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Mixed Methods Research of Integrated Cellulosic Biorefinery (ICBR) Scale-Up Barriers in the United States: A Case Study

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Abstract

Second generation (cellulosic) biofuels provide an attractive solution to reduce the dependence on fossil fuels and to address concerns about competition with food crops and land use change confronting the U.S. first generation biofuels. However, the production of cellulosic biofuels has not yet become widely commercialized. The integrated production of second generation cellulosic biofuels and biochemicals, that is, the integrated cellulosic biorefinery (ICBR), offers an opportunity to effectively utilize feedstock fractions, diversify value stream outputs, improve financial performance, and mitigate risks. A dearth of literature exists addressing potential barriers to the scale-up of this industry. Thus, this study deployed a mixed methods approach with an initial qualitative phase for construct development, followed by a quantitative phase for construct confirmation and validity. In Phase I, a qualitative e-survey was conducted among eighteen academic and industrial experts, which identified a list of eight barriers to the scale-up of the ICBR. In Phase II, 228 experts (34% response rate) responded to the quantitative surveys, which included RATING (5-point likert-type scale from 1=not a barrier to 5=very high barrier) and RANKING (TOP three highest barriers) questions of the eight identified barriers. RATING results, validated by RANKING results, showed that competition vs. petro-chemicals, high production costs, and policy uncertainty represented the top three barriers to the U.S. ICBR scale-up. Also, Phase I experts indicated that consistent government funding & incentives and, to a lesser extent, new technology development and education of end-use consumer will be required to address these barriers. Overall, results highlight the mixed methods exploratory research approach and contribute to extant debates on the future commercial development of the U.S. ICBR.

Keywords: Integrated cellulosic biorefinery; cellulosic biofuels; energy security; food vs. fuel; Renewable Fuel Standard (RFS); mixed methods research

1.0 Introduction

Due to increasing concerns over greenhouse gas (GHG) emissions from the combustion of fossil fuels and associated climate change impacts, the U.S. Department of State (DOS) submitted an Intended Nationally Determined Contribution (INDC) to the United Nations Framework Convention on Climate Change (UNFCCC) to cut net GHG emissions by 26-28 percent below 2005 levels by 2025 (The White House, 2015). At the G20 Summit held on September 4, 2016, the U.S. formally committed to the Paris Climate Accord, which sets a long-term goal of keeping the increase in global average temperature to well below 2°C above the pre-industrial level (Chemnick, 2016; European Commission, 2016). The U.S. will continue its commitments under the agreement through November 4, 2020, in accordance with Article 28 of the Paris Agreement, even though the current administration announced a U.S. withdrawl from the agreement on August 4, 2017. Supported by these government policies, the quest for environmentally benign sources of energy for our needs has become urgent in recent years. A variety of renewable energy sources are being studied in the U.S., including solar,

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wind, hydro, nuclear, and biomass. Renewable biofuels recovered from biomass are key to promoting rural economic development while mitigating several key negative aspects associated with petroleum products, including unreliable global supply, price volatility, and carbon emissions (Gegg et al., 2014).

The U.S. biofuels industry is currently dominanted by first generation biofuels produced directly from crops, e.g. corn-grain ethanol and biodiesel, which account for over 90% of the total renewable biofuels within the U.S. (Chen et al., 2017; Environmental Protection Agency, 2015). However, first generation biofuels seem to create some controversy among scientists and policymakers. Concerns exist about the sourcing of feedstocks, including competition with food, land use change, and the impact of edible feedstock on biodiversity (Chen et al., 2016; Naik et al., 2010). As a result, many industrial, governmental, and research interests have a renewed interest in second generation (cellulosic) biofuels (Brown & Brown, 2013; Mohr & Raman, 2013). Compared to first generation biofuels, cellulosic biofuels provide a potential solution to address the food-fuel and land use debates by utilizing non-food feedstocks that can grow on lands that are not necessarily suitable for food crops, while meeting the strigent targets of GHG emission reductions. Nevertheless, U.S. cellulosic biofuels have yet to become widely commercialized due to a variety of issues, including high production costs, policy uncertainty, and strong competition from petroleum-based counterparts (Balan et al., 2013; Chen & Smith, 2017; Chen et al., 2016; FitzPatrick et al., 2010). On July 5, 2017, the Environmental Protection Agency (EPA) proposed volume requirements under the Renewable Fuel Standard (RFS) program for biofuels for calendar year 2018. According to this proposal, the production volume of cellulosic biofuel will be reduced by 30% from 312 million gallons (MG) in 2017 to 238 MG in 2018 due to unexpected slow development (Environmental Protection Agency, 2017; Lane, 2017).

Facing these issues, several researchers have suggested a short-to-medium term strategy for the sustainable development of the U.S. cellulosic biofuels industry; that is, to integrate the production of biochemicals with cellulosic biofuels (Bozell, 2008; Bozell & Petersen, 2010; Cherubini, 2010; Cherubini & Strømman, 2011; FitzPatrick et al., 2010). Biochemicals represented approximately 4% of U.S. chemical production in 2014 (Golden et al., 2015) and are forecasted to account for at least 45 percent of all U.S. chemicals by 2025 (Bardhan et al., 2015). According to a 2014 USDA report, the U.S. production of bio-based chemicals could generate $775 million in added value by 2017 and $3 billion per year by 2022 (Nexant, 2014). The emerging biochemicals industry may also contribute to the U.S. rural economy by providing 19,000 jobs in 2022 (Nexant, 2014). More recently, according to a new Biotechnology Innovation Organization (BIO) report, the renewable chemical industry is estimated to make up 11 percent of the $3,401 billion global chemical market by 2020 (de Guzman, 2016). As a result, this integrated cellulosic biorefinery (ICBR) scenario can contribute to the effective utilization of feedstock fractions, to diversified value stream outputs, to the improvement of financial performance, and to the mitigation of potential market and political fluctuations (Bozell, 2008; Bozell & Petersen, 2010; Fernando et al., 2006; FitzPatrick et al., 2010).

To date, research on ICBR has largely been conducted to improve and optimize the performance of individual conversion processes with techno-economic studies (Andiappan et al., 2015; Dang et al., 2016; Ng et al., 2013). However, apart from technology development, a variety of issues should be taken into acount to commercialize ICBR, such as political, environmental, and market issues. The ***overall goal*** of this paper is to develop a list of major barriers and potential solutions to the scale-up of the U.S. ICBR and to quantitatively assess the relative degree that these barriers inhibit the commercialization of U.S. ICBR via a mixed methods research approach.

2.0 Research Design

This research deployed a mixed methods sequential exploratory design for "developing and testing a new instrument" (Creswell & Clark, 2011; Dillman et al., 2014; Jick, 1979; Sandelowski, 2000). Specifically, this research design is characterized by an initial phase of qualitative data collection and analysis for issue and/or factor identification, followed by a phase of quantitative data collection and analysis for factor confirmation and validation (Fig. 1). Phase I conducted a pilot study with "select" academic and industrial experts to develop a list of barriers to the scale-up of the U.S. ICBR and to explore potential solutions to identified barriers. Phase II implemented a quantitative study with nationwide academic and industrial experts to evaluate and validate identified barriers via rating and ranking questions.

Phase I: Qualitative Pilot/Exploratory Study	Phase II: Quantitative Confirmatory Study
Problem: Barriers to the Commercialization of Integrated Cellulosic Biorefinery (ICBR) / Integrated Production of Cellulosic Biofuels and Biochemicals	
Phase I: Qualitative Pilot/Exploratory Study	**Phase II:** Quantitative Confirmatory Study
Objective: Develop and collate potential barriers confronting the commercialization of the U.S. ICBR industry & explore potential solutions to these identified barriers.	**Objective:** Quantitatively evaluate and validate barriers to ICBR commercialization via rating and ranking questions.

Implications:

- Results highlight issues to existing industrial players and new entrants when designing and managing an ICBR system;
- Findings may be used by government researchers to better inform policies aimed at encouraging this industry.

Figure 1. Mixed methods design for research on barriers to the commercialization of integrated cellulosic biorefineries.

2.1 Phase I: Qualitative pilot/exploratory study

2.1.1 The pool of experts

A nonprobability purposive sampling method was employed to reach a targeted sample quickly and to ensure the assembly of a sample with known or demonstrable experience and expertise in the U.S. bioenergy, biofuel and bio-based products areas (Trochim, 2000). This qualitative pilot study identified eighteen experts from universities, national labs, and the industrial sector through exploratory documentary analysis and internet searches (Table 1).

University and industrial experts were identified by searching recent publications (2010 to 2015) via google scholar with the following four keywords/phrases: advanced biofuels, cellulosic biofuels, second generation biofuels, and integrated biorefinery. The ten most cited articles for each keyword were used to identify "experts." Overall, forty articles published in peer-reviewed journals, including *AlChE Journal*, *Biofuels, Bioprocessing and Biorefining (Biofpr)*, *Biomass & Bioenergy, Bioresource Technology*, *Biotechnology and Bioengineering*, *Chemical Engineering Journal*, *Chemical Engineering Research and Design*, *Energy Policy*, *Energy & Environmental Science*, *Environmental Science & Technology*, *Fuel*, *Green Chemistry*, *Renewable Energy,* and *Renewable & Sustainable Energy Reviews,* were selected. Of the forty articles, only the corresponding authors were included in our sample frame, resulting in forty identified experts who received our qualitative survey. Ten university experts and five industrial experts participated in this pilot study, resulting in a response rate of 37.5 percent (15/40).

In addition, government experts were solicited from the four U.S. national labs devoted to research and development of renewable liquid transportation fuels: (1) the Forest Products Laboratory in Madison, WI; (2) the National Renewable Energy Laboratory in Golden, CO; (3) the Oak Ridge National Laboratory in Oak Ridge, TN; and (4) the Pacific Northwest National Laboratory in Richland, WA. Experts from three of the four (75%) national labs participated in the pilot study.

2.1.2 Factor measurement and data collection

The data for this pilot study were obtained from an online survey (e-survey) conducted June to July, 2015 via SurveyMonkey® to decrease time and costs and to provide access to geographically dispersed subjects (Burns, 2010; James, 2007). A three-email strategy was applied for the data collection. The first email included

Table 1. List of participants for Phase I – qualitative pilot/exploratory study.

Participant	Sector	Expertise/Job Title
A	University	Technology of bio-based chemicals & products
B	University	Technology of integrated cellulosic biorefineries
C	University	Technology of cellulosic biofuels
D	University	Energy systems of biofuels
E	University	Technology of cellulosic biofuels & biorefineries
F	University	Economics of bio-based products
G	University	Policy of cellulosic biofuels
H	University	Technology of bio-based chemicals
I	University	Policy of bio-based products
J	University	Policy of cellulosic biofuels
K	National lab	Technology of cellulosic biofuels & bio-based chemicals
L	National lab	Environmental science of biofuels & bioproducts
M	National lab	Technology of cellulosic biofuels & biorefining
N	Industrial consultant	Technology and policy of biofuels & biochemical
O	Industrial consultant	Energy systems of biofuels
P	Industrial consultant	Energy systems of biofuels
Q	Industrial consultant	Technology of biofuels & biochemical
R	Industrial producer	CEO of bio-based chemicals & products plant

an embedded URL link to a SurveyMonkey® website, followed by two reminder emails at one-week intervals (Dillman et al., 2014). The e-survey instrument consisted of two open-ended questions designed to address the following topics: (1) barriers to the integrated production of biochemicals and cellulosic biofuels; and (2) potential solutions to identified barriers.

Thematic analysis was deployed for processing the qualitative information and coding the survey results into categories (Boyatzis, 1998). In this study, three coders, consisting of graduate students at Pennsylvania State University, were used. This three-coder protocol increases the reliability of thematic analysis and serves as a tie-breaking mechanism. In cases in which coders did not agree, themes were assigned by the two-thirds majority.[1]

2.2 Phase II: Quantitative confirmatory study

2.2.1 Study population

To test and validate the identified variables confronting the scale-up and development of the U.S. ICBR, expert perspectives throughout the U.S. biorefinery supply chain from feedstock to end-use value streams were pursued. The data used for analysis in Phase II were collected via quantitative surveys conducted from July to November, 2015. The sample population for this study included all attendees of the 2015 annual meetings of the seven U.S. Department of Agriculture (USDA) National Institute of Food and Agriculture (NIFA) Coordinated Agricultural Projects (CAPs) (Table 2) (NIFA, 2015).

To balance industrial expert group representation, attendees to the following two industrial conferences were added to our sample population: (1) the 5th National Advanced Biofuel Conference & Expo (NABC&E) and (2) the 12th Advanced Bioeconomy Leadership Conference (ABLC) (Table 2). The NABC&E is tailored to industry professionals engaged in producing, developing and deploying advanced biofuels, biobased platform chemicals, polymers and other renewable molecules. The ABLC provides a venue for senior leadership in the advanced bioeconomy focusing on advanced low carbon fuels, chemicals, and materials, plus advanced policies and financing strategies.

The Phase II quantitative surveys were administered to 678 academic and industrial expert participants, resulting in 228 respondents (34% response rate) (Table 2). The samples analyzed in this paper are non-probability con-

1 If the three coders had different interpretations, they were required to provide one general theme after further discussion. However, this did not apply to our study.

Table 2. Academic and industrial participants of seven USDA coordinated agricultural projects (CAPs) and two industrial conferences.

Regional CAPs and industrial conferences	Academic researchers (& participants)	Industrial experts (& participants)
Advanced Hardwood Biofuels Northwest (AHB)	82 (n=24)	14 (n=5)
Bioenergy Alliance Network of the Rockies (BANR)	63 (n=7)	6(n=1)
CenUSA Bioenergy	57 (n=13)	8 (n=6)
Southeast Partnership for Integrated Biomass Supply Systems (IBSS)	74 (n=26)	6 (n=3)
Northwest Advanced Renewable Alliance (NARA)	98 (n=47)	22 (n=5)
The Northeast Woody/Warm-season Biomass Consortium (NEWBio)	83 (n=52)	6 (n=5)
Sustainable Bioproduct Initiative (SUBI)	54 (n=9)	5 (n=1)
National Advanced Biofuel Conference & Expo (NABC&E)	-	40 (n=14)
The 12th Advanced Bioeconomy Leadership Conference (ABLC)	-	60 (n=10)
Total:	**511 (n=178)**	**167 (n=50)**

venience samples which, arguably, represent a unique set of knowledge and experience throughout the U.S. biorefinery supply chain from feedstock logistics, process development, economic/business, and sustainability analysis (Chen & Smith, 2017).

2.2.2 Factor confirmation and data collection

Based on Campbell and Fiske (1959) and Cuzzocrea and Sawilowsky (2009), a Multitrait-Multimethod Matrix (MTMM) was proposed as a valid method to measure each of several traits by each of several methods to ensure construct validity. The semi-structured survey instrument for Phase II consisted of RATING questions designed to examine the degree of each identified barrier from Phase I. A follow-up RANKING question was designed to force differences which may not have been produced in the RATING questions (Dillman et al., 2014) and to validate the relevance of these barriers to the integrated production of biofuels and biochemicals (Campbell & Fiske, 1959; Cuzzocrea & Sawilowsky, 2009).

Administration of the quantitative surveys included both onsite paper-based surveys during each 2015 annual AFRI CAP meeting and industrial conference, plus follow-up e-surveys, administered within a 4-week window following each venue, to increase response rates and address nonresponse bias issues. To assess non-response bias, two separate early-late respondent comparisons were conducted using a two-sample t-test on select survey questions: (1) those who responded to the initial onsite paper-based surveys (early respondents; n=147) were compared to the follow-up e-survey (late respondents; n=89); and (2) e-survey early respondents (1st email; n=52) were compared to e-survey late respondents (2nd and 3rd email; n=37). This methodology assumes late respondents generally behave more like non-respondents and therefore, may be used as a proxy for non-respondents (Armstrong & Overton, 1977; Miller & Smith, 1983; TRC, 2009; Welch & Barlau, 2013). The variables used for this comparison were years of experience and two measures of barriers to the integrated production of cellulosic biofuels and biochemicals: (1) the degree of competition vs. petro-chemicals and (2) policy uncertainty. The t-test indicated that, with 95% confidence, no significant differences were found between early and late respondents on their mean years of experience and perceptions of the two identified barriers, thus, setting aside nonresponse bias concerns.

According to modern scientific studies (Gary, 2007; National Center for Research Methods, 2009; TRC, 2009; Welch & Barlau, 2013), post-stratification is a technique to adjust for nonresponse bias by weighting, which includes two essential steps: (1) identifying a set of "control totals" for the population that the survey ought to match; and (2) calculating weights to adjust the sample totals to the control totals. In this study's quantitative survey, the population and sample distribution of USDA CAPs and industrial conferences were available. The weights for each program or conference were calculated as ["Weight = population % / sample %"] and applied to the responses to reflect the total sample population. Unadjusted and weighting-adjusted responses on the three variables previously tested by early-late respondent comparisons were also compared with a two-sample t-test. No significant difference at the 0.05 level was found between unadjusted and weighting-adjusted responses. Therefore, no evidence of significant nonresponse bias exists for this sample.

3.0 Results and Discussion

This section starts with the barriers identified through exploratory qualitative open-ended survey questions with the Phase I academic and industrial participants (n=18). Secondly, a discussion considers potential solutions to salient ICBR scale-up barriers from the Phase I qualitative pilot survey. Thirdly, we compare the average rating of the identified barriers based on the responses from the Phase II survey respondents (n=228), followed by the ranking results to validate the rating results and to better delineate the top three barriers in a meaningful and interpretable way.

3.1 Identification of barriers to the ICBR from Phase I (qualitative pilot study)

> **Question:** *In your opinion, what is the highest BARRIER to the integrated production of cellulosic biofuels and biochemicals?*

This open-ended question provided insightful thoughts regarding the highest perceived barriers to the integrated production of cellulosic biofuels and biochemicals from the Phase I experts (n=18). The authors interpreted responses to suggest eight common ICBR scale-up barriers (Fig. 2). Many of these barriers were linked to each other. For instance, technology uncertainty was associated with capital availability, and policy uncertainty influenced direct investments into the ICBR.

3.1.1 New technology availability

Four of the eighteen expert participants indicated ***new technology availability*** as the highest integrated production barrier (Fig. 2). The integrated production of both cellulosic biofuels and biochemicals requires additional processes to convert lignocellulosic biomass to renewable biochemicals. Also, two of the participants mentioned that technology is still at early stages of development and that additional challenges will be faced in transitioning to full, industrial scale production.

> *"Adding coproduct production potentially involves more 'new' steps that will require time/effort to learn how to operate well." (Participant A)*

> *"The availability of broad based technology to carry out production of chemicals, and the technology still has to be proven at large scale – struggling to get beyond pilot stage still –needs clear independent evidence of performance." (Participant L)*

3.1.2 Capital availability

Four respondents acknowledged that the ICBR faced the challenge of ***capital availability*** (Fig. 2). Of these, three respondents believed that unproven new technology was linked to the level of investment or funding.

> *"Adding another production process increases biorefinery capital cost – imposes a bigger financing hurdle to overcome." (Participant C)*

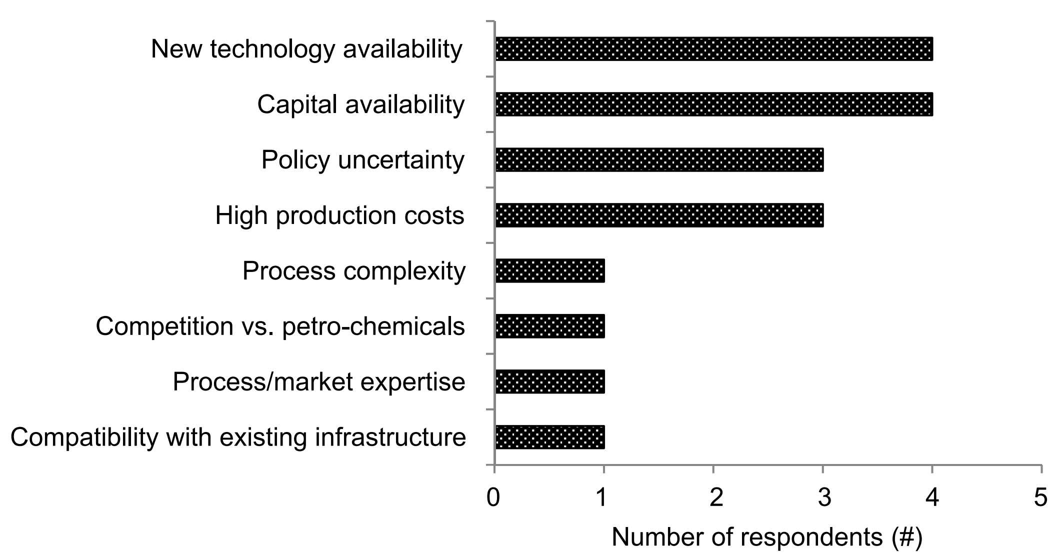

Figure 2. Perceived barriers to the integrated production of cellulosic biofuels & biochemicals solicited from the qualitative pilot study with experts [n=18].

"From an industry perspective, capital availability will be the major barrier to the integrated manufacturing of bioproduct and biofuel, and investors are hesitant to invest in technologies that have not been set-up for commercial manufacture yet." (Participant R)

3.1.3 Policy uncertainty

Policy uncertainty was acknowledged by three participants as the highest barrier to the integrated production scenario (Fig. 2). Also, policy uncertainty was associated with a negative impact on attracting investment.

"Stable and consistent policy will attract long-term investment, which is critical to drive forward biofuel technology as well as biochemical sector." (Participant G)

3.1.4 High production cost

Another three of the eighteen expert participants considered ***high production costs*** as the highest barrier to integrated cellulosic BRs (Fig. 2).

"…The cost of biofuels and bio-based chemicals derived from integrated cellulosic biorefineries given current technologies will be higher than that of petrochemically-derived materials or non-cellulosic biobased chemicals." (Participant H)

3.1.5 Additional barriers

Additional barriers to the scale-up of integrated cellulosic biorefineries included ***process complexity***, ***competition vs. petro-chemicals***, ***product/market expertise***, and ***compatibility with existing infrastructure***.[2]

3.2 Potential solutions to the barriers to ICBR from the qualitative pilot study

In order to explore potential solutions to the significant barriers to the commercialization of the ICBR identified in Phase I, and thus, to develop managerial implications, the Phase I pilot study concluded with an open-ended question as follows:

Question: *Can this highest barrier be overcome? How so or why not?*

According to the responses from eighteen expert participants, three common solutions were identified, including ***consistent government funding & incentives***, ***new technology development***, and ***education of the end-use consumer***.

3.2.1 Consistent government funding & incentives

Eleven of our eighteen participants indicated the importance and necessity of ***consistent government funding & incentives*** for a successful integrated cellulosic BR scenario. Most participants suggested that policy stability was critical to attract long-term investment. One participant advocated the need of equal government policies for both biofuels and biochemicals.

"Yes. Political commitment can drive investment and support for technology development through necessary loan guarantee or other forms of support." (Participant L suggested a solution to new technology availability)

"Yes. Need consistent and long-term government policies that level playing field of biofuels and bioproducts production. Consistent policy can help in access to capital. Costs can be reduced given research and development funding." (Participant M suggested a solution to high production costs)

"Yes. The government needs to encourage investors to invest in these integrated bioproduct/biofuel technologies just as it has encouraged them to invest in traditional corn ethanol biorefineries. Additional boost in investment in research on developing/improving integrated bioproduct/biofuel processes is required. (Participant R suggested a solution to capital availability)

Also, government plays an important role – through the taxation of carbon – in contributing to economic competitiveness of integrated cellulosic BRs.

"Yes. If there is economic incentive to do so, e.g., by implementation of policies that incentivize such production, e.g., imposition of attributes of carbon tax. Foremost, much greater policy certainty is needed, certainty that the improved sustainability attributes of cellulosic biofuels and biochemical technology will be valued such that their higher costs of production compared to current (fossil fuel-based) technologies can be justified." (Participant J suggested a solution to high production costs)

3.2.2 New technology development

New technology development was the second most frequently mentioned solution to the successful integrated production of cellulosic biofuels and bio-based chemicals. Four participants stated that new technol-

2 Each variable was mentioned by only one expert; therefore, no statement was provided.

ogy development, such as R&D in enzymes, conversion yields, and microbial technology, will ensure the scale-up of integrated cellulosic biorefineries. Meanwhile, the cooperation between industry and academic sectors were suggested by participant B as a promising solution to the technological barrier confronting the integrated production of cellulosic biofuels and biochemical.

> *"Yes, the scale-up needs new technology development, which could be achieved via cooperation and engagement between industry and academia." (Participant B suggested a solution to process complexity)*

3.2.3 Education of end-use consumer

One participant mentioned the lack of customer preference in terms of price premium when comparing bio-based chemicals with petroleum-based alternatives and emphasized the importance of ***education of end-use consumer*** regarding the environmental benefits of bio-based products.

3.3 Confirmation of barriers to the ICBR by Phase II rating (quantitative confirmatory study)

In Phase II's quantitative paper-based surveys and e-surveys, the study's 228 respondents were asked to RATE the relative "degree" of the eight barriers by answering the following fixed-format question:

> **Question:** *Please indicate the degree to which you consider the following 8 factors as BARRIERS to the integrated production of biochemical and cellulosic biofuels.*[3]

This study's 221 participants, collectively, rated the eight barriers as moderate to high, which underscores the relevance of the eight factors, identified from the former pilot study, to the integrated production of biofuels and biochemicals. Overall, ***competition vs. petro-chemicals***, ***high production costs***, ***policy uncertainty***, and ***capital availability*** were rated as significantly higher barriers[4] versus the remaining four, with overall mean values of 3.97, 3.89, 3.86, and 3.75 (Table 3). The high production costs of cellulosic biofuels and biochemicals was highlighted by a cost competitiveness analysis in a recent USDA report (Nexant, 2014), which stated that with higher production costs, cellulosic biofuels and biochemicals are less likely to be economically competitive with traditional petroleum-based alternatives. ***Policy uncertainty***, the third highest barrier, is supported by several studies indicating the adverse impact of unreliable policies on the large-scale production of bio-based chemicals (Carus et al., 2011; Carus & Dammer, 2013). ***Capital availability*** was rated as the fourth highest barrier overall, which highlights the difficulty for the business community to attract capital investment with nascent technology and an uncertain political environment (Maity, 2015).

The second tier of ICBR scale-up barriers included ***process complexity*** (3.48), ***new technology availability*** (3.40), ***compatibility with existing infrastructure*** (3.39), and ***product/market expertise*** (3.32) (Table 3). These results are in line with existing literature suggesting that the availability of new conversion processes for biochemicals and the compatibility with existing infrastructure are critical to the commercial development of the ICBR (Bozell & Petersen, 2010; de Jong et al., 2012; Richard, 2010). Also, the fuel and chemical value stream outputs of the ICBR will require unique knowledge about products, channels, and end-use consumers.

Respondents were organized according to their self-described expertise into four groups: (1) Feedstock (F); (2) Processing (P); (3) Economics/Business (E/B); and (4) Sustainability (S) (Table 3). Significant differences between respondent group mean values were found at the p=0.10 significance level (using ANOVA) for three out of the eight drivers identified in this study (Table 3). In particular, Economics/Business experts (E-B) largely viewed potential ICBR industry scale-up barriers differently than the other three groups. E-B participants viewed ***product/market expertise*** as relatively higher impeding factors compared to the other three expert groups. On the other hand, E-B and Sustainability (S) experts rated ***competition vs. petro-chemicals*** as a lower obstacle to integrated cellulosic BR than Feedstock (F) specialists and Processing (P) scientists. Meanwhile, Processing scientists (P) rated ***process complexity*** as a significantly higher barrier to the commercialization of ICBR than the other experts. The comparison among research groups provides a basic understanding of the commonality between bioenergy researchers.

3 The degree of these eight barriers were measured using a 5-point Likert-type scale, from 1=not a barrier to 2=low barrier to 3=moderate barrier to 4=high barrier to 5=very high barrier.

4 Using Pairwise Comparisons based on two-sample t-tests at the p=.10 level.

Table 3. The mean value of the RATING[1] of the eight barriers to the integrated production of biochemicals and cellulosic biofuels and significant differences of perceived barriers among four participant categories: Feedstock (F), Processing (P), Economics/Business (E-B), and Sustainability (S).

	Overall (n=221[2])	F (n=85)	P (n=71)	E-B (n=39)	S (n=26)		
Scale-up BARRIERS	Mean value					Sig.[3]	Pairwise Comparisons[4]
1. Competition vs. petro-chemicals	**3.97**	4.08	4.10	3.68	3.65	**0.031**	P, F > E-B, S
2. High production costs	**3.89**	4.01	3.80	3.82	3.88	0.393	
3. Policy uncertainty	**3.86**	3.87	3.86	3.81	3.88	0.992	
4. Capital availability	**3.75**	3.71	3.79	3.84	3.60	0.730	
5. Process complexity	**3.48**	3.36	3.69	3.42	3.38	**0.071**	P > F, S, E-B
6. New technology availability	**3.40**	3.33	3.59	3.26	3.35	0.172	
7. Compatibility with existing infrastructure	**3.39**	3.44	3.39	3.37	3.30	0.866	
8. Product/market expertise	**3.32**	3.32	3.29	3.55	3.04	**0.074**	E-B > S
Pairwise Comparisons[4]	**1-4>5-8**	1,2>3-8; 1-7>8	1>5-8; 1-7>8	2>3-8	1-3>4-8	-	-

1 Rating was measured using a 5-point Likert-type scale, from 1=not a barrier to 2=low barrier to 3=moderate barrier to 4=high barrier to 5=very high barrier.
2 Seven incomplete responses were deleted, resulting in 221 responses entering the final analysis.
3 Based on a parametric analysis of variance (ANOVA) test, bold = significant at the 0.10 level.
4 Based on a two-sample t-test at the 0.10 significance level.

3.4 Validation of barriers to the ICBR by Phase II ranking (quantitative confirmatory study)

A follow-up RANKING question was designed to better explain and validate the RATING scale responses regarding potential barriers to the scale-up of the U.S. ICBR (Dillman et al., 2014).

> **Question:** *Please indicate the TOP 3 highest barriers to integrate the production of biochemicals into a second generation (cellulosic) plant, by using the pull-down menu of the 8 BARRIERS listed in former rating question.*

All responses were given a value weighting of 3 points for the "#1 RANKED commercialization barrier," 2 points for the "#2 RANKED commercialization barrier" and 1 point for the "#3 RANKED commercialization barrier." Interestingly, the three highest RATED barriers to integrated cellulosic biorefinery (Table 3) were also identified as the highest RANKED barriers in Figure 3, providing a measure of construct validity. ***Competition vs. petro-chemicals*** was the #1 ranked *"highest barrier"* by 56 expert participants and with a cumulative score of 239 when participants were forced into a rank-ordering (Fig. 3). The second ranked commercialization barrier

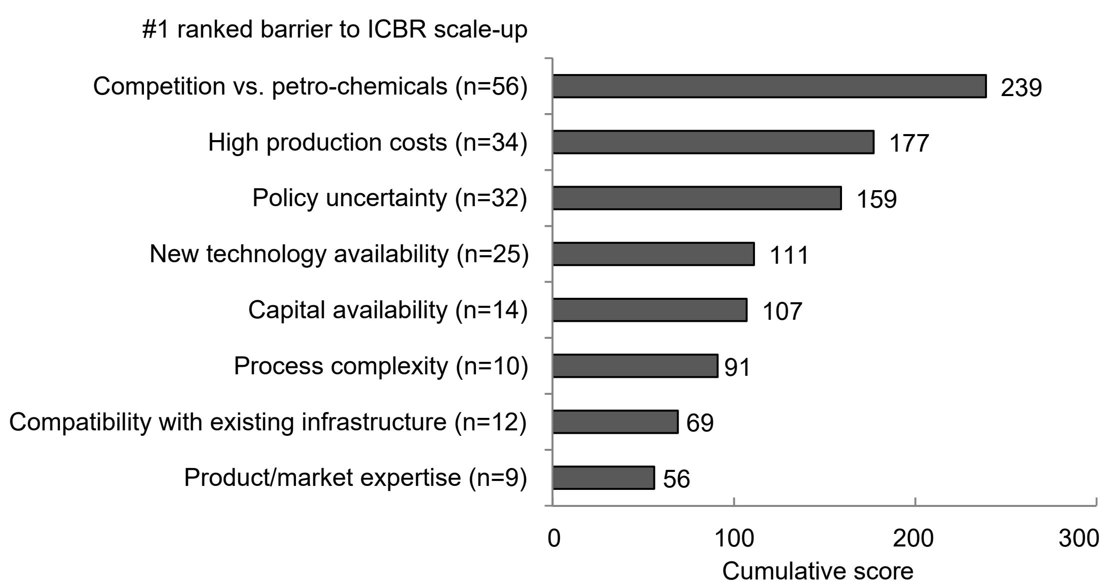

Figure 3. Number of "#1 RANKED commercialization barrier" and cumulative score for the eight barriers by all respondents [n=204].

was ***high production costs*** with a cumulative score of 177, followed by ***policy uncertainty*** with a cumulative score of 159 (Fig. 3).

4.0 Conclusions

Cellulosic biofuels represent a promising solution to reduce U.S. dependence on fossil fuels and increase energy security, while addressing the food-vs.-fuel debate confronting the U.S. corn-grain ethanol industry. Significant progress has been made in the last decade with respect to research and development. However, the U.S. cellulosic biofuels industry has yet to become widely commercialized due to a variety of reasons, such as high production costs, policy uncertainty, and strong competition from petroleum-based fuels. The integrated cellulosic biorefinery scenario provides many practical benefits including the effective use of feedstock fractions, diversified value stream outputs, improved financial performance and risk mitigation.

Overall, the results of this study illustrate the applicability of the mixed-methods exploratory sequential design for the U.S. cellulosic biorefinery industry. Specifically, the Phase I qualitative e-survey, administered to eighteen "select" experts, identified eight barriers confronting the commercial development of the U.S. integrated cellulosic biorefinery (ICBR) (producing both cellulosic biofuels and biochemicals). In Phase II, 228 academic research and industrial experts from seven USDA CAPs and two pertinent industrial conferences confirmed the importance of these eight barriers by rating them as moderate to high. Most importantly, results from a combination of rating and ranking questions revealed that the top three successful scale-up barriers to the ICBR include ***competition vs. petro-chemicals***, followed by ***high productions costs*** and ***policy uncertainty***. While mixed methods research can provide rich insights into the barriers to the integrated production of cellulosic biofuels and biochemicals in the United States, these results may not be generalizable to the worldwide cellulosic biorefinery industry as a whole. The types of barriers are likely to vary across different geographic, political, and socioeconomic contexts.

The comparison among research groups provides a basic understanding of the commonality between bioenergy researchers. This study's results also highlighted the differences among self-described participant groups. In particular, Economics/Business experts rated ***product/market expertise*** as a relatively higher impeding factor compared to the other three expert groups, and viewed ***competition vs. petro-chemicals*** as a significantly lower obstacle to the ICBR scale-up versus Feedstock specialists and Processing scientists. Meanwhile, Processing scientists rated ***process complexity*** as a significantly higher barrier to the commercialization of the ICBR than the other experts. The identified perceptional differences among participants regarding the factors confronting the U.S. cellulosic biofuels industry are understandable since each expert group has their own research focus and interests. These findings also highlight the significance of examining issues from multiple perspectives and highlight the value of the integrated USDA NIFA CAP research program.

This paper highlights a number of implications for existing industrial players, new entrants and policymakers. ICBR success is perceived to require ***supportive and consistent government funding & incentives***. As discussed in this study, the successful ICBR calls for a level playing field of policy support for both biofuels and biochemicals. Among the government policies and incentives, loan guarantees, R&D funding and monetizing carbon were suggested to help renewable biofuels and biochemicals achieve cost-competitiveness with petroleum-based counterparts. Additionally, competition with petroleum-based alternatives requires ***new technology development*** to reduce overall production costs, and more importantly necessitates the ***education of end-use consumers*** regarding climate impacts and the environmental benefits of renewable bio-based products. This study contributes to extant debates regarding the future commercial development of the Integrated Cellulosic Biorefinery (ICBR).

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