Transactions of the American Nuclear Society
Paper 34241; Providence, RI, June 13–17, 2021

Replacing Liquid Fossil Fuels and Hydrocarbon Chemical Feedstocks With Liquid Biofuels Using Nuclear Heat and Hydrogen

C. Forsberg*, B. Dale[1], D. Jones[2] and L. M. Wendt[3]

**Massachusetts Institute of Technology, Cambridge, MA, 02139, cforsber@mit.edu*
[1]Michigan State University. East Lansing, MI, bdale@egr.msu.edu
[2]North Carolina State University, Raleigh, NC 27695, dsjones5@ncsu.edu
[3]Idaho National Laboratory, Idaho Falls, ID, lynn.wendt@inl.gov

INTRODUCTION

The largest energy sector in the United States is transportation. It is dominated by fossil fuels in the form of gasoline, diesel and jet fuel [1]. Liquid fossil fuels are also central to meeting other variable energy demands such as seasonal heating and peak electricity production. Fossil-fuels are the primary feedstock for the chemical industry.

We propose replacing these liquid hydrocarbons with biofuels produced in large-scale bio-refineries where nuclear energy provides the required heat and hydrogen. A workshop is being organized to further explore this nuclear biofuels future: *Can a nuclear biofuels system enable liquid biofuels as the economic low-carbon replacement for all liquid fossil fuels and chemical industry fossil fuel feedstocks where nuclear energy provides the low-carbon heat and hydrogen at the bio-refinery?* Only limited studies [2] have examined this option. The authors can be contacted for additional workshop details.

Biomass is a source of energy and also a source of carbon. Because plants remove carbon dioxide from the atmosphere there is no net addition of carbon dioxide to the atmosphere by burning biofuels. The conversion of biomass into high-quality liquid hydrocarbon biofuels is energy intensive. If the biomass is the carbon source and also the energy source for liquid biofuels (equivalent to gasoline, diesel and jet fuel) production, more than half the biomass must be burned to provide energy for the conversion process. If external sources of energy are available, the energy content of the biomass-derived liquid hydrocarbon fuel may be double the energy content of the initial biomass. Some sources of biomass have low energy values (sewage sludge, etc.) but a high carbon content when viewed as a carbon feedstock. The external energy requirements (nuclear inputs) for liquid biofuels could exceed 10% of the total energy consumption of the U.S. The only other low-carbon concentrated energy source for large bio-refineries are fossil fuels with carbon capture and sequestration (CCS).

There are three key technologies required to achieve this vision of biomass-derived liquid hydrocarbon fuels: (1) consolidation of biomass into a dense storable economically-shippable year-round-available commodity to enable large-scale bio-refineries, (2) bio-refineries at the scale of a 250,000 barrel per day oil refinery for economics of scale and the capability to make the variable product slate and (3) nuclear heat and hydrogen. Each is discussed below.

Many experts have proposed [3] burning biomass with CCS as a way to remove carbon dioxide (CO_2) from the atmosphere. The economics would most likely depend on a carbon tax where an equivalent fee in dollars per ton of CO_2 would be paid for removal of CO_2 from the air and its sequestration. Nuclear bio-refinery flowsheets enable variable production of fuels and nearly pure CO_2 streams for low-cost CCS. A market for sequestered CO_2 would provide a significant additional revenue stream at times of low seasonal demand for fuels or excess biomass feedstock production with low prices.

BIOMASS FEEDSTOCK AVAILABILITY

Globally biomass could meet a quarter of future low-carbon energy demands [4] if burnt in furnaces and boilers. If external sources of heat and hydrogen are used, the energy content of liquid biofuels can be almost double that of biomass feedstocks [5]. In contrast, conventional processes that convert biomass to ethanol (fermentation) use biomass as an energy source and also as a feedstock and thereby must use a third of the energy value of the biomass in the conversion process. External energy biorefinery inputs can reduce the land footprint by a factor of two for the same fuel.

The estimated U.S. harvestable biomass (carbon content about 80% that of petroleum) is a billion tons per year [6] and could meet most transport fuel demand. However, this is not the entire story. First, the demand for liquid fuels [7] is expected to decrease because of (1) continued improvements in engines and (2) the use of electricity in transportation (electric cars and plug-in hybrid electric vehicles). Second, there are other biomass carbon feedstocks if the demand is for a high-carbon feedstock and not primarily as an energy source. This includes biomass available at paper mills, municipal trash and other low-energy value biomass.

The other factor is that agriculture is flexible—it is designed primarily for food production so that is what it does. Agriculture can be changed [8] to produce the same quantities of food and larger quantities of biomass for fuel and chemicals. First, food is primarily grown to feed animals with a traditional diet. However, that diet can be changed to maximize food and biofuel production. 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 an excellent feedstock for biofuels. Third is the productivity growth of American agriculture has been greater than any other sector. For example, corn yields have gone from 20 to 180 bushels per acre. It may be possible to double the biomass yield of the corn plant if we chose to design a corn plant with a 20% lower starch yield (the corn grain) but with more corn stalks and leaves.

The evidence indicates there is sufficient biomass to replace fossil fuels for transportation and chemical feedstocks if large external inputs of hydrogen and heat are provided at large-scale refineries.

LARGE-SCALE BIO-REFINERIES

The predictions a decade ago of a large-scale cellulosic biofuels industry have not materialized. The feedstock costs are similar to crude oil but small bio-refineries have high capital costs per unit of liquid fuel produced. For several reasons, low-cost production of liquid biofuels requires large-scale production facilities, equivalent to a 250,000 barrel per day oil refinery [9].

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 [10, 11] show similar economics of scale for cellulosic bio-refineries.

Efficiency. Large refineries and large bio-refineries are more cost-efficient than smaller plants as equipment efficiency increases with throughput. However, more important is the ability to convert all feedstock into the desired products. In a large refinery, a “small” secondary stream can be upgraded into gasoline, diesel and jet fuel. In a small refinery it is not economically viable to upgrade such secondary streams.

Variable Feedstocks and Products. Large integrated refineries can accept wide variations in crude oil and produce a variable product slate—different products for winter than summer. Small refineries can accept a limited number of crude oil types and produce limited product slates. Existing bio-refineries generally produce a single product (such as ethanol) or perhaps a few byproducts. Research for future biorefineries include coproducts such as adipic acid and byproducts such as sodium sulfate [12]. That is a viable strategy for filling niche markets. It is not a viable strategy if the goal is to replace liquid fossil fuels. Large bio-refineries will be similar to large integrated oil refineries.

The requirements of a large-scale bio-refinery define the system as shown in Fig. 1. The first requirement is massive external heat and hydrogen inputs to (1) drive down biomass feedstock requirements and (2) enable the use of lower-cost biomass feedstocks with a high carbon content but low energy content. Large oil refineries have steady-state heat loads measured in gigawatts and represent about 3% of total U.S. energy demand.

Large bio-refineries will have much larger energy inputs in the form of heat and hydrogen than large oil refineries. In addition to the traditional refinery heat demand, there will be added heat demand to remove water from the biomass feedstock and a massive hydrogen demand to replace the oxygen found in biomass to produce hydrocarbons. Such biorefineries will convert biomass with a typical composition near $CH_{1.44}\ O_{0.66}$ into an overall composition near CH_2, requiring removal of oxygen and its replacement with hydrogen. The only concentrated energy sources that can match that energy demand are nuclear and fossil fuels with CCS. The fossil fuel option is limited to geographical areas with low-cost fossil fuels and low-cost sequestration sites for carbon dioxide. The process flowsheets described below imply heat and hydrogen into biofuels consuming more than 10% of total U.S. energy consumption.

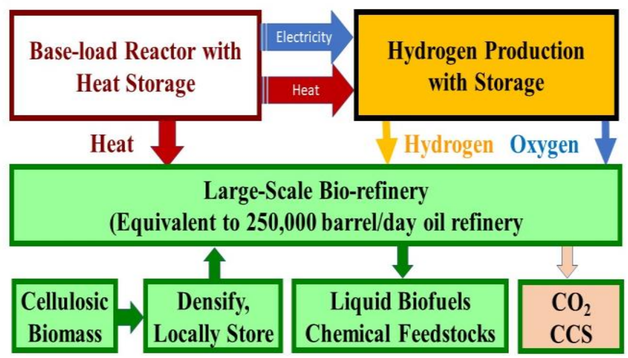

Fig. 1. Nuclear bio-refinery system

The primary global biomass form is cellulosic materials. As currently harvested and stored these are low-density feedstocks where the economics limit truckload shipment distances to 20-50 miles and thereby limit bio-refineries to relatively small sizes because of feedstock supply limitations. Large bio-refineries require a larger collection radius, hence biomass would need to be delivered by long-haul trucks, rail and/or barge [13]. But, because biomass bulk density have a major impact on logistics cost, large bio-refineries would require the development and commercialization of technologies [14] to convert cellulosic biomass into storable, dense, economically-transportable feedstocks. If converted to an intermediate dense, storable product, cellulosic feedstock can be economically shipped to large-scale bio-refineries to enable economics of scale similar to those of oil refining. Biomass densification would take place closer to the farmgate and in facilities denominated as depots [15]. There are multiple processes in the early stage of development to produce a dense storable transportable biomass products; but, the overall challenge is commercialization where the densification processes and the bio-refineries must grow at the same time.

There are many ways to convert biomass into high-quality liquid fuels. We chose as the base-line the Fischer-Tropsch process that has been used to produce liquid hydrocarbon fuels since the 1940s. It can accept almost any carbon-containing feedstock because it converts all feedstocks into a hydrogen carbon-monoxide feedstock and then reassembles the molecules into the desired products. 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 newer Shell natural gas-to-liquids plant in Qatar produces 260,000 barrels per day of liquid fuels.

The first step is gasification where a mixture of carbon, oxygen (O_2) 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. There is a massive experience base with this process because gasification is also used to produce syngas for the production of various chemicals where a wide variety of feedstocks are used.

$$\text{Carbon} + \text{Oxygen} + \text{Steam} \rightarrow CO + CO_2 + H_2$$

The O_2 can be provided by air or pure O_2. Pure O_2 reduces equipment size and increases efficiency because one is not heating the nitrogen in air—but there is the added cost to produce pure O_2. In a low-carbon economy, the likely hydrogen production routes are low-temperature water electrolysis or high-temperature electrolysis (HTE)—steam electrolysis. HTE is favored if the hydrogen is produced from nuclear plants because (1) low-cost steam partly replaces more expensive electricity in the production process and (2) the process is more efficient. In a nuclear bio-refinery there will be large economic incentives to use the byproduct O_2. The heat, hydrogen and O_2 requirements imply co-locating within a kilometer or two the nuclear plant and bio-refinery. Recent studies [16] indicate that nuclear plants coupled to HTE have the potential to produce lower cost hydrogen than wind or solar routes to hydrogen and are potentially competitive with fossil fuel methods to produce hydrogen in parts of the U.S.

The second step involves gas cleanup and the conversion of the syngas to the proper ratio of carbon monoxide and hydrogen by separating out CO_2 or adding hydrogen. Again, heat can be added by the nuclear reactor or chemical reactions. The CO_2 can be (1) recycled with the addition of hydrogen to produce a carbon-monoxide hydrogen mixture through the water-shift reaction or (2) sequestered underground. Unlike fossil fuels with CCS, the process produces pure CO_2 that dramatically lowers the cost of CCS.

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. Different catalysts can produce other chemical feedstocks.

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

LIQUID BIOFUELS FROM PAPER MILLS, MUNICPAL TRASH AND OTHER SYSTEMS

There are a set of smaller bio-refinery market opportunities where the economics may be favorable because the biomass is collected for other purposes in a central location to produce another product. The single largest such opportunity is an integrated paper, pulp and wood products plant. In a paper plant, cellulose is separated from the pulp wood and converted to paper. The wastes are burned to provide the energy for the paper process. These plants could be converted to nuclear paper and biofuels plants where the nuclear reactor provides heat for paper production and heat/hydrogen for liquid biofuels production from the wood wastes that would have otherwise been burned. Paper mill size is limited by the economic distance to ship low-density pulp wood to the central mill. The energy demand is significant because the nuclear reactor produces heat for paper production and heat/hydrogen to convert the other biomass into liquid fuels.

Other potential feedstocks include the conversion of carbon-containing wastes (municipal trash, sewage sludge, etc.) into liquid biofuels. Such wastes today are centrally-collected with payments made for disposal. Because many cities are on the ocean or large rivers, such wastes may be shipped by low-cost barge to relatively large bio-refineries.

ECONOMICS

The economics of liquid fuel production strongly favors large facilities—driven by the economics of scale and the ability to convert a larger fraction of the feedstock into valuable products. Nuclear reactors produce cheap heat and somewhat more expensive electricity because of the Carnot cycle that requires multiple units of heat to produce one unit of electricity [1]. Large biofuels refineries require massive constant quantities of heat, hydrogen and potentially O_2. The energy source matches the need.

On an energy basis, the cost of the biomass feedstock is about the same as the cost of crude oil today. Feedstock and energy costs create the potential for an economically competitive replacement for liquid fossil fuels and chemical plant feedstocks.

OBSERVATIONS AND CONCLUSIONS

There are several challenges. The largest challenge is the belief that biofuels are in direct competition with food production, even though national biomass resource assessments take into account future demands for food, feed and fiber [6]. Moreover, advanced biofuel production would use nonfood-based sources like grasses and crop residues.

The reality is that the primary challenge for Western agriculture for more than 50 years has been finding markets for surpluses. The second challenge is integration across the agricultural, oil refinery and nuclear energy communities. Third is the slow siting and licensing schedules for nuclear power plants. The techno-economic challenges include (1) commercialization of technologies to convert cellulosic biomass into a storable, dense, economically-transportable feedstocks that enables large-scale bio-refineries and (2) developing the technology for a bio-refinery at oil refinery scale. It is unclear if significant research and development work is required for modified processes or whether this is primarily an integration challenge.

Nuclear biofuels systems could potentially be deployed at scale in less than 20 years. Most of the technologies exist. The agricultural sector developed the ethanol industry in about a decade. Facilities required to densify biomass into a dense shippable product could be deployed in a similar period of time. The deployment of shale fracking and the associated processing facilities occurred in a little over a decade. The oil industry has the capabilities to rapidly develop and deploy bio-refineries. Limit on deployment rates may be the siting and licensing process for nuclear plants.

Replacing liquid fossil fuels and chemical feedstocks with drop-in nuclear biofuels avoids developing and commercialization of dozens of technologies to decarbonize an economy built on fossil fuels. In that context, large-scale nuclear bio-refineries have the potential to be the fastest route to decarbonize a large fraction of the U.S. economy.

ACKNOWLEDGEMENTS

This work was supported by the Shanghai Institute of Applied Physics (SINAP) of the Chinese Academy of Sciences and the INL National Universities Consortium (NUC) Program under DOE Idaho Operations Office Contract DE-AC07-05ID14517.

REFERENCES

1. C. Forsberg and S.M Bragg-Sitton, “Maximizing Clean Energy Utilization: Integrating Nuclear and Renewable Technologies to Support Variable Electricity, Heat and Hydrogen Demands, *The Bridge*, 50 (3), fall 2020.
2. C. Forsberg and B. Dale, “Replacing Liquid Fossil Fuels with Liquid Biofuels from Large-Scale Nuclear Biorefineries” *Applied Energy Symposium: MIT A+B*, August 12-14, 2020 • Cambridge, MA.
3. National Academies of Sciences, Engineering and Medicine 2019, Negative Emissions Technologies and Reliable Sequestration: A Research Agenda, Washington D.C.: The National Academies Press (2019).
4. B. Dale et al. “Take a Closer Look: Biofuels can Support Environmental, Economic and Social Goals” Environmental Science and Technology, 48, (7200-7203)
5. M. Holtzapple, S. Lonkar and C. Granda, “Producing biofuels via the carboxylate platform”, Chemical Engineering Progress, 111 (3), 52-57 (March 2015)
6. U.S. Department of Energy. 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks. doi: 10.2172/1271651. http://energy.gov/eere/bioenergy/2016-billion-ton-report.
7. W. H. Green et. al., *Insights into Future Mobility*, Massachusetts Institute of Technology (2019) http://energy.mit.edu/wp-content/uploads/2019/11/Insights-into-Future-Mobility.pdf
8. B. Dale et al. “Biofuels Done Right: Land Efficient Animal Feeds Enable Large Environmental and Energy Benefits,” *Environmental Science and Technology*, 44, 8385-8389, 2010
9. F. E. Self, E. L. Ekholm, and K. E. Bowers, Refining Overview—Petroleum, Processes, and Products, CD-ROM, American Institute of Chemical Engineers (2007).
10. S. Kim and B. E. Dale, “A distributed cellulosic biorefinery system in the US Midwest based on corn stover,” *Biofuels, Bioproducts and Biorefining (Biofpr)*, 2016. DOI: 10.1002/bbb.1712
11. S. Kim and B. E. Dale, “Comparing alternative cellulosic biomass biorefining systems: centralized versus distributed processing systems”, *Biomass and Bioenergy*, 74, 2015, 135-147. https://www.sciencedirect.com/science/article/pii/S0961953415000288.
12. Davis, Ryan E., et al. Process Design and economics for the conversion of lignocellulosic biomass to hydrocarbon fuels and coproducts: 2018 biochemical design case update; biochemical deconstruction and conversion of biomass to fuels and products via integrated biorefinery pathways. No. NREL/TP-5100-71949. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2018.
13. R. J. Stoklosa et. al, “Techno-economic comparison of centralized versus decentralized biorefineries for two alkaline pretreatment processes”, *Bioresource Technology*, 226, 9-17, 2017. http://dx.doi.org/10.1016/j.biortech.2016.11.092
14. Gonzales, Daniela, Erin M. Searcy, and Sandra D. Ekşioğlu. "Cost analysis for high-volume and long-haul transportation of densified biomass feedstock." Transportation Research Part A: Policy and Practice 49 (2013): 48-61.
15. Gonzales, Daniela S., and Stephen W. Searcy. "GIS-based allocation of herbaceous biomass in biorefineries and depots." Biomass and Bioenergy 97 (2017): 1-10.
16. E. Ingersoll and K. Gogan, *Missing Link to a Livable Climate: How Hydrogen Enabled Synthetic Fuels Can Help Deliver the Paris Goals*, September 2020. https://www.lucidcatalyst.com/hydrogen-report