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Replacing all Crude Oil with Cellulosic Liquid Hydrocarbons (Gasoline, Diesel, Jet Fuel and Chemical Feed Stocks) with Massive Hydrogen and Heat Inputs at the Bio-Refinery

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We have undertaken a series of studies and workshops [1-4] on replacing all crude oil with cellulosic liquid hydrocarbons—gasoline, diesel, jet fuel and chemical feed stocks. In the United States, crude oil products provide 48% of energy to the final customer: residential, commercial, industrial and transportation. Replacement of crude oil in the U.S. would decarbonize about half the U.S. economy. Four questions were asked. First, what is the long-term demand for non-fossil liquid hydrocarbons? Second, can we replace all crude oil with cellulosic liquid bio-fuels? Cellulosic biomass is the primary form of biomass on earth and not a food for humans. Third, what are the hydrogen requirements to convert biomass into liquid hydrocarbon fuels? Last, how fast can we transition off crude oil with an affordable fast transition?

This option could potentially replace crude oil in 20 years because it is based on American strengths in agriculture and the oil/gas industry—using existing infrastructure. It requires massive quantities of hydrogen and heat to large integrated bio-refineries. The strategy would result in a quarter to half of U.S. natural gas consumption being used to produce hydrogen with co-produced carbon dioxide sequestered underground to avoid increasing the carbon dioxide content of the atmosphere. Heat to the refineries would be provided by nuclear reactors.

What is the Future Demand for Liquid Hydrocarbons?

We use liquid hydrocarbons (gasoline, diesel and jet fuel) because of their remarkable chemical properties including high energy density, low storage costs and low cost to transport long distances from producer to consumer. If crude oil had never existed, we would have invented gasoline, diesel and jet fuel. These liquid fuels can be made from many carbon-containing feed stocks. They are currently made from crude oil, coal, natural gas and biomass. If we are to eliminate increasing atmospheric carbon dioxide concentrations, liquid hydrocarbons must be made from non-fossil feed stocks. The first questions are (1) what is the future demand for hydrocarbon fuels and (2) do we have sufficient non-fossil carbon feed stocks to produce the desired quantities of hydrocarbon liquids?

We assessed [1] the demand for liquid hydrocarbons—gasoline, diesel, jet fuel and chemical feed stocks. The U.S. consumes 18 million barrels of crude oil per day. The demand for liquid hydrocarbons could go as low as 10 million barrels per day before the costs of replacing liquid hydrocarbons with other technologies dramatically increases causing serious reductions in the U.S. standard of living. *This is the set of markets where economic replacements for hydrocarbons is expensive.* Our estimates for future liquid hydrocarbon demand include chemical feed stocks, jet fuel, diesel, hybrid vehicles (gasoline-fueled vehicle with a small battery to improve engine efficiency) and plug-in hybrid electric vehicles (vehicle fueled with grid electricity and gasoline). Hybrid and plug-in hybrid vehicles lower gasoline and diesel hydrocarbon fuel demand. We do not include significant deployment of battery all-electric vehicles (BEV) that have large batteries. The liquid hydrocarbon fuel demand could be as high as 20 million barrels per day if liquid fuels have to replace any significant fraction of the hourly to annual energy storage functions of natural gas and coal. There are multiple technology options [5] to meet these needs.

We concluded [1] massive deployment of BEVs is unlikely because (1) they are unaffordable for the majority of Americans and most of the world, (2) long deployment times and (3) their large-scale use significantly increases electricity prices for everyone. Other reports [6] also describe the challenges with BEVs. All-electric battery vehicles require large quantities of non-earth-abundant materials where the costs are high and prices will increase with larger-scale deployment. Internal combustion engine vehicles are inexpensive because they are made of earth-abundant iron, aluminum, plastic and sand---and contain only very small quantities of less abundant materials. In contrast, the average BEV (Mechanical Engineering April/May 2023) includes large quantities of less earth-abundant elements: Copper: 53.2 kg, Lithium: 8.9 kg, Nickel: 39.9 kg, Manganese: 24.5 kg, Cobalt: 13.3 kg, Graphite: 66.3 kg, Zinc 0.1 kg and Rare Earths: 0.5 kgs. For example, the amount of rock ore that must be crushed to just produce the nickel in one of these batteries exceeds that for the steel in a gasoline-fueled car. The use of non-earth-abundant elements results in high-cost vehicles suitable for the wealthiest 5% of the plant—about 20% of Americans.

Unlike earth-abundant materials such as iron and aluminum ore that are found in many countries, most of non-abundant elements are only found in large quantities in a few countries. Many of those countries are taking steps to raise prices and force manufacture of batteries and other such products from these non-abundant-materials in their countries. This includes Indonesia that has a large fraction of the global nickel supply and requires initial processing of nickel in-country. Chile, with a large fraction of the global lithium and copper resources, has announced new rules for lithium and plans to build batteries in Chile. It is likely that going forward China, South Korea and/or Japan will make deals to build the local battery plants serving global markets in exchange for access to these materials. At the same time, the U.S. government has denied mining permits for nickel mining in Minnesota and copper mining in Alaska. Dependence on foreign non-abundant elements for such batteries will likely make the U.S. non-competitive in battery manufacture.

Separate from the cost challenge is the decade-long time to open new mines. To meet global projected battery demand, nickel mining must increase by a factor of 20 and lithium mining by a factor of 40. Even if cost is no objective, it implies many decades to increase mining for a transition to all-electric transportation systems. Using all-electric vehicles to replace vehicles burning hydrocarbon liquid fuels is not a viable route unless radical changes in battery chemistry where the entire battery uses earth-abundant elements—but that technology does not currently exist.

Can we replace all crude oil with cellulosic liquid bio-fuels?

The United States currently consumes 18 million barrels per day of crude oil. We developed a pathway [2-4] to replace all crude oil with cellulosic hydrocarbon drop-in fuels that (1) could produce 25 million barrels of hydrocarbon liquids per day without significant impacts on food and fiber prices and (2) large-scale sequestration of atmospheric carbon dioxide. Cellulosic biomass is the most common form of biomass on earth and includes corn stover, trees and kelp. Plants remove carbon dioxide from the atmosphere. If we use them to make liquid fuels, the burning of the fuel returns that carbon dioxide from the atmosphere with no net addition of carbon dioxide to the atmosphere. Our strategy does not include sugars, vegetables oils or carbohydrates that are currently used for most biofuels production. These feed stocks are insufficient to replace crude oil and compete with human food demand.

Gasoline, diesel and jet fuel are made of carbon and hydrogen. Most current biofuels strategies use biomass as (1) a carbon source to produce the hydrocarbon product and (2) an energy and chemical source for the chemical conversion process. The traditional conversion of biomass into gasoline, diesel and jet fuel involves using some of the biomass carbon for (1) removal of 40% by weight of the oxygen in biomass as carbon dioxide, (2) the production of hydrogen that is incorporated into the hydrocarbon product and (3) the energy to operate the process. Only a fraction of the biomass carbon ends up in the final product. Our strategy uses massive quantities of external heat and hydrogen for converting cellulosic biomass into hydrocarbon liquids. *Cellulosic biomass is the carbon source in the product hydrocarbons, not the energy and hydrogen source for the conversion process*. The oxygen in biomass is removed by adding external hydrogen to produce water. With the conventional strategy, U.S. biofuels production is limited to ~6 million barrels per day versus 25 million barrels per day with external heat and hydrogen inputs to the bio-refinery. In short, the major difference between this strategy and the traditional biofuels strategy is the abandonment of the campfire model of biofuels processing where much of the biomass is consumed ("burnt") in the biofuels production process. Campfires should be left to the Boy Scouts and people who like fireplaces.

The use of external heat and hydrogen inputs have two effects: (1) doubles hydrocarbon liquid fuels produced per ton of cellulosic biomass feed stock and (2) makes hydrogen (not biomass) the primary cost of liquid hydrocarbon fuels. If biomass feedstock is not the primary cost component of biofuels, one can pay more for cellulosic biomass without large impacts on final liquid fuel costs.

The system design is shown in Fig. 1. The low density of biomass makes it uneconomic to ship long distances. To overcome this challenge, cellulosic biomass is shipped short distances to local depots where it is converted into intermediate products that can be shipped long distances to large integrated bio-refineries. There are four depot options where the choice partly depends upon biomass characteristics. The bio-refineries convert the intermediate products into gasoline, diesel, jet fuel and other products. Most of these bio-refineries will be existing integrated oil refineries with some additional front-end processing of the feed stocks. The refineries incrementally convert over time from crude oil to biomass feed stocks.

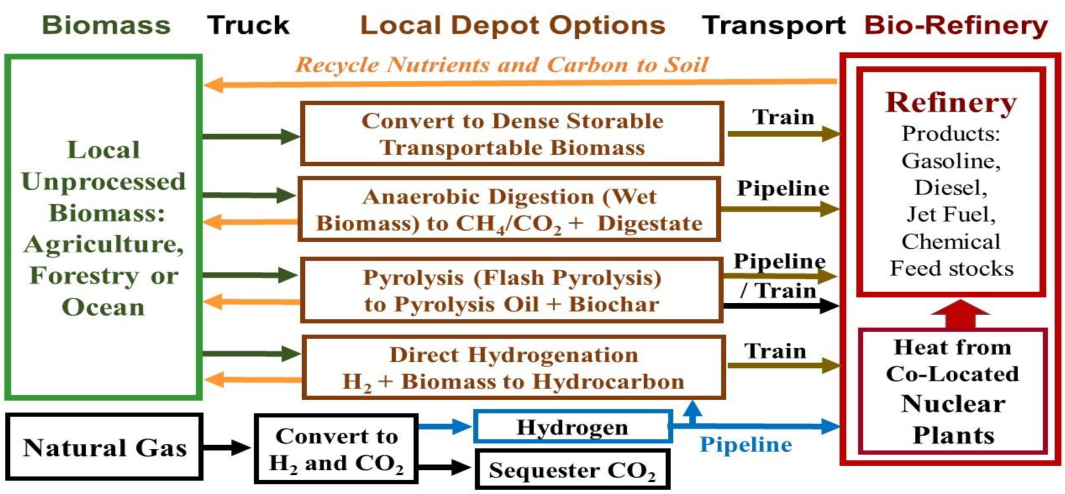

Fig. 1. Near-term Design for a Cellulosic Liquid Hydrocarbon Production System

The system enables recycle of stabilized carbon, soil nutrients and carbon char to the soil—primarily from the near-the-farm depots. This capability creates the basis for long-term sustainable agriculture/forestry and large scale sequestration of atmospheric carbon dioxide in the form of carbon in the soil. It uses a small fraction of the total cellulosic bio-carbon (orange lines) to make the total system strongly carbon negative by sequestering carbon in soil where it improves soil properties.

In this context, there is a major difference between biofuels and food production. With food production, we mine nutrients (potassium, phosphorus, etc.) from the soil by consuming food because they are needed for human health. With biofuels production, these elements must not be in the final hydrocarbon fuel—they destroy engines. The chemical processes are chosen to recycle nutrients and some carbon to improve long-term soil productivity.

What are the hydrogen requirements to convert biomass into liquid hydrocarbon fuels?

The conversion of cellulosic biomass to liquid hydrocarbons requires massive quantities of hydrogen—about 20 kilograms of hydrogen per barrel of liquid hydrocarbon biofuels. There are process tradeoffs between hydrogen required, quantities of biomass and biomass characteristics. In the near term, the low-cost low-carbon hydrogen source is conversion of natural gas to hydrogen with underground sequestration of the byproduct carbon dioxide. For 10 million barrels per day of liquid hydrocarbons, this input will require a quarter or more of U.S. natural gas production capability.

Because of the existing hydrogen and natural gas industries, this appears achievable. Hydrogen would be shipped via pipeline to the bio-refineries. In the longer-term or in locations without low-cost natural gas, nuclear hydrogen and other hydrogen production methods would be used. The main bio-conversion processes would be done at large bio-refineries [2] with typical throughputs of 250,000 barrels per day—mostly existing refineries with front-end modifications. The gigawatts of steady-state heat required per refinery are provided by nuclear reactors co-located with bio-refineries. This may become the largest use of nuclear energy because of the scale of liquid hydrocarbon demand. These would be high-temperature reactors to match refinery requirements. Heat can only be shipped short distances. Existing refineries use gigawatts of heat and consume about 10% of the energy value of the crude oil to run the refinery.

How fast can we transition off crude oil?

As experts in oil refineries, biofuels and agriculture would recognize, the technologies to implement the above approach exist at different commercial scales—mostly for different purposes. The largest barrier to rapid adoption is the variable price of crude oil that has, on an inflation adjusted basis, varied from $20 to 180/barrel in the last 50 years. Oil prices are currently about $80/barrel, near the estimated cost for such large-scale cellulosic biofuels systems assuming hydrogen prices at $2/kg. *The cost of hydrogen is the primary cost driver*. The primary business and financial risk to replacing crude oil is the risk that the price of crude oil will collapse about the time refineries convert to liquid hydrocarbon biofuels production. That economic risk can be eliminated by (1) a carbon tax on fossil carbon dioxide emissions or (2) a government guarantee of a minimum price per barrel of cellulosic hydrocarbon biofuels. The government would provide payments for hydrocarbon biofuels only if crude oil prices went below some agreed upon price per barrel.

This strategy requires changes in agriculture and modifications of the big crude-oil refineries but not changing the entire U.S. economy. That enables a fast transition off fossil crude oil with large-scale sequestration of atmospheric carbon dioxide as carbon char and residues in soils and massive economic benefits to rural America. The natural gas industry becomes the hydrogen supply industry where the primary markets are ~100 large integrated bio-refineries—mostly the existing crude oil refineries with front-end modifications. American agriculture provides most of the biomass with systems that recycle nutrients and carbon char to the soils for long-term agricultural and forest sustainability.

Example feed stocks [3] include corn stover (the part of the corn plant you do not eat) and double cropping. In this context, what is not generally appreciated is the remarkable productivity of American agriculture where productivity has grown about twice as fast as manufacturing. For example, corn yields in a century have gone from 20 to 25 bushels per acre to 180 bushels per acre—with proportional increases in corn stover (leaves and stocks). Double cropping was done in the Midwest in the early 1900s to grow forage crops for horses—plant in the fall and harvest a low-grade forage crop in the spring. When tractors arrived, the horses disappeared and the land was left bare in winter—now available for cellulosic biomass production while growing corn and soybeans in the summer. The goals are large-scale cellulosic biomass production and not impact food or fiber prices while increasing the sustainability of American soils.

This approach is built upon existing American strengths and infrastructure in agriculture and the oil/gas industry—thus the potential for deployment within 20 years given the speed American agriculture built ethanol plants in the past and the speed of the natural gas fracking revolution. It uses the existing crude oil refinery infrastructure. It provides a fast evolutionary pathway for the oil/gas industry [2] to become a negative carbon emitter producing liquid hydrocarbon biofuels (gasoline, diesel and jet fuel) and using natural gas for hydrogen production with sequestered carbon dioxide. Industry is slowly heading toward this solution.

Oil products provide 48% of the energy to the final customer in the U.S. and a third of global energy supplies. It follows that replacing crude oil with hydrocarbon biofuels made from cellulosic biomass with massive inputs of hydrogen make this the largest future hydrogen market. It is the fast route to decarbonize half the U.S. economy built upon American strengths and mostly existing infrastructure. It does not depend upon rebuilding half the U.S. economy while preserving high-paying blue collar jobs and help maintaining affordable light vehicles that enables economic opportunity by access to the full job market. Last, it is built on earth-abundant materials, as is required for any global solution to the energy and climate challenges.

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