Energy-Efficient Technologies

4. Agriculture and Forestry

4.1 Conversion of Biomass to Bioproducts

4.2 Advanced Agriculture Systems

4.3 Plant/crop Engineering

4.1 CONVERSION OF BIOMASS TO BIOPRODUCTS

Technology Description

Annual crops, perennials, and short-rotation woody species represent plant/crop-based resources that are a renewable source material in the food, feed, and fiber industries. The current market of biobased materials exceeds 85 million tons/year. The use of such biobased processes to produce materials and products provides a modest but significant reduction in GHGs by two measurable effects. First, lowering the use of petroleum-based feedstocks reduces the inherent emissions associated with these feedstocks, since biobased products are synthesized from ambient CO_2 currently in our atmosphere. Second, the use of biobased processes has shown some potential for emitting roughly the same, or in some cases fewer, GHG emissions as petroleum-based processes.

System Concepts

- The United States has significant forestry or plant/crop-based resources, including forestry, rangeland, and a highly productive agricultural system. In the past 50 years, these resources have been largely focused toward food, feed, and fiber production.
- Use of forestry/crop resources for energy, or as basic building blocks for industrial production, has been limited because of a poor fit with the current hydrocarbon processing system. However, this is not an either/or system choice.
- The concept being proposed involves developing manufacturing platforms employing the uniqueness of biobased materials to provide society's materials needs or integrated manufacturing platforms that overcome the poor fit scenario described earlier.

Representative Technologies

- New biotechnologies for plant growth and production and biotechnology and benign chemical synthesis for conversion of biomass materials into products.

Technology Status/Applications

- Corn wet-mills, pulping operations, and dimensional lumber facilities represent a significant segment of the industrial community. All are cost-effective. What is not cost-effective or is poorly implemented is the development of broader economic platforms based on forestry/crop-derived inputs. DOE and other federal agencies have been applying their technologies to the development of these new manufacturing options.

Current Research, Development, and Demonstration

RD&D Goals

- It is more suitable in this pathway to outline directional goals (i.e., goals that outline a direction rather than an end point).
- To implement at least 10% of basic chemical building blocks arising from plant-derived renewables by 2020 with development concepts in place to increase this to 50% by 2050.
- To develop economically viable manufacturing platforms for selected products (such as plastics, textiles, cosmetics) by 2020 using plant-based (crop, forestry, processing) systems that produce renewable feedstocks.
- To build collaborative partnerships among industrial stakeholders, growers, producers, academia, and federal/state governments to develop small- to large-scale commercial applications such that the distinction between processing biobased materials for food, feed, and fiber and the manufacturing of basic materials will begin to disappear.

RD&D Challenges

- There are three major challenges in establishing these biobased manufacturing platforms:
  - Using forestry/agriculture-based inputs in modified but existing processing systems.
  - Developing new or modified forestry/agriculture-based plant/crop production systems to provide desirable feedstocks.
  - Integrating these approaches to create optimized systems that generate these new economic platforms based on the use of biomass-derived inputs.
- What is needed is a larger suite of viable examples to demonstrate the potential for a renewables-based approach. There is simply not enough available technology to establish an even larger role of forestry/agriculture-based products and materials, especially in benign organic syntheses, biotechnology, and new materials development.

RD&D Activities

- DOE's OIT is leading the effort in producing biobased products. The FY 1996 and 1997 budgets were about $8.4M and $3M, respectively. The USDA's Agricultural Research Service (ARS) and the Cooperative State Research Extension and Education Service (CSREES) also are engaged in similar work. The ARS budgets in FY 1996 and FY 1997 have been about $20M/year (exclusive of their effort in ethanol). The CSREES effort in FY 1996 and FY 1997 spent about $3.5M/year. Industry is sponsoring work. Although the exact numbers are not available, two examples provide some idea of magnitude. Genencor and Eastman Chemicals are pursuing a $30M/5 year 50:50 cost-shared project with the NIST/ATP program to develop biocatalysts for chemical processing. DuPont has announced an effort in biological production of 1,3 propanediol from corn syrup as a precursor to new polymers. This is one of several efforts by industry.

Recent Success

- Citric acid is an acidulent used in food processing and was produced by fermentation using paraffin oils from petrochemical sources until the 1980s. Currently, this 300 million lb/year commodity chemical is produced solely and economically from fermentation of corn syrup. The rayon fabric and cellophane packaging market is based solely on wood and is commercially viable. Recently, the production of high-fructose corn syrup from corn starch for food sweeteners has become a commodity market with more than 12 billion lb produced annually.

Commercialization and Deployment

- The current, annual U.S. production market for biobased products and materials is more than 85 million tons. At an average value of $0.25–0.50/lb, the total annual sales are between $45B and $85B. The major manufacturers are the pulp/paper, grain processing, and food processing industries. The concept is the development of new manufacturing platforms compatible with the market drivers, and, where appropriate, integrated with existing chemical, forestry, and agricultural manufacturing operations. There is no attempt to replace efficient hydrocarbon processing, but rather to develop alternative processing capabilities to establish new manufacturing platforms. This involves a paradigm shift, not a battle over competing technologies. Critical challenges to widespread deployment are noted under RD&D challenges.

Potential Benefits and Costs

Carbon Reductions

2–5 MtC/year	2010
10–15 MtC/year	2020
15–25 MtC/year	2030

RD&D Expenditures

- Federal RD&D funding requirements for this pathway: $25–50M/year through 2010
- $50–75M/year through 2020
- $10–15M/year through 2030 (should be essentially market driven by then).
- Because of the limited number of examples to demonstrate commercial viability, substantial federal funds are necessary through the year 2020.

Market

- The major contributors to the carbon reduction values noted are reductions related to the displacement of petroleum typically used to manufacture products. In addition, if cogeneration of energy were employed in biomass-based manufacturing analogous to the pulping industry's use of biomass as a fuel, additional energy savings could be achieved. These cannot be calculated exactly but can be estimated. For example, processing energy for chemicals amounts to about 3 quads of energy. If biobased materials processing involved cogeneration of power analogous to the forestry industry (50%) on 10% of the chemicals volume, then purchased energy could be reduced by about 0.15 quads, reducing net GHG emissions.

Nonenergy Benefits and Costs

- This technology involves developing new manufacturing platforms and not displacing petrochemical platforms. It would lead to development of a new mode of operation within existing infrastructures or development of altogether new infrastructures.

Risk Factors

Technical Risk

1 2 3 4 ⑤ 6 7 8 9 10
Low High

- Much technical information is available, but there are limited numbers of applied technologies.

Commercial Risk

1 2 3 4 ⑤ 6 7 8 9 10
Low High

- Very limited number of examples to demonstrate full commercial viability.

Ecological Risk

1 2 ③ 4 5 6 7 8 9 10
Low High

- Technologies for conversion of biomass to products generally produce fewer negative environmental impacts than do traditional production processes.

Human Health Risk

1 2 ③ 4 5 6 7 8 9 10
Low High

- Farming and agriculture have low human health risks. Chemicals production has slightly higher risk factors.

Economic Risk

1 2 ③ 4 5 6 7 8 9 10
Low High

- If successful, the technologies would strengthen the economy and create American jobs.
- Generally perceived as a "green technology" by the public.

Regulatory Risk

1 2 3 ④ 5 6 7 8 9 10
Low High

- Qualifying bioproducts from biomass for use in commercial manufacturing carries some regulatory risk, but the industries involved are well versed in this area.

Key Federal Actions

- Establish a federal RD&D program to develop improved conversion technologies for agricultural/forestry products, and develop viable and economic examples of biobased-product manufacturing technologies.
- Establish stronger interagency and federal agency–industry partnerships with increased involvement with suppliers of feedstocks represented by professional agriculture and forestry societies, cooperatives, and ecological interest groups.

4.2 ADVANCED AGRICULTURE SYSTEMS

Technology Description

Advanced agriculture systems enable a process of collecting and using increasingly detailed site-specific information in conjunction with traditional farm management tools such as agronomy, machinery, finance, and marketing for accessing and applying the best available information to better manage individual farming operations. In addition, these systems provide for improved understanding, control, and, perhaps, manipulation of microbial processes at plant roots and in soils to control flows of carbon and nitrogen. These systems provide an integrated capability to improve environmental quality while enhancing economic productivity by increasing energy efficiency, optimizing fertilizer and other chemical applications, and conserving soil and water resources.

System Concepts
- Global positioning infrastructure and remote and in situ sensors for soil, crop, and microclimate characterization.
- Cropping system models, data and information analysis, and management tools.
- Variable rate application control systems and smart materials for prescription delivery.
- Biological and chemical methods for manipulating microbial processes to increase efficiency of nutrient uptake and to suppress GHG emissions.

Representative Technologies
- Global positioning satellites and ground systems, and satellite- and aircraft-based remote and in situ electrical, magnetic, optical, chemical, and biological sensors.
- Advanced artificial intelligence and information networking technologies; autonomous control and robotics systems; and soil, crop, moisture, pest, and microclimate responsive (smart) materials.
- Biological and chemical methods for microbial process manipulation.

Technology Status/Applications
- Many first-generation precision agriculture technologies are available for application and are in use on ~10% of U.S. farms.
- Information management and networking tools; rapid soil characterization sensors; selected crop stress, yield, and quality sensors; and a systematic integration of all technologies for all major cropping systems are not yet at technical performance levels required for application.
- Strong understanding of soil microbes and relationships exists in the agriculture, energy, and university research community.
- Capability exists to develop smart materials and methods for microbial manipulation.

Current Research, Development, and Demonstration

RD&D Goals
- Technologies that improve production efficiencies and reduce energy consumption by 4% by 2010, 16% by 2020, and 39% by 2030.
- Remote and field-deployed sensors/monitors and information management systems for accurate, real-time monitoring and analysis of crops, soils, water, fertilizer, and agricultural chemicals use/efficiency to meet the fertilizer and energy reduction goals.
- Smart materials for prescription release: four to five main crops by 2010 (10 chemicals); 20 crops by 2020; and all important crops by 2030.
- Advanced fertilizers and technologies to improve fertilizer efficiency and reduce nitrogen fertilizer inputs by 20% by 2020.
- Methods of manipulating microbial processes to materially increase the efficiency of nitrogen uptake and suppress CO_2 emissions.
- Initial systems models and prototype operation by 2000 on selected cropping systems that are major contributors to U.S. food and fiber use and export.
- Deployment of first-generation integrated system models, technology, and supporting education and extension infrastructure by 2002.
- Complete transition of first-generation system development to the private sector by 2004.

RD&D Challenges
- Site-specific agriculture in general requires advances in rapid, low-cost, and accurate soil nutrient and physical property characterization; real-time crop water need characterization; real-time crop yield and quality characterization; real-time insect and pest infestation characterization; autonomous control systems; and integrated physiological model and massive data/information management systems.
- Smart materials that will release chemicals based on soil and crop status depend on modest breakthroughs in materials technology.
- Improved understanding of specific soil microbial processes is required to support development of methods for manipulation.
- Models that represent accurate understanding of plant physiology must be coupled with models that represent soil processes such as decomposition, nutrient cycling, and water storage and flows to understand how ecosystems respond to atmospheric change.
- Detailed and simultaneous examination of biogeochemical reactions that occur in near-surface groundwater is required to improve understanding of nutrient cycling, GHG concentration, and degradation of contaminants.
- Improved understanding of the pathway by which nitrate is reduced to gaseous nitrogen is required to support scaling of emissions estimates associated with the nitrogen cycle.
- The microecological consequences of expanding carbon stock in soils resulting from suppressing CO_2 emissions are unknown or uncertain.

RD&D Activities
- Complementary efforts are under way in both public and private sectors.
- Sponsors include USDA, DOE, NASA, universities, state agencies, commodity groups, and sensor and satellite developers; the principal funding comes from USDA.
- Current funding level provided by U.S. government sponsors is estimated at $40M.

Recent Success

- High-resolution satellite imagery can be used to identify stress and disease in some crops at 1-to-2 m resolution.
- Research programs have related reflectance spectra to disease or nutrient status.
- Technology was developed to coextrude recyclable plastics with ammonium polyphosphate for continuous ammonium release in the presence of water.
- Research programs have demonstrated performance of microbially encapsulated fertilizer.
- Rf-link deployable field sensors exist for ground moisture monitoring.
- Commercial sensors exist for CO_2 and ammonia gas monitoring and for accurate yield monitoring of grain and tuber crops.

Commercialization and Deployment

- Global positioning systems, geographic information system software for parameter mapping, remotely sensed imagery, selected yield monitors, and selected variable rate control systems for seed, fertilizer, and chemical applications are commercialized and in application in the United States, Canada, Australia, and Europe.
- Slow-bleed release pesticides are available commercially.
- No commercial methods for microbe manipulation are available.
- Current traditional agricultural inputs (seed, fertilizer, chemicals), monitoring systems, and non–site-specific application equipment are competing technologies.
- The infrastructure in place for agricultural production will support these technologies with little change; however, the cost to compete with other technologies may initially be high until technology integration is complete.

Potential Benefits and Costs

Carbon Reductions
- 1–2 MtC/year by 2010, 5–10 MtC/year by 2020, 15–20 MtC/year by 2030

RD&D Expenditures
- Federal funding of $80M to $120M/year, equivalent to 2 to 3 times current expenditures, is needed through 2030.

Market
- Development and scheduling of delivery systems for water and nutrients. For example, injecting rather than broadcasting nitrogen on no-tillage corn can reduce nitrogen use by 35% to 59% and reduce costs by $5 to $20/acre.
- Market for technologies exists not only in the United States but worldwide. In developing countries dependent on agriculture, the market for improved agricultural systems is substantial.

Nonenergy Benefits and Costs
- Petroleum consumption reduction of 4% through 2010; 16% through 2020; 39% through 2030.
- Enhanced economic productivity while maintaining sustainable production to meet rapidly escalating international food, fiber, alternative feedstock and renewable energy demands, improved soil fertility, improved environmental quality.

Risk Factors

Technical Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

- Durability, shelf life, field life, yields, and reaction rates are issues.
- Not clear whether materials can be manufactured that are both appropriately sensitive and deployable.

Commercial Risk

1 2 3 ④ 5 6 7 8 9 10

Low High

- Sensors are expensive, and it has not been demonstrated that they can be manufactured cheaply and in large quantities.
- Many unit processes and components already exist.
- Power sources and property rights to processes and microbes are issues.
- Industry has little experience manufacturing smart materials and may require some infrastructure changes to accommodate these.
- Manufacturing or growing microbes may impose limits.

Ecological Risk

1 2 3 ④ 5 6 7 8 9 10

Low High

- Potentially harmful waste streams in manufacturing and workplace environments.
- Controlling release of fertilizers and chemicals and microbes into the environment is an issue.

Human Health Risk

1 2 3 ④ 5 6 7 8 9 10

Low High

- Potential health risks result from possible environmental releases described as ecological risks.

Economic Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

- Recycling used-up or worn-out sensors; potential annual recycling.
- Recycling used-up or worn-out substrate; plans are to make such materials from recycled material and use it multiple times.
- Society is generally averse to risks associated with genetically altered or artificially propagated microbes in the environment—concern with "superbugs."

Regulatory Risk

1 2 3 ④ 5 6 7 8 9 10

Low High

- Regulatory issues may arise from the manipulation of microbes and the introduction of genetically engineered microbes to the environment.

Key Federal Actions

- Allocate funding in sufficient quantities to support end product completion and measure performance toward specific objectives.
- Sustain a directed basic and applied research effort on sensors, information sciences, materials, and microbial processes.
- Establish a federal initiative to develop a multiagency, public/private, joint program.
- Apply systems engineering and integration disciplines to effectively develop and guide program formulation and implementation.

4.3 PLANT/CROP ENGINEERING

Technology Description

Plant/crop engineering involves improving plant productivity and utility in capturing solar energy and converting it to chemical energy through traditional and functional genomics; genetic engineering; and developing transgenic plants for the purposes of increased biomass production, increased carbon fixation, improved nitrogen utilization and recycling, and biomass conversion technologies. DOE has invested significantly in understanding energy conversion technologies, hence bringing to bear a significant resource to this most basic of energy storage and conversion needs.

System Concepts

- Plant genomics: development of genomic maps for detailed studies of genomes, genes, and genetic processes. Traditional genomics includes gene mapping, molecular cloning, large scale DNA sequencing, data management and computational analysis. Plant genomics is necessary for the development of new or improved crop and forest species that promote sustainability and profitability of plant production and improvement of quality.
- Photosynthetic efficiency: physiological and genetic control of photosynthetic pathways for efficient sunlight capture and conversion to biomass.
- Nitrogen fixation and metabolism: genetic control of nitrogen cycling and nutrient use efficiency. Technologies that optimize the efficiency of nitrogen use by plants to ensure site sustainability while minimizing losses of nitrous oxide from soil.
- Functional genomics for high-performance plants: using the tools of traditional genomics to focus on the structure and function of novel gene sequences from a variety of organisms. For example, functional genomics may employ biomass genotypes from extreme environments or biomass genotypes that express novel characteristics to identify and isolate novel gene sequences.
- Gene expression, compartmentalization, and timing: once identified, desirable genes must be introduced successfully into target biomass species and expressed (i.e., make their product). For these genes to be useful in carbon management, technologies need to routinely accomplish stable gene insertion into host genomes, including desirable biomass species that may be difficult to transform, and to prove reliable the expression of these genes over time and in diverse environments.
- Plant engineering for end use: development of new or modified plants that will enable or assist the development of breakthrough biomass conversion technologies and allow plants to serve as biological factories for production of chemicals, enzymes, materials, and fuels.

Representative Technologies

- Use of plant assembly fundamentals to create fast-growing tree crops that produce high-strength structural wood and composites for use in construction.
- High-resolution mapping with techniques such as amplified fragment length polymorphism analysis.
- Genetic transformation: the use of cellular and molecular techniques to insert a single target gene into the DNA of an organism.
- In situ hybridization to determine the location of DNA sequences and genes on chromosomes.

Technology Status/Applications

- With more than 2100 field trials of crops under way in 1995/1996, the technology is obviously viable. However, the time necessary to develop a new plant with desired traits needs to be reduced to bring to bear the full effect of this technology.
- Genetically engineered species comprised nearly 20% of the cotton crop.

Current Research, Development, and Demonstration

RD&D Goals

- Increasing the ability to express cloned genes by a factor of 10 will reduce cycle time for development of new transgenic field crops from 5–10 years to 2–5 years and the cycle time for forestry cultivars from 7–15 years to 3–7 years.
- Increasing the number of completed genome maps of selected plant species from zero to five in 10 years.

RD&D Challenges

- Plant genomics; photosynthetic efficiency improvements; nitrogen fixation and metabolism; functional genomics for high-performance plants; gene expression (compartmentalization/timing); and plant engineering for end use. Using high-resolution analytical techniques such as DOE's Advanced Synchrotron Light Source. Employing the potential of advanced sensor technology to correlate performance properties of agriculture/forestry materials with genetic and structural composition (this is being evaluated now with some success by DOE scientists).

RD&D Activities

- DOE spends about $25M annually on basic plant engineering and about $8M annually on sustainable forestry and biomass feedstock development. USDA's budget in their Cooperative State Research Extension and Education Service spent $57M in 1996/1997 with an additional $11M in global change R&D. The Agricultural Research Service spent about $30M.

Recent Success

- Transgenic cotton resistant to the boll weevil comprised 2.5 million acres of 14 million acres planted in 1997. The following genetic traits have been engineered into plants that are now reaching the commercial market: insect, virus and herbicide resistance, specialty oils, slower ripening, and increased pectin.

Commercialization and Deployment

- Fractions of major crops (15–20% of soybean, cotton, corn) are being planted with transgenic seeds. Industrial funding is significant, with a seed market sales projection of $6 billion in 2005. Increased use of both conventional and hybrid plants (alfalfa, wood wastes, bagasse, willow), for energy production is nearing commercial reality. Forestry and agricultural crops bred for energy use are currently being evaluated. Major seed and agrichemical companies are involved in agricultural systems along with USDA and farmers. Forestry issues are being studied by DOE and USDA. A critical challenge to widespread deployment is economics. The freedom-to-farm capability may drive more development in plant/crop engineering.

Potential Benefits and Costs

Carbon Reductions

- Because of the strong interdependency of plant engineering technologies, biomass conversion technologies, and advanced agricultural systems, carbon reductions are incorporated into reductions reported for biomass conversion technologies and advanced agricultural systems pathways.

RD&D Expenditures

- Most R&D activities will require federal funds, especially initially until sufficient field data exists to verify technology.
- Current annual federal expenditures exceed $130M.
- Annual federal RD&D budget required for this pathway: to 2020, $155M/year; 2020 to 2030, $140M/year.

Market

- For energy production derived from biomass, the current 2–4 quads of energy produced could be impacted by a reasonable fraction with plants engineered for energy production uses (increase in lignin, decrease in alkali salts, etc.). This displaces currently heavy coal dependence. For biomass to bioproducts, the impact would be to reduce oil imports needed to synthesize organic chemicals. The realistic goal is a displacement of about 1 quad of energy embodied in petroleum feedstocks.

Nonenergy Benefits and Costs

- Development of crop plants with improved properties such as nutritional quality and extended storage life.

Risk Factors

Technical Risk

1 2 3 ④ 5 6 7 8 9 10

Low High

- Unproven technology with minimum of field data.

Commercial Risk

1 2 3 ④ 5 6 7 8 9 10

Low High

- Historic precedent in developing hybrid plants/trees has been very successful.
- Infrastructure for developing new techniques exists.

Ecological Risk

1 2 3 4 ⑤ 6 7 8 9 10

Low High

- May increase ecological advantages, but life-cycle impacts will need to be studied.

Human Health Risk

1 ② 3 4 5 6 7 8 9 10

Low High

- Plant research is generally very benign.

Economic Risk

1 2 3 ④ 5 6 7 8 9 10

Low High

- Public often perceives genetically engineered organisms as a threat. Alterations of pathways often can be defeated by the plants themselves.

Regulatory Risk

1 2 3 4 ⑤ 6 7 8 9 10

Low High

- Once new transgenic plants show value, these risks will diminish. The converse is true. If problems arise, regulation will remain.

Key Federal Actions

- Increased support to resource-intensive but beneficial efforts such as sequencing of plant genomes. Increased support to DOE's efforts in relating plant engineering to energy applications.