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

Industrial Technologies Program




Industrial Feedstock Flexibility

Workshop Results

December 2009

About This Report

This report summarizes the results of the August 19–20, 2009, Industrial Feedstock Flexibility Workshop, sponsored by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, Industrial Technologies Program. The workshop brought together 34 industrial feedstock end users, technology manufacturers, university researchers, and national laboratory researchers. Participants were asked to identify high-priority research and development (R&D) opportunities, barriers to R&D in these areas, and R&D pathways for achieving industrial feedstock flexibility and facilitating the use of more cost-effective and energy-efficient conventional feedstocks.

Dr. Dickson Ozokwelu led the effort at the U.S. Department of Energy's Industrial Technologies Program. The workshop was facilitated by Nancy Margolis, Mauricio Justiniano, Joe Monfort, Sabine Brueske, and Ridah Sabouni of Energetics Incorporated.

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Industrial Feedstocks

Industrial feedstocks are raw materials used to make industrial products and thousands of consumer goods. Many industrial products are made from oil and natural gas feedstocks, which have a high energy content that could otherwise be used as fuel to heat homes, run vehicles, and power manufacturing processes.

Each year, over 30% of the energy end use in the U.S. manufacturing sector—seven quadrillion Btu—is consumed in the form of non-fuel feedstocks, as shown in Figure 1. This consumption is equivalent to the energy in almost 40% of the gasoline used by vehicles in the United States each year. Feedstocks can account for up to 70% of the production cost of intermediate and semi-finished goods, and fluctuations in the cost of natural gas and oil feedstocks directly affect the cost of producing goods. In recent years, the lack of competitively priced feedstocks has helped push large manufacturing operations overseas, where lower-cost feedstocks are available.

To date, government-sponsored research and development (R&D) has focused on developing alternatives to natural gas and petroleum fuels for the power and transportation sectors, and has not included opportunities for the manufacturing sector to make consumer goods. Additional R&D is needed to enable the sustainable and cost-effective substitution of alternative feedstocks for conventional feedstocks in the production of goods, such as basic chemicals, plastics and resins, steel, and aluminum, among others.

The substitution of alternative feedstocks for natural gas and crude oil in the production of goods would have the following benefits:

- Increase the competitiveness of the U.S. industrial sector by providing flexibility to hedge against energy price volatility
- Enhance national energy security
- Reduce environmental emissions
- Create "green" jobs

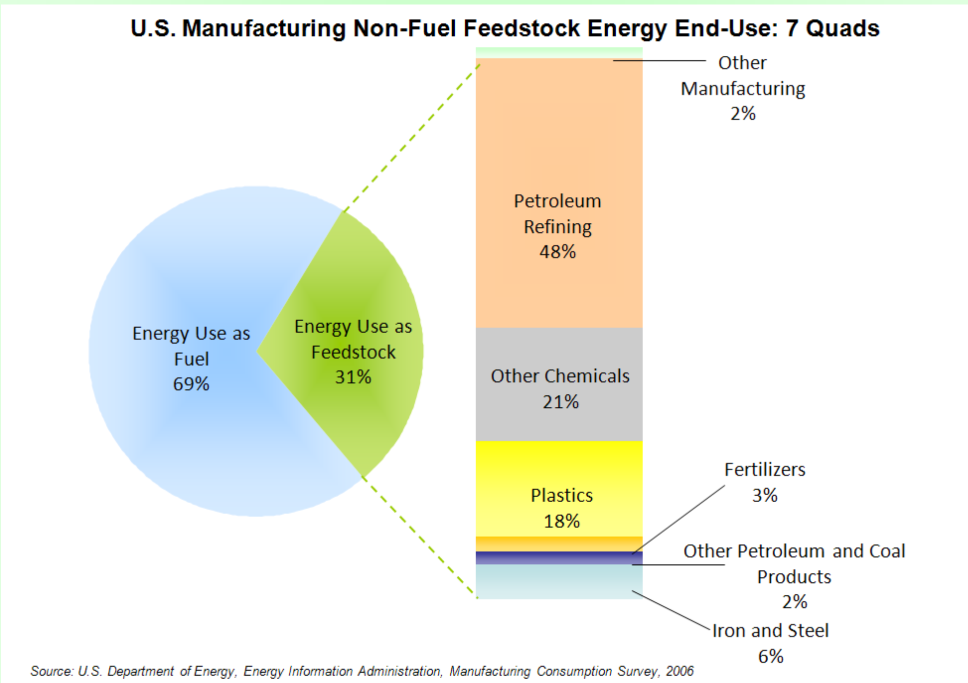


Figure 1. Feedstocks account for 31% of the energy end-use of the U.S. manufacturing sector

Introduction

On August 19–20, 2009, the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE), Industrial Technologies Program hosted an invitation-only workshop on industrial feedstock flexibility in Atlanta, Georgia. The workshop focused on exploring the most promising opportunities for achieving industrial feedstock flexibility to help reduce industry's dependence on oil and gas, enhance energy security, increase competitiveness, and support climate goals.

The workshop brought together 34 industrial technology developers and end users, along with experts from government, national laboratories, and academia. The purpose of the workshop was to identify key industrial feedstock research and development (R&D) focus areas, barriers to R&D in these areas, and R&D pathways for achieving industrial feedstock flexibility and facilitating the use of more cost-effective and energy-efficient conventional feedstocks.

The workshop began with a welcome presentation from Dr. Dickson Ozokwelu of the DOE Industrial Technologies Program, followed by a plenary session that included the following presentations:

- David Graf, Dow Chemical Company: "Alternative Feedstocks: A Dow Perspective"
- Linda Beltz, Weyerhaeuser Company: "Bio-based Feedstocks"
- William Choate, BCS Incorporated: "Alternative, Renewable, and Novel Feedstocks for Producing Chemicals"

After the plenary presentations, workshop participants divided into three breakout groups to discuss the following topics:

- Alternative bio-based feedstocks
- Alternative fossil-based feedstocks
- Energy-efficient conventional feedstocks

Following the breakout group sessions, a closing plenary session was held, which consisted of reports from the three breakout groups.

The rest of this report is structured as follows:

- Chapters 1 through 3 summarize the results of the three breakout group sessions.
- Appendix A contains the workshop agenda.
- Appendix B is a list of the workshop participants.
- Appendix C provides contact information for the workshop coordination team.

Participating Companies:

- **The Dow Chemical Company**
- **Weyerhaeuser**
- **BP Amoco**
- **Archer Daniels Midland**
- **Linde**
- **Eastman Chemical Company**
- **General Electric**
- **Shell Global Solutions**
- **RTI International**
- **Myriant Technologies**
- **Chart, Inc.**
- **One Planet Technologies, LLC**

The plenary session presentations are available online at http://www.sentech.org/roadmap/Feedstock_Workshop.html.

Major Findings

Workshop participants identified a variety of high-impact R&D opportunities. The following were common findings across the breakout groups:

- ***Improved separations*:** All three groups identified the need for improvements in separations. This is a broad category applicable for both pre- and post-treatment, gases and liquids, low-intensity applications, and high-temperature applications. Participants agreed on the need for low-cost separation technologies and processes. Improved separation could improve carbon dioxide sequestration, improve process performance, and reduce capital expenses. Specific R&D opportunities include advances in membranes, resins, reactive extraction, and thermal separation processes, such as distillation.
- ***Industrial reactions:*** Participants also identified industrial reactions as a key R&D area for potential improvements. Participants recognized the need for low-cost, feed-flexible gasification for chemical feedstock production; specifically, the development of high-pressure gasifiers that can achieve high carbon conversions while minimizing tars and light hydrocarbons, with good heat integration and hot gas cleanup capabilities. Participants also identified catalysis as a major opportunity for industrial reaction improvements. Specific R&D opportunities include advances in catalyst selectivity and conversion performance to reduce manufacturing cost. Process intensification also presents another major opportunity to improve industrial reactions.
- ***Direct conversion*:** The bio-based and fossil-based feedstock groups identified direct conversions as a tremendous opportunity for industrial feedstock processing. The bio-based feedstock group identified the need for direct conversion of biomass to chemical feedstocks and materials, without further processing. The alternative fossil-based feedstocks group recognized that the ability to transform coal directly into products, thus avoiding the syngas route, would also offer significant benefits to industry. The group also identified an opportunity for stranded gas conversion, by liquefying it in situ and converting methane directly to aromatics via an improved process.

1. Alternative Bio-Based Feedstocks

During the brainstorming portion of the workshop, participants in the alternative bio-based feedstocks group identified high-impact R&D opportunities to advance the use of alternative bio-based feedstocks in industry. After finishing the exercise, the group selected the five highest-priority R&D opportunities, focusing on those that would have the strongest impact in terms of increased energy and carbon emissions savings, reduced production costs, increased energy security, and increased industrial competitiveness. Table 1 presents the prioritized list of high-impact R&D opportunities.

The group identified improvements in thermal-chemical conversion processes as a key R&D focus area. Specific opportunities that the group recognized include the development of low-capital and small-scale gasification and Fischer-Tropsch processes; carbon sequestration; and developing metallurgical coke, bio-based alternatives for iron/steel manufacturing.

The group also identified improvements in separation processes as an important R&D topic. Specific opportunities that the group recognized include the development of membranes, utilizing cleaner ways to extract lignin, and water purification management.

The group also identified the development of direct conversion processes as an important R&D opportunity. The group recognized two clear R&D routes: (1) direct conversion to materials that do not require further chemical or biochemical processing, and (2) direct conversion to chemical feedstocks.

The group also identified process integration as an important R&D area. Of particular interest are the on-site collection/densification of biomass and the development of "green chemical parks to process from biomass to chemicals/materials," also on site.

The group also recognized that biomass supply is a very important issue. Specific R&D opportunities that the group identified include the development of genetically modified crops for tailored processing, increasing the supply of bioderived fatty acids for use as chemical feedstocks, and partial substitutions with biomass.

In the second session of the workshop, participants identified the barriers to the five highest-priority R&D opportunities. Table 2 presents the list of identified barriers.

In the third session of the workshop, the group broke down into subgroups and conducted a "pathway analysis" for each of the top opportunities. To complete this exercise, the subgroups filled out two worksheets for each opportunity:

- The first worksheet describes the current state of the technology, the desired end state, and the potential impacts of achieving the desired end state.
- The second worksheet identifies the necessary R&D pathways to achieve the desired end state, the timeframe, and DOE's role.

The completed pathway analyses are shown after Table 2.

Table 1 - Bio-Based Feedstock Group

High-Impact R&D Opportunities

Integration and Localization	Pre-treatment and Feed Preparation	Biomass Supply
• Collection/densification of biomass on site ●●●● • Development of "green-chemical parks"; from biomass to chemicals/materials on the same site ●●● • Ability to locally process biomass to product stream ●● • Processes that handle various feedstock compositions ● • Utilize local bio-resource for industry or required application ●	• New methods for biomass preparation for conversion (grinding, etc.) ●● • Elemental analysis of bio-feedstocks ● • Compacting of woody biomass into pellets • Supercritical CO_2 pretreatment/saccharification of biomass	• Genetically modified crops for tailored processing ●●● • Increase supply of bioderived fatty acids for use as chemical feedstock ●● • Partial substitution with biomass ● • Use vegetable oils for chemicals instead of using them for fuel use • Sewage sludge to syngas fractionization; also municipal solid waste (MSW) • Advanced/intensive silviculture/agriculture methods and tools

Direct Conversion Processes	Separations	Biochemical Conversion Processes	Thermal-Chemical Conversion Process
• Direct conversion to materials that don't require further chemical or biochemical processing ●●●●● • Direct conversion to chemical feedstocks ●●●●●	• Separation processes and technologies ●●●●●●● • Membrane processes for separation ●● • Cleaner way to extract lignin ●● • Water purification management ●● • Non-enzymatic pathways for fractionation and depolymerization of bio-based feedstocks ● • Synergy to sequester heavy metals	• Glycerol fermentation to chemicals ●● • Sugar-to-propanol to propylene via fermentation and dehydration • Sugar-to-ethanol to ethylene via fermentation and dehydration on the U.S. Gulf Coast	• Develop low-capital and small-scale gasification and Fischer-Tropsch processes ●●●●●●● • Metallurgical coke bio-based alternative for iron/steel ●●● • Carbon sequestration ●●● • Develop better catalysts for converting syngas that are robust and cost effective ●● • Conversion of lignin to benzene and aromatics + C_3 ●● • Production of process hydrogen from biomass ●● • Syngas conditioning and cleanup ●● • Biomass gasification; high-pressure mechanism ● • Synthetic natural gas and methane activation ● • Use of CO_2 as oxidant • Bio-alternative to graphite for iron/steel/ceramics

TABLE 2 - BIO-BASED FEEDSTOCK GROUP

R&D BARRIERS

SEPARATION PROCESSES AND TECHNOLOGIES	ECONOMIC AND MARKET	DEVELOP LOW-CAPITAL GASIFICATION AND F-T PROCESSES
• Ionic liquids – very expensive. Need to lower costs • Membranes that work under process conditions – pH, temperature, etc. • Variability of feedstocks – process streams (waste materials) • Low-cost, high-throughput separation of dissolved/difficult components (that is reliable) • More commercial membrane suppliers for separations	• Requires strong cooperative effort between industry and thought leaders – requires right intellectual property and commercial incentives • DOE-funded R&D for bio-based products comparable to fuels-funded technology programs • Size of market – introducing new supply will lower demand and price • Capital for scaling from bench to commercial • Access to capital for small businesses • Cost per ton of biomass may make collection/densification too expensive • R&D/pilot funding for biochemical material process development • Land use requirements (public perception, cost, availability) • No clear economic reasons to use bio-based feedstock	• Feedstock flexibility adds capital expenditures for gasification • Need to understand how much conditioning and cleaning of syngas is necessary prior to catalytic processing • Need to understand how content and composition affect gasification behavior • Catalyst poisoning by alkali, nitrogen, sulfur, acids • Lack of commercially demonstrated design • Need to understand how to build cost-effective, flexible, regional gasifiers • Improved heat recovery for gasification • Feeding systems for pressurized gasification

TABLE 2 - BIO-BASED FEEDSTOCK GROUP

R&D BARRIERS (CONT'D)

COLLECTION/DENSIFICATION OF BIOMASS ON SOURCE SITE	DIRECT CONVERSION TO CHEMICAL/FEEDSTOCKS
• Year-round biomass feedstock availability at commercial-scale quantities • Equipment development • Integrate biomass with existing infrastructure (grain elevators, silos, truck, etc.) • Chemical stability of bio-feedstocks • Pyrolysis oil refining infrastructure • Biomass already expensive; densification adds costs • Removing moisture from biomass without too much energy input • Lack of agreed-upon, demonstrated analysis protocols • Need for small-scale, efficient process to minimize transportation costs • Pelletization of biomass to prepare it as feed for processing	• Lack of demonstrated science • Separations and direct conversion – technical ideas and new approaches, e.g., ionic liquids membranes • Systems analysis and economics to determine best product mix • Selectivity of processes • Need to produce a chemical or material exactly like existing chemicals (to fit infrastructure) • Difficult to displace existing technology • Strong bonds between cellulose and lignin • Understand how to lose the "O" in biomass with little economic penalty • Cost of process to reduce $C_xH_yO_z$ • Industrial acceptance • Direct conversion to chemicals – very technically challenging, e.g., consolidated bioprocessing (CBP) • Capture/use of waste heat (low temperature)

R&D Opportunity: Develop Low-Capital Biomass Gasification for Fischer-Tropsch Processes

Forest residues and agricultural waste can be best utilized through gasification.

Current State of Technology or Process

Although coal gasification technology is relatively well developed and exists at a commercial scale, biomass gasification is not understood as well.

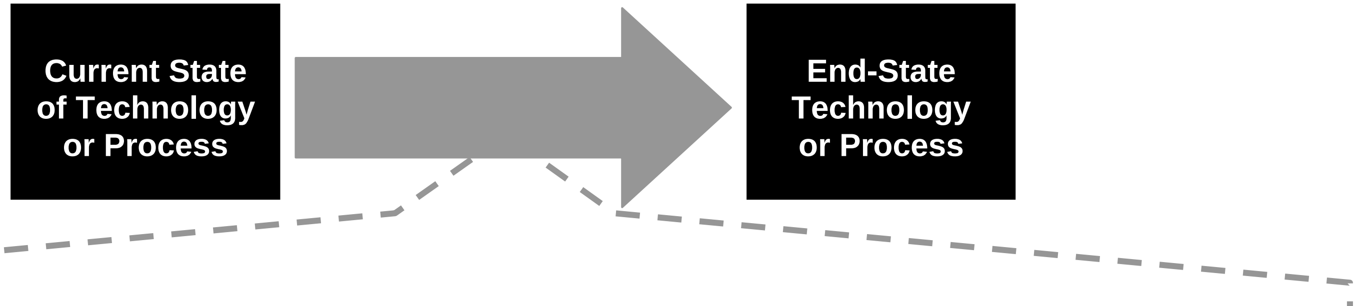
End-State Specifications of Technology or Process

- A flexible fuel (high-pressure) gasifier, capable of achieving high carbon conversion while resulting in low tars, low small hydrocarbons
- Heat integration is utilized to achieve energy efficiency
- Low cost scale gasifiers for 50–1,000 tons/day
- Dry feeder for pressurized gasifiers
- Gas conditioning at high temperature to remove tars, C_1-C_4 hydrocarbons, desired CO/H_2 ratio
- Cleanup of alkali, Cl, S
- Highly selective catalysts to produce a variety of chemicals for syngas

Potential Impacts

	LOW				
Energy Consumption	1	2	**3**	4	5
Greenhouse Gas Emissions	1	2	3	4	**5**
Input Costs	1	2	**3**	4	5
Products and Markets	1	2	3	4	**5**
Energy Security	1	2	3	4	**5**

R&D Opportunity: <u>Develop Low-Capital Biomass Gasification for Fischer-Tropsch Processes</u>



Key Knowledge and/or Technology Advancements *(Required to get from the current state to an effective technology solution)*	**Time Frame** *(Near, Mid, Long, or Unknown)*	**DOE Role**
• New technology for feeding solid biomass at pressurized conditions	Near	Funding
• Fundamental understanding of the kinetics of biomass gasification for optimum design	Near	Funding
• Understanding of the role of ash composition on slagging characteristics	Near	Funding
• Determining contaminant thresholds for materials and catalysts	Near - Mid	Funding
• High-temperature gas conditioning (removal of tars, smaller hydrocarbons, etc.)	Mid	Funding
• Cleanup of alkali, sulfur, and chlorine from high-temperature gas	Near - Mid	Funding
• Highly selective catalysts, capable of producing a variety of chemicals from syngas	Mid - Long	Funding

Other Guidance	*Risk mitigation would go a long way to bring industry into the arena. Tax incentives and cost-sharing would help as well.*

R&D Opportunity: Separation Processes and Technology

This is a broad area that is being subdivided into two main areas: (1) pretreatment of biomass feedstock and (2) post-treatment of intermediates, products, and co-products, along with air/O_2 separation units (ASU) needed for gasifier operation.

Current State of Technology or Process

Pretreatment

1. Acid
2. Enzymatic hydrolysis of biomass-sugar; followed by subsequent reductions to chemicals
3. Liquefaction
4. Washing, drying, and grinding
5. Fatty acids (products and alcohols), and triglycerides (fuels, glycerine, and surfactants)

Post-treatment

1. Membranes – e.g., increase alcohol yield, separate salts, and purify solvents and H_2O
2. Ion exchange –removal of salts
3. Reactive extractions – remove impurities or products of interest
4. Distillation
5. Crystallization
6. Cryogenic – O_2/N_2 separation

End-State Specifications of Technology or Process

Pretreatment

1. Combine unit operations. Simplify things. One pot for pretreatment/ separation/conversion products – end state ideally continuous process.
2. Liquid-liquid equilibrium (LLE) using ionic liquids – efficient/no loss/easy regeneration of ionic liquid/cheap Ionic liquid, nontoxic.
3. Enzymes – no loss or degradation, significant reduction in costs.
4. Bacteria, fungi – robust, survive pH changes.

Post-treatment

1. Scalable, low-cost, multi-suppliers of commercial membranes.
2. High-capacity ion exchange resins, high-selectivity, low-cost resistant to fouling, easy to regenerate, long-lived, not-friable.
3. Reactive extractions – solvent long-lived, easy to regenerate, low-cost, low-toxicity, low-losses.
4. Distillation – maximize thermal efficiency, design process flow to minimize amount of distillation.

Potential Impacts

	LOW				
Energy Consumption	1	2	3	4	**5**
Greenhouse Gas Emissions	1	2	3	4	**5**
Input Costs	1	2	3	4	**5**
Products and Markets	1	2	3	4	**5**
Energy Security	1	2	3	4	**5**

R&D Opportunity: Separation Processes and Technology

Key Knowledge and/or Technology Advancements *(Required to get from the current state to an effective technology solution)*	Time Frame *(Near, Mid, Long, or Unknown)*	DOE Role
Research funding, federal/state tax incentives, and loan guarantees:		All research activities
• Genetic research: Genetic modification of feedstocks or organisms that have enzymes in their DNA that will act during metabolism to fractionate biomass to sugar and convert sugar to chemicals, all in one step.	Long	Solicitations, interagency cooperation with USDA/NIH/national labs/universities
• Incentives: Loan guarantees and carbon tax credit for renewable chemicals.	Near, Sustained	Reproduce incentives seen in production of ethanol and other liquid transportation fuels; for chemicals and other biofuels
• Improve regulatory environment: Genetic modification research, new solvents such as ionic liquids, and international standardization.	Sustained	Interagency and international collaboration
• Build multidisciplinary pilot-scale separation lab: Convert lab-scale processes to industrial scale at dedicated national laboratory facility. Demonstrate separation processes at close to commercial scale.	Mid, Sustained	DOE support, Congressional support, protection of intellectual property

Other Guidance *Pretreatment and post-treatment separations would benefit from all of the general initiatives listed above. Near-term action would be to set up a lab (or a group of labs/center of expertise) to demonstrate/research new ideas in a variety of separation methods and unit operations. Need to make answering solicitation/funding appropriate partners (universities, industries, national laboratories) easier and more transparent.*

R&D Opportunity: Direct Conversion of Biomass to Chemical Feedstocks

No additional guidance was provided.

Current State of Technology or Process

- Gasification and Fischer-Tropsch
- Fermentation and separation
- Fermentation and chemical conversion

  EtOH → C_2H_4

End-State Specifications of Technology or Process

- Capable of being performed on distribution basis
- Can be stopped at any stage or different degree of conversion
- Product at each stage has value to an existing customer or market (with little or no manipulation)
- New intellectual property
- Simplified process, fewer unit operations than alternatives
- All inputs can be renewable
- No waste, or waste such as CO_2 easily sequestered
- Operating costs lower than alternatives, capex ≤ alternatives
- Compatible with existing infrastructure

E.g., supercritical H_2O reaction process. Reactions in plants, polynumerization in plants

Potential Impacts

	LOW				
Energy Consumption	1	2	**3**	4	5
Greenhouse Gas Emissions	1	**2**	3	4	5
Input Costs	1	2	3	4	**5**
Products and Markets	1	2	3	4	**5**
Energy Security	1	2	3	**4**	5

R&D Opportunity: Direct Conversion of Biomass to Chemical Feedstocks

Current State of Technology or Process → **End-State Technology or Process**

Key Knowledge and/or Technology Advancements *(Required to get from the current state to an effective technology solution)*	**Time Frame** *(Near, Mid, Long, or Unknown)*	**DOE Role**
• Transfer technology from the laboratory scale to a meaningful pilot scale	Near	Fund construction of pilot plant. Brokering/teaming across value chain.
• For some technologies, such as green plant-based, need bio-engineering	Near	Funding
• Fundamental research to find the range of products that can be produced	Mid	Funding

Other Guidance

R&D Opportunity: Direct Conversion to Materials

Replacing fossil fuels with renewable energy virtually eliminates CO_2 footprint for ironmaking/steelmaking process/carbon black.

Current State of Technology or Process

- All of these materials are fossil fuel based (coal & oil)
- Large amounts of CO_2 generated in current technologies
- Air combustion results in sensible heat losses (N_2, CO_2 superheated)
- Historically, charcoal basis for C products before coal/oil

End-State Specifications of Technology or Process

Produce material without further processing – replacing nonrenewable materials

- Metallurgical coke – steelmaking/ironmaking
- Carbon fibers – aerospace/automobiles transportation composites
- Carbon black – rubber tires (carbides – blades, graphite refractories)
- Graphite – aluminum, ceramics (carbon anodes)
- Capture CO_2/all CO_2 sequestered (goal net-zero CO_2)

Potential Impacts

	LOW				
Energy Consumption	1	2	3	4	**5**
Greenhouse Gas Emissions	1	2	3	4	**5**
Input Costs	1	2	**3**	4	5
Products and Markets	1	2	3	**4**	5
Energy Security	1	2	3	**4**	5

R&D Opportunity: Direct Conversion to Materials

Key Knowledge and/or Technology Advancements *(Required to get from the current state to an effective technology solution)*	**Time Frame** *(Near, Mid, Long, or Unknown)*	**DOE Role**
• Pyrolysis/and other technologies to convert biomass into acceptable products	Long	• Funding of opportunities (cost-sharing with industry)
• Characterization of current products (needs to allow for alternatives)	Short	• Oversight of development
• Comparison with biomass based products	Short	• Policy to encourage industry use of biomass based materials
• Partnerships (academic/engineering/producers/users) intellectual properties	Mid	
• Scale-up of facilities	Mid	

Other Guidance

R&D Opportunity: Collection and Densification of Biomass on Source Site

Biomass supply that is economical and practical is a prerequisite for enabling bioproducts/biofuels production. This goes beyond "supply" studies to the practical development required for implementation.

Current State of Technology or Process

- Wide range of biomass types that will be utilized (forest residuals, agricultural residuals, etc.).
- Transporting biomass to the user is expensive.
- Forest: wood chips, logs, bulk truck energy crops – bulk or bale.
- Agricultural: bulk or bale, silo.
- Algae: slurry.
- Developmental – baling of forest/ agricultural residuals. Needs development for non-uniform sites.
- Most development by large private land owners/equipment suppliers.

End-State Specifications of Technology or Process

- Densified: pelletizing
- Optimized:
  - Torrefaction
  - Dried
  - Physical form ready-to-convert (ground, etc.)
  - Pyrolysis oil
  - Liquefaction product
  - Removal of contaminants (metals, macro)
  - Defoliated
- Sustainable biomass eco-system – removal of more biomass, residual change, nutrient/soil profile
- Applicable/expandable to small land owners as well as large land owners – lease basis available for those not able to purchase
- Truck/rail transport
- Distributed, decentralized, preprocessing depots
- Downstream use infrastructure for biomass

Potential Impacts

	LOW				
Energy Consumption	1	2	3	4	**5**
Greenhouse Gas Emissions	1	2	3	**4**	5
Input Costs	1	2	3	**4**	5
Products and Markets	1	**2**	3	4	5
Energy Security	1	2	3	**4**	5

R&D Opportunity: Collection and Densification of Biomass on Source Site

Key Knowledge and/or Technology Advancements *(Required to get from the current state to an effective technology solution)*	**Time Frame** *(Near, Mid, Long, or Unknown)*	**DOE Role**
• Harvest/densification equipment development	Mid	Fund/tax benefits encouraged
• Defoliation equipment	Unknown	Fund/tax benefits encouraged
• Demonstration of approaches at pilot/demo scale	Mid	Fund
• Development/optimization of mobile/distributed-scale units for processing "optimized" biomass	Long	Fund
• Building/using downstream refining infrastructure for receiving/utilizing compacted biomass – create the demand	Long	Fund pilot and fundamental R&D required for downstream. Inform policymakers
• Analysis, characterization, and standards for biomass	Mid	Facilitate knowledge transfer: NIST/national labs
• Minimization of variability in a flexible feedstock – control uniformity (e.g., blending)	Long	Fund uniformity from varied feedstocks (mixed sources) (agriculture, forestry, urban)
• Life-cycle assessment of biomass supply – collection, densification on source site vs. transported in non-optimized state	Near	Fund study

Other Guidance *This is a critical area that needs broad biomass definition, beneficial tax policy and focused funding for optimization of biomass.*

R&D Opportunity: Develop "Green Chemical Parks" That Integrate Biomass, Chemicals, and Energy Operations

No additional guidance was provided.

Current State of Technology or Process

- Isolated biomass processing facilities; e.g., corn to ethanol.
- Chemical plants near oil refineries. Pulp mills near forests.
- Exists in other parts of the world, e.g., China.
- CHP power and heat systems exist in pulp and paper mills and chemical plants – combines energy and product.
- Benefits of integration demonstrated in some cases – e.g., Flambeau River demonstration plant claims energy and cost benefits of combining gasification/ biodiesel plant with pulp and paper mill.
- Closest in pulp and paper industry is on-site precipitated calcium carbonate plants. Also, power boilers and turbine generators have been sold to power utilities.

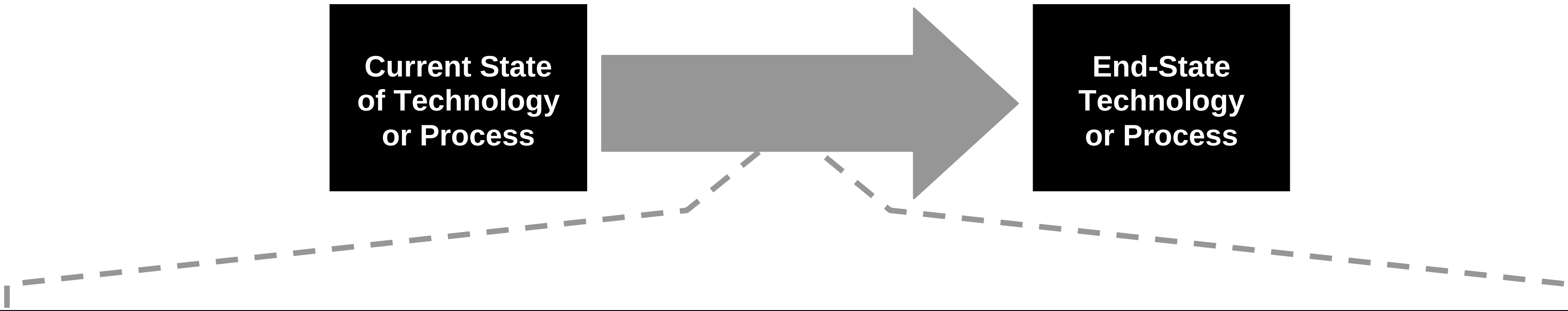
End-State Specifications of Technology or Process

- Integrated production facilities for processing biomass to a range of product streams, including biofuels, chemicals, and others:
  - Benefits of scale: larger plant size, common overhead and support functions, shared infrastructure, common waste treatment
  - Benefits of integrated heat and power systems
- Integration with facilities making traditional products
- Combination of industries: chemicals, pulp, paper, power, fuels, wood products, etc.

Potential Impacts

	LOW				
Energy Consumption	1	2	3	4	**5**
Greenhouse Gas Emissions	1	2	3	4	**5**
Input Costs	1	2	3	4	**5**
Products and Markets	1	2	**3**	4	5
Energy Security	1	2	3	4	**5**

R&D Opportunity: Develop "Green Chemical Parks" That Integrate Biomass, Chemicals, and Energy Operations



Key Knowledge and/or Technology Advancements *(Required to get from the current state to an effective technology solution)*	**Time Frame** *(Near, Mid, Long, or Unknown)*	**DOE Role**
• Industries understand each other's needs and opportunities: - Collaboration, workshops - Identify potential synergies	Near	Sponsor workshops – bring industries together
• Establish vision for initial case – limited partner base, active support from federal government, small pilot-scale effort to show benefit of integration, scalability, financial structures, and liability	Near - Mid	Coordinate – sponsor – fund
• Develop new technologies for combined production operations and alternatives	Mid	Fund
• Define platform components – materials that work together	Near	Coordinate – studies led by DOE

Other Guidance

R&D Opportunity: Biochemical Conversion as the Prime Example of a Direct Conversion Process

Has the potential for a transformational change in technology (i.e., one-pot synthesis). Represents a unique opportunity for the American chemical industry.

Current State of Technology or Process

- Currently take pretreatment biomass, fractionation, purification - C_5-C_6 sugar. This goes to a fermenter, which produces mixture of products/byproducts.
- Challenge to find organism that can handle C_5-C_6 sugars.
- Organism has to be able to survive the product, pH change.
- Byproducts ~ 10%, but takes several batches to make products.
- Fermentation makes alcohols and acids that can be dehydrated and used.

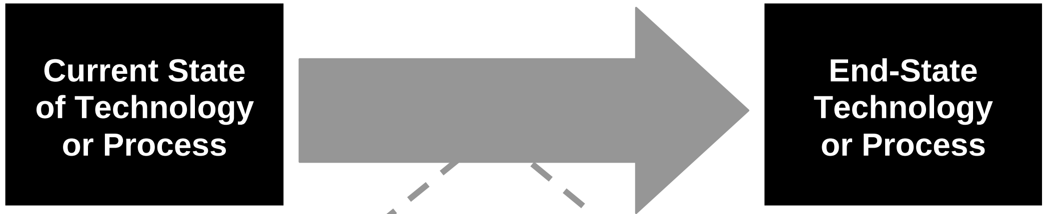
End-State Specifications of Technology or Process

- One-pot synthesis – throw "raw" feedstocks into vat and produce desired chemical:
  - Needs biomass pretreatment
  - Needs organism to do synthesis
- Target:
  - One pot to handle C_5-C_6 sugars to transform 65% product
  - Ideally have organism that can also handle ~35% lignin
  - Products include olefins (C_2, C_3), adipic acid
  - Use a variety of feedstock: algae, forest products, and specially designed crops

Potential Impacts

	LOW				
Energy Consumption	1	**2**	3	4	5
Greenhouse Gas Emissions	1	**2**	3	4	5
Input Costs	1	2	3	4	**5**
Products and Markets	1	2	3	4	**5**
Energy Security	1	2	3	4	**5**

R&D Opportunity: Biochemical Conversion as the Prime Example of a Direct Conversion Process



Key Knowledge and/or Technology Advancements *(Required to get from the current state to an effective technology solution)*	**Time Frame** *(Near, Mid, Long, or Unknown)*	**DOE Role**
• Organisms – genetic engineering to produce chemical of choice plus enzymes	Long	Funding from government for genetic engineering
• Finding organisms that can work on all components of biomass simultaneously (carbohydrates and liquids)	Long	Microbiological research
• Developing biomass that is very low in liquid content	Long	Plant biology
• Developing reaction where multiphase reactions can be carried out (heterogeneous systems)	Long	
• Development of better organisms to produce chemical other than C_2 products	Near	Reactions using heterogeneous substrates/ nanocatalysis
• Funding to develop meaningful-scale pilot facilities	Near – Mid	Solicitation/loan guarantees, shared facility (e.g., at national laboratories)

Other Guidance

R&D Opportunity: Pretreatment and Feed Preparation of Biomass

Biomass needs to be sized into a form (such as pellets) where it can be easily fed into the processing units on a continuous basis.

Current State of Technology or Process

The current state was not defined.

End-State Specifications of Technology or Process

- Technologies exist to reduce the biomass feed to a desirable size, at the lowest cost, with scalable capability, and in modular form.
- A good basic understanding of the role of various pretreatment methods (solvents, acid/base, supercritical water) exists. The role of particle size (effect of surface/volume ratio, transport rates) is well understood. The role of moisture content is defined.

Potential Impacts

	LOW				
Energy Consumption	1	2	3	**4**	5
Greenhouse Gas Emissions	**1**	2	3	4	5
Input Costs	1	2	3	**4**	5
Products and Markets	**1**	2	3	4	5
Energy Security	1	**2**	3	4	5

R&D Opportunity: Pretreatment and Feed Preparation of Biomass

Key Knowledge and/or Technology Advancements *(Required to get from the current state to an effective technology solution)*	**Time Frame** *(Near, Mid, Long, or Unknown)*	**DOE Role**
• An understanding of various technologies for size reduction has been established. The amount of energy consumed per unit of weight of biomass versus size has been established. The effect of moisture needs to be quantified.	Near - Mid	Funding
• The size reduction technologies are scalable, and are also available in modular form.	Mid - Long	Funding
• To understand the effect of particle size, severity of pretreatment, and moisture content on the amount of chemicals, impurities, biomass fractionation, and degradation. Several pretreatments can be studied: - Supercritical water - Acid/base - Organic solvents (acetone, methanol)	Near	Funding

Other Guidance *Risk mitigation, cost-sharing, partnering with the corporation.*

R&D Opportunity: Carbon Sequestration

Maximize the carbon sequestration net benefit of biomass.

Current State of Technology or Process

- Slow-growing (minimum harvests could be years)
- Current waste of feedstock:
  - Corn – use small % of plants
  - Trees – waste
- Currently, dry feedstocks use substantial energy to convert

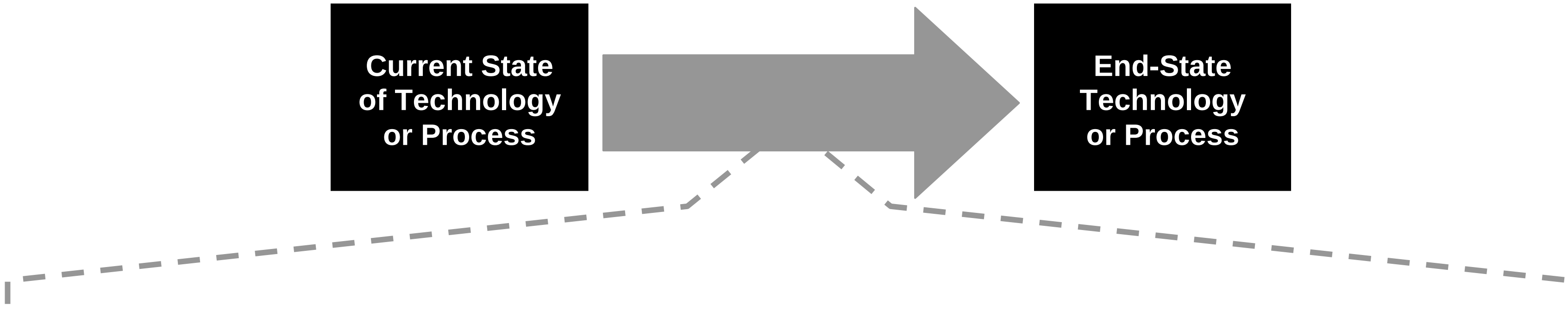
End-State Specifications of Technology or Process

- Maximum sequestration of CO_2 in biomass
- Fast growth
- Complete use of feedstock/land
- Minimize energy/losses in use of biomass conversion

Potential Impacts

	LOW				
Energy Consumption	1	2	3	**4**	5
Greenhouse Gas Emissions	1	2	3	4	**5**
Input Costs	1	**2**	3	4	5
Products and Markets	1	2	**3**	4	5
Energy Security	1	2	3	4	**5**

R&D Opportunity: Carbon Sequestration



Key Knowledge and/or Technology Advancements *(Required to get from the current state to an effective technology solution)*	**Time Frame** *(Near, Mid, Long, or Unknown)*	**DOE Role**
• Best practice and genetic engineering to maximize CO_2 sequestration	Near	RFP – Funding
• Land-use studies to optimize efficiency: policies for land use and multiple crops	Near	Policy help from DOE
• A study of the partial oxidation of biomass – exothermic to syngas	Mid	Policy help from DOE
• Direct-fired biomass versus syngas for biomass efficiency	Mid	Policy help from DOE
• Water removal practices with minimal energy (technologies): - Passive solar - Solvent extraction - Waste heat from process	Mid	Policy help from DOE
• Small mobile biomass converters	Mid	Policy help from DOE

Other Guidance

2. Alternative Fossil-Based Feedstocks

Participants in the alternative fossil-based feedstocks group identified high-impact R&D opportunities to advance the use of alternative fossil-based feedstocks in industry. The group then selected the five highest-priority R&D opportunities, focusing on those that would have the strongest impact in terms of increased energy and carbon emissions savings, reduced production costs, increased energy security, and increased industrial competitiveness. Table 3 presents the prioritized list of high-impact R&D opportunities.

The group identified gasification as a key R&D focus area. In particular, the group recognized R&D opportunities for the development of gasifiers that accept more than one feedstock, such as coal/biomass co-fired gasifiers; reducing the costs associated with gasification; and high-temperature gas cleanup.

The group also identified the alternative acquisition of fossil-based feedstocks as a second key R&D focus area. Specific opportunities that the group recognized include oil shale in situ production, followed by stranded gas technology to liquefy it in situ, and in situ coal-to-syngas conversion at the point of extraction.

The group identified the development of new processes as a third key R&D activity. Of particular interest is the direct transformation of coals to products by avoiding the syngas route. A specific opportunity for stranded gas use is to liquefy it in situ and convert methane (CH_4) directly to aromatics, without syngas, via improved methods over those known today. Another novel process of interest is the use of solar fuels for the direct production of CH_4 and other feedstocks.

The group identified separations as another key R&D opportunity for alternative fossil-based feedstocks. Of interest are improvements in high-temperature filtration, carbon dioxide separation when using coal as feedstock, and air separation units.

In the second session of the workshop, participants identified the barriers to the five highest-priority R&D opportunities. Table 4 presents the list of identified barriers.

In the third session of the workshop, the group broke down into subgroups and conducted a “pathway analysis” of each of the top opportunities. To complete this exercise, the subgroups filled out two worksheets for each opportunity:

- The first worksheet describes the current state of the technology, the desired end state, and the potential impacts of achieving the desired end state.
- The second worksheet identifies the necessary R&D pathways to achieve the desired end state, the timeframe, and DOE’s role.

The completed pathway analyses are shown after Table 4.

Table 3 - Alternative Fossil-Based Feedstocks

High-Impact R&D Opportunities

Alternative Acquisition of Feedstocks	Gasification and Related Processes	New Processes	
• Oil shale in situ production (better than tar sands) ●●●● • Stranded gas technology to liquefy in situ ●●● • In situ coal-to-syngas at point of extraction ●● • Better in situ water cracking for tar sands (Canadian Process) • Efficient sorting of MSW – pull out high-value carbon products • Better catalysts for tar sands/shale • Harvesting gas hydrates	• Gasifiers that accept more than one feedstock ●●●●●● • Coal/biomass co-fired gasifier • Gasification (lower cost) ●●●● • High-temperature (warm or hot) gas cleanup ●●● • Detailed cost assessments of gasification process ● – Differences made with separation and purification options – Stable market price for carbon • Gasification – macro-efficient, better control and measurement and quality of feedstocks • Measure quality/quantity of feedstocks up front • New fluidized beds for coal • Economical scale-down of gasifiers for chemical applications • Impurities in feedstock during gasification – Impact catalyst downstream; materials of construction for the gasifier • Operate gasifier with carbon separation in order to produce H-rich syngas • Solid carbon is separated out	• Transform coal directly to product ●●●● • Catalyst – when you change the temperature of operation, you change the selectivity ●●● • Solar fuels direct production of CH_4, other feedstocks ●●● – Distributed or centralized solar fuel capabilities – "Reverse photosynthesis" catalysis, electrochemical – produce materials from CO_2 and H_2O • Improved process for direct methane to aromatics without syngas ●●● • Liquefy natural gas aromatics to a useful feedstock • Bioprocessing of alternative fossil fuels (coal beds) ●● • H_2 supplies for reaction (other than syngas) ●● – Water splitting – Photocatalysis • Fischer-Tropsch alkane and reform to aromatics (technology needed) ● • Technology to convert syngas to chemical product – CO to chemicals directly (no Fischer-Tropsch)	• Selective conversion of feedstock we already have (alkanes) to products without the olefins● • Waste-heat recovery – convert it to a productive use of energy – use to process feedstocks ● • Low-conversion (10%–20% of feedstock) processes – use feedstock we currently can't use, e.g., methane/ethylene separation (commercially viable) • Direct coal to aromatics • Combining nuclear and fossil (cogeneration of electric and H_2 with next-generation reactor) • Integration of different industries to optimize waste streams as feedstocks • Integration of solar furnaces into chemical processes • Hydrogen storage • Plasma gasification • Rocket hydrogeneration

TABLE 3- ALTERNATIVE FOSSIL-BASED FEEDSTOCKS

HIGH-IMPACT R&D OPPORTUNITIES (CONT'D)

MEASUREMENTS & CONTROLS (ENVIRONMENTAL)	SEPARATION
• S, Hg control – heterogeneity of coal, oil, tar sands • Lower NO_x, SO_x emissions	• High-temperature filtration – separation materials ●●●●● • CO_2 separation when using coal as feedstock ●●● • Air separation units – improved efficiency ● – Cryogenic or membrane • Separations efficiency • Olefin and paraffin

Table 4 - Alternative Fossil-Based Feedstocks

R&D Barriers

Lower Cost Gasification High-T Gas Cleanup	Gasifiers That Accept More than One Feedstock	High Temperature Filtration Separation Materials	Transform Coal to Direct Product
• Oxygen for gasification • Gas cleanup • Generation of high temperature • Many of the unit operations are well established • High-temperature structural material • Separation methods for impurities in various feedstock, to reduce impact to downstream catalysis	• Materials issues change temperatures • Gasifier construction material/liner • Needs an integrator (owner) • Economic materials of construction that can withstand impurities, corrosion, etc. • Characterization of feedstock • Maintaining consistent temperature, slag characteristics	• Catalyst for generation • Increasing lifetime of unit • Developing tool to assess performance – when does it need to be replaced? • Reducing poisoning of material • Maintenance (self-cleaning) • Low recovery • Efficiency of separations • Filter manufacturer • Materials that can be operated in high- temperature separation environments • High-temperature materials • Poor selectivity, poor yield • Achieving mechanical or structural integrity in harsh environments	• Availability of H_2 • Need reductant (cheap) or way to handle CO_2 • Products from coal must be scrubbed of mercury and sulfur • Bio-transformation – reaction rate and capacity of bugs takes forever • New catalyst kinetics • Difficulty in solids processing • Cracking technology is unknown (except liquification) • Pathways not clear • Basic coal chemistry – unreactive, cross-linked polyaromatics

Table 4 - Alternative Fossil-Based Feedstocks

Barriers to Achieve Top Opportunities (cont'd)

Oil Shale – In Situ Production	Solar Fuels – Direct Production of CH_4 and Other Feedstocks H_2 Supplies for RXN (Water Split/Photocatalysis)	Stranded Gas (Liquefy In Situ) Direct CH_4 to Aromatics
• Economical process for generation and recovery of syngas • Precise control of gases produced • Cost to recover product • Energy-intense electrical heating • Insufficient water • Environmental issues • Byproducts – how do you deal with them? • Risks related to safety	• Finding alternative catalyst chemistries other than expensive noble metals • Achieving high surface area of collector/active device components • Low energy • Big footprint for viable quantity of product • Efficiency of solar capture needs to increase • Rates of chemical reaction • Reducing recombination rates of e^- and p^+ so that only useful materials are produced • New catalyst (PV) – VIS	• Self-propelled, GTL small scale • Stranded gas could pose problem with kinetics • CH_4 to aromatics will require catalyst discovery • Catalyst improvement • Separations need with known system • Hard to compete with LNG • Regulations/environmental impact in utilizing stranded gas • The inability to process in confined space • Remote locations to do chemistry • Disbursed source vs. capital cost

R&D Opportunity: Lower-Cost, Feed-Flexible Gasification for Chemical Feedstock Production

Gasification is an established technology for creating chemicals from carbon feedstocks. However, it is not currently cost-competitive for most chemicals vs. petroleum. Achieving lower cost would enable the use of coal, biomass, etc. instead of petroleum.

Current State of Technology or Process

- Established technology, but too expensive
- Air separation unit (ASU) is the most expensive item
- Syngas is cleaned cold, losing efficiency
- Most entrained-flow gasifiers run on one feedstock and are optimized for that
- Circulating fluidized bed gasifiers are more flexible but have poorer quality syngas for chemicals (too much CH_4, tar)

End-State Specifications of Technology or Process

- Significantly lower cost for syngas – higher efficiency, lower capital expenditure
- Operational robustness for varying feedstocks (different rank coals, waste, biomass)
- Lower GHG emissions
- Minimal impact on downstream chemical processes

* could be cheaper than >$100/bbl oil

Potential Impacts

	LOW				
Energy Consumption	1	**2**	3	4	5
Greenhouse Gas Emissions	1	**2**	3	4	5
Input Costs*	1	2	3	**4**	5
Products and Markets	1	2	**3**	4	5
Energy Security	1	2	3	4	**5**

R&D Opportunity: Lower-Cost, Feed-Flexible Gasification for Chemical Feedstock Production

Key Knowledge and/or Technology Advancements *(Required to get from the current state to an effective technology solution)*	**Time Frame** *(Near, Mid, Long, or Unknown)*	**DOE Role**
• Dry-feed technology for pressurized (high-efficiency) gasifiers: - Low-rank coals, biomass – maintain HHV, temperature	Mid	R&D demonstration funding
• ASU improvement or replacement (with post-gasifier N_2 separation)	Long	R&D demonstration funding
• Process control to maintain temperature, slag performance, and operability for varying feedstocks	Mid	R&D demonstration funding
• Better analytical tools for coal (and other feedstock) properties - Real-time monitoring of feed properties	Mid	R&D demonstration funding
• Studies of slag properties as a function of feedstock properties	Mid	R&D demonstration funding
• Materials of construction robust to temperature swings and corrosion	Long	R&D demonstration funding
• Hot gas cleanup – remove S_1 metals, etc., from hot syngas	Mid - Long	R&D demonstration funding
• Demonstration (pilot) facilities for high-efficiency (pressurized) gasifiers (with R&D facilities for producing chemicals from syngas)	Mid	Funding and demonstration

Other Guidance

R&D Opportunity: Cost-Effective Extraction of Oil Shale for Use as Chemical Feedstock

Provides an existing infrastructure – compatible fossil feedstock with domestic supply.

Current State of Technology or Process

Two options:

- Mining, then upgrading via heat
- In situ – electrical heating underground

End-State Specifications of Technology or Process

- Low-cost, secure feedstock
- Lower energy use than current recovery process
- Minimal new infrastructure needed
- Minimal impact on downstream chemicals

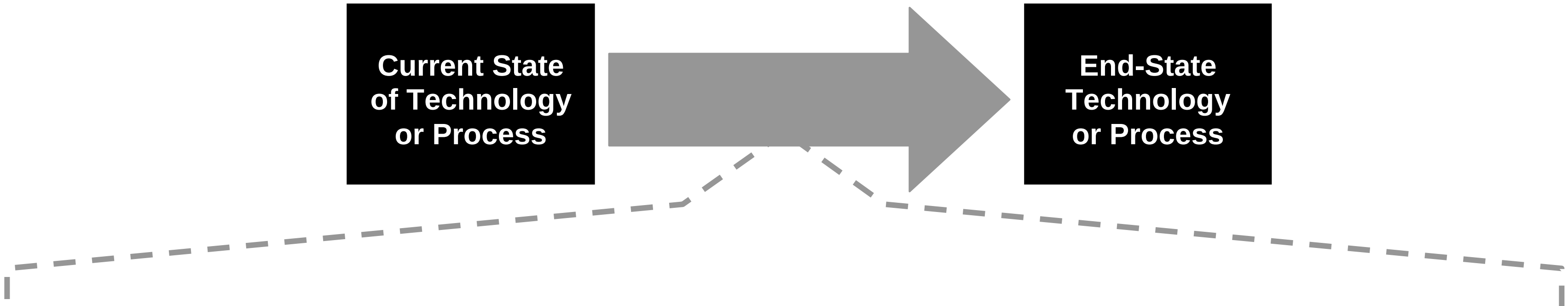
Comments on Potential Impacts

- Little change in existing products/markets (applicable to all)
- More expensive than $60/bbl crude (potentially less expensive than biomass at $150/bbl crude)
- More GHGs and more energy required vs. crude oil; possibly less energy than biomass; more energy than crude
- Energy security rating is based on using domestic sources

Potential Impacts

	LOW				
Energy Consumption	1	2	**3**	4	5
Greenhouse Gas Emissions	1	**2**	3	4	5
Input Costs	1	2	**3**	4	5
Products and Markets	1	2	3	4	**5**
Energy Security	1	2	3	4	**5**

R&D Opportunity: Cost-Effective Extraction of Oil Shale for Use as Chemical Feedstock



Key Knowledge and/or Technology Advancements *(Required to get from the current state to an effective technology solution)*	**Time Frame** *(Near, Mid, Long, or Unknown)*	**DOE Role**
• Downhole burners – direct heating of shale to high T - Example is gas turbine running underground	Long (10 yrs)	Funding for R&D and then demonstration (applies to all)
• Chemical cracking (in situ) to make chemical products directly	Long	
• Alternate heat sources (nuclear, microwave, etc.)	Long	
• Bioprocessing – microbes that break down shale	Long	
• Environmental containment: - Groundwater - Atmosphere - Microbes	Very long	

Other Guidance

R&D Opportunity: Transform Coal Directly to Products

No additional guidance provided.

Current State of Technology or Process

- Coal gasification:
  - Syngas to alkanes or products (FT)
  - Broad distribution of n-alkanes
- Coal liquification:
  - Wide variety of liquid products
  - S, N impurities
- Both are largely fuel plays, some C1, C2 byproducts
- Selectivity is too low for chemicals
- Coal to SNG:
  - Natural gas + CO_2 sequestered
  - Fuel but no chemical plant

End-State Specifications of Technology or Process

- Minimal steps to convert coal to chemicals
- Limited product distribution to desired products only
- Target is coal to functionalized hydrocarbons
  - C_0, C_3, C_6, BTX, EtOH, etc.
- Lower capital and cost compared to traditional gasifier to syngas to FT/etc.
- Reduce energy need vs. traditional routes:
  - Fewer steps, less manipulations
- Can be applied at a large scale:
  - Reliable, operable, cost effective
- Either manage CO_2 via utilization with reductant, sequestration, or other mechanism

Potential Impacts

	LOW				
Energy Consumption	1	2	**3**	4	5
Greenhouse Gas Emissions	1	**2**	3	4	5
Input Costs	1	2	3	4	**5**
Products and Markets	1	2	3	4	**5**
Energy Security	1	2	3	**4**	5

R&D Opportunity: Transform Coal Directly to Products

Current State of Technology or Process → **End-State Technology or Process**

Key Knowledge and/or Technology Advancements *(Required to get from the current state to an effective technology solution)*	**Time Frame** *(Near, Mid, Long, or Unknown)*	**DOE Role**
• Fundamentals on coal conversion to chemicals by catalysis: - Hydrogenation, cracking, oxidation (selective) - Catalyst and process technology development	Mid - Long	High-risk, high-reward, but government support needed to minimize industrial risk.
• Develop source of cheap hydrogen donors for reduction: - Catalysis to complement - Other sources to consider: Methane? Other alkanes? Biomass with water gas shift (WGS)?	Mid - Long	Broad impact across fuel and chemicals industries. Government leadership will foster industrial collaborations.
• Solids processing and use within the process: - Handle in the process as a slurry - Handle byproducts and slags/salts	Mid	Limited but some potential collaborations.
• Basic fundamentals of coal and impurity characteristics: - Reaction rates, impurity effects	Mid	Very basic research that is best fostered by DOE or government.
• Catalyst discovery to work with coal – Hetcat? Spray-on salts? Recovery? Lifetimes? Entrainment? - Potential to adapt high-throughput research (HTR) screening - Selectivity to desired products	Mid	High-risk, high-reward, but government support needed to minimize industrial risk.

Other Guidance

R&D Opportunity: Stranded Gas – Liquefy In Situ or to Aromatics

Stranded gas is gas that is currently uneconomical to recover or ship. Associated gas is natural gas from oil wells that may be useful.

Current State of Technology or Process

- Price pyramid, with lowest price on top:
  - $3–$4 MMBtu – large: world-scale used for LNG
  - $6–$8 MMBtu – mid-size: beginning to be used for LNG
  - $10–$12 MMBtu – small-scale: distributed
- Stranded gas is only stranded until it can be economically shipped
- Large fields are LNG sources
- Smaller fields are potential for chemicals:
  - Chemicals compete with LNG
  - Need on small to mid scale
- GTL or MeOH (syngas) chemistry
- MeOH has low Btu

End-State Specifications of Technology or Process

- Cost-effective recovery of methane as value-added product
- Non-syngas route to minimize cost and capital, plus scale of syngas too high
- Process that is selective to desired value-added product – not a fuel
- Mth – aromatic plus H_2 value
- Capital is key cost effect
- Infrastructure to ship products

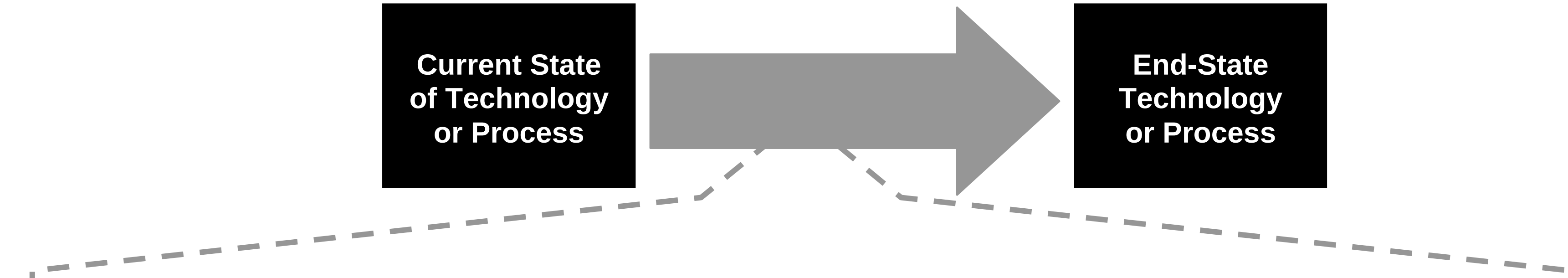
Comments on Potential Impacts

- Higher numbers indicate a more beneficial impact in terms of national goals
- Energy consumption and GHG emissions are similar to current fuels

Potential Impacts

	LOW				HIGH
Energy Consumption	1	**2**	3	4	5
Greenhouse Gas Emissions	1	**2**	3	4	5
Input Costs	1	2	3	**4**	5
Products and Markets	1	2	3	**4**	5
Energy Security	1	2	3	4	**5**

R&D Opportunity: Stranded Gas – Liquefy In Situ or to Aromatics



Key Knowledge and/or Technology Advancements *(Required to get from the current state to an effective technology solution)*	**Time Frame** *(Near, Mid, Long, or Unknown)*	**DOE Role**
• Conceptual designs and economics on novel process designs: - Catalyst - Process schemes - Gas purification of "natural gas" - Separation improvement/definition	Mid	Coordination of project across multiple interested industrial partners. Support demonstration of concepts.
• Modular plant designs (movable)	Mid	Funding to support new idea.
• Relative economic studies of comparative routes and uses	Near	Coordination of project across multiple interested industrial partners. Support demonstration of concepts.
• Catalyst breakthroughs: - Methane to benzene - Methane selective oxidation - Methane to olefins	Long	Support long-range, high-risk, high-reward projects that industry needs governmental support to pursue.
• Improve gas cleanup/separations (CH_4/CO_2/N_2/H_2S)	Mid - Long	Support long-range research with multiple impacts.

Other Guidance

R&D Opportunity: CO_2 Conversion to Feedstock

Zero environmental footprint. Removes CO_2 from environment (via artificial photosynthesis or other methods). Could produce hydrogen from various feedstocks. Catalyst for other feedstocks. Increase efficiencies. Scale up and lower cost of the catalysts. A very green technology area.

Current State of Technology or Process

- Proof-of-concept state. Low-grade efficiencies have been achieved. This technology is in its infancy.
- Limitations: materials, low efficiency, capturing efficiency of sun/solar energy is low.
- Critical gaps: light absorption, good conductivity in materials.
- Catalysts: integration of PV devices.

Current efficiency is 1% for solar-fueled methods.

End-State Specifications of Technology or Process

- Couple to an exhaust waste stream to remove CO_2; need concentrated CO_2 source
- Operational requirement: 10% efficiency
- Broad range of UV/VIS (visible light) capture capabilities

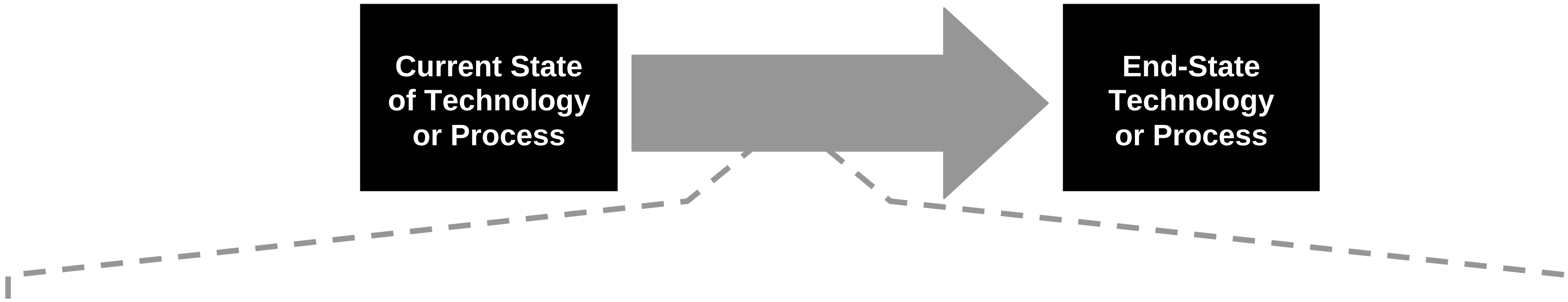
Comments on Potential Impacts

- Values reflect coupling input to other electricity sources, i.e., wind

Potential Impacts

	LOW				
Energy Consumption	1	2	3	4	**5**
Greenhouse Gas Emissions	1	2	3	4	**5**
Input Costs	1	2	3	**4**	5
Products and Markets	1	2	3	4	**5**
Energy Security	1	2	3	4	**5**

R&D Opportunity: <u>CO_2 Conversion to Feedstock</u>



Key Knowledge and/or Technology Advancements *(Required to get from the current state to an effective technology solution)*	**Time Frame** *(Near, Mid, Long, or Unknown)*	**DOE Role**
• Materials – catalysts, coating • Electrical conduction • Photocatalysts (PV) • Integration to produce higher efficiencies: processes, materials, devices • Exploration of long-term reliability: failure studies, efficiencies, degradations • Cost/economics: raw materials, manufacturing • Scale-up issues • Trade-off reduction of footprint by development of higher efficiency PV/wind power • Smart solar cell, wind turbines, year-long operations	Long (all activities)	• Funding • Formation of technical teams • Industrial, academic, and DOE laboratory collaborations

Other Guidance

R&D Opportunity: High-Temperature Filtration – Separation Materials

Feedstock synthesis and separation processes often require temperature reductions to achieve filtration/separation because of the limitations of low-temperature materials currently used. Would achieve energy savings required to cool and reheat processing gases through the filtration/separation devices.

Current State of Technology or Process

- Particulate filtration

End-State Specifications of Technology or Process

- Particulate filtration from PM_{10} to nanoscale
- Longer lifetime, so pretreatment or prefilters may be necessary
- Particulate removal efficiency:
  - To go into turbine without causing damage
  - To go into catalyst bed without building up particles
- Gas purity needs – remove any environmental contaminant or potential catalyst poisoners, like heavy metals
- Self-cleaning, regeneration, long lifetime, chemical inertness of filler structure integrity

Potential Impacts

	LOW				
Energy Consumption	1	2	3	4	**5**
Greenhouse Gas Emissions	1	2	3	4	**5**
Input Costs	1	2	**3**	4	5
Products and Markets	1	2	3	**4**	5
Energy Security	1	2	3	**4**	5

R&D Opportunity: High-Temperature Filtration – Separation Materials

Current State of Technology or Process	→	End-State Technology or Process

Key Knowledge and/or Technology Advancements *(Required to get from the current state to an effective technology solution)*	Time Frame *(Near, Mid, Long, or Unknown)*	DOE Role
• Procedure, process, material to clean in situ at high temperature without disrupting the gasification process: - Catalytic surface or component (including entire unit) to keep clean or involved in the cleaning process - Able to withstand thermal excursion during startup/shutdown/maintenance • Integrated system that encompasses filtration and separation performance: - High selectivity to specific process grades - High flux - Filtration performance demonstrated from nanoscale – PM_{10} - Environmentally benign materials of construction - Versatile and flexible • Technology must be scalable to commercial application • Materials development - High-temperature, low-cost, support or facilitate catalysis, manufacturable	Long	• Funding • Partnership facilitation • Consortia • Functional teams • Risk-sharing • Regulatory and policy foresight

Other Guidance

3. Conventional Feedstocks

Participants in the conventional feedstocks group identified high-impact R&D opportunities to improve conventional feedstock processing. The group then selected the five highest-priority R&D opportunities, focusing on those that would have the strongest impact in terms of increased energy and carbon emissions savings, reduced production costs, increased energy security, and increased industrial competitiveness. Table 5 presents the prioritized list of high-impact R&D opportunities.

The group identified low-intensity separations, to replace conventional distillation, as the top R&D opportunity to improve the energy efficiency of feedstock processing. Improved gas separation would allow carbon dioxide (CO_2) sequestration, improve process performance, and also reduce capital expenses in manufacturing. Among others, improvements in gas separations include sulfur removal from natural gas, removal/separation of oxygen from air, nitrogen purification, separation of CO_2 from various gases for sequestration, and separation of olefins from other olefins and/or alkanes.

The group also identified improvements in the performance of industrial reactions as key R&D opportunities. Specifically, the group recognized the following R&D opportunities for reactions: improvements in catalysis conversion and selectivities; process intensification through better mixing and heat transfer; and the use of new technologies, such as microreactors, to process heavy molecules.

The group identified the reduction of greenhouse gases in feedstock processing as another important R&D area. Opportunities include carbon capture and storage technology with lower capital and operating costs, the use of alternative energy sources, improved understanding of chemistry, and the development of commercial carboxylation processes.

Participants also identified a need to utilize lower-cost (heavier and/or dirtier) feedstocks to improve operating margins. The replacement of alkenes with alkanes would be one example of this kind of substitution.

In the second session of the workshop, participants identified the barriers to the five highest-priority R&D opportunities. Table 6 presents the list of identified barriers.

In the third session of the workshop, the group broke down into subgroups and conducted a "pathway analysis" for each of the top opportunities. To complete this exercise, the subgroups filled out two worksheets for each opportunity:

- The first worksheet describes the current state of the technology, the desired end state, and the potential impacts of achieving the desired end state.
- The second worksheet identifies the necessary R&D pathways to achieve the desired end state, the timeframe, and DOE's role.

The completed pathway analyses are shown after Table 6.

TABLE 5 – ENERGY-EFFICIENT CONVENTIONAL FEEDSTOCKS GROUP

HIGH-IMPACT R&D OPPORTUNITIES

H_2 PRODUCTION	CARBON FOOTPRINT/ ENVIRONMENTAL	REACTION PERFORMANCE	PARTNERING	IN SITU TECHNOLOGIES
• Low-cost H_2 production (e.g., more efficient hydrolysis) in petroleum refining	• GHG emissions reduction to lower carbon footprint ●●● • Improved CO_2 capture/use	• Improved catalyst performance – conversion and selectivity, sulfur-tolerable catalysts ●●● • Encourage process intensification reactions – better mixing and heat transfer leading to reduced feedstock consumption ●●● • Apply new and better technologies to existing processes (e.g., microreactors for cracking heavy chemicals) ●●● • Target selection – new reactions to convert feedstocks to more easily separable mixtures • Field-enhanced processes (e.g., focused heating versus bulk heating, microwave and catalysts)	• Partnerships with electric/power industry – technology collaboration between chemical industry and utilities (e.g., IGCC to produce chemicals and power) ●●● • Enterprise modeling or solutions, tax incentives for partnering processes ●	• In situ processing to transportable forms from remote locations ●●● • Distributed production, microtechnology plants for stranded gas conversion to products

Table 5 – Energy-Efficient Conventional Feedstocks Group
High-Impact R&D Opportunities (cont'd)

Product Recycling	Lower cost Conventional Feedstocks	Improved Separation	Policy
• Recycled products • Waste stream recycling requirement	• Upgrade less-valuable feedstock (heavier, "dirtier") (e.g., greater use of alkanes for chemicals production) ●●● • Improve current process selectivities to higher-valued products/feedstock (e.g., FCC technology to strengthen C_3 supply chain, FCC to produce diesel and light olefins) • Decentralized collection of off-spec feedstocks for processing.	• Low-intensity separations (e.g., to replace distillation) ●●●●●● • Improved gas separations ●●● – CO_2 – O_2/N_2 – H_2 – H_2S – CH_4 – Contaminants • Separate olefins from hydrocarbon streams easily and at low cost • Introduction of pretreatment process to extract/separate high-value products	• Legislation to subsidize and encourage production ●●● • Education of policymakers (and vice versa) • Tax incentives

Table 6 – Energy-Efficient Conventional Feedstocks Group

R&D Barriers

Low-Intensity Separations (Replace Distillation)	Upgrade Less Valuable Feedstock	Improved Catalyst Performance (Conversion/Selectivity)	Improved Gas Separation	Encourage Process Intensification Reactions
• Finding one approach • Cost performance level • No one wants to be guinea pig • Large-scale separations have large investments (barrier to adopting alternatives) • Need to demonstrate new separating agents/processes • Distillation works and has huge experience base (need demonstrations of alternatives, at scale)	• More energy needed to process "dirty" feedstock	• Expensive, risky, long-term research needed • Limited number of companies in technology development and commercialization and often with different priorities	• Membranes – need better properties (permeance, selectivity, cost)	• Competing priorities for limited capital and budget • Need to prove process improvement using microchannel reactors at large scale • Need to demonstrate energy, economic, etc. benefits

GHG Emissions Reduction	Partnerships with Electric and Power Industry
• Unknown and uneven tax/credit on emissions • Need new technology (applies to multiple opportunities) • Need to reduce capital costs (applies to multiple opportunities) • Identify useful (valuable) byproducts from CO_2	• No incentive to work together, no drivers • Utilities' concern for liability/reliability with alternatives • Reluctance to change (applies to multiple opportunities) • Partnering – confidentiality, secrecy in chemical industry • Not playing with the same rules

R&D Opportunity: Low-Intensity Separations (Replace Distillation)

Often separations are a high-capital and energy-intensive portion of chemical processes. A major goal in chemicals production is to lower capital requirements for the separation process.

Current State of Technology or Process

- Current separation processes, such as distillation, are mature and well established
- There is little risk to applying new separation technologies

End-State Specifications of Technology or Process

- Lower capital costs with greater or equal performance
- Lower energy use with greater or equal performance
- Reliable, low-cost, robust technology to allow the use of lower-cost, impure feedstocks
- 240 TBtu/yr may be gained due to improved separations of the top 100 chemicals

Potential Impacts

	LOW				
Energy Consumption	1	2	3	4	**5**
Greenhouse Gas Emissions	1	2	3	4	**5**
Input Costs (Savings)	1	2	3	4	**5**
Products and Markets	1	2	3	4	**5**
Energy Security (Chemicals)	1	**2**	3	4	5
Energy Security (Fuels)	1	2	3	4	**5**

R&D Opportunity: Low-Intensity Separations (Replace Distillation)

Current State of Technology or Process	→	End-State Technology or Process

Key Knowledge and/or Technology Advancements *(Required to get from the current state to an effective technology solution)*	Time Frame *(Near, Mid, Long, or Unknown)*	DOE Role
• Use of membranes requires high-performance (permeance and selectivity) at attractive cost	Timeframe is separation specific	• Funding to help research, development, and demonstration • Consider acquisition of closed/available plant for demonstration
• Demonstration of the technology at a commercial or near-commercial scale	Mid to Long (<5 to >5 yrs)	
• Better distillation column performance (packing, divided wall designs)	Mid	

Other Guidance

R&D Opportunity: Upgrade Less-Valuable Feedstocks (Heavier and Dirtier Feedstocks) That Are Less Costly

Less-costly feedstocks provide opportunity for higher margins, e.g., replace alkenes with alkanes.

Current State of Technology or Process

- Less expensive feedstocks are more difficult to process.
- Selectivity is typically lower for alkane conversions.
- Existing catalyst systems were invented for current processes. Completely new catalyst systems will be needed to process lower-value feedstocks.

End-State Specifications of Technology or Process

- Same conversion per pass at same selectivity
- Same compounds with same performance properties
- Drop in technology replacement
- High-selectivity processes
- Lower-cost products

Potential Impacts

	LOW				
Energy Consumption	1	2	**3**	4	5
Greenhouse Gas Emissions	1	**2**	3	4	5
Input Costs	1	2	3	4	**5**
Products and Markets	1	2	3	**4**	5
Energy Security	1	**2**	3	4	5

R&D Opportunity: Upgrade Less-Valuable Feedstocks (Heavier and Dirtier Feedstocks) That Are Less Costly

Current State of Technology or Process → **End-State Technology or Process**

Key Knowledge and/or Technology Advancements *(Required to get from the current state to an effective technology solution)*	Time Frame *(Near, Mid, Long, or Unknown)*	DOE Role
• New catalysts • Improved process technologies • Demonstrations at near-commercial scale	Mid (< 5 year)	• Help fund high-risk, expensive RD&D

Other Guidance

R&D Opportunity: Improve Catalyst Performance in Selectivity and Conversion

There is a need to further improve the gains that have been achieved in catalyst performance over the years. This will allow utilization of lower-quality feedstock, improved efficiency of utilization of feedstock, and reduced energy consumption during conversion, and will drive the overall costs of production. This may lead to smaller, more-efficient plants with a lower carbon footprint.

Current State of Technology or Process

- Limited number of companies in catalyst development
- Many catalysts with low selectivity and performance leading to high energy consumption and use of more feedstock than is necessary

End-State Specifications of Technology or Process

- Improved efficiency of feedstock utilization
- Reduced energy consumption
- Improved tolerance of impurities
- Improved catalyst tenability

Potential Impacts

	LOW				
Energy Consumption	1	2	3	4	**5**
Greenhouse Gas Emissions	1	2	3	4	**5**
Input Costs	1	2	3	4	**5**
Products and Markets	1	2	3	4	**5**
Energy Security	1	2	**3**	4	5

R&D Opportunity: Improve Catalyst Performance in Selectivity and Conversion

Current State of Technology or Process → **End-State Technology or Process**

Key Knowledge and/or Technology Advancements *(Required to get from the current state to an effective technology solution)*	Time Frame *(Near, Mid, Long, or Unknown)*	DOE Role
• More basic R&D on catalyst development • Pilot plants for process development (a national catalyst testing center): - Service center with reactor flexibility	Near (<5 year)	• Funding national lab to mitigate risk and perform screening

Other Guidance

R&D Opportunity: Improved Gas Separations

- Sulfur removal from natural gas, removal/separation of O_2 from air, nitrogen, separation of CO_2 from various gases for sequestration
- Improved gas separation will allow for CO_2 sequestration, improve process performance, and reduce capital expense
- Separate olefins from olefin streams or other streams (olefin/alkane mixture)

Current State of Technology or Process

- Membranes are limited by cost and performance. Need to reduce membrane size, improve chemical resistance, and prove performance at scale.
- Adsorption technology is known, but improved gas separations are not commercialized.
- Need to reduce cost.
- Small- to pilot-scale demonstrations only.
- Different membranes are required for different separations.

End-State Specifications of Technology or Process

- Need a commercially available system
- Need to be economically viable for a given process
- Need a smaller footprint
- Need higher performance
- Increase natural gas availability by improving the separations process
- Upgrade the value of formerly waste streams

Potential Impacts

	LOW				
Energy Consumption	1	2	3	**4**	5
Greenhouse Gas Emissions	1	2	3	**4**	5
Input Costs	1	2	**3**	4	5
Products and Markets	1	**2**	3	4	5
Energy Security	1	2	**3**	4	5

R&D Opportunity: <u>Improved Gas Separations</u>

Current State of Technology or Process → **End-State Technology or Process**

Key Knowledge and/or Technology Advancements *(Required to get from the current state to an effective technology solution)*	**Time Frame** *(Near, Mid, Long, or Unknown)*	**DOE Role**
• Need better understanding of materials and their performance (materials science). • Need to have defect-free membranes at large scale – development in manufacturing process or membrane design efforts. • Improve temperature stability, improve pressure stability – ceramics work here but have adsorption issues. Need new studies and better understanding of adsorption of organics onto ceramics. If we solve this, will have good membrane performance.	Long (> 5 years)	• Funding for high-risk research

Other Guidance

R&D Opportunity: Encourage Process Intensification Reactions

This will improve control of endothermic and/or exothermic reactions, save energy, reduce capital cost, reduce waste, improve the process, and reduce footprint.

Current State of Technology or Process

- State of the art is an immature science
- This also includes processes other than microchannel reactors and screening
- Microchannel reactors are being developed

End-State Specifications of Technology or Process

- Robust modeling tools for rapid screening development

Potential Impacts

	LOW				
Energy Consumption	1	2	3	4	**5**
Greenhouse Gas Emissions	1	2	3	4	**5**
Input Costs	1	2	3	4	**5**
Products and Markets	1	2	**3**	4	5
Energy Security	1	2	3	**4**	5

R&D Opportunity: Encourage Process Intensification Reactions

Current State of Technology or Process	→	End-State Technology or Process

Key Knowledge and/or Technology Advancements *(Required to get from the current state to an effective technology solution)*	Time Frame *(Near, Mid, Long, or Unknown)*	DOE Role
• Better understanding of cost savings and impact • A need for better understanding of basic science behind process change	Long (> 5 years)	• Support U.S. concerns to foster technology domestically and commercialize these technologies in the United States.

Other Guidance

R&D Opportunity: Greenhouse Gas Emissions Reductions

Greenhouse gas emissions may be taxed or regulated in the future. Caps may be imposed and global regulations may influence production. Global climate change may result from excessive GHG emissions.

Current State of Technology or Process

- Cost of capture and sequestration of CO_2 is high

End-State Specifications of Technology or Process

- CO_2 is a feedstock
- CO_2 is captured and sequestered safely and economically
- No CO_2 is produced

Potential Impacts

	LOW				
Energy Consumption	1	2	3	4	**5**
Greenhouse Gas Emissions	1	2	3	4	**5**
Input Costs (unknown)	1	2	3	4	5
Products and Markets	1	2	3	4	**5**
Energy Security	1	2	3	**4**	5

R&D Opportunity: Greenhouse Gas Emissions Reductions

Key Knowledge and/or Technology Advancements *(Required to get from the current state to an effective technology solution)*	Time Frame *(Near, Mid, Long, or Unknown)*	DOE Role
• Low-cost CO_2 capture and sequestration needed • Use of alternative energy sources to power energy plants – may be driven by future legislation • Need to understand chemistry of CO_2 • Commercial, improved carboxylation processes	Long (> 5 years)	• Encourage, sponsor, fund R&D and demonstrations

Other Guidance

R&D Opportunity: Partnerships with Electric/Power Industry

Large amount of wasted energy is produced and not used to produce electricity.

Current State of Technology or Process

- Utilities and chemical industry do not work together
- Scale imbalance at times between electricity and chemical plants
- Utilities concerned over reliable supply to the grid from alternative supply

End-State Specifications of Technology or Process

- Combined electric and chemical production from same sites
- Economic incentives – industrial zones
- Low-temperature (<150 °C) energy utilized more
- Cost-sharing on new chemical/power plants

Potential Impacts

	LOW				
Energy Consumption	1	2	3	4	**5**
Greenhouse Gas Emissions	1	2	3	4	**5**
Input Costs	1	2	3	4	**5**
Products and Markets	1	2	3	**4**	5
Energy Security	1	2	3	4	**5**

R&D Opportunity: Partnerships with Electric/Power Industry

Key Knowledge and/or Technology Advancements *(Required to get from the current state to an effective technology solution)*	Time Frame *(Near, Mid, Long, or Unknown)*	DOE Role
• Zoning requirements	Mid (< 5 years)	Fund information and modeling
• State utility commissions		
• Modeling to understand reliability for grid distribution when electricity is derived from alternative sources		
• Gathering and applying knowledge from successful implementations in Europe (Denmark)	Long (> 5 years), for demonstration of chemical power production site	Support information gathering and publication
• Cost-sharing on new chemical power production sites for demonstration site		Support demonstration

Other Guidance

Appendix A. Workshop Agenda

Day 1

8:00 am	Registration and breakfast
9:00 am	Opening Remarks *Dr. Dickson Ozokwelu, U.S. Department of Energy, Industrial Technologies Program*
9:30 am	Alternative Feedstocks − A Dow Perspective *David Graf, Dow Chemicals Company*
10:00 am	Bio-based Feedstocks *Linda Beltz, Weyerhaeuser*
10:30 am	Vision 2020 Alternative, Renewable and Novel Feedstocks for Producing Chemicals *Bill Choate, BCS Incorporated*
11:00 am	Break and proceed to breakouts Group 1 − Alternative bio-based feedstocks Group 2 − Alternative fossil-based feedstocks Group 3 − Energy-efficient conventional feedstocks
11:15 am	Breakout Topic 1: Identify high-impact opportunities to save energy, reduce feedstock costs, improve energy security, and increase competitiveness.
12:00 pm	Lunch
1:30 pm	Continue Breakout Topic 1
2:30pm	Breakout Topic 2: Identify the barriers of the top 5-10 opportunities, and prioritize top barriers.
3:30 pm	Break
3:45 pm	Breakout Topic 3**:** Define highest priority R&D pathways to facilitate the use of low-cost feedstocks and alternative feedstocks in industry.
4:45 pm	Adjourn for the day

Day 2

8:00 am	Breakfast
8:30 am	Continue Breakout Topic 3: Finish R&D pathways and prepare presentation for plenary
10:20 am	Coffee break
10:35 am	Reconvene in plenary and present group reports
12:00 pm	Adjourn

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