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Idaho National Laboratory
Idaho Falls, Idaho 83415

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Towards Net-Zero: Nuclear-Assisted Waste Biomass to Liquid Fuel in Eastern Idaho

Grant Hawkes[1*], Kathleen Sweeney[1]

[1]Idaho National Laboratory, Idaho Falls, Idaho

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ABSTRACT

A nuclear assisted carbon negative hybrid energy process that enables production of synthetic bio-crude oil and biochar from Eastern Idaho waste biomass is proposed. The process integrates nuclear powered electricity with high temperature steam electrolysis and biomass hydropyrolysis. The bio-crude oil is of sufficient composition and blended with traditional crude oil at a refinery. Hydrogen from the electrolyzer is pressurized and inserted into the pyrolyzer. Non condensable gases generated in the hydropyrolysis process are burned with oxygen from the electrolyzer to produce heat for the electrolyzer, biomass dryer, and pyrolyzer. The biochar is returned to the soil via fertilizer application and remains there for thousands of years. Since the total process uses nuclear generated electricity, the carbon in the biochar is ultimately sequestered from the atmosphere, thus making the process carbon negative. Using Eastern Idaho wheat or barley straw, this hybrid energy process has the potential to provide an alternative petroleum source. Two options exist for the system design: 1) send electricity from the nuclear plant and straw to a chemical processing plant to produce the bio-crude and biochar, 2) construct the biomass processing facility near the nuclear plant to allow use of nuclear-generated process heat to drive the chemical. Process model description and results are discussed. The process is sized to produce gasoline and diesel at the rate that the INL fleet uses every day.

Keywords: Hydropyrolysis, Biomass, Bio-Crude, Nuclear Electricity

1. INTRODUCTION

A chemical process is described that ultimately takes carbon out of the atmosphere and sequesters it for thousands of years in the soil. Eastern Idaho wheat and barley straw (waste biomass) is converted to bio-crude and biochar with a fast hydropyrolysis unit and is intimately integrated with a high temperature steam electrolyzer (HTSE). The US government climate change website (1) notes that CO2 levels are increasing and are at the highest level ever. When non-fossil electricity such as nuclear power is used to produce hydrogen via HTSE, hydrogen from the electrolysis flows into the hydropyrolysis unit with bio-crude as a product. Oxygen from the HTSE process is used to combust noncondensable gases produced from the hydropyrolysis process. Heat from the combustion of these noncondensable gases provides heat for the entire process. A similar process (2) has been proposed by the author in 2021. The notable difference is that this new proposed process injects the hydrogen into the pyrolyzer, whereas the earlier process uses the hydrogen in a bio-oil upgrading process after the pyrolyzer.

Unique to this paper is the integration of hydrogen into the pyrolysis process. This process as shown in Figure 1 is an idea to use waste biomass from crop residue in Eastern Idaho (United States) where barley

*Grant.Hawkes@inl.gov

straw and wheat straw are plentiful. This waste biomass is converted into bio-crude and biochar and integrated with a HTSE unit. The process is powered by nuclear electricity or some other form of non-fossil electricity. Barley straw and wheat straw are gathered at a chemical processing site. The straw currently is used for animal bedding and feed during the winter. The bio-crude oil is blended with traditional crude oil at a refinery in Salt Lake City, Utah and made into diesel and gasoline. The biochar product is mixed with fertilizer and spread onto the wheat and barley fields in Eastern Idaho where it is sequestered for thousands of years. This makes the entire process carbon negative since carbon is taken out of the atmosphere and placed in the soil. The diesel fuel and gasoline returned from the refinery is used in the Idaho National Laboratory (INL) fleet of buses and vehicles. This process will point the INL towards its goal of Net-Zero by 2030.

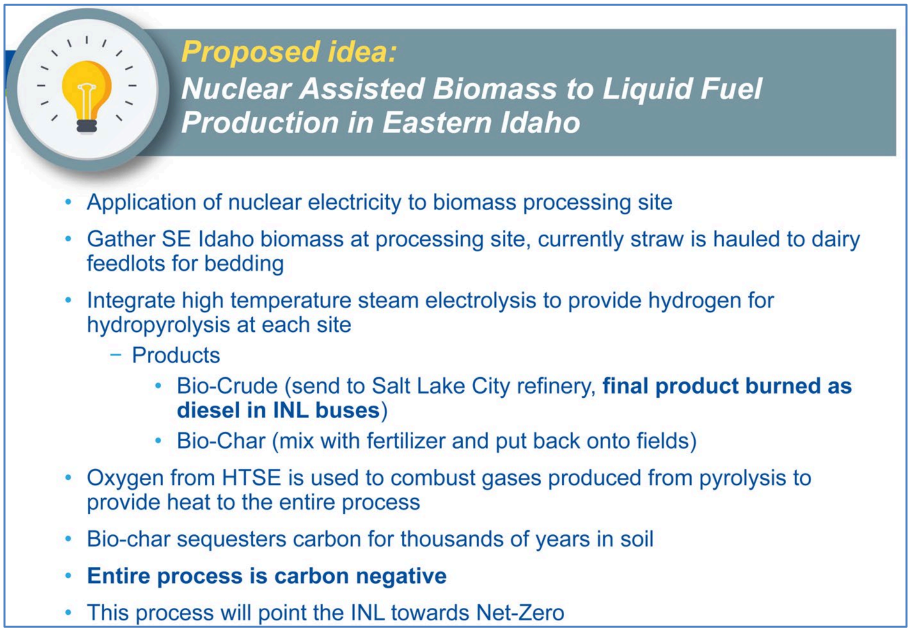

Figure 1. Proposed idea for nuclear assisted carbon negative process.

The proposed steps as shown in Figure 2 for this process are described as 1) gather the waste biomass from fields and transport to a chemical processing plant. This plant would be located so that the maximum transportation distance would be about 50 miles, 2) send nuclear generated electricity to the processing plant to supply electricity to the HTSE unit, integrate hydrogen to hydro pyrolyze the waste straw to create bio-crude, biochar, and noncondensable gases. Biochar and ash are produced in this step. 3) Send the bio-crude to an oil refinery for blending with traditional crude oil for further processing and send biochar and ash to a fertilizer plant. 4) Blend the biochar and use as the foundation of a carbon-based fertilizer and include the ash. These products are then returned to the fields where the barley straw and wheat straw were grown and used to produce the next crop. Micronutrients that plants need such as magnesium and copper are returned to the field with the ash and the chemicals in the field remain in a state of equilibrium.

Current management and usage practices of straw is to haul the straw to dairy feedlots and use the straw as bedding or as feed to the dairy cows. This concentrates the micronutrients in the soil at the dairy farm. After several years of this practice, micronutrients will need to be purchased from the fertilizer company and placed on the field via fertilizer application. It is important to note that only one half to three fourths of the straw is taken off the field in the form of straw bales. The remaining straw worked back into the soil via field cultivation and is vital for the health of the soil. Figure 3 shows bales of barley straw in a field in Eastern Idaho.

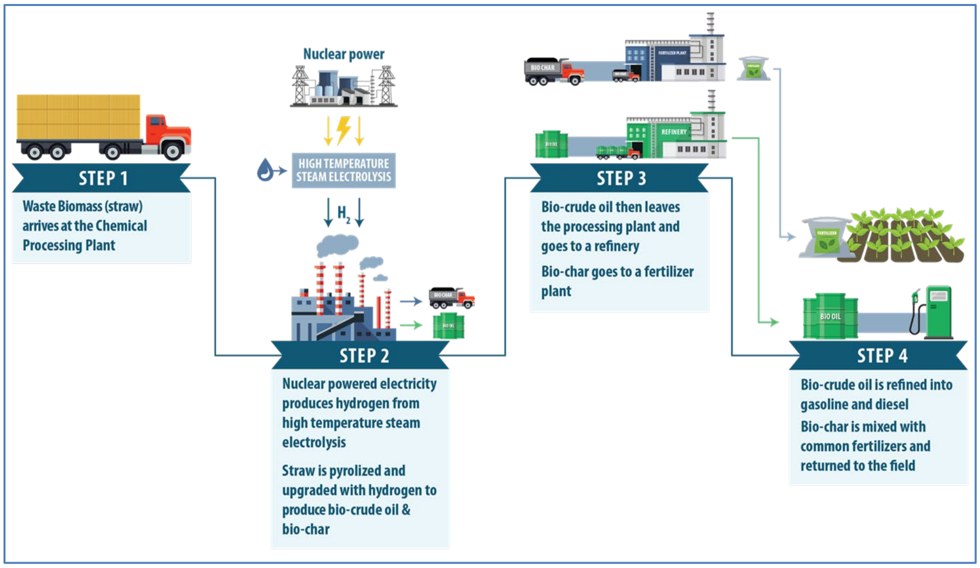

Figure 2. Overall process description.

Momentum is building for processes where waste biomass is converted into hydrocarbon fuels with massive amounts of nuclear heat and electricity as noted in (3) and (4). These articles propose replacing all traditional crude oil with bio-crude made from waste biomass and processed with nuclear heat and electricity. Synthetic fuels are vital in the decarbonization of transport and industry by 2050 and can be blended in fossil fuels or can completely replace them in existing ships, airplanes, or industrial technologies. Nuclear power could help to bring down the production costs of synthetic fuels.

Figure 3. Bales of barley straw in Eastern Idaho.

Figure 4 shows a perspective view (looking northwest) of eastern Idaho where the Idaho National Laboratory (INL) is. This figure shows a nuclear plant located at the INL. This was recently a possibility but has been cancelled as of now. Rich farmland is shown along the edge of the eastern and southern side of the Snake River plain. This plan proposes a nuclear power plant at the INL, and three biomass chemical processing plants located in the center of three agricultural areas in eastern Idaho. As noted, these plants are located so as not to transport the biomass more than 50 miles to any plant. Electricity from the nuclear plant is delivered to each chemical processing plant to run the electrolyzer. Bio-crude is piped to Salt Lake City (200 miles) and blended with traditional crude oil at a traditional oil refinery.

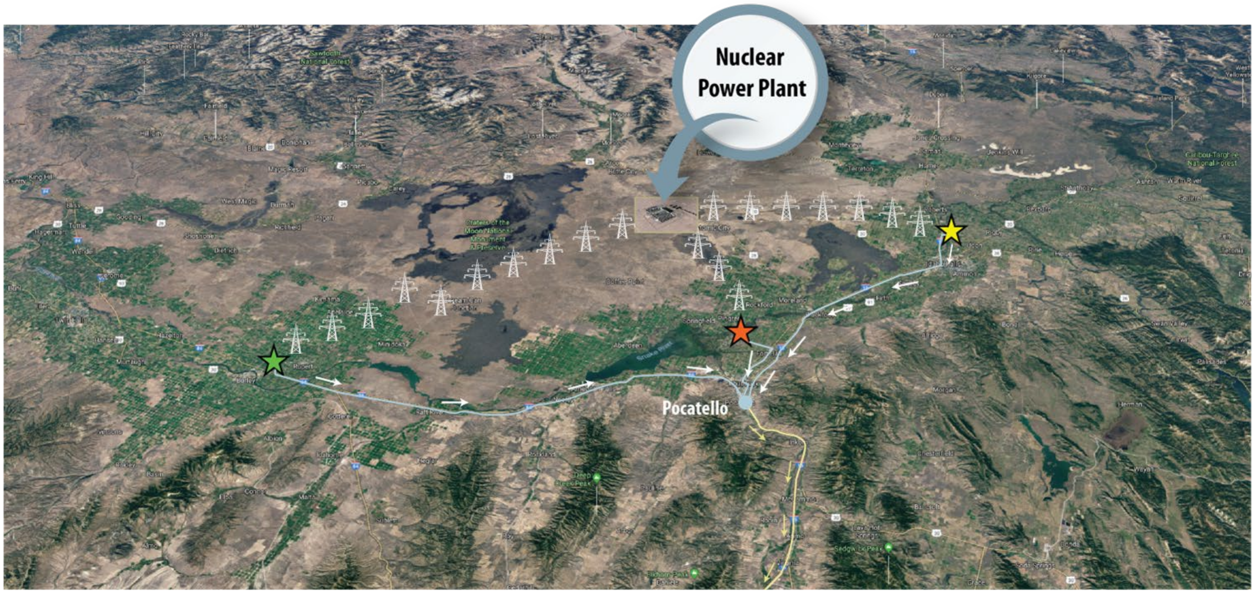

Figure 4. View of eastern Idaho with processing plants located near biomass and nuclear plant at INL.

2. PROCESS MODEL

A process model using the ASPEN software (5) was used to model the chemical process of the fast hydropyrolysis of Eastern Idaho waste biomass of barley or wheat straw. Figure 5 shows a block flow diagram of the process. Inputs to the chemical process are wheat or barley straw, water, and nuclear-powered electricity. Outputs are bio-crude oil, biochar, ash, and exhaust gases of carbon dioxide and water. Figure 5 shows a process based on 1.0 kg/s of biomass at 15% moisture content. These results are then scaled to match the INL vehicle fleet requirements of 2,225 gallons/day, which requires 3,000 gallons/day of bio-crude.

Figure 6 shows the ASPEN model conditions and flow diagram for this process. This model uses Peng-Robinson equation of state for conventional components. Both biomass and biochar are modeled as nonconventional components. The biomass is dried in a dryer where the moisture content is reduced from 15% to 7%. The dried biomass of 0.91 kg/s then enters the hydropyrolysis unit that operates at 400°C and 40 bar. Hydrogen from the HTSE unit is compressed to 40 bar and injected into the pyrolyzer at 0.05 kg/s for a total input of 0.96 kg/s. The hydropyrolysis reactor is modeled using RYEILD using pilot plant data. The products were input into ASPEN from 2011 research from the Shell's IH2 pilot plant process (6). The composition of the bio-oil and gas produced were estimated from experimental data for catalytic hydropyrolysis of crop straw (7). Output products of 0.16 kg/s noncondensable gases, 0.18 kg/s biochar, 0.05 kg/s ash, 0.21 kg/s of bio-crude, and 0.36 kg/s water. Water into the electrolyzer is at 0.45 kg/s, with oxygen out at 0.40 kg/s, and hydrogen out at 0.05 kg/s. Nuclear powered electricity in at 6.84 MW was determined from an electrolyzer efficiency of 38 kW-hr/kg for hydrogen production with a HTSE unit at 800°C.

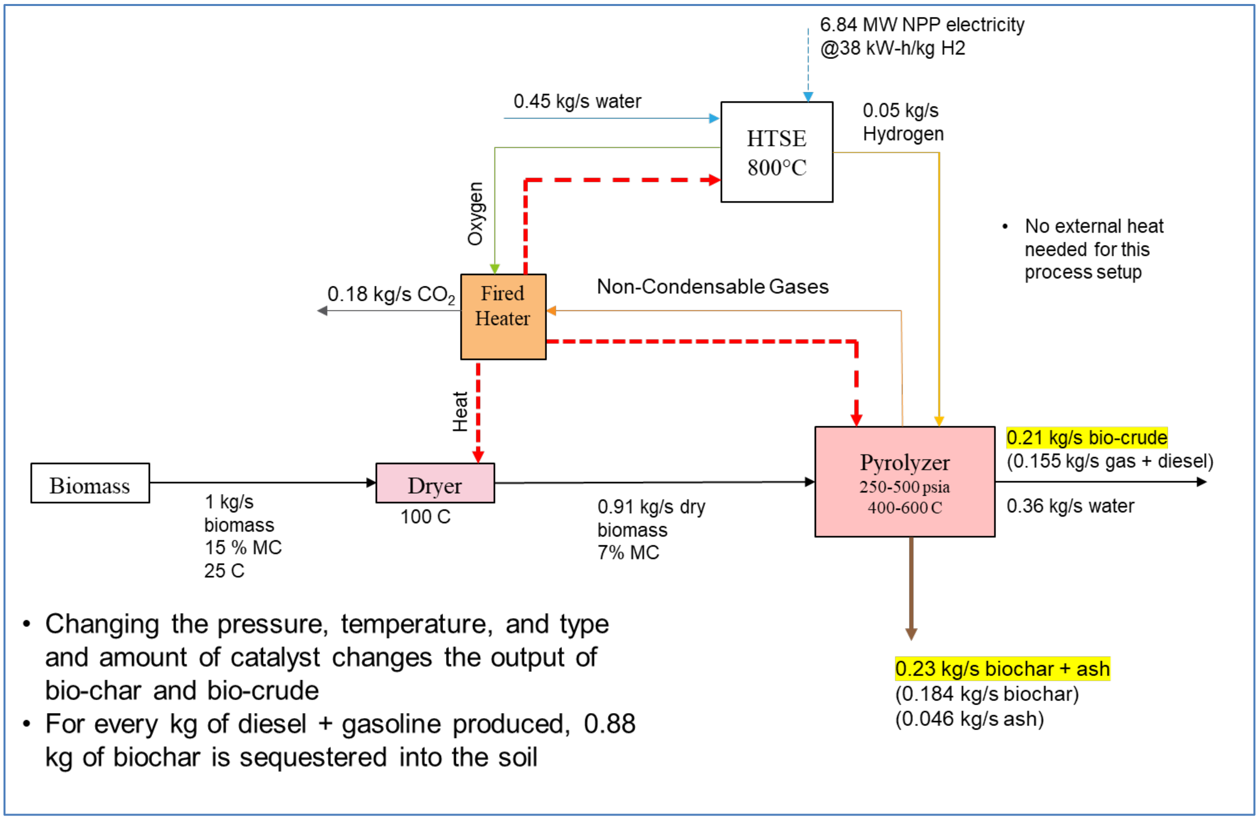

Figure 5. Integrated hydropyrolyzer and block flow diagram.

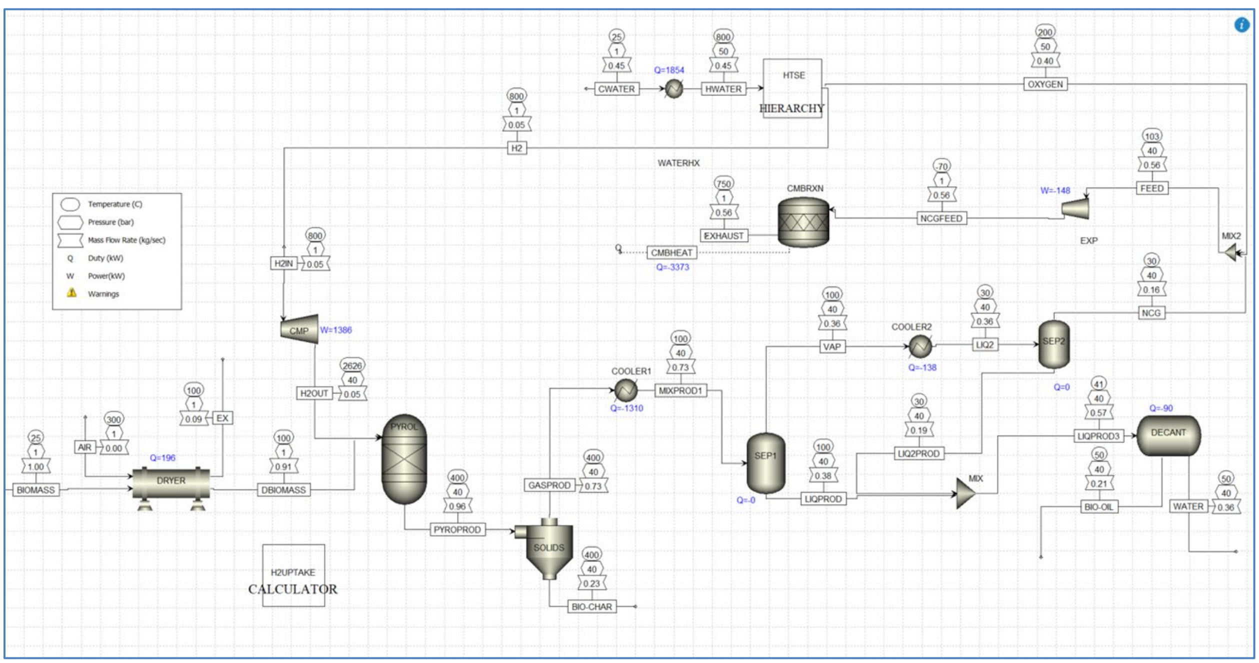

Figure 6. ASPEN process model conditions and flow diagram.

3. SYSTEM REQUIREMENTS FOR STRAW AND NUTRIENT CYCLE

This section discusses the straw requirements to provide enough fuel for the INL fleet of vehicles and buses that currently requires about 2,225 gallons/day. The micro-nutrients necessary for the plants and the cycle that they go through is also discussed.

3.1. Straw and Electrical Power Requirements to Supply INL Fleet with Fuel

Table I shows a list of parameters required to produce 2,225 gallons of fuel per day (FY22) for the INL fleet of vehicles and buses. The total amount of Eastern Idaho straw available is 457 bales of straw per day, assuming 1,200 pounds per bale of straw. This amount comes from (8). This process requires 85 bales of straw per day. The bio-crude required to produce the fuel is 3,000 gallons (72 barrels) per day, assuming 74% of (gasoline plus diesel) fuel conversion from bio-crude. The required electricity is 3.68 MW to power the electrolyzer. The water required for the electrolyzer is 0.24 kg/s (3.83 gal/min). The amount of biochar produced is 4,400 kg/day. This equates to 31,500 kg/day of CO_2 saved from the atmosphere. The bio-crude could be blended at the Marathon Oil Refinery in Salt Lake City which has a capacity of 66,000 barrels/day. Further calculations are displayed in Appendix A.

Carbon savings are calculated in Appendix A and based on the following:

- CO_2 emitted from the fired heater and buses is considered carbon neutral.
- 14 kg of CO_2 (Appendix A) is sequestered per gallon of diesel + gasoline produced.
- Net CO_2 reduction of **144%** compared to status quo of pumping oil out of the ground.
- Carbon sequestration of 11,500 metric tons per year.

Table I. Eastern Idaho straw available and resource requirements for INL fleet production.

Straw Available and Products	Amounts
Total Eastern Idaho straw available	100,000 tons/yr (8) 167,000 bales/yr 457 bales/day
Straw required for 72 barrels per day bio-crude	102,000 lb/day (85 bales/day) (1,200 lb/bale)
Electricity	3.68 MW
Water	0.24 kg/s (3.83 gal/min)
Bio-crude required for 2,225 gal/day fuel (assumes 74% of bio-crude refined into fuel)	72 barrels/day 3,000 gal/day
Gasoline (45% of crude)	1,350 gal/day
Diesel (29% of crude)	875 gal/day
Biochar produced (carbon sequestered)	4,400 kg/day (31,500 kg/day CO_2)

3.2. Straw Use

Current Eastern Idaho straw use is to bale the straw in the field and haul it to Southern Idaho where there is an abundance of dairies. Approximately 80% is used for bedding and 20% for feed (8). The same source states that 100,000 tons of straw are hauled from Eastern Idaho to Southern Idaho. What will dairies do with competition for this source of bedding and feed? The dairies will need straw for bedding and continue buying at a higher price. Straw is a low quality, cheap additional source of feed that would be supplanted with other feed choices such as alfalfa, grains, corn silage, etc. Economics will stabilize the change. About 1.25 tons (short) of straw is produced for a 100 bushel/acre yield (typical irrigated) of grain. Low cutoff is

0.5 tons for 50 bu/ac. Straw costs about $40/ton to bale and $20/ton to haul 50 miles, $15/ton to haul 5 miles (8).

3.3. Nutrient Cycle

Elements such as P, K, Mg, etc. come from soil in SE Idaho into straw and end up in manure in Southern Idaho. Eastern Idaho farmers must purchase these micro-nutrients after many years of this one-way track of the nutrients. Figure 7 shows dried manure piled in strips ready to be spread on Southern Idaho fields. It is currently too expensive (8) to haul this manure back to Eastern Idaho and spread on the fields to keep the nutrient cycle in equilibrium. This proposed process takes the biochar and ash and mixes them with fertilizer where the mixture is spread back onto fields in Eastern Idaho.

The question is raised if the micro-nutrients in the ash that is spread back onto the fields can be taken up by the wheat and barley plants. Reference (9) shows that ash from biochar has a high bioavailability when placed back onto the fields.

Figure 7. Dry manure piled in strips in Southern Idaho.

4. BIOCHAR

Biochar is a fine, porous material made mostly of carbon. It has several potential applications, the most intriguing being dual use as soil amendment and carbon sequestration agent. When considering biochar for agricultural applications, it increases nutrient availability, microbial activity, soil organic matter, water retention, and crop yields. Biochar decreases fertilizer needs, greenhouse gas emissions, nutrient leaching, and erosion. Biochar stays sequestered in the soil for thousands of years according to (10). Sufficient levels of biochar increase crop production in wheat by 11% (11).

5. CONCLUSIONS

A proposed chemical process based on hydropyrolysis integrated with high temperature steam electrolysis powered by nuclear electricity for waste agricultural biomass in Eastern Idaho that creates biochar and bio-crude oil has been discussed and modeled. The process is designed to create enough bio-crude to be refined to cover all the gasoline and diesel requirements for the INL vehicle fleet. The bio-crude oil is compatible with existing conventional crude oil and can be blended at current refineries. The biochar is returned to the soil via fertilizer application and remains there for thousands of years. Since the total process uses nuclear generated electricity, the carbon in the biochar is ultimately sequestered from the atmosphere, thus making the process carbon negative. Using waste biomass, such as wheat and barley straw or corn stover, as a renewable carbon source with supplemental hydrogen from high-temperature steam electrolysis (HTSE), this hybrid energy process has the potential to provide an alternative petroleum source. This process option transports the biomass to a processing plant away from the nuclear plant and just sends the electricity.

A fast pyrolysis process with hydrogen injection is used to convert the biomass to bio-crude and biochar, where hydrogen and oxygen from the HTSE unit are integrated into the process. Hydrogen is injected into the pyrolyzer with a catalyst, while oxygen is combusted with the noncondensable gases produced in the pyrolyzer to provide heat for the pyrolysis process, biomass drying, and heating the water for the electrolyzer. Straw availability and amounts needed along with the micro-nutrient cycle were discussed. Details of biochar and its use as a sequestration agent and soil amendment have been discussed.

ACKNOWLEDGMENTS

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APPENDIX A

Referring to Figure 5 =➔

Straw:

$$\left(\frac{2{,}225\ gal\_fuel}{day}\right)*\left(\frac{7.14\ lb_{fuel}}{1.0\ gal_{fuel}}\right)*\left(\frac{1.0\ lb_{straw}}{0.21\ lb_{crude}}\right)*\left(\frac{1.0\ lb_{crude}}{0.74\ lb_{fuel}}\right)=102{,}270\frac{lb_{straw}}{day}=\mathbf{85.2}\frac{\boldsymbol{bales}}{\boldsymbol{day}}$$

Electricity:

$$\left(102{,}270\frac{lb\_straw}{day}\right)*\left(\frac{1.0\ kg_{straw}}{2.2\ lb_{straw}}\right)*\left(\frac{1.0\ day}{86{,}400\ s}\right)*\left(\frac{6.84\ MW_{elec}}{1.0\ \frac{kg_{straw}}{s}}\right)=\mathbf{3.68}\ \boldsymbol{MW\_electricity}$$

Water:

$$\left(\frac{102{,}270\ lb\_straw}{day}\right)*\left(\frac{1.0\ kg\_straw}{2.2\ lb\_straw}\right)*\left(\frac{0.45\ kg\_water}{1.0\ kg\_straw}\right)*\left(\frac{1.0\ day}{1440\ min}\right)*\left(\frac{1.0\ gal\_water}{3.79\ kg\_water}\right)=\mathbf{3.83}\frac{\boldsymbol{gal\_water}}{\boldsymbol{min}}$$

CO2 Avoided (Biochar Sequestered):

$$\left(\frac{2{,}225\ gal_{fuel}}{day}\right)*\left(\frac{7.14\ lb_{fuel}}{1.0\ gal_{fuel}}\right)*\left(\frac{0.88\ kg_{biochar}}{1.0\ kg_{\ crude}}\right)*\left(\frac{1.0\ kg_{crude}}{0.74\ kg_{fuel}}\right)$$

$$*\left(\frac{1.0\ kg_{fuel}}{2.2\ lb_{fuel}}\right)*\left(\frac{44\ kg_{CO2}}{12\ kg_{biochar}}\right)=\mathbf{31{,}500}\ \frac{\boldsymbol{kg_{CO2}}}{\boldsymbol{day}}\ \textbf{Avoided}$$

$$\textbf{or}\quad\left(\frac{31{,}500\ kg_{CO2}}{day}\right)*\left(\frac{day}{2{,}225\ gal_{fuel}}\right)=\mathbf{14\ kg_{CO2}/gal_{fuel}}$$

Bio-crude:

$$\left(102{,}270\frac{lb_{straw}}{day}\right)*\left(\frac{0.21\ lb_{diesel}}{1.0\ lb_{straw}}\right)*\left(\frac{1.0\ kg_{diesel}}{2.2\ \ lb_{diesel}}\right)*\left(\frac{1\ gal_{diesel}}{3.22\ kg_{diesel}}\right)*\left(\frac{10\ kg_{CO2}}{1\ gal_{diesel}}\right)=\mathbf{30{,}500}\frac{\boldsymbol{kg\ CO_2}}{\boldsymbol{day}}$$

- Assumes all bio-crude has a CO_2 equivalent of 10 kg/gal and 100% of bio-crude is used.

Fired Heater Exhaust CO_2:

$$\left(102{,}270\frac{lb_{straw}}{day}\right)*\left(\frac{0.18\ lb_{CO_2}}{1.0\ lb_{straw}}\right)*\left(\frac{1.0\ kg_{CO_2}}{2.2\ \ lb_{CO_2}}\right)=\mathbf{8{,}370}\ \frac{\boldsymbol{kg\ CO_2}}{\boldsymbol{day}}$$

Carbon Savings:

$$\left(\frac{-31{,}500\ \frac{kg_{CO2}\ sequestered}{day}}{30{,}500+8{,}370+31{,}500=70{,}370\ \ \frac{total\ kg_{CO2}}{day}}\right)=\mathbf{-44.7\%}$$