# The Future of Gasoline, Diesel, Jet Fuel and Chemical Feed Stocks

C. W. Forsberg* and B. E. Dale
*Massachusetts Institute of Technology, Cambridge, MA, 02139, cforsber@mit.edu
[1]Michigan State University. East Lansing, MI, bdale@egr.msu.edu

If the world is to decarbonize quickly at an affordable cost, the primary route needs to be production of gasoline, diesel, jet fuel and chemicals from cellulosic biomass made with massive external heat and hydrogen inputs. Cellulosic biomass is the most abundant form of biomass on earth and includes a very wide variety of plant materials and organic residues, approximately 100 billion tons of such materials are fixed annually worldwide by photosynthesis. Examples include corn stover, forest debris and kelp. External heat and hydrogen inputs in the conversion process reduce the required quantities of cellulosic feedstock to enable meeting global liquid fuels demand without major impacts on food and fiber prices. Because plants remove carbon dioxide from the atmosphere to grow, there is no impact on atmospheric carbon dioxide by burning the resulting biofuels. Properly designed, the chemical conversion processes enable recycle of soil nutrients and sequestration of carbon char to soils that enable more sustainable agriculture and forestry.

Liquid hydrocarbon fuels, including gasoline, diesel and jet fuel, provide 48% of the energy to the final customer in the United States and a third of global energy. In comparison, electricity globally provides about 20% to the final customer. Most hydrocarbon liquids are made from crude oil—with smaller amounts from coal, natural gas and biomass. This is an accident of history. If we existed in a world with no fossil fuels, we would have invented liquid hydrocarbons similar to gasoline, diesel and jet fuel. Converting cellulosic biomass to liquid hydrocarbons uses mostly existing infrastructure—from modified oil refineries with new biomass inputs to our energy distribution systems. In the U.S. this option can enable rapid reduction in greenhouse gas emissions because it builds upon American strengths—agriculture and the oil/gas/chemical industry.

The primary barrier to replacing crude oil is our caveman view of biomass and biofuels. When man first discovered fire, he quickly started burning biomass as an energy source. The energy in a campfire is from converting carbon from biomass into carbon dioxide and hydrogen from biomass into water. When the cave man discovered he could convert sugar, grains and oils into alcohol, we had our first liquid biofuel—to fuel the human body and spirit. It is time to abandon our caveman belief systems. Leave wood campfires to the Boy Scouts and the alcohol to the brew masters and as a chemical feedstock.

This is a three-part story. We must first recognize we need massive quantities of liquid hydrocarbon fuels because these fuels are much more that sources of energy. Second, there is no shortage of cellulosic biomass to make liquid hydrocarbons if we chose to view biomass as a source of carbon to make liquid hydrocarbon biofuels—not primarily a source of energy. We need the carbon in biomass to make hydrocarbons that contain carbon and hydrogen—we can get the added energy for the conversion process from other sources. Last, this option takes advantage of American strengths in agriculture and the oil/gas/chemical industry that enables a fast transition off fossil fuels while reducing atmospheric carbon dioxide levels.

**Demand for Fossil Fuels and Oil**

Throughout human history, most humans lived in extreme poverty. That changed with the industrial revolution that used fossil fuels to enable billions of people to exit poverty. Worldwide, many billions more remain in poverty because they lack access to energy. Oil enabled today's modern society. The extraordinary ability of fossil fuels to eliminate poverty is because of the three characteristics of these fuels.

Fossil fuels are a low-cost dense energy source. The energy density of fossil fuels enables modern transportation. Nothing else comes close to hydrocarbon liquids as a concentrated energy source. When your car burns gasoline, the gasoline burns with oxygen from the air. Water and carbon dioxide are then released to the air. You do not need to carry oxygen for your car engine to operate. In contrast, with a battery you carry the fuel (lithium) and oxygen with a massive weight penalty. For aircraft and heavy trucks, minimizing weight is central because a pound more of fuel implies a pound less of cargo. Batteries will never approach the energy density of liquid fuels.

Fossil fuels are cheap to store. Today the U.S. stores about 6 weeks of energy in the form of fossil fuels, nuclear fuel and water behind dams---more than 3 million gigawatt hours of energy. This assures sufficient energy at all times from winter heating to the power for our industries. To provide a million gigawatt hours of storage using lithium-ion batteries would cost several hundred trillion dollars—far beyond the capability of our 23 trillion dollar economy. Today most electricity is stored in pumped hydro facilities where we pump water up the hill when excess electricity and have it flow through turbines to produce electricity when needed. We would have to expand this capacity by a factor of 2000. We have a severe shortage of mountains for that option.

Today there is a move to electrify cars and light trucks using lithium ion batteries. That only works for the richest 5% of the global population—the top 20% of the U.S. population. Internal combustion engine cars are cheap because cars are made of earth-abundant iron, aluminum, carbon and sand—with very small amounts of other materials. Electric cars are intrinsically expensive. They will become more expensive because they are made of non-earth-abundant materials such as lithium. As the demand goes up, prices will go up. Since the famous paper of Goeller and Weinberg, it is understood within the engineering community that if we are to assure a middle-class standard of living for 8 to 10 billion people, that civilization must build out of earth-abundant materials. We need solutions for all of humanity, not just the wealthiest 5%.

Work is underway to develop sodium-sulfur and aluminum-sulfur batteries made of earth-abundant low-cost elements. However, if successfully developed, these technologies are decades away from large-scale deployment. There are near-term options such as hybrid and plug-in hybrid vehicles that use small batteries to optimize engine performance and which can greatly reduce liquid fuel consumption.

Low-cost storage of natural gas is the enabling technology for low-cost wind and solar electricity. When the wind does not blow or it is nighttime, gas turbines using natural gas from low-cost storage systems provide the electricity. While there is much talk about utility batteries for electricity, the storage costs for battery storage are about four times the cost of generating electricity from wind and solar. Wind and solar are cheap only if used to reduce the consumption of natural gas. The price of solar and wind increase dramatically if not backed up by cheap natural gas.  Backing up wind and solar with batteries will more than double electricity costs.

The U.S. consumes about 18 million barrels of oil per day. That may be reduced to 10 million barrels per day before the costs of the alternatives to society explode. However, the future hydrocarbon liquid demand could be 20 million barriers per day if we do not find good methods to replace the storage functions of coal and natural gas.

The third remarkable characteristics of fossil fuels is that they are cheap to transport. The cost of crude oil and coal are about the same in any major port on earth. Without cheap transport of energy, countries such as Japan would live in poverty. Energy resources such as solar and wind are location dependent. Global equity and peace demand energy in forms that can be transported at low cost. Uranium that fuels nuclear reactors and liquid hydrocarbons meet that requirement.

**Cellulosic Liquid Hydrocarbons**

Because plants remove carbon dioxide from the atmosphere and convert it into biomass, we can produce hydrocarbon liquids from biomass without any impact on climate. If we burn those biomass-derived liquid hydrocarbons, we just return that carbon to the atmosphere…no net change in atmospheric carbon dioxide levels. The question: Is there sufficient biomass? That depends upon answering two questions: (1) how much biomass is needed and (2) what are the global supplies of biomass? The carbon in biomass serves four purposes in the traditional processes to convert biomass into liquid fuels

- Carbon in the final hydrocarbon liquid product that contains only carbon and hydrogen
- A method to remove oxygen that comprises 40% of the weight of typical biomass as carbon dioxide
- A method to produce hydrogen needed for the final hydrocarbon liquid product
- Energy to operate the chemical processes involved in biomass conversion.

This is true whether we are gasifying biomass and using the Fischer-Tropsch process to produce liquid hydrocarbons or starting with corn and using yeast to produce ethanol with conversion of ethanol into gasoline or jet fuel. In all these processes, only a fraction of the biomass carbon is in the final product. With this approach, biomass availability limits biofuels production.

There is an alternative chemical engineering strategy—choose cellulosic biomass feedstock as a carbon source for hydrocarbon liquid fuels production with massive external heat and hydrogen inputs at the refinery. Lignocellulosic biomass is the most common form of biomass and includes a wide variety of plant materials, available essentially throughout the world. The carbon in the biomass is the carbon in the final product. Externally supplied hydrogen removes oxygen in the biomass as water and provides the hydrogen required to produce hydrocarbon liquids. External heat and hydrogen provide the energy to operate the processes.

This has massive impacts. First, the quantities of liquid hydrocarbons produced per ton of biomass doubles. Second, external heat and hydrogen enable use of biomass feed stocks that are poor energy, food, and fiber sources but excellent sources of carbon for biofuel production. These include some forage crops, kelp and other high-moisture biomass. Last, the cost structure changes dramatically. External hydrogen becomes the largest single cost in producing liquid hydrocarbons and we can thus pay farmers more for the biomass with little impact on the final price of fuels but a very large increase in the amount of biomass farmers are willing to provide.

The feedstock is cellulosic biomass—the most abundant form of biomass on earth. Not starch (corn, wheat and rice), sugar or oils that are basic human foods. This strategy would enable the U.S. to produce in excess of 25 million barrels of hydrocarbon liquids per day without major impacts on food and fiber prices. In contrast, current estimates for biofuels production using traditional processes are near 6 million barrels of hydrocarbon liquids per day if we push production. We need a rethinking of biomass availability for biofuels—including the many urban myths that have little connection to agriculture. Two examples are illuminating.

In the U.S., one large potential source of cellulosic biomass is corn stover. Corn is what you eat; corn stover is the rest of the plant. Since the 1920s, average corn yields have increased from 25 bushels per acre to 180 bushels per acre. Corn stover production has increased by similar amounts—you need more corn stock and leaves to support more corn and prevent the plant falling to the ground from the weight of corn. Much of the cellulosic biomass that we need increases with food and fiber production.

We have excess cellulosic biomass production capacity. There has been a revolution in American agriculture—we no longer use horses to plow the fields and harvest the crops. Unlike tractors, horses require food year-round. At one time, much of the Midwest was double-cropped to produce a forage crop planted in the fall and harvested in the spring to feed the horses. Today most of the Midwest farmland is bare in winter. A second crop would reduce erosion, raise farm income and provide cellulosic biomass. What we need is a market for that non-food biomass.

In this context, there is a radical difference between producing biomass for food and fiber versus hydrocarbon biofuels. Food production mines the soil of nutrients such as potassium and phosphorous that we need for human health. In contrast, soil nutrients must be avoided in hydrocarbon liquids if we are not to damage engines and other uses of hydrocarbons. Many processes for advanced biofuels (anaerobic digestion, fast pyrolysis, etc.) produce hydrocarbons and a residual carbon residue that contains the nutrients. Returning this material to the soil improvise soil productivity, recycles nutrients and sequesters carbon in the soil. We have the option to improve long-term global agriculture sustainability while reducing atmospheric carbon dioxide levels.

The ingredients to make this future work are massive quantities of heat for the bio-refineries —gigawatts for each bio refinery. In most cases these refineries will be existing oil refineries with changes in some of the front-end processing. The only affordable low-carbon option for steady-state heat input at this scale is nuclear energy.

The other requirement is for massive amounts of hydrogen. While there are many hydrogen production options, the only low-carbon low-cost option available today is conversion of natural gas into hydrogen with the sequestration of the carbon dioxide byproduct underground. Today the U.S. produces about 10 million tons of hydrogen per year to produce fertilizers, as a chemical feedstock and conversion of crude oil into liquid fuels. Hydrogen production will have to be massively increased if crude oil is to be replaced by bio-crude oil.

Many projects are underway today for producing hydrogen from natural gas with sequestration of the carbon dioxide underground. The hydrogen industry is the first major industry to decarbonize because of a quirk in the production process. The primary cost in removing carbon dioxide from a fossil-fuel power-plant stack and sequestering the carbon dioxide underground is capture and purification of the carbon dioxide from the stack gas, not the cost of sequestering carbon dioxide underground. In the hydrogen production process from natural gas, most of the carbon dioxide leaves the process as pure carbon dioxide—whether you like it or not. The cost of carbon dioxide capture and sequestration is small compared to other industries. Some of these low-carbon hydrogen plants will sequester of 98% of the carbon dioxide. Today much of the hydrogen used by refineries is delivered by pipeline—the same system would be used to deliver low-carbon hydrogen to bio-refineries.

Recent studies indicate that with well-designed systems the climate impact of hydrogen from natural gas with carbon capture and sequestration approaches that of hydrogen from electrolysis using wind or solar. That is because of the large, embedded carbon dioxide emissions in building wind and solar systems coupled to hydrogen production systems relative to other hydrogen production technologies. Because we can convert cellulosic biomass to liquid fuels using hydrogen with recycle of nutrients in carbon char to the soil with sequestration of that carbon, the total biofuels system removes carbon dioxide from the air.

**Path Forward**

U.S. government policies for several decades have resulted in de-industrialization. The Chinese own the solar PV manufacturing business and are rapidly taking over global production of wind systems with the most experienced engineers in manufacturing. We may lead in science, but not in large-scale manufacturing. If the U.S. wants to compete in these areas, it will take massive subsidies and many decades to regain that experience with little assurance of success. In contrast, U.S. is the world leader in four areas: finance, software, agriculture and oil/gas/chemicals.

If we want to decarbonize quickly at an affordable cost, we must use existing infrastructure and technology rather than trying to replace technologies developed and deployed over more than a 100 years. For the oil, gas and chemical industry, we have the option to replace crude oil with cellulosic feed stocks by modifying the front end of the refinery but without requiring changes in the downstream oil and chemical industry. We can convert much of our natural gas industry into a hydrogen system to deliver the massive quantities of hydrogen via pipeline required by the bio refineries. Nobody can compete with American agriculture. For decades, the increases in productivity have been about twice that of American manufacturing. Their primary problem for about a century has been excess production of agricultural products because of a lack of markets. Time to put this excess capacity to work producing cellulosic biomass while massively increasing rural incomes.

Most of the technology for conversion to hydrocarbon biofuels is commercial—but not all at full scale. The biofuels industry is slowly moving in this direction. Three policy actions could massively accelerate the transformation. The first is a guaranteed price for cellulosic gasoline, diesel and jet fuel from the refinery. The price of crude oil swings wildly between $30 and $100/barrel over time making it financially risky to invest in any alternative where the plant may come on line when the price is low. Such a price guarantee would be paid only when oil prices are low. Second, partly in place, are incentives for hydrogen production from natural gas with sequestration of the carbon dioxide byproducts. Last, a clear strategy for incentives to sequester carbon in soil with recycle of inorganic nutrients for long-term sustainable agriculture and forestry.

We have a political class that likes to sell solutions based on future technologies where the challenges and costs are invisible and in many cases unknown. It is the fairy tale future. Any option that can significantly reduce carbon dioxide releases to the environment will have massive economic, environmental and social consequences. In the real world, new technologies have high failure rates, require many decades to scale up and must be economic relative to alternatives to be adopted by the world. Cellulosic gasoline, diesel and jet fuel may not be sexy; however, it is likely the low-cost fast way to decarbonize the global economy with massive benefits to rural economies and sustainable agriculture. Equally important, real change at large scale requires experienced successful competent organizations—the characteristics of American agriculture and the oil/gas/chemical industry. It is time for a decarbonization policy that is built on American strengths that can be implemented quickly.

## References

1. C. W. Forsberg and B. Dale, "Can large integrated refineries replace all crude oil with cellulosic feedstocks for drop-in hydrocarbon biofuels?", *Hydrocarbon Processing,* January 2023. Can large integrated refineries replace all crude oil with cellulosic feedstocks for drop-in hydrocarbon biofuels? (hydrocarbonprocessing.com)
2. C. Forsberg, "Addressing the Low-Carbon Million Gigawatt-Hour Energy Storage Challenge", *The Electricity Journal,* December 2021. https://doi.org/10.1016/j.tej.2021.107042