American Nuclear Society 2022 Annual Meeting
#37926, Anaheim, California June12-16, 2022

Replacing Crude Oil with Nuclear-Assisted Biofuels

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INTRODUCTION

A series of studies [1-3] and three virtual workshops held in August 2021 were undertaken to address the question: Can a nuclear-assisted biofuels system enable liquid biofuels as the economic low-carbon replacement for all liquid fossil fuels and hydrocarbon feedstocks and simultaneously enable negative carbon emissions? "Economic" is defined as economically competitive relative to other low-carbon replacement options for crude oil. "All" refers to the capability to replace the 18 million barrels of crude oil per day used by the United States. "Nuclear-assisted" refers to the provision of massive quantities of low-carbon heat and hydrogen at the refinery to fully utilize the carbon content of the biomass feedstocks. It is estimated that the prices for drop-in hydrocarbon liquid fuels would be equivalent to crude oil at prices between $60 and $70 per barrel.

THE CHALLENGE

A major challenge for the United States is the transition from fossil fuels to a low-carbon economy to minimize the risks of climate change. We focus here on oil: the most valuable and versatile of the fossil fuel resources. Since oil is a finite resource, a related challenge is to enable an eventual transition between oil and whatever energy sources will be available to humankind as oil availability decreases and its cost inevitably increases. However, the finite and decreasing nature of oil supplies is not the issue addressed here.

The primary fossil fuel used in the United States is oil. Oil provides about a third of the primary energy and almost half the energy input to the residential, commercial, industrial, and transportation sectors. Oil is the dominant energy source because of its relatively low cost, high energy density, ease of storage and ease of transport. Oil is also the major feedstock to the chemical industry for the production of everything from drugs to plastics.

Unless we find a drop-in replacement for oil, we must not only replace oil as an energy source but must also replace 150 years-worth of infrastructure that has been created to transport, store and use oil; pipelines, refineries, cars, aircraft, furnaces, chemical processes and a myriad of other systems. The development of these technologies took many decades and trillions of dollars of investment. The development and deployment of oil-replacement technologies will also take decades and trillions of dollars. *However, climate change (and probably the finite nature of oil supplies) must be effectively addressed on a significantly shorter timescale*.

Coupled with these considerations is that hydrocarbon liquids can also substitute for natural gas and coal. Oil can provide a near drop-in replacement for these other two fossil fuels in applications ranging from gas turbines to produce peak electricity to expanding oil's use for heating in the residential and commercial sectors. In a low-carbon society, the demand for liquid hydrocarbon fuels could decrease in the transport sector while increasing in other sectors depending upon the relative costs of providing low-carbon energy sources for these other sectors.

In total, liquid hydrocarbons are used as (1) an energy source, (2) a method for daily-to-seasonal energy storage, (3) a chemical feedstock, (4) a chemical reducing agent, (5) a method to enhance high-temperature radiative heat transfer in many furnaces and industrial processes and (6) other purposes. Our assessment is that the costs and difficulty will dramatically increase if liquid hydrocarbon use goes much below the equivalent of 10 million barrels per day of crude oil. New uses of liquid hydrocarbons to partly replace coal and natural gas could increase demand to the equivalent of 20 million barrels per day of crude oil.

To reduce the overall costs of the transition away from oil and to thereby speed the transition, we ask a series of related questions: Can we economically: (1) replace crude oil with low-carbon biomass, (2) modify oil refineries to become biorefineries that produce drop-in hydrocarbon replacements for gasoline, diesel, jet fuel, and chemical feedstocks from renewable plant biomass and (3) keep everything else essentially unchanged?

Green plants remove carbon dioxide from the air and convert it into biomass. When the biomass is burned, carbon dioxide is released to the atmosphere with *no net change in the atmospheric carbon dioxide concentration*. We examine a nuclear-assisted biofuels system in which biomass is the carbon source for the carbon in oil and nuclear energy is used to provide the heat and hydrogen to convert biomass into drop-in hydrocarbon biofuels.

To our knowledge, this is the first time this option has been considered in any depth.

SYSTEM DESIGN

There are two strategies to convert biomass into liquid hydrocarbon fuels. The traditional process to provide biofuels is shown in Equation 1 where biomass plus oxygen yields biofuels plus carbon dioxide. The carbon in the biomass serves three functions: (1) a source of carbon for the hydrocarbon fuel, (2) source of hydrogen and (3) an energy source for the conversion process.

$$\begin{gathered}\text{Biomass} + \text{Oxygen} \rightarrow \begin{matrix}\text{Hydrocarbon}\\ \text{Fuels}\end{matrix} + \begin{matrix}\text{Carbon}\\ \text{Dioxide}\end{matrix}\\ CH_{1.44}O_{0.66} + O_2 \rightarrow (CH_2)_xH_2 + CO_2\end{gathered} \tag{1}$$

We are presently examining an alternative strategy: biomass plus massive quantities of external heat and hydrogen are converted into hydrocarbon fuels and water. The hydrogen is used to remove the oxygen found in biomass and also to provide the added hydrogen required to produce a hydrocarbon fuel. Biomass is the carbon source for producing gasoline, diesel and jet fuel. Nuclear energy provides the low-carbon external energy source to produce hydrogen and heat. These nuclear energy inputs will be 10 to 20% of the total energy consumption of the U.S. and the world. For an economically viable system, massive steady-state heat and hydrogen inputs at large biorefineries are required that match the characteristics of nuclear systems.

$$\begin{gathered}\text{Biomass} + \text{Hydrogen} + \begin{matrix}\text{Nuclear}\\ \text{Heat}\end{matrix} \rightarrow \begin{matrix}\text{Hydrocarbon}\\ \text{Fuels}\end{matrix} + \text{Water}\\ CH_{1.44}O_{0.66} + H_2 + \text{Heat} \rightarrow (CH_2)_xH_2 + H_2O\end{gathered} \tag{2}$$

Using external heat and hydrogen inputs enables replacing all oil with biofuels using available biomass supplies. First, external heat and hydrogen more than doubles the quantities of hydrocarbon fuels per ton of biomass feedstock. *For a given amount of biofuels produced, this reduces the land requirements for biomass production by more than a factor of two*.

Second, external heat and hydrogen enable use of biomass feedstocks that are poor energy, food, and fiber sources but excellent sources of carbon for production of biofuels. The external heat and hydrogen provided by nuclear energy is the key enabling technology: there is sufficient biomass to provide the necessary carbon to replace oil without major increases in the costs of food and fiber—the other primary uses of biomass.

Assume, for example, that we wish to produce about 10 million barrels per day of diesel containing 85% carbon by mass, or roughly 460 million tons of carbon per year. Biomass contains approximately 50% carbon by mass (dry weight basis). Thus replacing 460 million tons of carbon in oil would require about 920 million tons of biomass per year. Our initial estimates are that the United States may be able to produce well over 3 billion tons of biomass annually on a sustainable basis when biomass is considered as a carbon source, not as an energy source. This is more than sufficient biomass to replace current US oil consumption of about 18 million barrels per day.

Note that we refer here to cellulosic biomass, sometimes called lignocellulosic biomass, not to starches, sugars, or vegetable oils which are the basis of today's biofuels industry. Cellulosic biomass is by far the most abundant source of biomass on earth. These other forms of biomass (starch, sugar and vegetable oils) do not exist in sufficient quantities to really address our need to replace petroleum, and they also represent significant potential conflicts with essential food and feed production.

The proposed system is shown in Fig. 1. Low-density cellulosic biomass is sent to local depots where it is converted into storable, stable, energy-dense forms suitable for long-distance transport to the nuclear-assisted biorefinery.

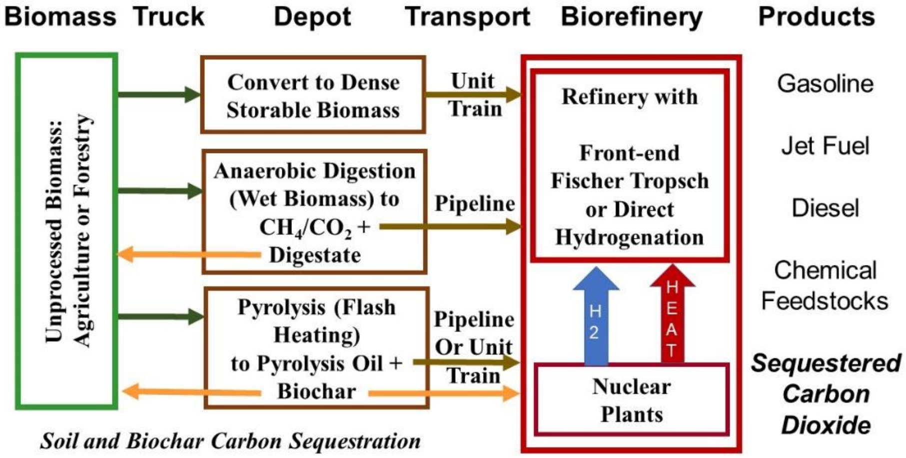

Fig. 1. Nuclear Biomass to Biofuels System

At the biorefinery the biomass is converted into hydrocarbon fuels and chemical feedstocks with massive inputs of nuclear heat and hydrogen. The liquid transport fuels are eventually burnt, thereby releasing carbon dioxide to the atmosphere. The resulting carbon dioxide is available to produce new biomass—thus there is a circular carbon dioxide cycle. Another option at the biorefinery is to produce variable quantities of liquid hydrocarbons and carbon dioxide that can be sequestered underground. If this is done, it results in negative carbon emissions; that is, it will reduce the carbon dioxide content of the atmosphere.

Large biorefineries, equivalent to a 250,000 barrel per day oil refinery, are required to minimize costs and enable variable production of gasoline, diesel, jet fuel and other products with time. *However, low-density cellulosic biomass cannot be economically shipped the long distances required to enable large biorefineries*. Therefore, local, near-farm processing depots are essential to convert biomass into energy-dense, stable, storable, economically-shippable intermediate commodities that will supply the large biorefineries.

There are three basic depot options that produce different storable, economically-transportable intermediate commodities. The choice between depots depends upon the type of biomass available. First, biomass may be densified and shipped as dry pellets. Pelletization is used to ship some types of wood very long distances to fuel boilers as a replacement for coal. Second, biomass may be fed to an anaerobic digester that produces a methane/carbon-dioxide gas mixture that is then shipped via pipeline to the refinery—plus a digestate that is returned to the soil. This is also a commercial process in some parts of the world to produce renewable natural gas or RNG. Third and last, there is flash heating of biomass that produces pyrolysis oil and biochar. The stabilized pyrolysis oil is shipped to the refinery. The biochar may be recycled with it accompanying nutrients to the soil or sent to the refinery to be converted into liquid fuels. Thus we have three distinct intermediate commodities emanating from the depots to supply the biorefineries: 1) dry pelleted biomass, 2) biogas (methane and carbon dioxide) and 3) pyrolysis liquids.

For biofuel production we only want carbon and hydrogen—not the other elements in biomass including oxygen, nitrogen, potassium and phosphorus. The depots and the biorefinery enable recycle of nutrients in digestate and biochar back to farms and forests to improve long-term soil productivity. The sustainability/circularity of this approach contrasts sharply with the dominant current model of food and fiber production as well as the burning of biomass that does not recycle nutrients back to the soil. The nuclear-assisted biofuels system combined with depots may help enable long-term sustainable agriculture and forestry—including refractory carbon sequestration in the soil that improves long-term soil productivity and reduces flooding and soil erosion.

At the biorefinery the intermediate biomass commodities are processed into a "biocrude oil" by direct hydrogenation of biomass or by the Fischer Tropsch process. This biocrude oil is then converted into hydrocarbon products by traditional, well-known refinery processes. These two processes are variants of existing, large-scale processes used to convert natural gas and coal into oil. These processes require massive quantities of hydrogen and concentrated heat sources (Equation 2) provided by low-carbon nuclear reactors.

The nuclear reactors providing the heat inputs to the biorefineries must be collocated with the biorefineries because heat can only be economically transported a few kilometers. Hydrogen can be produced on site or imported via pipelines. The heat inputs in traditional refineries are about 10% of the energy value of the liquid hydrocarbons that are produced. There are several options for hydrogen production.

First, hydrogen can be produced from natural gas with sequestration of the carbon dioxide byproduct. This may be the preferred option in locations with the combination of low-priced natural gas and good sequestration sites. Hydrogen by this process today is estimated to cost $1.50 to $2.00 per kilogram. It is also the low-cost process where cheap natural gas is available. Second, hydrogen can be produced by low-temperature (water) electrolysis and high-temperature (steam) electrolysis (HTE)—a more efficient process. Nuclear reactors produce heat that can be used to produce steam and electricity; thus, HTE is likely to be the most-favored nuclear hydrogen production process. All electrolysis processes are capital intensive, thereby creating incentives to operate hydrogen plants at high capacity factors. The U.S. Department of Energy has a major initiative to reduce the costs of hydrogen from these processes to $1.00/kg. That requires significant improvements in electrolyzer efficiency and reducing the capital costs.

There are two nuclear electrolysis process options that appear attractive to enable high capacity factors. The first option is that the reactor produce hydrogen for 85 to 95% of the time and peak electricity when high electricity prices exist. This strategy maximizes revenue while assuring high capacity factors for the hydrogen plant. It also addresses the challenge of meeting seasonal variations in electricity demand. The second option is a nuclear hydrogen gigafactory where the reactor factory, reactor site and hydrogen production facilities are collocated. Factory fabrication and deployment of reactors can dramatically lower reactor capital costs.

The refinery can produce carbon dioxide for sequestration when excess low-priced biomass is available or during times of low liquid-fuel prices. This option provides variable negative carbon emissions while stabilizing the price of liquid fuels caused by variable production of biomass or changing markets for liquid fuels over time. This potential income stream assumes a market for negative carbon emissions; that is, removal of carbon dioxide from the atmosphere.

ECONOMICS

Our initial cost estimate is that the cost of nuclear-assisted liquid hydrocarbon biofuels is equivalent to crude oil selling at between $60 and $70 per barrel. The largest cost component is for hydrogen. The costs of the delivered biomass to the biorefinery and refining costs are similar. The cost of biomass is smaller than for traditional biofuel processes because in a nuclear-assisted biofuels system the biomass is primary a carbon source and secondarily a hydrogen source. Much less biomass is required per unit of product than in traditional cellulosic biofuel processes. In traditional biofuels systems, the biomass is (1) the carbon feedstock, (2) the source of carbon to remove oxygen from the biomass and (3) the energy source to operate the process.

Commercialization will require incentives. Oil prices are highly volatile with average yearly prices in the last decade with a low of $37.22 to a high of $102.58 per barrel. The combination of (1) existing global capabilities to produce hydrocarbon products from crude oil and (2) the high volatility of oil prices makes investments in any replacement technology very risky and strongly discourages deployment of nuclear-assisted biofuels or, for that matter, *any alternative system* [4]. For liquid fuels, one option from the electric sector is “Contracts for the Difference”. In its simplest form, the government guarantees a minimum price for cellulosic biofuels to any biofuels producer for X years. If the sales price of biofuels when produced is below the guaranteed fuel price, the government makes up the difference. If the sales price of biofuels when produced is above the guarantee price, no payment is made. More complicated variants have the producer split the difference in added revenue when prices are above the guaranteed prices.

One other requirement is the definition of low-carbon biofuels. The likely transition strategy is that existing refineries convert incrementally over time from crude oil to biomass feedstocks. If 10% of the carbon feedstock into a refinery is biomass, 10% of the product should be considered low-carbon biofuels with any subsidies applying to low-carbon fuels applicable to these fuels.

CONCLUSIONS

The historical model for cellulosic liquid biofuels production has been dispersed biofuels plants where the size is limited to less than about 3,000 tons of biomass feedstock per day. This size was largely determined by the maximum economic shipping distance of unprocessed biomass to the biorefinery. All of the first-generation cellulosic biorefineries failed, at least in large part, because of the poor economics of small plants and the difficulties involved in handling unprocessed, raw biomass.

The biorefinery strategy proposed here is very different. We propose to use crude oil refineries with modified front-end processing to receive cellulosic biomass and process it to supply the rest of the refinery. Thus we propose to keep essentially unchanged the bulk of the refinery and thereby build upon 150 years of hydrocarbon liquid fuels processing. The strategy and system design are driven by the favorable economics of large-scale processes. Massive heat and hydrogen inputs minimize biomass feedstock requirements per unit of liquid hydrocarbon fuel product. Depots near farms and forests are required to convert raw cellulosic biomass into dense, storable economically-shippable commodities.

What we have proposed here is a new option that is in the early stages of development. Further studies should identify what policies and strategies would enable the most rapid transition to low-carbon liquid fuels produced from cellulosic biomass feedstocks, centered on very large biorefineries collocated with a nuclear reactor system.

ACKNOWLEDGEMENTS

This work was supported by the INL National Universities Consortium (NUC) Program under DOE Idaho Operations Office Contract DE-AC07-05ID14517. Bruce Dale gratefully acknowledges support from Michigan State University Ag/Bio Research and the USDA NIFA program.

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