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State of the Art in Biorefinery in Finland and the United States, 2008

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Abstract

The U.S. Embassy in Finland and the Finnish Ministry of Employment and Economy jointly sponsored a U.S. Embassy Science Fellowship to survey biorefinery research and development (R&D) activities in Finland and the United States and to seek cooperative research efforts between the two countries. The biorefinery effort in Finland started from concerns about global climate change and a need to comply with terms of the Kyoto agreement on greenhouse gas emissions. The biorefinery program in the United States started from concerns about the rising cost of crude oil and a desire to reduce dependence on foreign oil for U.S. transportation fuels. Although different in original intent, the two country R&D programs have many similarities and offer numerous opportunities for collaborative efforts. The program in Finland is more focused on direct replacement of high-carbon fuels, such as coal and peat, and gasification and gas reforming as a path toward transportation fuels. Chemical and biochemical research on biorefinery includes production of ethanol as a transportation fuel but is more focused on specialty chemicals and use of biomass chemical fractions in films and plastics. The U.S. focus is primarily on transportation fuels, with about equal efforts on gasification and Fischer–Tropsch reforming, and cellulose hydrolysis with fermentation to ethanol. This difference in emphasis is partially dictated by difference in raw materials. About two-thirds of the biomass available in the United States is dedicated annual crops and unused stalks and leaves of cereal grain agriculture. The bulk of the biomass available in Finland is thinnings and logging slash from softwood tree species. Agricultural residuals are more readily hydrolyzed than softwoods and, because of higher ash content, more difficult to handle in gasification and direct combustion. The difference in program emphasis between the two countries is largely a response to different climate and geographic conditions in Finland and the United States.

Keywords: Biorefinery, gasification, saccharification, hydrolysis, fermentation, Fischer-Tropsch

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Although every effort has been made to review this report with scientists and government staff in both Finland and the United States, ultimately, the contents of the report are the research, opinions, and conclusions of the author. The report does not represent opinion or policy of any government agency in either Finland or the United States.

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On the cover: The introduction of this report alludes to a comparison of current extractive energy use as parasitic and sustainable energy efforts as symbiotic—living within the renewable energy budget of the earth. A lichen is pictured on the cover to symbolize this noble goal. Photo courtesy of Francis Jones, www.bugwood.org.

Executive Summary

In 2008, with the United States of America beginning to re-evaluate national policies on global climate change and Finland agreeing to European Union targets for renewable transportation fuels, the two countries discovered many similarities in their goals for renewable fuels. As a result, the U.S. Embassy in Helsinki and the Finnish Ministry of Employment and Economy agreed to sponsor a project using the U.S. State Department's Embassy Science Fellowship program (ESF). The U.S. Embassy arranged the ESF, including local housing and travel. Tekes, the research funding agency of the Ministry of Employment and Economy, arranged access to government laboratories, universities, and corporations in Finland and organized the interviews needed to prepare a summary document of biorefinery research and development.

Visits and interviews in Finland occurred during a six-week resident period in May and June 2008. The U.S. portion of the report was completed on return to the United States in June. The report has been reviewed and revised by staff at the U.S. Department of Energy (DOE) and by the hosts for the visits throughout Finland.

The biorefinery program funded by Tekes and the Academy of Finland provides for a strong overall program. Compared with funding initiatives in the United States, hydrolysis methods leading to fermentation products receive somewhat less support in Finland, whereas gasification and pyrolysis receive somewhat more support. Nearly all the gasification efforts include at least a pilot-scale evaluation of reforming product gas to hydrocarbons using the Fischer–Tropsch process. The difference in emphasis between Finland and the United States is consistent with differences in available biomass. The United States has large amounts of available agricultural residuals and hardwoods, both of which respond well to hydrolysis methods. In contrast, softwoods, which are substantially more difficult to process with hydrolysis methods, make up the majority of available biomass in Finland.

Interest in ethanol as a fuel product seems greater in the United States than in Finland, but one Finnish company is producing fuel-grade ethanol from various industrial waste streams, and support for research on lignin- and carbohydrate-degrading organisms and enzymes is strong. Compared with U.S. funding, non-cellulose- (glucose-) based products are receiving relatively more interest in Finland, and much of the fractionation and hydrolysis work is targeted at pharmaceuticals, neutraceuticals, and specialty biomaterials applications.

The weakness in many plans to utilize wood or agricultural residuals to displace fossil-fuel-derived products is the inability to accumulate biomass on a scale comparable to competing products. The costs of collection, transportation, and storage of biomass limit the economically viable scale of processing facilities and the ability to compete directly with fossil-fuel-based products, which benefit from high energy density and a large economy of scale. The DOE cost projection for commercializing bio-based fuels requires a significant reduction in raw material cost, representing almost half the cost reduction needed for bio-based fuels to compete directly against gasoline and diesel fuel. A significant part of the raw material cost reduction is an expected increase in ethanol yield—from about 60 U.S. gallons per ton of biomass (227 L) to over 90 gallons per ton (341 L)—and similar improvements in processing efficiency with gasification and reforming. The most recent cost projection is that costs per delivered ton of biomass will fall for a few years as collection and transportation capabilities improve but will eventually rise back to about $60 per ton as the market builds and supplies tighten. Cost reductions are anticipated in single-pass harvesting for agricultural residuals, reduced biomass moisture, and higher density transport bundles. These are very formidable hurdles for agricultural biomass. They are even more daunting for wood residuals. Compared with the cost of providing roundwood to sawmills, harvest and transportation costs are much greater for forest thinning and residuals. All biomass utilization processes, or at least all processes targeted at displacing petroleum-based products, depend on improvements in harvest and transport. Finland has had an active program in forest biomass harvesting, and this is critical to making forest-based biofuels cost effective. The United States has focused more attention on improving productivity and harvesting of annual crops and agricultural residuals because this will contribute a larger share of the lignocellulose for alternative fuels in the United States.

The U.S. program is more focused on fuels than other products and is currently more focused on agricultural residuals than forest and forest products residuals. The emphasis on lignocellulosic ethanol and reforming synthesis gas to alcohols appears to be quite different from the major emphasis areas in Finland. For the saccharification and fermentation-based process, there is an extensive effort in the United States on genetic engineering solutions to several of the persistent needs. Of most interest is whether newer approaches such as rational design and directed evolution can provide the needed processing improvements.

A large part of the U.S. effort is in 13 demonstration plants using technologies including gasification with gas reforming, synthesis gas with fermentation, enzyme saccharification with fermentation, and acid hydrolysis with fermentation. Based on yields shown in the companies' published literature, and stated position in the research and development (R&D) progression, it is not clear that any of these projects have breakthrough technologies that will make their biofuel product commercially competitive with petroleum-based gasoline or diesel fuel. Several, however, are well established companies with highly successful R&D and investment track records and very likely have cost-effective—presumably profitable—technologies or ways to implement the technology. Based on the research goals of the Bioenergy Research Centers established by DOE, and the research project portfolios of DOE and the U.S. Department of Agriculture (USDA), there is concern among the grant agencies that progress in cellulose saccharification yield, five-carbon sugar fermentation, tar removal, synthesis gas cleanup, and overall processing costs is not sufficient to achieve the renewable fuels production targets established in the Energy Independence and Security Act.

There is recognition within DOE that the pulp and paper industry understands biomass management and may provide an implementation pathway for forest biomass to biofuels. Two pulp and paper mills are among the gasification–Fischer–Tropsch projects, and two prehydrolysis pulping projects have been funded by DOE. Several of the other DOE projects are co-sited with existing corn-ethanol plants or are managed by corn-ethanol producers who understand the harvest and transportation problems facing agricultural biomass users.

Based on renewed concerns within the United States on global climate change, and Finland's agreement to comply with European Union targets for CO_2 reductions in the transport sector, Finland and the United States now have very similar research needs and, not surprisingly, a number of similarities in the two programs. Although no formal cooperative process exists at this point, scientists in the two countries are already cooperating on research (Martinez and others 2008, Kilpeläinen 2007) and we should expect to see this continue. A remaining goal of this project is to expand this research cooperation. The two countries should consider collaboration on precompetitive research in Fischer–Tropsch catalysts, cataloging wood decay organisms and wood decay enzymes, cellulose recalcitrance to enzymes, and sustainability concerns, including how much biomass must be returned to agricultural soil to maintain soil productivity and the productivity impact of removing the tops, branches, and even roots that have been traditionally left in the forest.

State of the Art in Biorefinery in Finland and the United States, 2008

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Introduction

Several global developments have led to an intense interest in renewable energy on the part of industrialized countries of Asia, Europe, and the Americas. One development is the concern among climate scientists that the increase in atmospheric CO_2 will lead to climate disruptions and a growing consensus that the increase in atmospheric CO_2 is at least partially a consequence of intensive use of fossil fuels for energy. In response, the United Nations (UN) convened the Framework Convention on Climate Change. In 1997, targets for reducing greenhouse gases were ratified in Kyoto Japan, becoming the blueprint for reducing the impact of modern civilization on the earth's climate. Another development is recent fluctuations in petroleum costs, which have renewed concerns about the adequacy of known reserves and the potential for major supply disruptions. Industrial expansion and improving standards of living in Asia, South America, and Africa are increasing demand, and the supply of petroleum and petroleum products has not been able to keep up. The terms "Hubert's peak" or "peak oil" refer to projections that crude oil extraction will begin to decline within the next quarter century (IEA 2005). These projections, combined with the current supply pinch, have generated increasing public concern that industrial economies will need to adjust to tighter supplies and higher costs for petroleum-based liquid fuels and chemicals.

Finland is among the leaders of the industrialized nations in use of renewable fuels, with over 25% of total energy use provided by renewable sources. About 20% is biomass provided by industrial forestry and forest residuals (IEA 2007). Finland has no coal, oil, or gas resources. It has shown considerable resourcefulness as a nation, having doubled total energy use between 1970 and 2002, without increasing the use of coal and petroleum (Figure 1). This past success complicates Finland's efforts to roll back carbon emissions to below 1990 emission levels.

Until the recent concerns with climate change, the large coal and natural gas reserves in the United States reduced the incentive to encourage use of renewable fuels. Petroleum consumption in the United States has returned to usage levels of the 1970s, and natural gas consumption has increased significantly (Figure 2). However, the United States is a leader in the development of bio-based transportation fuels. In 2006, ethanol provided 2.6% of gasoline consumption (USDOE n.d.) with production doubling to provide nearly 5% of gasoline use by 2007. Nearly all the ethanol production is currently produced from starch hydrolysis and fermentation, placing a burden on grain supplies. The research and development (R&D) focus of the United States has now shifted to non-food biomass, and several cellulosic projects should begin to produce ethanol before 2010. The use of lignocellulosic biomass to produce transportation fuel has been a long-term interest of the U.S. government. The U.S. Department of Agriculture (USDA) and U.S. Forest Service (USFS) have biomass fuel research dating back to the 1930s (Saeman, 1945, Harris and Kline, 1949) and this has been an R&D focus in the U.S. Department of Energy (DOE) since it was formed in 1977 and assumed management responsibility for the National Laboratories. The United States has also become acutely aware that our reliance on foreign sources of petroleum is supporting governments that deny basic human rights and in some cases support international terrorist organizations.

Having signed the Kyoto treaty and as a member of the European Union (EU), which also ratified the treaty, Finland became subject to meeting the greenhouse gas reductions established for developed nations. Finland started a program to increase the use of biomass in direct combustion applications, such as district and industrial heat and power. Initial plans did not include a significant contribution of renewables to transportation fuels and considered peat as a renewable source of energy. Peat is the fraction of biomass that resists decay and that remains after the decay process is complete. In much of Finland, it is forming faster than it is being harvested for fuel, but the decay process is slow—up to 300 years—and the decay process emits methane, another greenhouse gas. The EU has rejected the use of peat as a renewable source of energy and insisted that Finland replace 10% of petroleum-based transportation fuel with liquid fuels from renewable sources.

The government of the United States contested several aspects of the Kyoto agreement and as a result declined to ratify the treaty. However, disruptions in crude oil supplies, a decline in value of the dollar, and by some accounts, crude oil speculation caused a 100% rise in the relative cost of gasoline and diesel fuel within the United States (Figure 3). Although the cost of gasoline in the United States is still well below the cost of fuel in Finland, the relative rise in price has had a large impact on public perceptions. The United States has responded with a national initiative to replace fossil fuels used in transportation with

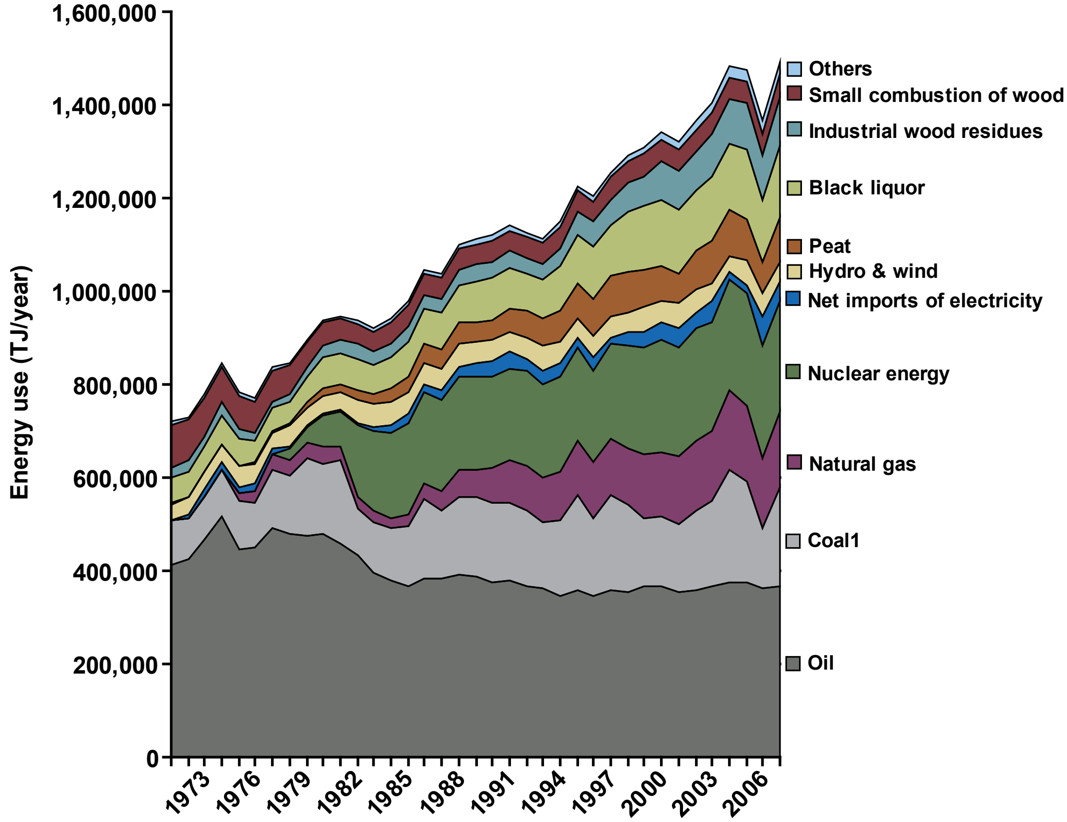

Figure 1. Energy use in Finland (Statistics Finland).

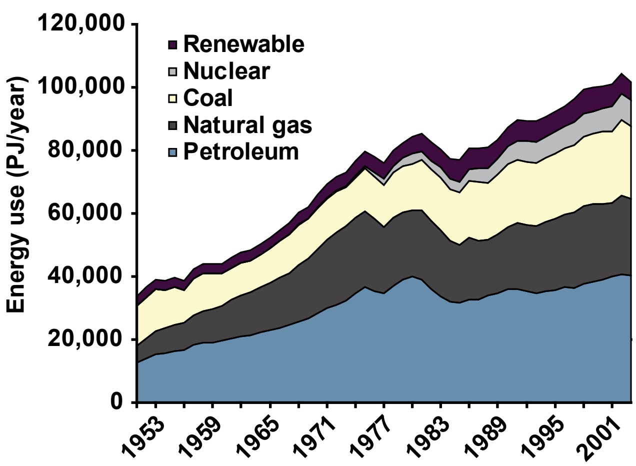

Figure 2. U.S. energy consumption (Statistical Abstract of the United States).

renewable liquid fuels. The production of ethanol from corn has tripled since 2000, and the United States now targets to replace 15% of its transportation fuel with renewable sourced fuels by 2017 (Bush 2007).

Although the United States did not agree to the Kyoto protocol, the U.S. Federal Government (Bush 2007, 2008) and several U.S. State governments (California 2006, Freeman 2006) have initiatives to control greenhouse gas emissions.

The success with biofuel applications in Finland provides valuable experience for increasing the use of renewable lignocellulosic fuel sources in the United States. Although the perception of petroleum transportation fuel prices is not as shocking in Finland as in the United States, Finland has now committed to EU targets replacing 2% of fossil transportation fuels with renewable fuels by 2008, 5.75% by 2010, and 10% by 2020. Finland may therefore benefit from U.S. experience and R&D in renewable lignocellulosic-based transportation fuels. With this convergence of interests, the U.S. Embassy in Finland and the Finnish Ministry of Employment and Economy requested an Embassy Science Fellowship from the U.S. State Department to help establish the state of the art in the biorefinery industry and research in the two countries.

Biorefinery: Basics and Concepts

Without a recorded history, it is difficult to determine whether wood became a construction material (as tool handles) before it became humankind's primary fuel, but as civilization advanced, wood and other photosynthetic plants certainly provided the primary fuel for heating, cooking, and nascent metallurgy. Wood was fuel long before it became dimension lumber and paper. Civilization's shift from primary reliance on wood fuel to fossil fuels is largely a modern convenience, with coal becoming a common fuel during the industrial revolution and petroleum following about

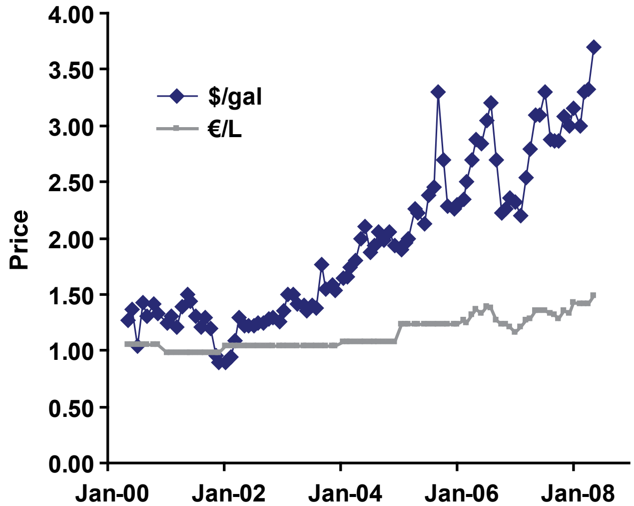

Figure 3. Relative fuel prices, U.S. dollars per gallon (3.8 L/gal) and euros/liter, January 2000 to January 2008. U.S. prices rose by 100% during this period, compared with about 30% in Europe. (Price in euros, Statistics Finland; price in dollars, personal log.)

100 years later. A major contribution was the development of steam power (1775), which eventually made intensive use of coal both necessary and possible. Fossil fuels provided huge benefits in energy density, but the centralization of supplies made coal use unrealistic for routine adaptation until transportation capabilities improved sufficiently to move large quantities of low-value materials long distances.

In this sense, current interests in biomass-derived fuels are a return to the past. However, the wide distribution of biomass that made it such a convenient historical fuel is one of the most intractable impediments to expanded use of biomass for fuel in modern centralized societies. Collection and transport have been and will continue to be one of the necessary focus areas of biofuel development in both countries. Many of these problems can be minimized with energy plantations, but energy crops have their own set of socio-economic costs and benefits. Biomass use as fuel today can be quite similar and far different from historic use. Short logs burning in a wood stove still provide heat for rural housing and cottages in both the United States and Finland. Improvements in stove efficiency and production of wood pellets have put a modern touch on this ancient process, but the romance of a traditional wood stove or fireplace persists. Differing by scale and efficiency, use of wood residuals in industrial energy production and district heating has become in many ways an ideal application, well scaled to the distributed supply and transport inefficiencies while providing very high energy efficiencies. Utilities and district heating plants in Finland have moved beyond heat by raising steam pressures to drive turbines and add electrical generation to district heating plants. These combined heat and power (CHP) plants provide exceptional energy efficiencies, although often at higher capital cost and low economy of scale relative to industrial utilities. District heating is not common in the United States, being restricted to business areas of central cities. Lack of a district heat market significantly reduces the energy efficiency of electrical utilities in the United States, but the shorter heating season makes extensive district heating a costly and less energy-efficient alternative. Use of biomass by electric utilities is practiced in several parts of the United States (Blain et al. 2003, Morris 2002), and co-firing some biomass with coal is becoming a common practice among coal-fired utilities.

Interest in biofuels in Finland and the United States goes beyond heat and efficiency. Both countries have intense interests in substituting photosynthetic-plant-based fuels for gasoline and diesel fuel used in transportation and for chemicals and polymers that make our modern societies possible. In the United States, this has taken initial form as ethanol produced from sugar and seed crops; in Finland, a diesel oil substitute produced from palm and rapeseed oils. The primary interests of both countries are to move beyond food and oil crops to use lignocellulose, the basic material of all photosynthetic plants, as the raw material for production of fuels. These so-called second-generation biofuels will be the subject of much of this report.

Lignin and Cellulose

The plant kingdom consists of a diverse group of species ranging from simple single-cell algae to complex vascular plants that make up the forests, grasslands, farms, lawns, and gardens of our everyday life. All plants have several features and functions in common. First and foremost, all plants use sunlight for energy needed to grow and reproduce. All plants combine two common chemicals—water and atmospheric carbon dioxide—to produce the polymers used to create the body of the plant and the support structure of macroscopic plants. It is this feature, absorbing carbon dioxide from the atmosphere and fixing it into plant material, that makes the plant kingdom key to restructuring a parasitic modern society into a sustainable symbiotic future society. Fuels produced from plant materials simply return the CO_2 sequestered by the plant to the atmosphere; as long as this process is conducted in a sustainable manner, it has no net impact on atmospheric CO_2.

Plants produce three main structural polymers (cellulose, hemicellulose, lignin) and one primary food storage polymer (starch). Plants produce numerous small molecules, such as fats and resins, that provide other food storage and defense needs. These compounds are also under study as potential fuel and high-value chemicals that will help the future biorefinery go beyond commodity fuels. However, these extractive chemicals are not generally available in high enough concentration to impact the materials and energy needs of our societies. Starch and the lignocellulosics dominate. Plant production of fats and oils is of interest as a biological source for diesel oil, but most biodiesel today uses food-grade oils obtained from seeds or nuts.

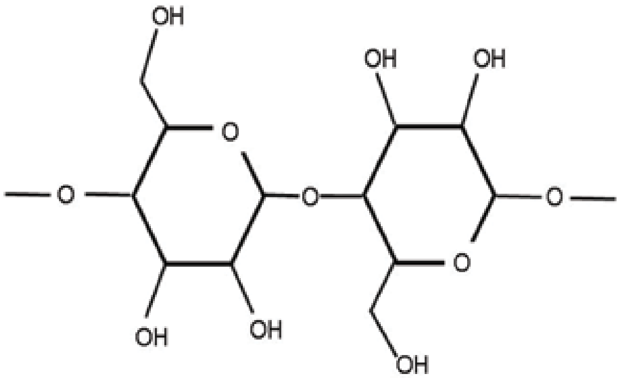

Figure 4. A simplified drawing of cellulose showing two glucose molecules.

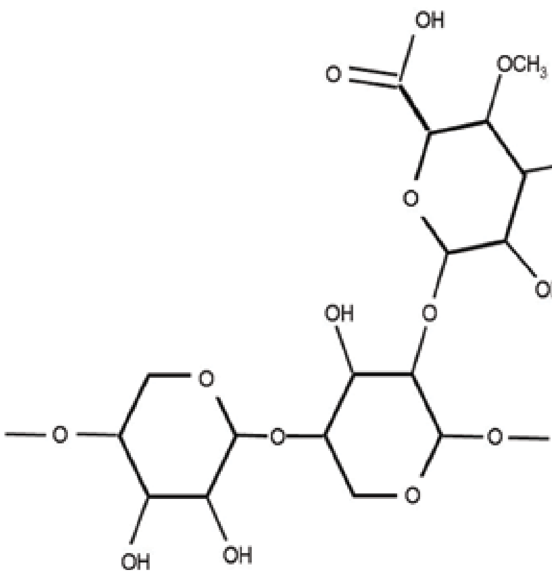

Figure 5. An example of a short section of glucuronoxylan, a hardwood hemicellulose.

The primary building block of the plant is glucose—common sugar. Glucose is a molecule of 6 carbons, 6 oxygens, and 12 hydrogens and is assembled in the plant by combining 6 carbon dioxide molecules and 6 water molecules to produce one molecule of glucose and 6 molecules of oxygen. The reaction requires energy, which is supplied by light through the biochemical processes known as photosynthesis:

$$6\ CO_2 + 6\ H_2O + h\upsilon \rightarrow C_6H_{12}O_6 + 6\ O_2$$

Plants use glucose for both cellulose and starch. In cellulose (Figure 4), glucose is linked into a straight-chain polymer of thousands of glucose monomers. The polymers are assembled in elementary fibrils with diameters ranging from about 4 nm to as much as 20 nm, depending on the species, and up to several microns long. Elementary fibrils are assembled into microfibrils, which are set up in layers to form the plants cell wall. As a long, straight-chain polymer, the cellulose chains in the fibrils organize into crystalline regions, providing greater strength and stiffness to this critical polymer. Starch is also a polymer of glucose with several critical differences: the primary bond between glucose monomers, shorter chain lengths, and short side chains. These differences make cellulose the plants primary cell wall polymer and resistant to degradation, and starch a universal food that is readily depolymerized into the glucose monomers and cellobiose dimers used by organisms as food.

Hemicellulose is really a collection of three or four polymers assembled from a variety of sugars—glucose, galactose, and mannose, six-carbon sugars very similar to glucose, and xylose and arabinose, five-carbon sugars ($C_5H_{10}O_5$). The hemicelluose polymers are all mixtures of two or more sugars and can be straight chain or have short side chains (Figure 5). They do not form crystals and are much less resistant to hydrolysis, either chemically by acids or by enzymes. Geese, cattle, and other animals that rely on grass and tree twigs for food digest the hemicellulose polymers into simple sugars as a major source of nutrition. The purpose of hemicellulose in the plant remains a topic of debate, but it represents 20% or more of most plants (Figure 6).

The final polymer in plants is lignin. Unlike the carbohydrates, which are all assembled from simple sugars, lignin is assembled from monomers similar to the spices vanillin (vanilla) and cinnamon. Lignin is a random cross-linked polymer. The bonds between monomers are chemically resistant, and the monomers have little value as food to most animals. Lignin is usually considered to be the glue that holds the cellulose polymers together into a cohesive cell wall and the cell walls together to form plant stems and tree trunks. Lignin makes up 15% or more of typical grasses and 20% to 35% of the wood in most trees (Figure 6).

Biorefinery

The basic conceptual framework for producing liquid transportation fuels from plant matter is not new. Historically, two approaches have been favored. The first relies on chemical similarities between cellulose and starch. Alcohol production from starch has been a commercial practice for centuries—at least as long as the popular beverages beer, whiskey, sake, and vodka have existed. By breaking down cellulose into the glucose monomers, it is suitable for fermentation in the same way, and the alcohol produced is capable of powering internal combustion engines. Two commercial methods were developed near the turn of the last century (1901 and 1909): concentrated acids and dilute acids (Kamm and others 2006). Concentrated acids dissolve cellulose and break it into the component glucose sugars in nearly quantitative yields. The major problem is that producing the acid is energy intensive and the process consumes almost as much energy as it can produce in transportation fuel. The dilute acid process avoids high energy requirements by using high temperatures and dilute acid to break down the cellulose. The product glucose, however, is

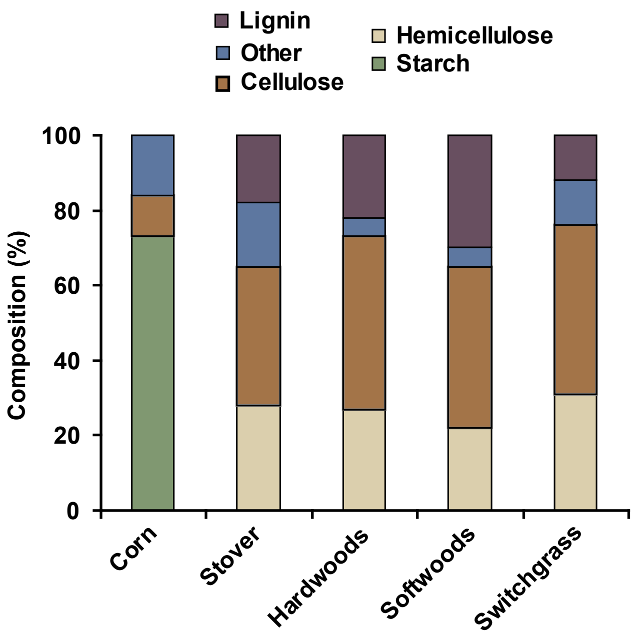

Figure 6. Typical composition of some representative plants.

unstable at the higher temperatures required by the process and decomposition reactions become dominant after about half the cellulose is converted (Saeman 1945, Mok and Antal 1992). The yield of glucose and subsequently ethanol is only about half of the theoretical amount. The dilute acid process has been pursued for over a century, with commercial-scale plants built in Germany, Russia, and the United States. Interest was typically high during times of conflict, when heavy demand and supply disruptions caused fuel shortages (Kamm and others 2006).

The second major approach to conversion of biomass to chemicals is thermochemical. In thermochemical processing, a combustible material is heated in the absence of air to produce a liquid called pyrolysis oil, or a mixture of gases. The two processes are usually referred to as pyrolysis and gasification, respectively. For coal and other substrates that lack oxygen atoms, some form of oxygen is also required. This can be supplied by steam, water, or substoichiometric air. The gas mixture from gasification is primarily carbon monoxide, carbon dioxide, hydrogen, and water and is called by various names including product gas, producer gas, and synthesis gas. Technically, synthesis gas is not the product gas from gasification but rather a gas mixture adjusted to provide ideal stoichiometry for a reforming reaction such as the Fischer–Tropsch synthesis of hydrocarbons. These thermochemical processes were also investigated vigorously, particularly during the First and Second World Wars. Although pyrolysis oil has never been found useful for much other than direct combustion in boilers or possibly turbines, the gas produced in gasification can be reformed into a number of products including hydrocarbons much like diesel fuel, methane (the major component of natural gas), methanol, hydrogen, and higher-chain-length alcohols (Hamelinck 2004). Most notable from a historical perspective was the use of gasifiers by Germany to produce fuel-grade hydrocarbons from coal during World War II (Anderson, et al., 1952; Schulz, 1999) Coal gasification and Fischer–Tropsch reforming have also been used extensively by the Republic of South Africa (Stiegel and Maxwell, 2001; Schulz, 1999). Biomass, much the same as coal, can be converted to product gas and reformulated into the same variety of products. The gas produced can also be used directly in gas turbines to generate electricity or as a replacement for natural gas in industrial processes. The gas produced is not considered suitable for direct substitution in natural gas distribution systems because the energy content is about two-thirds that of typical natural gas and the high concentration of hydrogen cannot be transported and contained in standard steel pipes and tanks. Coal gasification is still of interest in several parts of the world. The DOE is supporting an intensive evaluation of coal gasification for utilities because the product gas is more easily cleaned to remove sulfur and mercury, and a large fraction of the CO_2 produced when burning coal can be collected from the product gas and possibly sequestered in underground storage reservoirs. The combined cycle generating process, which involves combustion of the gas in a gas turbine and use of the exhaust heat to produce steam for use in a steam turbine, can also provide improved energy efficiency relative to the more common steam boiler used by the majority of the utilities in the United States. Similar biomass gasification processes have been studied by the DOE as a way to reduce the use of coal to generate electricity in the United States.

These concepts—cellulose hydrolysis, subsequent glucose fermentation and gasification, and subsequent producer gas reforming—have been under almost continuous investigation since 1920. Interest has intensified or waned with periodic changes in the price and availability of petroleum and public interest in alternative energy, environmental concerns, and now greenhouse gas and climate change. With one exception, the key features have remained constant. That exception is advances in enzyme technology that have been under investigation and development for 10 years or more but have a much shorter history of scientific pursuit in hydrolyzing cellulose into glucose. The caution is that the basics of enzymatic saccharification of cellulose to glucose have been under investigation since World War II, 60 years of research effort. Modern genetic methods can reduce the cost to produce the enzymes and can create cocktails of enzymes that are not available from one unmodified organism, but ultimately, the process is limited by pre-existing enzymes available from lignocellulosic-degrading organisms, and the majority of the enzymes used today are from organisms that have been known and used for this purpose for decades.

Although the basic approaches for producing transportation fuel from lignocellulose are relatively mature technologies,

Table 1. Summary comparison of Finland and the United States in size and economy[a]

	Finland	United States
Population (millions)	5.3	304
Area (km^2, thousands)	338	9,826
Forests (km^2, thousands)	257	3,020
Gross domestic products (billions)	$193	$13,800
Annual research (proportion of GDP)	3.4%	2.6%
Annual renewables R&D, 2007 (millions)	€ 25 ($40)	$574 (€ 363)
Total energy (EJ)	1.4	100
Renewable energy (PJ (%))	340 (23%)	7,210 (6.7%)
Biomass power (PJ (%))	300 (20%)	3,821 (3.6%)
Operating commercial gasifiers[b]	2	3
Planned gas-to-liquids demonstrations	1	3
Planned lignocellulosic ethanol	0	10

[a] $1.00 = € 0.632, June 9, 2008
[b] Lahti (50MW), Corensco (40 MW, waste), Stuttgart, AR (100 MW), Little Falls, MN (60 MW), Weyerhaeuser (50 MW kraft liquor).

they have largely remained at the R&D stage because the economics surrounding commercialization have generally not been favorable. Unless pricing structure in the fuels market is significantly altered or a breakthrough in one or more of the persistent barriers is achieved, the economics for producing transportation fuels from forest biomass are likely to remain marginal. Without significant advances, improvements will be incremental and very likely of an engineering nature. The pace of engineering improvements will increase when demonstration-scale and commercial-scale processes are running and capable of undergoing the types of detailed engineering and process scrutiny that have been used to improve industrial processes for two centuries. This is not to suggest that breakthroughs in the technologies for producing biofuels will not occur. However, a critical feature of more mature technologies is that the rate of scientific development is slower, and this should be anticipated for both the biochemical and thermochemical processing routes. Breakthrough advances in any technology cannot be predicted or scheduled. For well-researched processes, breakthroughs are often serendipitous because logical solutions have usually been tried without success. Recalcitrant cellulose and gasification tars and oils have both survived 100 years of research efforts. It is unrealistic to assume that people overlooked something obvious that is just waiting to be discovered. Modern researchers have vastly more powerful instrumentation, a far greater understanding of the fundamental science involved, and new tools and processes that were not previously available. With time, these tools may help provide the scientific breakthroughs that solve these problems. For now, these very difficult R&D challenges remain. To accelerate the commercialization of biofuels, an array of investment incentives may be necessary to reduce the economic risks of starting new biorefineries. Among major risks, the prices of commodities such as crude oil are very volatile, dependent on supply, demand, and even geopolitical considerations. Factors need to be considered—such as economic protections against price swings—to avoid a collapse of the developing biofuels industry when these alternative fuels enter the economy and impact the supply. Price supports have often been used to support agriculture and other desired industries, and they may be helpful to reduce risk and volatility in a capital-intensive commodity business such as biofuels.

Biorefinery in the United States and Finland

The United States and Finland have parallel interests in producing energy and transportation fuels from biomass, even if they arrived at these interests from different perspectives. Given the vast differences in size and population (Table 1), differences in the scale of their biomass research efforts should be expected. Whereas this is certainly the case, Finland's state-funded research program is more focused, with a larger percentage devoted to renewable energy. Biomass energy research in Finland represents 0.02% of GDP, compared with just 0.004% of GDP in the United States. To some extent, this recognizes the greater contribution of forestry, paper, and wood fuels in the Finnish economy.

Finland has been and is a leader in commercial implementation of biomass gasification. Currently operating are a mixed-fuel gasifier supplying product gas to a boiler in Lahti, and the Stora Enso Varkaus mill using a gasifier to recover heat value and aluminum from recovered Tetra Pak (Lausanne, Switzerland) liquid packaging containers. These two installations nearly equal the current operating investment level in the United States. A major difference in bioenergy emphasis in the United States is the 10 planned hydrolysis plants that are part of the DOE-funded integrated biorefinery and 1/10-scale biorefinery programs.

Purpose

This report provides a summary of implementation plans for biorefinery applications and government-supported research projects in Finland and the United States. It is an effort to define the state of the art for biofuels and bioproducts in

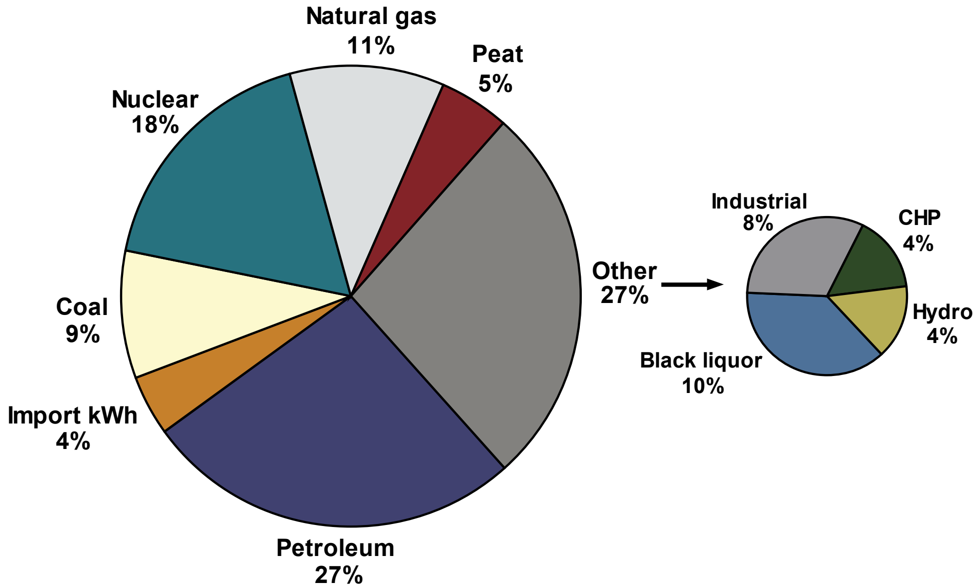

Figure 7. Energy use in Finland. Total use is 1.4 EJ.

the two countries. Providing a reliable sense of the latest developments in laboratories and pilot plants is impossible because these developments are invariably held confidential until published or patented. The report concentrates on announced commercial and pilot-scale demonstrations and publicly funded research projects. The assumption is that if people are still actively researching an area, it is recognized as a valuable R&D goal and has not been solved and had public release.

A number of long-standing technical impediments in biomass conversion remain to be resolved. Commercially applicable solutions to any of these problems would greatly improve the economics for producing a biofuel. Among these persistent goals are the following:

- Reduction of tars in gasification
- Less costly gas clean-up processes
- Improved gas reforming catalysts
- Increased saccharification rates and yield in wood hydrolysis to sugars
- Improved fermentation organisms that handle all sugars and high sugar and alcohol concentrations
- Improved fermentation organisms for producing other products—butanol, propane diol, hydroxyl-acids

To the extent that these are still active research areas, there is not an obvious consensus that drastic improvements have been achieved in any of these areas. Whether any breakthroughs have occurred and are still held as confidential is beyond the capabilities of this or any such report.

Existing Biorefineries

In considering the state of the art of biorefinery, there are really two states of interest: what already exists and the state of the science that will dictate products and processes in the future. The term biorefinery implies a process that mimics the forms or functions of a petroleum refinery. These interests do direct much of the science, but operating processes that effectively utilize biomass as fuel or chemicals satisfy the needs to replace fossil fuels and reduce the discharge of greenhouse gas to the atmosphere. This section broadens the discussion to include direct combustion as a replacement for other fuels in heat and power operations.

Finland has nearly doubled total energy use since 1970. This has been accomplished without increasing the use of petroleum and coal (Figure 1). Natural gas, nuclear energy, and black liquor from kraft wood pulping have supplied the bulk of the incremental energy needs, but hydropower and wood residuals have also contributed. This has made Finland a world leader in biomass energy. About 20% of total energy needs in Finland are supplied by biomass resources (Figure 7), ranking Finland third among EU nations for percentage of renewable energy (EUDGET 1997). The majority of the biomass use is supplied by Finland's comparatively large forestry and paper industries (Figure 8). Black liquor, the waste product containing about 50% of the wood used to make white papers and both bleached and unbleached paperboard, constitutes fully half of the renewable energy (Hakkila 2004). Another large part of the biofuel use is wood wastes generated at the paper mill site and burned to generate process steam and electricity (Tekes 2004). This includes nearly all the bark, some wood handling and chipping dust, and in some cases knots and other tree structures that do not pulp well. Furthermore, because the paper industry needs both steam for heating and drying and electrical power to operate motors and control systems, the steam produced in black liquor and waste wood boilers is used to generate electricity before being distributed and used in the mill as heat.

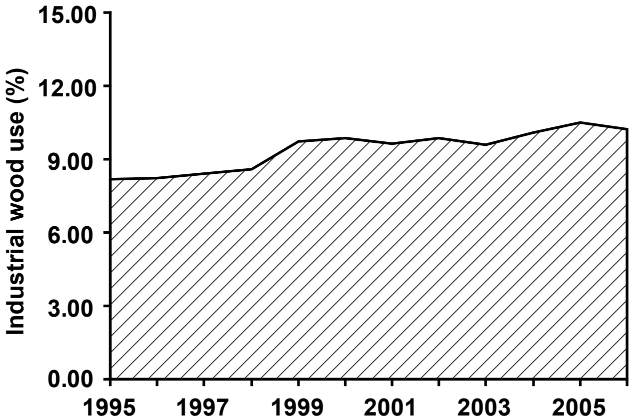

Figure 8. Industrial use of wood in Finland (Statistics Finland).

A growing use of wood in Finland is as district heating. Without a domestic supply of natural gas, Finland did not install a large natural gas distribution system for residential heating. Instead, this need is filled by central heating plants that supply steam or hot water to houses and small businesses in the district. This is cost effective in Finland because of the higher relative energy prices (since there are no domestic fossil fuels other than peat) and the long heating season, which improves the financial returns on the steam distribution infrastructure and makes the higher CHP energy efficiency available for a larger portion of the year. Many plants that used coal or peat as fuel were able to switch part of their fuel needs to wood and other biomass, and this use has been expanding (Tekes 2004). Many of these plants were initially—or have been converted to—combined heat and power (CHP) plants, where steam is produced at higher pressures and is used to generate electricity in backpressure turbines before supplying the lower pressure steam to the heating district. CHP plants are more energy efficient than stand-alone electric generation and account for about 75% of the heat and electrical needs in Finland (Tekes 2004).

The Finnish government is pursuing a policy of expanding the proportion of power and heat supplied by wood. This takes a number of forms: conversion of existing biomass boilers to handle wood, development of smaller scale turbines to make CHP cost effective at scales of 10 MW and below, and expanding the availability and cost competitiveness of wood residuals. The government provides incentives to land owners and harvesting companies to thin overgrown forests and collect logging residues (Tekes 2004). By one estimate, these efforts have tripled the use of forest biomass as fuel over the past 10 years, with a goal of increasing use an additional three times over the next 20 years (Tekes 2004).

With large reserves of coal, the United States has had little incentive to promote the use of wood as fuel or for production of chemicals. Overall biomass use for energy in the United States is just 3% (Figure 9), (USDOE/EIA 2008). The pulp and paper industry operates biomass boilers and black liquor recovery boilers in the United States but is a much smaller proportion of the economy, and the contribution to overall energy use is proportionately smaller. District heating is not as common in the United States because the heating season is shorter and cannot justify the expense of the steam distribution networks. As a consequence, most public utilities and private electrical producers do not have a significant outlet for supplying steam and operate at lower energy efficiency. The renewable contribution to electrical generation in the United States is about 9.5%. Of this renewable sourced electricity, hydroelectric provides nearly 75%, wind 11%, and the biomass about 6.25%. Nearly two-thirds of the biomass use is attributable to industrial users, the bulk of which produce pulp, paper, and other forest products. Of the 9.6 GWh of dedicated biofuel generating capacity, about 35% is installed in California. Much of this was in response to the Public Utilities Regulatory Policy Act of 1978, which required utilities to buy excess electricity generated by small producers at avoided costs (Blain and others 2003). In California, 43 biomass plants were constructed between 1980 and 1990. Many of the smaller and less efficient plants have shut down, but 29 of these plants are operating with over 700 MW in generating capacity. Biomass has not been the preferred choice for renewable sourced electrical capacity in California for over a decade. The current growth in renewable generating capacity in the state is predominately from wind turbines. This is the case throughout the United States, where installed wind turbine generating capacity has been increasing over 20% annually since 2001 (USDOE 2007).

In most of the United States, electrical power generation using biomass boilers costs more per megawatt-hour than generators operating on coal. Biomass supply is always a problem. The best way to reduce costs is to reduce the cost of the biomass, but this eliminates a large portion of the available wood because it is either too valuable as dimension lumber or too far away to transport to the utility. In California, biomass generators have typically not received government credit, subsidies, or other help. In fact, they did not even receive the disposal fee paid to waste haulers and landfills when the biomass utilities accepted wastes, even though in doing so they reduced the volume of materials going to landfills. Instead, the landfill or the waste haulers are allowed to collect and keep the disposal fee.

Both the United States and Finland have pursued biomass gasification and pyrolysis as advanced combustion options. Small commercial-scale gasifiers have been operated in Finland since 1983, with the operation of an Ahlstrom (Helsinki, Finland) designed low-pressure fluid bed gasifier at the Wisaforest Oy paper mill in Pietersaari and a similar but larger gasifier installed in Lahti to provide a product gas burned in a conventional boiler. In the United States, a similar biomass gasifier has been operated by a utility in

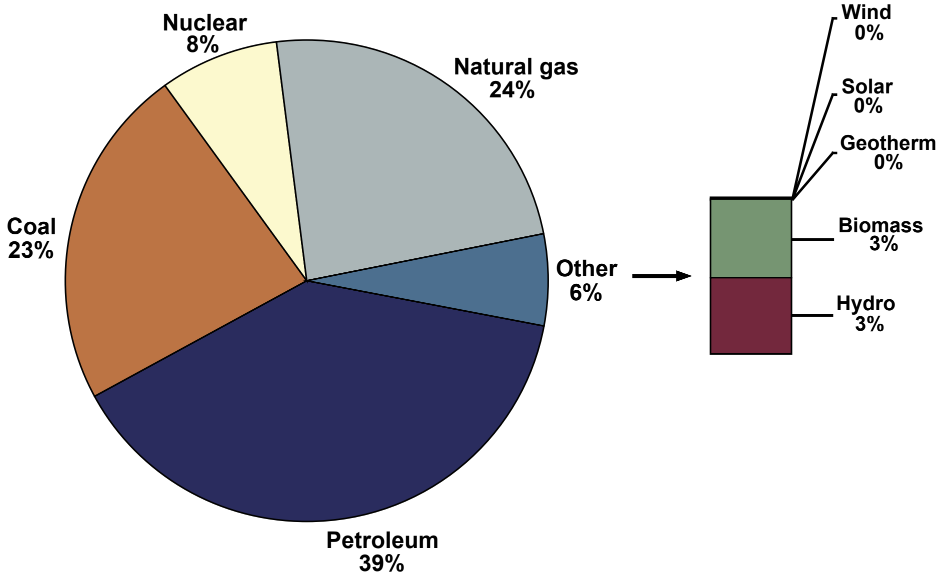

Figure 9. Energy use in the United States. Total use is 100 Quad in 2006 (105 EJ). (DOE Energy Information Administration, Annual Outlook, 2008.)

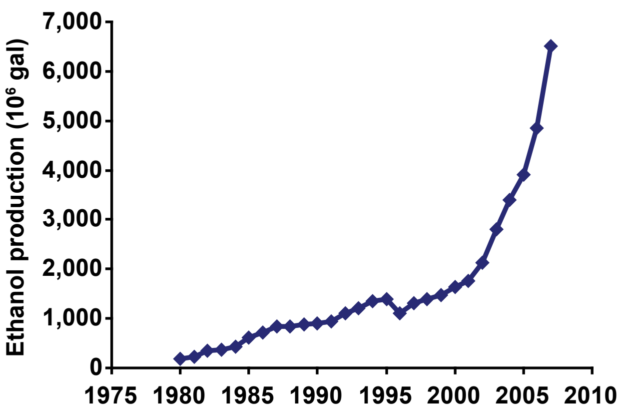

Figure 10. Ethanol production in the United States. (Source: Renewable Fuels Association.)

Burlington, Vermont. Whereas these gasifiers provide valuable experience in collecting and handling the biomass fuels, the designs are not directly applicable to the effort to reform the gas into liquid transportation fuels.

Both the United States and Finland have taken a step beyond these types of traditional uses of biomass with the development of an industrial sector supplying renewable transportation fuels. In the United States, this has taken the form of corn grain alcohol plants providing ethyl alcohol used as a fuel oxygenate, substitute fuel (up to 10% of gasoline), and E-85 (85% ethanol–15% conventional gasoline) usable in vehicles with engines designed for the high alcohol content (Figure 10). In addition, soybean oil and some other oil crops have been used to produce an esterified oil (fatty acid methyl ester, or FAME) used as a renewable component in diesel fuel. These applications have received considerable review for effectiveness because of the fuel needed to plant, fertilize, and harvest corn and soybean crops (Fargione and others 2008, Searchinger and others 2008). The impact on cost and availability of both corn and soybeans has been felt throughout the world. Much of the increase in corn and soybean prices must be due to the large petroleum demands of modern farming and the increase in the cost of fuel. The increase in prices is undeniable and, given the impact on food supplies in many developing countries, regrettable. The United States is moving away from the use of corn and other grains for fuel production, and the Energy Independence and Security Act of 2007 limits the credits for corn-derived alcohol to 15 billion gallons per year. The DOE has focused nearly all current efforts on using corn stalks, straw, and non-food plants as the raw material for transportation fuels. Research funded by USDA does support conversion of starch into higher value products that displace existing products manufactured from fossil fuels, but for biorefineries for producing transportation fuels, the USDA funding is also targeted at lignocellulosic raw materials. The farm bill passed in 2008 continues a $0.51/gal (€0.10/L) subsidy (tax credit) on corn-based ethanol and established a $1.01/gal (€0.20/L) tax credit for cellulosic ethanol. The bill also establishes an assistance payment for collection, harvest, storage, and transportation of eligible lignocellulosic biomass purchased by a biorefinery up to $45/ton (€38/tonne).

In Finland, renewable transportation fuel has taken the form of a dehydroxy hydrogenated oil produced from a mixture of palm oil, rapeseed oil, and waste fats and oils generated at rendering plants and other facilities. Neste Oil, the Finnish petroleum supply and distribution company, has commissioned one process line to supply this NExBTL diesel oil and has a second line under construction to double supply by 2009. This source of oil is not without problems (Fargione and others 2008), but Neste Oil has been careful to use certifiable oil supplies and is trying to avoid the undesirable land use impacts from displacing crop production (Tullo 2008). The worldwide impact on food availability and pricing has certainly been far less than that related to the use of corn for producing ethanol in the United States. Dehydroxy hydrogenated fats are also produced as a renewable diesel fuel in the United States, with a 300-bbl/day co-processing system at a ConocoPhilips refinery in Texas and a planned 5,000-bbl/day stand-alone plant being construction under a joint venture between Tyson Foods and Syntroleum in Louisiana (Tullo 2008).

The energy and fuel distribution company ST1 Oy is building a network to provide ethanol as a renewable fuel and gas oxygenate. To avoid competition with food products and because Finland does not have a large agricultural sector able to supply excess starch grain, the ST1 strategy is to produce ethanol from various waste streams. The company is building a network of small plants that use process food wastes from candy factories and bakeries as raw material. These plants hydrolyze starches to sugar and ferment the sugars to produce dilute alcohol, but the product is just distilled to 85% ethanol (15% water) for shipment to a centralized processing facility that dehydrates to absolute alcohol for fuel.

In summary, both the United States and Finland have a history of using biomass as combined heat and power in the forest products industries. Both countries also have experience with wood use in local utilities—in the United States for generating electricity and in Finland for CHP electrical and district heating. Both countries are currently using food-grade oils to make biodiesel. The United States has also developed an extensive corn ethanol industry that provides the fuel oxygenates needed in modern gasoline and now also supplements other transportation fuel needs. There is biomass supply available to expand the traditional solid fuel utility use of biomass in both countries. Finland continues to encourage conversion of local district heating to biomass or fuel mixtures including biomass. In the United States, coal-fired utilities continue to add biomass as a portion of the fuel mix. Both countries also recognize the need to expand biomass use to produce transportation fuels and chemicals and polymers that displace petroleum-based products.

Biorefinery Program in Finland

Publicly funded biorefinery research in Finland has centered around two coordinated initiatives by Tekes and two initiatives by the Academy of Finland. Tekes initiated the ClimBus program in 2004, which ended in 2008. It totaled €75 million distributed over five years. Tekes funding was approximately 50%, with the remainder provided by companies and other sources of matching funds. With the ClimBus program completed in 2008, Tekes launched the BioRefine program to run from 2007 to 2012. The BioRefine program coordinates and manages about €150 million, also with 50% from matching funds. Tekes funding supports applied science to engineering and pilot scale and is available to both universities and companies.

The ClimBus program focused on business opportunities for mitigating climate change. Specific objectives were to develop cost-effective, climate-friendly technologies that could be used by companies within Finland and also as future businesses or products, including services. The project included energy efficiency, renewable fuels, and utilization of greenhouse gases. In addition to supporting existing industry needs, the new technologies were to help generate new manufacturing and service businesses within Finland.

ClimBus supported 68 public research projects and 74 industrial research projects. Projects were not limited to biofuels or bioproducts but included projects to improve conventional combustion efficiency, combustion of recovered waste, and carbon management. Several biofuels and biorefinery projects were included:

- Evaluation of forest energy resources and the supply chain, including harvesting practices, transportation, costs, and uses of forest residuals (Tekes 2004)
- Evaluation of the suitability of domestic reed canary grass and barley straw as a feedstock for producing ethanol
- Improvements in a reed canary grass supply chain
- On-line moisture measurement of biofuels
- Fast pyrolysis to produce bio-oils and subsequent use
- Gasification, gas cleaning, and gas reforming to liquid fuels (McKeough and Kurkela 2008)

The BioRefine program has similar objectives but with an additional focus on technologies needed to develop second-generation transportation fuels—fuels produced from stalks and leaves of plants rather than seeds and storage tubers usually used as human or cattle food. This program aims to develop innovative technologies, products, and services based on national strengths. Another key objective is to increase national and international cooperation and networking between sectors and businesses in order to achieve further innovations. The program does not include stand-alone biomass combustion that is not integrated into other industrial processes or products.

The earlier ClimBus program did not ignore transportation fuels, but the proposed Finnish program to comply with Kyoto protocol was to focus more attention on stationary combustion sources to displace CO_2-intensive fuels like coal. This was a well-thought-out strategy that would have achieved the maximum reduction in CO_2 production and emissions in Finland. However, it did not technically comply with EU targets on transportation fuels, and the Finnish government has revised the internal goals and committed the country to displacing 5.75% of all transportation fuel with liquid fuels from renewable resources by 2010. Although the immediate commitments are satisfied by Neste Oil's investment in NExBTL diesel fuel, developing second-generation biofuels from lignocellulose or other non-food raw materials remains a critical goal in the new program.

Nine research universities in Finland have received grant funding from Tekes as part of the BioRefine program: University of Helsinki, Helsinki University of Technology (TTK), Åbo Academy, University of Jyväskylä, University of Turku, Lappeenranta University of Technology (LUT), University of Oulu, Tampere University of Technology (YUT), and University of Kuopio. A sampling of projects funded in the BioRefine program include production of fatty acids in algae and fungi for use in renewable diesel, kinetics of biomass pyrolysis, wood gasification and gas cleaning, new wood fractionation technologies, and an evaluation of bioactive wood polyphenols as antimicrobials.

In addition to the ClimBus and BioRefine programs, the Science and Technology Policy Council of Finland established an alternative funding process using approved second-party management to collect, select, and oversee projects. Tekes was assigned overall responsibility for the program. Of five proposed centers, Forest Cluster Ltd. was the first to be incorporated and issue a call for proposals. The process established has Tekes evaluate the entire package of proposals and decide to fund or reject as a package. This process offers the potential for more tightly coordinated projects while reducing the administrative burden on Tekes. In addition to the Forest Cluster, which has proposed research in renewable fuels, chemicals, and materials from trees, an Energy and Environment cluster is planned but was yet to be formed.

Additional funding is available in the biorefinery area from the Academy of Finland and through EU and other international grants. The Academy of Finland support goes beyond the sciences and encompasses a wide range of disciplines, including language studies, political science, and medicine. Support for science and technology tends to be on a longer time frame and more fundamental than projects typically supported by Tekes. The Academy has provided considerable long-term support for research on wood decay organisms and enzymes and bio-active wood chemicals. It supported a Center of Excellence at the Technical Research Centre of Finland (VTT) on Industrial Biotechnology that focused on enzymatic bioconversion of lignocellulosics (2000–2005).

The Academy of Finland has two biorefinery-related initiatives: Sustainable Productions and Products (KETJU: 2006–2010, €7.5 Million), and Sustainable Energy Research Program (SusEn: 2008–2011, €10.5 Million). Within the focused area of biorefinery, KETJU includes a consortium working to functionalize galactoglucomannans; a consortium on paper, bioenergy, and green chemicals from nonwood residues; and an individual project on improving the utilization of xylose. The SusEn program includes two projects on using algae to produce fatty acids, projects on polysaccharide-based biofuels and optimal treatment of lignocellulose to produce bio-ethanol, and a study of concepts for second-generation biofuels.

The KETJU program includes a joint request for proposals (RFP) with the French Agence Nationale de la Recherche, and the SusEn program includes projects with additional funding support from China, Poland, Luxembourg, and the Nordic funding organization. Joint RFPs were issued with Chile's National Commission for Science and Technology, and a similar RFP is planned with the Brazilian National Council for Scientific and Technological Development.

Government-Funded Research Centers

VTT Technical Research Center of Finland

VTT receives about a third of its funding from the Ministry of Employment and Economy, a third through competitive grants, and a third from corporate partners. Total annual funding is around €230 million (VTT 2007). Four of the BioRefine projects funded in 2007 and 2008 were awarded to VTT. Within the VTT organization are 46 knowledge centers, of which 6 are energy and forestry related. These knowledge centers have maintained active research on thermal and hydrolysis pathways for several decades. The knowledge center on wood harvesting and supply logistics is one of the few publicly funded R&D groups in this critical aspect of wood-residual-sourced fuels and raw materials. VTT has several extended research projects on second-generation renewable fuels, including projects on gasification, pyrolysis, and cellulosic ethanol. VTT is also conducting research on production of novel biomass-derived chemicals and materials.

METLA Finnish Forest Research Institute

METLA is part of the Finnish Ministry of Agriculture and Forestry, employs about 700 people, and has an annual budget of €54 million (METLA 2007). Nominally, 75% of the budget is provided by the Ministry and 25% is obtained through grants, contracts, and information services. METLA is the primary research organization for forest management, harvesting, and wood products. In 2007, METLA started a bioenergy program that includes projects on forest biomass production, impacts of intensive biomass harvesting, supply chain logistics, and new forest-based products. In this later project category is a project on extraction and uses of glucomannan polymers and oligomers.

MTT Agrifood Research Finland

MTT is also part of the Ministry of Agriculture and Forestry. State financing in 2007 was approximately €30 million, with joint project financing of €11 million and other income of about €3.7 million (MTT 2007). MTT staffing in 2007 was 627 permanent and 203 fixed-term employees. MTT has a project titled "From Fossil Fuels to Renewable Energy" focused on improving the profitability of agriculture through improved energy efficiency and efficient use of agricultural wastes to produce bioenergy or supply raw materials to biorefineries.

Biorefinery Science in Finland

As stated in the introduction, two common processes are used for converting lignocellulosics into other fuels. The hydrolysis route attempts to depolymerize cellulose and hemicellulose into component sugars and then uses fermentation organisms or direct chemistry to convert the sugars into a liquid fuel or useful chemicals. The second common route is thermal conversion, in which carbon-containing materials are heated under oxygen-deficient conditions to produce an oil or gas. The primary lignocellulosic resources for biofuels in Finland are thinnings from forest management processes to improve growth rates of preferred trees and other wood wastes from timber harvesting and processing plants. Because the majority of this material is softwood and softwoods are more difficult to processes with hydrolysis methods, Finland places less emphasis on these methods for production of fuels and more emphasis on the thermal routes. This is not to suggest that there is little research on hydrolysis and enzyme saccharification of biomass in Finland. There is a significant amount of research in these areas, but the interests are more for production of higher value chemicals and as support for industries that provide enzymes, process equipment, and expertise for hydrolysis-based biorefineries.

Tekes is supporting major research efforts in both areas. The following sections on biofuels research in Finland are separated into these two technologies—the thermal route and the hydrolysis route. In addition, there is considerable interest in Finland on products and chemicals that can be obtained from wood, whether as lower molecular weight extractive compounds or direct use of wood polymers.

Thermal Methods

Finland has decades of experience with wood gasification and pyrolysis (oil). This includes considerable effort to implement black liquor gasification and gasification of wastes and biomass throughout the 1990s. The pulp and paper industry has several incentives to pursue biomass gasification. The industry already operates conventional wood residual steam boilers using bark and wood dust generated in processing. Mills often recover convenient logging residuals to augment fuel needs and minimize costs. Most Finnish mills operate on these biomass fuels with minimal need for fossil fuels. One part of the process cannot be fueled directly from biomass: the lime kiln, which requires a gas or liquid fuel. This provides an incentive to the mills to operate gasifiers using the product gas to eliminate the last significant need for fossil fuel.

Two major pulp and paper companies are performing gasification studies. Stora Enso Oy has formed a joint venture company with Neste Oil Corporation to construct a 12 MW_{ther} oxygen-blown circulating fluidized-bed gasifier at the Varkaus mill. Working with Foster Wheeler Energia Oy (Bingert 2008) the project will test concepts for gas cleaning and a Fischer–Tropsch gas to liquids plant. If successful, the joint venture will construct a commercial-scale production plant to be located at one of Stora Enso's mills. VTT is acting as the main R&D partner in this project.

UPM-Kymmene is conducting gasification research working with the Gas Technology Institute and Carbona/Andritz to evaluate an oxygen-fired high-pressure gasifier on typical Finland forest residuals (Similä 2008). This project is evaluating gas cleanup and the Fischer–Tropsch gas-to-liquids processes, as well. In addition, Vapo, a forest fuels, peat fuels, and district heating service company, is evaluating gasification and Fischer–Tropsch reforming for peat and biomass resources.

VTT gasification research has been active since the 1970s. Early work included biomass gasification for lime kiln fuels, supplementary fuel for conventional steam boilers, black liquor recovery in the pulp and paper industry, and now gas reforming into renewable-sourced liquid fuels. This research includes biomass gasification performance and catalysts for tar removal (Kurkela and others 1996, Simell and others 1996). Where there is considerable experience producing Fischer–Tropsch hydrocarbon fuels using product gas from coal gasification, there is much less experience using product gas from biomass gasification. The Ultra Clean Gas (UCG) project started with Tekes funding in 2004 as part of the ClimBus program and extended to 2007 (McKeough and Kurkela 2008). Among other tasks, it evaluated gasifier designs, product yields, gas cleanup, and Fischer–Tropsch processing to liquid hydrocarbons. The project also evaluated the effects of gasifier size (throughput scale) on production costs. Scale is a critical economic factor in biomass conversion because high water content and bulky materials cause transportation cost to be high, but larger scale processes are usually less expensive per unit of output to construct and operate. Biomass-based processes need to optimize supply availability and transportation costs relative to process capital and operating costs. The project concluded that Fischer–Tropsch processes in the range of 200–400 MW_{feed} were viable. The VTT project reported an estimated production cost of €0.50/L ($2.5/gal) for Fischer–Tropsch liquids at the Climbus annual review in 2007 (Kurkela 2007). This analysis was based on a facility size of 200–300 MW_{therm} with integration to a papermill. Many of these processes have been tested in a 500-kW pilot-scale demonstration unit, including the gasifier design and gas cleanup. The UCG project also evaluated a distributed biomass pyrolysis system feeding a 300-MW_{feed} Fischer–Tropsch plant relative to a biomass-fed Fischer–Tropsch process of the same size. The evaluation concluded that costs would increase by 20% (McKeough and Kurkela 2008).

Current Tekes-funded projects in this area include fundamental studies of synthesis-gas production based on fluidized-bed gasification of biomass (VTT), BTL-liquid biofuels (UPM), and biodiesel from forest residues (Neste Oil). Tekes is also funding several projects on pyrolysis, including kinetics of biomass pyrolysis (Tampere), development of production and utilization of first-generation bio oils to advance use of pyrolysis oil (UPM), and integrated utilization chains of second-generation pyrolysis (VTT).

Hydrolysis Methods

The historic hydrolysis process used mineral acids to catalyze the hydrolysis of carbohydrate polymers into simple sugars. Most research has abandoned mineral acids and is now focused on the use of fungal and bacterial enzymes to catalyze hydrolysis to simple sugars. VTT has maintained an active research program in lignocellulosic enzymes since the 1980s. Researchers at VTT (Martinez and others 2008) and at universities in Finland are among the world experts in development and use of industrial enzymes. One of the most successful industrial enzyme processes is the application of xylanase to improve bleaching of wood pulp (Viikari and others 1994). With the prominence of the paper industry in Finland, Tekes provided critical support for this process. Researchers at VTT and Finnish universities led the research on isolation and testing of xylanase enzymes in this application. With decades of experience in fungal treatment of wood, ligninases to delignify wood, xylanases to remove xylans and accelerate bleaching, and cellulases to hydrolyze cellulose into glucose (Puls and others 1985, Juhas and others 2005) and condition cotton fabrics, Finnish scientists are at the forefront of research on fungal enzymes needed to hydrolyze lignocellulose to fermentable sugars.

Among projects in this research area, the ClimBus program has supported a VTT project to evaluate conversion of various raw materials to ethanol, pretreatment and hydrolysis technologies, and economic evaluations of the feasibility of ethanol production using the hydrolysis/fermentation route. This project has reported yields of barley straw and reed canary grass around 10 tonne/ha and good enzyme hydrolysis after steam explosion pretreatment (Pahkala and others 2007). A cooperative effort with MTT, the agricultural research institute in Finland, this study was more focused on biomass growth rate than conversion efficiency, but this is a critical consideration in Finland, where arable land is not plentiful and the growing season is short. Projects using hydrolysis methods and funded by the Biorefine program include the following:

- Pretreatments using pressurized hot water in a flow-through reactor, a joint project being carried out by the Finnish Forest Research Institute, Lappeenranta University of Technology, Åbo Academy, and KEUDA and evaluating Scotch pine, Norway spruce and silver birch
- Evaluation of two novel pretreatment processes, carried out by VTT and University of Helsinki
- Prehydrolysis-kraft pulping, being evaluated jointly by Lappeenranta University, University of Jyvaskyla, and Helsinki University of Technology
- Biorefineries—future business opportunity for forest cluster, University of Jyväskylä
- Industrially relevant, novel reaction routes for catalytic transformation of renewable biomaterials to high-value-added fine chemicals and complimentary products, Åbo Academy

VTT also has a €15 million project focused on the fundamentals of biorefinery—lignocellulose pretreatments, enzyme saccharification, and fermentation. A review of the literature shows excellent papers on the enzymology of cellulose and hemicellulose and the role of lignin and accessory enzymes in lignocellulosic hydrolysis (VTT) (Benko and others 2008) and on production and evaluation of thermotolerant cellulases (VTT) (Ohgren and others 2007).

UPM-Kymmene has teamed with Lassila & Tikanoja Plc. in piloting a waste-to-ethanol concept that will use waste paper, deinking sludge, or other industrial fiber-rich wastes as feed stock.

Value-Added Products

Interest in value-added chemicals and products is considerable. Nearly all the hardwood used by the Finnish kraft pulp and paper industry is birch. One project seeks to extract value from the bark removed before processing the birch for traditional products. Bark in general is rich in suberin, a hydrophobic waxy substance, and birch bark is also rich in betulin, which has anti-malarial and anti-HIV properties. Other examples include spruce bark, which is rich in stilbenes, and knots, which are enriched in polyphenols, lignans, and stilbenes. Many of these are biologically active compounds, and several have promise as antioxidants. Hydroxyl-acids can be found as degradation products of sugars in kraft black liquor. Glucomannan, which can be isolated from the process water of thermomechanical pulp (TMP) mills, has potential value as a food additive (Xu and others 2008) and as biodegradable films.

Projects on fractionation of wood provide interesting opportunities. This is not a new concept and has been a research objective of the paper industry and wood hydrolysis R&D programs for many decades. In the United States, the Lignol Innovations Inc 10% validation project using the Alcell solvent pulping process is based on the premise that there is higher value in lignin and hemicellulose (*vide infra*). However, there are very interesting developments in this area. For example, ionic liquids offer new opportunities for dissolving and fractionating wood (Kilpeläinen and others 2007). As a research tool, these processes are quite interesting; but as a potential industrial process, numerous issues will need to be addressed. Supercritical solvent systems are also of considerable interest but have been under study for a decade. Success with these concepts will depend on getting the high value for the lignin and hemicellulose fractions that was anticipated but not realized in the Alcell project.

Biorefinery Research Initiatives in the United States

The U.S. biorefinery initiative has been established in a number of Presidential directives and legislation. The two most recent set the following goals:

- The Advanced Energy Initiative (2006) established a goal to make cellulosic ethanol cost competitive with corn ethanol by 2012 (Bush 2006).
- The Energy Independence and Security Act of 2007 established a renewable fuel standard requiring 36 billion gallons of renewable fuels by 2022. This is nominally 15% of total petroleum use in the United States and nearly 25% of imported oil.

In the United States, four government agencies provide the bulk of research funding through competitive grants: U.S. Department of Energy (DOE), National Science Foundation (NSF), U.S. Department of Agriculture (USDA), and National Institutes of Health (NIH). Several other agencies have grant and research funding programs, the largest of which is the U.S. Department of Defense (DOD). For the most part, these programs are more selective and are not major funding sources. The exception is DOD, which has a very large research budget and is supporting research in biofuels. However, DOD research is not public, and little information is available on these activities.

DOE, NSF, and USDA all have grant programs in bioproducts and bioenergy. NSF focuses on fundamental science, typically without direct applications. DOE usually focuses on research development with timelines for commercialization of 5 to 10 years or less. USDA focuses on applied science with commercialization targets of 10 years. The DOE biofuels program is the largest in the United States but is a small fraction of the DOE research program.

DOE Bioenergy Initiative

The DOE has primary responsibility for setting and coordinating the national research agenda in renewable energy and biofuels. Total biomass program funding for 2007 was $270 million out of a total DOE budget of $24 billion.[1] DOE is concerned with all aspects of the biomass utilization effort, including collection and transportation, handling, processing, and product distribution.

[1]Biomass and bioenergy accounted for $195 million (2008). Genomics to life includes $75 million in the Bioenergy Research Centers.

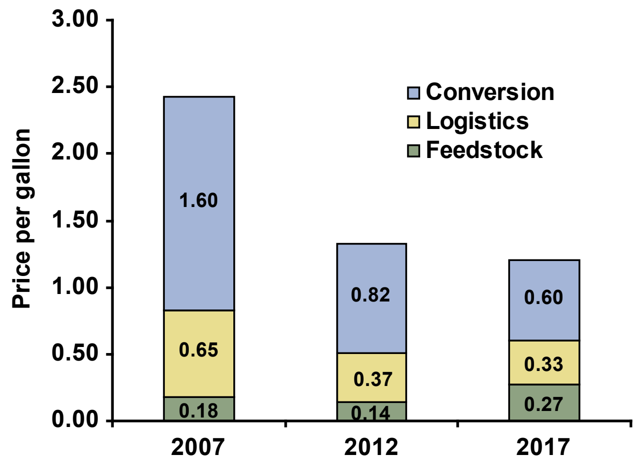

Figure 11. DOE projected production costs to make ethanol competitive with petroleum by 2012. Graph reproduced from USDOE (2008).

In 2006, the National Renewable Energy Laboratory projected a cost timeline for cellulosic ethanol (McMillan 2006) in their response to the President's Advanced Energy Initiative (Bush 2006). This estimated the production cost for lignocellulosic ethanol at $2.30/gal (€0.47/L) in 2005, the base year. The projected cost dropped to $1.06/gal (€0.22/L) by 2012 and $0.63/gal (€0.13/L) by 2020. Embedded in these projected costs was an 86% drop in the cost of the enzymes, a 75% decrease in converting costs, and a 63% decrease in delivered feedstock costs. One expressed concern in that cost projection was that delivered biomass decreased to $27 per oven-dry ton (odt) (€23 per oven-dry metric tonne (odmt)) by 2020, well below the current cost of pulp mill wood chips. The base case value for delivered biomass in 2005 was $50/odt (€42/odmt). The DOE updated the cost projection in 2008 (USDOE 2008) with an estimated base case cost of $2.43/gal (€0.49/L) for 2007 (Figure 11). The projected manufacturing cost in the new estimate drops to $1.33/gal (€0.27/L) in 2012 and $1.20/gal (€0.24/L) in 2017. The projected cost savings in this report include a 60% reduction in converting costs and a 40% reduction in supply logistics. The report projects a 50% increase in the grower payment (or stumpage price). The DOE deliberately separated the grower payment from the supply logistics to make it clear that all savings in delivered biomass were in supply logistics and improved conversion efficiencies. Actual grower payment increases from $13/odt (€11/odmt) in 2005, to $27/odt (€23/odmt) in 2012. Current pulpwood stumpage pricing in the United States ranges from $13 to $15/odt for hardwoods and $15 to $30/odt for softwoods. The delivered biomass cost to the plant is the sum of the logistic cost and the feedstock cost. This cost component drops overall by 28%, largely because of a projected increase in product yield from 65 gal/odt of corn stover (272 L/odmt) to 90 gal/odt (376 L/odmt). Feedstock cost is also discussed in an earlier report from DOE, the *Roadmap* *for Agricultural Biomass Feedstock Supply in the United States* (USDOE 2003). This report proposed a target price of \$30/odt (€ 25/odmt) as the required delivered feedstock cost because this made the cost of glucose from cellulose competitive with the historic \$0.07/lb (€0.11/kg) cost of sugar from corn starch and sugar crops. This cost goal remains but is relieved if converting yields can be improved.

The volatility of fuel prices and large increase in relative costs for petroleum-derived fuels since 2005 have obviously made the absolute values of these cost projections meaningless. However, the relative values and needed improvements to make cellulosic fuels cost competitive with corn starch and fossil fuel are largely unchanged. Even the starch-based cost has shown considerable volatility since 2006. The price of corn in the United States had been quite stable for years, but modern farm practices are energy intensive and if crop prices had not increased with the cost of petroleum, the U.S. farm economy would have gone into a recession. As it was, crop producers were doing much better than meat and dairy producers, who were faced with the increase in fuel and feed grain costs without a significant increase in product prices (USDA 2008). While fuel and grain costs were high, lignocellulosic ethanol was cost competitive with petroleum-based gasoline and ethanol produced from corn in the United States. But the price of corn decreased substantially with the drop in fuel prices and reversed this temporary cost advantage. The uncertainty about fuel prices has made it impossible to estimate the competitiveness of lignocellulosic fuel investments and has further complicated national efforts to develop renewable fuel alternatives. Currently, the U.S. government has provided an incentive of \$1.01/gal (€0.20/L) for production of second-generation renewable fuels. DOE has also provided large grants to support the construction of demonstration and commercial-scale production facilities.

A large portion of DOE funding is directed into three major programs: establishment of three Biorefinery Research Centers (\$75 million per year for 5 years), engineering and construction of six integrated commercial-scale biorefineries (a commitment of up to \$500 million), and nine 1/10-scale demonstration biorefineries (a commitment of \$240 million). Of the six initial integrated biorefinery proposals accepted by DOE, two have since withdrawn from further consideration, reducing this commitment to \$272 million.

These larger scale projects have proposed to use both thermochemical conversion routes, such as pyrolysis oils and gasification, and chemical and biological routes, including acid hydrolysis, enzyme saccharification, and fermentation. Using product gas, there is considerable research support for Fischer–Tropsch conversion to hydrocarbons but also catalytic conversion to higher order alcohols. A project on fermentation of product gas to ethanol was one of the integrated plant projects that withdrew from the DOE grant program. The biochemical routes are primarily focused on fermentation for ethanol but are also considering other chemical products such as butanol, lactic acid, polyhydroxy alcohols, and hydroxymethylfurfural.

In addition to these large-scale projects, DOE offers annual solicitations for applied biomass fuel- and chemical-related research projects. These smaller grant programs fund biomass-related research at the national laboratories and other eligible organizations. Applied projects funded by DOE typically require 20% or more in matching funds, and the development projects require greater than 50% in matching support.

Bioenergy Research Centers

The bioenergy research centers are part of the DOE genomics research program and, as such, all include significant contributions from genetic discovery and genetic engineering. The three centers were selected in 2007 and are to receive \$25 million per year for five years.

1. The Bioenergy Science Center (BESC) is organized by the DOE Oak Ridge National Laboratory in Oak Ridge, Tennessee. The center includes research to be conducted at the University of Tennessee, the Georgia Institute of Technology, the University of Georgia, Dartmouth College and the National Renewable Energy Laboratory. This center will focus on the resistance of plant fiber to breakdown into sugars and on energy crop systems from poplar and switchgrass. A major focus is to identify plants and/or genetically engineer plants with less cellulose recalcitrance. The project is centered around hybrid cottonwoods (*Populus trichocarpa, P. deltoides, P. nigra*). BESC also has a large project on consolidated bioprocessing of plant matter, incorporating the enzymatic digestion and fermentation processes within one microorganism. They are working on enzymes and enzyme combinations to improve the rates and yields in hydrolyzing cellulose. To accomplish these goals in a timely manner, BESC has dedicated considerable resources to develop high-throughput screening methods for pretreatments and enzyme treatments (Ritter 2008).
2. The Great Lakes Bioenergy Research Center is led by the University of Wisconsin in Madison, Wisconsin, and includes Michigan State University, the University of Florida, Iowa State University and the Illinois State University at Normal, Illinois. It also includes two DOE national laboratories: Oak Ridge National Laboratory and the Pacific Northwest National Laboratory. This center will focus on all phases of biomass production and processing. The biomass production research includes genetic engineering to improve cell wall processing, increasing the production of oils in plants, and biomass productivity. The biomass processing research includes improved enzymes through discovery and/or laboratory-created modifications and genetic engineering of cell-wall-degrading enzymes to be produced by plants. To improve biomass

conversion, the center will also work on incorporating cell-wall-degrading enzymes into traditional fermentation organisms to achieve consolidated bioprocessin

3. The Joint Bioenergy Research Institute is organized by the DOE Lawrence Berkeley National Laboratory. It includes the University of California at Berkeley, the University of California at Davis, and two other DOE national laboratories; Lawrence Livermore and Sandia. The Joint Bioenergy Research Institute is focused on understanding cell wall formation in rice and *Arabidopsis*. They will be looking for modifications to lignin and/or cellulose to enhance enzymatic processing. The center will also search for novel enzymes through new discoveries and look for organisms, or genetically modify organisms, to produce fuels such as longer chain alcohols or alkanes.

The Great Lakes Bioenergy Research Center and the Joint Bioenergy Research Center include gene modification by directed evolution or rational design in their project portfolios. The recently passed Energy Independence and Security Act of 2007 directs DOE to add three more Bioenergy Research Centers to encompass all six major geographic regions of the country.

Integrated Biorefineries

In February 2007, DOE awarded grants ranging from $33 million to $80 million in federal funds to support development of commercial-scale integrated biorefineries. Six projects were initially announced by DOE, but two have since abandoned their projects. Besides establishing operational processes for converting lignocellulose to liquid fuels and chemicals, the integrated biorefinery initiative and 1/10-scale biorefinery initiative (*vide infra*) are intended to initiate the development of biomass collection and handling methods, and the infrastructure for biofuel distribution and sales (DOE2 2008). Some of this is not needed for forest biomass that has been collected, transported, stored, and handled at reasonable full scale in the paper and lumber products industries, but the DOE effort is largely focused on agricultural residuals, corn stover, wheat straw, and dedicated fuel crops such as switchgrass. A potential problem with this focus is that it generates the renewable fuels industry in the same region as the existing corn ethanol industry and further aggravates the distribution problems the country already faces with ethanol transportation fuels. The projects, however, are not limited to agricultural residuals and several will use wood residuals as the primary feedstock. For both wood and agricultural residuals, we need improved methods to reduce handling costs for fuel grade materials; establishing harvesting and collection networks is one way to make progress on these problems and get energy crop agriculture started.

1. Abengoa Bioenergy received $76 million to build an 11.4 million gallon per year lignocellulosic ethanol plant to use 700 tons per day of agricultural residuals (corn stover, wheat straw, and switchgrass). The proposed plant is adjacent to an existing corn ethanol plant. The proposal includes a gasifier to provide energy for the lignocellulosic ethanol plant, with excess energy to supply the corn ethanol plant. The long-term strategy is to produce additional ethanol from the product gas. At their pilot facility in Nebraska, Abengoa is developing engineering data to scale the Kansas plant and a similar 1.3 million gallons per year cellulosic ethanol plant co-located with a grain ethanol plant in Salamanca, Spain. The ethanol yield in Spain can be estimated at 54 U.S. gallons (205 L) per tonne of lignocellulosic feedstock.
2. Alico Energy, LLC, was to receive $33 million to construct a gasification–ethanol facility in Florida. The method would have used a gasifier to provide the product gas, which was to be fermented to ethanol (Ahmed and Lewis 2007) using the organism and process developed by Bioengineering Resources, Inc., of Fayetteville, Arkansas. Alico has abandoned the project.
3. BlueFire Ethanol Fuels, Inc., Irvine, California, received $40 million for a proposed 19 million gallon per year concentrated acid hydrolysis and product sugar fermentation plant in Southern California. The process uses ion exchange media to collect the acid without diluting the sugar and then collects and reconcentrates the acid for reuse. They project a yield of 92 gallons (350 L) per tonne of biomass and a sulfuric acid makeup requirement of about 40 kg per tonne of biomass. The company has a continuous process pilot plant in Japan that has been operating for several years and can provide the engineering data for scale-up.
4. POET Project LIBERTY will receive up to $80 million to add a corn cob and stover lignocellulosic ethanol production line to an existing dry grind corn ethanol plant. The plant plans to use 700 tons per day of corn cobs and corn stover and produce 25–30 million gallons of ethanol per year. In their pilot-plant announcement in spring 2008, they indicate the expected yield is 80 gallons per ton (330 L/odmt). POET has Novozymes North America and E.I du Pont de Nemours and Co. as partners.
5. Iogen Biorefinery Partners, LLC, was to receive up to $80 million to construct a plant using mixed agricultural residuals and switchgrass to be sited in Idaho. Iogen is an enzyme manufacturer and has considerable experience with cellulosic ethanol production from wheat straw using a pilot plant in Ontario, Canada. The Idaho plant was proposed to use 700 odmt per day of lignocellulosic biomass to produce 18 million gallons per year of ethanol; 71 gallons (270 L) per tonne. This project has been suspended, but Iogen is proceeding with a facility in Canada.
6. Range Fuels, Inc., will receive up to $76 million to construct a gasification plant, with product gas being

reformed into mixed alcohols. The process is to be implemented in two phases, with the first demonstration-scale facility producing 20 million gallons per year of ethanol and the full-scale facility using 2,500 tons per day of waste wood to produce 100 million gallons per year of mixed alcohols (ethanol and methanol). The raw material usage and plant output suggest a yield of 110 gallons per ton (460L/odmt).

Of the integrated biorefinery plants, Abengoa Bioenergy, BlueFire Ethanol, and Iogen Biorefinery already have operating pilot or semi-commercial experience with their processes. Alico and Range Fuels intend to start at smaller scales. POET started a pilot-scale facility in South Dakota in late 2008.

10% Validation—Small-Scale Biorefineries

In January 2008, DOE announced four awards for demonstration lignocellulosic fuel plants to be sized at 10% of anticipated commercial scale.

1. ICM, Inc., will receive $30 million to construct a lignocellulosic biorefinery to be co-located by an existing 50 million gallon per year corn ethanol plant. The plant is to use varied agricultural residuals and switchgrass and a biochemical processing method. Novozymes is among the collaborators. There is insufficient information to estimate the process yield.
2. Lignol Innovations Inc will receive $30 million to construct a solvent pretreatment plant based on the Alcell pulping process, with subsequent saccharification and fermentation of the cellulose. The plant will be co-located by an existing petroleum refinery and will use 100 odt per day of hardwood and softwood to produce over 2 million gallons per year of ethanol (55 gallons per tonne, 240 L/odmt). Engineering and construction planning for this plant has been suspended due to problems raising additional funds in the current economy.
3. Pacific Ethanol, Inc., received $24.3 million to design and build a lignocellulosic ethanol plant to be co-located next to an existing corn ethanol plant in Oregon. Raw material is expected to be wheat straw, corn stover, and poplar wood residuals. The plant is based on the technology of the Dutch company BioGasol ApS and uses a steam/oxygen explosion process for pretreatment, enzymatic saccharification (Novozymes), and a proprietary thermophilic bacterium that converts both xylose and glucose to ethanol.
4. NewPage Corporation (formerly StoraEnso North America) will receive up to $30 million to construct and operate a wood-fueled gasifier and Fischer–Tropsch gas-to-liquids plant. The goal is 5.5 million gallons per year of hydrocarbon fuel using 497 tons per day of woody biomass. A key feature of this plant is integration with an existing pulp and paper mill complex using waste heat from the Fischer–Tropsch plant to supply the heating needs of the mill.

In April 2008, DOE announced three additional 10% scale awards:

1. Red Shield Pulp & Chemicals, LLC, received up to $30 million to install a pre-extraction process that adds ethanol fermentation to the traditional pulp and paper-making process. The project will restart an idle pulp mill in Old Town, Maine, and install the University of Maine pre-extraction process to produce a hemicellulose-rich sugar stream for the ethanol plant.
2. Mascoma Corporation received $26 million to build a cellulosic ethanol plant in Tennessee using switchgrass. The plant was to use Mascoma's proprietary process, probably based on the consolidated bioprocessing concept where one organism provides the saccharification enzymes and ferments mixed sugars to ethanol. Mascoma concluded that it is overcommitted and backed out of this project. The University has since formed a partnership with DuPont and Danisco to pursue the project.
3. Ecofin, LLC, will receive up to $30 million dollars to build a lignocellulosic biorefinery in Kentucky to convert corn cobs to ethanol. A unique feature of this plant will be the use of a solid-state enzyme process developed by Alltech, Inc.

In July 2008, DOE approved two additional 10% validation projects, a gasifier with Fischer–Tropsch hydrocarbons to be installed by Flambeau River Biofuels, LLC, and a lignocellulosic ethanol plant to be installed by Verenium Biofuels Corporation. Verenium has installed a 1.4 million gallon per year cellulosic ethanol demonstration plant in Louisiana and has been in testing and start-up since June 2008. The plant has a dilute acid pretreatment with a separate 48-hour five-carbon fermentation stage and a 72-hour simultaneous saccharification and fermentation stage for the cellulose (Patrick 2008). Verenium has licensed and proprietary technologies on five-carbon sugar fermentation and cellulosic enzymes that they intend to implement in the demonstration plant. Flambeau River Biofuels, LLC, is engineering a nominal 500 ton per day feed TRI gasifier with Fischer–Tropsch reformulation of product gas to hydrocarbons. This plant will be energy-integrated with an existing sulfite pulp mill.

The DOE has several other ongoing research initiatives that focus on improving feedstock collection and handling and reducing the costs of in-plant processing:

- $23 million for continued development of ethanologens and other fermentive organisms that are more robust to temperature and ethanol concentration (Cargill, Inc., Verenium Biofuels Corporation, E.I. DuPont de Nemours and Co., Mascoma Corporation, and Purdue University)
- $7.7 million for integration of gasification with catalyst-based reforming technologies (Emery Energy, Iowa State University, Research Triangle Institute, Southern Research Institute, and Gas Technology Institute)

- $34 million for continued improvements in saccharification enzymes for improved enzyme effectiveness and reduced enzyme cost (DSM Innovations Center, Inc., Genencor, Novozymes, Inc., and Verenium Biofuels Corporation)
- $18.4 million for the DOE/USDA Joint Biomass Research and Development Initiative, 21 grants for projects ranging from energy crops to production of bio-based plastics and composites

The USDA provides research grants through the Cooperative State Research, Education, and Extension Service (CSREES) National Research Initiative. The goal of CSREES in general is to advance the state of agriculture in the United States and support rural communities. The program supports applied research with a goal of successful application in about 10 years. The National Research Initiative is broadly based support of agriculture with two program areas focused on biorefinery projects. The Biobased Products and Bioenergy Production program distributed about $5 million in grant funds in 2007 and 2008, providing grants in two areas: (a) The biobased products area supports discovery and development of biobased products, such as plastic composites reinforced with lignocellulose materials, and polymers produced from lignocellulosics or from plants or microorganisms modified to produce suitable oligomers or monomers. (b) The bioenergy area focuses on research to improve production of ethanol or other suitable transportation fuels from grain-based or lignocellulosic-based feedstocks. The solicitation for 2008 specified lignocellulosics. These projects include genetic engineering of microorganisms to

- increase tolerance towards ethanol or fermentation inhibitors,
- increase the ability of specific microorganisms to ferment the broad range of sugars obtained from lignocellulosics,
- manipulate plant composition and structure to enhance enzymatic saccharification,
- produce saccharification enzymes using plants, and
- improve production of other fermentation products.

The program also supports searching for and development of more effective enzymes, kinetic and genetic research on enzyme function, and improved processing methods including separations and continuous processing methods.

The Biofuels and Biobased Products Small Business Innovation Grants (SBIR) support small businesses and start-up businesses working to complete development or implement projects in the biofuels area. These are typically short-term development grants with about a two-year application goal. Current SBIR grants include projects on membrane separations, pyrolysis oil filtration processes, and fermentation of xylose.

Smaller Research Grants

Saccharification

Both DOE and USDA are funding a significant amount of genetic engineering research on hydrolysis and enzymatic saccharification/fermentation processes. These projects include improving yields on existing fermentation products by suppressing competing product pathways, transferring specific metabolic (fermentation) capabilities into other useful organisms (Sedlak and Ho 2004, Ingram and other 1998), inserting cellulase enzyme production into fuel crop plants (Biswas and others 2006), and adding cell wall depolymerization (cellulase) capabilities to fermentation organisms (Zhou and Ingram 2001). These address some of the specific cost issues in the DOE long-term plan. It should be noted that similar research is included in the Biorefinery Research Centers.

Decreasing enzyme cost has been a DOE focus, and recruiting crops to produce enzymes is one scheme to achieve this goal. There is also an initiative to find or produce organisms capable of producing the cellulase enzymes and fermenting the product sugars—the so-called consolidated bioprocess approach. This includes at least two naturally occurring anaerobes with these capabilities (Warnick and others 2002, Zhang and Lynd 2005) and efforts to genetically engineer one organism with all these capabilities (Lynd and others 2005). The goal in these projects is not only to reduce the cost of the enzymes but also to simplify the process to one organism and set of process conditions.

A major limitation of existing lignocellulosic ethanol process capabilities is the length of time required to achieve high saccharification yields. High yields can be achieved in a number of ways but often take two or more days. Several efforts are focused on this problem, including many different pretreatment processes and efforts to discover or produce more robust enzymes (Baker and others 2005, Escovar-Kousen and others 2004). Much of this work is focused on thermophiles (Zhang and Lynd 2005, Baker and others 2005, Escovar-Kousen and others 2004) that can have accelerated metabolic processes, have more robust enzymes, and are more likely to have been overlooked in earlier efforts to find lignocellulose-consuming organisms. The efforts to genetically synthesize more robust enzymes through rational design and directed evolution extend beyond the now-common genetic engineering of transferring existing processes from one organism to another. These techniques certainly have endless possibilities, but this itself becomes part of the challenge. The enormity of the task and lack of an extended track record using these methods make it difficult to judge the probability of success or likely time frame needed to achieve it. We do know that millions of organisms have been working for millions of years to accomplish the same task, albeit with a less organized and efficient approach.

Value-Added Products

The primary focus at both USDA and DOE is on transportation fuels from lignocellulosic biomass. At USDA, research proposals on starch- and plant-oil-based chemicals and plastics—higher valued products that displace fossil-fuel-derived chemicals or materials—are still viewed favorably. DOE has longstanding interests in other fermentation-derived products (Werpy and Petersen 2004) that somewhat replicate interests of the U.S. Forest Service (Hajny 1981) and USDA. Among these, DOE has active research programs on polyhydroxyalkanoates and converting glycerol to propanediols. DuPont's fermentation process producing 1,3-propanediol is a notable commercial success in this regard. It should be noted that petrochemical routes to this chemical are not direct and are costly. It is still not clear that a starch-based fermentation route could compete directly against fossil-fuel-based chemicals where more direct synthetic routes are available. There are funded efforts for uses of starch and/or hemicellulose-based polymers for barrier films, expanded products, and other plastics and for use of sugars and extractives as pharmaceutical and nutraceutical precursors or products. There is considerable research interest in developing product value from lignin (beyond the Lignol Innovations project already mentioned). Compared with funding for transportation fuels, these research efforts are quite small and limited.

Feedstock and Supply

Feedstock and supply are recognized as a critical area to reduce costs, and both DOE and USDA support projects in harvesting and supply logistics. The DOE Office of Energy Efficiency and Renewable Energy (EERE) provided $10 million in 2007 to support projects in feedstock supply research. Examples include a project on single-pass harvesting, one on overall supply logistics, and one on infrastructure. Although of more interest to USDA, it typically does not have large amounts of grant money for this type of integrated research effort. Agricultural supply companies are fully supportive, and their engineering work on single-pass harvesting and other processes for collecting agricultural residuals represents the largest investment in this critical part of the process. There is no evidence that any company or organization has a good concept for lowering the cost of forest thinning carried out to improve growth rates or reduce fire risks. For natural forests, this type of biomass harvesting does not lend itself to modern concepts in engineering because it is small scale, disorganized, and distributed. The U.S. Forest Service, U.S. forestry companies, and Finland need real progress in this type of forest harvesting. With current methods, harvesting thinnings and other forest residuals is more expensive than pulpwood, and this problem is causing concerns among paper companies in the United States.

Summary

Although initially approaching biomass utilization from different directions and perspectives, the United States and Finland have arrived at nearly the same research focus on converting biomass to liquid transportation fuels and to materials and chemicals that replace petrochemical products. The overall goals of the two programs are now quite similar, differing only by emphasis.

The biorefinery program funded by Tekes and the Academy of Finland provides for a strong overall program. Compared with funding initiatives in the United States, Finland has maintained somewhat less support for hydrolysis methods leading to fermentation products and somewhat more support for gasification and pyrolysis. This difference in emphasis is dictated at least in part by the difference in available biomass, with hardwoods and agricultural residuals readily available in the United States and softwoods as the dominant low-value biomass available in Finland

In spite of the fact that ethanol as a fuel product seems to be of less interest in Finland, support for research on lignin- and carbohydrate-degrading organisms and enzymes remains strong. Comparing the levels of funding in the United States and Finland, non-glucose-based products seem to be of greater interest in Finland, and much of the fractionation and hydrolysis work is targeted to pharmaceuticals, neutraceuticals, and specialty biomaterials applications.

Finland has made a strong effort to increase the availability of low-value wood wastes through programs to assist forest owners in thinning overly dense stands and to create a market by encouraging utilities to substitute woody biomass for fossil fuels and peat. Where the U.S. DOE has focused biomass harvesting on agricultural residuals and agricultural energy crops, Finland has carried out considerable research in harvesting equipment and methods for wood wastes, baling and densification of waste-wood transport bundles, and inventory of available woody biomass. The fuel crop program in Finland is considerably smaller than that in the United States, appropriate to the much smaller proportion of land area suitable for agricultural crops. There is an active program in producing and harvesting reed canary grass and barley straw as agriculturally produced biomass suitable to the Finnish climate and growing season.

The program in the United States is more focused on fuels than other products and more focused on agricultural residuals than forest and forest products residuals. The program support for lignocellulosic ethanol and even projects on reforming synthesis gas to alcohols is quite different from the major emphasis areas in Finland. The United States has maintained an extensive effort on genetic engineering solutions to several of the persistent needs in saccharification and fermentation-based processes. Of particular interest is whether newer approaches such as rational design and directed evolution can provide the needed processing improvements.

A large part of the U.S. effort is in 13 ongoing demonstration plants using technologies ranging from gasification with gas reforming to enzyme saccharification with fermentation. Based on yields shown in the companies' published literature and stated position in the R&D progression, it is not clear which if any of these projects have breakthrough technologies that can approach the 90 gallons per ton (376 L/odmt) target yield DOE has established for 2012. Several, however, are well established companies with very astute R&D and investment track records and very likely have cost-effective and presumably profitable technologies or ways to implement the technology. Furthermore, larger scale continuous processes are needed to serve as platforms for routine engineering improvements in heat and material use that combine to make a much more efficient process. Based on research goals of the DOE Bioenergy Research Centers and the research project portfolios of DOE and USDA, there is not a conviction among grant agencies or the scientific community that critical improvements needed to make lignocellulose-based fuels cost effective relative to fossil fuels or starch-based ethanol have been achieved. To reach the government's renewable fuels goals, additional improvements in biomass logistics and biomass processing will be needed. Goals to increase cellulose saccharification yield, improve five-carbon sugar fermentation, improve gasification, tar minimization, and product gas cleanup, and generally reduce costs of lignocellulose-based processes remain.

As in Finland, the U.S. DOE recognizes that the pulp and paper industry understands biomass management and may provide an implementation pathway for forest-based biofuels. Two pulp and paper mills are among the gasification–Fischer–Tropsch projects, and two prehydrolysis pulping projects have been funded by DOE. The DOE is similarly looking to the existing corn ethanol industry in the United States to help establish the supply side for biorefineries using agricultural residuals. Several of the DOE projects are co-sited with existing corn-ethanol plants or are managed by corn ethanol producers.

Based on concerns within the United States (petroleum availability, energy security, and global climate change) and Finland's efforts to reduce CO_2 emissions and comply with EU targets for CO_2 reductions in the transport sector, Finland and the United States now have similar research goals in biomass energy, and the many similarities in the two programs is not surprising. Although there is not a formal cooperative process at this point, scientists are cooperating on research (Martinez and others 2008, Kilpeläinen and others 2007), and we should expect to see this continue. A remaining goal of this project is to see biorefinery research cooperation between the United States and Finland expand. Opportunities exist for shared research and experience in gasification, Fischer–Tropsch catalysts, and in particular, engineering of smaller scale Fischer–Tropsch plants. Both countries have existing projects on characterization of wood decay organisms, lignocellulosic decay enzymes, prehydrolysis kraft, and biomass pretreatment methods to improve enzyme saccharification efficiency. In general, it is easier to collaborate on pre-competitive projects where scientific advances can benefit all. As examples, projects in Fischer–Tropsch catalysts, cataloging wood decay organisms and enzymes, and cellulose recalcitrance to enzymes should be considered. Sustainability concerns are also shared. In agricultural applications, there is concern over how much biomass can be removed and how much must be returned to the soil to maintain soil productivity. The same concerns have been raised for forests, where tops and branches (and in Finland, even roots) that have been traditionally left in the forest are now removed for fuel—and in the future, biorefineries.

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