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Replacing Liquid Fossil Fuels with Liquid Biofuels from Large-Scale Nuclear Biorefineries

Charles Forsberg
Massachusetts Institute of Technology
Cambridge, MA, USA
cforsber@mit.edu

Bruce Dale
Michigan State University
East Lansing, MI, USA
bdale@egr.msu.edu

Abstract— Liquid fossil fuels (1) enable transportation and (2) provide energy for mobile work platforms and (3) supply dispatchable energy to highly variable demand (seasonal heating and peak electricity). We describe a system to replace liquid fossil fuels with drop-in biofuels including gasoline, diesel and jet fuel. Because growing biomass removes carbon dioxide from the air, there is no net addition of carbon dioxide to the atmosphere from burning biofuels. In addition, with proper management, biofuel systems can sequester large quantities of carbon as soil organic matter, improving soil fertility and providing other environmental services. In the United States liquid biofuels can potentially replace all liquid fossil fuels. The required system has two key features. First, the heat and hydrogen for conversion of biomass into high-quality liquid fuels is provided by external low-carbon energy sources--nuclear energy or fossil fuels with carbon capture and sequestration. The potential quantities of liquid biofuels are much smaller if biomass is used as (1) the carbon feedstock and (2) the source of energy for the conversion process. Using external energy inputs can almost double the energy content of the liquid fuel per unit of biomass feedstock by fully converting the carbon in biomass into a hydrocarbon fuel. Second, competing effectively with fossil fuels requires very large biorefineries—the equivalent of a 250,000 barrel per day oil refinery. This requires commercializing methods for converting local biomass into high-density storable feedstocks that can be economically shipped to large-scale biorefineries. Large-scale biorefineries also enable efficient coupling of nuclear reactors to the biorefinery.

Keywords— Biofuels, nuclear, heat, hydrogen

I. INTRODUCTION

Fossil fuels are today the preferred energy source because of their (1) low-cost, (2) ease of storage, (3) ease and low-cost to transport and (4) low-cost technologies to convert fossil fuels to heat or electricity. Liquid fossil fuels have the added advantage of being a high-density energy source enabling air travel and the use of long-distance heavy trucks. In these two applications added fuel weight and volume significantly reduces cargo capacity.

Fossil fuels provide almost all stored energy to address variations in energy demand—from cars to variable electricity production to seasonal home heating. In the United States coal inventories are typically 60 to 90 days of demand, oil inventories are 30 to 60 days of demand and natural gas inventories are 30 to 60 days. Electric vehicle battery storage is under a day. Hydro provides some storage for the electricity grid with large seasonal variations. However, today less than 18% of all energy used by customers (residential, commercial, industrial, and transportation) is in the form of electricity [1]. The remainder of energy is used in the form of heat. The total energy consumption in the United States is 25,155 TWh per year. To provide just one month of energy storage implies storing 2,000,000 GWh.

Current non-fossil energy storage options can't meet storage needs at the required scale. Today a single large hydro pumped storage facility provides 10s of GWh of storage. Large utility-scale battery systems have storage capacities measured in 10s of MWhs. The scale of these options is insufficient to meet low-carbon energy storage requirements. Going forward, there are only three practical large-scale energy storage options: (1) heat storage [2-4] coupled to heat-producing nuclear and concentrated solar power plants—including geothermal heat storage [5], (2) hydrogen [6] as a partial replacement for natural gas and (3) biofuels. Liquid biofuels can replace much of the energy storage capacity provided by liquid fossil fuels. Gaseous biofuel (i.e., renewable natural gas (RNG)) can provide the energy storage and all energy services currently provided by natural gas [7]. We touch lightly on RNG here.

The largest use of liquid fossil fuels is in transportation. Liquid biofuels have the potential to be a direct low-carbon drop-in replacement for gasoline, diesel and jet fuel. Equally important, they may enable large-scale use of electricity in transportation. There are two types of electric vehicles: (1) hybrid electric vehicles that have batteries and liquid-fuel engines and (2) all-electric vehicles. All-electric vehicles present massive challenges to the electricity grid. California studies [8] have examined the effects of when electric vehicles are recharged. Refueling primarily occurs in the early evening hours at times of peak electricity demand creating massive challenges for the electricity grid including massive needs for expensive electricity storage to match demand. This demand curve is driven by the single-car family for which work schedules require recharging the family vehicle when arriving home so it can be used later in the evening or in an emergency.

In contrast, hybrid electric vehicles avoid challenges to the electricity grid and add resilience to the energy system. If one has a hybrid vehicle, the gasoline supply assures the car is available at all times. The owner is willing to have the car battery charged at any time of low-price electricity because of assured drivability. Power failures are not a concern. In cold climates, the engine can provide power and heat—avoiding the rapid drain on batteries if used to heat car interiors. These and many other considerations lead to large incentives for biofuels at a scale that can replace most liquid fossil fuels.

We describe herein a biofuels system to produce drop in replacements for gasoline, diesel and jet fuel at the required scale. The system has two key characteristics. First, hydrogen and heat for conversion of biomass into liquid biofuels are provided by nuclear reactors; that is, biomass is primarily a source of carbon for fuels production and secondarily a source of energy. Half the energy content of the fuel may come from the nuclear systems. This dramatically reduces biomass feedstock requirements in terms of tonnage and the quality of the feedstock. Feedstocks with low energy value but a high carbon content become valuable for making liquid biofuels. Second, the system uses large-scale biorefineries to improve economics, maximize liquid fuels yields per unit of biomass and enable processing multiple types of feedstocks.

II. BIOFUELS PRODUCTION POTENTIAL

A. Resource Base

Globally biomass could meet a quarter of future low-carbon energy demands [9]. It is a low-carbon energy source because plants remove carbon dioxide from the atmosphere to produce biomass. As discussed later, with external sources of heat and hydrogen, the energy content of liquid biofuels can be almost double that of biomass feedstocks [10]. In contrast, processes that convert biomass to ethanol (fermentation) use biomass as an energy source and a feedstock. As a result at least a third of the energy value of the biomass is used in the conversion and a third of the carbon is released as carbon dioxide.

Recent assessments [11] have evaluated the potential of biofuels to meet U.S. liquid fuel demand. The U.S. annual transportation energy consumption is 29 EJ. This amounts to 0.6 billion tons of petroleum per year. The estimated U.S. harvestable biomass is a billion tons [12] with an energy value of 21 EJ. The carbon content of the petroleum is about 0.5 billion tons per year while the carbon content of the biomass is about 0.4 billion tons per year. There are three other factors that impact the potential of liquid biofuels to replace liquid fossil fuels.

- *Future liquid fuels demand* [13]. The demand for liquid fuels is expected to decrease. This is because of (1) continued improvements in engines and (2) the use electricity in transportation (electric cars and plug-in hybrid electric vehicles).

- *Increased biomass production*. Agriculture is flexible—it is designed primarily for food production so that is what it does. Agriculture can be changed [9] to produce the same quantities of food and larger quantities of biomass for fuel and chemicals for two reasons. First, food is primarily grown to feed animals where we choose the diet and can change that diet to maximize food and biofuels. Second, options such as double cropping (two crops in one year) are not used today because of the lack of demand for biomass that is not a good food for humans or animals but is excellent for biofuels.

- *Technology advances*. In the last 40 years the productivity growth of American agriculture has been greater than any other sector. Crop yields per acre keep rising over time.

The above considerations suggest that biomass feedstock is not a constraint on production of liquid biofuels at scale to meet transport and other liquid fuels demand. This assumes that biofuels not used as a large-scale stationary energy source for electricity production or heat for industry. These are lower value uses of biomass.

B. Processing Options

There are many ways to convert biomass into high-quality liquid fuels. It is currently unclear what flowsheet or flowsheets will be the preferred option. Processing options may vary depending on the type of biomass processed. We use one example herein—the Fischer-Tropsch flowsheet. This flowsheet in various forms has been used on a commercial scale to produce liquid hydrocarbon fuels since the 1940s. It is extremely versatile. The economics favor large facilities. Variants of this flowsheet today convert coal and natural gas into liquid fuels and carbon dioxide. It is a "brute force" process that converts all feedstocks into a hydrogen carbon-monoxide feedstock and then reassembles the molecules into the desired products. It is a three-step process.

The first step is gasification where a mixture of carbon, oxygen and steam produces syngas (more properly, "producer gas"). Heat is required and usually provided by the oxidation of carbon. However, heat can be provided from the nuclear reactor or by burning hydrogen. The carbon can be in any form—coal or natural gas or biomass. Biomass contains variable amounts of carbon, oxygen and water.

Carbon + Oxygen + Steam $\rightarrow$ $CO + CO_2 + H_2$

The second step involves gas cleanup and the conversion of the syngas to the proper ratio of carbon monoxide and hydrogen by separating out carbon dioxide or adding hydrogen. Again, heat can be added by the nuclear reactor or chemical reactions. The carbon dioxide can be recycled with the addition of hydrogen to produce a carbon-monoxide hydrogen mixture through the water-shift reaction.

The third step is the Fischer Tropsch process that produces the liquid fuels. Changing conditions changes the relative quantities of gasoline, jet fuel and diesel fuel. Other catalysts can produce other chemical feedstocks.

Liquid fuels: $CO + H_2$ (proper ratio) $\rightarrow$ Liquid fuels

The economics strongly favor large Fischer-Tropsch facilities. The Sasol coal-to-liquids plant in South Africa produces 150,000 barrels per day of liquid fuels. The Shell natural gas-to-liquids plant in Qatar produces 260,000 barrels per day of liquid fuels.

There are also multiple catalytic processes that selectively remove oxygen from biomass and add hydrogen to produce liquid biofuels. Table 1 summarizes the five major classes of processes [10].

TABLE I. YIELD AND HYDROGEN INPUTS FOR DIFFERENT LIQUID BIOFUELS PROCESSES (EXCLUDING FISCHER-TROPSCH)

Comparing Options to Produce Hydrocarbon Fuels from Biomass		
Platform (Process)	***Yield, Kg Octane per Kg Cellulose***	***Input Energy from Hydrogen (%)***
Thermo-chemical	0.310	0
Sugar	0.352	4.9
Carboxylate (Kolbe)	0.422	23.4
Carboxylate (2°Alcohol)	0.469	32.3
Carboxylate (1° Alcohol)	0.528	40.8

The gasoline yield (Octane) goes up with hydrogen input. Most of these processes have large heat demands. Much of this is lower-temperature heat for removal of water from the biomass or fuel mixtures.

We also note that fermentation is a potentially valuable processing option, but probably only for ethanol production and not higher molecular weight biofuels. Fermentation produces ethanol at high thermodynamic efficiency and good yields. Ethanol can be dehydrated and oligomerized to produce a range of fossil fuel replacements (C6 to C22 compounds-gasoline to diesel range fuels) by well-known technologies [14, 15]. The carbon dioxide arising from fermentation can be upgraded to renewable natural gas (RNG) using hydrogen/electricity from the nuclear reactor system (power to gas technology [16]), Biorefinery locations could also be chosen to take advantage of geological sequestration of carbon dioxide (carbon capture and storage of CCS). Organic residues resulting from the biorefinery system will likely be processed by anaerobic digestion, providing still more RNG and carbon dioxide. Overall the coupled biorefinery-nuclear system could produce a highly variable slate of biorefinery products to replace fossil fuels, liquid and gaseous.

C. *Large-scale Biorefineries*

Low-cost production of the final products imply large production facilities, equivalent to a 250,000 barrel per day oil refinery, for several reasons [17].

- *Economics of scale.* There are massive economics of scale in chemical processes. As a consequence, global refineries typically process 500,000 barrels of crude oil per day. Recent studies [18, 19] show similar economics of scale for cellulosic biorefineries.

- *Efficiency.* Large refineries and large biorefineries are more efficient than smaller plants. Part of this is that the efficiency of many types of equipment increases with throughput. However, far more important is the ability to convert all of the feedstock into the desired products. Fig. 1 shows the traditional integrated refinery flow sheet. In a large refinery, a "small" secondary stream can be upgraded into gasoline, diesel and jet fuel. In a small refinery it is uneconomic to upgrade such secondary streams. Such streams are sold as low-grade boiler fuel.

- *Variable Feedstocks and Products*. Large integrated refineries can accept wide variations in crude oil and produce a variable product slate—different for winter than summer. This includes changing the gasoline composition with season to lower the vapor pressure in summer when it is hotter to reduce air pollution. Small refineries can accept a limited number of crude oil types and limited products. Today's biorefineries produce single product (such as ethanol) or a few products. That is a viable strategy for filling niche markets. It is not a viable strategy if the goal is to replace liquid fossil fuels. Replacing fossil fuels requires multiple products where the demand and composition of different products varies by season. If the goal is to replace liquid fossil fuels, large integrated biorefineries capable of wide variations in feedstocks and products are required. The flowsheets in many parts of the plant will be similar and the complexity of such large biorefineries will match that of integrated oil refineries.

- *Variable product slate to increase revenue*. With the same oil input, large refineries can substantially improve revenues by changing their product slate of gasoline, diesel and jet fuel depending upon demand. This should also be true for a large biorefinery—producing variable quantities of fuels and chemical feedstocks. A large-scale bio-refinery, using the oil industry model, becomes the primary supplier of feedstocks to the chemical industry, thereby solving the chemical industry need for a low-carbon feedstock.

The economic requirement for a large low-carbon biorefinery has major system implications.

- *Nuclear heat and hydrogen requirements*. In the United States, transportation consumes almost 30% of all energy [1]. The previously described flowsheets imply that the nuclear energy inputs as heat and hydrogen into biofuels could exceed 10% of total U.S. energy consumption. The scale of such biorefineries and the requirements for steady-state heat and hydrogen inputs implies that only nuclear energy or fossil fuels with CCS can provide the inputs at the required scale. If fossil fuels are to provide the heat in a low-carbon world, the resultant carbon dioxide must be sequestered implying locating such a plant near carbon dioxide sequestration sites (i.e. Texas). The need for steady-state operation is driven by several considerations.
    - *Startup time*. Chemical separations systems such as distillation columns take hours to days to come to steady state operation. Until they reach steady-state conditions, the plant can't produce products of the required purities. This is in contrast to mechanical equipment (assembly lines), electrolytic cells and electrical equipment that reach steady state in minutes.
    - *Capital costs*. Refineries have high capital cost. It is uneconomic to operate at low capacity factors.

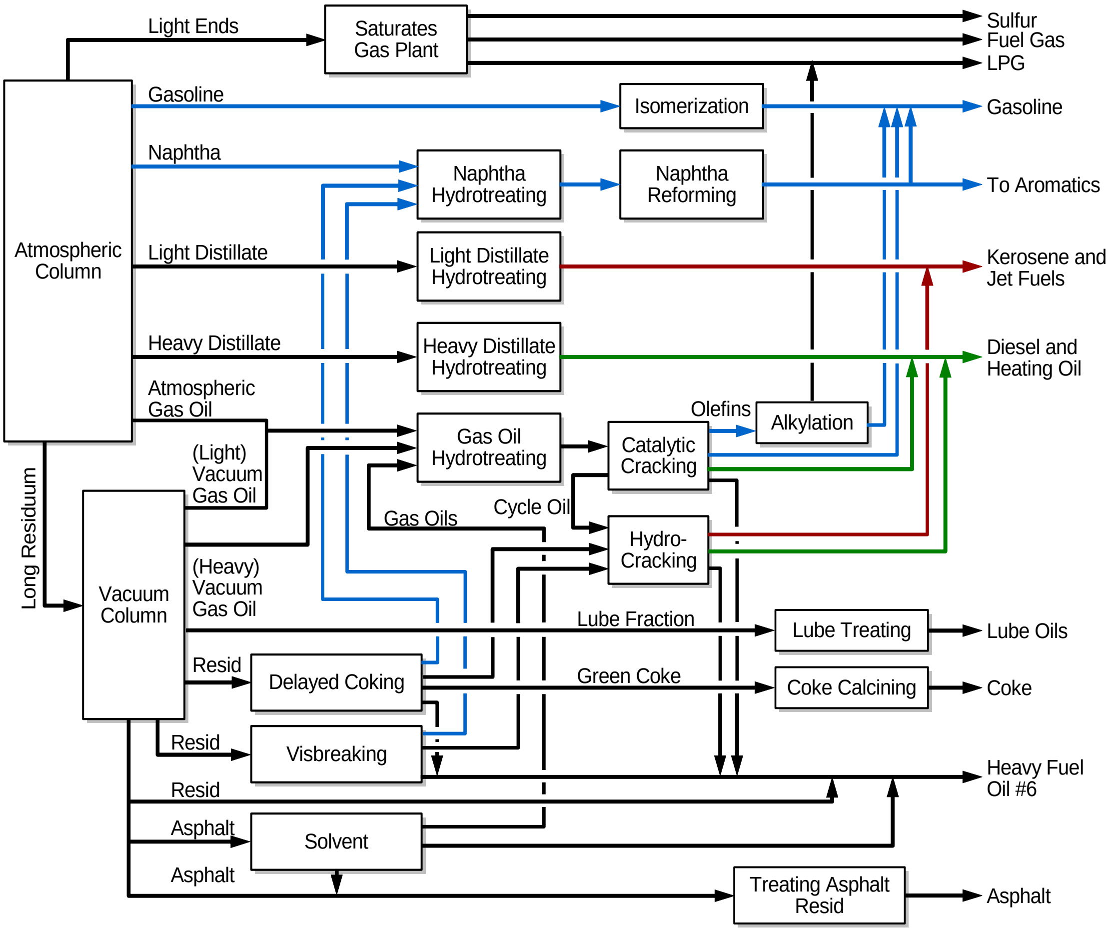

Fig. 1. Integrated Refinery Flowsheet.

- *Feed pretreatment*. The primary biomass form on this planet is cellulosic materials. As currently harvested and stored these are low-density feedstocks where the economics limit shipping distances to 20-50 miles. Large biorefineries require shipping biomass longer distances. That requires development and commercialization of technologies [18-20] to convert cellulosic biomass into storable, dense, transportable feedstocks. If converted to an intermediate dense storable product, cellulosic feedstock can be shipped to large-scale bio-refineries to enable economics of scale similar to those of oil refining. There are multiple processes in the early stage of development to produce a dense storable transportable product; but, the challenge is commercialization where the processes and the bio-refineries must grow at the same time.

D. Paper, Pulp and Biofuels

The largest users of biomass as an energy source are the paper and pulp industry. Pulpwood is converted into paper and many waste streams are burnt to provide heat for digestion of the pulp, drying of paper and other internal energy needs. Some waste streams are burnt to recover heat and chemicals. Many large paper and pulp mills have cogeneration plants with excess heat used to produce electricity that is sold.

If there are external sources of heat, much of the waste biomass could be converted into biofuels. One process to accomplish this is being tested at the pilot plant scale in Sweden. The scale of the industrial facilities and the central collection of biomass make such plants logical candidates for combined paper, pulp and biofuels production. We are not aware of any studies that have evaluated this set of options.

III. System Design

The system design [21] is shown in Fig. 2. Biomass is consolidated into dense, transportable forms and stored near its point of origin [18, 19]. It is shipped year-round to the biorefinery. This is the same model used for harvesting grain where the grain may be dried and then stored locally.

The nuclear reactors are collocated with the biorefinery as are hydrogen production facilities. Heat can be transported economically several kilometers. There are multiple hydrogen production technologies. It is generally thought that the most economic production option will be high-temperature electrolysis (HTE)—steam electrolysis of hydrogen.

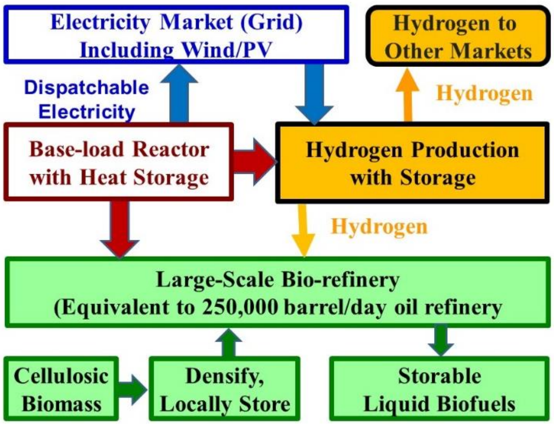

Fig. 2. Nuclear Biorefinery System

This process in the pilot-plant stage of development and has two advantages [21]: (1) a significant fraction of the heat input is in the form of low-cost steam and (2) the process is more efficient than competing processes.

IV. ECONOMICS

The economics of biofuels production depends upon the cost of delivered biomass, the biorefinery, and input energy. Delivered biomass is location dependent. Large scale upgrading of biomass to liquid biofuels implies massive energy inputs. The options are nuclear heat or fossil fuels with CCS. The fossil fuel option may be economic in the locations with low-cost fossil fuels and low-cost CCS, such as Texas. The cost of different energy sources are shown in Table 2. Nuclear energy provides low-cost heat. Nuclear reactors produce heat. It takes several units of heat to produce a unit of electricity. As a consequence, the levelized cost of heat (LCOH) is much less than the levelized cost of electricity (LCOE) from a nuclear reactor.

Wind and solar PV can produce low cost electricity but the cost of heat is high. Electricity can be converted into higher-temperature heat by resistance heating. One unit of electricity results in one unit of heat—making for more expensive heat. In addition, there is the cost of moving electricity. For the residential customer, about half the electricity cost is production and half the cost is in transmission and distribution. These transport costs are less for industrial facilities but still significant.

TABLE II. COST OF ELECTRICITY AND HEAT FROM DIFFERENT ENERGY SOURCES [22], YELLOW HEAT SOURCES ADD GRID COSTS

Technology	LCOE: $/MWh(e)	LCOH: $/MWh(t)
Solar PV: Thin Film Utility	43–48	43-48
Solar Thermal w Storage	98–181	33-60
Wind	30–60	30-60
Natural Gas Peaking	156–210	20-40
NG Combined Cycle	42–78	20-40
Nuclear	**112–183**	**37-61**

The other requirement for the biorefinery is very-large steady-state energy inputs because (1) chemical processes require long times to change production levels and (2) the high capital costs of a biorefinery require high capacity factors for low-cost production. The variable output of wind and solar does not match the input requirements for a biorefinery. The massive quantities of heat can only be transported economically over limited distances. Only nuclear and fossil fuels with CCS can provide the concentrated heat source that is required.

V. DEVELOPMENT CHALLENGES

A. *Policy Challenges*

Of all energy sources, biofuels are the least well understood by the public and policy makers. The biofuels debate is often framed as a choice between food and energy. However, since the 1930s the problem in the western world has been excess food production—there is untapped potential to produce large quantities of biomass for non-food applications. Food shortages are a consequence of distribution problems associated with poverty; they are not due to food production limitations.

The second policy challenge is integration across energy stovepipes. Nuclear, fossil, wind, solar and biomass are thought of as energy sources—each in their own box. Liquid biofuels at the scale required to replace liquid fossil fuels requires combining two energy sources—(1) biomass and (2) nuclear or fossil fuels with CCS.

B. *Technical Challenges*

The primary challenge [20] for large-scale low-cost biofuels and chemical production is the development and commercialization of technologies to convert cellulosic biomass into a storable, dense, transportable feedstock. The primary biomass form on this planet is cellulose. As currently harvested and stored, it is a low-density material where the economics limit shipping distances from 20 to 50 miles. If converted to an intermediate dense storable product, cellulosic feedstock can be shipped to large-scale bio-refineries to enable economics of scale similar to that used in the conversion of crude oil into gasoline, diesel and jet fuel. There are multiple processes in the early stage of development to produce dense, storable transportable products; but, the challenge is commercialization where the processes and the bio-refineries must grow at the same time.

The second technical challenge is development of the flowsheets and technology for a biorefinery at scale—the work has not been done. There are many options but no roadmap to sort out which options are the most economic. This includes coupling of nuclear reactors to the biorefineries. What is important in this context is that different processes have different heat requirements in terms of temperature. The optimum processes that couple to a high temperature reactor may not be the optimum processes that couple to a light water reactor.

C. *Deployment Schedules*

One of our conclusions is that a nuclear biofuels system could be deployed at scale in less than 20 years. This is based on three considerations. First, most of the technologies exist. What is required is demonstration at scale. Second, the agricultural sector developed the ethanol industry in about a decade. It is credible that the facilities required to densify biomass into a dense shippable product could be deployed in a relatively short period of time if there were economic incentives. Last, large-scale biorefineries are similar to large-scale oil refineries. The oil industry has the technical capabilities, project management skills and resources to develop and build biorefineries. It would be a variant of their current business.

VI. CONCLUSIONS

In the United States liquid fossil fuels can be replaced with low-carbon high-quality biofuels that are drop-in replacements for gasoline, diesel and jet fuels. Feedstocks are available, biomass feedstocks can be expanded and the feedstock costs are similar to crude oil. Biomass resources are sufficient if (1) external low-carbon heat and hydrogen are provided to biorefineries to avoid burning biomass for energy and (2) biomass is not used as a large-scale stationary energy source. Given the higher value of liquid fuels relative to stationary energy production, economics would probably drive the biomass to liquid fuels conversion rather than use as a stationary energy source. The energy inputs from nuclear plants to biorefineries could exceed 10% of total U.S. energy demand. Economics requires large biorefineries with their greater efficiency and economics of scale. Large-scale biorefineries require commercialization of technologies to densify biomass to enable economic shipment to biorefineries.

The fundamental challenge is not technical or financial. It is vision—bringing together the agricultural, nuclear and oil industries to assess and develop the option. This is not an option that can be created in a laboratory or by any single group. It is fundamentally a systems challenge to rethink biofuels.

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