Meeting U.S. Liquid Transport Fuel Needs with a Nuclear Hydrogen Biomass System

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Abstract

The two major energy challenges for the United States are replacing crude oil in our transportation system and eliminating greenhouse gas emissions. A domestic-source greenhouse-gas-neutral nuclear hydrogen biomass system to replace oil in the transportation sector is described. Some parts of the transportation system can be electrified with electricity supplied by nuclear energy sources that do not emit significant quantities of greenhouse gases. Other components of the transportation system require liquid fuels. Biomass can be converted to greenhouse-gas-neutral liquid fuels; however, the conversion of biomass to liquid fuels is energy intensive. There is insufficient biomass to meet U.S. liquid fuel demands and provide the energy required to process the biomass to liquid fuels. With the use of nuclear energy to provide heat, electricity, and hydrogen for the processing of biomass to liquid fuels, the liquid fuel production per unit of biomass is dramatically increased, and the available biomass could meet U.S. liquid fuel requirements.

1. Introduction

A path forward is defined to completely replace the use of fossil fuels in the transport system of the United States. The alternative system is based on the use of biomass and nuclear energy. The nuclear energy is used to produce electricity, heat, and hydrogen with some of the electricity used directly in the transport system. Nuclear energy is also used to provide heat and hydrogen for the processing of biomass into liquid transport fuels. The combined system is robust, can be implemented with near-term technologies with a smooth transition to more advanced technologies, and can expand to meet growing transport requirements. Components of the system are economic today.

Liquid fuels (gasoline, diesel, and jet fuel) today are produced from fossil fuels. Oil is the primary feedstock in most of the world. Liquid fuel production is a major economic, national security, and environmental challenge. Two-thirds of the U.S. demand for crude oil is met by imports. Most of the world's oil reserves are in the Mideast, an area that is politically unstable. Last, the burning of liquid fuels in transport systems is one of the primary sources of greenhouse gas emissions worldwide. Thus, there is a need for alternative transport fuels.

The fuel cycle for liquid fuels includes obtaining the feedstock; conversion of that feedstock to liquid fuels; transport of the liquid fuels to the user; and burning the liquid fuel in a car, truck, or airplane. Each step consumes energy. Figure 1 shows the greenhouse gas releases per vehicle mile[1] from a diesel-powered SUV for each step in today's fossil fuel cycle for liquid fuels. The greenhouse gas releases are roughly proportional to the energy consumed in each step. With the production of liquid fuels such as diesel from fossil fuels, the total fuel-cycle energy consumption and carbon dioxide releases to the atmosphere are 130 to 200% of the energy consumption and carbon dioxide released from the vehicle.

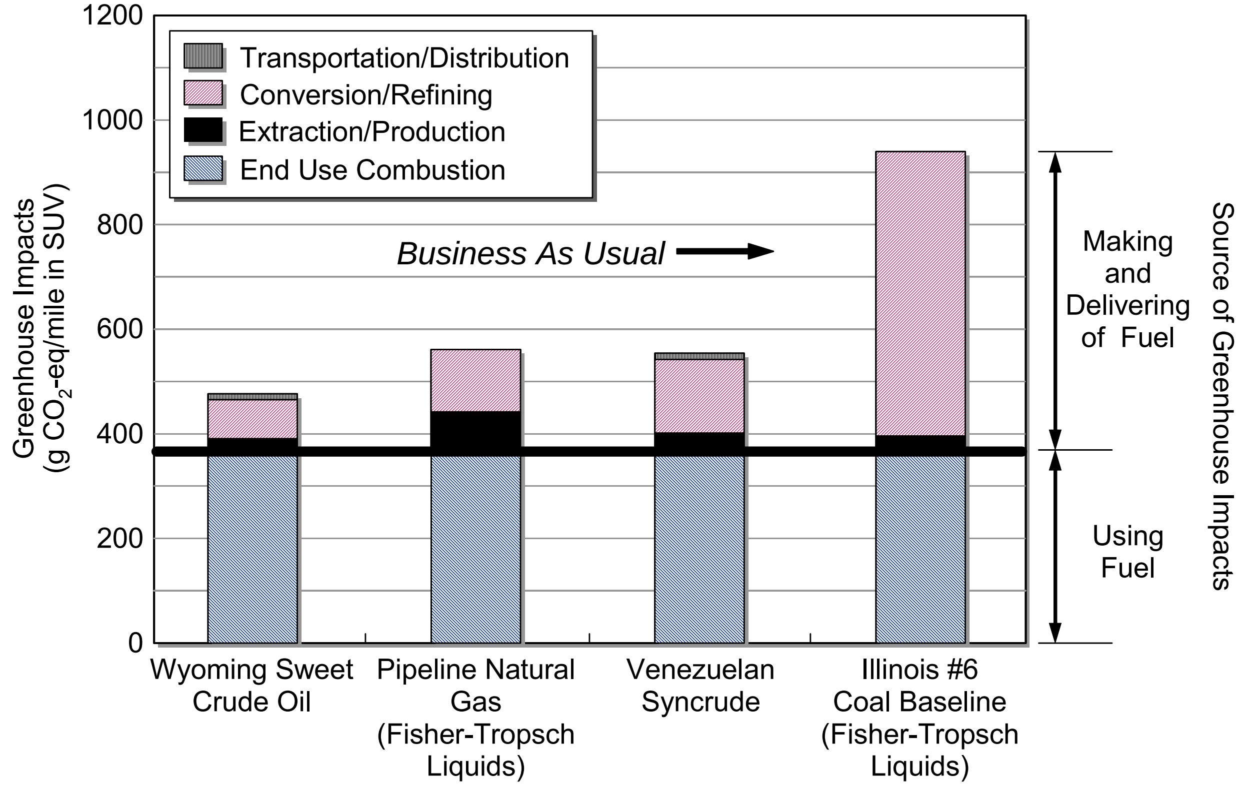

Fig. 1. Greenhouse gas releases per vehicle mile for diesel fuel produced from different sources.

The process of extracting high-quality sweet (low-sulfur) crude oil, converting it to diesel fuel, and transporting the diesel fuel to the fuel pump consumes relatively little energy and releases relatively small quantities of carbon dioxide. In contrast, if liquid fuels are made from coal, more energy is used in the production process than is available in the final fuel. As the stocks of high-grade crude oil are exhausted and liquid fuel is made from lower-grade resources, much more energy is needed to make a gallon of liquid fuel.

The production of liquid fuels from biomass has a somewhat different fuel cycle. Biomass is produced by sunlight, carbon dioxide from the atmosphere, and water. The biomass is converted to liquid fuels. The carbon dioxide from burning biomass fuels recycles the carbon dioxide back to the atmosphere. Like the fossil fuel cycle, significant energy required to convert biomass feedstocks to usable liquid fuels. Studies[2] indicate that the United States could produce about 1.3 billion tons of dry biomass per year for conversion to liquid fuels without major cost or availability impacts on the production of food or fiber. The energy value of that biomass can be viewed from several perspectives.

- *Energy value*. The energy content ($16 \cdot 10^6$ Btu/ton) of the biomass, if burned, would be equal to burning 9.8 million barrels of diesel fuel per day; however, additional energy would be required to grow, collect, and transport that biomass to furnaces.

- *Diesel fuel.* If all of the carbon (carbon fraction: 0.45) in the biomass were converted to diesel fuel, 12.4 million barrels of diesel fuel could be produced per day. This scenario assumes that nonbiomass energy sources provide the needed energy for operation of the biomass-to-fuel plants and to produce the hydrogen needed for the conversion process. The energy value of this diesel fuel exceeds that of the biomass if burned because of the non-biomass energy and hydrogen inputs in the biomass-to-fuel plant.

- *Fuel ethanol*. If the biomass were converted to fuel ethanol (89.8 gal ethanol/ton), the energy value of the ethanol would be equal to about 4.7 million barrels of diesel fuel per day. This calculation assumes that some of the biomass is converted into ethanol and that the remainder of the biomass provides the energy for the biomass-to-ethanol facilities. The energy value of the product ethanol is only half that of the original biomass.

The quantities of liquid fuels that can be produced from the nation's biomass depend upon whether an external energy source provides the energy for the conversion of biomass to liquid fuels. There is insufficient biomass to meet the nation's fuel demands if biomass is used as a feedstock for production of liquid fuels and as an energy source to operate the biomass-to-liquid-fuel plants. Nuclear energy—in the form of electricity, heat, and hydrogen—can provide this energy and enable biomass to become the primary source of liquid transport fuels.

This paper addresses four related issues: liquid fuel needs, the potential of using electricity for transportation, the viability of converting biomass into liquid fuels, and nuclear-energy inputs. The analysis assumes that hydrogen is used for production of biomass liquid fuels but not used directly as a transport fuel. From the perspective of the average person, no radical changes in the transport sector are assumed. The technologies are all relatively near-term technologies.

2. Liquid Fuel Needs

2.1 Fuel Type

Liquid fuels are chosen for use on the basis of two factors: (1) they can be easily made from crude oil, and (2) they have major advantages in terms of high energy density and safety. Energy density determines the distance between refuelings. Table 1 shows the properties of various possible future fuels[3] with different types of engines. These data show significant safety and vehicle range advantages in using liquid fuels such as diesel. The major advantage of direct use of hydrogen as a fuel is that it can be used in fuel cells with significantly higher efficiency. However, there are major technical, economic, and institutional challenges that will take significant time to overcome—including the difficulty in transitioning to a new fuel infrastructure. For this analysis, it is assumed that liquid fuels are the primary transport fuel.

Table 1. Comparisons of different fuel systems for automobiles

H_2 Storage Mechanism[a]	Engine Type and Eff (%)[b]	Est. Miles for a Tank of Fuel	LFL[c] (vol %)	UFL[d] (vol %)	Toxicity[e]	Storage Pressure (bar)	Storage Temp.
Compressed H_2	Fuel Cell: 70	219	4	74.2	MAH	700	Room
Liquefied H_2	Fuel Cell: 70	264	4	74.2	MAH	1	4 K
Metal hydride	Fuel Cell: 70	132	4	74.2	MAH	1	Room
Liquefied NH_3	Hybrid: 40	234	15.5	27	IDLH: 500 ppm	10	Room
Compressed CH_4	Hybrid: 40	416	5	15	AH	700	Room
Liquefied CH_4	Hybrid: 40	418	5	15	AH	1	109 K
Methanol	Hybrid: 40	285	6	36	TWA: 200 ppm; IDLH: 6000 ppm	1	Room
Ethanol	Hybrid: 40	285	3.3	19	TWA: 1000 ppm IDLA: 3300 ppm	1	Room
$LiBH_4$	Fuel Cell: 70	245	4	74.2	MAH	1	Room
Diesel hybrid	Hybrid: 40	800	0.77	5.35	Low (>1369 ppm for 8 h)	1	Room

[a]Metal hydrides at 5% H_2/lb metal at 8 lb/ft^3; Liquefied NH_3 = liquefied ammonia; $LiBH_4$ (lithium borohydride) as a 50% slurry in water.
[b]Eff = engine efficiency.
[c]Lower flammability limit.
[d]Upper flammability limit.
[e]MAH = minor asphyxiation hazard; AH = asphyxiation hazard; IDLH = Immediately Dangerous to Life or Health; TWA = Time Weighted Average, typically over 8 hours.

In parts of the world with high fuel costs, advanced diesels have become the preferred engine for cars and light trucks because of their excellent fuel economy. Engine technology is driving the fuel system toward diesels and ultimately toward hybrid diesels. In hybrid vehicles, an electric motor-generator-battery system provides the energy for rapid acceleration, recovers energy from braking, and provides energy for air-conditioning and other auxiliary systems when the vehicle is at stop lights. The internal combustion engine operates at the power level and engine speed that results in the highest fuel economy. This dramatically improves fuel efficiency because the efficiency of an internal combustion engine is strongly dependent upon engine speed and load.

For various reasons, ethanol is the primary biomass fuel being produced today: the technology already exists; the fuel is economic; and with an octane number of 113, the ethanol has special characteristics as an octane enhancer. In the United States, gasoline is the primary fuel for cars and light trucks. To obtain the required octane number for proper engine performance, an octane enhancer is added. Historically, the enhancer was tetra-ethanol lead, a compound that was banned because it caused heavy metal poisoning of children. The industry then turned to MTBE; however, this compound has caused serious groundwater contamination. Today, ethanol is becoming the preferred octane enhancer because of its lower environmental risks. Although, in effect, ethanol is both a fuel and a chemical additive, its value as an octane enhancer exceeds its fuel value. Fuel ethanol does have some drawbacks as well. As noted in Table 1, the range of diesel fuel vehicles is over twice that of a vehicle using fuel ethanol. This reflects the high oxygen content of ethanol, which takes up space in the fuel tank.

2.2 Fuel Demand

The United States consumes[4] slightly over 20 million barrels of oil per day, about two-thirds of which is used for transportation (Fig. 2). In the figure, the ethanol that is blended into the gasoline (the primary use of ethanol today) is included as part of the gasoline pool. Gasoline ($9.0 \cdot 10^6$ barrels/day) is the primary transport fuel, followed by diesel ($2.9 \cdot 10^6$ barrels/day), and then jet fuel ($1.6 \cdot 10^6$ barrels/day).

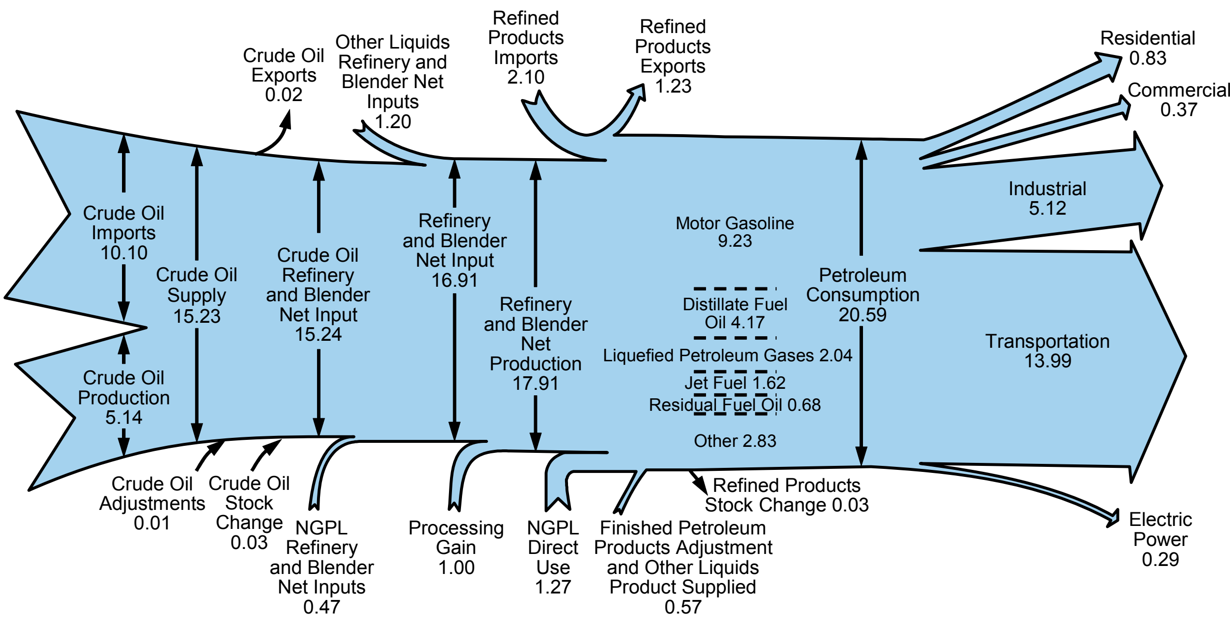

Fig. 2. U.S. oil production and consumption in 2006 (NGPL = natural gas plant liquids).

Future fuel demand is strongly dependent upon mileage standards, fuel prices, and technology. The U.S. vehicle fleet has relatively low fuel efficiency relative to those of other major industrial countries. As a consequence, more potential for rapid improvements in fuel efficiency exists. For example, because of the higher fuel prices in Europe, most new vehicles sold there are powered by more efficient diesel engines. This technology could rapidly penetrate the U.S. car and light truck markets because of (1) the large manufacturing experience base in Europe and Japan and (2) the similar infrastructures for gasoline and diesel engines. Honda's recent announcement that it will offer high-efficiency diesels in all car lines by 2010 suggests that such a change is already under way in response to higher fuel prices. Such a transformation could boost fuel economy measured in miles per gallon by ~33%. However, diesel fuel contains about 11% more energy, so the improvement in energy efficiency is ~22%.

Simultaneously, the introduction of hybrid vehicles implies major improvements in fuel economy. Full hybrid vehicles obtain about 40% better mileage than the equivalent gasoline or diesel vehicle. Hybrid vehicle technology is at an earlier stage of development than diesel technology; thus, there is the potential for more improvements. The two technologies are complementary. The use of diesel improves engine efficiency whereas hybrid vehicles enable the engine to operate at its most efficient speed and load. The U.S. demand for liquid fuels could be reduced significantly with relatively small changes in the market. Hybrid diesels could reduce oil consumption by over 3 million barrels per day.

3. Electric Transportation Options

Three electrification technologies that could reduce total demand for liquid transport fuels by 50% or more are in direct economic competition with liquid fuels.

- *Plug-in hybrid electric vehicle [PHEV]*. The PHEV is a hybrid car or light truck that has a larger battery system and functions as an electric vehicle for short trips and a hybrid vehicle (battery and liquid fuel) on longer trips. Because most vehicle trips are short trips, high-performance PHEVs can dramatically reduce liquid fuel consumption. It has been estimated that in principle, a 35-mile "all electric" range for cars and light trucks would reduce gasoline consumption by 74%, or about 6.7 million barrels of oil per day.[5] In practice, given that vehicles will not always be recharged, potential fuel reductions for cars and light trucks would be unlikely to exceed 50%.[6] Prototype PHEVs are operational, and Toyota Corporation has announced that the next generation of hybrid vehicles will include PHEVs.

  PHEVs have major potential advantages relative to traditional vehicle systems. Electricity is less expensive per vehicle mile than liquid fuels. Because PHEVs are multifuel (liquid fuel or electricity), they offer protection against local or national supply disruptions (hurricanes, war, boycotts). The vehicles also enable leveling of the electrical load with nighttime recharging of the batteries. With the use of non-carbon-emitting electricity production, no greenhouse gas is released when the vehicle is used in its electric mode. Last, the plug-in hybrids develop the electric vehicle infrastructure for hydrogen fuel cells that produce electricity for all-electric drive systems. The major challenge is to develop reliable affordable batteries or other energy storage devices.

PHEVs would enable nuclear energy to meet a major fraction of U.S. transportation needs. If the average gasoline fuel economy for cars and trucks is 20 miles per gallon, a million barrels of oil per day supports 8.2 million miles of travel per day. The same number of travel miles per day could be obtained with the electricity from twenty-three 1000-MW(e) reactors with a 90% capacity factor, assuming an electric fuel economy of 0.603 kWh/mile.[5] The fuel cost is low. At $0.10 per kilowatt, the electricity costs are $0.0603 per vehicle mile. For a car with a fuel economy of 20 miles per gallon, gasoline would have to sell for $1.21 per gallon to match this price.

- *Ground freight transport*. Recent analysis[3] indicates that liquid fuel consumption in the freight transportation system could reduced by over 80% by the combination of electrification of the railroads (as in Europe) with large-scale intermodal rail-truck systems. Most of the long-distance truck transport would be replaced by containerized freight that travels long distances by rail, with local delivery by truck. This type of transport would change about 5% of America's total energy demand from the use of liquid fuels to the use of electricity. If nuclear energy were used to produce the electricity, about fifty 1000-MW(e) reactors would also be required.

- *Air transport.* In the 1970s, the French government decided to build an electrified high-speed super train system to connect major metropolitan areas and reduce consumption of liquid fuels. That system has demonstrated that high-speed trains can replace air travel over distances of up to 500 miles because of lower costs, higher point-to-point speeds, and greater comfort. Simultaneously, rail stations have been built at major airports to provide point-to-point transport.

4. Biomass Options

4.1 Biological Resources

It is projected that by 2030 up to 30% of the liquid fuels consumed in the United States could be made from biomass[2,7] with an ultimate production capability twice as large. Long-term studies[8] indicate that biofuels could provide about 30% of the global demand in an environmentally acceptable way without impacting food production. Table 2 shows the estimated annual sustainable biomass production for the United States[2] to be about 1.3 billion dry tons.

Almost all of the biomass except "grains to biofuels" and some of the "process residues" are cellulosic feedstocks. The large biomass resources are crop residues (primarily corn stover) and perennials such as switch grass and poplar trees grown specifically for energy use on marginal lands. Today the primary biomass used to produce liquid fuels in the United States is corn (starch) that is converted to ethanol; however, as shown in Table 2, the resources of corn and other grains are limited. To make a major contribution to liquid fuel demands, biomass-to-fuels futures must be built on the much more abundant cellulosic feedstocks. Not included in this table are more advanced options such as growing algae.

Table 2. Sustainable annual biomass availability for liquid fuel production in the United States

Agriculture		Forest Residues	
Source	Millions of dry tons	Source	Millions of dry tons
Crop residues	428	Manufacturing residue	145
Perennial crops	377	Logging debris	64
Grains to biofuels	87	Fuel reduction treatments	60
Process residues	106	Fuel wood	52
		Urban wood waste	47
Total agriculture	998	Total forest	368

Plants are complex, possessing six biomass components that are potentially important in production of liquid fuels.

- *Cellulose*. Cellulose is the most common form of biomass and the principal constituent of wood. It is 40 to 60% of cellulose-rich feedstocks and is a biopolymer of glucose with a repeating unit of $C_6H_{10}O_5$. Hydrolysis can reduce cellulose to a cellobiose repeating unit ($C_{12}H_{22}O_{11}$) and ultimately to glucose ($C_6H_{12}O_6$). It is structured to be difficult to break down. This feature serves as a defense mechanism for plants, because only certain species of animals can digest cellulose.

- *Hemicellulose*. Hemicellulose is the second most common form of biomass and typically compromises 20 to 40% of most biomass. It is also a sugar biopolymer. However, unlike the other sugars, it is a highly branched chain of five- and six-carbon sugars. Like cellulose, only certain animals have the capability to digest it.

- *Lignin*. Lignin (Fig. 3), the component in cells that cements the cell structures together, is typically 10 to 25% of all lignocellulosic biomass. It is a highly polymeric, cross-linked aromatic structure with molecular weights near 10,000 and is derived primarily from coniferyl alcohol ($C_{10}H_{12}O_3$) via condensation polymerization. Lignin is believed to be the primary biological precursor to crude oil and because its molecular structure in many respects could be considered polymerzed gasoline.

- *Monomeric sugars*. Sugarcane, sugar beets, and several other plants have high concentrations of monomeric sugars. Traditional fermentation can directly convert these simple sugars into alcohol. This is the primary method that has been used to produce alcohol for human consumption for thousands of years. It is also the basis of fuel ethanol production from sugarcane in Brazil and in a few other locations where the combination of land, labor, and climate provides favorable economic conditions. Glucose ($C_6H_{12}O_6$) is the most common monomeric sugar. However, the availability of these feedstocks is limited because they are also used for food.

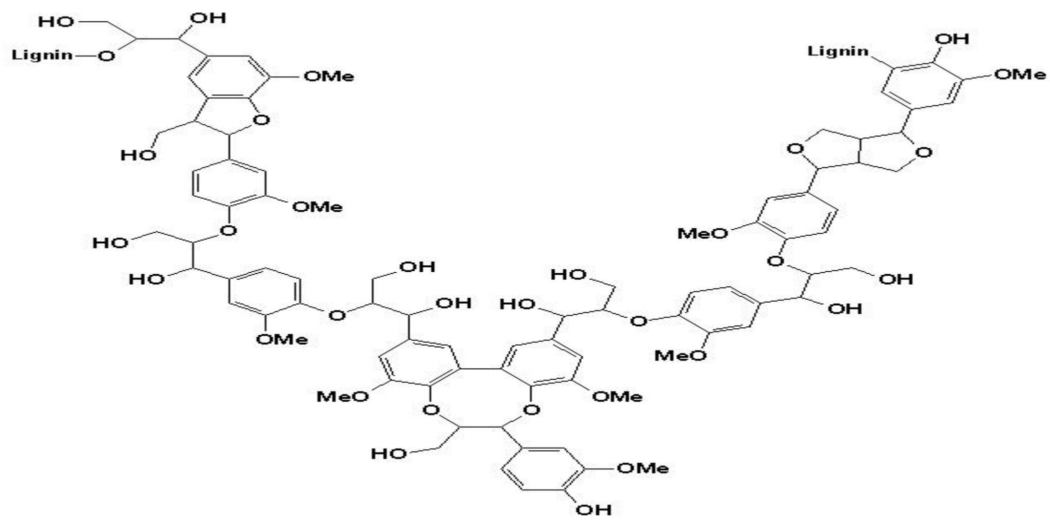

Fig. 3. Section of lignin polymer.

- *Starch*. Starch is a biopolymer of glucose, a monomeric sugar, with a repeating unit of $C_{12}H_{16}O_5$. It is the primary component of corn and other grains. Starch cannot be directly fermented to alcohol. An enzyme is required to break it down into simple sugars, which can then be fermented to alcohol. The resource availability of starch is an order of magnitude larger than that of monomeric sugars but is also constrained because starch is a food for humans and many farm animals.

- *Oils.* A few plants, such as soybeans, produce oils—making them a biological fuel resource that requires little processing to be converted into a transport fuel.

All plants contain significant amounts of cellulose, hemicellulose, and lignin. Cellulose-rich feedstocks typically contain 40–60% cellulose, 20–40% hemicellulose, and 10–25% lignin. A few plants contain significant quantities of monomeric sugars, starches, or oils. Databases provide the composition of many types of biomass, including secondary biomass such as municipal wastes.[9] In areas with appropriate climate and soils, plants can be chosen to produce sugars and oils. However, those plants will also have significant quantities of cellulosic materials because of the central role of these materials in plant structures. Consequently, a major component in any biomass-to-fuel future will be composed of cellulosic feedstocks.

The use of biotechnology to increase the biomass yields of plants for fuels is at an early stage of development, as is the use of biotechnology to alter the plant contents. Major work is under way to develop plants with (1) higher biomass yields and (2) selected biomass constituents. Over a period of a few decades, dramatic increases in biomass production may be possible with plants optimized for fuel production. For example, the corn yield per acre in the United States has increased by a factor of 6 over 80 years.[10] However, the biotechnology for optimizing plants for liquid fuel production is still at a very early stage of development.

4.2 Biomass Conversion Options

Biomass can be converted to three classes of liquid fuels: ethanol, biodiesel, and hydrocarbon fuels. The conversion options and the energy requirements of the process facilities are described.

4.2.1 Ethanol

The emphasis today in biomass-to-liquid-fuel production is on the production of fuel ethanol. The benefits of fuel ethanol have long been understood; however, the development of new biotechnologies is beginning to make this option technically and economically viable in large parts of the world. There are three primary feedstocks.

- *Monomeric sugars*. In Brazil sugarcane is the primary feedstock to produce ethanol from simple sugars. The sugarcane is squeezed to separate the sugar water from the cellulose-rich cane called bagasse. The sugar is then fermented to produce alcohol, and the bagasse is burned to provide the energy for the ethanol plant.

- *Starch*. In the United States corn is the primary carbohydrate that is converted to ethanol. Corn kernels contain carbohydrates (starch) and proteins. In the corn-to-ethanol process, enzymes convert the carbohydrates to sugar, which is then fermented to produce ethanol. About two-thirds of the corn kernel is starch that becomes ethanol. The nonfermentable components, which consist primarily of proteins and the by-products of fermentation, become animal food or are converted to other useful products. Because of the value of the protein as an animal food, these by-products are not burnt to produce energy to operate the plant. In most cases, natural gas is used to provide the energy to operate the plant. The rapid growth in fuel ethanol production is a consequence of three factors: (1) the development of low-cost enzymes to convert carbohydrates to sugars, (2) the need for an octane enhancer to replace MTBE, and (3) various incentives to encourage biomass to liquid fuel plants.

- *Cellulose and hemicellulose*. Because of feedstock availability, the primary source of fuel ethanol for the future is expected to be ethanol from cellulose and hemicellulose. Enzymes convert these feedstocks to sugars, which are then fermented to produce ethanol. A number of pilot plants are operating, the technology is advancing rapidly, and costs are decreasing. It is currently proposed to burn the lignin associated with the cellulose and hemicellulose to provide the energy to operate these plants.

The conversion of these feedstocks into ethanol is an energy-intensive process. Two forms of energy are consumed.

- *Fermentation*. The fermentation process converts sugars to ethanol using yeast. The yeast consumes sugar for energy and releases carbon dioxide in the process of converting the remaining sugars to ethanol.

- *Processing*. For the biomass to be converted to ethanol, the plant requires significant energy beyond that consumed internally in the fermentation process.

Consider the conversion of corn into ethanol—the primary production process for fuel ethanol in the United States. The non-solar-energy input to grow the corn and convert it to ethanol is typically about 70 to 80% of the energy value of the ethanol.[11] Most of that energy is supplied by burning fossil fuels. About one-half the energy input is in the form of low-temperature, low-pressure (150-psi) steam[12] used within the ethanol plant. The fermentation of sugars yields a mixture of water and alcohol. With corn, the mixture is typically >13% alcohol by volume. Above ~15%, the alcohol is toxic to the yeast. Distillation, an energy-intensive process using low-pressure steam, is required to separate the ethanol from the water. Smaller quantities of steam are required to sterilize the feed before fermentation and drying of various secondary products. After steam, the second-largest energy input for corn ethanol is fertilizer, particularly ammonia fertilizers.

Most U.S. ethanol plants use natural gas to produce steam and meet other energy needs. However, this process releases greenhouse gases and reduces the benefits of substituting ethanol for fossil fuels for liquid fuel production. The economics can be favorable because liquid fuels for transportation are more valuable than natural gas or other fuels. Ethanol production from all sources also consumes natural gas in the form of fertilizer. Natural gas is the feedstock for ammonia fertilizer production.

For ethanol plants based on corn, the fossil fuel consumption per gallon of ethanol can be cut in half by providing low temperature steam from existing or future nuclear reactors.[13–14] Because nuclear power plants are a non-greenhouse source of energy, this reduces the carbon dioxide releases from the entire corn-to-ethanol production process in half.

Nuclear power plants produce steam, which is then converted into electricity. Because ethanol plants require low-temperature, low-pressure steam, steam from the nuclear reactor would first go through high-pressure turbines to produce electricity and then be sent to the ethanol plant. In the ethanol plant, the steam would be condensed and warm water would be returned to the nuclear power plant. Almost all of the heat would come from condensing the steam. Modern steam systems would allow more than a mile of separation between the reactor and the ethanol plant; thus, the ethanol plants would be located beyond any security perimeter. The cost of such steam[13] is estimated to be $3–$4/million Btu, about half the cost of natural gas. The low cost is possible because the ethanol plant needs low-temperature steam; not the more valuable high-temperature steam.

Outside of the United States,[15] steam from nuclear plants has been used for district heating (45 reactors), desalting (10 reactors), and industrial purposes (25 reactors). However, this application of nuclear energy has not been used in the United States because of historically low natural gas prices and because nuclear plants were located in rural areas where there was no large demand for steam. With the rapidly increasing size of ethanol plants, the steam demands are now sufficiently large for the United States to consider using steam from nuclear plants for ethanol production. A large ethanol plant producing 100 million gallons of ethanol per year requires about 80 MW(t) of steam. The combination of increased natural gas prices, the growth in the size of ethanol plants, and the siting of ethanol plants in rural areas is now creating the option to use nuclear heat for ethanol production.

Current plans for conversion of cellulosic biomass to ethanol involve separation of the cellulosic components and the lignin components. Enzymes convert the cellulosic feedstocks to sugars, which are fermented to produce alcohol, while the lignin that can not be converted to ethanol is burned for energy. To maximize liquid fuel production per unit of biomass, the lignin must also be converted into liquid fuels. This can be done by using nuclear energy to provide the energy for ethanol production that is to be provided by burning lignin and than commercializing methods to convert the available lignin to liquid fuels.

Several processes to convert this lignin to hydrocarbon fuels are under development.[16–18] Because of the chemical structure of lignin (Fig. 3), the products are either high-value gasoline or high-value, high-octane (>100) oxygenates. Most of these processes require hydrogen for hydrotreating, a product that can be produced by nuclear reactors. If lignin is converted to liquid fuel and steam from nuclear plants replaces the lignin that was to be burnt as a fuel, the energy content of the liquid fuels per unit of biomass feedstock can potentially be increased by 50%, depending upon technological parameters and upon the specific biomass and its lignin content.

Use of nuclear energy for biomass-to-ethanol plants can reduce greenhouse gas releases in half and boost fuel production per unit of biomass by up to 50%. In this scenario, biomass would not be used as an energy source for biomass processing. The nuclear energy inputs into biomass-to-ethanol production would be 30 to 60% of the energy value of the liquid fuels that are produced. Most of the energy input is in the form of low-temperature heat; however, significant quantities would be hydrogen for conversion of lignin into gasoline and for use in the production of fertilizer. For ethanol from corn, the economics are favorable today. For ethanol from cellulose, the critical technology is development of methods to convert lignin to liquid fuels.

There are limitations on the use of nuclear energy to supply heat for liquid fuels from biomass. Biomass is expensive to transport. As a consequence, ethanol plants are located where biomass is available or where the by-products can be sold. This limits the potential sale of steam from nuclear plants to those plants near large sources of biomass or to river locations where low-cost barge transport may allow long-distance transport of biomass.

4.2.2 Biomass to Hydrocarbon Fuel

To maximize the energy value of the liquid fuel per unit of biomass, the final liquid fuel should be a hydrocarbon (Table 1). The energy value[16,19–20] of these liquid fuels per unit of biomass input is 3 to 4 times greater than that achieved by using biological processes to produce liquid fuels. This is a consequence of two factors.

- *Full carbon utilization*. All of the carbon is converted to fuel. None of the carbon is oxidized to carbon dioxide by the fermentation process used to produce ethanol.

- *High-energy fuel*. The biomass is fully converted into a hydrocarbon [$(CH_2)_n$] rather than into ethanol.

With these options, the energy and hydrogen content of the hydrocarbon liquid fuel are significantly greater than those of the initial biomass per carbon atom. This option requires significant external energy input in the forms of hydrogen, heat, and electricity. There are two technological approaches.

The first option is the Fisher-Tropsch process, which can convert all the carbon in the biomass to liquid fuels[20] when an outside source of hydrogen is supplied. This is the classical process for the conversion of fossil fuels to liquid fuels. There are multiple commercial Fisher-Tropsch plants that convert coal or natural gas to liquid fuels, primarily diesel fuel. It is a brute-force process that can process any carbon stream. The Fisher-Tropsch process has three major chemical reactions.

Oxidation of carbon: $2C + O_2 \rightarrow 2CO$

Water-gas-shift reaction: $CO + H_2O \leftrightarrow CO_2 + H_2$

Fischer-Tropsch: $(n/2 + m)H_2 + mCO \rightarrow C_mH_n + mH_2O$

Recent analysis[20] has provided estimated quantities of hydrogen required for conversion of biomass to diesel fuel. About 0.95 kg of hydrogen is required per gallon of diesel fuel produced. This assumes that heat is also supplied to the liquid fuel plant for drying of biomass (that is, hydrogen is not used to dry biomass). Large commercial electrolyzers[21] consume ~50 kWh per kilogram of hydrogen produced. Based on this analysis, ninety-two 1000-MW(e) nuclear reactors with a 90% capacity factor would be required to provide the hydrogen to produce 1 million barrels of diesel fuel per day from biomass. This assumes full utilization of the carbon in that biomass.

Alternatively, there is the potential to add hydrogen directly to biomass[22–23] to produce liquid fuels (hydrogenation). Sugar molecules are chains of carbon atoms similar to liquid fuels, except that many of the hydrogen atoms have been replaced by hydroxides (–O–H). Several processes, in the early stages of development, are being developed to replace the hydroxides with hydrogen atoms. If successfully developed, these processes have the potential for substantially lower costs than Fisher-Tropsch because (1) theoretically less hydrogen is required per unit of liquid fuel produced and (2) these alternative processes can potentially be implemented on a smaller scale.

For production of liquid fuels from biomass, plant size is a major issue. Biomass is bulky and heavy; thus, high costs are associated with its transport for any distance. For this reason, ethanol plants are distributed across the Midwest Corn Belt. A trade-off exists between the economics of scale for the biomass-to-fuel plants and the costs of biomass transport. The central requirement for both options is the need for hydrogen.

All of these estimates assume an average biomass. With a large-scale biomass-to-hydrocarbon fuel industry, there would be strong incentives to engineer the biomass to maximize hydrocarbon fuel yields by whatever process is used.

4.2.3 Biodiesel

The United States produces about 90,000 barrels per day of biodiesel from waste oils (cooking fat, etc.) and plant oils such as soybeans. With little processing, these oils can be converted to acceptable fuels.[11] The process energy input[24] is much less than that required for ethanol. However, the availability of such oils is limited. Oils are extracted from seeds; however, the biomass in the seeds after oil extraction is several times the quantity of oil. To maximize liquid fuel production, the biomass remaining after oil extraction will need to be converted to fuel by one of the processes outlined above. The development of plants to produce biodiesel provides a method to reduce process energy inputs per unit of liquid fuel, but does not alter the need for external energy for biomass processing to maximize liquid fuel production.

4.3 Biomass Futures

The biomass is available to meet the current liquid fuel needs of the United States if outside sources of energy can provide the heat and hydrogen for the conversion processes. Ethanol production with lignin conversion to liquid fuels with limited quantities of hydrogen is the first step. The second step is the production of hydrocarbon fuels that requires massive quantities of hydrogen. At the same time, there are strong reasons to believe that the ultimate capacity to produce liquid fuels may be much larger as the biotechnology and processing technologies are developed.

5. Hydrogen-Fueled Vehicles

The long-term transport option is the direct use of hydrogen for transportation. The nuclear-hydrogen biomass futures described herein create much of the infrastructure (hydrogen production systems) and technology (PHEVs) required for direct use of hydrogen. As such, a nuclear hydrogen biomass transport fuel system is an enabling system for other hydrogen futures.

A nuclear hydrogen biomass system is likely to encourage the earlier deployment of hydrogen-fueled vehicles in niche markets such as municipal buses, ferries, and other such applications. Onboard hydrogen storage is the single largest technical challenge for hydrogen-fueled vehicles; however, these classes of vehicles have “excess” space and thus do not require development of high-performance storage systems. However, the economic viability of such applications is strongly dependent upon having the hydrogen supply infrastructure and associated technologies.

In some markets where it will be extremely difficult for any hydrogen fuel technology to penetrate. The classic example is air travel. Studies[25] show large penalties for hydrogen-fueled aircraft. Weight restrictions imply that hydrogen would be stored as liquid hydrogen. However, the low density of liquid hydrogen relative to that of other liquid fuels implies larger storage tanks. The larger storage tanks result in a larger aircraft, with large increases in air friction and the need for more fuel to overcome this air friction. For such markets, nuclear hydrogen biomass liquid fuels may be the preferred long-term fuel option.

6. Nuclear Energy Inputs

If biomass is to meet the nation's need for liquid fuels, large quantities of external heat and hydrogen are required for the process facilities. There are many choices of nuclear reactors and hydrogen production options (electrolysis, high-temperature electrolysis, thermochemical, etc.) to supply heat and hydrogen. For part of the transportation market, liquid fuels will be in competition with electricity used in rail transport and for PHEVs.

If there were a national consensus, the experiences of France indicate that a transition away from oil could be conducted within 20 to 30 years. France suffered a series of oil-related shocks during WWII, the Suez crisis, the Algerian war of independence, and the 1973 oil embargo. The entire French economy was based on oil, including the generation of electric power. This led to a national consensus in April of 1975 that the country had to cut oil consumption. That consensus led to three programs: (1) use of nuclear energy to generate most of the electricity, (2) an industrial energy conservation program, and (3) the electric-powered French super trains to replace aircraft for travel distances up to a few hundred miles. These programs were implemented within about 25 years with drastic reductions in French dependency on oil. A transition away from crude oil as a transport fuel in the United States would require a similar level of effort relative to the total economy. The difference is more technological options now exist to eliminate crude oil in our transport system. Furthermore, these options are better understood than was the strategy that the French undertook when France made the decision to launch a program to reduce oil dependence.

7. Conclusions

A domestic greenhouse-neutral nuclear hydrogen biomass system to fully replace oil in the transportation sector is technically feasible today and could be implemented over a period of several decades. Nuclear energy would be used to produce electricity, heat, and hydrogen. Some of the electricity would be directly used for transportation. The liquid fuels would be made from biomass, with the energy input for biomass processing provided by nuclear reactors. By using nuclear energy to support the energy-intensive processing of biomass, liquid fuel production per unit of biomass is maximized while greenhouse impacts are minimized. Components of this strategy are economic today.

The conclusions are robust. Liquid fuel demands for transport could be reduced in half by combinations of several options such as diesel engines and plug-in hybrids. Independently, the biomass liquid fuel options could meet existing liquid fuel demands without reductions in oil demand. Rapid technological changes are occurring with the development of biological plants for fuel production, methods to process biomass, and plug-in hybrid vehicles, as well as in other areas. Consequently, the specific combination of biomass, nuclear energy, and liquid fuels for transportation will be determined by the results of this development work.

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