U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Biomass Indirect Liquefaction Strategy Workshop

Workshop Summary Report

July 2014

Biomass Indirect Liquefaction Strategy Workshop

A workshop summary report from the Biomass Indirect Liquefaction Strategy Workshop

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Golden, CO

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TABLE OF CONTENTS

INTRODUCTION

The U.S. Department of Energy's Bioenergy Technologies Office (BETO) held the Biomass Indirect Liquefaction Strategy workshop on March 20–21, 2014, in Golden, Colorado. The workshop focused on discussing and detailing the research and development (R&D) needs for biomass indirect liquefaction (IDL). Discussions focused on full IDL pathways, including feeder systems through fuel finishing. The workshop had four main goals:

1. To discuss, learn, and document the technical and economic barriers to cost-competitive IDL.
2. To clearly define the R&D needed to mitigate those barriers.
3. To develop a description of the needed R&D.
4. To identify a timeline of completing the research, development, and deployment (RD&D).

Representatives from government and national laboratories, academia, and industry attended the workshop; a distribution of the 40 workshop attendees among these sectors is shown in Figure 1. This report solely represents the views of the participants that attended the workshop (Appendix B: Participant List). It does not include any additional input from any other party and does not represent the views of BETO.

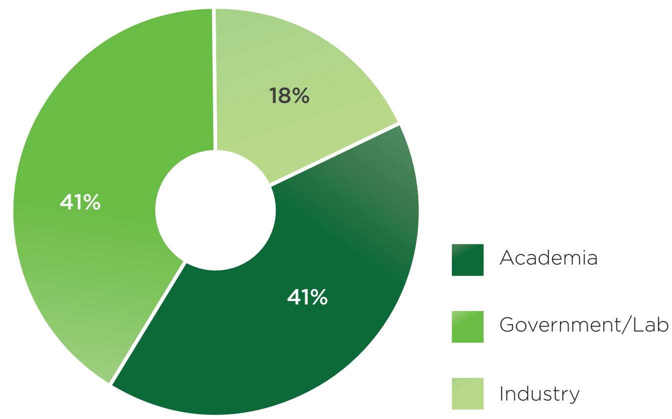

Figure 1. Distribution of workshop attendees from academia, government and national laboratories, and industry.

BACKGROUND AND WORKSHOP PROCESS

Brief Biomass Indirect Liquefaction Background

Indirect liquefaction (IDL) of biomass commonly includes gasification technologies to break down lignocellulosic feedstocks—such as wood and forest products—into synthesis gas (syngas)—primarily carbon monoxide and hydrogen. The makeup of syngas will vary due to the different types of feedstocks, their moisture content, the type of gasifier used, the gasification agent, and the temperature and pressure in the gasifier. The syngas produced undergoes clean-up and conditioning to become a contaminant-free gas having the appropriate hydrogen-carbon monoxide ratio. Among the contaminants removed during clean-up are tars, acid gas, ammonia, alkali metals, and other particulates. Once the desired syngas quality is achieved, the syngas can be catalytically converted into fuels and products.

The Bioenergy Technologies Office (BETO) has historically focused on biomass IDL processes targeted at both ethanol and hydrocarbon liquid transportation fuels. In the fall of 2012, scientists at the U.S. Department of Energy's national laboratories successfully demonstrated two cellulosic ethanol production processes at a cost of $2.15 or less per gallon. These processes included gasification of corn stover and woody feedstocks followed by clean-up and fuels synthesis. The team optimized an indirect steam blown gasifier, developed tar- and methane-reforming technologies, and vastly improved catalytic conversion technologies. Since achieving this target, BETO is focusing on biomass IDL technologies for the production of hydrocarbon transportation fuels such as diesel, gasoline, and refinery blendstocks.

Workshop Proceedings

A full workshop agenda can be found in Appendix A: Agenda. The workshop began with an introductory presentation from Paul Grabowski, a technology manager at BETO who specializes in the biomass gasification and IDL portfolio. Presentations continued from the following biomass IDL industry professionals, who discussed key hurdles that they had to overcome in their experiences with integrated biorefinery (IBR) projects:

- Dennis Schuetzle, President at Renewable Energy Institute International, who spoke about their 25 ton/day IBR in Toledo, Ohio.
- Joshua Pearson, Owner at JBP LLC, who spoke about the Clearfuels-Rentech 16 ton/day IBR in Commerce City, Colorado.
- Dan Burciaga, President and CEO at ThermoChem Recovery International, who spoke about their 4 ton/day facility in Durham, North Carolina.
- Niels Udengaard, Syngas Technology Manager at Haldor Topsoe, Inc., who spoke about their 20 ton/day facility in Des Plaines, Illinois.

These presentations can be found on the Biomass Indirect Liquefaction Workshop Web page (energy.gov/eere/bioenergy/biomass-indirect-liquefaction-workshop).

Participants said they were impressed to hear how far certain biomass IDL companies have already come and that the industry is far-enough along to provide BETO with specifics on hurdles that they have encountered and overcome. Participants pointed out that industry should continue to be honest with their challenges and that the more information that BETO can share from industry reports, the better it will be for the growth of the biomass IDL industry.

Following the morning of presentations, the remainder of the workshop included three facilitated sessions: (1) Feeder Systems, Gasification, and Syngas Clean-Up, (2) Catalyst Development for the Production of Intermediates and Final Products, and (3) Modeling and Other Enabling Technologies. In each of these sessions, participants were asked to discuss key R&D areas, needs, and the timeframes in which these R&D objectives should be accomplished. These needs were organized onto notecards, and participants discussed where each of the notecards fit on a brainstorm map. After each of the three sessions, participants were given five votes and were asked to select which R&D needs they thought of as having the highest importance. A call-out box in each section of this report shows which R&D needs received the most votes per session.

A full listing of the brainstorming outcomes is in Appendix C: Full Note Listing from Brainstorm Map. Brainstorming outcomes are referenced in the text of this report by parentheses referring to time frame of the research category in years, e.g. (0–3).

At the end of the workshop, participants were offered a chance to present concluding remarks. Their remarks and the outcomes of the three facilitated sessions are summarized in this workshop summary report.

WORKSHOP DISCUSSIONS

The following sections of this report summarize what participants noted in each of the workshop sessions as key challenges to the biomass indirect liquefaction industry. These challenges are noted with timeframe in years, i.e., (0–3). More information is found in Appendix C, where each challenge is categorized by session, research category, and timeframe.

Workshop discussions aimed to answer the following questions:

1. What are the areas of research for each session?
2. In what timeframe must these key R&D needs be completed?
3. What are the overall key R&D needs?

Session 1: Feeder Systems, Gasification, and Syngas Clean-Up

R&D Needs with Most Votes Breakout Session 1	
12 Votes	Multi-contaminate removal technology
10 Votes	Consortium of biomass handling companies to provide “best practices” and/or a user group
10 Votes	In-situ tar cracking or control • Catalytic gasification and additives or high temperature
10 Votes	On-line, real-time analytical measurement of low-concentration impurities

The first session of this workshop focused on biomass IDL front-end technologies, including feeder systems, gasifiers, and syngas clean-up systems. Participants highlighted the need for information databases and lessons learned from past projects, and emphasized that every new project should not have to re-invent the wheel for all of its equipment.

A large amount of discussion revolved around potential roles the Bioenergy Technologies Office (BETO) can play within the feedstock/gasifier interface area, focusing on ideal systems for the pressure boundary between feeders and gasifiers. Participants noted that many professionals in the biomass IDL business are not feedstock feeder experts, and it would be useful for BETO to help facilitate the process of fitting such feeder systems with biorefineries. A consortium of biomass handling companies could be formed, through which information on best practices could be released to the public (0–3). BETO could work with feeder companies on compiling a matrix that shows which feeders work with which feedstock/gasifier integrated systems. Current information from the coal and other related industries could also be useful. Participants acknowledged that it would be a hurdle for BETO to share propriety feeder system data; however, they stressed the importance of organizing the data to prevent industries from continually re-inventing the wheel (0–3).

Another approach to overcoming feeder system hurdles would be to have a user facility available to test specific feeder systems at pressure and scale for its integration into different gasifiers (3–5). This process would enable an easier transition to the next generation of biomass feeder systems. It could also be useful to look into pretreatment systems that could universally solve feed reliability problems for gasification feeding (0–3).

The gasification process for IDL does not face too many major challenges; however, there are still areas that could be improved. Participants said the main interest in R&D for gasification technologies was low-cost and efficient in-situ tar cracking and tar control (3–5–10–∞), but later conversations questioned how much effort should be put toward such a historically difficult challenge. The materials used in gasifier construction could be optimized to limit corrosivity issues. Material research of new metallurgy and other novel innovative materials could be used to reduce reactor corrosion issues at high temperatures (0–3). Participants suggested that BETO work with the Office of Energy Efficiency and Renewable Energy’s Advanced Manufacturing Office (AMO) on high-temperature materials such as those used in concentrated solar power and other potentially cross-cutting materials (3–5). Other interagency work can be done to investigate hybrid gasification systems, such as systems that also use coal and natural gas, to study how these fuels can most effectively be integrated (0–3).

Participants mentioned many needs for syngas characterization, including the characterization of syngas components all the way down to trace metal levels (0–3). It would be highly beneficial to syngas clean-up processes if these analytics could occur on-line and in real time to measure such low-concentration impurities (3–5). To remove these contaminants, syngas clean-up requires multi-contaminant removal technology, and more R&D should be conducted on low-cost adsorption/absorption systems (3–5). Innovative techniques such as hot gas filtration and new ways of process integration, such as combined unit ops, should be studied to help tailor syngas quality suitable for production of liquid fuels and bioproducts (0–5).

Session 2: Catalyst Development for the Production of Intermediates and Final Products

R&D Needs with Most Votes Breakout Session 2	
12 Votes	New materials for catalyst development (phosphides, nitrides, carbides) and Improving/innovating catalyst design to improve selectivity and productivity
11 Votes	Clean syngas affords possibilities for different back-end opportunities (e.g., bio to EtOH, methanol to gasoline) syngas to $
10 Votes	Improving reactor design to integrate catalyst • Membrane • Catalytic distillation • Slurry • Fixed beds • Fluidized beds • Circulating fluid beds • Ebullating beds • Microchannel

In the second session of the workshop, participants looked at challenges and areas of improvement for catalyst development for the production of intermediates and final products. New catalysts need to be designed, tested, and then produced at appropriate quantities, and each of these steps has challenges to overcome. Subtopics brought up in this session included higher-value proposition from catalysts, catalyst development infrastructure, alternative syngas conversion, process economics, biochar utilization, and renewable hydrogen. The timeline of the catalyst activities is not clearly defined because many of these catalyst-related activities are currently small scale. However, as they scale up, they will extend to future years. For example, a new catalyst can start at the proof-of-concept stage and then go on to demonstration in 10 or more years.

It is important for catalyst technologies to continue improving lifetime, yield, and selectivity to high-value fuels and products (0–3). Tunable and more selective catalysts should be composed to produce a non-wax hydrocarbon distribution with enhanced chain termination (0–3). These catalysts need to be resistant to coking, and would ideally be self-cleaning, possibly by containing mobile oxygen. Some of the effects of uncommon catalyst contaminants are not entirely understood, and to improve catalyst resistance, there needs to be a better understanding of the catalyst's limits (0–5). It would be beneficial to look into the costs versus tolerability of catalysts.

To obtain a better catalyst price/value, selectivity, and lifetime, there needs to be proof-of-concept, and possibly a new IDL catalyst development infrastructure. New and innovative catalyst design, production, and validation face complexities (0–3). There are many facilities that test catalysts, but it might be advantageous to have catalyst screening centers available for companies to use. It is important to be able to test at larger scales as these conditions change from lab scale to scales of several hundred pounds. These larger scale tests should also consider effective separations and recycling processes (3–5). In addition to scale factors, are time factors, and there is also a need for long-term testing. There needs to be support for long-term catalyst demonstrations (3–5); maybe these demonstrations can be replaced by a dependable accelerated deactivation test (3–5). Participants also mentioned the potential of a catalyst test protocol that would have defined metrics (0–3).

Participants discussed advances in (1) alternative syngas conversion and (2) process economics as two areas with significant R&D challenges. Obtaining clean syngas affords possible back end innovative opportunities. Outside of the more common Fischer-Tropsch and methanol to gasoline processes, are there other catalytic syngas processes that could prove valuable to industry (0–3)? Some other processes may include the conversion of syngas to higher alcohols, a process which participants noted requires more R&D on catalysts (0–3). Research and development can also be focused on catalytic or other cost-effective conversion methods of CO_2 to value-added products (0–3), and more effective and economic water gas shift processes.

To potentially improve process economics, R&D can be directed at enhanced reactor designs to better integrate catalysts. There is a large variety of reactor processes, and these processes need to be combined with catalyst development R&D. These design enhancements include—but are not limited to—reactors such as fluidized beds, circulating fluid beds, and ebullating beds, and separation processes such as membranes, catalytic distillations, microchannels, and slurry technology improvements (0–5). Some longer-term IDL process intensification challenges include aspects in series reactions, product separation and withdrawal, and catalyst filtration (5–10).

Session 3: Modeling and Other Enabling Technologies

R&D Needs with Most Votes Breakout Session 2	
12 Votes	Better fundamental models of gasification process (e.g., kinetics devolatilization, carbon reactions)
11 Votes	Support for computational fluid dynamics (CFD) models for gasifier and reactor optimization/scale-up
10 Votes	Develop and provide plug-in modules for unit operations
11 Votes	Biofuels computational center of excellence and CFD—kinetics–validation • Super computer • Experiment support and data for validation • Model development

The third and final session of the workshop covered a wide scope of IDL process-improvement challenges. Workshop participants filed these challenges into the following categories: process modeling, unit op/multi-physics modeling, sustainability modeling, enabling technologies, project assessment, and cross-cutting/info sharing. A main recurring theme from this session is that information, and the models that run the information, need to be easily accessible. It is disadvantageous for researchers to compile information and build and run their models in an information vacuum.

Participants noted that it is difficult to scale projects; this is mainly a catalyst issue. A solution could be to create a user facility that could specialize in scaling up technology from bench scale. Participants suggested that BETO could help in the development of these plug-in modules for unit operation scale-up, integration, and optimization analysis (0–3). There is a gap to fill because the catalyst companies prefer to work in tons, and the results of lab tests are often measured in grams (0–3). Participants agreed that there is a large immediate need for modeling work on process optimization and integration modeling through process simulations (0–3). This work should not exclude modeling the materials of construction and system interactions such as metallurgy, waste heat recycling, and refractor system integration (3–5). Some participants mentioned that there has already been substantial work researching materials and low-grade heat recovery, and that the remaining challenge, again, is the need to share information that already exists.

More specifically, a large portion of participants agreed that there is a great need for better fundamental models of gasification processes (e.g., kinetics, devolatilization, carbon reactions) in the near-term (0–3)—specifically, computational fluid dynamics (CFD) models for feeders, gasifiers, and fuel synthesis reactors to enable project optimization scale-up (0–3). Participants added that while the reactor modeling business is important for real-time control, there is also a need for real analytics on the chemistry of the reactions. In the mid-term, there is a great need for R&D on fundamental heterogeneous reaction models, including catalysts, bed materials, membranes, char, and ash (3–10). R&D in these areas is important because the appropriate data and basic properties are needed to model a gasification process. On a similar thread, participants acknowledged that there is some data available now, and it might be the most useful to, at the same time, make models as general as possible and as specific as possible with these basic properties. R&D should be conducted on a general model through which users can enter a general biomass material for specific screening tools. This model could be enhanced by using a pinch analysis or a sensitivity analysis to determine which variables are the most important so that users can perform analyses focused in these areas.

In reactor modeling, almost everything is crosscutting. There is currently much better computing and analytical power compared to 20 years ago along with a lot of expertise, but knowing where to obtain access to these resources is an issue. Many participants noted the value of a "biofuels computational center of excellence" that can cover multiple aspects of the biomass IDL process, including CFD, kinetics, and validation from use of a super computer and experimental support and data for validation (0–3). Some participants mentioned that the National Renewable Energy Laboratory has supercomputing capabilities, and maybe this or another resource could be used as a resource to provide CFD modeling and computation for users in biomass IDL reactor modeling.

In regards to techno economic analysis and life cycle assessment, participants would like less complex and more reliable software to analyze their biomass IDL processes. Current models, such as those in ASPEN and GREET, can sometimes be difficult to use, and lighter versions of these models or accompanying user interface "wizards" would be helpful to the RD&D community (0-3). It will also be valuable to incorporate water use and water reuse into these life cycle assessments across the entire IDL process. It would be ideal to have the capabilities to build a near net zero facility, and such water use variables can include feedstock dewatering technologies and proper/best uses for waste heats (0–3). In addition to techno economic analysis, IBR project assessment evaluations would help determine how product volumes and locations impact the product market (10+). Some data already exists for industry to learn such project site-specific detail, but this data is not well known and should be made more accessible (0–3). Also, once IDL gets to the nth plant stages, it would be beneficial to know the details of product markets (0–10).

PARTICIPANT CONCLUDING REMARKS AND SUMMARY

The following are summaries of some of workshop participants' concluding remarks:

- **Feedstock Feeder Systems**: Most of the participants were gasification and conversion developers and emphasized that and they do not want to spend large efforts on feedstock systems. The theme was that there is a need for something out there for the industry to easily access.
- **Gasification Technology**: Participants noted that there was not much specific discussion at the workshop yet about the technical and economic trade-offs surrounding pressurizing the gasifier and efficiently getting syngas up to pressure. There was also a discussion on in-situ tar cracking. Many participants noted that additional R&D in this area would be helpful while also noting that it has been researched for many decades without a solution. The question came up that if a topic is well studied and still not necessarily solved, should BETO focus efforts on trying to solve it?
- **Catalyst Development**: Syngas composition is a problem for catalyst developers because biomass gasification process conditions can vary drastically. It would help to set boundary conditions that can either rule in or out which catalysts to develop in this field.
- **Modeling and Intensification** Participants repeatedly brought up the lack of easily accessible reliable data. It was suggested that BETO's Bioenergy Knowledge Discovery Framework (KDF) could be utilized as a means of sharing such data. Adding a modeling database to the KDF would help users find relevant data and models and could be combined with data on feeder systems.

In summary, it was clear that the lessons learned from past projects would be highly beneficial information for future projects, and that in many cases, biomass IDL R&D does not need to necessarily reinvent the wheel; it just needs to keep improving and extending it.

APPENDIX A: AGENDA

Day 1–Thursday, March 20

TIME	EVENT
8:00 a.m.–8:30 a.m.	*Registration*
8:30 a.m.–9:00 a.m.	**Welcome and introduction – Paul Grabowski, Technology Manager, Bioenergy Technologies Office**
9:00 a.m.–11:30 a.m.	**Speakers discuss key challenges for biomass indirect liquefaction (IDL)**
9:00 a.m.–9:30 a.m.	Dennis Schuetzle, President at Renewable Energy Institute International
9:30 a.m.–10:00 a.m.	Joshua Pearson, Owner at JBP LLC
10:00 a.m.–10:30 a.m.	*Break*
10:30 a.m.–11:00 a.m.	Dan Burciaga, President and CEO at ThermoChem Recovery International
11:00 a.m.–11:30 a.m.	Niels Udengaard, Syngas Technology Manager at Haldor Topsoe, Inc.
11:30 a.m.–12:30 p.m.	*Lunch break*
12:30 p.m.–1:00 p.m.	**Explanation of workshop and introduction to Session 1**
1:00 p.m.–2:30 p.m.	Breakout Session 1: Feeder systems, gasification, and syngas clean-up
1:00 p.m.–1:30 p.m	What are the areas of research for feeder systems, gasification, and syngas clean-up?
1:50 p.m.–2:00 p.m.	*Break*
2:00 p.m.–2:15 p.m.	What are the overall key research and development (R&D) needs?
2:15 p.m.–2:30 p.m.	What is the order in which the key R&D needs must be addressed? In what time frame must these key R&D needs be completed?
2:30 p.m.–3:00 p.m.	**Afternoon break and introduction to Session 2**
3:00 p.m.–4:30 p.m.	Breakout Session 2: Catalyst development for the production of intermediates and final products
3:00 p.m.–3:30 p.m.	What are the R&D needs for catalyst development?
3:30 p.m.–3:50 p.m.	What are the areas of research for catalyst development?
3:50 p.m.–4:00 p.m.	*Break*
4:00 p.m.–4:15 p.m.	What are the overall key R&D needs?
4:15 p.m.–4:30 p.m.	What is the order in which the key R&D needs must be addressed? In what time frame must these key R&D needs be completed?
4:30 p.m.–5:00 p.m.	**Conclude Day 1**

Day 2–Friday, March 21

TIME	EVENT
8:30 a.m.–10:00 a.m.	**Breakout Session 3: Modeling and other enabling technologies**
8:30 a.m.–9:00 a.m.	What are the R&D needs for modeling and other enabling technologies?
9:00 a.m.–9:20 a.m	What are the areas of research for modeling and enabling technologies?
9:20 a.m.–9:30 a.m	*Break*
9:45 a.m.–10:00 a.m.	What is the order in which the key R&D needs must be addressed? In what time frame must these key R&D needs be completed?
10:00 a.m.–12:00 p.m.	**Report Outs/Conclusion** **What are the overall priority R&D needs for biomass IDL?**

APPENDIX B: PARTICIPANT LIST

FIRST NAME	LAST NAME	COMPANY
Craig	Brown	Catchlight Energy LLC
Dan	Burciaga	ThremoChem Recovery Int'l, Inc. (TRI)
Vann	Bush	Gas Technology Institute
Kevin	Craig	U.S. Department of Energy, Bioenergy Technologies Office
David	Dayton	RTI International
Anthony	Dean	Colorado School of Mines
Alan	DelPaggio	CRI Catalyst Company
Corinne	Drennan	Pacific Northwest National Laboratory
Cindy	Gerk	National Renewable Energy Laboratory
Paul	Grabowski	U.S. Department of Energy, Bioenergy Technologies Office
Joseph	Hartvigsen	Ceramatec, Inc.
Jesse	Hensley	National Renewable Energy Laboratory
Douglas	Jack	Sundrop Fuels Inc.
Ted	Krause	Argonne National Laboratory
Sarah	Luchner	BCS, Incorporated
David	Lynch	Enerkem Inc.
Kim	Magrini	National Renewable Energy Laboratory
Anthony	Martino	Sandia National Laboratories
Michael	Matzen	University of Nebraska–Lincoln
Wayne	McFarland	SynTech Bioenergy, LLC
Michael	Mundschau	TDA Research, Inc.
Joshua	Pearson	JBP LLC
Mark	Penshorn	SAIC
Karthikeyan	Ramasamy	Pacific Northwest National Laboratory
Dr. Dennis	Schuetzle	Renewable Energy Institute International
Reinhard	Seiser	University of California, San Diego
Christopher	Shaddix	Sandia National Laboratories
Ashokkumar	Sharma	Center for Sustainable Environmental Technologies, Iowa State University
Seth	Snyder	Argonne
Michael	Talmadge	National Renewable Energy Laboratory
Roy	Tiley	BCS, Incorporated
Scott	Turn	Hawaii Natural Energy Institute, University of Hawaii
Cynthia	Tyler	CNJV
Niels	Udengaard	Haldor Topsoe, Inc.
Zhiyou	Wen	Iowa State University
Kevin	Whitty	University of Utah
Paul	Wood	CH2M HILL

APPENDIX C: FULL NOTE LISTING FROM BRAINSTORM MAP

Workshop participants wrote proposed needs for research and development on notecards, which they then fit together onto a brainstorm map. After each session, participants were given five votes and were asked to select which R&D needs they thought of as having the highest importance. R&D needs are referenced according to the timeframe of the research category in years. The technology scale is also given for each R&D need (1 = proof of concept/feasibility through bench scale; 2 = non-integrated pilot scale; 3 = integrated pilot/demonstration). The following is the full listing:

Session 1 Results: Feeder Systems, Gasification, and Syngas Clean-Up

RESEARCH CATEGORY	TIMEFRAME (years)	R&D NEED	TECHNOLOGY SCALE	VOTES
Feeder Systems	0–3	Consortium of biomass handling companies to provide "best practices" User group	1	10
		Feedstock characteristics and performance Idaho National Laboratory database • Available • Added to	1/2/3	1
		More lesson learned • After Action Reviews • Post Project Disclosures	2/3	4
		Commercial equipment performance database or test facility	2/3	2
		What pretreatment is economical that can universally solve the feed reliability problem?	1	8
		Can coal feeders work for biomass? • Aerojet Rocketdyne • GE/Stamet • Other?	1	4
		Systems level analysis feedstock availability, impact	1	0
		Controls (bad logic) pressure boundary • Sensors/analysis for feedstock measurement	2	1
		Valves (erosion, leaks) • Pressure boundary • Durability/reliability	2/3	0
		Long-term feeder testing, under integrated and real-world conditions at pilot through commercial scale	3	0

RESEARCH CATEGORY	TIMEFRAME (years)	R&D NEED	TECHNOLOGY SCALE	VOTES
Feeder Systems	3–5	Feedstock pre-processing • Contaminant removal	1/2	1
		Materials separation • Dealing with biomass variation contaminants • Cost effective	2	0
		Feedstock pretreatment • Consistency • Densification (to liquids?)	2/3	0
		Integration of feedstocks vs. separate systems • Feed reliability	1	
		Feeder/gasifier integration Type/separation for fixed fluidized	1	3
		User facility to test your feeder at a prescribed scale Next-generation feeder demonstration	2	5
		Feeder introduction • Keep O_2/N_2 out and gases in	2	1
		Upstream elemental clean-up (S, CL, P metals)	2	
Gasification	0–3	Database of gasifier and performance	1/2/3	2
		Corrosion issues	1	
		Gasifier metallurgy and alternatives (1,400°–2,800°) Novel/innovative materials	1	4
		Natural gas and biomass: Best ways to integrate	3	8
	3–5	Staged gasification concepts O_2, H_2O, CO, air, etc.	1	1
		Hybrid systems Coal, CH_4, wastes, etc.		1
		Lower cost, small scale	2	
		Reactor design and scale-up	2/3	4
		Reach out to AMO on high-temperature materials crosscutting with concentrated solar power, etc.	3	4
		Process intensification • Pressurize tar reduction, etc. for high-quality syngas	2	
		Catalytic gasification for tar reduction	1/2	
		Tar build up mitigation/monitoring (prior to plugging) • Boiler soot blowers	1/2	1
		Prevent tar formation	2/3	
		Design to minimize contaminates (tars, heavy hydrocarbons) O2M optimization	3	1

RESEARCH CATEGORY	TIMEFRAME (years)	R&D NEED	TECHNOLOGY SCALE	VOTES
Gasification	5–10	In-situ tar cracking or control • Catalytic gasification and additives or high temperature	1	10
		Online tar measurement • Relative reading • Sensor development	1	3
Syngas Clean-Up	0–3	Acceptable contaminate levels based on process?	1	1
		Innovation tar an mature technology	1	
		Full characterization of all syngas components to trace levels	3	4
		Need a test platform for development and testing of new syngas cleaning	3	2
		Heat vs. catalytic tar break-up Tar removal	1/2/3	
		High-temperature filtration and integrated tar cracking	3	4
	3–5	Catalytic tar reforming • S resistance	2/3	2
		Integrated gasification tar removal demo	3	
		What else with waste? • More species and higher concentration	1	
		On-line, real-time analytical measurement of low-concentration impurities	1	10
		Prepare for increased feedstock compatibility Robust	1/2	
		Multi-contaminate removal technology	2	12
		Downstream solids separation • Filtration issues • Use commercially available (no need to reinvent) • Database	2	
		Process intensification (combined unit operations)	2/3	7
		CO_2 removal	2/3	2
		Tailor syngas cleaning to catalyst specifications	3	

Session 2 Results: Catalyst Development for the Production of Intermediates and Final Products

RESEARCH CATEGORY	TIMEFRAME (years)	R&D NEED	TECHNOLOGY SCALE	VOTES
Higher-Value Production from Catalyst	0–3	Higher-value proposition from catalyst (e.g., selectivity, lifetime, etc.)	1	9
		Poison-tolerant catalyst	1	
		Low-pressure catalyst	1	3
		Nanocatalyst	1	1
		Coking-resistant catalysts • Ideally self cleaning	1	1
		Free-radical inhibitors to reduce tar formation	1	
		New materials for catalyst development • Phosphides, nitrides, carbides improving/ innovating catalyst design to improve selectivity and productivity	1	12
		Tunable/more selective/non-wax hydrocarbon distribution (enhanced chain termination)	2	8
		Catalysis for benzene		
		Effects of “uncommon contaminants” (HCN, NH_3) on catalysts • Understanding of limits	1/2/3	4
	3–5	Attrition-resistant primary gasification catalyst	1/2	3
		Improve yield selectivity for products	1/2/3	2
		Need support for long-term catalyst demonstration	3	7
Alternative Syngas Conversion	0–3	Clean syngas affords for possibilities different back-end opportunities (e.g., bio to EtOH, methanol to gasoline) syngas to $	1	11
		Homogeneous catalyst for syngas conversion	1	1
		Catalyst for syngst to higher alcohols	1	3
		Demonstration Scale	3	
Process Economics	0–3	Catalytic/other conversion of CO_2 (cost effective)	1	9
		Catalysts to enhance gasification and syngas production (add with biomass)	1	
		Program level procurement of commercial catalyst	1/2/3	
		Small footprint system to reduce capital hurdles (e.g., Fischer-Tropsch	2	2
		Understanding of: • Catalyst lifetime • Projected market • Catalyst component availability Need to recycle or dispose	1	

RESEARCH CATEGORY	TIMEFRAME (years)	R&D NEED	TECHNOLOGY SCALE	VOTES
Process Economics	0–3	Catalyst recycling	1	
	3–5	Intensified/economic/efficient water gas shift		6
		Oxygenates to HC (mid-distillates) Process Intensification	2/3	
		Temperature (exotherm, local and across reactor) control and stability	1/2/3	3
		Reactor thermal management	2/3	1
		Complementary catalyst systems: dry reforming to maximize Bio-CO. Efficient H_2 to balance.	3	4
		Acceptable tolerance levels of contaminants, inerts. • Impact on upstream clean-up costs	3	
		Improving reactor design to integrate catalyst • Membrane • Cat distillation • Slurry • Fixed beds • Fluidized beds • Circulating fluid beds • Ebullating beds • Microchannel	3	10
	10+	Scale-up of slurry bed reactors for fuel synthesis For distributed applications (<100 megawatts)	1/2/3	1
		Process intensification • Series reactions • Product withdraw • Cat filtration	2/3	6
Biochar Utilization	0–3	Use biochar as catalyst support for syngas reactions	1	1
		Catalyst manufacturing and scale capability Many formulations don’t scale	3	
Catalyst Development Infrastructure	0–3	Catalyst screening: facility access to rapid screening capability	1	1
		Database of catalyst performance • Feedstocks • Products/product quality • Poisons/tolerance • Lifetime	3	3

RESEARCH CATEGORY	TIMEFRAME (years)	R&D NEED	TECHNOLOGY SCALE	VOTES
Catalyst Development Infrastructure	3–5	Catalyst test protocol • Packed bed reactor • Syngas composition • Analytical • Deactivation • Equilibrated catalyst	2	9
		Accelerated deactivation test	2	
		Online real-time monitoring of deactivation	3	
		Effective separations and recycling	3	4
Renewable H_2	0–3	Renewable H_2 (biomass) for liquid upgrading	1-2	1

Session 3 Results: Modeling and Enabling Technologies

RESEARCH CATEGORY	TIMEFRAME (years)	R&D NEED	TECHNOLOGY SCALE	VOTES
Process Modeling	0–3	Develop and provide plug-in modules for unit operations	3	11
		Process optimization and integration modeling (process simulation)	3	4
	3–5	Materials of construction—modeling systems integration • Metallurgy • Refractory		3
Unit Operations / Multi Physics Modeling	0–3	Biofuels computational center of excellence computational fluid dynamics (CFD)–kinetics validation • Super computer • Experiment support and data for validation • Model development	1	11
		CFD modeling—debottleneck processes • Gasifiers • Fischer-Tropsch slurry reactors • Feeders	1	1
		Mechanistic modeling of tar formation based on biomass-specific properties	1	
		Support for CFD models for gasifier and reactor optimization/scale-up	2	12

RESEARCH CATEGORY	TIMEFRAME (years)	R&D NEED	TECHNOLOGY SCALE	VOTES
Unit Operations / Multi Physics Modeling	3–5	Improved analytics for species measurements		
		Better fundamental models of gasification process (e.g., kinetics devolatilization, carbon reactions)	2	16
		Separations modeling		
		Surface computation models		
	5–10	Fundamental heterogeneous reaction models • Catalysts • Bed materials • Char, ash • Etc.	1	10
		Process intensification	3	
		How to validate a flow-chemistry model and ensure scalability • New/better instrumentation		1
		Modeling catalyst chemistry and processes	1	
Sustainability Modeling	0–3	Develop simplified life cycle assessment model/ user interface “wizard”	3	7
		GREET-Lite		2
		Incorporate water use/reuse Elimination in life cycle assessment		1
Enabling Technology	0–3	Solid waste handling and disposal	3	
	3–5	Catalyst prototyping user facility	2/3	3
		Low-grade heat recovery options and sharing		1
		Analytical techniques • In-situ/on-line improved real-time controls • Off-line		1
		Support development of water recovery and reuse technology	3	2
		Feedstock dewatering technology		1
		Separations technologies		1
	3–5	Technology to remove fouling (e.g., tar fouling) from process components and piping	2	
		Low cost, scalable air separation systems	2	4
	5–10	Physical, thermal, and chemical properties for model inputs	1	
Project Assessment	0–3	Clarification on goals: cheapest product or newest technology	1/2/3	
	3–5	Process considerations for high-value products	3	
	10+	Volume/location impact product market	3	3

RESEARCH CATEGORY	TIMEFRAME (years)	R&D NEED	TECHNOLOGY SCALE	VOTES
Crosscutting Information Sharing	0–3	Adding modelling and enabling technology to Bioenergy Knowledge Discovery Framework	3	
		Biomass characterization to include eutectics and slagging information for example		
		A comprehensive, easily accessible (graphical user interface) directory of computational and expertise: • Gas-phase chemistry • Condensed phase chemistry • Metal-acid catalyst sites		3
		Accessible data for site-specific decisions		3
	3–5	Advanced manufacturing • Components • Unit operations • Engineering/design • Shop fabrication • Modularization	2	1
		Chemical reaction algorithms (plug-in-play) allowing for heat rate • Reaction order • Biomass atoms		5

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