should not be simply seen as a threat or a magical solution. Like anything else, they can do good or bad." (Food and Agriculture Organization, 2015)

4.3 Biodiesel Challenges

In addition to the food-fuel issue, biodiesel fuels also face challenges related to environmental, economic and social impacts (Castanheira et al., 2014). In the case of crop-based feedstock, representing approximately 71% of U.S. biodiesel production in 2015, specific issues include seasonal crop availability and similar land use change concerns associated with corn-grain ethanol production (Bomb, 2005; Castanheira et al., 2014; Gnansounou, Panichelli, Dauriat, & Villegas, 2008; Rabago, 2008). Including animal fat and restaurant grease-based biodiesel, overall challenges to biodiesel include potential infrastructure modifications to move fuel from production facilities to personal vehicles, storage shelf life and related distribution and infrastructure modifications, NOx emissions, low-temperature operability, and reduced energy content than petrodiesel (Bomb, 2005; Castanheira et al., 2014; Howell & Weber, 1995; Rabago, 2008; Yoon, 2011).

5.0 Transition to cellulosic alcohols

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). Due to concerns over "food-versus-fuel", land-use change and GHG emissions, non-edible cellulosic alcohols, primarily ethanol and butanol, are gaining momentum in U.S. road transportation fuel markets (Mohr & Raman, 2013; Schnepf, 2010). 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 et al., 2013; FitzPatrick et al., 2010; Pacini et al., 2014). Researchers from the University of California at Berkeley, Stanford University, and Argonne National Lab estimated that, on a life-cycle basis, cellulosic ethanol could lower GHG emissions by around 90 percent relative to petroleum-based gasoline (Energy Efficiency & Renewable Energy, 2014b; Farrell et al., 2006; Schmer, Vogel, Mitchell, & Perrin, 2008).

5.1 Cellulosic Alcohol Biorefineries

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 (Fulton, Morrision, Parker, Witcover, & Sperling, 2014; Lane, 2014). Currently, eleven U.S. "bolt on" cellulosic biofuel biorefineries are in start-up mode (Table 2) with two having launched commercial-scale production: POET-DSM "Project Liberty" (Sept. 3, 2014) and Quad County Corn Processors (July 1, 2014) ("Four commercial", 2014).

Table 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; QCCP, 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) ("Four commercial", 2014; DuPont, 2015b; INEOS, 2013). Fifteen biorefineries produce cellulosic ethanol as the major product; Butamax focuses on the production of n-butanol (Table 3).

5.2 Conversion Technologies

Enzymatic/dilute acid hydrolysis and fermentation are the leading conversion technologies deployed in the U.S. to produce cellulosic alcohols (Balan et al., 2013; Brown & Brown, 2013; Coyle, 2010). Due to the recalcitrance of lignocellulose, a composite of cellulose, hemicellulose and lignin, pretreatment is required to separate the lignin and improve enzymatic and microbial break down of biomass into sugars (Himmel et al., 2007). Various pretreatments are available, such as wet oxidation, dilute acid, steam explosion, ammonia fiber expansion (AFEX), mechanical extrusion, liquid hot water, lime, organosolv, and ionic liquid (Balan et al., 2013; FitzPatrick et al., 2010). After separating from lignin, cellulase enzymes or acid is used to depolymerize cellulose into glucose, which is then fermented to ethanol (Fig. 10).

Consolidated bioprocessing (CBP) combines enzyme production, enzymatic hydrolysis, and fermentation into the same reactor and has been adopted by Aemetis and Mascoma to produce cellulosic alcohols (Brown & Brown, 2013). CBP is purported to reduce capital and

Table 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	Sugarcane bagasse	Ethanol, acetic acid	0.7	(Advanced Ethanol Council, 2013) (American Process, 2015)
	Thomaston, GA	Non-food based biomass, woodchips	Ethanol, succinic acid, BDO	Up to 0.3	
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)
Coskata	Madison, PA	Woody chips, MSW	Ethanol, ethylene	NA	(Coskata, 2015)
DuPont Biofuel Solutions	Nevada, IA	Corn cob	Ethanol	30	(Dupont, 2015a)
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 et al., 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)

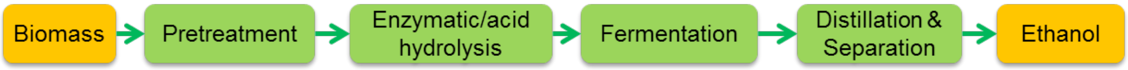

Fig. 10. Cellulosic ethanol via enzymatic/dilute acid hydrolysis (modified from (Balan et al., 2013))

operating costs as compared to separate enzymatic/dilute hydrolysis & fermentation (Brown & Brown, 2013; Olson, McBride, Shaw, & Lynd, 2012) (Fig. 11).

6.0 Growth of cellulosic- and algae-based hydrocarbon biofuels

6.1 *Hydrocarbon Biofuels Biorefineries*

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 4).

6.2 *Conversion Technologies*

Lignocellulosic biomass and algae can be converted to renewable hydrocarbon biofuels by thermochemical and hybrid (combined thermochemical and biochemical) technologies (Yue, You, & Snyder, 2014). Three specific processes for the conversion are: 1) gasification of biomass to syngas (carbon monoxide and hydrogen) and further conversion of syngas to liquid fuels via Methanol-to-Gasoline (MTG) or Fischer-Tropsch (FT) syntheses; 2)

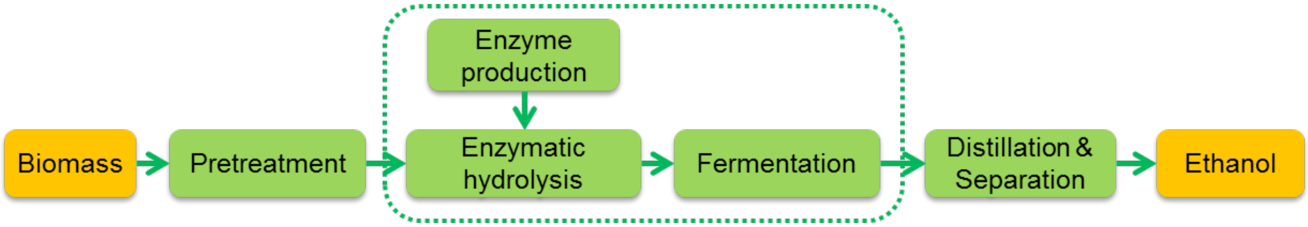

Fig. 11. Cellulosic ethanol via consolidated bioprocessing (CBP) (modified from (Brown & Brown, 2013))

Table 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 et al., 2015; Sapphire, 2014)
Solazyme	Peoria, IL	Soladiesel, Solajet	(Bardhan et al., 2015; Solazyme.com, 2014)

fast pyrolysis or liquefaction of biomass to produce bio-oils followed by upgrading to liquid hydrocarbon biofuels via hydroprocessing; and 3) biochemical conversion of biomass to ethanol followed by catalysis or bioforming to hydrocarbon biofuels (Fig. 12).

7.0 Challenges confronting the U.S. cellulosic- and algae-based biofuels industries

7.1 Challenges of Cellulosic Biofuels

Compared to petro-based gasoline and diesel, cellulosic biofuels enjoy improved sustainability, energy security and lower GHG emissions. However, cellulosic biofuels are confronting high entry barriers that inhibit their entrance to the U.S. transportation fuel markets. These barriers include feedstock costs and availability, high production costs, and policy uncertainty (Cheng & Timilsina, 2010; Cheng & Timilsina, 2011; Oltra, 2011; Pimentel & Patzek, 2005).

7.1.1 Feedstock Costs and Availability. Long-term investments in research, demonstration and deployment are ongoing to develop and fully scale cost-effective and time-sensitive supply chains for cellulosic biofuel biorefineries (Richard, 2010; Yue et al., 2014). In contrast to corn-grain and oilseeds, lignocellulosic feedstocks are generally less expensive; however, lower bulk density and higher moisture content results in significant logistical challenges (Balan, 2014; Coyle, 2010; Richard, 2010). Feedstock costs, estimated at 35-50 percent of total cellulosic ethanol production costs, consist of both the raw materials and the logistics costs, including harvesting, collecting, storing, preprocessing, and transporting biomass to biorefineries (Coyle, 2010). Feedstock availability issues related to environmental and social considerations represent another challenge. For agricultural residues and wastes, harvesting may be restricted by

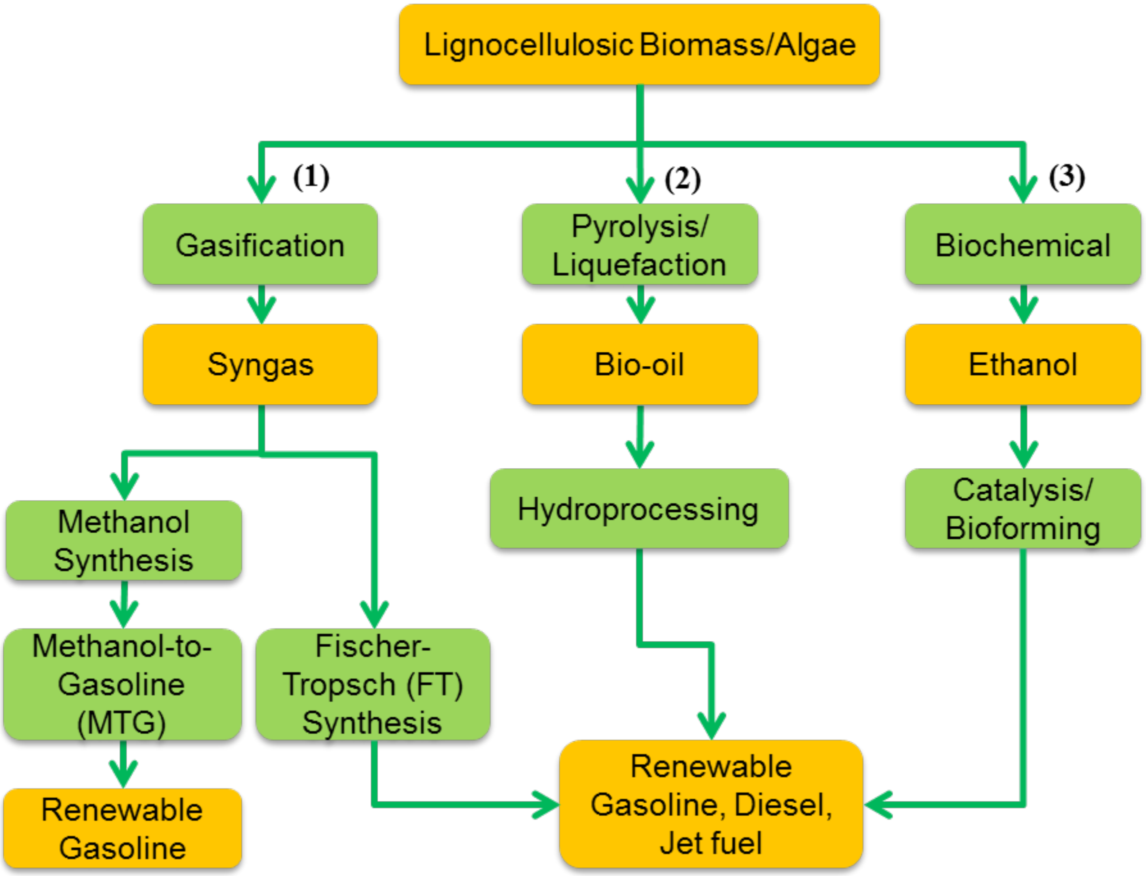

Fig. 12. Simplified conversion processes for cellulosic- and algae-based hydrocarbon biofuels (modified from (Balan et al., 2013; Brennan & Owende, 2010; Brown & Brown, 2013; Naik et al., 2010; Yue et al., 2014))

sustainability criteria and soil quality maintenance which can impact the steady year-round supply of biomass to the biorefinery (Coyle, 2010; Wilhelm, Johnson, Karlen, & Lightle, 2007). For example, corn stover represents three-fourths of all available biomass, yet 30% of it must remain on the fields after harvest to mitigate water and wind erosion (Energy Efficiency & Renewable Energy, 2011; Ertl, 2013; Gallagher et al., 2003; Graham, Nelson, Sheehan, Perlack, & Wright, 2007). For forestry residues, there is no clear consensus on the minimum amount of organic material required to remain on site to maintain ecosystem services (Daioglou, Stehfest, Wicke, Faaij, & Vuuren, 2015); however, research is currently addressing forest biomass inventories in response to changing land uses and climatic conditions (Hollinger, 2008; Temesgen et al., 2015).

7.1.2 High Production Costs. Compared to the relatively mature fermentation process for corn-grain ethanol and trans-esterification for biodiesel, cellulosic biofuels are still at their early stages of development with most of these technologies at pilot or demonstration scale (Balan et al., 2013). The main technical obstacle of producing cellulosic biofuels is the tough, complex structure of lignocellulosic biomass cell walls and the need to separate lignin (Hahn-Hägerdal, Galbe, Gorwa-Grauslund, Lidén, & Zacchi, 2006; Houghton, Weatherwax, & Ferrell, 2005; Zhu et al., 2015). As a result, relatively immature and untested technologies for large-scale production challenge the economic-competitiveness of U.S. cellulosic alcohols and cellulosic hydrocarbon biofuels (Coyle, 2010). For example, on January 2016, U.S. Department of Energy (DOE) researchers reported achieving a cellulosic ethanol production cost of $2.15 per gallon (National Renewable Energy Laboratory, 2016). At this cost, cellulosic ethanol is not competitive with petroleum-based gasoline when oil prices are below $50 per barrel (Center for Climate and Energy Solutions, 2009).

7.1.3 Policy Uncertainty. Stable and consistent policies enabled first generation U.S. corn-grain ethanol biofuels to grow dramatically to approximately 15 billion gallons by 2015 (Dahmann, Fowler, & Smith, 2016). Second generation biofuels, however, have struggled to reach commercial scale production due, in part, to policy uncertainty (Dahmann et al., 2016; Dinneen, 2016). This uncertainty is reflected in the fluctuating Renewable Volume Obligations (RVOs) under RFS set by the U.S. Environmental Protection Agency (EPA) (Lane, 2015). RVOs are the obligated quantities of biofuels for companies that supply gasoline or diesel transportation fuel for the retail market (Schnepf & Yacobucci, 2013). The U.S. EPA has been tasked with the implementation of the RFS by calculating and establishing RVOs based on RFS2 volume requirements and U.S. Energy Information Association (EIA) projections of gasoline and diesel production for the coming year (Environmental Protection Agency, 2015b; Schnepf & Yacobucci, 2013). EPA then issues an annual notice of proposed rulemaking and a final rule by November 30 of each year to set the RFS for each ensuing year (Schnepf & Yacobucci, 2013). However, in light of recent and dramatic oil price drops, biofuel exports and retired Renewable Identification Numbers (RINs)[1], current U.S. law and policy for cellulosic and other advanced biofuels have neither provided adequate stimulus nor a clear a direction to foster stable and predictable development and commercialization (Dahmann et al., 2016).

As an alternative approach, California has taken a leadership role in developing and implementing a Low Carbon Fuel Standard (LCFS) with the goal of establishing:

> "…average carbon intensity values for various fuels such as gasoline, diesel, biofuels, natural gas, and electricity. Carbon intensity values are calculated using a life-cycle analysis, which accounts for all greenhouse gas emissions associated with a fuel's production, distribution and use — as opposed to a simple measure of carbon emissions when a fuel is burned" (Dahmann et al., 2016; Langston et al., 2011; Yeh et al., 2012).

In addition to California, a LCFS is being explored elsewhere, including Oregon, Washington and in the eastern U.S. where 11 states signed a 2009 Memorandum of Understanding to adopt a "Clean Fuels Standard" (Dahmann et al., 2016; Yeh et al., 2012). This type of carbon-based policy tool could greatly impact the future direction of the U.S. biofuels industry in terms of feedstock use, plant siting and technology deployment.

7.2 Challenges of Algae-Based Hydrocarbon Biofuels

Algal feedstocks enjoy high growth rates and tolerance to varying environmental conditions, which allows them to survive and reproduce in low quality high saline water unsuitable for agriculture (Energy Efficiency &

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[1] RIN refers to a serial number (a unique 38- character) to a batch of biofuel for the purpose of tracking its production, use and trading as required by Renewable Fuels Standard (RFS) (Schnepf & Yacobucci, 2013)

Renewable Energy, 2014a; Naik et al., 2010). Similar to lignocellulosic hydrocarbon biofuels, drop-in algae-based hydrocarbon biofuels also benefit from existing fuel distribution networks and lower GHG emissions. However, feedstock cultivation, processing, and logistics issues pose significant challenges and various technological and economic barriers remain (Energy Efficiency & Renewable Energy, 2014a; Hughes, Gibbons, Moser, & Rich, 2013; Lee, 2013; Oltra, 2011; Sheehan, Dunahay, Benemann, & Roessler, 1998).

8.0 Discussion

Corn-grain ethanol and biodiesel are relatively mature U.S. first generation biofuels due in part to stable and supportive policies, established conversion technologies, and synergy with existing U.S. food production systems. In 2015, 208 U.S. corn-grain ethanol biorefineries produced approximately 15 billion gallons of ethanol. However, first generation corn-grain ethanol biofuels are facing challenges to further growth in term of the ethanol "blend wall", the "food-versus-fuel" debate, and consumer acceptance related to engine wear and reduced energy content (Table 5).

Biodiesel is a renewable substitute for diesel fuel (up to 100%) with favorable lubricity properties which may extend the life of diesel engines (Energy Efficiency & Renewable Energy, 2015a; Pacific Biodiesel, 2016). In 2015, 162 biodiesel refineries produced about 1.26 billion gallons of pure biodiesel (B100), of which 71 percent of the production used vegetable oil seeds with the balance derived from animal fat and restaurant grease. The crop-based biodiesel faces similar food-fuel and land use change issues and all biodiesel fuels face infrastructure, shelf life, energy content, NOx emission, and low-temperature operability issues (Table 5).

Driven by the "food-versus-fuel" debate and concerns over GHG emissions, second generation cellulosic alcohols (e.g. cellulosic ethanol and butanol) are gaining interest from researchers, policymakers and investors. By using non-food based feedstocks, cellulosic alcohols offer an opportunity to reduce impacts on food supply and price, impose less competition on land use, and further reduce GHG emissions by around 90 percent relative to petroleum-based gasoline (Table 5). As of January 2016, eleven "bolt-on" and sixteen "stand-alone" U.S. cellulosic alcohol biorefineries have been established in the U.S.

Table 5. Summary of the opportunities and challenges confronting U.S. biofuels

Fuels	Opportunities	Challenges
Fossil fuels	Meets current energy needs	Price volatility GHG emissions Energy insecurity
Corn-grain ethanol	Renewable substitute Oxygenate About 10% of US gasoline consumption	"Food-fuel" Ethanol "blend wall" Consumer acceptance
Biodiesel	Renewable substitute Up to 100% blends Increased lubricity	"Food-fuel" Land use change Infrastructure Energy content Shelf life NOx emissions Low-temperature operability
Cellulosic alcohols	Renewable substitute "Food-fuel" Lower lifecycle GHG emissions	Feedstock costs/availability Production/capital costs Policy uncertainty Technical, environmental and societal constraints
Cellulosic hydrocarbons	Renewable substitute "Food-fuel" Lower lifecycle GHG emissions Drop-in	
Algae-based hydrocarbons	Renewable substitute "Food-fuel" Lower lifecycle GHG emissions Drop-in High potential yields Flexible feedstock siting	Feedstock cultivation/ processing/logistics Production costs Energy/water/nitrogen/phosphorus requirements

Second generation non-food based drop-in cellulosic and third generation algae-based hydrocarbon biofuels eliminate the food-fuel issue and infrastructure/engine compatibility concerns [166] (Table 5). Cellulosic alcohols and cellulosic hydrocarbon biofuels face several potential challenges associated with feedstock costs and availability, high production and capital costs, policy uncertainty, and various technical, environmental and societal constraints. As of January 2016, seventeen U.S. companies were producing or proposing to produce hydrocarbon-based "green" gasoline, renewable diesel and/or biojet. Early success of these pioneering projects is critical to attract capital investment and create demand (Brown & Brown, 2013).

In spite of high potential yield and the ability to grow algae in locations unsuitable for agriculture, algae-based hydrocarbon biofuels are challenged by feedstock cultivation, processing, and logistics issues, technology (large volume requirement of water, nitrogen and phosphorus), and economic barriers (high production costs and high energy requirements) that need to be addressed in the coming years (Energy Efficiency & Renewable Energy, 2014a; Hughes et al., 2013; Lee, 2013; Oltra, 2011; Sheehan et al., 1998).

9.0 Conclusions

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 petrofuels in terms of overall economics and proven environmental benefits without perceived negative impacts on performance. And, the lessons learned from corn/grain ethanol suggest that specific and stable policies addressing feedstock infrastructure/logistics, capital formation, and environmental issues may more rapidly and effectively advance the adoption and diffusion of next generation renewable liquid fuels. Addtitionally, researchers have recognized that innovative technology underpins a strong bioeconomy (The Biomass Research and Development (R&D) Board, 2016). Therefore, further research and development on technological advances should be encouraged and supported to help lignocellulosic liquid biofuels achieve economic-competitiveness. 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.

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