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Techno-economic assessment of integrated hydrochar and high-grade activated carbon production for electricity generation and storage

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Abstract

This paper deals with process simulation and techno-economic assessment on a bioenergy system for sustainable electricity production from low-grade biomass resources such as forest and agricultural residues, which is suitable for rural areas in developing regions susceptible to intermittent electricity supply. The core of the system is hydrothermal carbonization of wet biomass for production of hydrochar, followed by wet milling and direct combustion of the obtained hydrochar slurry fuels for heat and power generation. In order to improve the economy and make the process a closed-loop system, the paper also identifies a bio-refining strategy focusing on production of high-grade activated carbons for energy storage using supercapacitor. Aspen Plus software package is used as simulation and optimization tool. The result shows that the proposed system is highly feasible both technically and economically. The cost of electricity varies from 0.2 to 0.4 \$/kWh in the efficiency range of (40 % to 20 %), which depends on the hydrothermal carbonization operating conditions.

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Keywords: Hydrothermal carbonization; forest residues; slurry fuel; process simulation; techno-economic assessment

1. Introduction

Nowadays, although consistent electricity supply is taken for granted, it may be rare in some rural areas of developing regions. This makes life and economic development in the areas subjected to intermittent electricity supply harder. A possible solution to this problem is to use charcoal slurry fuels, blend of locally produced charcoal suspended in water or diesel for heat and power generation.

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Recently, a closed-loop bioenergy system has been conceptually designed and analyzed, which consists of two HTC processes: high T and low T HTC [1]. The main product of High-T HTC is hydrochar and the main by-products are water soluble organics that can be converted to super porous AC via further HTC at low temperatures, followed by activation. The produced AC is very much suitable for supercapacitor. Wet hydrochar can be milled and characterized for use as water or water diesel slurry fuel, suitable for combustion in respectively industrial furnaces and diesel engines for heat and/or power generation. Such a system would have very positive environmental impacts. The replacement of fossil fuels with biomass residues would contribute to the effort of greenhouse gas emission reduction and sustainable development. On the other hand, water in the slurry fuels will help reduce local peak temperatures and thus reduce NO_x formation during combustion. If the AC helps solve completely the gap between today's capacitor (short lifetime) and battery (low power), low-cost supercapacitors would be viable for electric personal cars, reducing significant emissions from transport. As a follow-up, the work reported in this paper was carried out for a techno-economic assessment of the conceptual process and system reported in our earlier paper [1].

2. Process design and analysis

Fig. 1 presents the design of a closed-loop system, adapted from our earlier study [1], for electricity production and storage (using supercapacitor) suitable for rural areas in developing countries, which may be suffering from intermittent electricity supply, which is based on hydrothermal carbonization (HTC). In this system, centralized production of hydrochar slurry that can be blended with diesel or biodiesel or other viscous biocrude is proposed.

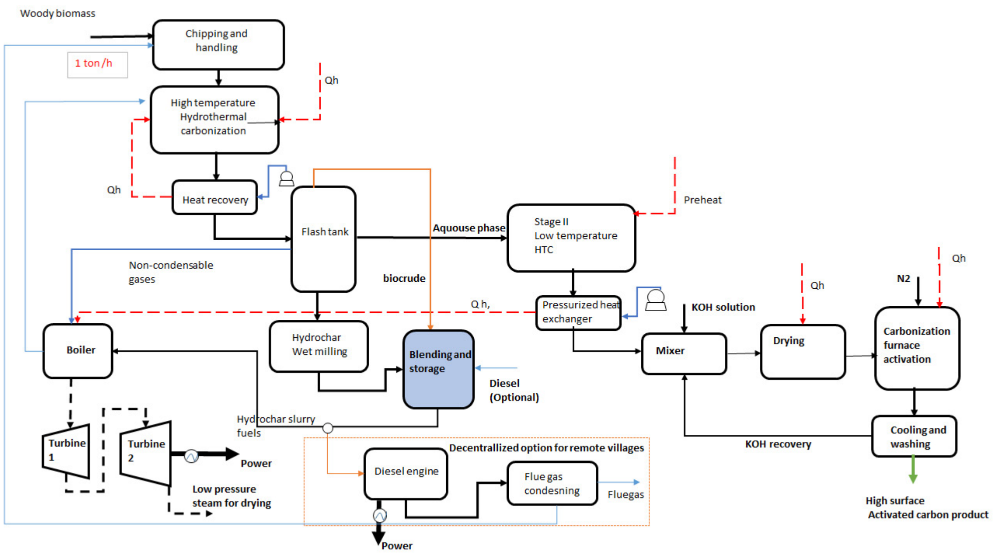

Fig. 1. Process design of the closed-loop system.

Feedstock such as woody biomass are chipped and conveyed to a semi-batch autoclave reactor, which use hot compressed water as reaction medium. Typical temperature range can be in the range of 250 to 350°C and the pressure in the system near a subcritical system. The main product from the process is carbon rich solid (Hydrochar). By-products include hot compressed process water, oily and water soluble organics (Oil and Aqueous), and CO_2 gas with traces of CH_4, sulphur and hydrocarbon compounds [2]. In principle, like charcoal produced via *thermal carbonization*, hydrochar can be used as fuel, reduction agent, metallurgical coke, activated carbon, fertilizer, and soil conditioner [3, 4], of which the first (as fuel) is a focus of this study. The gas products can be burned to provide heat back to the HTC process. Heat and/or power can be recovered (Energy recovery) from the hot compressed water using high-pressure heat exchanger and/or steam turbine, which can be integrated to the (Separation) flash tank. This has been verified experimentally at the pilot plant VERENA (Germany) operating with a 100 kg/h throughput (large biomass particles) [5]. The water soluble organics by-product can be converted to high-grade activated carbon (AC) via further HTC at low temperatures (Low-T HTC) followed by activation [6]. More importantly, *wet hydrochar* can be burned in the *water slurry form* (Fuel) in industrial furnaces (Boiler) and/or (Diesel engine) for heat and/or power generation. Such furnaces can be equipped with *flue gas condensers* (FG condensing) for recovering the latent heat bound to the fuel water that follows the flue gas (Wet flue gas) in the gas form. The present project takes advantage of low-cost wet biomass resources and the HTC process (*no need of pre-drying the feedstock*) to produce hydrochar slurry fuels (*no need to dry hydrochar*) and high-grade AC for energy production and storage applications. A focus is on production and combustion of hydrochar slurry fuels for heat and/or power generation.

2.1. Production and combustion of hydrochar slurries

An important application of hydrochar from HTC is direct combustion for heat and power generation. Due to the removal of hemicellulose and water-soluble ash fractions during HTC treatment, the combustion of hydrochar is more stable and environmentally friendly than that of raw biomass material [3, 4]. HTC treatment also greatly improves the grindability of biomass [3, 4]. Thus, hydrochar can be easily ground down to very small particle sizes to improve its combustion performance and efficiency.

It has been reported that burning biochar in the form of water slurries in diesel engines is a feasible and promising means for energy production from biomass, which is particularly suitable for remote and small scale power generation [7, 8]. In general, suspending biochar particles in water will form biochar slurry fuels, which are similar to coal water slurry fuels [8-11]. It has been found that size distribution, surface area, and porosity of fuel particles affect slurry rheological and atomization properties, making the fuel a non-Newtonian fluid [12]. Higher water contents in the slurry increase the self-ignition temperature and slurry fuels burn in two stages: first the volatiles combustion, followed by heterogeneous char combustion, with oxygen diffusing to the char surface. In addition, the combustion duration of slurry fuels increases considerably compared to diesel fuels. Recently, a comprehensive study on combustion characteristics of a biochar slurry in a direct injection diesel engine and the impact on the injection system performance has been reported [13]. The study has proven that a biochar slurry fuel can produce adequate sprays and burns with very good results in a diesel engine. However, erosion and premature wearing of the fuel injector nozzles was reported. Similar problems were found critical for the operation of the fuel injector, and the conclusion is that the *fuel ash content has to be kept low for optimal injector operation* [14]. The HTC process is known to reduce the ash content of biomass [3, 4], and thus more optimal injector operations can be expected for combustion of hydrochar slurry fuels.

2.2. Utilization of aqueous sugars for production of high-grade activated carbon for supercapacitor

High surface activated carbon production for porous electrodes is recognized as new electricity storage in the form of supercapacitors, which can increase the specific capacitance. For this reason, high-grade AC materials with high-specific surface area (>1200 m^2/g) have been chosen as electrode materials for supercapacitors. In addition, AC with a spherical shape can benefit from the capacitive performance of supercapacitors because the homogeneous package can decrease the resistance of electrolyte diffusion, and the space between the spheres can make the electrolyte accessible to the electrode, both of which help to efficiently form the electric double layer [15]. However, AC produced via thermal carbonization or HTC of native biomass followed by chemical activation are usually not spherical but irregular-shaped [16]. It is due to the fact that only those "soft" plant tissues (hemicelluloses) without an extended crystalline cellulose scaffold can lose their original structure, forming globular carbonaceous nanoparticles, and "hard" plant tissues cannot form spheres [17]. On the other hand, it is reported that micro-mesoporous carbon spheres (3-6 μm) with good morphology and simultaneously with a large surface area of 3062 m^2/g were successfully prepared from hemicelluloses via HTC followed by KOH chemical activation [6]. Electrochemical performance in supercapacitors was also evaluated for the obtained AC spheres, and gave excellent results. Due to abundant micropores and ample oxygen functionalities, the samples were able to achieve a high capacitance of 318 F/g as electrode material in supercapacitors. The plentiful micropores also lead to excellent CO_2 and CH_4 adsorption capacities at ambient pressure and 0°C.

3. Flowsheet development in Aspen Plus and sub-models explanation

Chipping and screening: The chipper model is implemented based on industrial data, through a chipper model function as shown in Equation 1.

$$P_{CH} = \frac{X_{CH}}{S_{CH}} \cdot M_{IN-CHIP} \qquad [1]$$

Specific power consumption (P) for the chipper ($_{CH}$) is based on the mass flow into the chipper, where X is the electricity consumption [kW] for the static load, S – static load [kg/h] and M – feedstock mass flow [kg/h]. The screening model is based on a built in model, here a gyratory screen with multiple deck is modelled to accommodate broader particle size distribution (PSD) range.

Hydrothermal carbonization process and reactor: The sub-model for the carbonization reactor is modelled through a yield reactor that is controlled by FORTRAN expressions for predicting yields of char, biocrude, aqueous soluble compounds and non-condensable gases. The model neglects the ash chemistry and further refinement is required to know the solubility of alkaline in the form of salts. The model data used for the high temperature carbonization is 350 °C and 20 bar pressure in the process reactor. The hydrochar separation model is based on a simple splitter model, where solid phase hydrochar is separated from biocrude and soluble aqueous phases. The model components for the biocrude used are phenol and acetic acid. To preheat the process reactor indirectly, a portion of the gases separated from the HTC product along with the diesel-blended char-slurry product is burned to preheat the HTC reactor. The mass yields results for the carbonization process are depicted as shown in Table 1.

Table 1. Hydrothermal carbonization process yields results.

Mass balance	Pressure [MPa]					
[kg/kg daf biomass] for	0.1	0.4	0.8	1.2	1.6	2
CHAR	0.31	0.32	0.35	0.37	0.39	0.41
TAR	0.36	0.34	0.31	0.29	0.26	0.23
Phenol	0.18	0.17	0.16	0.14	0.13	0.11
Acetic acid	0.18	0.17	0.16	0.14	0.13	0.11
Water	0.23	0.23	0.25	0.26	0.27	0.28
Biooil(tar + water)	0.59	0.58	0.56	0.54	0.53	0.51
GAS	0.11	0.11	0.10	0.10	0.09	0.08
H_2	0.00	0.00	0.00	0.00	0.00	0.00
CH_4	0.01	0.01	0.01	0.01	0.01	0.01
C_2H_4	0.00	0.00	0.00	0.00	0.00	0.00
CO	0.05	0.05	0.05	0.05	0.05	0.05
CO_2	0.05	0.05	0.04	0.04	0.03	0.03
TOTAL (CHAR+GAS+TAR)	1.01	1.01	1.01	1.01	1.01	1.01

Wet-milling: Hydrochar separated from the HTC stage 1 process is milled by wet ball-mills which is similar to conventional coal mills, however, specific energy consumption can differ based on the grindability properties, grindability of hydrochar improves with increasing hydrothermal conversion temperature.

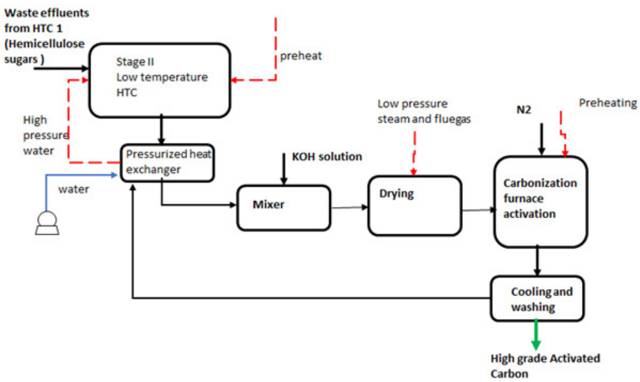

Fig. 2. Hydrothermal carbonization (Stage II) for high grade activated carbon production.

Specific energy consumption for the wet-mill is user imposed into the grinder model, and the capacity of the wet-mill is specified into the Aspen Plus built in grinder model which is based on the Gates–Gaudin–Schuhmann models for the particle size distribution [18]. The maximum particle size at the outlet specified in the model is 1 mm. Particle sizes below 1 mm are suspended in the slurry, and can then be stored in a blending tank for further transport to the remote end-users to run their diesel engines or use in slurry combustion boilers for high pressure steam production and micro CHP for heat and power generation.

Hydrothermal carbonization process of hemicellulose sugars (Stage II): The soluble hemicellulose sugars separated from stage 1 is further processed by low temperature carbonization (Fig. 2). This reactor is modelled based on the conversion based stoichiometric reactor, the model compound for low temperature carbonization is based on the pentose sugar Xylose. The xylose five-carbon sugars are hydrothermally processed at low temperature (160 to 200°C) at a long residence time of 8 hours. The yield data for this process, see Table 2, is summarized from [19]. The overall yield is meant to be only for the second stage process. The overall yield for the utilization of aqueous sugars generated from the first stage process can be 10 %.

Table 2. Mass yields of high surface biocarbon/activated carbon for supercapacitors.

Aqueous sugars from hydrothermal carbonization	39 %
Thermal activation	27 %
Overall yield of high surface carbon	10 %

Drying of KOH activated carbon: Drying is very necessary prior to carbonization in a carbonization retort to control the surface of carbon. A belt dryer model is used, with air as a drying medium. As shown in Fig. 3, air goes through first heat exchangers (HE) where heat from recycled air is recovered, next the air is preheated by flue gas, and the last heat exchanger is used when flue gas is not sufficient to provide heat and then low-pressure steam is used. Hot air is split into two streams that are directed to the second and third stage respectively. Thereafter they are mixed and directed to the first stage. The heat demand is dependent on the moisture content in the feedstock.

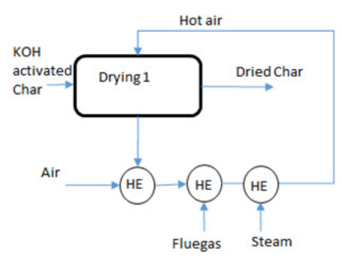

Fig. 3. AC drying.

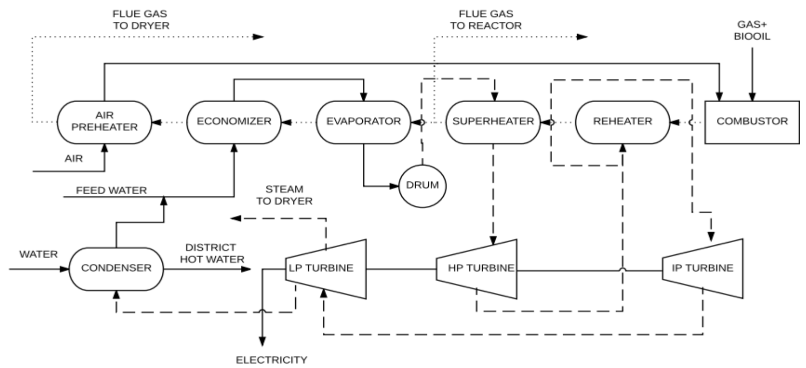

Fig. 4. CHP process flow diagram.

The Aspen Plus CHP flowsheet for the combustion of gases and hydrochar slurry is shown in Fig. 4. The combustor is simulated by the built in Aspen Plus Gibbs reactor model. Hot flue gases generated from the combustion chamber is heat exchanged through the reheater, superheater, evaporator (boiler drum) and economizer to produce high-pressure steam of 40 bars and 430°C. The hot flue gas from the air-preheater supplies heat to the dryer. The power to steam ratio is kept constant at 0.18. HP steam is expanded in a series of steam turbines (high pressure, intermediate pressure and low pressure) where electricity is produced. LP steam after the LP turbine is used for drying and hot water production, which is recycled back to the hydrothermal carbonization process and excess heat can be used as a product for process heat or district heat. Recycled condensed steam is mixed with the make-up water and pumped to the economizer.

Carbonization of activated char: KOH activated char is carbonized in the batch retort, here in our model a simple stoichiometric based conversion reactor is assumed. Activated char is decomposed to carbon through the reaction ($Char + N_2 \rightarrow CO + C + N_2$), where nitrogen is just an inert to sweep the char into the process reactor.

4. Techno-economic assessment

Energy efficiency of Hydrochar suspended crude: Fig. 5 shows the electrical efficiency for suspending char in the slurry made of crude after milling to below 0.1 mm. The char suspension in biocrude is not yet demonstrated. However, there are several pilot research activities on direct coal slurry use in diesel engines. Electrical efficiency reported by Soloiu et al. [13] for hydrochar slurries in diesel engines is in the range of 30-35 %. Typical coal-based power plants have efficiency in the range of 36 to 38 %.

On the other hand, long residence times in hydrothermal carbonisation can yield phenol like compounds and recovering steam via depressurization using a pressure reduction valve after the HTL reactor through staged flash tanks and recycle of steam back to the hydrothermal reactor will reduce the preheating energy consumption. The assumption in the CHP modelling is an engine based on the turbo-expander combustion model. The modelling components assumed in Aspen Plus are a compressor for compressing the air with a compression ratio of 20, a Gibbs model for combustion (adiabatic) of the fuel mix, the flue gas is expanded in the turbo-expansion (expansion model), and finally heat recovery. A significant simplification of the Aspen Plus yield model is that the crude is based on the phenol compound, while acetic acid is separated out from the crude. In our case, biomass-based slurries are made through the hydrothermal carbonisation route. Adding high heating value crude to the char suspension can increase the electrical efficiency. In that scenario, achieving high electrical efficiency is the objective of our concept. However further analyses are required with respect to the crude blending with char and its heating value characteristics must be studied for various HTC operating conditions under subcritical conditions with longer residence time to achieve higher energy efficiency. Current hydrothermal liquefaction (HTL) technologies, like VERENA and PERK, work at very high pressures, with the aim of maximizing the crude efficiency. However, the charcoal quality is not similar to coal. This needs optimal operating conditions for production of char and crude simultaneously under HTC conditions. Further operating conditions and yield characteristics of woody biomass need to be analysed and model refinement is required to arrive at accurate electrical efficiency data. The electrical efficiency in Fig. 5 is merely for conceptual proofing purpose.

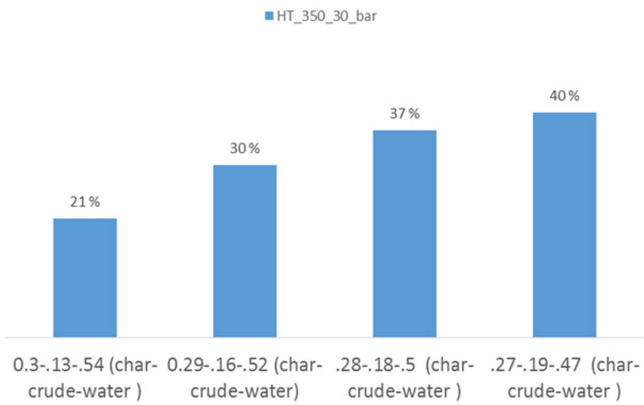

Fig. 5. Electrical efficiency for hydrochar slurry combustion in the engine - Hydrochar slurry composition is a blend of char-crude-water, slurry composition char (0.3-0.27), crude (0.13 to 0.19) and water (0.54-0.47).

The equipment purchase cost is defined as

$$C_{TPEC,i} = C_{S_b,I_b}(S/S_b)^m \quad [2]$$

where $C_{TPEC,i}$ is the equipment purchase cost evaluated for each equipment i, C_{S_b,I_b} is the base year equipment purchase cost for base-case equipment size S_b, m is the equipment scale-index, S is actual equipment size based on scale specification. The purchase equipment and installation cost was evaluated based on the function defined by Kempegowda et al. [20], this is a modified version of the Guthrie-Ulrich method [21], which includes pressure, materials and required auxiliary systems, i.e., electric system, piping and valves, instrumentation and control, through simple multiplication factors. The purchase and installation cost is defined as $C_{S,I,i} = f_{overall}C_{TPEC,i}(I/I_b)k_t^{n-n_b}$, where $C_{S,I,i}$ is the equipment purchase and installation cost evaluated for each equipment i, the cost index I used in this study is based on the Chemical Engineering Plant Cost Index (CEPCI). The cost factors and scaling factors developed in this work are depicted as shown in Table 3.

Table 3. Purchase equipment costing base scaling factors.

Equipment Name	Number required	Scale specification	Scaling stream flow	New stream	Installation factor	Pressure factor	Material factor	2015/base CEPCI factor
Log wood storage	1	kg/h	33500	13589.11	2.34	1	1	1.46
Wood chips storage	1	kg/h	33500	7987.35	2.34	1	1	1.46
Chips conveyor	1	kg/h	33500	7987.35	2.37	1	1	1.46
HTC reactor	1	kg/h			2.59	1.4	1	1.95
Flash tanks	2	m^3	9500		2.59	1.4	1	1.95
Compressor	1		10	0.20	2.51	1	1	1.46
Hydrochar milling	1	kW	50	70.00	2.37	1	1	1.46
Turbo engine-CHP	1	MWe	10.3	0.77	2.37	1	1	1.46
Gas burner	1	m^3/h	1	748.27	2.19	1	1	1.46
Flue gas scrubber	1	m^3/h	10	1.75	2.50	1	1	1.46
Bag filter	1	ft^2	12.1	4555.42	2.50	1	1	1.46

The percentage cost distribution is shown in Fig. 6. Total cost of the stage 1 hydrothermal carbonization process is estimated to be 29 MM$. Net power is anticipated assuming that phenol can be extracted as the coproduct of high activated carbon capacitor production. This needs further validation. The electrical efficiency of the hydrochar slurry engine can as shown in Fig. 5 varies from 21 to 40 %, depending on the blending and char slurry suspension and its chemical composition. A further study will be carried out for the production of activated carbon from the aqueous phase at low temperature. This part needs more experimental data for sizing the equipment. A preliminary estimation suggest that the cost per kWh for the production of hydrochar suspended electricity varies from 0.2-0.4 $/kWh. The key to achieve feasibility relies on the engine performance.

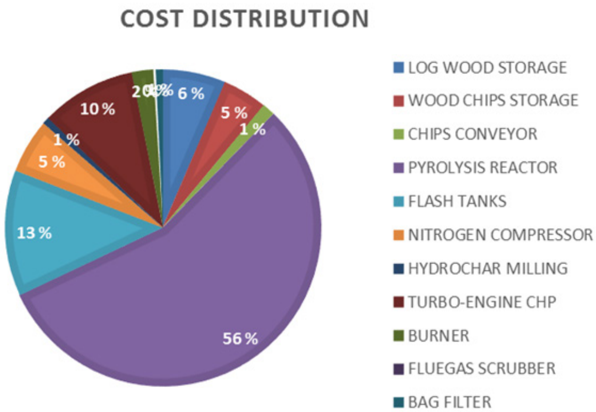

Fig. 6. Cost of hydrothermal carbonization coupled turbo-engine (stage 1 process).

5. Concluding remarks

A closed closed-loop bioenergy system has been developed and analysed, which consists of two HTC processes: High-T and Low-T HTC. The main product of High-T HTC is hydrochar and the main by-products are water-soluble organics that can be converted to super porous AC via further HTC at low temperatures, followed by activation. The produced AC is very much suitable for supercapacitors. Wet hydrochar when milled can be used as water slurry diesel fuel, suitable for combustion in industrial furnaces or diesel engines for heat and/or power generation. This system would have very positive environmental impacts. The replacement of fossil fuels with biomass residues contribute to the effort of greenhouse gas emission reduction and sustainable development. On the other hand, water in the slurry fuels will help reduce local peak temperatures and thus reduce NO_x formation during combustion. If the AC helps solve completely the gap between todays capacitors (short lifetime) and battery (low power), low-cost supercapacitors would be viable for e.g. electric personal cars, reducing significantly emissions from transport. Preliminary costing for the 60 TPD hydrochar plant gives a cost of 29 MM$. The electrical efficiency of the overall process is estimated to vary from 21 to 40 %, which depends on the hydrothermal carbonization process and the hydrochar slurry composition. Further work will be carried out to evaluate parametric influence and sensitivity on the electrical efficiency. Activated carbon production from the aqueous phase and extraction of phenol from the hydrothermal carbonization can reduce overall electricity production cost.

Acknowledgements

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