THE TECHNOLOGY ROADMAP FOR PLANT/CROP-BASED RENEWABLE RESOURCES 2020

RESEARCH PRIORITIES FOR FULFILLING A VISION TO ENHANCE U.S. ECONOMIC SECURITY THROUGH RENEWABLE PLANT/CROP-BASED RESOURCE USE

RENEWABLES VISION 2020
EXECUTIVE STEERING GROUP

ABOUT THIS ROADMAP

A broad range of private and public sector groups contributed to production of this document. This "roadmap" sets forth research priorities for fulfilling goals previously identified in the *Plant/Crop-Based Renewable Resources 2020* vision document. The vision was also the product of input from representatives from a wide range of industries. The effort started under the leadership of the National Corn Growers Association in 1996. Many other organizations subsequently joined the collaboration and signed the Vision Compact at the 1998 Commodity Classic Convention. The U.S. Department of Agriculture and the U.S. Department of Energy are supportive of this multi-industry effort.

Coordination and analysis of the inputs, organization of the workshops, and preparation of this roadmap document were carried out by Inverizon International Inc. on behalf of the Executive Steering Group (Appendix 1). The recent workshops were hosted by Dow AgroSciences LLC and facilitated by Energetics Inc. (Appendices 4 and 5). Direction for the continuing Vision activities is provided by the Executive Steering Group.

THE TECHNOLOGY ROADMAP FOR PLANT/CROP-BASED RENEWABLE RESOURCES 2020

CONTENTS

EXECUTIVE SUMMARY

The technological success of the petrochemical industry is a tough act to follow. Industry and consumers have come to expect an unending stream of new and improved plastics and other materials to be provided in unlimited quantities. The fossil fuels from which the industry works, however, are finite—and often imported—so we need an additional source of durable, high-performance materials. Renewable materials from home-grown crops, trees, and agricultural wastes can provide many of the same chemical building blocks—plus others that petrochemicals cannot.

Despite the expertise and ingenuity of U.S. industry and tremendous productivity of U.S. agriculture and forestry, plant-based sources cannot automatically shoulder a major share of our chemical feedstock demand. Today, U.S. industry only makes minor portions of some classes of chemical products from plant-derived materials. Important scientific and commercial development breakthroughs are needed. Petrochemicals, agriculture, forestry, and other industries—as well as government—must make major coordinated efforts to most effectively increase the use of plant-derived chemicals. This document evaluates research priorities for surmounting these technological challenges and sets out a technology roadmap for increasing the use of plant-derived materials for chemical building blocks.

Plant/Crop-Based Renewable Resources 2020: A Vision to Enhance U.S. Economic Security Through Renewable Plant/Crop-Based Resource Use was published in January 1998 (see Directions, Goals, and Targets on page 10 and back cover for print and electronic availability information). Among other things the vision document set a target of using plant-derived materials to meet 10% of chemical feedstock demand by 2020—a fivefold increase. The vision document generated widespread support and led to the formation of the multi-industry Executive Steering Group (see Appendix 1), which authored this roadmap for meeting that target.

Several industries will need to contribute to successfully achieve this renewable resources vision. The Executive Steering Group therefore turned to a broad range of disciplines, including crop production, forestry, genomics, chemical processing, fermentation, industrial enzymes, materials science, biotechnology, plant physiology, and product manufacturing. The steering group sought input on key barriers, research goals, and interactions among related areas from more than 120 scientific experts and marketing professionals. The workshops, personal interviews, and feedback sessions provided the base for the research and development priorities set by this 2020 vision roadmap.

Currently, with the exception of lumber for wood products, trees for pulp and paper products, and cotton for garments, a very low volume of renewable resources is used to manufacture consumer goods. Key opportunities to increase the use of renewable resources can be grouped into four main areas:

1. Basic plant science — e.g., altering plant metabolic pathways to produce certain carbon molecules with valuable functional properties
2. Production — e.g., lowering unit production costs for consistent-quality raw materials
3. Processing — e.g., more economically separating diverse materials
4. Utilization — e.g., improving material performance through better understanding structure-function relationships for plant constituents.

Within each of these opportunity areas, the Steering Group selected specific goals and priorities for focused attention. Research areas with high-priority rankings include:

- Engineered metabolic pathways to enhance the yield of specific molecules
- Design, production, and handling of dedicated crops
- New separations technologies to better handle heterogeneous plant components
- Advanced (bio)catalysts for monomeric and polymeric conversions
- Elucidation of structure-function relationships for plant constituents
- Rural development to support production, marketing, and utilization of plants.

Balanced and coordinated advances within these research areas will pave the way to meeting the 2020 vision target of a fivefold increase in renewable resource use. Figures 11A to 11D detail goals for these priority research areas.

Cost of materials surfaced many times as a major issue during the steering group’s investigations. Lowering unit costs is critical for sustainable economic growth. Because the best products will be those with the greatest difference between value created and cost to produce, it is very important to understand the true costs and values of alternative chemical feedstocks. Clearly defining market value segments for different product types is also very valuable, as it allows identification of high-value uses for plant-derived chemicals and materials.

Improving product performance is also a key to success. Plant-based materials are now often viewed as inferior, especially when compared to highly evolved materials designed for specific uses. It is true that today’s renewable resource chemicals do not compete well in certain areas.

Starch- and plant-protein-based glues, for example, do not have the strength of petrochemical-derived superglues.

On the other hand, plant-derived chemicals have unique advantages for other uses. Recombinant proteins, for example, can be designed and produced in plants to provide tissue glues analogous to the fibrinogen that naturally forms around a flesh wound. Emerging technologies offer dramatic new capabilities to alter plant metabolic pathways, opening up unprecedented opportunities to produce high-value chemicals from renewable resources.

No one industry alone can provide the basis for major gains in renewable resource chemical use. Although exciting research opportunities exist in areas such as biopolymers, stereospecific molecules, new enzymes, novel materials, and transgenic design, progress in isolated technical areas will not be sufficient. We must take a broad view of future consumer needs and emphasize interrelated research projects conducted in a parallel and coordinated manner. Reaching the vision target for the use of renewable resources requires focus in direction, integration of disciplines, application of the best scientific minds, utilization of the most advanced technologies, and continuing discussions at the highest intellectual levels.

The long-term well-being of the nation and maintenance of a sustainable leadership position in agriculture, forestry, and manufacturing, clearly depend on current and near-term support of multidisciplinary research for the development of a reliable renewable resource base. This document sets a roadmap and priorities for that research.

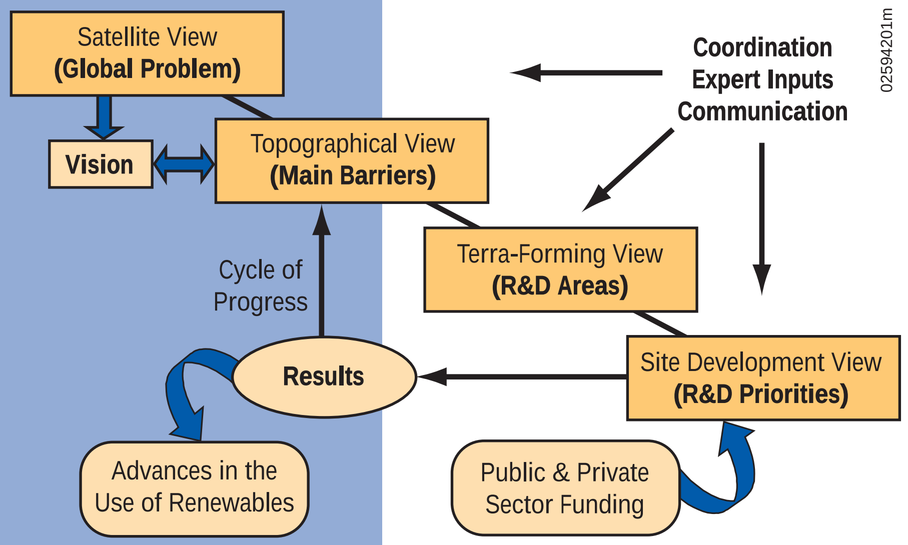
INTRODUCTION

This document provides a roadmap for advancing the *Plant/Crop-Based Renewable Resources 2020* vision. It was written to:

- Support the vision direction
- Identify the major barriers to progress
- Focus attention on priority research areas.

The process used to reach this defining point included the coordination of concept development, collection of expert testimony, organization of multi-disciplinary workshops, listening sessions, priority ranking exercises, and team-based action planning. A unique aspect of the process has been the breadth of professional experts involved, from growers to chemists, to biotechnologists, to petroleum-derived material scientists, to marketers of renewable and non-renewable products. Further details are given in the appendices.

Figure 1. The approach taken for the roadmap was to sharpen the focus until priority areas for action were defined.



The approach taken for this roadmap was to use the Renewable Resources 2020 vision high level view as a starting point and work through incremental layers of focus (Fig. 1) until results-oriented priorities were defined. These priorities are the areas where research will provide maximum leverage for sustainable growth in the use of renewables.

The breadth of experts in use of bio-based feedstocks in chemical manufacturing involved in developing this roadmap reflects the extent of the science required to understand and address the issues. However, there are three main industries today (Fig. 2) that are central to the issues, each of which employs several diverse sciences: agriculture, forestry, and the petrochemical industry.

AGRICULTURE/FORESTRY

Agriculture is taken in a broad sense to include crop production, range, and pasture lands. The output materials from these land areas, and forestry, are "bio-based" and are renewable through primary production from solar energy, atmospheric carbon dioxide, and terrestrial nutrients. The United States has significant resources in good soils, extensive natural water distribution, and a technology base that allows both resource protection and resource use to generate a wealth of renewable production every year.

Crops are produced at high levels of efficiency on more than 400 million acres in the United States, with corn, wheat, and soybeans accounting for the majority on both area and volume bases. Basic agricultural production provides 22 million jobs in output processing, handling, and selling feed, food, and fiber. It generates around $1 trillion in economic activity and makes up over 15% of GDP. Everyone in the United States benefits through a safe and secure food supply, more than adequate levels of nutrition, and a shopping bill that is less than 10% of average disposable income. Although there are fewer than 2 million farmers, the quantity and quality of crop production continues to improve due to the efficient utilization of inputs and the effective application of new technologies. For example, in 1998, there were more than 50 million acres of major crops that had genetically engineered varieties or hybrids planted (Appendix 2).

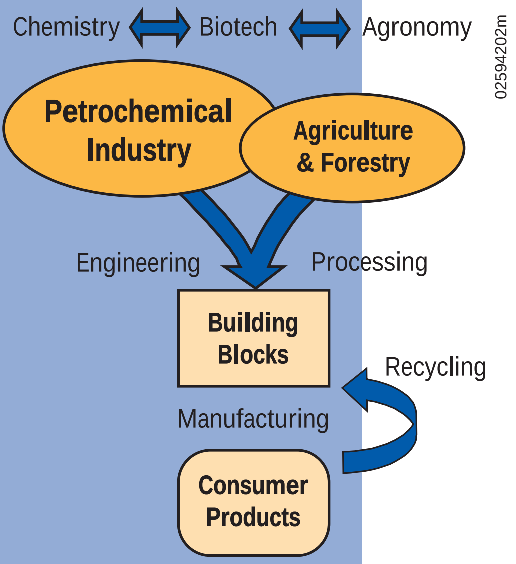


Figure 2. The majority of consumer goods are currently made from hydrocarbons produced by the petrochemical industry. Forestry contributes a significant portion of materials via lumber and pulp, while agriculture is primarily focused on feed and food provision. Scientific developments will allow changes in the relative contributions of these two industries and the chemical industry, leading to increased use of renewable inputs.

Pastures and range cover about 800 million acres in the United States and are typically used for grazing cattle, sheep, or other ruminants. In many areas, the intensity of production is limited by relatively low annual rainfall. However, in recent years there have been genetic improvements in the varieties grown allowing higher yields under restrictive conditions.

Forestry occupies more than 650 million acres in the United States, employs 1.4 million people, and generates $200 million per year in products. Wood itself is highly versatile and has many uses from furniture to energy-efficient building materials. In addition, U.S. forestry is the source of about 100 million tons/year of paper, paperboard, and pulp. Over the past 10 years the paper segment has increased faster than the lumber use segment (Fig. 3). Wood and paper products have the highest recycle rate with some 40 million tons of paper per year being reused.

The U.S. forestry industry has already developed its "Agenda 2020" vision and several associated roadmaps. Among other things, that vision calls for additional research to improve sustainable forest productivity by improving management practices, improving energy performance, and enhancing recycling. This renewable resources roadmap covers agriculture as well as forestry and seeks to complement the forestry Agenda 2020 effort, focusing in particular on use of both agriculture and forestry materials for chemical production.

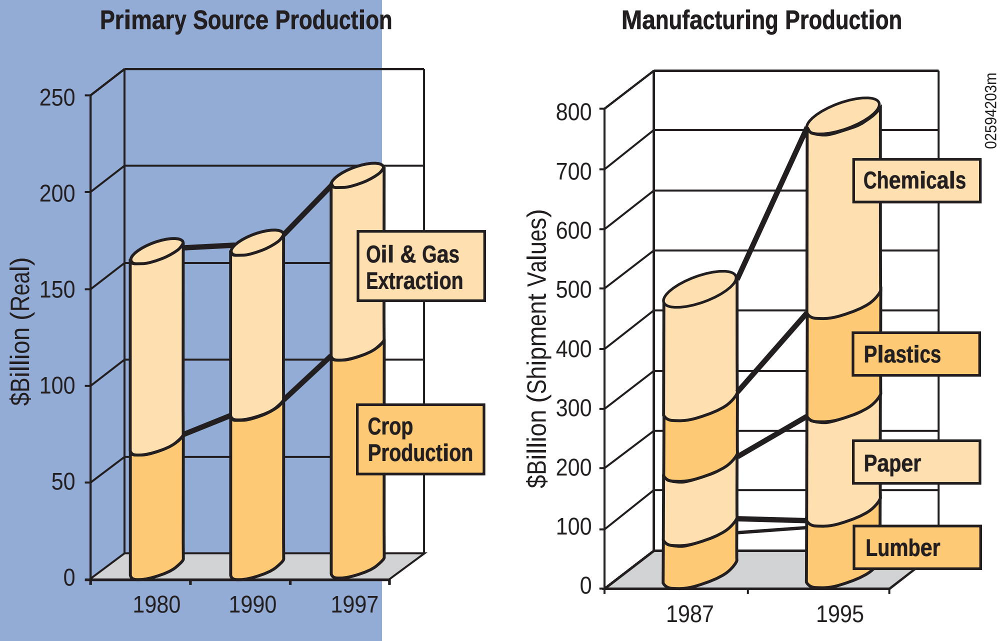
Agriculture and forestry are poised on the brink of a quantum leap forward through the further application of exciting new tools such as genomics and transgenic plants. In the near future, it will be possible to produce a higher quantity of improved quality crops than even imagined just a few years ago. In addition to feed and food, it will be possible to provide raw materials for industrial uses. For example, cotton fibers, wood ligno-celluloses, corn carbohydrates, soybean oils, and other plant constituents will be altered via designed changes in metabolic pathways. Moreover, with the insertion of specific enzyme-coding genes, it will be possible to create completely novel polymers in plants at volumes sufficient for the economic production of new consumer goods.

The rate of application of technological advances to plants and crops in the United States will play a major role in maintaining a sustainable leadership position in agriculture, forestry, and manufacturing. The long-term well-being of the nation clearly depends on near-term support of the research necessary for developing a renewable resource base. The justification for such an intense focus and the priorities for immediate research are contained in this roadmap for plant/crop-based renewable resources.

PETROCHEMICALS

Chemistry, engineering, physics, and geology are just a few of the sciences that have been applied in the petrochemical industry to impact our lives in ways that were difficult to imagine just 50 years ago. This industry has been very successful in creating a range of products: from high performance jet fuel to basic building blocks and petro-polymers such as polypropylene, styrene, acrylonitrile, polyvinylidene chloride, and polycarbonate.

Figure 3. Comparison of change in economic contribution (current $) for selected segments of the U.S. economy. On the production side, crop production (excluding animal production) has increased significantly more than oil and gas extraction. On the manufacturing side, wood and lumber products have shown relatively flat growth, although paper has increased. The increase in plastics and chemicals reflects our current reliance on hydrocarbon-based products.



Source: DOE-EIA. USDA

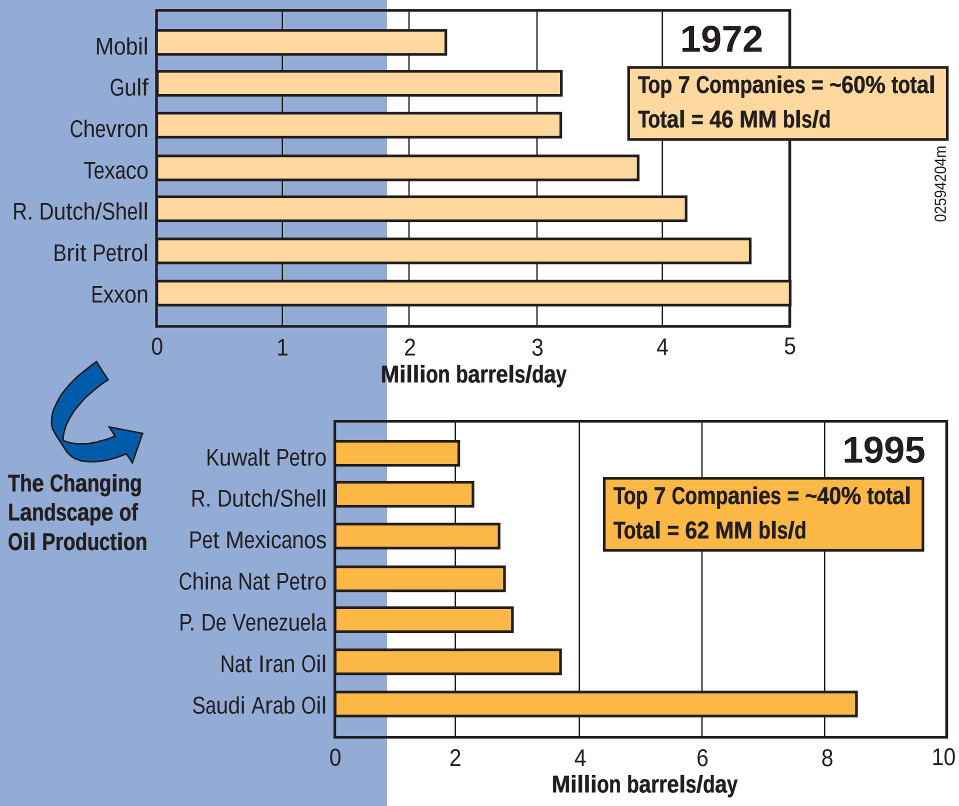
The petrochemical industry is capital intensive and has built a considerable infrastructure to handle and process fossil fuels. The United States uses approximately 13.9 million barrels per day of hydrocarbon inputs, mostly for various types of fuel.

About 2.6 million barrels per day petroleum equivalent are used for the creation of chemicals and industrial building blocks. (See details in Appendix 3.)

The production of industrial chemicals and plastics has increased considerably in recent years (Fig. 3). The plastics industry alone directly employs 1.2 million people, and supports 20,000 facilities that produce plastic goods for sale. Without the billions of dollars on research and development in plastics we would be without many of the now commonly accepted objects that we tend to take for granted. Without a renewable source of building blocks for plastic goods, a time will come when petrochemical-derived plastic becomes too expensive for widespread consumptive use at the levels enjoyed today.

On the one hand, some estimates suggest that there are a trillion barrels of oil yet to be extracted and with current prices close to $10/barrel, why should anyone be concerned? There are many estimates, however, as to the actual quantity of reserves, and many assumptions for and against various figures. The world of crude oil production is also changing rapidly (Fig. 4) and additional uncertainty is expected.

Figure 4. Top companies in crude oil production in 1972 versus 1995, in million barrels per day. Original data taken from DOE-Energy Information Administration.



The Changing Landscape of Oil Production

On the other hand, the fact that fossil fuel resources are finite cannot be disputed. It may be more important to consider the potential for price sensitivity as supply peaks, rather than to debate a theoretical time point when the oil will run out. Any finite source follows a bell-shaped curve in supply, with the price being a reverse image of the "bell." Many can remember the "oil crisis" of the 1970's, but we recovered from that warning shot. Recently, several independent sources indicate that the top of the "bell" in terms of incremental production increase will be reached within 20 years (Appendix 3).

In any case, we should keep in mind that the United States is already reliant on crude oil imports. We now import about 50% of our oil (Appendix 3). If imports of crude oil were to cease today, the proven fossil fuel reserves in North America would be sufficient for 14 years of consumption at current rates. With existing levels of import and no increase in use, the indigenous proven reserves would last about 28 years. Of course, there will be new and improved extraction technologies, such as horizontal drilling and nuclear magnetic resonance borehole imaging. Yet, even with a few more years added to the extractable supply, the margin of error here is very slim.

Supplementing the use of petrochemicals with renewable resources in more than minor volumes must start soon. The research to accomplish that must start immediately.

Irrespective of the debate on the timing of a supply-side decline in fossil fuels, demand continues as the population expands and standards of living in the emerging nations increase. It is projected that long before renewable resources become a replacement for fossil fuels, they will become necessary as a supplement. Thus, for any one of several reasons, it is important that the United States devotes attention to the development of a renewable resource base for industrial raw materials.

DIRECTION, GOALS, AND TARGETS

The "Vision" is to provide continued economic growth, healthy standards of living, and strong national security through the development of plant/crop-based renewable resources that are a viable alternative to the current dependence on nonrenewable, diminishing fossil resources.

In the "Plant/Crop-Based Renewable Resources 2000" vision publication—see back cover of this document for ordering information), the directional targets for success included "achieve at least 10% of basic chemical building blocks arising from plant-derived renewables by 2020, with development concepts in place by then to achieve a further increase to 50% by 2050."

Also note that total resource consumption is increasing rapidly—certainly in global terms but also within the United States. Because the 10% goal by 2020 is relative to total production—a fourfold to fivefold increase relative to consumption levels today—it will likely be much greater in absolute terms. If consumption levels themselves double by 2020, then the absolute volume target for renewables will also double (Fig. 5).

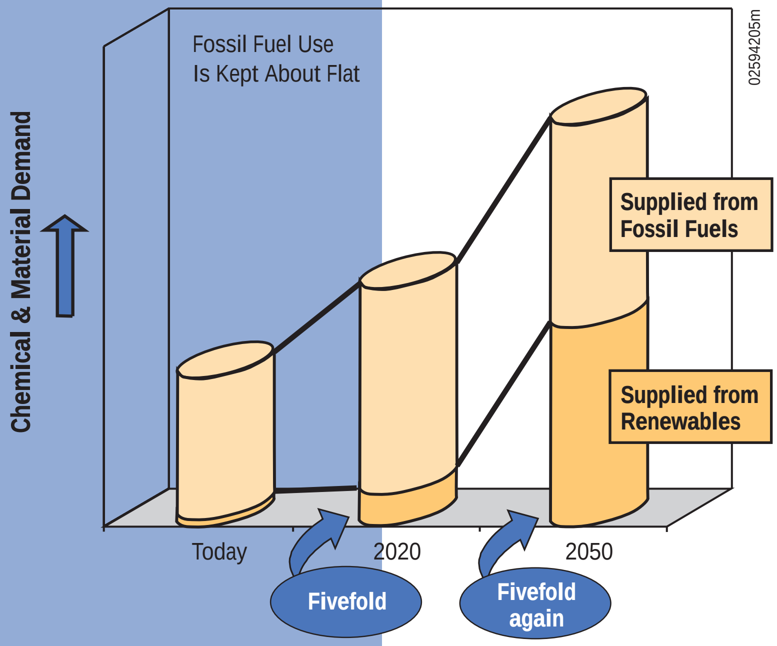


Figure 5. Directional representation of chemical and material needs and the portion fulfilled by plant/crop-based renewable resources. Note that the vision for a fivefold increase by 2020 is expected to set the stage for another fivefold increase by 2050, and that at that point, renewable resource inputs begin to match the use of fossil fuels to meet the projected growth in demand for consumer goods.

In other words, it is not expected that renewable resources will completely replace hydrocarbon sources within a static demand environment. It is expected that as demand for consumable goods increases, renewables sources will have to be developed to meet an ever-increasing portion of the incremental demand. Over a 20-30 year timeframe, the target level for renewables should stabilize the use of fossil fuels at approximately the levels consumed today. This concept has major implications in that:

a) Renewables are not competing directly with nonrenewables—this is not a competitive replacement strategy.

b) Both renewable resources and nonrenewable resources will be needed to meet demands in the 20-year timeframe.

Beyond the 30-year timeframe, it may be necessary to rely more on renewable resources as fossil fuels become expensive and limiting. Fortunately, the support and research required to meet the near-term targets is entirely consistent with requirements for longer-term progress. These are directional targets and state clearly that the challenge ahead is significant, that actions are required today, and that we must begin building the road that leads to increased utilization of renewable resources.

In addition to an operational renewable resource base, certain other targets have been viewed as being important; these include:

- Establishing systems that integrate the supply, manufacturing, and distribution activities through supporting infrastructure to enhance economic viability
- Improving the understanding of plant metabolism, via functional genomics, to optimize the design or use for specific value-added processes; in addition to the use of current inherent components, exploring novel polymer production and use
- Ensuring the development of new processes with more than 95% efficiency, plus co-processes that use all by-products to eliminate waste stream issues; making sure the new platform is consistent with goals for particular environmental circumstances
- Crosschecking that specific goals and research targets are consistent with the goals for renewable fuels/energy needs
- Developing approaches to ensure a consistency in supply whether in production or distribution; keeping factors such as price/volume, performance, geographical location, quality, etc. within defined limits on an annual production basis; developing standards for these factors
- Building further collaborative partnerships to improve vertical integration; supporting success via enhanced rural development.

Success in achieving the vision target of a fivefold increase in renewable resource use by 2020 will require that the majority of the goals outlined in this roadmap are achieved. Genetically modifying plants to produce specific metabolic products and developing complementary chemical modifications are expected to allow success with the fivefold target. These advances will also set the stage for further achievements beyond 2020.

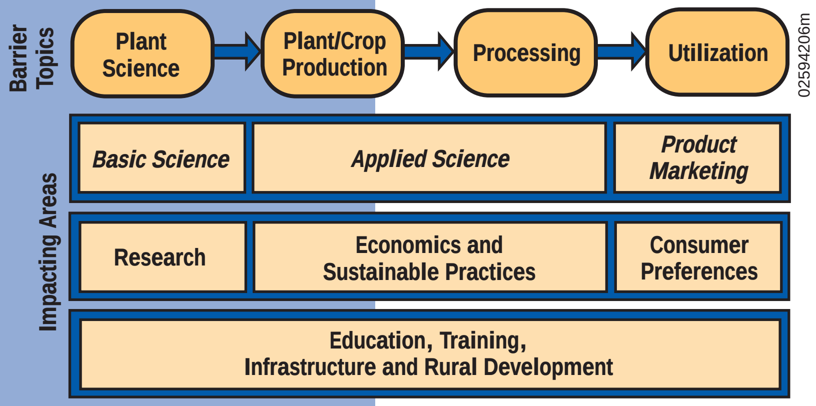
TECHNICAL AND MARKET BARRIERS

Given that the accepted global view is that there must eventually be an increase in the use of renewable resources, it is useful to sharpen the focus to areas where progress is slow or limiting. Situational analysis of the manufacture of consumer goods, and the current relatively low use of renewable inputs, indicates that significant barriers (Fig. 6) exist in several key areas.

In addition to each of the individual barrier areas, an additional complication arises due to the large degree of interaction among the areas shown in Figure 6. For example, if we assume that altering the biological composition of a particular source crop would be beneficial, then this may have consequences on the process required, the type and performance of materials to be utilized, the infrastructure required to support this use, and the scientific education of students who may be subsequently employed within such a system. The dynamics are such that a change in one part of the "barrier topography" has a considerable ripple effect throughout the system.

The degree of interactive impact is an issue to manage, rather than an absolute restriction. The petrochemical industry has effectively managed such issues over the years by funding the required research and adapting to each advance. For example, crude oil is actually heterogeneous and comes in source-dependent light and heavy grades which impacts refining fractions. Advances in catalysis and polymer chemistry, as well as in refining, have played a major role in the current status of plastic material utilization. Together these factors have interacted positively, and have positively impacted the overall national industrial economy.

Figure 6. The identified barriers can be segmented into four main topic areas covering basic plant science through to utilization. The main disciplines and activities affecting the barriers are also shown.



For each of the four main barrier topic areas, current technical and market barriers to the expanded use of plant-derived renewable resources were determined from various inputs, including two workshops with multidisciplinary experts. The major barrier topics are outlined in Figure 7 and the major barriers are discussed below.

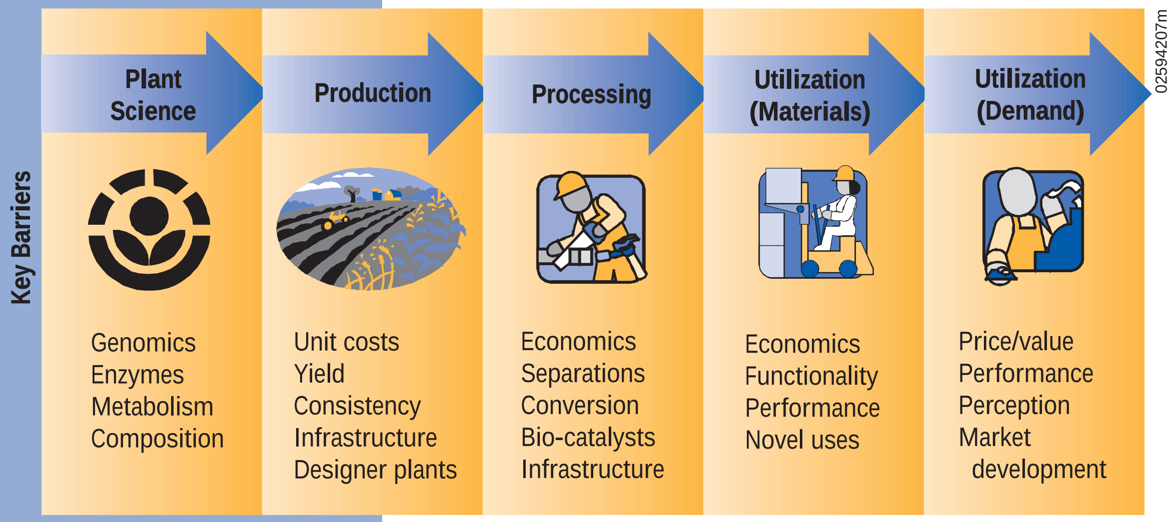


Figure 7. Top ranked major barriers identified within each barrier topic grouping within the overall system for conversion of renewable resources into consumer goods. "Utilization" has been subdivided to draw a distinction between technical/ materials driven barriers, and market/demand driven barriers.

Utilization (Materials): Economics: Unit Costs

An imposing barrier to entry for current plant-derived materials, and the issue most often debated, is the competitive cost situation. In many cases, the current cost of using plant-based materials is viewed as being relatively high, and not competitive with hydrocarbon-based processes. However, the cost-competitive situation contains several highly complex interactions among the key factors: value of product, cost of materials, volume of throughput, degree of processing required, and performance of the building blocks used. Thus, strategies for the future will not be successful if based on cost reduction alone.

The most important economic driver is not cost per se, but rather the differential between price obtained and cost to manufacture (Fig 8). Price obtained is a function of factors such as product utility, performance, and consumer preference and demand. Cost to manufacture is a function of factors such as raw material cost, supply consistency, process required, waste handling cost, and investment.

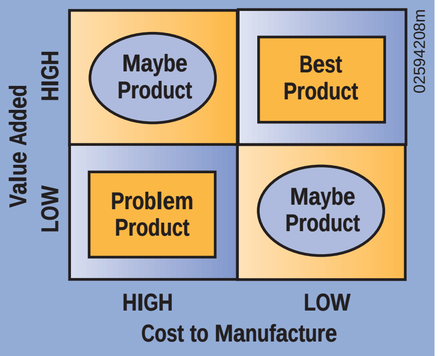


Figure 8. Segment chart indicating the viable product options relative to cost of manufacture (cost of materials and/or processing) and value added features (price).

In cases where plant-derived material is processed into molecular constituents that are to be utilized in a conventional hydrocarbon processing system, the cost of the component parts will be critical—for example, when grains are processed into C_6 skeletons. This approach fits with the lower cost driver that exists in competitive commodity industries, and applies to a segment of the potential uses for plant-derived materials. However, in the longer term, using "cost only" comparison is problematic due to the factors discussed here and an inability to accurately predict the future cost of fossil fuels.

Performance and processing efficiency is relatively high for hydrocarbons in the current world of consumer goods. However, this is not an inherent characteristic of fossil fuels. The industry has had a hundred years of research, three generations of trained scientists, and millions of government dollars in support, to reach the current level of performance.

Plant-based materials are often viewed as being of inferior performance when compared to highly researched materials that have been designed specifically for effective manufacture from hydrocarbon sources. Exploring how plant-derived materials fit into this situation is only one approach, and the current volume use in this way is limited. Other complementary approaches are related to technical developments in understanding the performance of plant-derived materials, and/or genetically altering plants to provide constituents with the desired functionality.

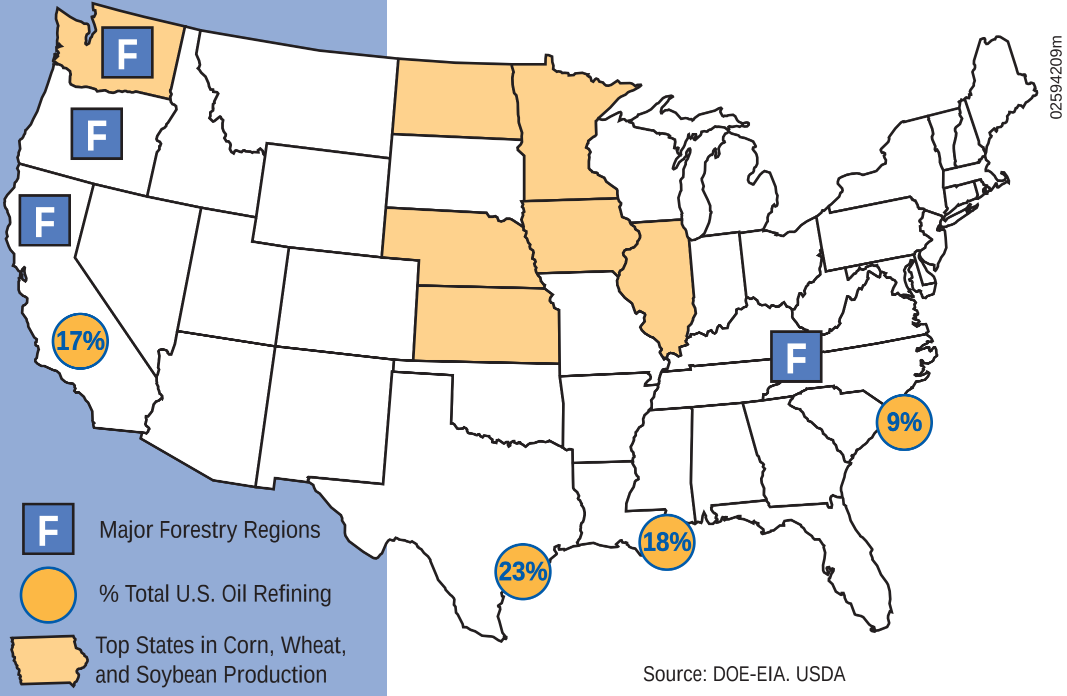
Utilization (Demand): Cost of Market Development

A key barrier to the use of plant-derived materials is the high cost of developing the market, even when unique new products have been created. As in many emerging product markets, research in new products begins in small companies that are under-capitalized and lack the resources needed to go beyond the laboratory scale. The success rate for commercialization is low and promising products often languish through lack of volume generation. A major effort is needed to examine improved approaches for product development, support mechanisms, and market development in relation to products that utilize renewable resources.

The entrenchment of standards based on petrochemical products, and the lack of standards derived from bio-based products, creates another barrier to successful competition with petrochemical products, particularly in areas in which direct competition occurs.

Processing: Infrastructure: Distribution

Over many years, the petrochemical industry has built up an effective infrastructure for processing and distributing hydrocarbon-based products. Due to reliance on imported crude oil, much of the U.S. infrastructure is geographically located around the coastline (Fig. 9). Thus, many current processing facilities are not well situated for the collection of large volumes of plant-derived material. Where plant materials are processed in lumber mills, oil crushers, or corn wet mills, these are situated adjacent to areas of supply. A transition to more plant-derived materials will require further integration of supply and processing/ manufacturing. An example of the new infrastructure is the manufacturing facility being built in Nebraska, by the Cargill-Dow joint venture, to process corn starch into the biodegradable polymer, polylactic acid. Strategies and actions should be explored to determine the priorities and focus for rural development that would best encourage the increasing use of renewable resources.



Source: DOE-EIA. USDA

Figure 9. U.S. distribution of oil refining compared to crop/forest production.

Production: Yield, Consistency, and Infrastructure

Since large volumes of plant-derived materials are not used today, outside of the lumber and pulp industries, the concerns over supply and distribution are future potential issues rather than existing facts. Nevertheless, these are important and must be addressed as part of the progress toward the goals for renewables.

Consistency of supply is an unknown in terms of quantity and quality. When plant-derived materials are processed to simple carbon molecules, the consistency may be less critical. For example, fermentation today can handle seasonal differences in components, and commodity grains can generally be used. However, when specific components (e.g. polymers) are designed and methods developed to extract those directly, then the quality and quantity will become important.

In some ways, the uncertainty over supply consistency is really a form of risk management. In the future, both petrochemical supply and renewable supply will carry increased risk. For petrochemicals, further supply uncertainty may arise from political changes in other world areas. For plant-derived materials, weather may be an uncertain factor locally, while specialty plants with less commodity type production may result in more trading uncertainty. These are not necessarily "killer" issues but will require considerable attention to ensure economic viability within the evolving infrastructure.

There is another aspect of uncertainty that surfaces as a potential threat to consistent supply and that is the "food versus industrial" use of crops in the future. One side of the debate is the shortage of supply theory. "How can agriculture feed a burgeoning population and supply raw materials for consumer goods?" "Won't crops used for feed-stocks be redirected to the food supply in times of world famine or drought?" Good questions. However, the implied assumption is that we have a choice. The demand side is growing for both food and raw materials and even if we do not develop renewable industrial resources then food itself will still run out at some point in time. A solution to the food problem may also be a solution to the raw material problem. Thus it is imperative that new technologies, such as biotechnology, be applied to the supply side to maintain the types of productivity increases that agriculture has achieved previously.

Utilization (Demand): Perception

Plant-derived materials carry an inferior image: possibly based on the use of materials prior to the "petrochemical age." Of course, for some manufacturers the performance is inferior because it has never been optimized—this tends to reinforce the inferior perception in general.

Despite extensive publicity about environmental issues, consumer demand for plant-based products is not sufficient to create a market pull for technology development. Despite a desire for more environmentally friendly products, the average U.S. consumer does not typically pay extra for "green" products. Thus, current progress in renewables is based primarily on technology push. Increased market pull would create more powerful incentives for companies to invest in plant-based building blocks, especially when industry acceptance is lagging due to entrenched petrochemical products.

Without impetus for change, there is not much change. Thus, with no financial incentives one way or another, the status quo is likely to be maintained.

Processing: Separations

The lack of techniques for separating plant components constitutes a critical barrier to the use of plants for industrial purposes. Trees have high levels of complex materials such as lignocellulose. These materials make for good strength, but are difficult to separate into useful molecular components. The harvested portion of most crops is the seed, which contains carbohydrate, protein, oil, and hundreds of different components. Thus, conventional grains are well designed to support germination and growth but are difficult to manage as sources of individual materials. Processes have developed to remove crude fractions, such as oil crushing or sugar extraction, but it remains difficult to isolate particular protein types or pure carbon skeletons.

The high cost and technical difficulty of dealing with very dilute aqueous streams is a problem that must be addressed before economic plant-based processes can be established. Processing systems that integrate the reaction with product separations (e.g. catalytic distillation) might be a viable solution, but such systems are limited and have not been explored for plant-based applications.

Even when new constituents are added via insertion of specific genes, there will be a need for advanced separations to recover the material of interest. For example, biopolymer development is currently limited by the lack of clean, economically viable fractionation processes. If plant components cannot be separated effectively, it may not be possible to control the characteristics and quality of the final product.

Processing: Conversion

One way to deal with the different components in plants is to convert these heterogeneous materials into simpler molecules—in much the same way that fossil fuels are converted—that can be used in other reactions. For plant-based materials, viable processes may require high performance multifunctional biocatalysts or heterogeneous catalysts that can perform multiple tasks and are recyclable as well.

Another key barrier is the lack of knowledge on how to deal with natural differences in plant components and characteristics from one plant to the next within the same species. Compounding the problem is the lack of tools for measuring plant variability to the level needed for feedstock considerations.

Fermentation is used with some crops to convert crude heterogeneous inputs, for example, commodity yellow corn into desired materials such as dextrose or ethanol. The types of conversions, utilization of by-products, and separations remain areas for improvement.

In general, the complex chemistry of plant systems makes the design of new or modified plant-based processes more difficult. There is also an abundance of oxidative chemistry already developed to support hydrocarbon-based chemical manufacturing, but little focus on the reduction chemistry needed for plant-based systems. Closely related to this is the lack of practical co-factor systems for reductive biocatalysts.

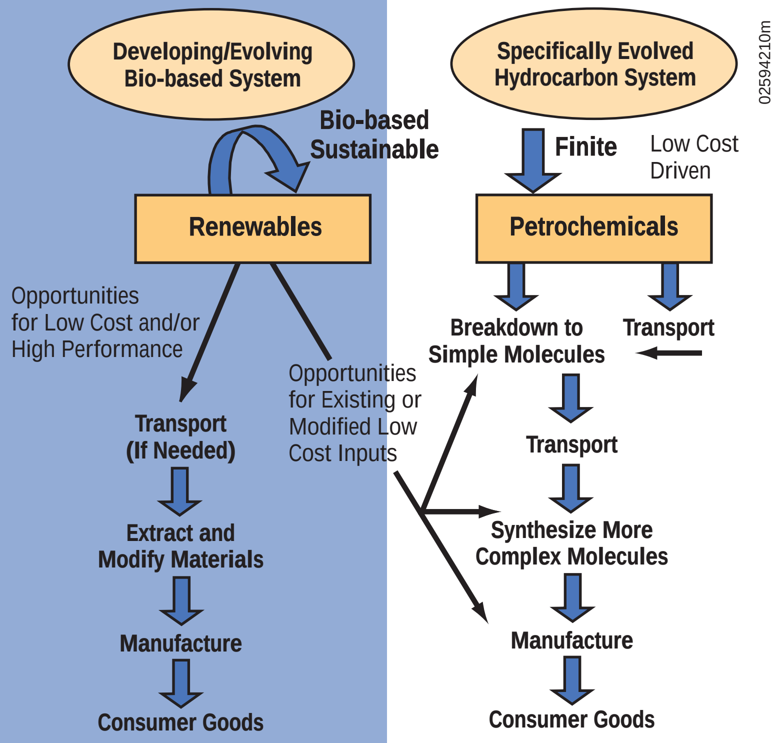
An additional significant barrier to the development of processing for plant-derived materials is the lack of current technical education and training. While some chemical engineering curricula offer a biochemical focus, most graduating chemical engineers have only a very basic knowledge of bioprocesses and a limited knowledge of important bio-separations. For many years, the training of process chemists and engineers has been focused on hydrocarbon chemistry, with little consideration of the needs for processing plant-derived renewables.

Utilization (Materials): Functionality

An alternative way to deal with the different components in plants is to take advantage of their functionality. Petrochemicals are degraded into simpler molecules which are then used to resynthesize more complex materials, including polymers (Fig. 10). Plants already contain several types of polymers that are used in many products. For example, cellulosic fibers from wood pulp and starch from potatoes and corn are used for many industrial processes. However, with the exception of paper and vegetable oils, only a few of these are used at any significant volume in the current processing system. While several reasons exist for limited volume uses, a major restriction is lack of understanding of the functionality (performance) in relation to cost.

Recently, experimental plastic films have been made from plant-derived protein polymers, demonstrating the potential for such uses. Also, plants have specific stereochemistry resulting in chiral molecules of value (sugars, vitamins, amino acids). However, in general, the reactivity and functionality of plant building blocks are not well understood, which has been a limitation to the generation of ideas for new uses.

Figure 10. Comparison of the utilization systems for petrochemicals and renewable resources. The petrochemical chain is largely driven by low cost of inputs, while the renewable use chain can be driven by either low cost of inputs or added value (for new uses or for feeding into the existing petro-stream) or by added value via designed high performance functionality.



Production: Designer Plants
Plant Science: Genomics

Recent developments in transgenic plants have demonstrated the high potential for specific manipulation via genetic engineering. While transgenics offer exciting possibilities, much research remains to be done to fully utilize this approach.

A major barrier is the lack of understanding of inherent metabolic pathways in plants to the degree required for design of particular polymers and other materials. Biosynthesis utilizing solar energy—captured via chloroplasts—may be highly efficient, plus such designs must also avoid disruption of vital pathways. Thus, plant metabolism and regulation of carbon flow are limiting factors with our current level of knowledge.

It is expected that recent advances in functional genomics will begin to contribute the understanding required for designer materials. However, this area of science is just beginning and receives limited support compared to analogous efforts in the medical area. Additional progress in genetic transformation is also required to allow more specific gene insertion and routine transformation of plastids as well as nuclear events.

While there is now widespread research in plant transformation, genomics, and bioinformatics, there is very little direct investigation of the application of these emerging technologies for specific research on renewable resources.

To some extent, an upward spiral of scientific knowledge is required to remove the major barriers. Typically, others have called for multi-disciplinary research to address this issue. However, there must be a focused and coordinated effort to provide the appropriate progress to overcome existing barriers in a timely manner. In other words, the study of gene regulation must be closely interrelated with the study of functionality of inherent polymers, and these with separations engineering, and so on.

REASEARCH AND DEVELOPMENT NEEDS

Following identification of the main barrier topics and specific barriers within each of those areas, attention was focused on determining the research and development actions required to overcome those barriers.

The overall roadmap has been divided into four sections in alignment with the four major barrier topics:

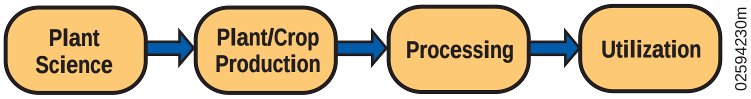
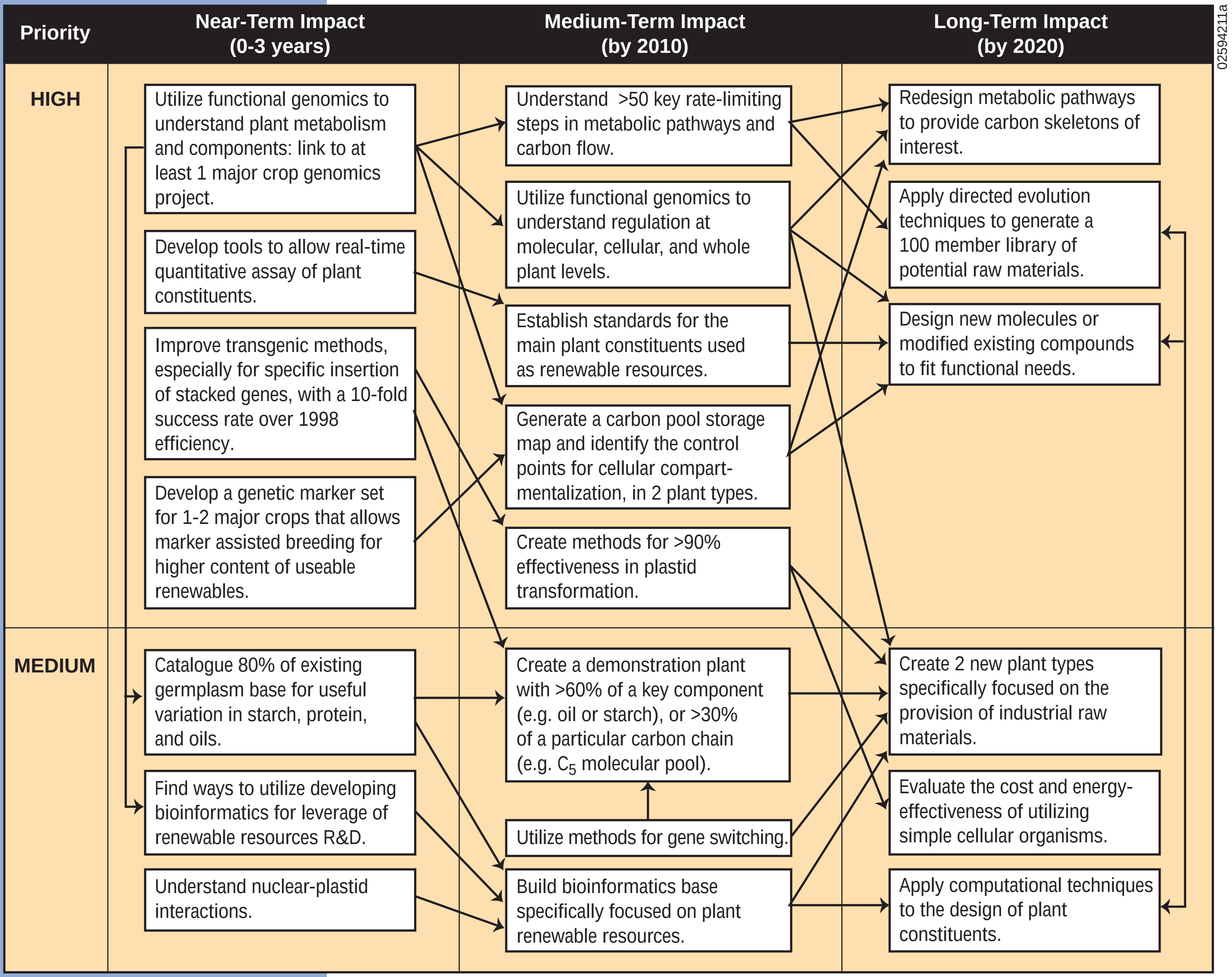


Figure 11A. Goals for PLANT SCIENCE research.



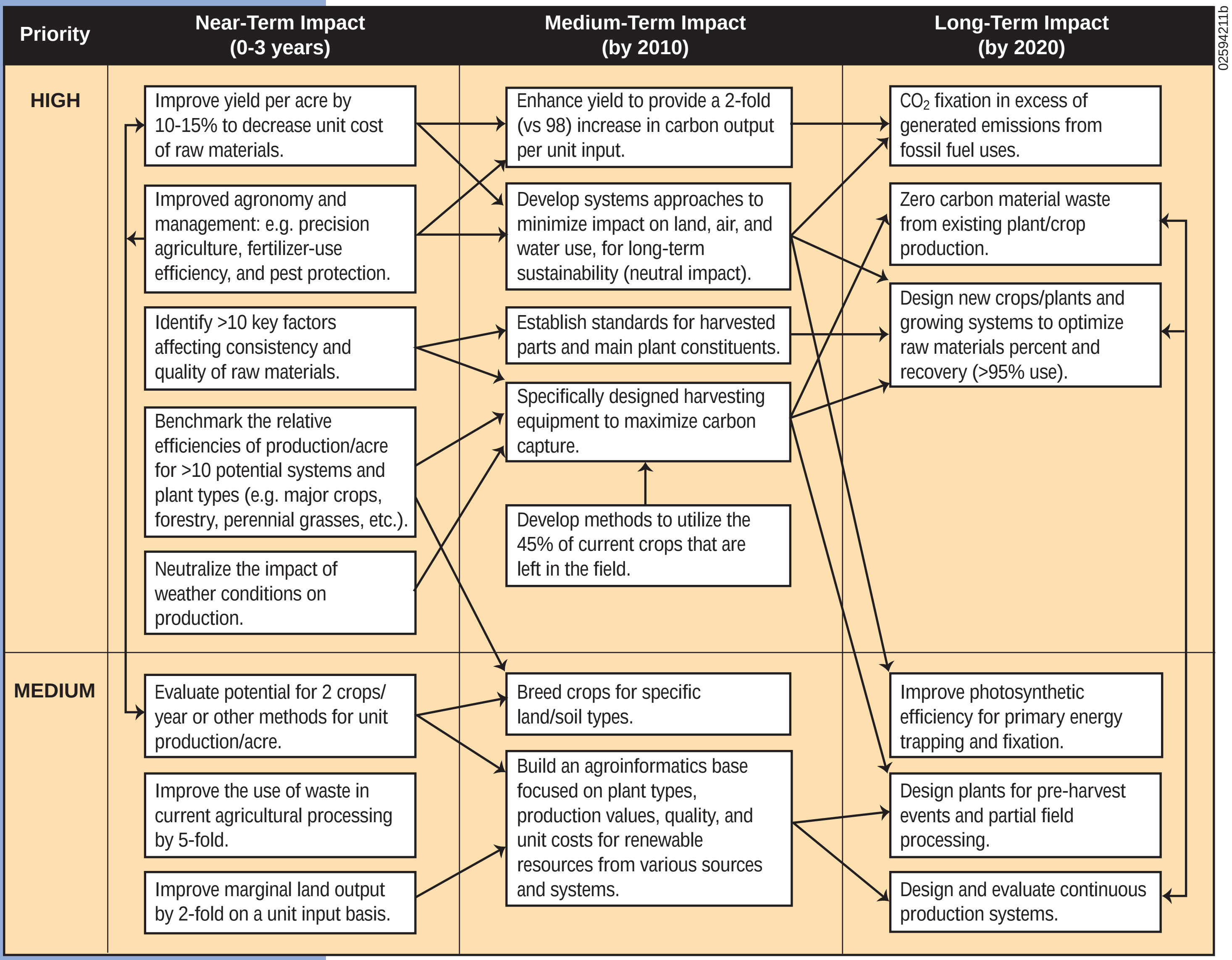
Priority	Near-Term Impact (0-3 years)	Medium-Term Impact (by 2010)	Long-Term Impact (by 2020)
HIGH	Utilize functional genomics to understand plant metabolism and components: link to at least 1 major crop genomics project. Develop tools to allow real-time quantitative assay of plant constituents. Improve transgenic methods, especially for specific insertion of stacked genes, with a 10-fold success rate over 1998 efficiency. Develop a genetic marker set for 1-2 major crops that allows marker assisted breeding for higher content of useable renewables.	Understand >50 key rate-limiting steps in metabolic pathways and carbon flow. Utilize functional genomics to understand regulation at molecular, cellular, and whole plant levels. Establish standards for the main plant constituents used as renewable resources. Generate a carbon pool storage map and identify the control points for cellular compartmentalization, in 2 plant types. Create methods for >90% effectiveness in plastid transformation.	Redesign metabolic pathways to provide carbon skeletons of interest. Apply directed evolution techniques to generate a 100 member library of potential raw materials. Design new molecules or modified existing compounds to fit functional needs.
MEDIUM	Catalogue 80% of existing germplasm base for useful variation in starch, protein, and oils. Find ways to utilize developing bioinformatics for leverage of renewable resources R&D. Understand nuclear-plastid interactions.	Create a demonstration plant with >60% of a key component (e.g. oil or starch), or >30% of a particular carbon chain (e.g. C_5 molecular pool). Utilize methods for gene switching. Build bioinformatics base specifically focused on plant renewable resources.	Create 2 new plant types specifically focused on the provision of industrial raw materials. Evaluate the cost and energy-effectiveness of utilizing simple cellular organisms. Apply computational techniques to the design of plant constituents.

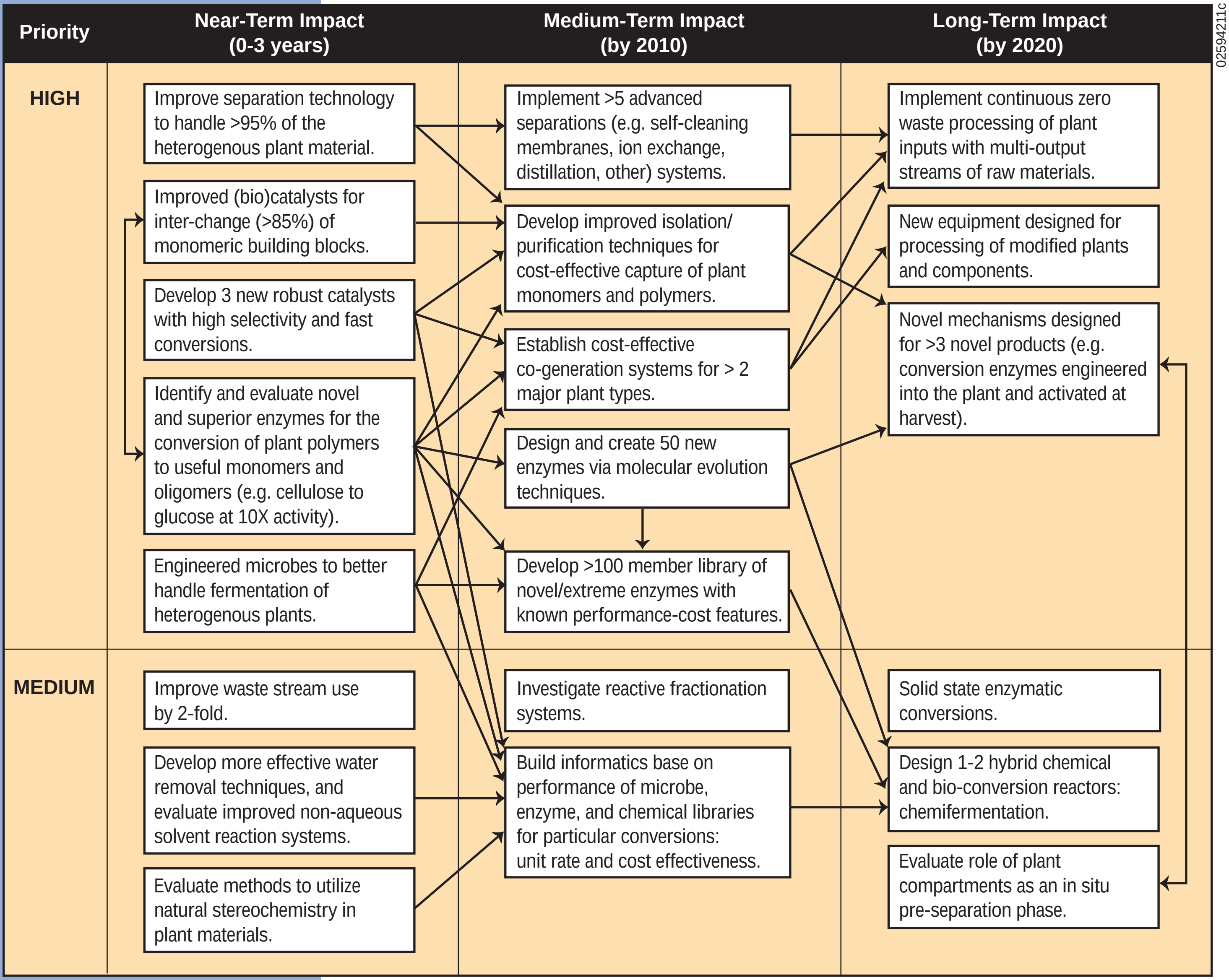
Figures 11A–11D contain details of the quantitative research goals ranked by priority for each of these barrier topics. Within each topic the research goals are also aligned by expected timeframe for impact. Arrows depict the main relationships and linkages among goals.

The nearer-term goals indicate achievements and projects that can be used to measure progress toward the advances required to meet the vision target of a fivefold increase in renewable resource use by 2020.

The research goals (Figs 11A-D) were condensed into a one-page summary overview of the types of research expected to have major impact on achieving the vision (Fig. 12).

Figure 11B. Goals for PRODUCTION research.



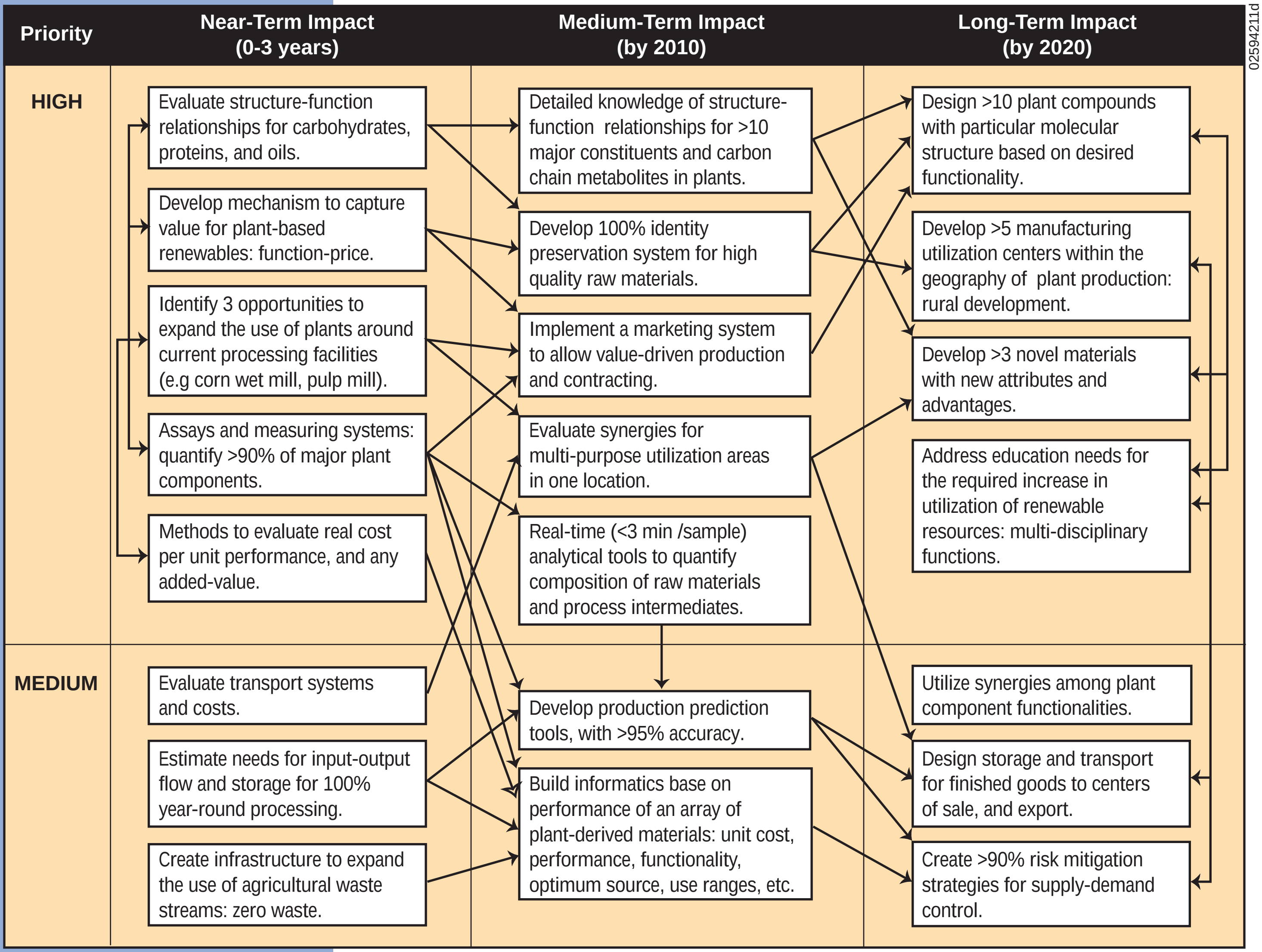


Priority	Near-Term Impact (0-3 years)	Medium-Term Impact (by 2010)	Long-Term Impact (by 2020)
HIGH	Improve separation technology to handle >95% of the heterogenous plant material. Improved (bio)catalysts for inter-change (>85%) of monomeric building blocks. Develop 3 new robust catalysts with high selectivity and fast conversions. Identify and evaluate novel and superior enzymes for the conversion of plant polymers to useful monomers and oligomers (e.g. cellulose to glucose at 10X activity). Engineered microbes to better handle fermentation of heterogenous plants.	Implement >5 advanced separations (e.g. self-cleaning membranes, ion exchange, distillation, other) systems. Develop improved isolation/ purification techniques for cost-effective capture of plant monomers and polymers. Establish cost-effective co-generation systems for > 2 major plant types. Design and create 50 new enzymes via molecular evolution techniques. Develop >100 member library of novel/extreme enzymes with known performance-cost features.	Implement continuous zero waste processing of plant inputs with multi-output streams of raw materials. New equipment designed for processing of modified plants and components. Novel mechanisms designed for >3 novel products (e.g. conversion enzymes engineered into the plant and activated at harvest).
MEDIUM	Improve waste stream use by 2-fold. Develop more effective water removal techniques, and evaluate improved non-aqueous solvent reaction systems. Evaluate methods to utilize natural stereochemistry in plant materials.	Investigate reactive fractionation systems. Build informatics base on performance of microbe, enzyme, and chemical libraries for particular conversions: unit rate and cost effectiveness.	Solid state enzymatic conversions. Design 1-2 hybrid chemical and bio-conversion reactors: chemifermentation. Evaluate role of plant compartments as an in situ pre-separation phase.

Figure 11C. Goals for PROCESSING research.

Several projects exist today that are considered leading edge forerunners in the development of renewable resources for industrial raw materials. We can "test" the robustness of the proposed research activities by exploring the linkages between examples of these leading projects and the research summary map.

Figure 13 shows the linkage with polyhydroxybutyrate (PHB) which is being developed in transgenic plants. Figure 14 shows the linkage with polylactic acid (PLA) which is being produced from corn starch through enzymatic reactions. The Cargill-Dow joint venture has already undertaken sufficient research to move PLA into commercial development with multi-million dollar investment in manufacturing facilities.



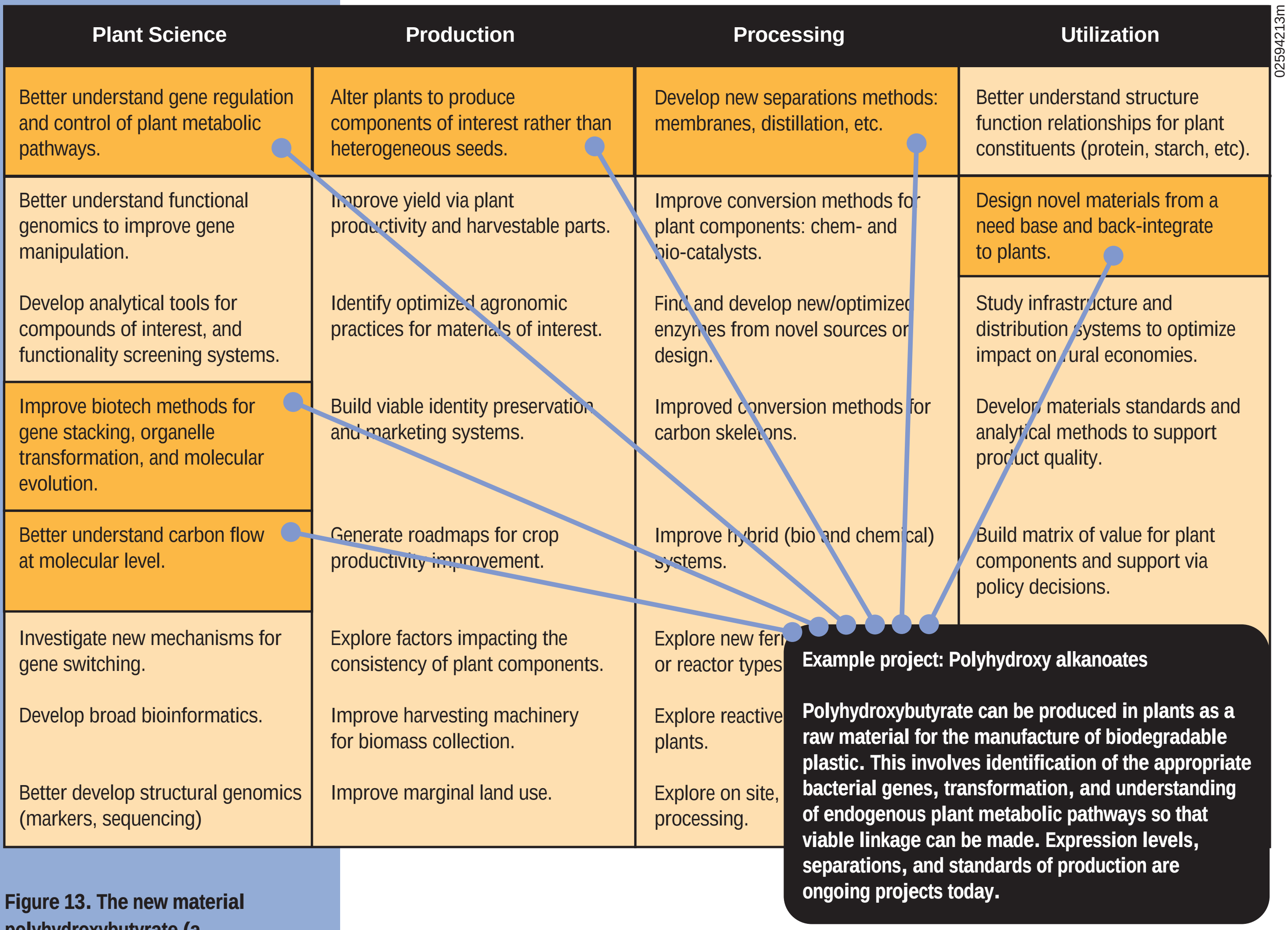
Priority	Near-Term Impact (0-3 years)	Medium-Term Impact (by 2010)	Long-Term Impact (by 2020)
HIGH	Evaluate structure-function relationships for carbohydrates, proteins, and oils. Develop mechanism to capture value for plant-based renewables: function-price. Identify 3 opportunities to expand the use of plants around current processing facilities (e.g corn wet mill, pulp mill). Assays and measuring systems: quantify >90% of major plant components. Methods to evaluate real cost per unit performance, and any added-value.	Detailed knowledge of structure-function relationships for >10 major constituents and carbon chain metabolites in plants. Develop 100% identity preservation system for high quality raw materials. Implement a marketing system to allow value-driven production and contracting. Evaluate synergies for multi-purpose utilization areas in one location. Real-time (<3 min /sample) analytical tools to quantify composition of raw materials and process intermediates.	Design >10 plant compounds with particular molecular structure based on desired functionality. Develop >5 manufacturing utilization centers within the geography of plant production: rural development. Develop >3 novel materials with new attributes and advantages. Address education needs for the required increase in utilization of renewable resources: multi-disciplinary functions.
MEDIUM	Evaluate transport systems and costs. Estimate needs for input-output flow and storage for 100% year-round processing. Create infrastructure to expand the use of agricultural waste streams: zero waste.	Develop production prediction tools, with >95% accuracy. Build informatics base on performance of an array of plant-derived materials: unit cost, performance, functionality, optimum source, use ranges, etc.	Utilize synergies among plant component functionalities. Design storage and transport for finished goods to centers of sale, and export. Create >90% risk mitigation strategies for supply-demand control.

Figure 11D. Goals for UTILIZATION (and Infrastructure) research.

Plant Science	Production	Processing	Utilization
Better understand gene regulation and control of plant metabolic pathways.	Alter plants to produce components of interest rather than heterogeneous seeds.	Develop new separations methods: membranes, distillation, etc.	Better understand structure function relationships for plant constituents (protein, starch, etc).
Better understand functional genomics to improve gene manipulation.	Improve yield via plant productivity and harvestable parts.	Improve conversion methods for plant components: chem- and bio-catalysts.	Design novel materials from a need base and back-integrate to plants.
Develop analytical tools for compounds of interest, and functionality screening systems.	Identify optimized agronomic practices for materials of interest.	Find and develop new/optimized enzymes from novel sources or design.	Study infrastructure and distribution systems to optimize impact on rural economies.
Improve biotech methods for gene stacking, organelle transformation, and molecular evolution.	Build viable identity preservation and marketing systems.	Improved conversion methods for carbon skeletons.	Develop materials standards and analytical methods to support product quality.
Better understand carbon flow at molecular level.	Generate roadmaps for crop productivity improvement.	Improve hybrid (bio and chemical) systems.	Build matrix of value for plant components and support via policy decisions.
Investigate new mechanisms for gene switching.	Explore factors impacting the consistency of plant components.	Explore new fermentation methods or reactor types.	
Develop broad bioinformatics.	Improve harvesting machinery for biomass collection.	Explore reactive enzymes within plants.	
Better develop structural genomics (markers, sequencing)	Improve marginal land use.	Explore on site, at harvest, processing.	

02594212m

Figure 12. Summary of key research and development activities, based on the individual goals shown previously. These have been ranked from top to bottom within each of the four barrier areas according to expected impact on progress toward the vision for renewable resources.

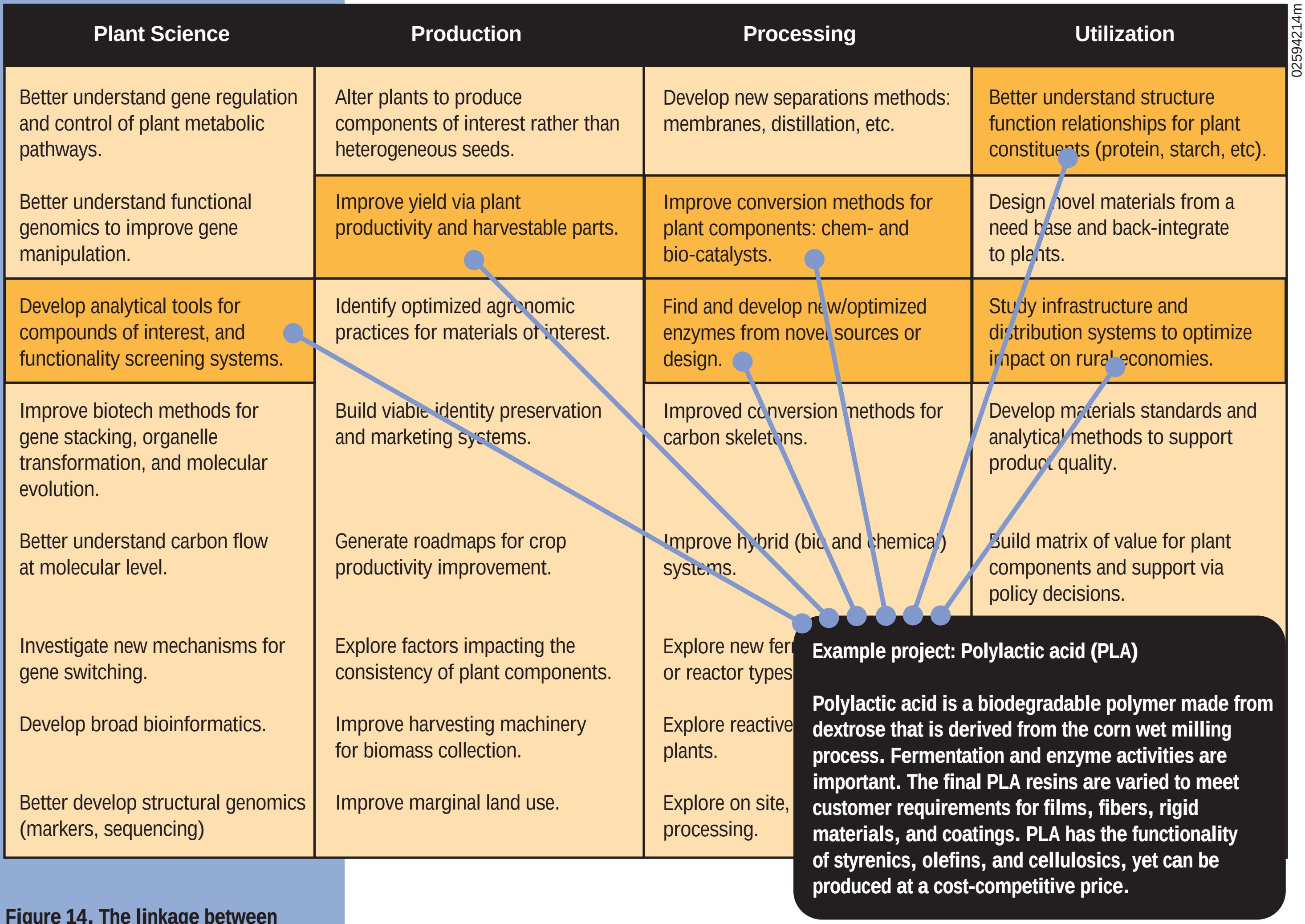


Plant Science	Production	Processing	Utilization
Better understand gene regulation and control of plant metabolic pathways.	Alter plants to produce components of interest rather than heterogeneous seeds.	Develop new separations methods: membranes, distillation, etc.	Better understand structure function relationships for plant constituents (protein, starch, etc).
Better understand functional genomics to improve gene manipulation.	Improve yield via plant productivity and harvestable parts.	Improve conversion methods for plant components: chem- and bio-catalysts.	Design novel materials from a need base and back-integrate to plants.
Develop analytical tools for compounds of interest, and functionality screening systems.	Identify optimized agronomic practices for materials of interest.	Find and develop new/optimized enzymes from novel sources or design.	Study infrastructure and distribution systems to optimize impact on rural economies.
Improve biotech methods for gene stacking, organelle transformation, and molecular evolution.	Build viable identity preservation and marketing systems.	Improved conversion methods for carbon skeletons.	Develop materials standards and analytical methods to support product quality.
Better understand carbon flow at molecular level.	Generate roadmaps for crop productivity improvement.	Improve hybrid (bio and chemical) systems.	Build matrix of value for plant components and support via policy decisions.
Investigate new mechanisms for gene switching.	Explore factors impacting the consistency of plant components.	Explore new fer or reactor types	
Develop broad bioinformatics.	Improve harvesting machinery for biomass collection.	Explore reactive plants.	
Better develop structural genomics (markers, sequencing)	Improve marginal land use.	Explore on site, processing.	

Example project: Polyhydroxy alkanoates

Polyhydroxybutyrate can be produced in plants as a raw material for the manufacture of biodegradable plastic. This involves identification of the appropriate bacterial genes, transformation, and understanding of endogenous plant metabolic pathways so that viable linkage can be made. Expression levels, separations, and standards of production are ongoing projects today.

Figure 13. The new material polyhydroxybutyrate (a biodegradable plastic material) mapped on the renewable resources research areas shows excellent linkage to several high level priorities, indicating that these are indeed relevant goals for research on the leading edge.



Plant Science	Production	Processing	Utilization
Better understand gene regulation and control of plant metabolic pathways.	Alter plants to produce components of interest rather than heterogeneous seeds.	Develop new separations methods: membranes, distillation, etc.	Better understand structure function relationships for plant constituents (protein, starch, etc).
Better understand functional genomics to improve gene manipulation.	Improve yield via plant productivity and harvestable parts.	Improve conversion methods for plant components: chem- and bio-catalysts.	Design novel materials from a need base and back-integrate to plants.
Develop analytical tools for compounds of interest, and functionality screening systems.	Identify optimized agronomic practices for materials of interest.	Find and develop new/optimized enzymes from novel sources or design.	Study infrastructure and distribution systems to optimize impact on rural economies.
Improve biotech methods for gene stacking, organelle transformation, and molecular evolution.	Build viable identity preservation and marketing systems.	Improved conversion methods for carbon skeletons.	Develop materials standards and analytical methods to support product quality.
Better understand carbon flow at molecular level.	Generate roadmaps for crop productivity improvement.	Improve hybrid (bio and chemical) systems.	Build matrix of value for plant components and support via policy decisions.
Investigate new mechanisms for gene switching.	Explore factors impacting the consistency of plant components.	Explore new fer or reactor types	
Develop broad bioinformatics.	Improve harvesting machinery for biomass collection.	Explore reactive plants.	
Better develop structural genomics (markers, sequencing)	Improve marginal land use.	Explore on site, processing.	

Example project: Polylactic acid (PLA)

Polylactic acid is a biodegradable polymer made from dextrose that is derived from the corn wet milling process. Fermentation and enzyme activities are important. The final PLA resins are varied to meet customer requirements for films, fibers, rigid materials, and coatings. PLA has the functionality of styrenics, olefins, and cellulosics, yet can be produced at a cost-competitive price.

Figure 14. The linkage between the proposed summary research activities and the commercial development of polylactic acid (PLA). Again, the key areas for successful PLA production match the leading priorities in our research activities summary table. Thus, the research activities described here, and the individual goals underlying these activities (described previously) appear to be "on target" with advanced projects in renewable resource development.

COORDINATED APPROACH

The future utilization of renewable resources will require a multi-disciplinary, cross-industry approach. While exciting opportunities exist for research achievements in many areas such as biopolymers, stereospecific molecules, new enzymes, novel materials, and transgenic design, a major consideration is that progress in single isolated technical areas will not be sufficient. It will be much more powerful to have inter-related research projects conducted in a parallel and coordinated manner. The outcome should produce improved fit and flow through the development cycle (Fig. 15), and avoid progress in one area that results in a "surprise" at another point in the system.

Clearly, a multi-disciplinary approach is required to achieve effective progress. However, it is doubtful that any one organization can provide the breadth and depth of research skills required for the overall needs. Thus, research support may be given to one part of the cycle but this should be done in concert with other projects within the cross-industry system.

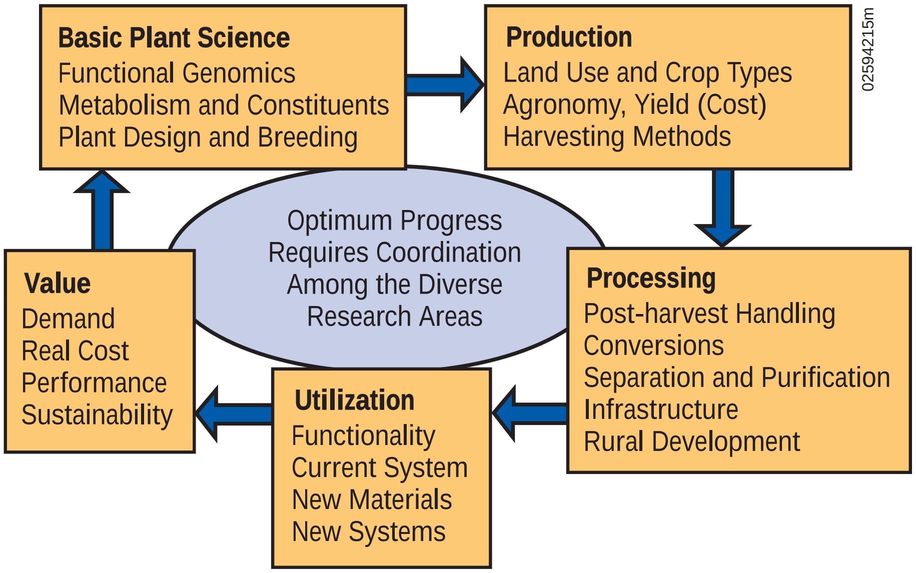


Figure 15. Representation of the interrelated multi-tasks required to be in alignment for the optimization of renewable resource utilization. Based on the main barriers identified from a broad range of inputs.

This need was mentioned in the original "Plant/Crop-Based Renewable Resources 2020" vision which called for simultaneous progress along a technology "front" with directed focus on limiting "hot spots" as required. Focusing on the appropriate research—with correct timing and with communication to the broad but related points in the system—will require coordinated direction.

For example, a scientist may discover a whole new polymer with functional potential to be the source for an advanced biodegradable plastic replacement. However, the value of this research result is limited until: the appropriate gene is found; it is expressed in the correct viable metabolic pathway; the optimum crop type is grown with enough yield for cost-effective sourcing; a process is created to separate the component polymer; and a method is developed to utilize the material in the manufacturing of the novel product.

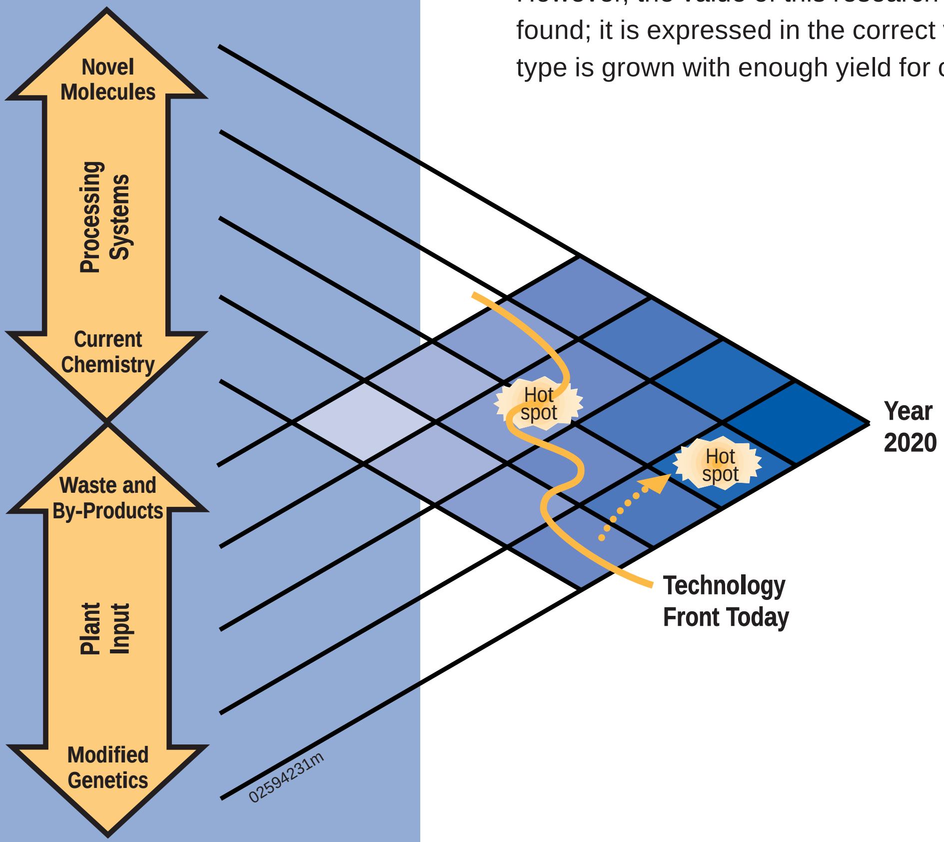


Figure 16. Fulfilling the renewable resources 2020 vision requires research and development advances both in the use of plant inputs and in processing systems. "Hot spots" are particular research priorities that merit special attention because they could be key to moving the entire "technology front" forward.

Doing the research and development for each of these steps in a sequential manner will take many years. The optimum approach is to ensure coordinated, parallel processing of research results and key target areas. Such an approach should also encourage partnerships and involvement of the private sector.

In other words, it is important to move the "technology front" forward in a balanced manner that takes into account the fact that the production and utilization of renewable resources is not one industry, but impacts many.

Currently, plants/crops are used for biomass and a range of raw materials such as starch, protein, fatty acids, and isoprene-based compounds. Forestry is a major contributor through pulp and paper. Soybeans are used in printing inks and paints. Corn enters several industrial use channels via the wet mill fermentation process. However, the relative volume contribution remains low. A new opportunity has been presented by genetic engineering which promises to allow metabolic manipulation to produce desired functional materials.

This roadmap has highlighted potential ways for progress and has identified goals in specific components of the system. Achieving success with these goals will provide the opportunity to hit the vision target of a fivefold increase in renewable resource use by 2020—and will set the stage for a further ramp-up in use of sustainable renewable resources beyond 2020.

Addressing the issues and achieving success with the roadmap goals is not a matter of choice. We must be ready to meet the ever growing demand for consumer goods and energy by using all of our natural resources. Research implemented today will allow choices in products tomorrow.

Renewable resources require focus in direction, application of the best scientific minds, use of the most advanced technologies, and continued discussion at the highest intellectual levels. The roadmap that has been generated here provides a picture of the needs and requirements for research and development in order to begin to implement a successful renewable resource strategy for the United States. In addition, priority areas for support have been selected from among several identified research and commercial development needs, to allow the greatest return on investment in the critical arena of advanced renewable resources.

Within the next generation, the world will change in many irrevocable ways. Fortunately, we can envision the need and have the scientific intellect to keep pace with these changes. America needs leadership that will continue to recognize, support, and move rapidly to meet the need to expand the use of sustainable renewable resources. Continued scientific breakthroughs and technology progress—such as the roadmap outlined by this document—will be required to meet the resource use challenges that lie ahead for meeting product demand.

APPENDIX 1

EXECUTIVE STEERING GROUP

In late 1997, the "Plant/Crop-Based Renewable Resources 2020" vision was developed under the leadership of the National Corn Growers Association (NCGA) with support from the U.S. Department of Energy's Office of Industrial Technologies. Soon after publication in early 1998, widespread backing for the "vision" was demonstrated by many who signed a supporting compact at the Commodity Classic convention. Today, more than 40 organizations have demonstrated support for the visionary platform that was first started by the NCGA.

During 1998, the "vision" gained considerable momentum and an Executive Steering Group (ESG) was formed from a coalition of industry and grower groups. The ESG includes a range of organizations representing production of crops and forests through to utilization of raw materials for industrial processing and manufacturing. The ESG determined that it should focus on:

a) Building the roadmaps necessary to identify the priority areas for research that would allow increased use of plants as renewable resources for industrial materials

b) Generating further support from the U.S. industrial base, for action in the near-term that will help secure a sustainable and healthy economic future

c) Highlighting the areas within renewable resource research where the federal government could use taxpayers' dollars with maximum effect to aid rural development and to ensure sustainable high standards of living across the nation.

THE FOLLOWING INDIVIDUALS AND ORGANIZATIONS ARE MEMBERS OF THE ESG:

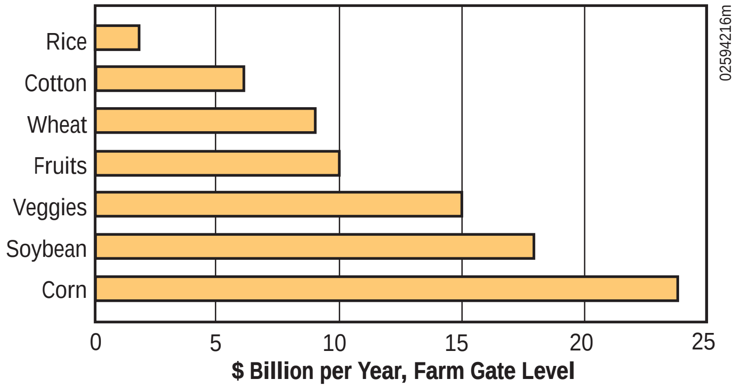
Earl Beaver — Monsanto Company
Scott Berg — American Forest & Paper Association
Marion Bradford — A.E. Staley, Mfg. Co.
Kyd Brenner — Corn Refiners Association
Mark Dungan — United Soybean Board
Mehmet Gencer — BF Goodrich Company
Bob Hovden — Cargill, Inc.
Donald Johnson — Grain Processing Corporation
Richard La Duca — Genencor International, Inc.
Jim McLaren [Chair] — Inverizon International, Inc.
Jim Miller — National Association of Wheat Growers
David Mobley — General Electric Corporate R&D
Bob Mustell — National Corn Growers Association
Michael Pelowski — Great Lakes Chemical Corporation
David Rowe — Dow Chemical Company
Mary Kay Thatcher — American Farm Bureau
Tom Tillett — Rohm and Haas Company

APPENDIX 2

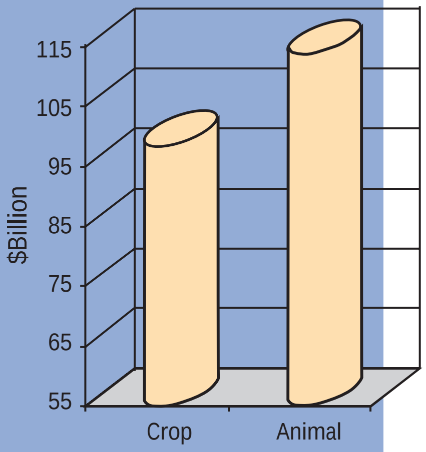
AGRICULTURAL AND FORESTRY STATISTICS

Basic agricultural production provides 24 million jobs in production, output processing, handling, and selling feed, food, and fiber. The industry generates around $1 trillion in economic activity and makes up more than 15% of GDP. Everyone in the United States benefits through a safe and secure food supply, more than adequate levels of nutrition, and a shopping bill that is less than 10% of average disposable income.

Crops are produced at high levels of efficiency on more than 400 million acres in the United States with corn, wheat, and soybeans accounting for the majority on both area and volume bases. Typical annual production values for the main crops grown are shown in the bar chart below.



Source: USDA-ERS

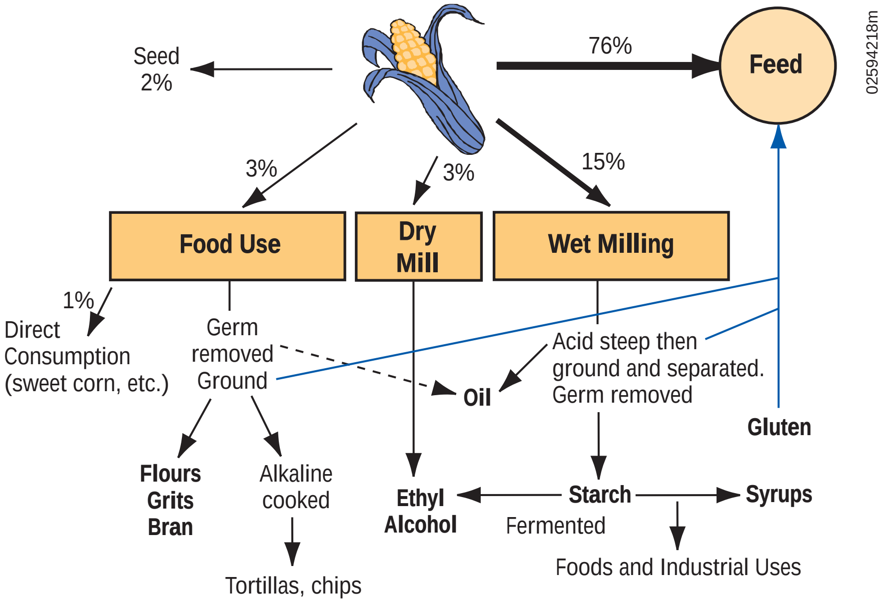


Two Million Farmers Use:
- $11 B in Fertilizers
- $9 B in Pesticides
- $6 B in Fuel and Oil
- $3 B in Electricity

Source: USDA-ERS

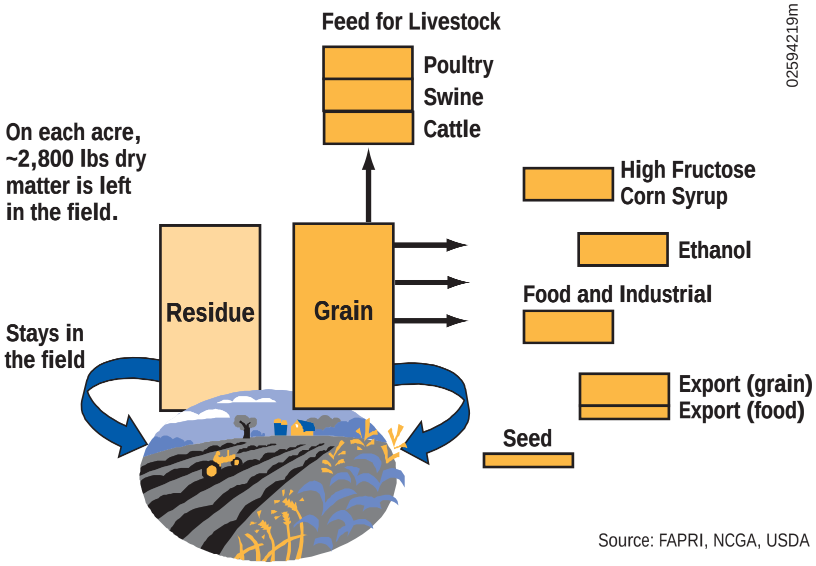
Although there are fewer than 2 million farmers, the quantity and quality of crop production continues to improve due to the efficient utilization of inputs and the effective application of new technologies. Annual production and primary economic inputs can be summarized as shown in the chart at the left.

Crop production is a significant economic generator with almost $100 billion in farm-gate level value and considerable leverage throughout the value added chain. For example, corn is used in more than 3,500 products as shown below.



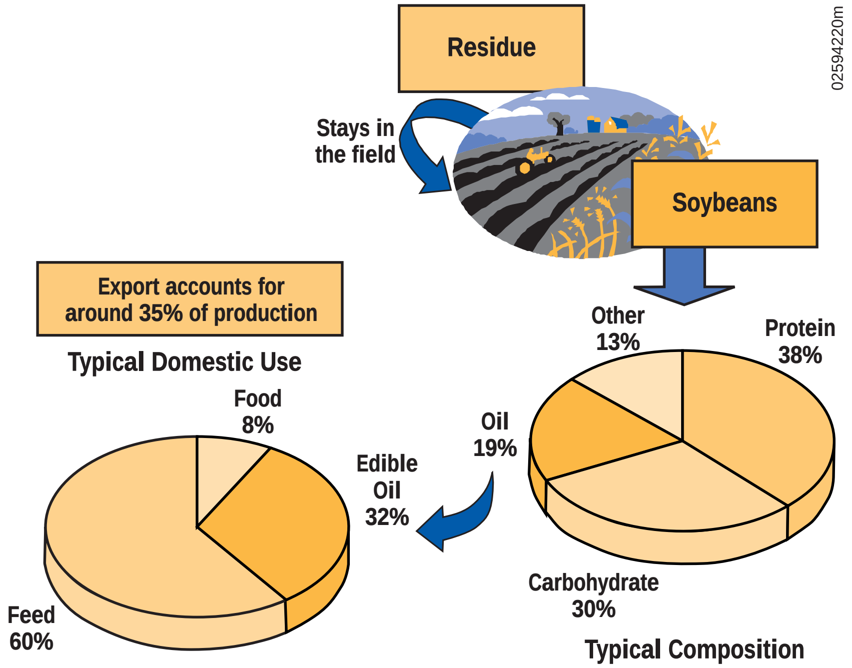
Source: USDA, Corn Refiners Association, NCGA

Despite the large number of products that corn eventually contributes to, there is potential for improved utilization via both designed constituents and ways to use the residue that flows through a combine but is left in the field. A field of corn is very effective at capturing solar energy. The graphic below shows how a field of corn is used.



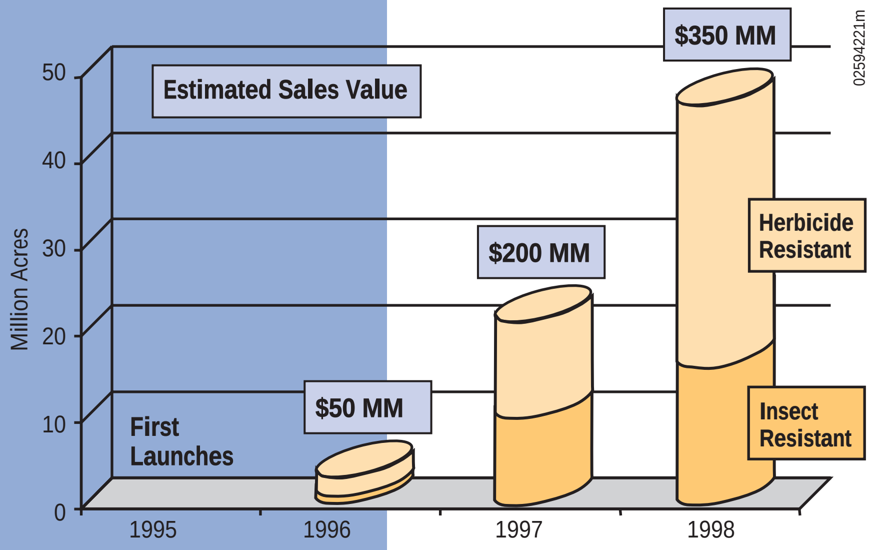
Source: FAPRI, NCGA, USDA

In a similar manner, soybeans are also used for many products. Primarily grown for their protein and oil content, the processed materials find ways into many industrial goods, from printing inks to glues. The illustration below shows uses for a typical field of soybeans.



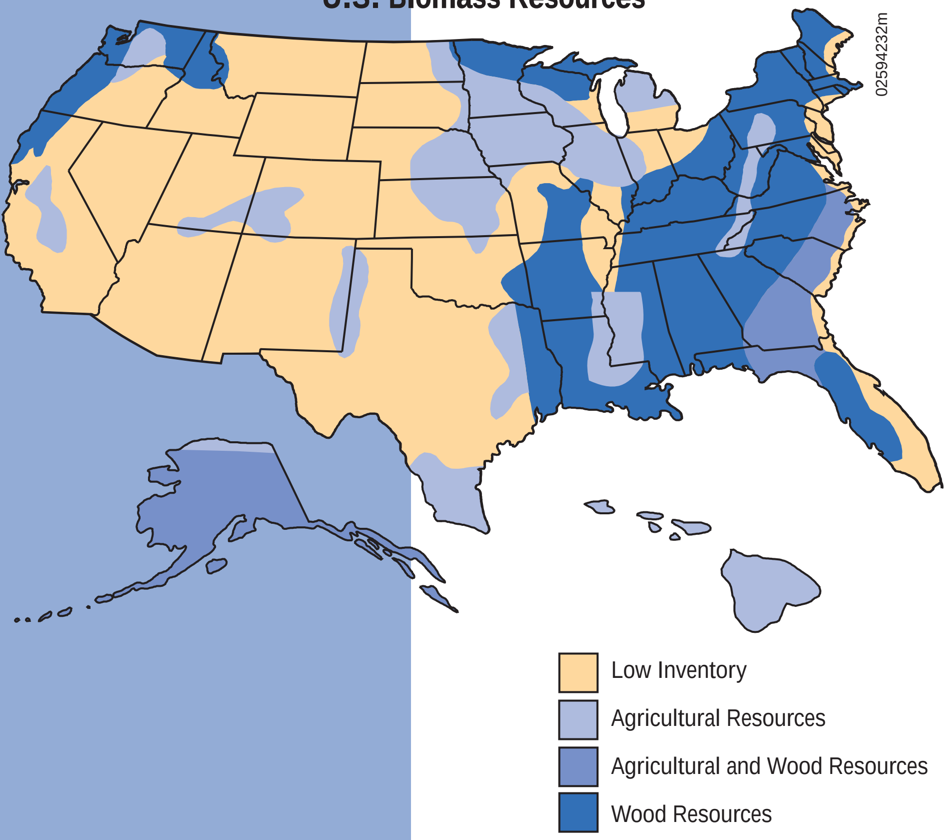
Other crops, such as wheat also have a considerable amount of residue that is left in the field or lost at various stages of processing into many products. Improving the utilization of current crops is one way to begin moving toward the renewable resource vision.

Another approach that will contribute significantly towards progress in renewables use is to understand the functionality of certain natural compounds and to design plants with altered content of the desired materials. The use of transgenic crops in the United States has increased rapidly as shown in the chart at the left.



To date, commercial transgenics have been related to crop protection traits—providing advantages in production efficiency or unit yield. Within the next few years, additional traits related to plant composition will enter the marketplace. Experiences with crop protection and quality traits will assist in understanding how to grow, harvest, and market future crops with traits for improved industrial raw materials.

U.S. Biomass Resources



As the map at the left shows, much of the United States is blessed with available renewable resources.

Pastures and range cover about 800 million acres in the United States and are typically used for grazing cattle, sheep, or other ruminants. In many areas, the intensity of production is limited by relatively low annual rainfall. However, in recent years there have been genetic improvements in the varieties grown which allow higher yields under restricted conditions.

Forestry occupies more than 650 million acres in the United States, employs 1.4 million people, and generates $200 million per year.

Different types of trees grow at different rates and require different conditions. However, in general, forests fix around 2 tons of carbon/acre/year which helps sequester some of the atmospheric carbon dioxide.

Wood itself is highly versatile and has many uses from furniture to energy-efficient building materials. In addition, U.S. forestry is the source of around 100 million tons/year of paper, paperboard, and pulp.

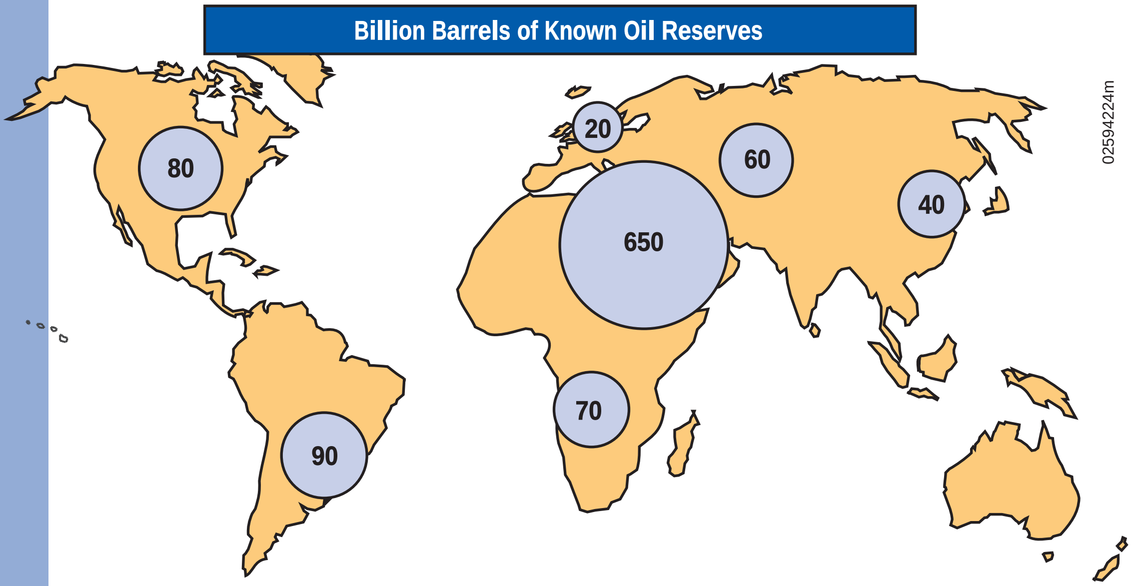
Over the past 10 years the paper segment has increased faster than the lumber-use segment. Despite the use of electronic communication via computers, the demand for paper has continued to increase. Wood and paper products have the highest recycle rate with some 40 million tons of paper per year being reused.

In the future, it is expected that genetic engineering of trees will provide for easier manipulation of current constituents and/or allow the production of more specific useful materials. In either case, trees will form an integral portion of the future renewable resource base.

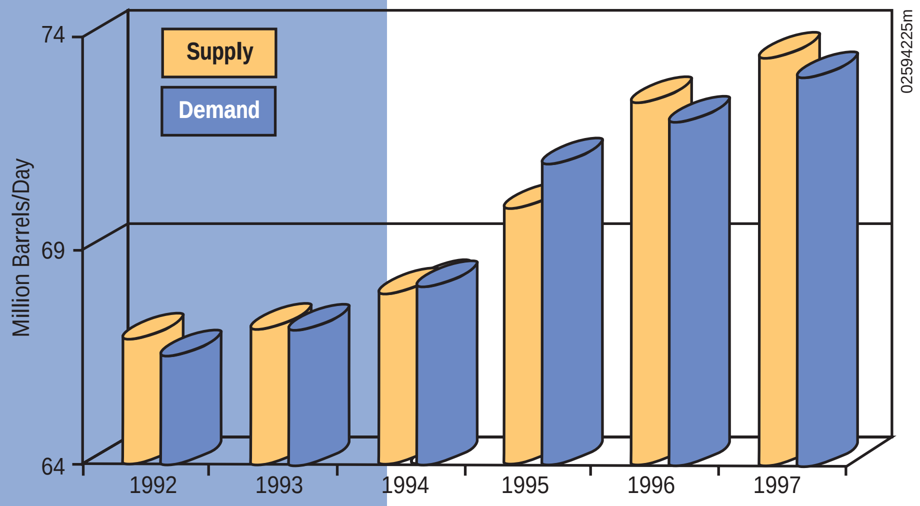
Appendix 3

Petrochemical Statistics

The world has a finite supply of fossil fuels. Although significant coal and natural gas reserves exist, crude oil is generally taken as an indicator of the supply side for fossil fuels. Two aspects of the remaining global supply are important: total amount and distribution among countries, as shown in map below.



Source: DOE-Energy Information Administration

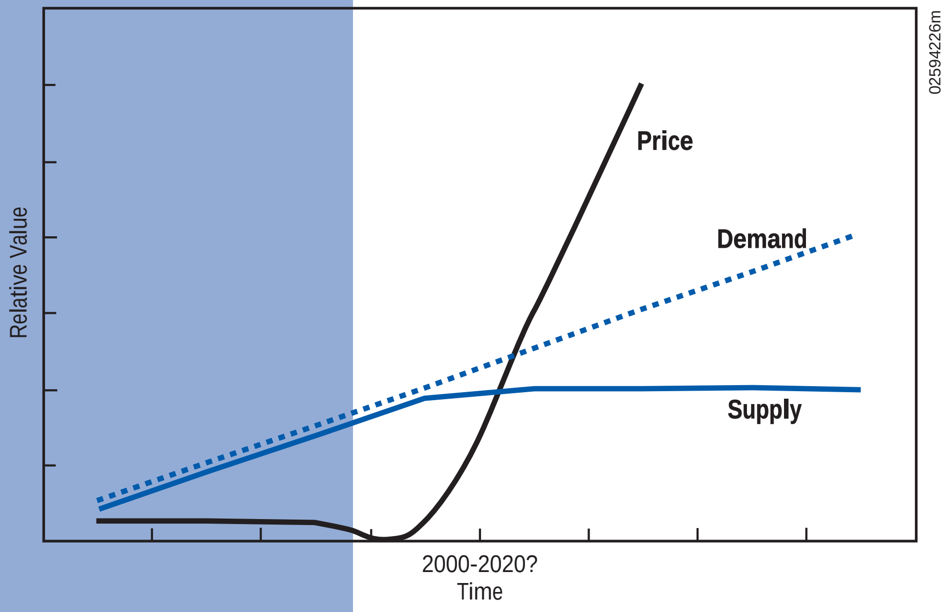


Source: DOE-Energy Information Administration

There has been much debate about the duration of supply of fossil fuels. Duration is an important question, but is not as critical as the supply-demand balance. Over the past five years, supply has been in balance with demand (at the macro level) as shown in the chart at the left.

There are two aspects of this supply-demand chart that are important:

1. Demand appears to be increasing.
2. It is not possible to determine when supply will no longer be able to keep up with this demand.



Regardless of the correct answer to the question of how long fossil fuels will last, the economics of the petrochemical industry will change whenever the supply-demand balance changes. It can reasonably be expected that the balance will change long before the supply is compromised. Such a situation will result in large shifts in the price of oil and basic industrial inputs, much like the U.S. "oil crisis" of the 1970s.

We cannot accurately determine whether the 2000-2020 time period will be a crisis or not. However, we can expect that the more renewable resources are used to supplement fossil fuels, the further back the crisis period will be pushed.

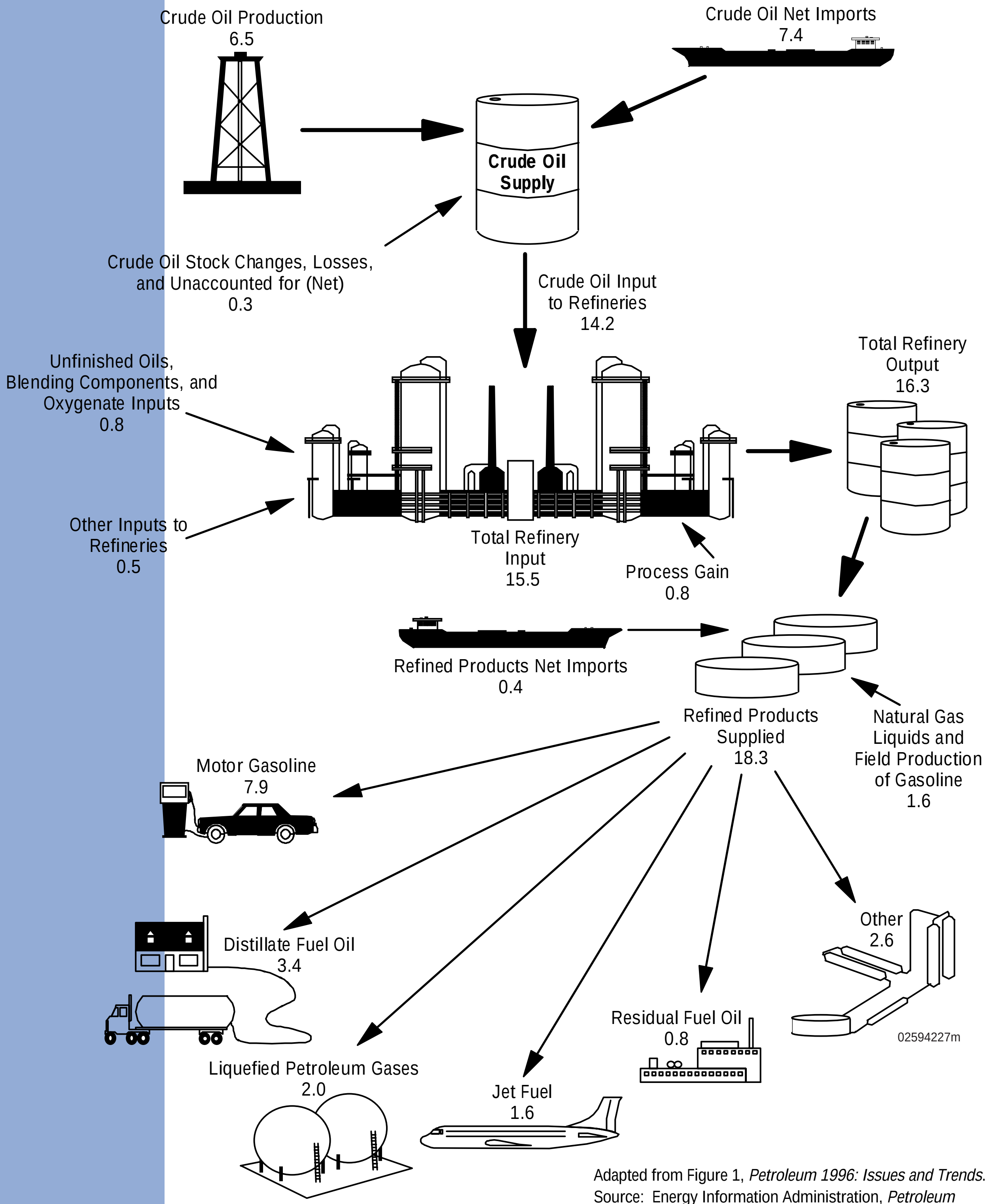
The petrochemical industry has been hugely successful, with more than 70,000 different products. The sector will continue to develop and expand the use of innovative products such as polycarbonate resins, polyvinylidene chloride, and resin-compatible fiberglass. One out of every eight U.S. patents are awarded to the chemical industry.

The successful trends of the petrochemical industry indicate that demand for industrial raw material will continue, both worldwide and in the United States. Even if the global situation were to remain in balance (and it will likely not), the U.S. situation is that imports have already overtaken domestic supply. Thus, there is a question of security as consumer goods rely more and more on an uncertain supply—from aspects of total amount, price, and distribution of control.

The following page shows the source and utilization of petroleum-based products in the United States.

U.S. Petroleum Flow, 1996

(Million Barrels per Day)



Adapted from Figure 1, *Petroleum 1996: Issues and Trends.*
Source: Energy Information Administration, *Petroleum Supply Annual*, DOE/EIA-0340 (June 1997), Table 3.

APPENDIX 4

WORKSHOP RESULTS: RESEARCH NEEDS AND PRIORITIES

The research and development requirements mentioned in eight different working groups* were condensed into the following topic areas (not ranked):

Plant Science	Production
Develop structural genomics (sequencing)	Identify key traits of interest
Develop functional genomics	Improve yield via plant productivity
Develop methods for information sharing and addressing intellectual property issues	Explore factors impacting consistency
Develop bioinformatics	Lower losses to pests and diseases
Explore gene regulation and control of metabolic pathways	Characterize germplasm
Study gene switching	Improve precision farming
Develop map of carbon flow	Build market contract systems
Improve primary energy flow in systems	Decrease costs
Improve gene transformations	Develop fast growing species
Investigate gene stacking	Improve harvesting machinery for biomass
Apply gene shuffling and molecular evolution	Improve agronomic practices to protect soil and water
Develop plastid transformation	Alter plants to contain one major component of interest
Explore plant mimics (CO_2 fixation)	Study double cropping
Explore single cell organisms	Investigate perennials versus annual plants
Develop improved analytical tools	Improve use of marginal land
Enhance proteomics research	Enhance photosynthetic efficiency
Generate model systems	Develop methods for improved residue use
Establish training centers	Generate roadmaps for crop productivity improvement

02594228m

* The workshops were held in Indianapolis, Indiana, in August and September, 1998.

Processing	Utilization
Use non-aqueous solvents	Research performance needs
Use extremophiles as a source of novel enzymes	Improve materials standards and analytical methods
Develop new membrane technologies for separations	Better understand structure function relationships for plant constituents (protein, starch, etc)
Develop water removal methods	Structure taxes to encourage use of renewables
Find ways to use known targets more effectively (e.g. starch)	Explore value of natural stereochemistry
Search for new catalysts	Define added value
Improve conversion methods	Develop novel materials and uses
Decrease costs	Build matrix of value for plant components
Improve hybrid (bio and chemical) systems	Generate a plant polymer economy
Explore enzymes within plants	Study infrastructure and distribution systems
Design new microbes for fermentation	Explore impact on rural economies
Develop biochips for process control	Develop improved analytical tools for product value
Improve distillation	Identify export opportunities
Design new reactors to suit plant material	Develop bio-material array for combo uses
Explore partial processing in the field	Compare life-cycle analysis costs/value
Develop more selective catalysts via screening	Develop comparative risk analysis for bio-based economy
Establish multi-functional facilities	
Investigate reactive fractionation	
Find novel reaction media	
Develop improved microbes	

02594229m

APPENDIX 5

ATTENDEES AT RENEWABLE RESOURCES WORKSHOPS

Charles	Abbas	Archer Daniels Midland Company
Thomas	Abbott	U.S. Department of Agriculture, ARS — National Center for Agricultural Utilization Research
Irshad	Ahmed	Pure Energy Corporation
Kerr	Anderson	Dow Chemical Company
William	Apel	Idaho National Engineering and Environmental Laboratory/Lockheed Martin Idaho Technology Company
Robert	Bloksberg-Fireovid	Department of Commerce, NIST-Advanced Technology Program
Marta	Bourke	Calgon Carbon Corporation
Joe	Bozell	National Renewable Energy Laboratory
Kyd	Brenner	Corn Refiners Association
Robert	Brown	Iowa State University
Ting	Carlson	Cargill, Inc.
Helena	Chum	National Renewable Energy Laboratory
Jeff	Conrad	U.S. Department of Agriculture, Biobased Products Coordinating Council
Al	Cotter	National Corn Growers Association
Clark	Cummins	Dow Chemical Company
Brian	Davison	Oak Ridge National Laboratory
Mark	Dungan	United Soybean Board
Ron	Erikson	Great Lakes Chemical Company
Kellye	Eversole	Eversole & Associates
Doug	Faulkner	U.S. Department of Energy, OIT
Frank	Flora	U.S. Department of Agriculture, ARS — National Program Leader
Tom	Foglia	U.S. Department of Agriculture, ARS — Eastern Regional Research Center
Jim	Frank	Argonne National Laboratory
Mehmet	Gencer	B.F.Goodrich Company
David	Glassner	National Renewable Energy Laboratory
Melinda	Hamilton	Idaho National Engineering and Environmental Laboratory/Lockheed Martin Idaho Technology Company
Milford	Hanna	Industrial Agricultural Products Center
Bob	Harris	New Uses Council

Richard	Herrett	Agricultural Research Institute
Lou	Higgs	Milestone Technology Inc.
Don	Holt	University of Illinois
Judy	Jarnefeld	New York State Energy Research and Development Authority
Peter	Johnsen	U.S. Department of Agriculture, ARS — National Center for Agricultural Utilization Research
Larry	Johnson	Center for Crops Utilization, Iowa State University
Don	Johnson	Grain Processing Corporation
Gerhard	Knothe	U.S. Department of Agriculture, ARS — National Center for Agricultural Utilization Research
Gloria	Kulesa	U.S. Department of Energy, OIT
Rich	La Duca	Genencor International, Inc.
Dennis	Lamb	Great Lakes Chemical Company
Zennon	Lysenko	Dow Chemical Company
James	McLaren	Inverizon International, Inc.
Dennis	Miller	Michigan State University
Jim	Murry	Pendleton Flour Mills
Robert	Mustell	National Corn Growers Association
Christine	Nieland	National Corn Growers Association
Norm	Olson	Iowa Energy Center
Mark	Paster	Monsanto Company
Vic	Patton	UOP LLC
Gene	Petersen	National Renewable Energy Laboratory
Paul	Reep	Milestone Technology Inc.
David	Rowe	Dow Chemical Company
Colin	Scanes	Iowa State University
Tom	Schechinger	Iron Horse Custom Farming LLC
Sharon	Shoemaker	California Institute of Food & Agriculture Research, University of CA-Davis
Merrill	Smith	U.S. Department of Energy, OIT
Graham	Swift	Rohm & Haas Company
Denise	Swink	Deputy Assistant Secretary, U.S. Department of Energy, OIT
Mary Kay	Thatcher	American Farm Bureau Federation
Tom	Tillett	Rohm & Haas
Mitch	Tvinstra	Kansas State University
Suellen	Van Ooteghem	U.S. Department of Energy, FETC
Bhima	Vijayendran	Battelle
Ingrid	Watson	U.S. Department of Energy, OIT
Todd	Werpy	Pacific Northwest National Laboratory
Clay	Williams	OmniTech International Inc.

Please direct comments or questions about this document to either:

James McLaren, President, Inverizon International, Inc. and Chair,
Executive Steering Group, 314-530-6943, ‘mclaren@inverizon.com’
or
Doug Faulkner, Office of Industrial Technologies, Energy Efficiency
and Renewable Energy, U.S. Department of Energy, 202-586-2119,
'doug.faulkner@ee.doe.gov'

This document and its predecessor "Vision" document *Plant/Crop-Based Renewable Resources 2020: A Vision to Enhance U.S. Economic Security Through Renewable Plant/Crop-Based Resource Use* can be found on the Internet at **http://www.oit.doe.gov/agriculture/**

For printed copies of this "Roadmap" document or the "Vision" DOE/GO-10098-385 call (800)-363-EREC.

DOE/GO-10099-706
February 1999

Printed with a renewable-source ink on
paper containing at least 50% wastepaper,
including 20% postconsumer waste.