Nuclear-Assisted Integrated Pulp, Paper and Biofuels Plants

Charles Forsberg (cforsber@mit.edu)* and Jeremy Shook (JShook@epri.com)

*Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA, 02139
†Electric Power Research Institute, Charlotte, NC. 28262

INTRODUCTION

Pulp and paper plants are large consumers of energy, including heat and electricity. Most of the heat is produced by burning dried black liquor residues from the paper-making process and hog fuel (bark, other forest residues) that is not used to make paper. We investigate herein the option of using nuclear reactors to provide heat, electricity and hydrogen thus enabling the use of these biomass wastes for the production of liquid hydrocarbon fuels rather than energy for making paper—with sequestration of some carbon and recycle of forest nutrients. This enables creation of integrated pulp, paper and biofuels (PPB) plants. The nuclear energy input could exceed 5% of total U.S. energy demand.

Most proposals to use nuclear energy in industrial applications replace fossil fuels as a heat source. While nuclear energy reduces carbon emissions, it does not change the revenue or product slate of the industrial facility. In this application, nuclear energy could increase plant revenue from the sale of high-value liquid hydrocarbons for fuel and chemical feed stocks. Trees remove carbon dioxide from the air and convert it into biomass. Converting these materials into liquid hydrocarbons and burning those hydrocarbons returns the carbon dioxide to the atmosphere with no net increase in atmospheric carbon dioxide levels.

Unlike other methods to produce biofuels, the biomass is at the paper and pulp mill. There is no added cost for purchase and collection of biomass. Separately, forests are under stress, from invasive insects to extreme weather, that kills some trees. In many locations if this biomass is not removed, it creates major fire risks, but there is no economic incentive to remove this forest biomass. Much of this biomass is unsuitable for paper making. The proposed system may enable the existing paper industry biomass collection system to collect this biomass for added liquid fuels production.

EXISTING PAPER AND PULP INDUSTRY

In the paper process, pulpwood is digested and the fiber is converted into paper. The bark and other wastes from the paper process are burned to provide most of the energy for the process—including drying the paper. About half the incoming biomass leaves as the paper product and half is burned to provide energy to operate the process [1]. Figure 1 shows the total energy input into the paper industry by source [2]. Two thirds of the energy input is from burning biomass. External energy sources such as natural gas and electricity from the grid provide about a third of the energy input—typically about 100 MW.

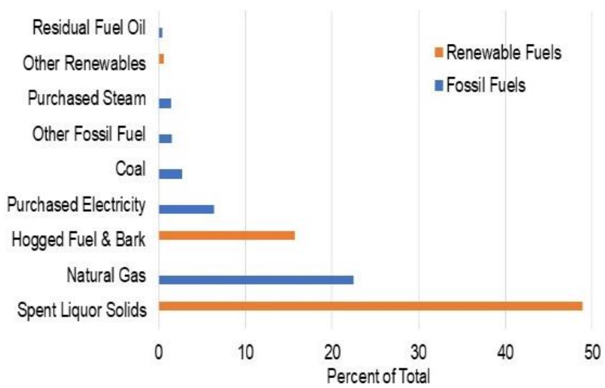

Figure 1. 2018 Energy Inputs into the Pulp and Paper Mills

The primary pulp and paper process is the Kraft process [1, 3, 4]. Pulp and paper plants burn two major biomass wastes to produce heat—each with its own characteristics.

Hogged fuel and bark. This waste stream is created when bark and other materials are stripped from the pulpwood and not used in the paper making process. It also includes secondary wastes from harvesting of pulpwood used as an energy source for pulp and paper mills. Processes are being developed to convert such feed stocks into liquid hydrocarbons.

Spent (black) liquor solids. The second and largest waste stream is the spent liquor solids from the pulping process. This stream contains the non-fiber components of pulpwood that can't be converted into paper. The burning of this waste stream produces heat and recovers chemicals from the papermaking process that are recycled back to the plant to produce paper as NaOH and Na_2S. If this stream were to be converted into biofuels, new or modified processes would need to be developed to allow recovery of the chemicals for the pulp and paper plant. There are multiple process options including options of recovering organics that would be viable feedstocks for liquid hydrocarbon fuels production.

BIOFUELS PRODUCTION

In traditional processes for converting biomass into liquid hydrocarbons, the biomass carbon serves four purposes: (1) carbon in the final hydrocarbon liquid product, (2) a method to remove oxygen that comprises 40% of the weight of typical biomass, (3) a method to produce hydrogen for the hydrocarbon product and (4) 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 using a fermentation process to produce ethanol with conversion of ethanol into a hydrocarbon liquid. In all these processes, only a fraction of the biomass carbon is in the final product.

With massive external heat provided by on-site nuclear reactors and hydrogen produced on-site or imported by pipeline, there is the potential to double the ultimate yield of liquid hydrocarbons per unit of feedstock [5]. There are multiple process options where the choice will be partly determined by feedstock characteristics and by market prices for different products.

Fast pyrolysis. Dry biomass is rapidly heated to about 500°C producing a liquid bio crude oil, a char and gases [6, 7]. The bio char can be recycled to the soil to improve soil productivity or used as a feedstock for hydrocarbon fuels production. The pyrolysis oil is chemically unstable and corrosive. It is upgraded into a more stable product by hydrogenation using hydrogen or an electrolysis process. Fast pyrolysis is commercial on a small scale.

Direct Hydrogenation. Biomass can be converted into hydrocarbons by direct catalytic hydrogenation. The process is used to upgrade some types of crude oil and has been developed for coal liquefaction. However, biomass direct hydrogenation processes are at an earlier in the development stage.

Anaerobic digestion. The biomass in a liquid slurry is sent to biological digesters to produce (1) a methane/carbon-dioxide gas mixture shipped via pipeline to the refinery and (2) a carbon and nutrient-rich digestate that is returned to the soil. Experience shows that recycle of this digestate improves long-term soil fertility and carbon content [8]. The process produces renewable natural gas and is commercial in some parts of the world for some types of biomass.

Today, some of these processes are used to convert forest wastes into liquid hydrocarbons. However, new or modified spent liquor processes will be required to convert this steam into biofuels, recycle chemicals to the paper process and recycle nutrients and carbon to forest soils. The availability of massive external heat and hydrogen creates multiple new options to produce hydrocarbon biofuels to increase plant revenue.

The economic transport distance for raw biomass is 30 to 50 miles because of its low density. This limits the size of paper and pulp plants. However, there are large amounts of waste biomass (hog fuel) that can provide added biomass for biofuels production at further distances. Today, biomass is pelletized to (1) increase its density and (2) enable economic long-distance transport as animal food or boiler fuel. For example, the DRAX power station in the United Kingdom burns 7 million tons of biomass per year—with much of this pelletized biomass from the United States. This transport option would enable a PPB plant to accept biomass at longer distances for larger-scale biofuels production including wastes from other forest product plants (wood, plywood, etc.) and forest debris.

Wood products and shipment of pelletized biomass to distant boilers remove nutrients from the soil because the products contain trace nutrients such as potassium and phosphorus. In contrast, one does not want such trace nutrients in hydrocarbon liquid fuels. Paper is primarily cellulose $(C_6H_{10}O_5)_n$ that does not contain major quantities of these trace nutrients. The nutrients are primarily in the spent liquor solids, hog fuel and bark. We have the option to recycle these nutrients back to the soil for long-term sustainable forests. Fast pyrolysis, anaerobic digestion and potentially direct hydrogenation generate refractory carbon that can be returned to the soil to sequester carbon, improve soil properties and recycle trace nutrients [5, 9, 10].

Carbon holds water and has other desirable soil-building properties. Such carbon residues remain in the soil for centuries to millennia. Recycle of this carbon to forest soils could become a major additional source of revenue [10] in countries that provide payments for removal of carbon dioxide from the atmosphere and sequestration of carbon. Effectively, the PPB plants could have an additional revenue stream from negative carbon emissions with the potential to vary liquid hydrocarbon and carbon char production with market prices determining relative rates of production from the same biomass.

There are programs that grow forests to sequester carbon in the form of live trees—but the trees die and bacteria convert the cellulose back to carbon dioxide that limits the amount of stored carbon in live trees. In contrast, larger amounts of carbon can be sequestered as refractory carbon in soil while improving forest soil productivity.

Low-grade bio-oil can be (1) burnt in furnaces or (2) sent to large integrated refineries for upgrading into gasoline, diesel and jet fuel [5, 10, 11, 12]. The economics favor large refineries for final conversion of such bio crude oils into hydrocarbon products. Oil refineries can blend such feedstocks with crude oil and over time convert to large-scale (250,000 barrel per day) bio refineries. Refineries can also send such feedstocks to hydro-treatment units or fluidized catalytic crackers for upgrading. There are tradeoffs on how much upgrading at the PPB plant versus at the refinery. This has a large impact on PPB plant energy requirements.

The ability to pelletize various forest and forest industry wastes with shipment to PPB plants significantly increases the potential for liquid hydrocarbon production while using many of the capabilities of pulp and paper mills. These other inputs include wastes from plywood mills, sawmills, and forest debris to reduce fire hazards. Many of these biomass sources are not useable forms of biomass for the pulp and paper industry but become feedstocks if these plants become PPB plants. The U.S. billion-ton biofuels report [13] is a starting point on the potential of these added feed stocks.

USE OF NUCLEAR ENERGY FOR PULP AND PAPER PROCESSES

External energy inputs to the pulp and paper industry are about 1% of the U.S. energy consumption. Internal energy inputs (burning biomass) are about twice the external energy inputs. Total energy consumption (external and biomass) is about 3% of U.S. energy consumption. Converting the biomass that is burnt into liquid fuels may double energy consumption. If add biomass from other sources is shipped in as pelletized biomass, the energy consumption will be much larger.

The chemical processes will define the required temperatures and quantities delivered heat—as well as electricity demand. Traditional paper plants have massive low-temperature steam demands; however, some of the options for liquid hydrocarbon production require significant amounts of high-temperature heat and massive quantities of hydrogen.

To meet plant heat and electricity demands, co-sited nuclear plants, like existing paper and pulp mills, will be cogeneration plants. If the processes require hydrogen, the hydrogen can be: (1) produced on-site or (2) shipped to the site by pipeline. In the United States, there are multiple demonstrations of hydrogen production at existing nuclear power sites. The pulp and paper industry is the largest industrial generator of electricity. Many of the options will create economic incentives to sell electricity to the grid. If the plant requires a small amount of high temperature steam, some steam goes to the process and most steam is sent through a high-temperature turbine producing electricity with the lower-temperature steam exiting the turbine going to the PPB processes. Depending upon internal electricity demand, there may be large quantities of electricity to sell to the grid with low production costs because it is part of this cogeneration system.

Some large chemical plants with co-generation systems sell variable amounts of electricity to the grid depending upon prices. This involves varying production or including storage within the chemical plants of energy or some intermediate product that enables parts of the plant to operate at steady state while other processes operate at variable rates. Similar options exist for PPB plants.

CONCLUSIONS

On-site nuclear heat, hydrogen and electricity could enable paper and pulp plants to become PPB plants with nuclear energy inputs approaching 5% of the total U.S. primary energy consumption. Canada proportionally has a larger pulp and paper industry than the U.S. and thus this strategy would be a larger fraction of Canadian energy consumption. The nuclear reactors must be co-located with the PPB plants because heat can be only shipped short distances. Hydrogen can be generated (1) locally or (2) off-site with shipment via pipeline. The liquid biofuels could be an equal or larger source of plant revenue than paper and a partial replacement of crude oil. Some process options enable sequestration of carbon in soils (negative carbon emissions) that would become an added source of revenue helping to create sustainable forestry and improving long-term soil productivity. Depending upon chemical flowsheet choices that determine temperatures of required heat, the nuclear plants may become significant sources of electricity to the grid.

The Massachusetts Institute of Technology (MIT), North Carolina State University (NCSU) and the Electric Power Research Institute (EPRI) are planning a workshop later this year to further explore this set of options from several perspectives and address uncertainties. The workshop will address: (1) pulp and paper system design (paper, biofuels, recycled nutrients, sequestration refractory carbon) (2) choices for chemical recycle within Kraft process given the new goals and the availability of external heat and hydrogen, (3) concepts for on-site nuclear facility design, (4) the business case and (5) potential business structures between the PPB plant and utilities.

Globally there are other similar markets. For example, the production of sugar cane involves recovery of the sucrose from sugar cane. Sugar cane is squeezed to release the sugar solution that is converted into sugar. The residual biomass (bagasse) is burned to produce heat for sugar recovery. If external heat and hydrogen is provided by nuclear reactors, the residual biomass becomes a biofuels feedstock with the option to produce liquid hydrocarbon fuels, recycle soil nutrients, and sequester refractory carbon to the soil.

REFERENCES

[1] S. LIPIAININEN, et. al., "Pulp and Paper Industry in Energy Transition: Toward Energy-Efficient and Low Carbon Operation n Finland and Sweden", *Sustainable Production and Consumption*, 28, January 2022. https://doi.org/10.1016/j.spc.2021.10.029

[2] C. FORSBERG and A FOSS, Fission Battery Markets and Economic Requirements, *Applied Energy*, 329, 2023, 120266. https://doi.org/10.1016/j.apenergy.2022.120266

[3]. R. J. RAGAUSKAS, Basics of Kraft Pulping and Recovery Process, http://biorefinery.utk.edu/technical_reviews/Kraft%20Pulping%20and%20Recovery%20Process%20basics.pdf

[4] A. van HEININGEN, "Pulp", *Kirk-Othmer Encyclopedia of Chemical Technology*, 2020. https://doi.org/10.1002/0471238961.1621121607051403.a01.pub3

[5] C. W. FORSBERG and C., B. DALE, *Can a Nuclear Biofuels System Enable Liquid Biofuels as the Economic Low-carbon Replacement for All Liquid Fossil Fuels and Hydrocarbon Feedstocks and Enable Negative Carbon Emissions? Workshop Proceedings*, Massachusetts Institute of Technology, MIT-NES-TR-023. April 2022. https://canes.mit.edu/download-a-report

[6] C. H. LAM, *et. al.*, "Towards sustainable hydrocarbon fuels with biomass fast pyrolysis oil and electrocatalytic upgrading," *Sustainable Energy & Fuels*, 2017.

[7] R. C. BROWN, "The role of pyrolysis and gasification in a carbon negative economy," *Processes*, 2021.

[8] B. E. DALE, et al. "Biofuels done right: land efficient animal feeds enable large environmental and energy benefits." *Environmental Science and Technology*, 44 (22), 8385-8389, 2010. https://doi.org/10.1021/es101864b

[9]. L. SCHULTE MOORE and J. JORDAHL, editors, *Carbon Science for Carbon Markets: Emerging Opportunities in Iowa*, CROP 3175, Iowa State University Extension and Outreach, Ames, Iowa, 2022.

[10] C. W. FORSBERG, B. E. DALE, D. S. JONES, T. HOSSAIN, A.R.C. MORAIS and L. M. WENDT, "Replacing Liquid Fossil Fuels and Hydrocarbon Chemical Feedstocks with Liquid Biofuels from Large-Scale Nuclear Biorefineries", *Applied Energy*, 298, 117525, 15 September 2021. Replacing liquid fossil fuels and hydrocarbon chemical feedstocks with liquid biofuels from large-scale nuclear biorefineries - ScienceDirect

[11]. S. van DYK et. al., 'Drop in" Biofuels: The Key Role that Co-Processing will Play in Its Production", International Energy Agency Bioenergy, 2019

[12] C. W. FORSBERG and B. DALE, "Nuclear Energy: Enabling Production of Food, Fiber, Hydrocarbon Biofuels, and Negative Carbon Emissions," *Nuclear News*, January 2023. Nuclear energy: enabling production of food, fiber, hydrocarbon biofuels, and negative carbon emissions -- ANS / Nuclear Newswire

[13] U.S. Department of Energy, *Billion Ton Report*, 2016.
https://www.energy.gov/eere/bioenergy/2016-billion-ton-report