Agriculture & forestry for energy, chemicals, & materials
The road forward

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Abstract

The document calls for a national mobilization, by academe, government, and industry, to expeditiously move the United States economy from mainly petroleum-based industry to a more sustainable biological- and petroleum-based industry, calling for 100-plus billion gallons annually of transportation fuel and value-added chemicals and materials produced from biomass. The plant-based agricultural and forestry traditional commodity and new value-added markets can be simultaneously served without long-term negative impacts of one on the other, provided there is major biosource and bioprocess innovation for biobased industrial products. The benefits will be far-reaching, from self-sufficiency in transportation fuel to more sustainable industries, revitalization of rural economies, and improved balance of payments, to mitigation of environmental problems. Targets for biosources, processes, and costs are proposed as well as an integrated structure for success by 2025.

The urgent need for alternative sources to petroleum to secure our needs for energy, chemicals, and materials is broadly recognized by academe, government, industry, and the public. Success in addressing this need will benefit our physical, economic, and environmental future. Plant-based agriculture and forestry products are major alternative feedstock sources to petroleum. This document provides a strategic plan for agriculture and forestry to become major sources of energy, chemicals, and materials by 2025.[1] The plan:

- expands plant-based agriculture and forestry from commodity crops for traditional uses to value-added markets utilizing traditional and new biosources
- highlights benefits to security, economic growth, the environment, and sustainability
- maps the way to biobased energy, chemicals, and materials, with focused R&D on sources and conversion processes and scale-up for challenging but achievable outcomes
- provides structural and strategic guidance for expeditious implementation and goal attainment

These measures in energy, chemical, and materials production should be accompanied by conservation.

The plant-based agriculture and forestry roles are expanded from low-return commodity crops for food, feed, and fiber *(Figure 1, Quadrant I)* to value-added markets *(Quadrants II, III, IV)*.

QUADRANT I—COMMODITY CROPS AND TREES PROVIDE FOOD, FEED, AND FIBER FOR TRADITIONAL MARKETS.

Almost all of today's plant-based agriculture and forestry are in this quadrant, which continues to be challenged by excess production and low prices requiring subsidization of large-acreage field crops. Although there will be growth in domestic and export markets for food and fiber, we project that improved productivity from genetic and agronomic/silvicultural inputs will keep pace, without requirement for additional acreage.

QUADRANT II—TRADITIONAL CROPS (E.G., CORN, SUGARCANE, OIL SEEDS) FOR FIRST-GENERATION BIOBASED INDUSTRIAL PRODUCTS.

Existing examples are ethanol from corn and sugarcane, biodiesel from soybean and other oil crops, glucose from corn starch for polymer synthesis (e.g., polylactic acid, DuPont's Sorona®, and polyalkanoates) and for a variety of value-added and commodity chemicals. This quadrant uses existing crops and mainly existing processes for new markets and is aggressively expanding so that, in the long term, it may represent 15–25% of biosources for industrial products. The limited availability of additional suitable land to grow traditional crops beyond their continuing primary uses as food and feed, and their lower biofuel yields and less energy-efficient biofuel production compared to that projected for Quadrant III, will limit the biobased industrial product role of Quadrant II. However, Quadrant II is driving market acceptance and infrastructural development for Quadrant III.

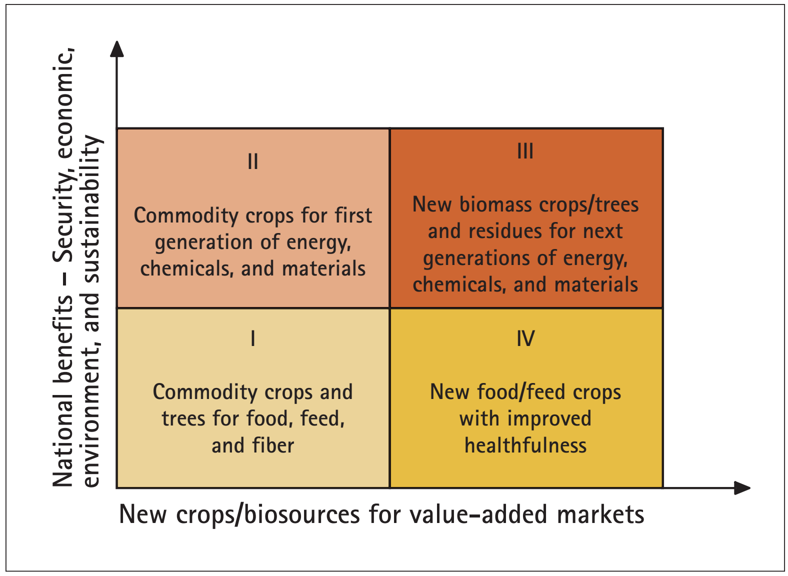

Figure 1. Plant-based agriculture and forestry biomass inputs to traditional and new, biobased product streams

QUADRANT III—NEW CROPS AND UNUSED RESIDUES FROM AGRICULTURE AND FORESTRY, PROJECTED TO BECOME THE MAJOR SOURCES (75–85%) OF BIOBASED INDUSTRIAL PRODUCTS. Of the estimated 1.3 billion tons of feasibly available biosources for biobased industrial products, about 1.2 billion tons (crop residues, perennial crops, agricultural wastes, forestry residues, and urban residues) are in this quadrant.[2] Greater use of dedicated biomass crops will improve further the robustness and reliability of this source. Characteristics of these dedicated perennial herbaceous crops (e.g., switchgrass, elephant grass, and *Miscanthus*) and woody species (e.g., willow and hybrid poplar) are fast growth, high biomass yields, and low input costs, with, in many cases, annual or less-frequent harvests. With new, underdevelopment processes, they will provide large quantities of cost-competitive biofuels and feedstocks for chemicals. New and traditional fiber crops will be utilized to produce fibers, blends, and composites with functional advantages for specific uses. The new crops will be improved both by plant breeding and by molecular technologies for biomass yield, water-use efficiency, ease in processing, and content of desired chemicals.

The ability to engineer the feedstock for end-use is inherent to biosources and not possible with fossil fuels. For the most part, Quadrant III crops will be grown on non-prime agricultural land, such as underutilized and abandoned farmland, and will not compete for prime agricultural land required by the commodity crops grown for the food and feed markets. These new crops may be region-specific. This quadrant is a new market for agriculture and forestry, but realization will require major innovation both in biosources and in processing.

QUADRANT IV—NEW CROPS FOR FOOD/FEED MARKETS WITH SAFER AND MORE-HEALTHFUL PRODUCTS. This quadrant is a major opportunity[3,4] for positive impact of agriculture on human health, with strong potential to contribute significantly to containment of escalating domestic healthcare costs for diet-based diseases such as obesity, diabetes, cardiovascular ailments, some cancers, and possibly some neurodegenerative diseases. Early examples include oil-crops with more healthful oils, functional foods, and Golden Rice for decreased blindness in developing countries. Acreage for Quadrant IV crops will come from decreased acreage for Quadrant I, with no requirement for net additional acreage for Quadrants I and IV.

The plant-based agricultural and forestry traditional commodity and new value-added markets can be simultaneously served without long-term negative impacts of one quadrant on any other, provided there are major innovations in biosources and bioprocessing for biobased industrial products. Many attendant benefits will accrue from these new crops and new markets, with major positive impacts on many of the most pressing challenges of the twenty-first century. It is emphasized that need for plant and animal agriculture and forestry to maintain global competitiveness over the long term in all four quadrants will require appropriate continuing support for fundamental research.[5]

Benefits

Transition from the inherently unsustainable dominant use of petroleum of the twentieth century to a more sustainable use of agricultural and forestry sources in combination with efficient use of declining petroleum reserves will address many of the most challenging problems of the twenty-first century. Improved sustainability is a built-in benefit of biobased products. Other benefits are listed below:

ECONOMIC SECURITY

- Substantially decrease or, in time, eliminate the need for the up to 60% of petroleum currently imported, especially from politically unstable regions
- Energy self-sufficiency would increase reliability of inputs for manufacturing, transportation, electricity, and heating

ECONOMIC STRENGTH

- Additional annual gross farm-gate revenue estimated at $40-plus billion
- Economic and job-creation benefits to rural communities[6]
- New rural investment of a minimum of $200 billion for biofuel-production plants as well as additional investment for chemical and material manufacturing
- Annual capital export reduced by savings in cost of petroleum imports, which were about $250–300 billion in 2006
- New value-added chemicals and materials for domestic and export sales
- Securing market leadership in agriculture, forestry, and industrial biotechnology

ENVIRONMENT AND HUMAN HEALTH

- Reduce substantially future increase in net greenhouse gas emissions
- Mitigate global climate change
- Reduce pollution of air, water, and soil from petroleum-combustion by-products
- Reduce human-health impacts of petroleum-combustion by-products

The way to biobased energy, chemicals, and materials

The major focus should be on Quadrant III, utilizing new crops and unused residues with new processes to produce biobased industrial products, with a projected 75–85% of the sources and products occurring in this quadrant. A smaller focus should be on Quadrant II, using traditional crops with objectives of optimization of crops and processes for improvement in yields, economics, and efficiency. Hybrid processing plants that, for example, use corn grain and stover may be important in bridging from Quadrant II to III. The plan outlined in this document exclusively addresses Quadrant III and focuses sequentially on liquid transportation fuels, organic chemicals, and organic materials.

LIQUID TRANSPORTATION FUELS—Immediately the US should establish a national plan to develop, validate, and build the agriculture/forestry production, processing, and distribution systems for 50 billion annual gallons of biofuel by 2025 (matching the goal of the 25x'25 Alliance) and 100-plus billion annual gallons by 2035. Genetic and management inputs should increase annual biomass yields to >10 dry tons per acre from non-prime agricultural land. The processing goal should be 100–200 gallons of ethanol or equivalent per dry ton of biomass. Achieving the above goals would enable 50–100 million acres to sustainably produce 100 billion gallons annually. The acreage need would be reduced by use of agricultural, forestry, and urban residues.

Other goals are a cost of <$1 per gallon of ethanol and a capital cost of approximately $2 per annual gallon capacity for processing plants. For comparison, Brazilian sugarcane ethanol is projected to produce 1,000–2,000 gallons per acre. Butanol, with its preferable biofuel characteristics of greater energy content and direct use in cars without engine modification and transportation via existing pipelines, may be an attractive alternative to ethanol as a transportation fuel. Yield of butanol from biomass on an energy-content basis will need to match that targeted for ethanol. Conversion of biomass to methane via anaerobic fermentation or gasification will provide another biobased transportation-fuel option.

In a parallel goal, by 2025, the US should develop high-oil-yield crops for manufacture of 2 billion gallons of biodiesel to substitute for 5% of the 40 billion gallons of petroleum-based diesel now consumed as transportation fuel. Plant oil content should be increased in vegetation as well as in seed; waste animal fats will also be used.

In the longer term, when fuel cells or another emerging technology replaces internal combustion engines, these biosources and the bioalcohol plants could provide alcohol for in-vehicle conversion to hydrogen, a more efficient transportation fuel.

Biosource Crops—These will be low-input perennial herbaceous or woody species. The species/variety will be dictated by regional growing conditions and may be grown as mixed or monocultures. Plants that use water more efficiently, e.g., C_4 species, may be preferred, especially in areas of limited rainfall. At most, a few crops/trees should be selected so as to enable major agronomic/sylviculture and genetic improvements, as has occurred so successfully in the major food/feed crops.

Goals should be sustainable long-term production consistent with soil and water conservation, improved conversion of solar energy to biomass, optimum water-use efficiency, low total production cost, ease of processing, and annual or less-frequent harvesting in a stable form for transportation and storage. At $40 per dry ton and a yield of 10 tons per acre, farmers would receive a gross return of $400 per acre; low production costs and use of non-prime agricultural lands should make the biomass crops competitive with high-input-cost annual grain crops. High biomass yield and low cost of production are key.

Processing—Two quite different processing approaches are being evaluated at the pilot-plant level for conversion of a variety of biosources to alcohol and other biofuels. Processes should aim to be as non-biomass-specific as possible so as to have the option to use a broad variety of biomass sources.

- The cellulosic and hemicellulosic process utilizes a pretreatment followed by enzymic hydrolysis to sugars that are fermented to ethanol. This process, already operating in a 1-million-annual-gallon pilot plant,[2] yields 70–80 gallons of ethanol per ton of biomass; substantial improvements in pretreatment and enzyme hydrolysis as well as in scale-up are needed.
- The physical method uses gasification to convert all of the carbon to syngas, then uses either a chemical or biological catalyst to produce ethanol. Yields of 100–200 gallons of ethanol per ton of biomass are reported. Further demonstration, including scale-up, is needed. Pyrolysis may be an alternative to gasification to produce oil from biomass. Other physical processes, such as hydrocracking vegetable oils, produce both gasoline and diesel. Advantages of physical processes such as gasification are the ability to use a broad spectrum of biomass and to utilize all of the biomass carbon—cellulosic, lipid, protein, and lignin.

The ultimate goal of 100-plus billion gallons of domestically grown and produced liquid transportation biofuel is so critical to the US's future that both the cellulosic-enzymic and the physical processes should be developed aggressively and in parallel. At least one economic high-yield process will enable attainment of this goal.

The transesterification process to produce biodiesel from plant and animal oils and fats is well established at commercial levels, with improvements such as continuous versus batch processes being evaluated, but there is no need for a new process as there is for ethanol. The total amount of oil-seed/fat available may limit production of large amounts of biodiesel.

Distribution and combustion engines—For ethanol to become a major biofuel, dedicated pipeline distribution will be needed, since production will occur in rural areas of biomass production, while most volume will be used elsewhere. Such dedicated pipelines will not be needed for butanol or biomethane. Auto manufacturers plan to produce E85 vehicles that will use 85% ethanol, which will be necessary for transportation-fuel ethanol to increase from the current 5-plus billion to 100-plus billion gallons.

ORGANIC CHEMICALS—Low-cost glucose or other plant chemicals that can be converted, probably by genetically modified microorganisms or enzymes, or chemical catalysts, to end-use chemicals or to monomers or other feedstocks such as ethylene, will be key to chemical production from biosources. Glucose, or equivalent cost of $0.04 per lb, should be the goal. Low-cost ethanol (<$1.00 per gallon as projected for transportation fuel) might be converted to competitively priced ethylene, a major feedstock from petroleum used by the chemical industry. The relative quantity of chemicals will be small (only 5–10%) compared to transportation fuels, but the opportunity for value-addition will be larger. Biorefining-type processes will be the norm in this area. Industry will probably drive this area, with inputs by academe and government.

ORGANIC MATERIALS—Most organic materials are biobased, e.g., cotton, silk, wool, linen, paper, cardboard, and lumber. However, there is further opportunity for new fiber crops (kenaf, milkweed, flax, etc.) with different fiber characteristics that will provide functional advantages, either as the fiber directly or as blends or composites in clothing, auto bodies, furniture, building materials, etc. Genetic modification of plants could improve fiber yields and/or produce functionally improved fibers or, in time, even blends. Combinations of public-sector research and development with industries will be needed in this area, where end-use evaluation and acceptance will be key.

The structure

The urgent need to replace much of US imported petroleum used for energy, chemicals, and materials requires a structure for expeditious success. Government, academe, and industry will need to play major roles. In some areas (e.g., energy and transportation fuels), government in partnership with industry and academe should provide leadership, including major investment in R&D and demonstration plants. Government might have a single responsible entity for the energy/transportation fuels area so as to focus, integrate, and optimize the relevant activities of the US Departments of Commerce, Defense, Energy, and Transportation, Environmental Protection Agency, National Science Foundation, and USDA, with those of academe and industry. The effort should integrate from biosource through process to commercialization, with the commercial products as the focal point. All tools should be used: biological, chemical, and physical. Interdisciplinary[7] and interorganizational teams of government, industry, and academic researchers should be used with mission-oriented focus on the goals.

The recognition of national economic benefits and need for expeditious accomplishment of these challenging goals justifies a substantial public investment for research, development, and early commercialization. The equivalent of only 2.5–3 cents per gallon of the current 180 billion gallons of liquid fuel consumed nationally would equal $5 billion annually. Such an amount would attract innovative, entrepreneurial, and management talent to achieve the above goals of 50 billion gallons of biofuels by 2025 and 100-plus billion by 2035. Such an investment is probably less than 2% of the cost of the imported petroleum during the next 20 years and provides a solution for this continuing and growing cost and major export of capital.

Government should establish policy to encourage farmers to grow biomass crops and woody species to assure risk capital investment by the private sector, including farmers, in start-up and processing facilities. Also, government should have policy to facilitate market entry, such as biofuels mandates and other market-introduction incentives.

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REFERENCES

1. The US National Agricultural Biotechnology Council's 1998 *Vision for Agricultural Research and Development in the 21st Century* identified the future role of agriculture and forestry in meeting energy, chemical, and material needs in addition to their traditional, and continuing, roles in providing food, feed, and fiber. The National Research Council's 2000 *Report on Biobased Industrial Products* set targets of 50% of transportation fuels, 90% of organic chemicals, and 99% of organic materials as originating from agricultural and forestry crops and residues during this century.

More recently, the US energy coalition 25x'25 produced its vision: "By 2025 America's farms, forests, and ranches will provide 25% of the total energy consumed in the United States while continuing to produce safe, abundant, and affordable food, feed, and fiber." The NABC 2007 meeting, *Agricultural Biofuels: Technology, Sustainability and Profitability* (held May 22–24 at South Dakota State University, Brookings, South Dakota) further defined opportunity and issues.

2. 2005 USDA and DOE Report: *Biomass Feedstocks for a Bioenergy & Bioproducts Industry: Technical Feasibility of a Billion-Ton Annual Supply.* The annual Canadian biomass is estimated at 0.3–0.6 billion tons (Ralevic *et al*, BioCap Canada Foundation/Queens University); the first cellulosic-ethanol pilot plant was established in Canada.

3. NABC (2002) *Report 14 on Foods for Health: Integrating Agriculture, Medicine and Food for Future Health.* Ithaca, NY: National Agriculture Biotechnology Council.

4. NABC plans to address this opportunity in a future report.

5. As an example, 2004 Report of the Research, Education, and Economics Task Force of the USDA: *National Institute for Food and Agriculture—A Proposal.*

6. Testimony by Ron Miller of the Renewable Fuels Association on January 10, 2007, to the US Senate Agriculture, Nutrition, and Forestry Committee states that the 5.3 billion gallons of ethanol produced in 2006 created 160,000 jobs in all sectors of the economy, increased household income by $6.7 billion, and reduced oil inputs by 170 million barrels, valued at $1.26 billion.

7. Koonin S. *Science* 311:435 (2006). With reference to transportation fuels, Koonin stated, "This is a multidisciplinary task in which biologists, agronomists, chemical engineers, fuel specialists, and social scientists must work to integrate and optimize several currently disjoint activities."

This article has been cited by:

1. Nicola M. Reid, Tracey H. Bowers, Gareth Lloyd-Jones. 2008. Bacterial community composition of a wastewater treatment system reliant on N2 fixation. *Applied Microbiology and Biotechnology* **79**:2, 285-292. [CrossRef]