Opportunities and Obstacles in Large-Scale Biomass Utilization: The Role of the Chemical Sciences and Engineering Communities: A Workshop Summary

ISBN
978-0-309-27864-5

60 pages
8 1/2 x 11
PAPERBACK (2013)

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OPPORTUNITIES AND OBSTACLES IN LARGE-SCALE BIOMASS UTILIZATION

The Role of the Chemical Sciences and Engineering Communities

A WORKSHOP SUMMARY

Sheena Siddiqui, Douglas Friedman, and Joe Alper, *Rapporteurs*

Chemical Sciences Roundtable

Board on Chemical Sciences and Technology

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, NW Washington, DC 20001

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This study was supported by the U.S. Department of Energy under Grant DE-FG02-07ER15872, the National Institutes of Health under Grant N01-OD-4-2139 (Task Order 25), and the National Science Foundation under Grant CHE-1231459 and Grant 0936388.

International Standard Book Number-13: 978-0-309-27864-5
International Standard Book Number-10: 0-309-27864-3

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, NW, Keck 360, Washington, DC 20001; (800) 624-6242 or (202) 334-3313; http://www.nap.edu.

Printed in the United States of America

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Preface

The Chemical Sciences Roundtable (CSR) was established in 1997 by the National Research Council. It provides a science-oriented apolitical forum for leaders in the chemical sciences to discuss chemistry-related issues affecting government, industry, and universities. Organized by the National Research Council's Board on Chemical Sciences and Technology, the CSR aims to strengthen the chemical sciences by fostering communication among the people and organizations—spanning industry, government, universities, and professional associations—involved with the chemical enterprise. One way it does this is by organizing workshops that address issues in chemical science and technology that require national or more widespread attention.

On May 31, 2012, the CSR held a one-day workshop that explored the current state of sustainable fuels and chemicals, and the issues surrounding their scalability for large-scale use. The workshop will also discussed the chemistry and chemical engineering opportunities to sustainably produce large-scale quantities of biofuel.

The workshop featured both formal presentations and working group deliberations in an effort to stimulate engaging discussions among participants from widely varying fields. Key questions that the participants were asked to address included:

- What is the current state of technology in large-scale production of sustainable fuels and chemicals?
- What are the benefits and weaknesses of current technologies?
- What are the technological and commercial barriers to scaling sustainable technologies?
- How can we best combine chemical technologies of different scales to maximize impact?
- How can we identify ways in which chemical technologies of different practical scales can complement each other?

This document summarizes the presentations and discussions that took place at the workshop. In accordance with the policies of the CSR, the workshop did not attempt to establish any conclusions or recommendations about needs and future directions, focusing instead on issues identified by the speakers and workshop participants. In addition, the organizing committee's role was limited to planning the workshop. The workshop summary has been prepared by the workshop rapporteurs, Sheena Siddiqui, Douglas Friedman, and Joe Alper, as a factual summary of what occurred at the workshop.

IMPORTANT NOTE ABOUT INTERNET WEBSITES

The Internet information provided in this Summary was correct, to the best of our knowledge, at the time of publication. It is important to remember, however, the dynamic nature of the Internet. Information on websites can be transient, and is not always validated or verifiable. Resources that are free and publicly available one day may require a fee or restrict access the next, and the location of items may change as menus and homepages are reorganized.

Acknowledgment of Reviewers

This workshop summary has been reviewed in draft form by persons chosen for their diverse perspectives and technical expertise in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making the published summary as sound as possible and to ensure that it meets institutional standards of objectivity, clarity, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this workshop summary:

Maureen McCann, Purdue University
Javad Tavakoli, Lafayette College
Helena Chum, National Renewable Energy Laboratory
Robert Brown, Iowa State University

Although the reviewers listed above provided many constructive comments and suggestions, they did not see the final draft of the workshop summary before its release. The review of this summary was overseen by **Sharon Haynie,** E. I. du Pont de Nemours & Company. Appointed by the National Research Council, she was responsible for making certain that an independent examination of this summary was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this summary rests entirely with the authoring committee and the institution.

Contents

APPENDIXES

Acronyms

BIO	Biotechnology Industry Organization
CSR	Chemical Sciences Roundtable
DOE	U.S. Department of Energy
GW	gigawatt
EISA	Energy Independence and Security Act of 2007
NREL	National Renewable Energy Laboratory
PSG&E	Public Service Gas and Electric Company
RFS2	U.S. Renewable Fuels Standards
USDA	U.S. Department of Agriculture

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Introduction and Overview[1]

"Competing with the scale of the petroleum industry is a real challenge for the biomass economy"
Paul Bryan

"There is money to be made right now in biomass."
Jeffrey Steiner

Over the past two years, the federal government has released several reports highlighting the importance of biomass as a potential source of economic growth and energy independence. In January 2011, for example, the Congressional Research Service issued a report titled *Agriculture-Based Biofuels: Overview and Emerging Issues* that reviewed the evolution of the U.S. biofuels sector and the role that federal policy has played in shaping its development. In August, 2011, the Department of Energy (DOE) released *2011 U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*, which detailed U.S. biomass feedstock potential nationwide. The report "examined the nation's capacity to produce a billion dry tons of biomass resources annually for energy uses without impacting other vital U.S. farm and forest products, such as food, feed, and fiber crops."[2] Then in April 2012, the White House Office of Science and Technology Policy issued the National Bioeconomy Blueprint, a large portion of which described the importance of biomass as a source of energy and chemicals for manufacturing.

To explore the role of the chemical sciences in developing large-scale uses for biomass in the production of fuels, chemicals, heat, and power, the National Academies' Chemical Sciences Roundtable (CSR) held a workshop on May 31, 2012. Key topics addressed during the workshop included

- The current state of technology in large-scale production of sustainable fuels, chemicals, heat, and power.
- The benefits and weaknesses of current technologies.
- The technical and commercial barriers to scaling up sustainable technologies.
- The optimal ways of combining chemical technologies of different scales to maximize impact.

The workshop began with an introduction by co-chair **Paul Bryan**, an independent consultant, who reminded the audience that the goal of the workshop was to identify opportunities and obstacles in large-scale biomass production, in general, and ways in which the chemical sciences can further those opportunities and overcome those obstacles. He then reviewed some of the challenges of scale in biomass production, starting with feedstock production, the crop side of this subject. Improving production means increasing biomass yields per acre; decreasing the fertilizer, pesticide, and water inputs; altering plants in a way that makes their conversion to sugars easier; and expanding the range where these crops can be grown. Moving to the chemical or biochemical side of production means improving conversion of harvested biomass into raw materials with increased yield and selectivity; lowering capital costs; and expanding the range of outputs beyond ethanol, biodiesel, and a few other select products.

But even as progress is being made in each of these areas, Bryan said, the supply chain for biomass and its products is only going to be as strong as its weakest link, and today, those weak links include a limited supply of conventional feedstocks; challenges in feedstock harvesting and collection; feedstock transportation and seasonal storage; operating at an efficient scale; and transporting and distributing intermediate and finished fuels and other products. He asked that the workshop participants focus their thinking and conversations on identifying and overcoming these supply chain barriers that represent limits to scaling biomass utilization to a scale

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[1] The role of the Chemical Sciences Roundtable was limited to planning the workshop, and this workshop summary has been prepared by the workshop rapporteurs as a factual summary of what occurred at the workshop.

[2] U.S. Department of Energy. U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry. 2011 [online]. [https://bioenergykdf.net/content/billiontonupdate]. Accessed Oct. 9, 2012.

that will address important societal issues regarding sustainability and climate change.

As one example, he discussed the carbohydrate supply chain. Today, if all of the global production of cereal grains were converted to ethanol, leaving nothing for food, the total output would be approximately 14 million barrels of oil equivalent per day. In contrast, current crude oil production is approximately 85 million barrels of oil equivalent per day. Clearly, conventional carbohydrates cannot make a significant impact on the world's demand for petroleum-based fuels, chemicals, and materials. What can meet that demand is lignocellulose, both from waste and purposefully grown energy crops. Recent estimates from the DOE's Billion-Ton study put the total U.S. biomass potential of lignocellulose in the range of 1.0 to 1.6 billion tons, which would be enough to meet the demands of the U.S. Renewable Fuels Standards (RFS2) as set out in the Energy Independence and Security Act of 2007 (EISA), and generate enough additional biomass for electricity generation and the production of chemicals and other materials.

Another obstacle is what Bryan calls the tyranny of distance. Although it is expensive to drill a well to collect crude oil or natural gas, a single well produces massive amounts of product that can be fed into a pipeline for distribution. Biomass, in contrast, is sparsely distributed, and even the highest yielding energy crop will require many times the area of an oil or natural gas field to produce the equivalent amount of energy. This will be a challenging problem to solve, one that DOE is addressing through its Uniform Feedstock Format. The idea is that small depots would convert biomass into a uniform, pellet-like material that could be handled as a quasi-liquid and easily transported to central storage or processing facilities. Seasonality is another significant issue, Bryan added, one that will require developing a mix of biomass sources that will together produce a steady supply of feedstock to a processing plant.

There is also the issue of process scale. Today, the world's largest ethanol plant is rated at 175 million gallons per year, the energy equivalent of approximately 12,000 barrels of oil per day. The largest petroleum refining facility in operation today can process about 1 million barrels of oil per day, and the smallest economically efficient refinery handles 200,000 barrels per day.

OVERVIEW OF THE WORKSHOP

After Bryan's introductory remarks, the workshop consisted of two presentations on feedstocks and conversion technologies, followed by three presentations and corresponding breakout sessions on value chains for the production of fuels, chemicals, heat, and power from biomass. These presentations and discussions are summarized briefly below and in Chapters 2-6 of this workshop report. The workshop concluded with a panel discussion and an open comment period.

Feedstocks and Conversion Technologies

Bryce Stokes, senior advisor with CNJV, a contractor to DOE, summarized the main findings of DOE's Billion-Ton Study update, for which he was a co-director, noting that the United States has the resources to produce a sufficient supply of renewable biomass to meet its 2030 goal of producing one billion tons of biomass for energy uses without impacting other vital U.S. farm and forest products. The 2011 report included county-level projections showing that necessary land use changes will occur slowly and that a significant amount of biomass will come from increased production of energy crops and increased use of corn stover and straws. The report noted that the woody portion of municipal solid waste can become a substantial contributor to biomass resources. Given the diffuse nature of biomass, collecting and distributing biomass on the billion-ton scale will be challenging. The report also outlines a vision for creating a uniform commodity feedstock from biomass.

Brian Duff, chief engineer and acting deployment team leader for the Office of Biomass Program at DOE, discussed the security, environmental, and economic reasons why the United States should develop biomass-based fuels, chemicals, and power industries. He noted that tapping into the enormous value of petrochemicals and specialty chemicals is a place where chemistry can play a huge role in realizing value from biomass conversion, particularly since these are high value added products that would use very little of the available biomass. He then introduced the two major sets of technologies—biological and thermochemical—for converting biomass into biofuels and chemicals and remarked that the list of building blocks, secondary chemicals, intermediates, and end products that can be made from biomass feedstocks is virtually limitless, just as it is with petroleum.

Value Chains

Chris Somerville, professor of alternative energy and director of the Energy Biosciences Institute at the University of California in Berkeley, gave a broad perspective on the challenges that need to be addressed to develop economically viable schemes for converting lignocellulosic biomass into fuels or intermediates that can be converted into other chemicals. The biggest challenge is to move from the current batch processing system to one that more closely resembles the continuous flow process used in producing fuels from oil. He discussed the potential advantages of continuous flow processing and explained that the development of such a system will require new separation and purification technologies. Attracting researchers with the necessary skills in chemistry and chemical engineering to this field represents a substantial challenge.

Robert Brown, founding director of the Bioeconomy Institute at the Iowa State University, discussed the pros and cons of the two routes for thermochemical conversion of lignocellulosic biomass into intermediates that would then undergo further processing to produce fuel or chemicals. Gasification, which is well developed for use with coal, produces syngas that can then be converted using chemical catalysts into a variety of fuels and chemicals. Pyrolysis produces charcoal, which can be used as a supplemental fuel for the pyrolysis reactor, or an acidic, oxygenated bio-oil that has the potential to be processed much like petroleum. The chief technical obstacle facing both of these processes is purifying the immediate reaction process of inorganic chemicals that will contaminate subsequent processing steps. While gasification technology is fairly well understood, the same is not true for pyrolysis, and Brown stressed the need for chemists and chemical engineers to study this process, as well as to work on the contamination issue.

Jeffrey Steiner, national program leader for biomass production systems at the U.S. Department of Agriculture (USDA) Agricultural Research Service and agency lead of the USDA Regional Biomass Centers, reviewed the use of biomass to generate heat and power. He noted that the development of a biomass-based power industry in the United States suffers from the lack of a national policy guiding biomass utilization. He also described some of the small-scale systems that are being developed, tested, and deployed for turning biomass into methane that can then be used locally to cogenerate electricity and heat.

General Observations

The final chapter summarizes the panel discussion and compiles some general observations made by the individual workshop participants that apply broadly to the opportunities and obstacles in large-scale biomass utilization and the role of the chemical sciences and engineering in addressing these issues.

ORGANIZATION OF THIS WORKSHOP SUMMARY

This report was prepared by rapporteurs Sheena Siddiqui, Douglas Freidman, and Joe Alper for the Chemical Sciences Roundtable as a factual summary, in chronological order, of what occurred at the workshop. The views contained in the report are those of individual workshop participants and do not necessarily represent the views of all workshop participants, workshop session breakout groups, the planning committee, or the National Research Council. In accordance with the policies of the CSR, the summary does not attempt to establish any conclusions or recommendations about needs and future directions, focusing instead on issues identified by the speakers and workshop participants.

This summary is organized according to the presentations and breakout discussions that were based on three different aspects of the value chains for converting biomass into fuels, chemicals, heat, and power. Overview presentations on the value chains set the stage for breakout sessions that explored the following questions:

1. What is the current state of technology in large-scale production of sustainable fuels and chemicals?
    a. How can we best combine chemical technologies of different scales to maximize impact?
    b. How can we identify ways in which technologies of different practical scales can complement each other?
2. What are the technologies and commercial barriers to scaling up sustainable technologies?
3. What skills will chemists and chemical engineers need to enable a growing biomass economy that are not widely held and/or taught today?
4. Where can we exploit existing transportation infrastructure to meet the new needs, and where must we build new infrastructure?

ONLINE COMPONENT

In trying to make the workshop material readily available to the public, the Board on Chemical Sciences and Technology developed a hub for information relating to the ***Opportunities and Obstacles in Large-Scale Biomass Utilization: The Role of the Chemical Sciences and Engineering*** workshop. At the time of this publication, additional material relating to the workshop could be found at http://dels.nas.edu/global/bcst/biomass. It includes speaker PDF presentations and presentation recordings, and breakout session summary slides.

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Feedstocks and Conversion Technologies

"This is a big deal, because we are saying the primary amount of biomass will come from energy crops that have not yet been established, have not yet had enough research and information on optimizing production yield and systems. There is a lot of work to be done to make this come true."
Bryce Stokes

"We have the land, the will, and by bringing our sciences together we can provide the way for using biomass for feedstocks and commodities in our biorefineries."
Bryce Stokes

"Initially, advanced biofuels will be produced in integrated supply chains; no one will grow new crops without an assured customer, and no one will finance or build new conversion capacity without an assured source of feedstock. Truly fungible products will be traded as commodities, but most products will also form part of an end-to-end supply chain in early applications."
Bryan Duff

INTRODUCTION

As participants in the workshop discussed, biomass utilization is an important addition to the nation's energy economy. Bryce Stokes explained the future potential of biomass production in the United States and noted that the billion-ton goal is attainable. Biomass could potentially be used to displace about 30 percent of the petroleum consumption or produce 5 percent of the electricity used in America. Brian Duff pointed out that biomass is also very useful for transportation, as it can be processed into high-density fuels for a wide variety of vehicles. The participants in the workshop discussed in detail the challenges and opportunities for developing biomass utilization for both electricity generation and production of fuels and chemical feedstocks.

The United States has enough land and technological knowledge to produce over one billion tons of biomass per year at $60 or less per ton for use in making fuels and chemicals and generating power without impacting current uses agricultural and forestry acreage, noted **Bryce Stokes**, senior advisor with CNJV, a contractor to DOE.

A significant amount of that biomass will come from increased production of energy crops, with increased use of corn stover and straws also making a significant contribution to the increase, said Stokes. **Brian Duff**, chief engineer and acting deployment team leader for the Office of Biomass Program at DOE, said that there is also a real opportunity to make efficient use of the woody component of municipal solid waste and construction and demolition wood. However, a major challenge to utilizing these resources will be developing a cost-effective system for getting widely distributed, non-uniform biomass to fuel, chemical, and power production sites. In the meantime, research has developed a variety of biological and thermochemical schemes for turning biomass into fuels, chemicals, and energy. The list of building blocks, secondary chemicals, intermediates, and end products that can be made from biomass feedstocks is virtually limitless, just as it is with petroleum.

FEEDSTOCKS AND RAW MATERIALS

Bryce Stokes noted that the United States has abundant, renewable biomass resources to use for feedstocks, although the supply today and the form in which most of it exists is not sufficient to meet the 30 percent petroleum displacement goal that the nation needs for energy, chemicals, and other materials. However, he said, with the supply of land in the United States, combined with the nation's technological prowess and its people, it should be possible to grow enough biomass to meet those needs. Moreover, it should be possible to do so within a resource management and sustainability framework that meets other social demands.

Starting with available land, Stokes explained that there are six major classes of land, drawing mainly from a 2011 report from the U.S. Department of Agriculture:[1]

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[1] Nickerson, C., R. Ebel, A. Borchers, and F. Carriazo. 2011. Major Uses of Land in the United States, 2007. Economic Information Bulletin No. 89. December 2011 [online]. Available: http://www.epure.org/pdf/0w3ea6c089-8164-d04c.pdf.

- Cropland, which includes all land currently used to grow crops, idle cropland, and cropland used only for pasture. Total cropland in the lower 48 states is approximately 408 million acres.[2]
- Grassland pasture and range, including permanent grassland and other non-forested range and pasture, totals about 612 million acres.[3]
- Forest-use land is total forestland as classified by the U.S. Department of Agriculture (USDA) Forest Service, excluding an estimated 80 million acres used primarily for parks, wildlife areas, and other uses. Forest-use land totals 576 million acres in the lower 48 states.[4]
- Special-uses land includes areas for rural transportation, recreation and wildlife, various public installations and facilities, farmsteads, and farm roads, including the 80 million acres of forested land noted above. There are approximately 169 million acres in this category.[5]
- Miscellaneous land includes areas in various uses not inventoried, marshes, open swamps, bare rock areas, desert, tundra, and other land generally of low agricultural value and total about 68 million acres.[6]
- The urban land base includes streams and canals less than an eighth of a mile wide, and ponds, lakes, and reservoirs covering less than 40 acres. This category total about 60 million acres.[7]

Land use is not uniform across the United States but varies according to soil type, climatic conditions, and other facts. Figure 2-1 shows the major uses of land in 2007.

Biomass Resources

Stokes discussed some of the major forest and agricultural biomass resources that could serve as feedstocks. Forest resources include logging residues, which are very inexpensive to buy, but collecting them and converting them into something that can be transported can be expensive. Forest thinnings are trees removed for fire control or health improvements and the wood is usually not sellable, so it could be used as a feedstock resource. Conventional wood, in contrast, is marketable, but Stokes said that some of this wood may be diverted for use as a feedstock resource. Fuelwood is wood that goes to the pulp and paper industry for making heat and power for their plants. It also includes a few of the electrical power plants that use wood. Finally, there are the mill residues, pulping liquors, and urban wood resides, such as waste paper and yard trimmings, that could serve as energy feedstocks, though collection is the big issue because many of these are diffuse resources.

Agricultural resources include grains that go into biofuel production, oil crops, and crop residues. Energy crops include perennial grasses, such as switchgrass, bluestem, Miscanthus, and others, and perennial wood crops, which include poplar, willow, pine, and eucalyptus, among others. Agriculture also generates animal manures and food and feed processing residues that could serve as production feedstocks, as well as municipal solid waste, landfill gases, and annual energy crops such as sorghum.

He then reviewed the 2011 update of DOE's Billion-Ton report, for which he was a co-lead. The Billion-Ton Update examines the nation's capacity to produce a billion dry tons of biomass resources annually in the 48 coterminous states for energy uses without impacting other vital U.S. farm and forest products, such as food, feed, and fiber crops. The study provides industry, policy makers, and the agricultural community with county-level data and includes analyses of current U.S. feedstock capacity and the potential for growth in crops and agricultural products for clean energy applications. He noted that the 2011 study, unlike the earlier 2005 study, examined both current use and potential use up to 2030, and it included methodology to examine biomass potential at the county level. The 2011 study also included the costs for getting biomass to the roadside for transport and includes scenarios based on crop yields and tillage practices as well as sustainability criteria. The report, as well as all of the data, are available at www.bioenergykdf.net.

To develop county-level projections, Stokes and his colleagues used the POLYSYS economic model developed at the University of Tennessee Agricultural Policy Analysis Center (www.agpolicy.org). This model is anchored to the USDA's 10-year baseline projections for eight major crops, and it includes projections for biomass resources that include corn stover, straws, and energy crops. The model also incorporates USDA-projected demands for food, feed, industry, and export, and works on a land base that includes

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[2] Nickerson, C., R. Ebel, A. Borchers, and F. Carriazo. 2011. Major Uses of Land in the United States, 2007. Economic Information Bulletin No. 89. December 2011 [online]. Available: http://www.epure.org/pdf/0w3ea6c089-8164-d04c.pdf.

[3] Nickerson, C., R. Ebel, A. Borchers, and F. Carriazo. 2011. Major Uses of Land in the United States, 2007. Economic Information Bulletin No. 89. December 2011 [online]. Available: http://www.epure.org/pdf/0w3ea6c089-8164-d04c.pdf.

[4] Nickerson, C., R. Ebel, A. Borchers, and F. Carriazo. 2011. Major Uses of Land in the United States, 2007. Economic Information Bulletin No. 89. December 2011 [online]. Available: http://www.epure.org/pdf/0w3ea6c089-8164-d04c.pdf.

[5] Nickerson, C., R. Ebel, A. Borchers, and F. Carriazo. 2011. Major Uses of Land in the United States, 2007. Economic Information Bulletin No. 89. December 2011 [online]. Available: http://www.epure.org/pdf/0w3ea6c089-8164-d04c.pdf.

[6] Nickerson, C., R. Ebel, A. Borchers, and F. Carriazo. 2011. Major Uses of Land in the United States, 2007. Economic Information Bulletin No. 89. December 2011 [online]. Available: http://www.epure.org/pdf/0w3ea6c089-8164-d04c.pdf.

[7] Lubowski, R.N., M. Vesterby, S. Bucholtz, A. Baez, and M. Roberts. 2006. Major Uses of Land in the United States, 2002. Economic Information Bulletin No. (EIB-14) May 2006.

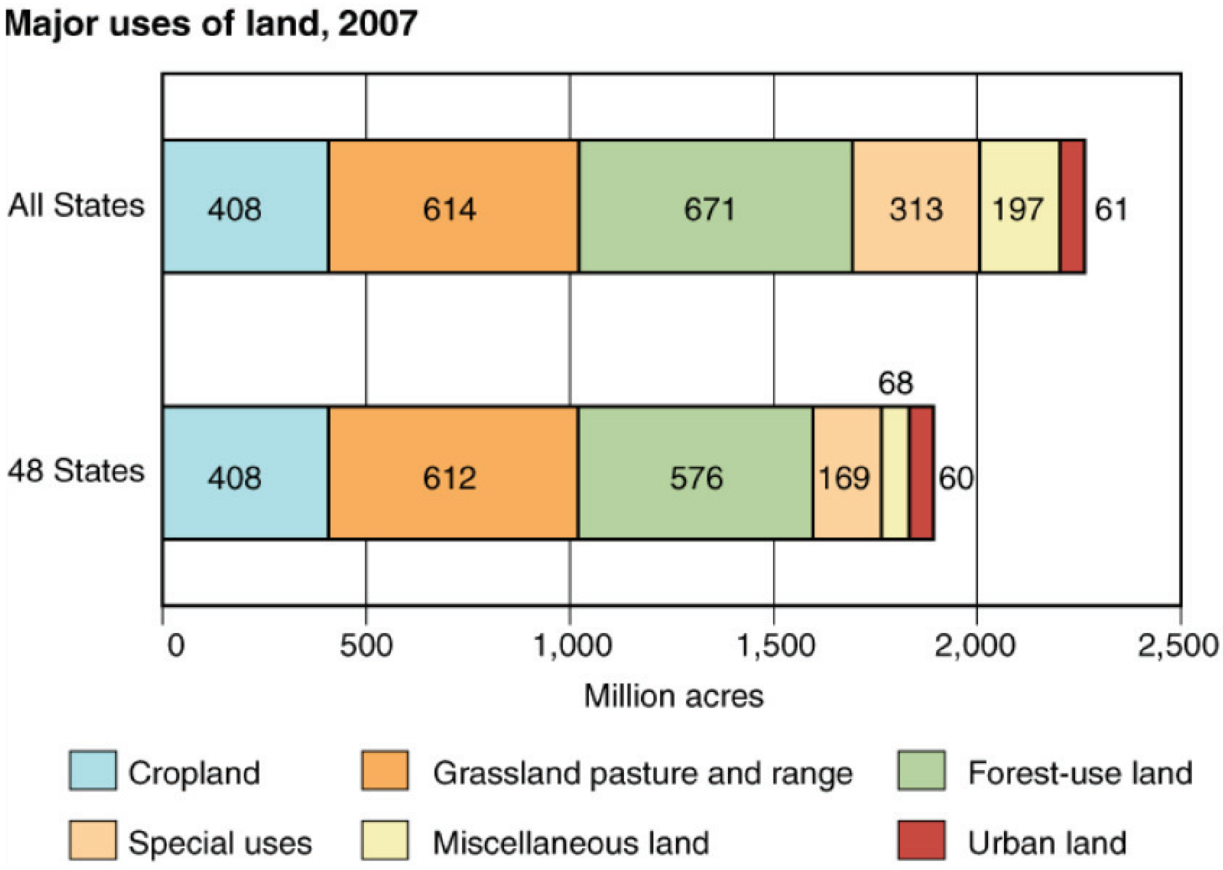


FIGURE 2-1 Land use summary. The first diagram shows land use for all states, and the second includes all states except Alaska and Hawaii. The land use is significantly affected by Alaska as it has a large forestry-use, special-use and miscellaneous other land areas and small cropland and pasture areas.
SOURCE: Cynthia Nickerson, Robert Ebel, Allison Borchers, and Fernando Carriazo. Economic Information Bulletin No. (EIB-89). 67 pp. December 2011. http://www.ers.usda.gov/Publications/EIB89/EIB89.pdf.

250 million acres of cropland, 22 million acres of cropland pasture, 61 million acres for hay production, and 118 million acres of permanent pasture. The update is based on the USDA baseline scenario extended to 2030 and a high-yield scenario that increases corn yields by 1 percent annually over the baseline projections and that energy crop yields increase by 2-4 percent annually as a result of a concerted research and development effort. The high-yield scenario also assumes that a larger amount of cropland will move to no-till practices that allow for greater residue removal for feedstock use within sustainability limits that prevent soil erosion and retain water and nutrients. Stokes noted that a significant amount of effort went into modeling crop residue sustainability.

The model also assumed that energy crops would only be grown on cropland, cropland pasture, and permanent pasture without irrigation and using minimum tillage practices. Energy crops also had to pay for themselves; that is, the economic return had to be greater than that from other agricultural uses. Land use was assumed to change slowly between now and 2030, though land use for energy crops will increase from 63 million acres in the baseline scenario to 79 million acres under the high-yield scenario. Stokes remarked that this is significant because the model predicts that the primary amount of biomass will come from energy crops that have not yet been established and for which there has not been enough research and information on optimizing production yield and systems.

The bottom line, said Stokes, is that current combined resources from forests and agricultural lands total about 473 million dry tons annually at $60 or less per dry ton. About 45 percent of that is currently produced and the remainder is potential additional biomass. Under both baseline and high yield scenarios, biomass resources are predicted to total from nearly 1.1 billion dry tons annually by 2030 under the baseline scenario to as much as 1.6 billion dry tons annually under the high-yield scenario. A significant amount of that biomass under both scenarios will come from increased production of energy crops, with increased use of corn stover and straws also making a significant contribution to the increase. Very little of the increase comes from forestry because current production there is already high. Stokes made the point that woody mill residues will not contribute to increased energy production because very little primary mill residue goes unused. Waste from pulp and paper mills is already being used to make energy, he explained. There is, however, a real opportunity to make efficient use of the woody component of municipal solid waste and construction and demolition wood, with Stokes calling this combined resource a potential gold mine.

Figure 2-2 summarizes all of the data in a county-level map showing that there is the potential to have fairly well distributed access to many types of feedstocks at the $60 or less per dry ton by 2030. Stokes noted that the Billion-Ton study did not include algae as a potential feedstock—algae was the subject of a parallel study—but that it did identify 106 million acres of suitable land for algae production with the potential to produce 58 billion gallons of algal oil per year. Those figures drop to 2.4 million acres of land and 5 billion gallons of algal oil per year when only considering lands that optimize productivity and minimize water use. These maximally productive sites are clustered in the southwest and along the Gulf Coast.

The Feedstock Delivery System

Stokes then turned to the subject of raw material handling and supply systems, briefly discussing some of the different systems that are being developed and studied; see Figures 2-3 and 2-4. For example, a system to handle switchgrass produces large square bales as the switchgrass is being harvested. The resulting bales require industrial equipment to load onto trailers. Another system for switchgrass uses a field chopper and solar energy to dry the harvested grass in the field. This type of system eliminates bale handling and de-baling and increases the energy density of the final feedstock, but it does require two passes through the field, one to cut the switchgrass, the second to collect it after drying. He also described a single-pass system (Figure 2-4) for collecting corn residue that greatly increases the efficiency of collection and transport, and systems for harvesting trees and short-rotation wood crops such as willow.

It is important when developing any collection system, he said, to consider total cost, including the expense of drying materials at a refinery and labor costs. He added that a possible goal of research and development efforts could be to reduce the variability and uncertainty around feedstock quality specifications in terms of sugar content, moisture, and ash. A commodity feedstock for energy and chemical

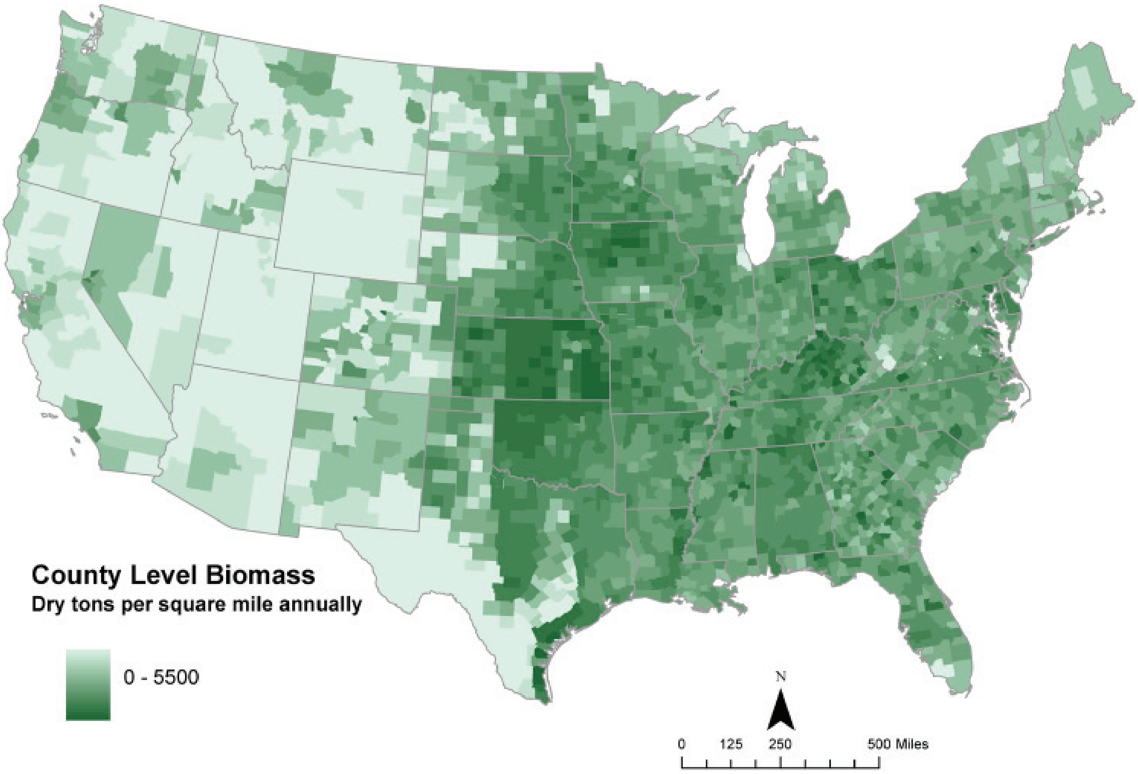


FIGURE 2-2 Potential county-level resources at $60 per dry ton or less in 2030 under baseline assumptions.
SOURCE: 2011 U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry.

FIGURE 2-3 Bulk-format system to harvest, handle, store, and deliver low-moisture switchgrass.
SOURCE: Image taken from Stokes presentation.

FIGURE 2-4 Single-pass harvest system for corn and corn stover.
SOURCE: AGCO Corporation.

production, explained Stokes, needs to be reliably available, have uniform density and stability, and must be readily stored. As far as algae is concerned, he explained that the biggest production barrier today is that the fundamental biology of algae is poorly understood. There is active fundamental and applied research ongoing on algae as a potential source of biomass, but he noted that translating indoor lab results to outdoor production environments is not a trivial matter.

A variety of different programs are addressing research and development needs to address the grand challenges and achieve the vision of producing one billion tons of biomass annually at a cost of $60 or less per ton. A joint USDA-DOE program, for example, is focusing on genomics-based research that will lead to the improved use of biomass and plant feedstocks for the production of fuels. This five-year, $40.1 million effort focuses on a range of plants, including rice, switchgrass, sorghum, and poplar, among others. The private sector is involved, as well, developing high-biomass dedicated energy crops with increased nitrogen use efficiency. Stokes noted one effort, the Knowledge Discovery Framework supported by DOE, that will serve as a biomass research and development resource library into which the large network of institutions in the Regional Biomass Feedstock Partnership will deposit data annually.

The Uniform Commodity Feedstock Vision

The bottom line, said Stokes, is that there needs to be a transition from picking up materials with inefficient systems and just chopping it up or baling it and hauling it to the biorefinery. This approach, he said, is not meeting quality specs, is not integrating well into biorefineries, and is wasting money. Instead of trying to feed biomass directly to a biorefinery, the desired system should aim to transform raw biomass into high-density, stable, commodity feedstocks at or close to the site of production. Biomass preprocessing at local preprocessing depots could become the link between biomass producers and refiners. Such depots would provide flexibility for local communities to produce feedstocks customized for biochemical, thermochemical, and combustion conversion facilities. But in addition, he said, preprocessing depots would also enable the production of renewable products, such as livestock feeds and soil amendments, that would increase the economic return on such facilities. Stokes described an ongoing effort at the Idaho National Laboratory to develop a highly instrumented, portable, modular process demonstration unit designed to represent one replicable depot that would address scale-up issues and produce quantities of densified materials meeting specific formulations.

In a uniform commodity feedstock vision, preprocessing depots would serve biomass production operations within a 5- to 20-mile radius. The uniform feedstock would then be transported by interstate trucks, short-line railroads, and internal waterways to shipping terminals similar to centralized grain elevators and then on to biorefineries as needed.

In closing, Stokes said that the physical and compositional characteristics of the feedstock determine conversion process and process efficiency and costs. One of the goals of research is to increase the value of the biomass feedstock, which would increase costs on the front end, but reduce costs further at the conversion end. Another goal going forward should be to increase biomass accessibility, he said. The nation has sufficient biomass resources, but its distribution does not match that of industry today. Finally, conservation and operational practices affect not only costs but intangible benefits for society as a whole. In summary, the United States has the land, the will, and by bringing our sciences together, we can provide the way to use biomass for feedstocks and commodities in our biorefineries.

Discussion

Paul Bryan asked Stokes to list a few low-hanging fruits in terms of biomass supply. In response, he listed forestry residues and crop residues. Since these are already produced, the development of economical collection and preprocessing systems could produce results in the short term.

Emily Carter, from Princeton University, asked about the potential importance of algae and oil crops. Stokes replied that there was not enough information to include those in the Billion-Ton report, but that they do have real potential as energy and chemical feedstocks. He noted that some studies are including those sources. In response to a comment from **Rich Green**, of DOE, about the feasibility of boosting yields of biomass crops, Stokes noted that the Billion-Ton report places great faith in research, and particularly genomics, to boost crop yields.

CONVERSION TECHNOLOGIES

Brian Duff, from DOE, began his presentation with a review of why biomass and biofuels are so important. He said that while he would focus his remarks on biofuels, he considers biofuels to be a representative subclass of chemical products that should be made from biomass. He also noted that it is important to consider what he characterized as the awe-inspiring scale of today's global petrochemical industry when thinking about where the biomass conversion field is today. He added, though, that today is a very exciting time for this nascent endeavor given the convergence of the chemical sciences, synthetic biology, biotechnology, and environmental biotechnology.

Energy, said Duff, is a global challenge involving issues of security, the environment, and the economy, and clean energy offers potential solutions for each of these. Clean energy can translate into energy self-reliance and developing a stable, diverse energy supply that does not depend on importing oil from countries that can be antagonistic toward the United States. Developing locally produced clean, renewable energy could also reduce the amount that our military now spends to protect our access to imported oil. In terms of the environment, clean energy means clean air, mitigating climate change, and reducing greenhouse emissions.

Clean energy can also translate into jobs, rural economic development, and rebuilding a manufacturing base, as well as maintaining our innovation edge and reducing our dependence on a resource whose price fluctuations have a significant impact on the economy. DOE estimates that each biorefinery would produce 50-75 new direct jobs and an additional 3,000 indirect jobs supporting the biorefinery and its employees. A local source of clean energy would also have a major impact on the nation's balance of trade, potentially eliminating the flow of $300 billion a year in economic value out of the country that could instead go to biomass producers and processers here in the United States (Figure 2-5). Developing a sustainable local source of biofuels will contribute greatly to maintaining the nation's economic prosperity and quality life, said Duff.

He noted that the Department of Defense and the airline industry are, at least in part, driving the demand to develop biofuels. The airline industry, for example, will have to meet European sustainability and biofuels requirements. Other considerations, he said, are that liquid fuels are a premium product application unmatched in terms of energy density

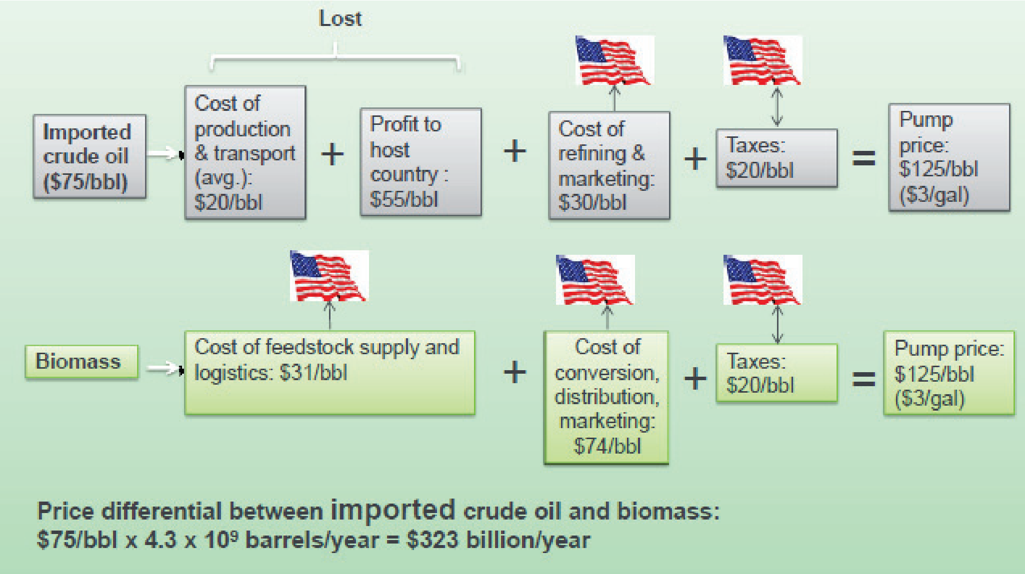


FIGURE 2-5 The value of biofuels. The cost difference between importing crude oil and biomass.
SOURCE: EIA Annual Energy Review (Duff presentation).

and convenience. In the near term, biofuels are the only alternative that fits the U.S. lifestyle. In addition, given that biomass is not unlimited, the "best use" of biomass dictates that it be used in the highest value product applications. And while converting the nation's auto and truck fleet to electricity sounds like a laudable goal, Duff added, that does not solve the greenhouse gas emissions as long as powerplants produce electricity using coal and natural gas. Liquid fuels from biomass, he stated, are really the only option in the near term.

The Potential of Biomass for Fuels, Chemicals, and Power

Biomass, said Duff, has the potential to dramatically reduce dependence on foreign oil for fuels and chemicals. It can also promote the use of a diverse, domestic and sustainable energy resource and establish a domestic bioeconomy, as well as reduce carbon emissions from energy production and consumption. He estimated that a national system of biorefineries would consist of 300 to 500 plants, creating jobs in rural economies that cannot be outsourced. Developing a biomass-based fuel economy would reduce carbon emissions and mitigate the direct and indirect costs of oil imports, with positive impacts on the balance of trade and demands on our military. It would also support and potentially expand U.S. leadership and innovation in chemical engineering and chemistry.

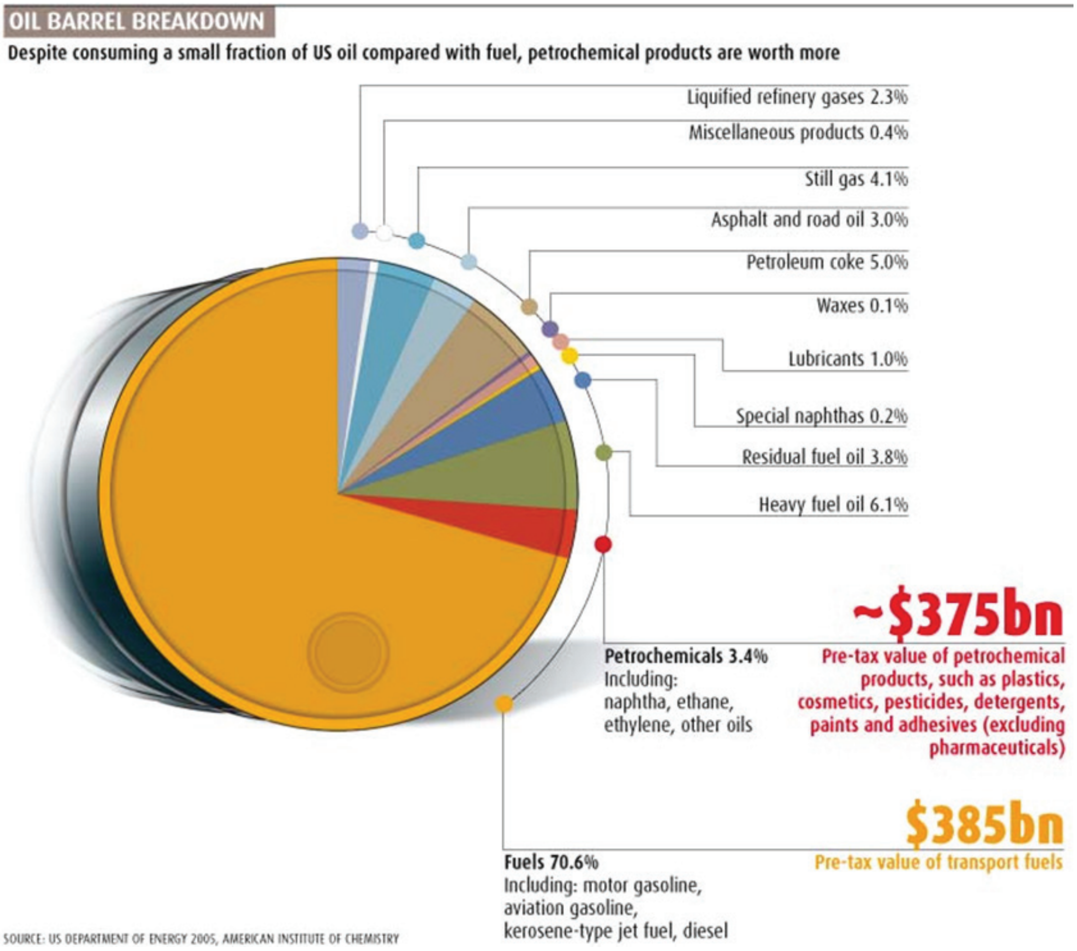
In creating a biorefinery infrastructure, pace will be as important as direction, Duff explained. It is not possible to replace a multi-trillion-dollar petroleum-based infrastructure with a biomass-based infrastructure overnight. The supply of biomass needed to support that infrastructure will not be available immediately either. It will be necessary to balance the pace of the transition with the cost of the resulting disruptions. Economics, he said, must be the driving force behind this transition. However, the economics of oil presents a real problem given that there are many non-monetized costs that do not appear in the price of oil. Biofuels, for example, have to meet a greenhouse gas emissions reduction requirement to meet the requirements of the Renewable Fuel Standard (RFS2) that oil does not. As Duff put it, biofuels have to perform all of the miracles of sustainability and still be priced lower than oil. That is a conundrum that challenges the biofuels community. He also noted that even under the provisions of RFS2, biofuels will only replace less than a quarter of the U.S. demand for liquid fuels.

According to DOE estimates, said Duff, the use of agricultural, forest, and urban waste streams, combined with energy crops and algae, could replace about 50 percent of imported crude oil. What is needed to meet this target, he explained, are flexible platforms that can process current and future products, and a portfolio approach that can be optimized across multiple feedstocks and regions. In thinking about such platforms, Duff's program at DOE considers fermentable sugars, syngas, and biological oils from pyrolysis, oil seeds, and algae. These would be used to produce ethanol, renewable hydrocarbon fuels that match our current infrastructure's needs, and home heating oil.

As far as greenhouse gas emissions are concerned, the transportation sector's contribution is dwarfed by the power sector. Of the 985 gigawatts (GW) of electrical power generated in the United States, biomass—primarily waste and wood—accounts for about 13 GW, or 1.3 percent of the total. Even if all of the 1 billion tons of biomass were diverted to energy production, it would account for only 47 GW, or 4.7 percent of demand. However, that same 1 billion tons of biomass would generate about 65 billion gallons of gasoline, which would meet about 30 percent of U.S. demand. The best use of biomass, said Duff, is for fuels and chemicals, and that includes diesel and jet fuel and a variety of specialty chemicals that also come out of every barrel of oil. Duff pointed out that although 70.6 percent of a barrel of oil is converted into fuels worth $385 billion annually, the 3.4 percent that is converted into petrochemicals is worth some $375 billion annually (Figure 2-6). Tapping into the enormous value of petrochemicals and specialty chemicals is a place where chemistry can play a huge role in realizing value from biomass conversion, particularly since these are high value added products that would use very little of the available biomass.

Biomass Supply and Value Chain

At DOE, the biomass program's strategic focus is on achieving sustainability across the supply chain. This includes producing feedstocks in a way that preserves nutrients and maximizes carbon cycling, as well as minimizing the impact on land and resource use. In the conversion phase, the emphasis is on minimizing water consumption and air pollution while maximizing efficiency by integrating technology from feedstock to product. In the distribution step, the goal is to reduce the carbon footprint of new facilities and to use the co-products in order to maximize return and minimize risk associated with relying on a single product, such as ethanol. And finally, there has to be a product that is in demand. Each of these components will need to be integrated, for as Duff said, no one is going to grow a crop if there is no plant to take it to, and no one is going to finance a new plant if there is no crop or market for its product.


OIL BARREL BREAKDOWN

Despite consuming a small fraction of US oil compared with fuel, petrochemical products are worth more

SOURCE: US DEPARTMENT OF ENERGY 2005, AMERICAN INSTITUTE OF CHEMISTRY

FIGURE 2-6 Value in a barrel of crude oil.
SOURCE: DOE (Image taken from Duff presentation).

From a value perspective, existing waste streams, both agricultural and municipal, have potential because they avoid impacts on food, feed, and land, nutrient, and water use. Duff said that new oilseed crops, algae, and fast-growing grasses and trees are also likely to fit into the value chain needed to make competitively priced biofuels. The challenge, as Stokes noted earlier, is in integrating all of these different sources of biomass into a consistent feedstock. He noted that research is under way on a real-time near-infrared monitoring system that would provide a compositional analysis of each truckload of biomass coming into a preprocessing depot. He also commented that biomass resources have low energy density, high water content, are perishable, and above all, have a high oxygen content compared to petroleum.

Before leaving this subject, Duff commented on the goal of $60 per dry ton of biomass. Today, companies in the United States are building pellet mills to ship biomass pellets to Europe that sell at a price of $120 per ton. In this case, European countries have decided to reduce dependency on Russia and Ukraine for natural gas and power and they are willing to pay a premium price to achieve that goal. He said the only way to get to $60 or lower per dry ton is by developing processing technologies that increase bulk density and improve harvesting efficiency. Another possibility is to realize the potential of algal production of biomass and feedstocks as part of an integrated biorefinery.

Conversion Technologies

There are two basic options for converting biomass to product—biochemical and thermochemical. Duff explained that there are two classic thermochemical options, gasification and pyrolysis, each of which produces different intermediates. Gasification involves rapid heating and partial oxidation to produce syngas, which is largely carbon monoxide and hydrogen (see Figure 2-7). This process operates at very high temperature and also produces unconverted tars that must undergo reforming. Contaminants in syngas output must be removed to avoid deactivating or destroying the efficiency of downstream catalytic process operations. While gasification works well with petroleum and natural gas, the sulfur, nitrogen, phosphorous, potassium, and mineral content of biomass complicates matters. Also, the high oxygen content of biomass results in the production of significant quantities of carbon dioxide, which reduces carbon efficiency. Research by chemists and chemical engineers is needed to develop new catalysts that resist contamination and have improved selectivity. The advantage of syngas is that it creates a blank slate of single carbon atoms that can be used to build many possible molecules, including gasoline, diesel, and jet fuel, and a variety of value-added building blocks such as methanol, ethylene, and naphtha. Syngas, said Duff, has the potential to replace the entire barrel of oil except perhaps for asphalt.

In pyrolysis, lower temperatures are used to break down biomass into smaller molecules such as oxygenated aromatics, ketones, organic acids, and other oxygenates, as well as light hydrocarbon gases (see Figure 2-8). In addition to the lower energy input to achieve biomass deconstruction, pyrolysis has a high theoretical yield for liquid products. With upgrading, the pyrolysis products can be fed directly into existing petrochemical refineries.

The classic biochemical conversion route involves pretreating biomass with either enzymes or acid to release sugars that are then fermented. Another biochemical route uses anaerobic digestion to produce methane, though several new technologies short-circuit this process prior to full degradation to methane in order to produce carboxylic acids that can then be converted into diesel and jet fuel. Duff believes there is a great deal of potential for other products to come

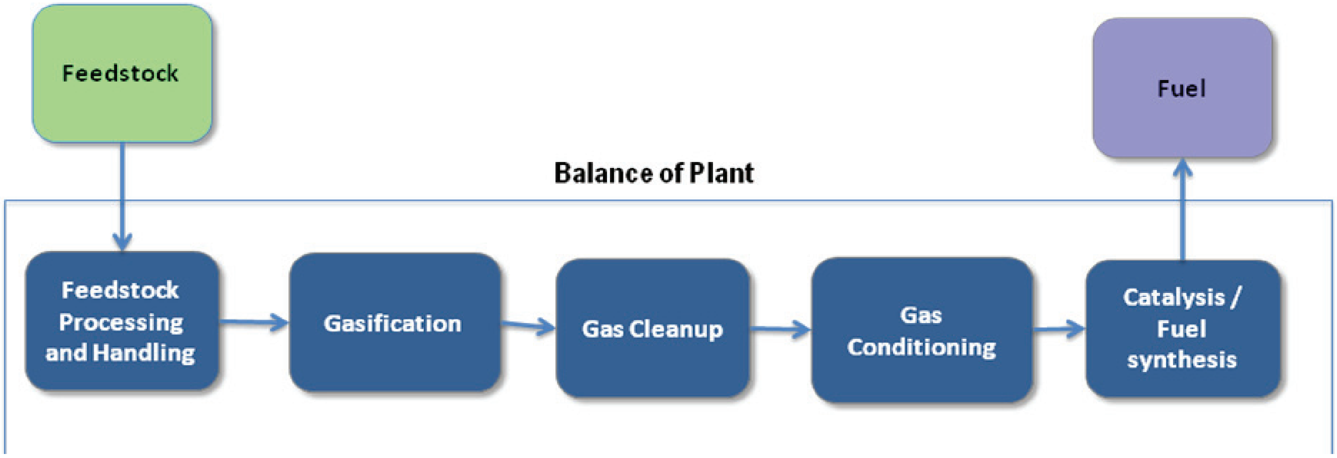


FIGURE 2-7 Thermochemical conversion of biomass via gasification.
SOURCE: DOE (Image taken from Duff presentation).

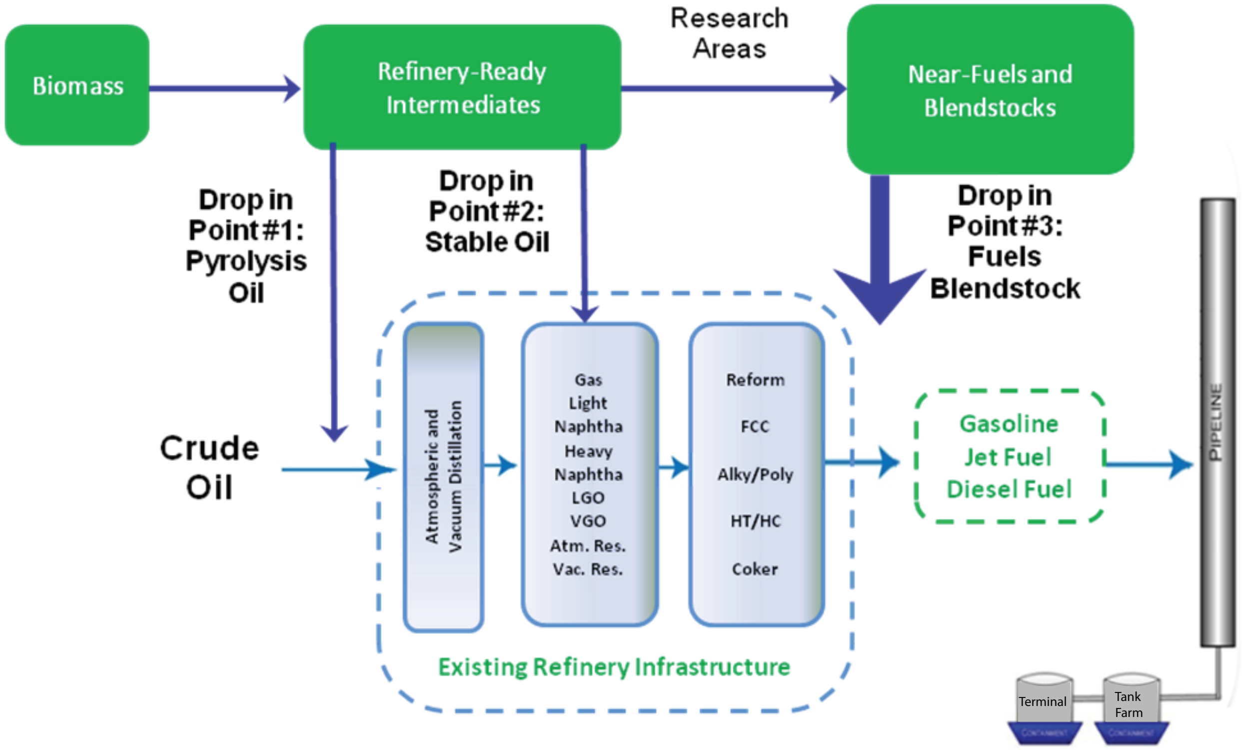


FIGURE 2-8 Thermochemical conversion of biomass via pyrolysis and drop-in points that could use today's petrochemical infrastructure.
SOURCE: Image taken from Duff presentation.

out of this type of process development. In addition, there is a new process called electrofuels that is attempting to capitalize on geoautotrophs and other bacteria that create energy by metabolizing minerals or even electricity and use that energy to produce fuel molecules. DOE is investing heavily in research aimed at developing the electrofuels process to synthesize fuel. There are also hybrid systems under development, such as one that merges syngas production via gasification with bacterial fermentation to produce fuel and another that takes the sugars produced from biomass degradation and uses chemical catalysts to convert them into fuel.

The last pathway that DOE is investigating uses algal oil as an intermediate that is then upgraded to make fuel (see Figure 2-9). Again, substantial research and development is needed for the use of algal oil at a commercial scale. One of the most significant challenges algal oil faces is its heavy use of water.

Duff concluded his talk by noting that the list of building blocks, secondary chemicals, intermediates, and end products that can be made from biomass feedstocks is virtually limitless, just as it is with petroleum. One issue that needs to be solved is the high oxygen content of biomass; aviation fuels, diesel, and gasoline all have low oxygen requirements. Again, this a place where chemists can contribute greatly by developing catalysts to deoxygenate biomass intermediates.

Discussion

Tom Richard, of Pennsylvania State University, asked why so much effort is being put into the production of sugars from biomass when organic acids may have more uses as chemical feedstocks. Duff agreed with that assessment and noted that work on oilseeds and algae are more heavily focused on organic acid production. He added that it would be a good idea to look at the conversion of lignocellulose into organic acids rather than sugars.

From the perspective of greenhouse gas mitigation, commented **David Stern** of ExxonMobil, the best use of biomass would be to burn it and make electricity and he wondered why DOE was not looking at the power option for biomass. Duff agreed with that assessment but noted that converting a billion pounds of biomass into electricity would be miniscule compared to reducing greenhouse gas output by the power generating industry. He added that sustainability is about more than greenhouse gas emissions; in his mind, quality of life is an important consideration. Stern agreed with that remark and added that he felt that the real value of biomass conversion lies in rural development and job creation as part of the bigger picture of sustainability. Paul Bryan also voiced support for looking at sustainability through this larger lens.

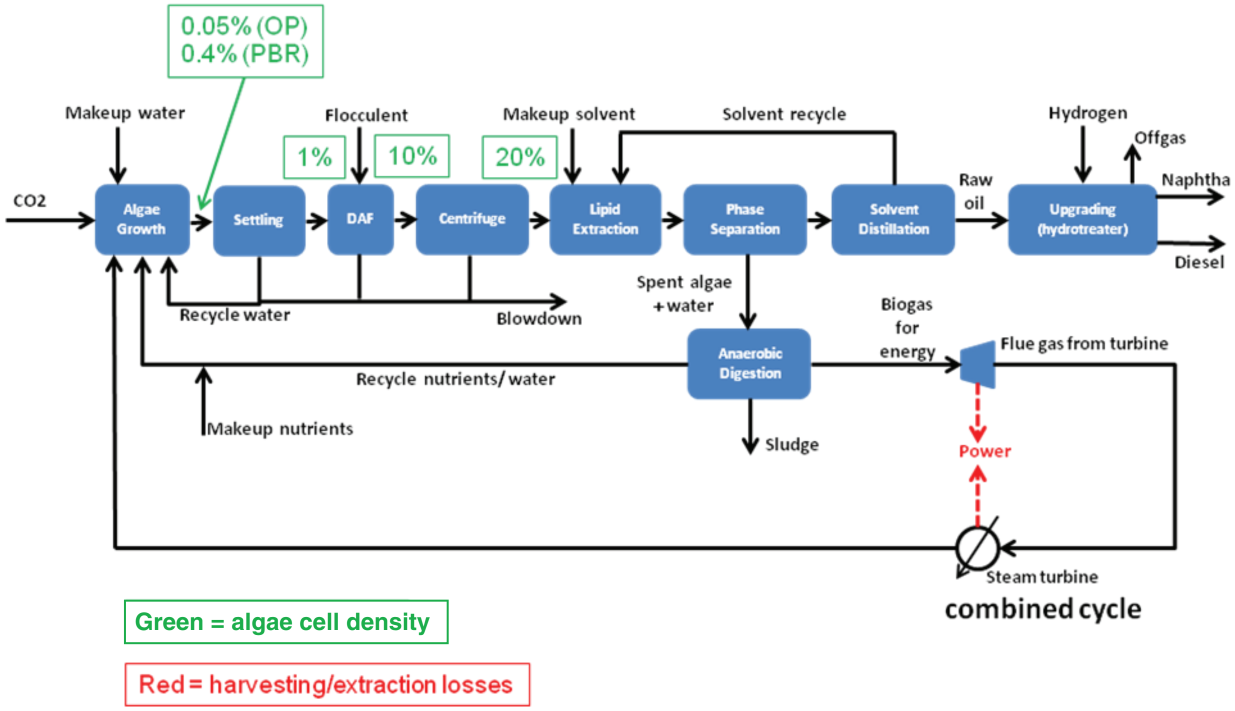


FIGURE 2-9 The intermediate produced by the algal pathway is algal oil.
SOURCE: Image taken from Duff presentation.

3

Fuels and Chemicals from Biomass via Biological Routes

"We have to drive a substantial amount of cost out of both operating and capital costs in order to make this work."
Chris Somerville

"It should be hard to displace a mature trillion dollar industry."
Chris Somerville

INTRODUCTION

Using biological systems to convert biomass into fuels and chemicals is already feasible, but the costs of doing so make the resulting products uncompetitive economically at present with those produced from petroleum. According to **Chris Somerville**, professor of alternative energy and director of the Energy Biosciences Institute at the University of California in Berkeley, currently, biological conversion processes are done in batch mode, which has a substantial impact on capital costs and throughput. Successfully developing continuous flow processes could have a marked positive effect on the economic competitiveness of biomass-derived fuels and chemicals. Creating such processes, however, will require significant advances in pretreatment and separations technologies, and realizing those advances requires recruiting chemists and chemical engineers to attack these problems.

BIOLOGICAL ROUTES TO FUELS AND CHEMICALS

The biological conversion of cellulosic biomass into fuels and chemicals should be straightforward, said **Chris Somerville**, but as companies have begun building commercial-scale bioconversion facilities it has become clear that putting theory into practice is more challenging than expected. One challenge is dealing with the complexity of the overall process of converting lignocellulosic biomass into ethanol. Using the National Renewable Energy Laboratory (NREL) Aspen model for bioconversion as an example, he noted that there are 21 unit processes that require engineering solutions and equipment. As a result, the capital recovery costs for a bioconversion plant are substantial, totaling about $1 per gallon of ethanol.

A closer look at these costs reveals some surprises, said Somerville. Lignin drying boilers and wastewater treatment account for 55 percent of the capital costs. A 50-million-gallon facility built using the NREL process could produce up to one billion gallons a year of wastewater that contains as much as 2 percent solids, necessitating the construction of a large wastewater treatment facility. Boiler costs are so high because it must handle solids, and constructing a solids boiler for a 50-million-gallon facility makes little sense economically. In fact, it might be more efficient to eliminate the boiler, pelletize the lignin and other solids, and sell them to a coal power plant. Figure 3-1 shows the contribution to the overall cost by process area and capital, operations, and fixed costs.

Turning to process costs, feedstock costs are reasonable, about $0.74 per gallon, but pretreatment, hydrolysis, and cellulase enzyme total about $0.83 per gallon, with total operating costs of about $2.15 per gallon of ethanol. Somerville said that given that ethanol has two-thirds the energy density of gasoline, this scheme does not work economically. A substantial amount of cost must be driven out of both operating and capital in order to make this work, and the first step that is needed to do that, he said, is to realize that all of the existing processes are fundamentally batch processes. Though he admitted that this is a radical view, he believes that ethanol production facilities need to follow in the footsteps of petrochemical plants and turn to continuous processes, which the chemical industry has shown is the only way to operate economically at commercial scale.

Turning Batch Processes into a Continuous Process

Batch processes, he explained, are inherently inefficient because they never operate at an optimal place in terms of sugar concentration, lignin inhibition, or microorganism

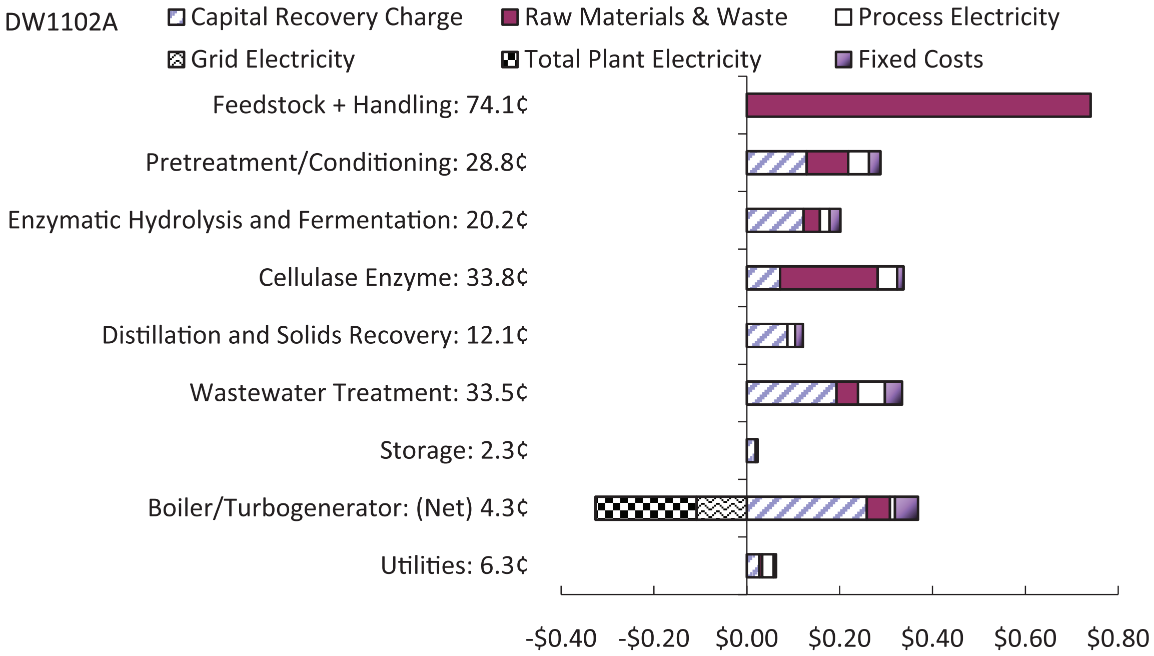


FIGURE 3-1 Contribution to minimum selling price of corn-derived ethanol from each process area.
SOURCE: Humbird et al. (2011). NREL/TP-5100-47764 (Somerville presentation).

performance. Batch processes produce dilute fuel that needs to be concentrated, catalysts and microorganisms are basically burned after each batch is processed, and wastewater generation is substantial. In addition, the entire process is shut down after each batch is completed, during which time capital equipment sits unused.

In the ideal process scheme, sugars are loaded into the fermentation tanks at an optimal rate and fuel is removed continuously. One scheme for reaching this optimum is to use a plugged reactor concept based on the continuous removal of fuel (see Figure 3-2). This concept relies on liquid/liquid extraction or an ethanol-selective membrane to achieve fuel separation under continuous operating conditions, and depending on the concentration of the sugar input, there will be little or no waste water to handle. Developing liquid/liquid extraction processes and new ethanol-selective membranes are areas in which the chemical sciences can make substantial contributions.

In a hypothetical continuous process that Somerville discussed, biomass would be ground and fed into a lignin removal process that feeds polysaccharides into a polysaccharide depolymerization process using enzymes or chemical catalysts that can be recycled. He made note of ongoing research that has produced heterogeneous platinum on carbon catalysts with extremely high activities. A concentrated sugar solution would then be fed in a fermentation reactor, with fuel separation and volume adjustment being performed continuously. And while there are challenges remaining to optimize this process, the only real stumbling block today is implementing lignin removal at the beginning of the process in a way that minimizes polysaccharide loss and recycles the lignin solved at very high efficiency.

In reviewing some of the approaches being explored today, Somerville said that each has limitations. Acid pretreatment is inexpensive, but it removes valuable hemicelluloses as well as lignin and it also produces some downstream inhibition. Various ionic liquids will dissolve cellulose and also separate polysaccharide-lignin mixtures, but ionic solvents are currently too expensive and would require recycling efficiencies of 99.999 percent to work economically. A more promising approach, one that needs the attention of the chemical sciences, is to develop catalysts that will partially depolymerize lignin. He noted that there have been some successes reported with model systems, but that this is still an area of research that is underexplored. Studies using supercritical water also look promising, though the engineering challenges of working at the required high pressures are substantial.

Studies on continuous pretreatment technologies have examined weak acid/high temperature and strong acid/low temperature combinations, as well as the use of aqueous bases, with or without ammonia and with or without added oxidants. So far, the strong acid/low temperature approach appears to be the most promising, and it produces a very pure sugar solution after a solid/liquid separation step. Both hydrochloric acid and the extraction solvent are recycled efficiently. Somerville said a major issue is building durable and safe process equipment that works with strong, concentrated acids such as 40 percent hydrochloric acid.

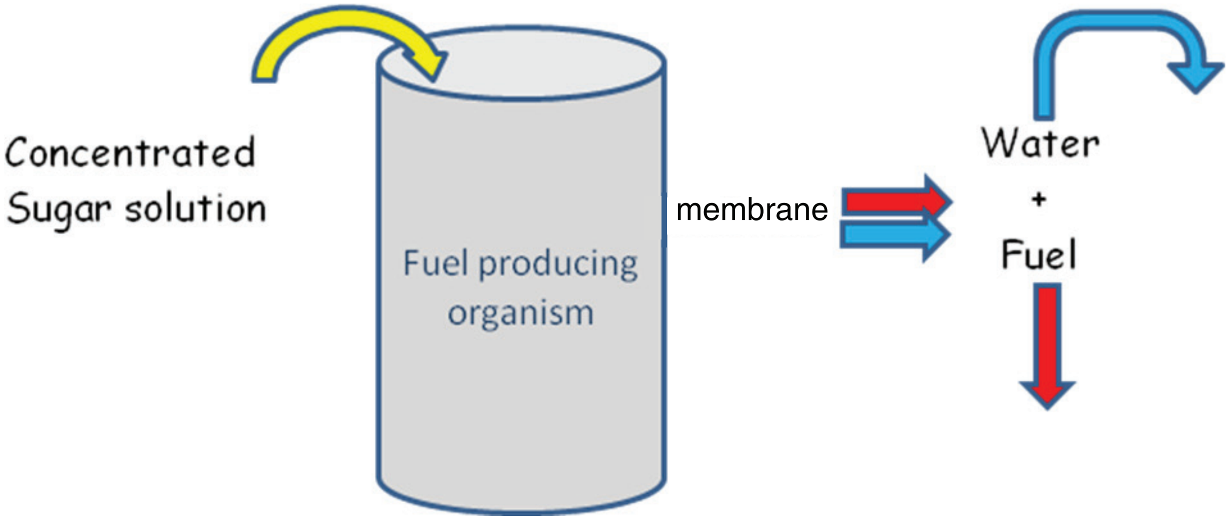


FIGURE 3-2 Plugged reactor concept for continuous fuel production.
SOURCE: Image taken from Somerville presentation.

In concluding his talk, Somerville noted two other challenges that require the attention of chemists and chemical engineers. The first is producing optimized depolymerization catalysts, whether they are enzymes or chemical catalysts, in very large quantities at an affordable price. The second is to develop large-scale anaerobic processes that produce gasoline and diesel fuel from sugars.

Discussion

In response to a question about how much progress was being made on developing a continuous fermentation process, Somerville said that Yong-Su Jin at the University of Illinois would be publishing the results of a study demonstrating efficient continuous fermentation of C12 sugars rather than C6 sugars. Tom Richard asked Somerville to discuss some of his work on developing new enzymes of pretreatment, and Somerville noted that his group has identified enzymes from cow rumen that operate efficiently at high temperature, but that the major limitation in developing those enzymes for industrial use today is the inability to engineer their favorite production hosts to produce them in the necessary quantities. He remarked that this is a fundamental piece of science that needs the attention of the research community.

Somerville then expanded on the need to develop ways of converting sugars into fuels. In his opinion, the most promising long-term strategy is to make short-chain alcohols and then use long-established chemistry to produce mixtures of the longer-chain isoalkanes that are used in jet fuel and diesel. He noted that chemists at his institute are exploring old chemistries that had largely been forgotten because they produce mixtures, but since fuels are mixtures of products, those chemistries may actually be useful today. Getting chemists to change their way of thinking to appreciate reactions that produce mixtures was a real challenge because that idea goes against the paradigm of modern chemical science.

BREAKOUT DISCUSSION

This breakout session was led by **Leonard Katz**, associate professor at the University of California, Berkeley, and a member of the scientific advisory board of Lygos. The discussion about biological technologies for biomass conversion focused on whether the biological conversion of biomass into chemical and fuel should be conducted in an integrated biorefinery or whether it should be broken into components. The argument was made that preparing biomass for processing should be one component, that deconstruction to produce sugars would be a second component, and that conversion of sugar into fuel or chemicals would be a third process. Developing these three processes together into an integrated biorefinery was considered by many breakout group members to be too risky at this stage of technology and capacity development. However, the discussion also raised the possibility that it might be economically and technologically attractive to combine biomass preprocessing and deconstruction into an integrated process or to combine deconstruction and fermentation in an integrated process. Many breakout group members said that determining the optimal configuration is an area that needs further study and analysis.

One idea that was raised during the discussion was that there may be a market for lignin as a carbon-neutral source of energy and that there may be advantages to removing lignin from biomass at local facilities close to the biomass source. Such an approach might improve the economics of biomass conversion by reducing the amount of material that would need to be transported to larger processing facilities for conversion to sugars while also providing an energy source to support local industry.

The major technological and commercial barriers to scaling up sustainable technologies involve moving from batch processing to continuous processing, at least up to the stage of sugar production. It was noted by several breakout group members that batch processing of biomass to produce sugar on a scale needed to produce 21 billion gallons of ethanol a year by 2022 was untenable economically. Producing that much ethanol in batch fermentation plants would require 525 40-million-gallon plants at $40 million apiece.

Most breakout group members believe that fuel production and chemical production should be considered separate pathways, much like they are in the petrochemical industry. While many breakout group members agreed that fuel production from sugars via fermentation should be done through a continuous process to be truly economical and scalable, production of most chemicals is best done in batch mode, at least based on the extensive experience of the chemical industry. It was noted during the discussion from a member of the group that 90 percent of organic chemicals used today are made in batch operations. This percentage reflects the production of the many hundreds of specialty chemicals which are done in relatively small batches, whereas the top 100 commodity chemicals, which represent by mass the bulk of synthesized organic chemicals, are produced in continuous-flow batches. The chemical industry is already exploring the production of chemicals from biomass independent of fuel production.

The breakout group discussed the need to solve technological issues involving economical production of enzymes to meet a variety of demands. Many members of the group concurred that technology development was needed to design enzymes with higher activities, that could pretreat biomass prior to sugar production, that would resist inhibition by lignin or organic acids, and that will function in alternative environments, such as in ionic solvents or under pressure. There was substantial discussion, with no consensus, about whether it was better to build better and less expensive enzymes or to engineer microorganisms to that can perform multiple steps in the conversion process. The suggestion was made that the biomass field could learn from the pharmaceutical industry, which makes extensive use of secondary metabolism by engineered microorganisms to produce high-value products. The breakout group also noted the need to develop methods for conducting large-scale anaerobic fermentation to achieve more efficient conversion of sugars to product.

Addressing the issue of needed skills, the breakout group concurred that fundamental process engineering is "a dead field" that attracts little interest among researchers and few funding opportunities, but that this field should be reinvigorated if technological barriers are to be addressed. What little process engineering research does occur is largely conducted overseas. The same appears to be true for separations technology and surface chemistry, and the breakout group agreed that chemists need to receive better training in these key technological fields. Some members of the group highlighted the need for universities to establish biofuels courses which has already been done at the University of California, Berkeley. Some group members noted the need for biochemists to receive more training in enzymology, a field that once flourished.

According to Katz, members of the group said chemical engineers also need a new set of skills to contribute to the development of a biomass-based industry. Chemical engineers today receive very little training in batch processing or in the design and operation of continuous enzymatic processes. Both of these deficits need to be addressed immediately, according to the breakout group members, Katz said.

Turning to issues of transportation infrastructure, the individual breakout group members concurred that the costs of biomass collection and transportation needed to be addressed if biomass is to make a significant contribution to the production of fuel and chemicals. The members of the group said that the biomass industry will have to depend on the existing transportation infrastructure given the huge expense of creating a new one. It was noted during the breakout group discussion that $4 billion was invested in an ethanol pipeline system that is only at 25 percent of capacity now.

One idea from the group was that it may be necessary to subsidize stover collection by secondary harvesting services to meet supply considerations if the market develops for the products of biomass conversion given that there is little economic incentive today for farmers to collect stover. The group also noted that storage of corn stover or corn cobs, which could also be a good source of biomass, is expensive and is actually a significant economic barrier that needs to be addressed. The breakout group raised the idea of developing a slurry-based pipeline system for biomass or a system for converting biomass into pellets for easier transport.

The breakout group concluded its discussions with a comment about the idea of converting biomass to so-called drop-in fuels versus expanding the amount of ethanol produced. The group said that it is hard to compete with ethanol in terms of net energy return from sugar because ethanol's high oxygen, low carbon content closely matches that of sugars. For advanced biofuels based on hydrocarbons, fatty acids produced by algae or oil crops are likely to be the better feedstock.

4

Fuels and Chemicals from Biomass via Thermochemical Routes

"If you can provide inexpensive lipids, we can turn them into aviation fuel, diesel, and gasoline without too much trouble."
Robert Brown

INTRODUCTION

The two primary approaches to using thermochemical process to convert biomass into fuels and chemicals are gasification and pyrolysis. Gasification produces syngas, a mixture of carbon monoxide and hydrogen that is already used in the petrochemical industry. Pyrolysis produces bio-oil, a thick, corrosive mixture that in some respects resembles crude oil, and charcoal, which can be used as either an energy source or a carbon sequestration agent. Both approaches yield intermediates that are then used as feedstocks for further processing. An advantage of using thermochemical processing, as opposed to biological processing, is that it can more readily break down lignocellulosic materials in a controlled manner to produce high concentrations of desired intermediates. An important obstacle to thermochemical processing is the inorganic contaminants in biomass, which can foul the catalysts used to convert syngas or bio-oil into fuels and chemicals, said **Robert Brown**, founding director of the Bioeconomy Institute at Iowa State University.

THERMOCHEMICAL ROUTES TO FUELS AND CHEMICALS

The choice of whether to use a biochemical route, which uses enzymes and microorganisms to generate desired products, or a thermochemical route, which uses heat and catalyst to generate product, depends on the type of feedstock being processed, said Brown. The three major classes of biomass, he explained, are lipid-rich biomass, which historically has been soybeans but that would include algae in the future; lignocellulosic biomass; and waste biomass, which is a mixture of all different kinds of feedstocks.

The beauty of lipid feedstocks is that they are nearly hydrocarbons that are not difficult to turn into aviation fuel, diesel, and gasoline, Brown noted. In fact, petroleum companies have developed and proven large-scale processes for making fuels from lipid biomass, but all of these operations have been shut down for one reason, said Brown—the high cost of the feedstock. If ongoing research can successfully develop cheaper feedstocks, such as those that could grow on marginal land, thermochemical conversion of those feedstocks into fuels will be attractive. Algae may prove to be one of those feedstock sources, but algae also produce high levels of protein that will need to be dealt with in an economically viable manner, by turning it into either fuel, which will involve catalytic removal of nitrogen, or food.

Lignocellulose is naturally recalcitrant to degradation, but thermochemical approaches can break down lignocellulose in a controlled manner that produces high concentrations of desirable molecules. See Figure 4-1 for lignocellulose's structure. The question that needs to be asked, said Brown, and one that he does not have an answer to, is whether efforts should focus on lignocellulosic or lipid feedstocks. In essence, this comes down to a decision as to what kind of plant should be used to deoxygenate carbohydrates—a petrochemical-type plant that produces carbon dioxide and water as the waste stream, or a green leafy plant that also deoxygenates and decarboxylates sugars *in situ*.

Gasification and Pyrolysis

Turning to the concept of thermochemical processing, Brown explained that the basic idea is that a feedstock is depolymerized into what DOE calls a feedstock intermediate and what Brown calls a thermolytic substrate. The thermolytic substrate then undergoes some type of upgrading, either through biological or chemical processes, to produce a biofuel. The two major types of thermochemical processes are gasification and pyrolysis.

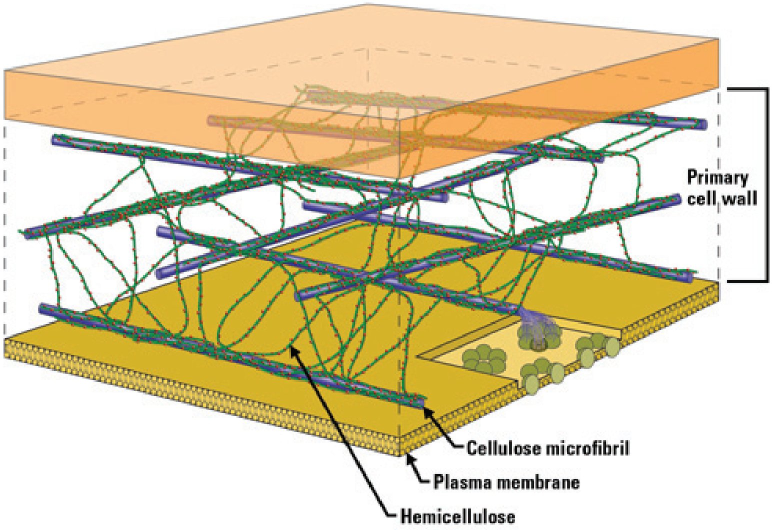


FIGURE 4-1 Lignocellulose structure.
SOURCE: Office of Biological and Environmental Research of the U.S. Department of Energy Office of Science.

Gasification, Brown explained, is the thermal decomposition of organic matter into flammable gases, using either a bubbling fluidized bed reactor or an entrained flow gasifier to produce syngas. These technologies have been commercialized for coal, but in some respects they work even better with biomass. Though gasification is in theory an equilibrium process at very high temperatures and long residence times, in practice equilibrium is obtained rarely and so the process generates tar, char, and small amounts of contaminants that agronomists would like to claim as nutrients. These contaminants, which include small amounts of alkali metals, sulfur, nitrogen, and chlorine that must be removed before upgrading in order to prevent poisoning of catalysts. Removal of each contaminant requires its own catalyst, adding substantial costs to any gasification process.

A significant advantage of the gasification process is that there is no question of what to do with lignin, as it is turned into syngas, too. Gasification can also handle virtually any feedstock, including waste streams, and produce a uniform intermediate product for upgrading. It can also be used to produce heat, power, fuels, or chemicals and allows for energy integration into biorefinery operations.

Technical challenges are particularly challenging in terms of developing technologies that can cost-effectively remove contaminants from the gas stream (Figure 4-2). Gasification operations must also be integrated with fuel synthesis operations, which is not a simple matter given that fuel synthesis occurs at high pressures and under exacting stoichiometries. From a commercial perspective, gasification only works economically at large scale, which translates into high capital costs that could be as high as $10 per gallon of annual plant capacity. Brown added that biomass gasification must also compete with steam reforming of natural gas, which while not a renewable resource is a domestic resource that would move the country away from imported petroleum and reduce greenhouse gas emissions compared to petroleum.

The other major thermochemical technology is fast pyrolysis, which rapidly heats biomass in the absence of oxygen to produce three products: syngas, charcoal, and a liquid mixture of organic compounds and water known as bio-oil that is recovered from pyrolysis vapors and aerosols (see Figure 4-3). Charcoal, also known as biochar, can be used as a carbon sequestration agent. In combination with the bio-oil, biochar presents an opportunity for producing carbon-negative fuel, said Brown.

Fast pyrolysis, he explained, is characterized by residence times of 0.5 to 2 seconds, a very high rate of heating at moderate temperatures of 400–500°C, and the production of a liquid that looks like petroleum but smells like barbecue sauce. Typically, 60–70 percent of the weight of biomass is converted to bio-oil (see Figure 4-4). The yield of biochar ranges from 13 to 15 percent and that of syngas is in the 13–25 percent range. The syngas can be used as an energy source to support this process.

Pyrolysis chemistry is poorly understood, and Brown stressed the need for chemists and chemical engineers to study this process. Studies at Iowa State have found that pyrolysis converts cellulose into products in a number of competing parallel pathways. This work has also shown that alkali present in biomass acts as a powerful catalyst that produces undesired light oxygenates, and so research is needed to understand how to control or suppress this process. Chemists can play a critical role in this research and help produce a more valuable product in the end. (To see a figure of pyrolsis chemistry, please see Figure 4-5.)

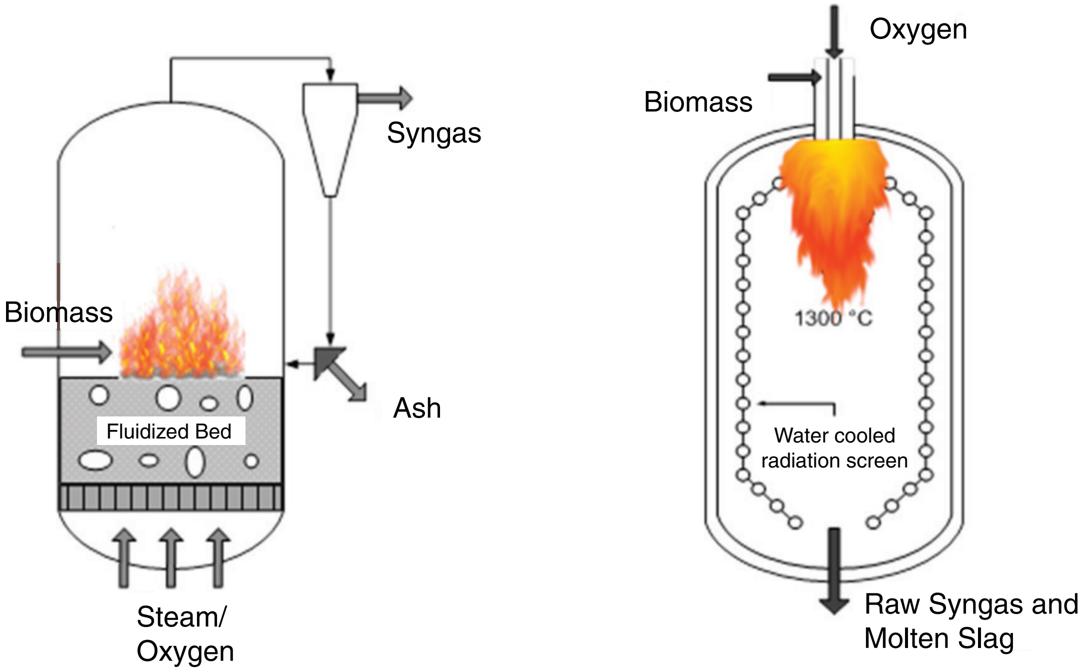


FIGURE 4-2 Gasification can be done in either a low-temperature fluidized bed system (left) or a high-temperature entrained-flow gasifier (right).
SOURCE: Office of Biological and Environmental Research of the U.S. Department of Energy Office of Science.

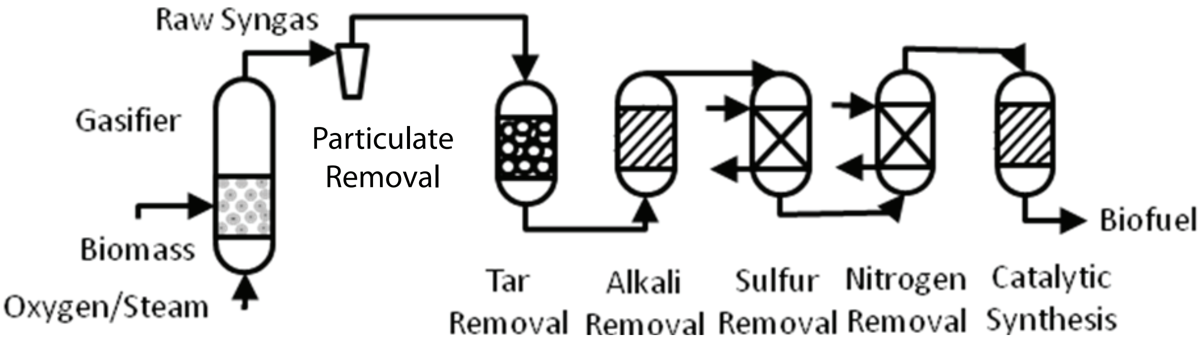


FIGURE 4-3 Removing impurities from biomass-generated syngas is a major challenge.
SOURCE: Office of Biological and Environmental Research of the U.S. Department of Energy Office of Science.

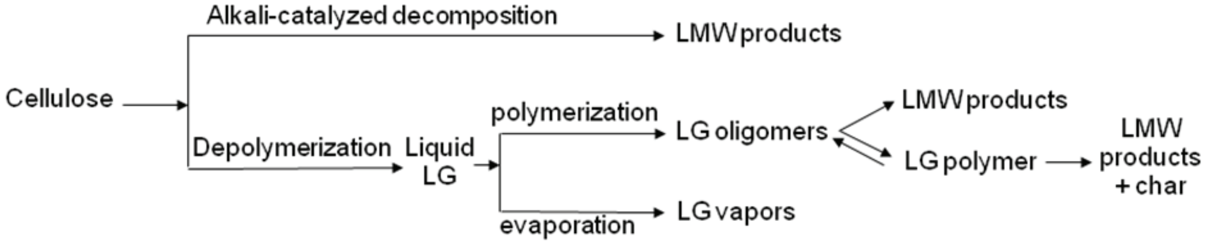
From a technical standpoint, the advantages of fast pyrolysis are that it occurs rapidly and at atmospheric pressure. It is a pathway to drop-in fuels or hydrocarbons, and it can produce multiple products. Commercially, fast pyrolysis offers the lowest-cost option for drop-in biofuels today, and bio-oil can be economically produced on a scale as small as 200 tons per day, which offers opportunities for distributed processing. Small facilities, located near the source of biomass, could produce bio-oil that would then be transported to a centralized facility just as is done with petroleum today.

The primary technical challenges facing fast pyrolysis, according to Brown, are that bio-oil is unstable, corrosive, and contains high levels of oxygen and water. Also, as he already mentioned, the fundamentals of pyrolysis are poorly understood. Commercially, there have been no demonstrations of bio-oil production and upgrading. Also, the pathway to finished fuels is still uncertain, though he remarked that the fact that there are many possibilities that have not yet been explored is what excites him as a researcher.

Other Pyrolysis Routes

Brown then briefly discussed two other types of pyrolysis—catalytic pyrolysis and solvolysis. Catalytic pyrolysis employs catalysts in the pyrolysis reactor or immediately downstream before bio-oil recovery to produce

FIGURE 4-4 Bio-oil produced by fast pyrolysis of biomass.
SOURCE: Office of Biological and Environmental Research of the U.S. Department of Energy Office of Science.



Note: LMW (low molecular weight products) include H_2O, CO_2, 5-HMF, furfural, furan, carboxylic acid, etc.

FIGURE 4-5 Pyrolysis chemistry.
SOURCE: Office of Biological and Environmental Research of the U.S. Department of Energy Office of Science.

highly reduced molecules that are more stable and more easily turned into fuels. Some researchers, he noted, have claimed that they have produced diesel fuel directly via catalytic pyrolysis, and while this represents a big advance, the product still needs some upgrading before it can be used as a fuel. The main challenge here is that yields are relatively low because of coking. Nonetheless, a large number of companies are exploring this approach even though the fundamental chemistry is not well understood.

Solvolysis is pyrolysis in a solvent, and it has two major manifestations. One involves direct liquefaction to produce a bio-crude that is similar to bio-oil but more deoxygenated. The other approach uses hydrothermal processing to produce sugar and a lignin-like product. The advantages and challenges with solvolysis are similar to fast pyrolysis with the added challenge of operating at high pressures. Brown noted that two start-up companies are working on commercial prototypes using solvolysis, one using direct liquefaction, the other hydrothermal processing.

Brown concluded his talk by briefly discussing various approaches for upgrading thermolytic substrates, and focused his remarks on the solubilized carbohydrates that can be produced. These are essentially highly concentrated solutions of sugars, typically greater than 20 weight-percent, which would have to be diluted to use for fermentation.

Discussion

Paul Bryan asked about the possibility of producing methanol as a pyrolysis product and using it as a fermentable intermediate. Brown replied that this is a good possibility, among probably a dozen others, that the market will need to assess. A participant asked if the high aromatic content of fast pyrolysis is a problem given that the fuel industry is moving away from aromatics. Brown responded that aromatics are expected to be an important component of fuels for some time to come. They are particularly produced by catalytic pyrolysis using zeolites, but through further research alkanes might instead be produced.

Mark Barteau, from the University of Delaware, asked if co-processing of biomass with natural gas might be a way of shifting the carbon-hydrogen-oxygen ratio without using expensive hydrogen. Brown replied that with natural gas at the $2 level, this idea makes perfect sense and could provide a bridge to advanced drop-in biofuels. **Helena Chum**, from NREL, asked about the optimal scale for biomass processing, and Brown said that the issue of scale has to balance the fact that larger plants are probably offering economies of scale as far as process and capital costs are concerned, but that larger plants also have increased costs to transport biomass. He guessed that the optimal size for a plant that converted thermolytic substrates into transportation fuels would be somewhere in the 2000–3000 tons per day range although distributed processing facilities might be substantially smaller.

BREAKOUT DISCUSSION

This breakout session was led by **Douglass Elliott**, of the Pacific Northwest National Laboratory, and the discussions began with the participants noting that there are a number of large-scale (greater than 500 tons per day of biomass) and pilot-scale (under 50 tons per day of biomass) demonstration projects, for both gasification and pyrolysis, either under construction or in the planning stage. The group acknowledged that gasification technology, while well proven with other feedstocks such as coal, may to struggle to compete with cheap, abundant, long-term supplies of natural gas. Having said that, many breakout group participants concurred that gasification is likely to be "omnivorous"; that is, it is likely to be adaptable for use with a wide variety of feedstocks. It was suggested, in fact, that while natural gas is the feedstock of choice today, it could serve as a bridge technology to biomass feedstocks in the future. Another suggestion was to integrate a corn stover gasifier into corn ethanol plants. Lignin and unconverted sugars could also be mixed into the corn stover for gasification. It was noted that such a plant is on the drawing board.

The breakout group discussed the use of gasification or natural gas to upgrade the bio-oil produced by pyrolysis and thought this was worth exploring. It was noted that Finland has been adding small pyrolysis chambers to existing fluidized bed combustion boilers. The pyrolysis unit uses some of the heat from the boiler system and in return feeds char and other byproducts of pyrolysis back into the boiler's combustion chamber.

Turning to the subject of technological and commercial barriers, the breakout group noted that economic analyses and life cycle analyses are missing from most thermochemical conversion studies, particularly for combined systems. Some participants suggested that such studies be funded because there are many interesting concepts being developed today, but there is little thought being given to cost analysis. In the same vein, the breakout group described the need for better coupling of basic, translational, and applied research studies and noted that DOE could help fill that gap.

Another area of research that needs to be bolstered, some group participants noted, concerned the development of technologies to efficiently handle biomass solids of different characteristics and to determine how to best mix different biomass sources to produce bio-oil with more consistent properties. Some members of the breakout group also identified the need to develop methods for feeding biomass feedstocks into reactors at pressure, to design catalysts that are more tolerant of the poisons in biomass and of water and steam, and to perform separations at lower energy intensity. A basic research question that still needs answering, according to many breakout group members, was whether it might be best to process biomass as fractionated components rather than as the natural biocomposite that is lignocellulosic biomass.

The breakout group briefly discussed the belief that most efforts today focus too much on market "push" and not enough on market "pull." In other words, the many members of the group noted, research was needed to identify products that could be made in an economically competitive manner from bio-oil or syngas. One approach to developing market pull that is being followed to some extent, the group noted, is to demonstrate how bio-oil or syngas would integrate seamlessly into existing petrochemical streams. Such efforts to develop market pull could help address the problem of attracting capital to this area.

In terms of skills needed, the breakout group said the main deficit in training in its opinion was the lack of interdisciplinary coursework and collaboration among engineering, chemistry, biology, and plant science investigators. Some breakout group members also noted they would like to see a greater emphasis in chemical engineering education on using carbon from biomass as opposed to just from petroleum.

Addressing the transportation infrastructure issue, the breakout group noted that there are far more questions than answers concerning how to best move biomass into a processing system and then move the direct products of biomass conversion into the secondary processing stream. Many members of the breakout group concurred that they would like to see the emphasis on using existing infrastructure and trying to make products that can be fit into today's infrastructure at as early a point as possible.

5

Heat and Power Production from Biomass

"We are not going to displace huge, huge hunks of our energy requirements with biomass."
Jeffrey Steiner

"If you have a ton of biomass, the best way to avoid greenhouse gas emissions is to burn it, and displace coal or even natural gas. You get the biggest bang for your buck."
David Stern

INTRODUCTION

Burning biomass to produce energy and heat is nothing new, but doing so at a large scale still cannot compete economically with coal and natural gas. Local, small-scale biomass-to-power systems may prove to be the most efficient way of generating energy from biomass. Already, small-scale production of natural gas from biomass and on-site co-generation of electricity and heat is widespread in Europe. Farm-sized units are in operation in the United States as well.

BIOMASS CONVERSION TO HEAT AND POWER

In introducing the subject of generating heat and power from biomass, **Jeffrey Steiner**, national program leader for biomass production systems at the USDA Agricultural Research Service and agency lead of the USDA Regional Biomass Centers, noted that today biomass, including grain ethanol, only accounts for more than 4 percent of total U.S. primary energy consumption, a very small number. He also reiterated earlier comments that even the latest Billion-Ton study acknowledged that biomass is not going to displace huge chunks of the nation's energy needs, as we currently consume it. He did say, though, that biomass is going to be an economic force in the future and that there is money to be made in the biomass arena.

One factor that is complicating the economic development of biomass, said Steiner, is that the United States does not have a policy on biomass, which he contrasted to that of other countries, using Uruguay as an example. While there is the billion ton goal for 2030, there is no policy concerning the optimal uses of the biomass and how producing that much biomass fits into existing structures of agriculture and forestry. There is no clear picture, said Steiner, about soil and water resources, the role of landowners and financiers, and the supply chain that is going to be needed to make biomass an economic reality.

He noted, too, that most of the emphasis of the previous speakers has been on large-scale development, but small-scale pellet stoves and biogas generators are also likely to have their place. In Ireland, for example, small pellet stoves are the predominant source of heat in villages. He also remarked that other factors, such as carbon budgets, can factor into the decisions of how best to use biomass, and again he used Ireland as an example. The very efficient Edenderry Power facility has been burning peat to meet the country's carbon targets, but peat is not a renewable resource, so the plant is now blending in Miscanthus or willow with the peat to meet its carbon targets. This change has affected feedstock quality and chlorine emissions that now have to be accounted for.

Moving from the large scale to the small scale, Steiner described an on-farm gasification facility in Rockford, Washington, that costs about the same as a combine, some $300,000. This is a very sophisticated piece of equipment that is automated and produces about 30–40 percent syngas. Another example of a small-scale facility is an anaerobic digester near Limerick, Ireland, that takes waste from dairy, chicken, and pig farms and converts it to gas that is then burned to produce electricity that is fed into the national electrical grid.

Steiner noted that there are 186 farm-based anaerobic digesters operating in the United States, as well as about 1,500 wastewater treatment systems that utilize biogas and another 576 landfill operations that harvest biogas. In contrast, Germany has over 12,000 digesters operating. However, burning this biogas as a source of energy may not be the most efficient use of it. It may be more efficient to use it for chemical production or to clean it efficiently and feed it into natural gas pipelines.

Concluding his remarks, Steiner said that there needs to be a transition in thinking about each of these processes linearly and to integrate all aspects of biomass utilization in a way that maximizes efficiency. By doing so, it should be possible to eliminate waste products and instead have them serve as feedstocks for other processes.

BREAKOUT DISCUSSION

One of the main themes of this breakout group's discussion, which Steiner led, is that the generation of heat and power from biomass may best be done at a smaller rather than larger scale in the United States. This is in contrast to Europe, where economic and political drivers have created a demand for biomass-generated power on a large scale. The point was raised that community-scale or even home-scale digesters that would turn local wastes into gas that would be burned for heat or in a small co-generation facility might be economically viable, and it was noted that a Korean company is making a home-scale system. What is needed, some members of the group noted, was scientific performance data from systems of this scale that would allow a sound case to be made for use of local biomass in this way.

In fact, the many breakout group members said, the field as a whole needs solid modeling to determine the minimum- and maximum-sized operations that make economic sense based on performance metrics. It was also noted by some members that there is a need to develop a matrix identifying which fuel source is most economical at what scale. The group noted, though, that an impediment to performing such modeling work is the absence of such metrics for smaller scale systems. Given that the field of power generation from whatever source is seen as being mature with no need for research, the group commented that such metrics are not likely to be generated soon. Some breakout group members said that a formal analysis of state-of-the-art technologies that are available should be done, particularly in Europe and Asia, to look at how the performance of those systems could inform decision making in the United States.

There is also the perception, the group commented, that large-scale biomass production is slated for liquid fuels production given that there are other ways of making electricity and power sustainably. It was also raised by some participants that first coal, and now natural gas, is so inexpensive that biomass cannot compete in the large-scale power generation area. The one thing on the horizon that could change this economic reality, the group said, is the Environmental Protection Agency's scientific panel decision in less than three years on how to classify biogenic emissions. If the panel ultimately decides that biogenic emissions should not be included in greenhouse gas emissions accounting schemes, that could be an incentive to use biomass on a large scale for power and heat generation.

Many members of the breakout group noted that the lack of a national policy on the use of biomass to generate power and the lack of public understanding of biomass as a local power resource are topics that need addressing. They went on to note that such policies and public information campaigns need to be data-driven, and those data are largely missing.

Turning to the discussion of the skills needed to move this field forward, the many breakout group members concurred that the field needs to attract chemists and chemical engineers to the field, but doing so will require first overcoming the perception that there are no jobs in the field. In general, though, the breakout group noted that students in technical subjects need education in economics, policy, and sociology in order to be able to communicate within the multidisciplinary teams required to move the field forward. The breakout group also recognized the need for having life-cycle analysis and quantification of uncertainty added to technical programs.

This breakout group did not have much to add on the subject of the transportation infrastructure other than that there is a need to assess the existing infrastructure to see how it can be best used to move biomass. The group noted that transportation needs depend on scale, technology, and economics and again pointed to the need to conduct a systems analysis if the goal is to optimize the existing system to handle expanded use on the relevant geographical and mass scale.

In the ensuing open discussion, a workshop participant noted that the United States produces more power from biomass through direct firing than Europe. What Europe has done is make use of the heat generated during biomass combustion to a far greater degree, largely because of the prevalence of district heating systems in Europe.

6

Final Thoughts

After completing all of the presentations and breakout sessions, the workshop held a final panel discussion to summarize the day's findings. The panel consisted of **William Hitz** of E. I. du Pont de Nemours, **Emily Carter** of Princeton University, and **Rina Singh** of the Biotechnology Industry Organization (BIO). Paul Bryan, the workshop co-chair, asked each panelist to identify one to three new and important ideas gleaned from the workshop.

Hitz said that he was excited about the possibility of using ethanol as the primary fermentation output but then using ethanol as the starting material to make other chemicals more reduced than ethanol. Carter was encouraged by the idea of using natural gas as a bridge technology to move from coal to biomass as the primary fuel for generating electricity. She thought that this route would develop a biomass industry that would eventually scale enough to make a final transition to producing fuels economically from biomass.

Singh was impressed by the potential of thermochemical conversion technologies and was encouraged that biological and thermochemical conversion were on equal footing in terms of research interest. She noted, though, that she was disappointed by the overall lack of discussion of the economics of any of the technologies discussed at the workshop. She also remarked that the 2012 Farm Bill before Congress calls for funding research on technologies for conversion of biomass to renewable chemicals that stress energy efficiency.

In the ensuing open discussion period, Mark Barteau followed up on the subject of bridge technologies by noting that Delaware enticed Bloom Energy to construct a natural gas-fired fuel cell power plant in the state by passing legislation that counts natural gas-powered fuel cell-generated electricity as part of the state's renewable portfolio. While that may be a stretch, he added that it was his belief that the real interest lies in having biomass be the ultimate source of gas for those fuel cells rather than fossil natural gas. The take home lesson, he said, is that as the biomass community thinks about bridging and transitions it should think not just about technology but also policy and legislation. Carter agreed with this comment and added that discussions that she has been having with the leadership of Public Service Gas and Electric Company (PSG&E), New Jersey's largest publicly owned utility, raised the issue that there is a need for a national policy about electricity. Power grids, she said, are regional and on an interstate basis one electron is no different from any other electron. What happens as a result, she explained, is that PSG&E ends up idling expensive plants that use renewables and that are better for the environment because these plants cannot compete economically with dirty coal plants feeding electricity into the regional grid.

Charles Anderson, from the Pennsylvania State University, commented that the solar energy industry is looking at combining natural gas and solar power plants as a way of being able to produce electricity consistently. Another possible bridging approach might be to combine biomass-fed plants with solar as a way of moving both technologies forward. Continuing on the theme of coupled plants, **Thomas Richard**, also of Penn State, wondered what became of an idea that was popular five to ten years ago of the integrated biorefinery that would produce high-value chemicals as a means of supporting the production of lower value fuels. Hitz responded that industry may have moved away from this idea because the drive to produce low-cost biofuels has become the dominant push. But he agreed that the idea of using a common feedstock to make high-value chemicals might create enough demand for that feedstock to get the front end of the infrastructure going to then make cheap biofuel.

Hitz added that the field needs to continue to evolve its ideas and work on both the supply and demand side together. In other words, a feedstock infrastructure that generates a shippable, densified feedstock will not develop unless there is already an end use for it and vice versa. His recommendation was that the community focus on developing a front-end to back-end solution that would demonstrate the viability of taking biomass and making an economically viable product. Once that happens, he said, then parties might jump in who are interested in developing the supply side or the processing supply. The challenge is figuring out how to evolve that system. Carter added that small companies that she has talked with are looking primarily at making high-value chemicals as a way of getting into the larger biodiesel business eventually.

In a cautionary note, Bryan said that the high cost of separation and purification technologies presents a challenge for the integrated biorefinery idea. Each product needs its own separation, purification, storage, and distribution infrastructure, he explained, and so every product being made needs to pay off at least that part of the process, which in his experience, he said, is often the most costly part of a continuously operating refinery operation. This approach may be more feasible with batch processing.

Helena Chum added to this thread by describing how the Brazilian ethanol industry is evolving. It started largely by converting sugar cane to sugar, using ethanol to maximize profits and eventually to produce electricity. Over the past three years, however, Brazil had shifted its output and is now using 10 percent of its sugar production to make higher value products such as polyethylene and other chemicals. There is a major emphasis in Brazil now to develop the biorefinery concept. The point is that by building a biomass-to-fuels infrastructure, biomass is now a commodity with potential as a feedstock for chemicals and other applications. She added that RFS2 is creating the same situation in the United States. The point that she wanted to make, she said, was that chemists need to think more about the whole system of agriculture and forestry, energy and other products, and the biomass landscape as a whole.

Singh noted that while there are some integrated refineries in the petrochemical industry, these are a number of companies that focus on specialty chemicals. These companies are not vertically integrated, but are instead capitalizing on one aspect of the value chain, something that she thinks could take place in the biomass world with the development of commodity sugars that would be analogous to commodity oil. She added that there are 10 BIO member companies that are working on producing cheap, sustainable supplies of feedstock sugars.

Robert Greene, from DOE's Office of Basic Energy Sciences, asked what a more ideal biomass would look like, and Hitz responded that in his opinion, the biggest improvements today would be on the transportation side, that is, making bigger bales of material rather than in increasing the sugar content of the biomass by a few percent. From an economics perspective, increasing the volume of material that could be hauled on a truck would be the place to have the biggest impact. However, he added that it is still important to continue studying how to increase sugar content and change the structure of plant carbohydrates and lignin to make them more easily converted into sugars. But those efforts will take time to yield advances. Jeff Steiner added that the key thing that has to happen is that people working in the process side need to be talking more to the people working on the supply side to make sure everyone's needs and interests are aligned. Hitz agreed and cited an illustrative example. Grasses may become a good feedstock, but it would be a better one if it stood erect in the field until it was totally dry. Those kinds of mundane features need to be communicated.

GENERAL OBSERVATIONS

Throughout the workshop, speakers made general observations about the issues associated with large-scale biomass utilization and the role of the chemical sciences in addressing these issues. These observations are gathered here to capture the broad themes emerging from the workshop. These themes should not be seen as consensus conclusions of the workshop and are associated with the speaker who made that observation.

- Total global production of cereal grains as a feedstock cannot meet even a fraction of the demand for renewable fuels and chemicals. Doing so will require making use of lignocellulosic materials. (Bryan)
- Solving the "tyranny of distance," seasonality, and feedstock variability problems will require the development of technologies that can convert a wide variety of biomass sources at local depots into a uniform, transportable feedstock for further processing at centralized biorefineries. (Bryan and Stokes)
- With sufficient research and development, the United States has enough available land to produce biomass in sufficient quantities to meet the demand as a renewable source of fuel, chemicals, power, and heat in a manner that is sustainable and that does not compete with food. (Stokes)
- It is not possible to replace a multi-trillion-dollar petroleum-based infrastructure with a biomass-based infrastructure overnight. Economics must be the driving force behind this transition, but policy can help ease this transition. (Duff)
- Tapping into the enormous value of petrochemicals and specialty chemicals is a place where chemistry can play a huge role in realizing value from biomass conversion, particularly since these are high value added products that would use very little of the available biomass. (Duff)
- Both thermochemical and biochemical conversion of biomass into a feedstock for fuel and chemical production is promising, but there is a significant need to create catalysts that can remove contaminants from this

feedstock and that are more tolerant of contaminants in downstream processing. (Duff and Brown)

- Algae have potential as a source of lipids that could be used as a feedstock for fuel, chemical, and energy production, but a great deal of basic research is needed to realize this potential. (Duff)
- To achieve cost-competitive biological conversion of biomass into ethanol or other feedstocks will require moving from batch to continuous-flow processes, a transition that will require a substantial amount of chemical and chemical engineering research, particularly with regard to the development of catalysts and separation technologies. (Somerville)
- Basic research on the chemistry of thermal conversions, via both gasification and pyrolysis, is needed to better tailor these processes to the meet the demands of working with biomass feedstocks. (Brown)
- The lack of a national policy on the use of biomass in power and heat generation is impeding developments in this field. (Steiner, Barteau, and Carter)
- The economics of biomass-to-power systems may benefit from the development of small-scale systems as opposed to large-scale power plants. (Steiner)
- Methane may serve as an important bridge technology between oil/coal and biomass. (Hitz)
- Production of high-value chemicals is an area worth exploring in detail as it represents a potentially viable approach of creating demand for a biomass feedstock. (Hitz, Carter, Chun, and Singh)

Appendixes

A

Statement of Task

The Chemical Sciences Roundtable will hold a one-day public workshop on **May 31, 2012**, in **Washington, DC**, that will explore the current state of sustainable fuels and chemicals, and the issues surrounding their scalability for large-scale use. The workshop will also discuss the chemistry and chemical engineering opportunities to sustainably produce large-scale quantities of biofuel. Both formal presentations and working groups will be components of the workshop in an effort to stimulate engaging discussion among participants from widely varying fields.

Key questions to be addressed include

- What is the current state of technology in large-scale production of sustainable fuels and chemicals?
- What are the benefits and weaknesses of current technologies?
- What are the technological and commercial barriers to scaling up sustainable technologies?
- How can we best combine chemical technologies of different scales to maximize impact?
- How can we identify ways in which technologies of different practical scales can complement each other?

B

Workshop Agenda

Organized by:
Paul Bryan, Independent Consultant; Jennifer Sinclair Curtis, University of Florida;
Luis Martinez, Rollins College on behalf of the Chemical Sciences Roundtable
NAS Keck Center, Room 100, 500 5th St. NW, Washington, DC 20001

MAY 31, 2012

8:00 a.m. Continental Breakfast
8:30 a.m. Welcome & Introduction to Workshop
Paul Bryan, Planning Committee Member

FEEDSTOCKS & CONVERSION TECHNOLOGIES
Chair, Rich Greene, US Department of Energy

8:40 a.m. **Bryce Stokes**, CNJV/Department of Energy
General Feedstocks & Raw Materials Talk

9:40 a.m. **Brian Duff**, Department of Energy, Energy Efficiency & Renewable Energy
General Conversion Technologies Talk

10:40 a.m. Break

VALUE CHAINS
Chair, Jennifer Sinclair Curtis, University of Florida

11:00 a.m. **Chris Somerville**, University of California, Berkeley & Energy Biosciences Institute
Fuels and Chemicals [from Biomass] via Biological Routes

11:30 a.m. **Robert Brown**, Iowa State University
Fuels and Chemicals [from Biomass] via Thermochemical Routes

12:00 p.m. **Jeffrey J. Steiner**, USDA Agricultural Research Service
Heat and Power Production [from Biomass] 2

12:30 p.m. Lunch *(on your own)*

BREAKOUT DISCUSSIONS

1:30 p.m. **Three Parallel Discussions based on Value Chains:**
Group 1: Fuels and Chemicals [from Biomass] via Biological Routes
Room 202

Breakout Session Leader: **Leonard Katz**, Lygos & University of California, Berkeley
Group 2: Fuels and Chemicals [from Biomass] via Thermochemical Routes
Room 206

Breakout Session Leader: **Douglas C. Elliott**, Pacific Northwest National Laboratory
Group 3: Heat and Power Production [from Biomass]
Room 208

Breakout Session Leader: **Jeffrey J. Steiner**, USDA Agricultural Research Service
3:40 p.m. Break

PLENARY REPORT BACK & WRAP-UP

Chair, Paul Bryan, Independent Consultant

4:00 p.m. Reports from Breakout Discussions

4:30 p.m. Wrap-up Panel Discussion
William Hitz, Dupont
Emily Carter, Princeton University
Rina Singh, Biotechnology Industry Organization (BIO)

5:30 p.m. Adjourn

C

Biographies

GUEST SPEAKERS

Robert Brown, Iowa State University (ISU), is the founding director of the Bioeconomy Institute (BEI) at ISU, a university-wide initiative that coordinates research, educational, and outreach activities related to biobased products and bioenergy. The BEI has helped established several new research enterprises at ISU including the NSF-sponsored Center for Biorenewable Chemicals, the Biobased Industries Center, the BioCentury Research Farm, the Biorenewables Research Laboratory Building, the NSF-sponsored EPRSCoR RII project, and the USDA-sponsored CenUSA Bioenergy project. Dr. Brown also helped establish ISU's Biorenewable Resources and Technology (BRT) graduate program, the first such degree-granting program in the United States. He wrote *Biorenewable Resources: Engineering New Products from Agriculture*, which is used around the world as a textbook for courses in biorenewables (including ISU's BRT 501). Dr. Brown's other administrative duties include directing the Center for Sustainable Environmental Technologies, a $3 million per year research enterprise focusing on thermochemical processing of biomass and fossil fuels. The center has pioneered a variety of innovative technologies including syngas fermentation, gasification of bio-oil, production of sugars, bioasphalt, and co-firing pellets from the fast pyrolysis of biomass, and use of biochars as soil amendment and carbon sequestration agent. Dr. Brown has published over 120 refereed papers and is PI or co-PI on over $70 million in cumulative research funding. He is a Fellow of the American Society of Mechanical Engineering, a Distinguished Iowa Scientist of the Iowa Academy of Science, and the recipient of the David R. Boylan Eminent Faculty Award for Research at ISU in 2002. He received an R&D 100 Award from *Research and Development Magazine* in 1997 and was named one of the "Top 100" researchers in bioenergy by Biofuels Digest in 2010.

Brian Duff, EERE, U.S. Department of Energy, is currently the chief engineer and acting deployment team leader for the Office of the Biomass Program at the U.S. Department of Energy in Golden, Colorado. Mr. Duff is a biochemical process engineer with 30 years of experience in biotechnology and renewable energy from biomass; he holds a bachelor of science degree in biology from Lehigh University and a master of science degree in chemical engineering from Stanford University. His primary expertise is in microbial bioconversion processes and the production of fuels and chemicals from lignocellulosic biomass.

Chris Somerville, University of California, Berkeley & Energy Biosciences Institute, is currently the Philomathia Professor of Alternative Energy and EBI Director of the Melvin Calvin Laboratory at the University of California, Berkeley. Dr. Somerville received his B.Sc. in mathematics from the University of Alberta (1974), and his Ph.D. in genetics from the University of Alberta (1978). Dr. Somerville's research focuses on the synthesis of plant cell wall polysaccharides, the relationship of the structures to cell wall functions, and how the system is regulated.

Jeffrey J. Steiner, USDA Agricultural Research Service, is the USDA Agricultural Research Service National Program Leader for Biomass Production Systems and agency lead of the USDA Regional Biomass Research Centers. His responsibilities include strategic planning and coordination of research for sustainable production of dedicated energy crops and their genetic improvement. He also is involved in the development of partnerships with the Department of Energy, Federal Aviation Administration, and Department of Navy, and with technology providers and other businesses interested in advanced biofuel development. Previous to this assignment, Dr. Steiner was Senior Advisor for Bioenergy in the USDA Office of the Chief Scientist, and was the principal co-author of the President's Interagency Working Group *Growing America's Fuels* report. He received his Ph.D. from Oregon State University, and is a fellow of the American Society of Agronomy and Crop Science Society of America.

Bryce Stokes, PhD, CNJV/Department of Energy, is a Senior Advisor with CNJV, a contractor to the U.S. Department of Energy at the Golden Field Office. He is providing support to the DOE Biomass Program in Washington, DC. He received his B.S. and M.S. from Mississippi State University in engineering and Ph.D. from Auburn University in forestry. He worked as a Forest Engineer for Weyerhaeuser Company prior to joining the USDA Forest Service in Auburn, Alabama, as a Research Engineer. He later served as Project Leader for the Engineering Unit at Auburn and then served as National Program Leader for Forest Operations Research as part of the Resource Use Sciences Staff in the R&D Washington Office. His 30 years of research focused on harvesting machine and system design and management; biomass recovery and utilization; reducing forest operations environmental impacts; and specialty systems for pine thinning and wet area harvesting. During his career he also had staff co-responsibility for biomass, carbon sequestration, climate change, and sustainability with his agency, department, and in federal interagency working groups. He had co-responsibilities in industrial partnerships for forest productivity and life-cycle analyses. He previously served in a support role for the USDA Energy Council and is Past Chair of the USDA Biobased Products and Bioenergy Coordination Council and the Federal Working Group on Woody Biomass Utilization. He is active in the Council on Forest Engineering, Forest Products Society, and the American Society of Agricultural and Biological Engineers. He served as a U.S. representative to International Energy Agency tasks on conventional forestry and short-rotation crops for energy 10 years. He has over 140 scientific and technical publications. He co-led the update of the Billion-Ton Report.

PANELISTS

Emily Carter, Princeton University, is the Founding Director of the Andlinger Center for Energy and the Environment at Princeton University and the Gerhard R. Andlinger Professor in Energy and the Environment, as well as Professor of Mechanical and Aerospace Engineering and Applied and Computational Mathematics. She is a theorist/computational scientist first known for her research combining *ab initio* quantum chemistry with dynamics and kinetics, especially as applied to surface chemistry. Later, she merged quantum mechanics, applied mathematics, and solid state physics in her linear scaling orbital-free density functional theory (OF-DFT) that can treat tens of thousands to more than a million metal atoms quantum mechanically, her embedded correlated wavefunction and *ab initio* DFT+U theories that combine quantum chemistry with periodic DFT to treat electronic ground and excited states and strongly correlated materials, and her fast algorithms for *ab initio* multi-reference correlated wavefunction methods that permit accurate thermochemical kinetics and excited states to be predicted for large molecules. She also was a pioneer in quantum-based multiscale simulations of materials. Her research into how materials fail due to chemical and mechanical effects (e.g., corrosion and stress) led to new insights into how to optimally protect these materials against failure (e.g., by doping, alloying, or coating). Her current research is focused entirely on enabling discovery and design of molecules and materials for sustainable energy, including converting sunlight to electricity and fuels, providing clean electricity from solid oxide fuel cells, clean and efficient combustion of biofuels, and optimizing lightweight metal alloys for fuel-efficient vehicles. Professor Carter received her B.S. in chemistry from UC Berkeley in 1982 (graduating Phi Beta Kappa) and her Ph.D. in chemistry from Caltech in 1987. After a year as a postdoctoral researcher at the University of Colorado, Boulder, she spent the next 16 years on the faculty of UCLA as a professor of chemistry and later of materials science and engineering. She moved to Princeton University in 2004. She holds courtesy appointments in chemistry, chemical engineering, and three interdisciplinary institutes (PICSciE, PRISM, and PEI). The author of over 250 publications, she has delivered more than 400 invited lectures all over the world and serves on numerous international advisory boards spanning a wide range of disciplines. Her scholarly work has been recognized by a number of national and international awards and honors from a variety of entities, including the American Chemical Society (ACS), the American Vacuum Society, the American Physical Society, the American Association for the Advancement of Science, and the International Academy of Quantum Molecular Science. She received the 2007 ACS Award for Computers in Chemical and Pharmaceutical Research, was elected in 2008 to both the American Academy of Arts and Sciences and the National Academy of Sciences, in 2009 was elected to the International Academy of Quantum Molecular Science, and in 2011 was awarded the August Wilhelm von Hoffmann Lecture of the German Chemical Society.

William Hitz, Dupont, received his Ph.D. from Iowa State University in 1978 and did postdoctoral work at the DOE Plant Research Lab at Michigan State University. Since 1980 he has been in various research and research management positions with DuPont and DuPont/Pioneer. Dr. Hitz' research interests are in carbohydrate chemistry and metabolism and in fatty acid and lipid synthesis. The primary outcome of the work in crop plants has been metabolic engineering of grain quality in corn and soybean to produce grains improved for their end use in human or animal nutrition. Since 2007 he has been one of the technical leads for biological steps in the conversion of cellulosic feed stocks to ethanol in DuPont Industrial Sciences with commercialization through DuPont Cellulosic Ethanol. Dr. Hitz has been part of the enzyme discovery, the C5/C6 ethanologen and the feed stock assessment teams. His larger interests in biofuels stem from an upbringing on a family farm through a career tied to conversion of the outputs of agriculture to usable products.

Rina Singh, Biotechnology Industry Organization (BIO), is currently the Director of the Policy, Industrial and Environmental Section at the Biotechnology Industry Organization (BIO). Singh previously served as the business development manager at Ashland Inc. She was appointed by the president and CEO as member of an innovative 10-member team assembled to develop a new strategic direction for Ashland, identifying investment opportunities for $1.5 billion resulting from divesture of petroleum refining operations. Singh held general management positions in the technology and business development areas of Ashland, including bioproducts business development manager and platform technology manager. She started her career at The Dow Chemical Co. as a senior research chemist in the Engineering Thermoplastics Group. The holder of 24 patents and publications, Singh received a B.S., a doctorate in natural products (synthetic organic chemistry), and a postdoctoral degree in polymer science from McGill University.

BREAKOUT SESSION LEADERS

Douglas Elliott, Pacific Northwest National Laboratory, has over 35 years of research and project management experience in the Battelle system at the Pacific Northwest National Laboratory (PNNL). His work has mainly been directed toward development of fuels and chemicals from biomass and waste. His experience is primarily in high-pressure batch and continuous-flow processing reactor systems. This research has also involved him in extensive study of catalyst systems. In addition to process development, chemical and physical analysis has also been a significant part of his work. While at Battelle, Mr. Elliott's research has involved such subject areas as biomass liquefaction and hydroprocessing of product oils, catalytic hydrothermal gasification of wet biomass and wastewaters, and chemicals production from renewable sources. His work in biomass liquefaction has involved him in International Energy Agency Bioenergy tasks as the representative for the U.S. and currently as the leader of the Task 34 on Pyrolysis.

Leonard Katz, Lygos and University of California, Berkeley, is currently an associate professor at the University of California, Berkeley, and serves on the Scientific Advisory Board for Lygos. His research areas include bio-inspired approaches to biofuels, calixarene-bound metal clusters, calixarene-modified nanoparticles, grafter calixarene oxide surfaces, and grafted calixarenes as single-site heterogeneous catalysts. He received his Ph.D. from the California Institute of Technology in 1999. Dr. Katz has published more than 95 papers and is an inventor with more than 25 patents issued. He has also pioneered efforts to manipulate modular PKS systems to produce new compounds. Dr. Katz's credentials include research director and industrial liaison officer of the Synthetic Biology Engineering Research Center, former V.P. of Biological Sciences at Kosan Biosciences, Inc., and co-inventor of Lygos' technologies.

Jeffrey Steiner (see bio in Guest Speaker section)

ORGANIZING COMMITTEE

Paul Bryan, Independent Consultant, was, until late 2011, Program Manager for Biomass at DOE/EERE. Currently, Dr. Bryan is an independent consultant. He previously spent 15 years with Chevron in California and Western Australia, most recently as Vice President of Biofuels Technology. Prior to that, he spent eight years in academia (MIT, Colorado School of Mines) and industry (Union Carbide). His educational background includes degrees in chemical engineering from Penn State (B.S.) and UC Berkeley (Ph.D., 1985), and a post-doc in applied thermodynamics at the Ecole des Mines—Paris. He has been active in a variety of industry and professional organizations, including the Separations Division of the AIChE, the North American Membrane Society, the Gas Processors Association, and the Gordon Research Conferences.

Jennifer Sinclair Curtis, University of Florida, is Distinguished Professor in the Chemical Engineering Department at the University of Florida (UF). Prior to this, she held administrative roles as Department Chair of Chemical Engineering at UF and Associate Dean of Engineering and Department Head of Freshman Engineering at Purdue University. Professor Curtis received a B.S. in chemical engineering from Purdue University (1983) and a Ph.D. in chemical engineering from Princeton University (1989). She has an internationally recognized research program in the development and validation of numerical models for the prediction of particle flow phenomena. She is the co-author of over 100 publications and has given over 160 invited lectures at universities, companies, government laboratories, and technical conferences. Professor Curtis is a recipient of a Fulbright Senior Research Scholar Award, a NSF Presidential Young Investigator Award, the American

Society of Engineering Education's (ASEE) Chemical Engineering Lectureship Award, the Eminent Overseas Lectureship Award by the Institution of Engineers in Australia, the ASEE's Sharon Keillor Award for Women in Engineering, and the AIChE Fluidization Lectureship Award. She currently serves as Associate Editor of the *AIChE Journal* and on the Editorial Advisory Board of *Industrial & Engineering Chemistry Research, Powder Technology,* and *Chemical Engineering Education*. She has served on the National Academy of Engineering's (NAE) Committee on Engineering Education and has participated in two NAE Frontiers of Research Symposiums (2003 and 2008). Currently, she is a Board member of the National Academies' Chemical Science Roundtable, as well as the Council for Chemical Research.

Luis E. Martinez, Rollins College, is an associate professor of chemistry at Rollins College in Winter Park, Florida. Dr. Martínez's research interests are the discovery, development, and application of unique, transition metal-mediated, solid-phase synthetic methods for the high-throughput synthesis of pharmacologically active small molecules and the concurrent assessment of the chemical genetics of the resulting compound libraries in infectious disease, immune response, oxidative stress, and cell cycle control. Martínez's experience spans both academia and business. Prior to his position with UTEP, Martínez served as a Senior Account Executive with Feinstein-Kean Healthcare, an Ogilvy PR Worldwide Company. Martínez has also been involved with scientific workforce diversity and American competitiveness, broadening participation in research and the recruitment and retention university minority faculty and students in science for over a decade. He has been actively involved with SACNAS (Society for the Advancement of Chicanos and Native Americans in Science) and has served as a member of the SACNAS Board of Directors for eight years. In addition to his current service on the SACNAS Board, he also currently sits on the ACS Minority Affairs Committee. Martínez received his B.S. in chemistry with honors in 1991 from Trinity University (San Antonio, Texas) and his Ph.D. in organic chemistry from Harvard University in 1997.

ADVISOR TO THE COMMITTEE

Richard Greene, Office of Basic Energy Sciences, DOE, is Lead for the Photochemistry and Biochemistry Team in the Chemical Sciences, Geosciences, and Biosciences Division of the Office of Basic Energy Sciences, Office of Science, U.S. Department of Energy. Following various bench positions at the National Center for Agricultural Utilization Research, a USDA Agricultural Research Service (ARS) laboratory in Peoria, Illinois, he was selected Leader of the Biopolymer Research Unit. He served in that capacity from 1990 to 1999, where he directed a broad program of biochemical, biophysical, microbiological, and genetic research. Studies focused on interactions of natural polymers, particularly polysaccharides, with biological systems. During his tenure, the Biopolymer Research Unit generated several commercial products from bench discoveries and won two R&D 100 Awards. In 1999, Dr. Greene moved to ARS Headquarters in Washington, DC, to work in the Office of International Research Programs, where he became its Director in 2003. In 2006, he came to DOE to manage the Energy Biosciences Program. When the Energy Biosciences Program merged with the Solar Photochemistry Program to form the Photochemistry and Biochemistry Team in 2008, Dr. Greene was selected Lead. The Team supports fundamental research on the molecular mechanisms involved in the capture of light energy and its conversion into chemical and electrical energy through biological and chemical pathways. Dr. Greene is the author of over 80 peer-reviewed journal articles and patents. He served for 9 years on the Editorial Board of *Applied and Environmental Microbiology*. Other major honors include two USDA Secretary Awards, an Arthur S. Flemming Award, along with election as U.S. Representative to the Governing Body of the Agricultural Cooperative Research Programme, Organisation for Economic Cooperation and Development (OECD). Dr. Greene received his B.A. in biochemistry from Cornell University (1976) and his Ph.D. in biochemistry from Cornell University (1982).

D

Workshop Attendees

First Name	Last Name	Affiliation
Dawn	Adin	Department of Energy
Charles	Anderson	Pennsylvania State University
Carmela	Bailey	USDA National Institute of Food and Agriculture
Mark	Barteau	University of Delaware
Paul	Berlowitz	ExxonMobil
Michael	Berman	Air Force Office of Scientific Research
Carole	Bewley	National Institutes of Health
Bill	Borghard	ExxonMobil R&E
Matt	Brien	
Nikki	Brown	Pennsylvania State University
Robert	Brown	Iowa State University
Paul	Bryan	Independent Consultant
Emilio	Bunel	Argonne National Laboratory
Allison	Campbell	Pacific Northwest National Laboratory
Mark	Cardillo	Henry Dreyfus Foundation
Emily	Carter	Princeton University
Daniel	Cassidy	U.S. Department of Agriculture
A.Will	Castleman, Jr.	Pennsylvania State University
Richard	Cavanagh	National Institute of Standards and Technology
Yongsheng	Chen	Pennsylvania State University
Helena	Chum	National Renewable Energy Laboratory
Chuck	Coronella	University of Nevada, Reno
John	Cowie	Agenda 2020 Technology Alliance
Kevin	Craig	U.S. Department of Energy, Office of Biomass Programs
Tony	Crooks	U.S. Department of Agriculture, Rural Development
Robert	Czincila	Department of Transportation
Marina	Denicoff	U.S. Department of Agriculture
Brian	Duff	DOE, Energy Efficiency and Renewable Energy
Douglas	Elliott	Pacific Northwest National Laboratory
Mark	Emptage	DuPont
Miguel	Garcia-Garibay	University of California, Los Angeles
Joseph	Graber	U.S. Department of Energy

First Name	**Last Name**	**Affiliation**
Jeff	Hazle	American Fuel & Petrochemical Manufacturers
William	Hitz	DuPont
Wenyu	Huang	Iowa State University
Sharon	Ji	Johns Hopkins University
Kristen	Johnson	DOE, Biomass Program
Shawn	Johnson	U.S. Department of Transportation
Stephen	Kaffka	California Biomass Collaborative
Leonard	Katz	Lygos & University of California, Berkeley
Ryan	Kerney	Department of Energy
John	Kozarich	Activx Biosciences, Inc.
Xiaohang	Liu	University of Maryland
Devinder	Mahajan	U.S. Department of State
Ken	Moloy	Dupont Central Research and Development
Mark	Nelson	DuPont
Vladimiros	Nikolakis	CCEI/ University of Delaware
Charles	Noelke	DuPont Company
Gerard	Ostheimer	U.S. Department of Agriculture
Robert	Peoples	ACS Green Chemistry Institute®
Fred	Petok	Energy Division, RD U.S. Department of A
Tanja	Pietrass	National Science Foundation
Matt	Platz	National Science Foundation
Arthur	Ragauskas	Georgia Institute of Technology
Douglas	Ray	Pacific Northwest National Laboratory
Tom	Richard	Pennsylvania State University
Mike	Rogers	National Institute of General Medical Sciences
Eric	Rohlfing	Office of Basic Energy Sciences, Office of Science, and Department of Energy
Mark	Schofield	Haverford College
Mark	Segal	U.S. Environmental Protection Agency
Jennifer	Sinclair Curtis	University of Florida
Rina	Singh	Biotechnology Industry Organization (BIO)
Chris	Somerville	University of California, Berkeley & Energy Biosciences Institute
Addison	Stark	Massachusetts Institute of Technology
Nora	Stein	Office of Management and Budget
Jeffrey	Steiner	USDA Agricultural Research Service
David	Stern	ExxonMobil
Bryce	Stokes	CNJV/Department of Energy
Miguel	Suazo	Biotechnology Industry Organization (BIO)
Kimberly	Swanson	
Evonne	Tang	The National Academies
Javad	Tavakoli	Lafayette College
Patricia	Thiel	Ames Laboratory/Iowa State University
Carol	Werner	Environmental and Energy Study Institute
Jack	Werner	Institute for Sustainable Power
Chaowen	Xiao	Pennsylvania State University

E

Origin of and Information on the Chemical Sciences Roundtable

In April 1994 the American Chemical Society (ACS) held an Interactive Presidential Colloquium entitled "Shaping the Future: The Chemical Research Environment in the Next Century."[1] The report from this colloquium identified several objectives, including the need to ensure communication on key issues among government, industry, and university representatives. The rapidly changing environment in the United States for science and technology has created a number of stresses on the chemical enterprise. The stresses are particularly important with regard to the chemical industry, which is a major segment of U.S. industry in terms of trade and employment opportunities for a technical workforce. A neutral and credible forum for communication among all segments of the enterprise could enhance the future well-being of chemical science and technology.

After the report was issued, a formal request for such a roundtable activity was transmitted to Dr. Bruce M. Alberts, chairman of the National Research Council (NRC), by the Federal Interagency Chemistry Representatives, an informal organization of representatives from the various federal agencies that support chemical research. As part of the NRC, the Board on Chemical Sciences and Technology (BCST) can provide an intellectual focus on issues and fundamentals of science and technology across the broad fields of chemistry and chemical engineering. In the winter of 1996 Dr. Alberts asked BCST to establish the Chemical Sciences Roundtable to provide a mechanism for initiating and maintaining the dialogue envisioned in the ACS report.

The mission of the Chemical Sciences Roundtable is to provide a science-oriented, apolitical forum to enhance understanding of the critical issues in chemical science and technology affecting the government, industrial, and academic sectors. To support this mission the Chemical Sciences Roundtable will do the following:

- Identify topics of importance to the chemical science and technology community by holding periodic discussions and presentations, and gathering input from the broadest possible set of constituencies involved in chemical science and technology.
- Organize workshops and symposiums and publish reports on topics important to the continuing health and advancement of chemical science and technology.
- Disseminate information and knowledge gained in the workshops and reports to the chemical science and technology community through discussions with, presentations to, and engagement of other forums and organizations.
- Bring topics deserving further in-depth study to the attention of the NRC's Board on Chemical Sciences and Technology. The roundtable itself will not attempt to resolve the issues and problems that it identifies—it will make no recommendations, nor provide any specific guidance. Rather, the goal of the roundtable is to ensure a full and meaningful discussion of the identified topics so that the participants in the workshops and the community as a whole can determine the best courses of action.

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[1] American Chemical Society. *Shaping the Future: The Chemical Research Environment in the Next Century.* American Chemical Society Report from the Interactive Presidential Colloquium, April 7-9,1994,Washington, D.C.