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Biocarbonization process for high quality energy carriers: Techno-economics

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Abstract

This work deals with a process design and techno-economic analysis (TEA) of the enablement of biocarbonization processes for production of biocarbon, biocrude, biomethane, biofertilizer and heat. Three case scenarios are developed with high levels of integration: a) Biocarbonization process for maximized biocarbon and heat; b) Co-carbonization of algae and woody biomass for biocrude and biochar; and c) Combined co-carbonization and biochemical platform. The approach used here is the combination of process modelling and simulation. Depending on the market dynamics, yields of products can be optimized. Holistically, the proposed processes attempt to reduce solid residues, gaseous emissions and liquid effluents generated in the biocarbon value chain.

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Keywords: Biocarbonization; Process modeling and simulation; Process synthesis; Techno-economics

1. Introduction

The strong demand of solar panels, semiconductors for electronic chips and metal alloys has led to an increasing consumption of silicon. This in turn consumes coal and coke as the traditional reducing agents for silicon production. The consumption of fossil reducing agents is attractive due to their low price. However, coal and coke are non-renewable resources and consuming them in these industries are emission intensive (CO_2, SO_2, NOx, heavy metals and HCl). In addition, their high ash content makes its disposal a problem. In this context, a very attractive alternative is charcoal, produced from renewable biomass resources, which normally has low ash content, as well as sulphur, nitrogen, heavy metals and chlorine. Traditionally, charcoal is produced from biomass via carbonization, which is a pyrolysis process occurring in the absence of or with limited oxygen [1, 2]. The process can be pressurized or atmospheric.

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The atmospheric biocarbon production process can be further classified based on the operating temperature range and the heating rate/residence time in the process [3-5]. The charcoal yield and the quality of the carbon (fixed carbon content) of carbonization processes are normally determined by the severity of the pyrolysis conditions and the feedstock properties [6, 7]. The quality of charcoal to be utilized in metallurgical industries have stringent technical specifications including high fixed carbon (>70 wt%) and relatively low volatile matter. Due to the relatively low fixed carbon content of biomass, compared to coal/coke, these requirements and the increasing demand of charcoal may lead to deforestation, which is a serious sustainability issue. This challenges greater efforts towards more sustainable charcoal production processes, which is the objective of the present work dealing with a process synthesis and techno-economic analysis for more sustainable biocarbonization processes producing various marketable products such as charcoal (biocarbon), biocrude, biomethane and bioheat.

2. Approach

Here we are proposing three interesting case scenarios based on carbonization and co-carbonization platforms; case a) Carbonization process for maximized charcoal and with district heat integration, case b) Co-carbonization integration for biocrude and biocarbon, case c) Pyrobiomethane coupled thermo-biochemical platform for biocrude, biofertilizer and biomethane. Our approach involves tailor made process models that were developed based on both empirical and semi-empirical techniques. Process plant design is carried out in the commercial softwares Aspen Plus and SuperPro and is supported with Fortran programming. Mass and energy balances of the process, process sizing, and user based capital expenditures and operating expenses are considered. The methodology of techno-economic analysis is explained in details elsewhere in our literatures [8, 9], and are established. Details of the process cases will be explained briefly. Fig. 1 shows the process diagram for the biocarbonization plant. Main process steps are i) feedstock handling consisting of logwood storage, debarking, chipping and screening and chips drying, ii) carbonization process and iii) combined heat and power (CHP) process. Feedstock characteristics used in the simulations are shown in Table 1.

Table 1. Feedstock characteristics

Feedstock	Fixed carbon (% wt. dry)	Volatiles (% wt. dry)	Ash (% wt. dry)	C (% wt. daf)	H (% wt. daf)	O (% wt. daf)	N (% wt. daf)	S (% wt. daf)	Cl (% wt. daf)	HHV (MJ/kg dry)
Spruce stem wood	27.27	72.43	0.3	47.38	6.4	46.1	0.09	0.01	0.002	19.9
Spruce bark	26.85	70.62	2.53	49.09	6.06	44.38	0.45	0.02	0.04	20.25

2.1. Case A: Forest logwood to biocarbon (for metallurgical industry), combined heat and power coproducts

Logwood handling: Logwood harvested from the forestry is transported via trucks to the carbonization plant. Typically, for Norwegian conditions, logwood harvested will have a cut length of 3 m. The diameter of the logwood can vary from 0.15 m to 0.5 m according to information from Norwegian Institute of Bioeconomy Research. Logwood moisture content also varies based on the wood species harvested in the forestry. Spruce is very common in Norwegian forestry.

Debarking: Bark is the outer part of the logwood. According to information from suppliers, increased length enhances the efficiency of drum chipping. Typical volumetric loading is in the range of 25-35 %, drum speed is around 4-7 rpm. In our estimation, we assumed the length according to an industrial quote (length: 18 m, and 5 m diameter). Residence time in the debarking process is around 40 mins according to the company Armando Augusto Silva Lda (Jan 2016). In the Aspen Plus model the debarker model is to remove bark from the logwood. A user-defined function is developed using Fortran in Aspen Plus to estimate the specific electricity consumption [kW] as a scaling parameter.

Chipping: The chipper is based on industrial scale data gathered through personal communication. Based on the industrial scale data, a simplified chipper model is introduced in Aspen Plus through user-defined Fortran expressions. Specific power consumption [kW] for the chipper is calculated based on mass flow into the chipper. The screening model is based on the Aspen Plus built in model, here a gyratory screen with multiple decks is modelled to accommodate broader particle size distribution range, weight fractions data are based on Laitila et al. [10].

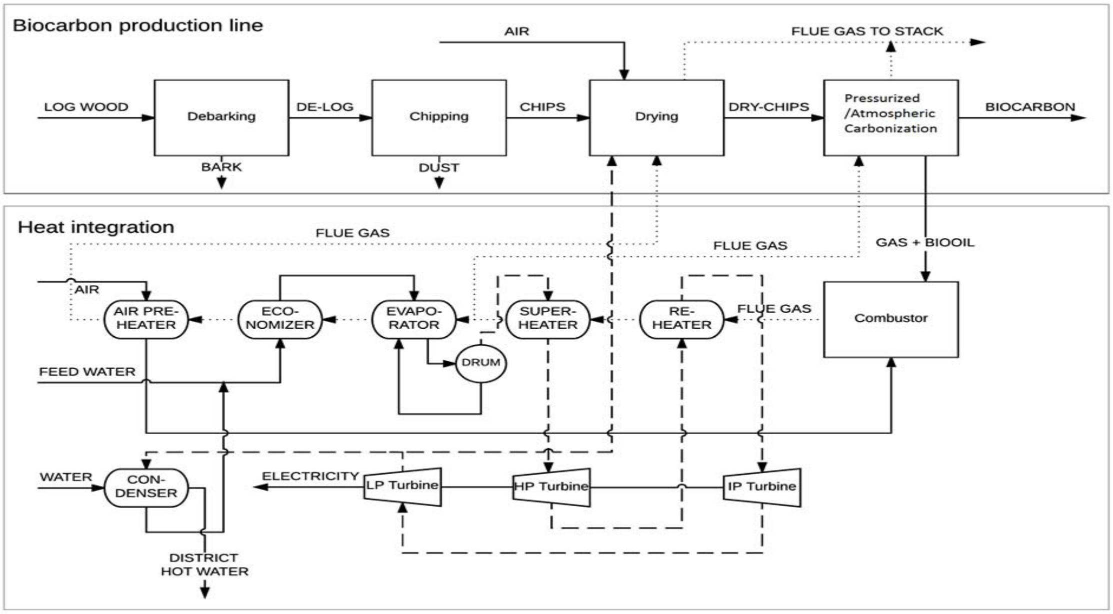

Fig. 1. Process diagram for the biocarbonization plant

Chips drying: Three stage drying is developed by assuming a belt dryer model, drying medium is air. Heat is supplied by flue gas and low-pressure steam from the CHP unit. Drying rate is calculated based on a drying curve for wood chips, rate curves are gathered from Johansson et al. [11] and normalized data are implemented in the Aspen Plus model.

Carbonization modelling: The model for the carbonization/pyrolysis is based on an user-defined yield calculator. Heat to the reactor is supplied by flue gas. The pressure in the pressurized pyrolysis process is provided by compressed nitrogen. Pyrogas and biooil products are burnt in a combustor to produce heat for the pyrolysis process and for CHP production. The main product is biocarbon.

Product yield modelling: In this work, our modelling approach is very novel in terms of predicting yield of products. We developed an empirical equation to predict the char yield via a multifunctional modelling approach. We used experimental data from various literature sources [6, 12-15] considering the char yield data as a function of temperature (T), pressure (p) and particle size (diameter, d). The method implemented involves curve fitting of the experimental data using a Box-Behnken approach [16], here the advantage is inclusion of the possible interaction of process variables such as T, P and d. It is a type of response surface design that does not contain an embedded factorial or fractional factorial design. The yield function developed is shown in the following equation.

$$y^*=126.3-0.3406\cdot T-4.5\cdot p+4.13\cdot d+0.00031\cdot T^2+0.19\cdot p^2-0.204\cdot d^2+0.0050\cdot T\cdot p-0.00971\cdot T\cdot d+2.29\cdot p\cdot d \quad (1)$$

Biocarbon CHO composition (weight fraction) is based on the empirical equations developed by Neves et al. [17]. The gas yield (kg/kg daf biomass) function is also based on the empirical equation, which is a function of temperature (T in °C) according to Neves et al. [17]. Main gas compounds in the pyrolysis gas are usually H_2, CH_4, C_2H_4, CO, H_2O and CO_2. Additionally an equation for the pyrolysis gas LHV was used to close the energy balance. The difference between input and output char and gas yields are the biooil. Even though biooil contains several compounds, to reduce the modelling complexity and to close the CHO balance, we assumed a biooil composition having phenol and acetic acid as a model compounds.

CHP process modelling in Aspen Plus: Biooil and non-condensable gases are combusted in the combustor; the combustor is simulated by the built in Aspen Plus Gibbs reactor model. Hot flue gases are passing through a series of heat exchangers (superheater, re-heater, evaporator and flash drum using built in Aspen Plus heat exchanger models) as a boiler model and superheated steam is expanded in steam turbines for power production. Low-pressure steam is heat exchanged to produce hot water. Details of the model are described elsewhere by Kempegowda et al. [8].

2.2. Case B: Co-carbonization value chain based on logwood mixed with algae for maximized biooil and biochar for carbon sink

Here as shown in Fig. 2, process models are similar to the previous case, however, dewatered algae is introduced to the drying process and dried algae is blended in different proportions to produce biooil as a main product and biocarbon/biochar as a side-product. The pyrolysis yield models were extended by gathering experimental data for algae from various literatures.

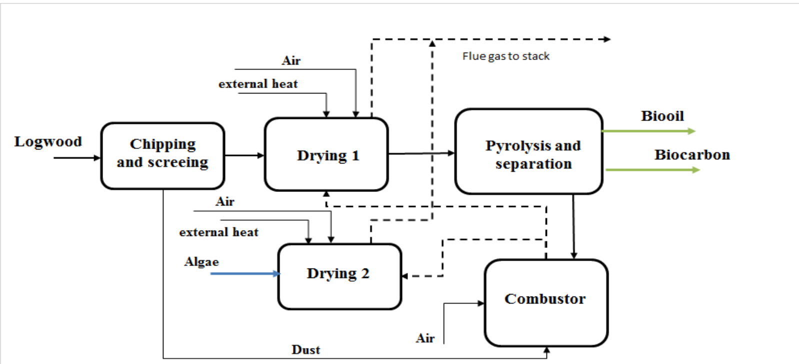

Fig. 2. Co-carbonization process for biooil and biochar

Here the advantage of blending algae with forest woody biomass is that the algae has high lipid content, enhancing the oil content, as well as the decomposition of carbohydrates starts at lower temperature, which facilitates internal supply of hydrogen for enhanced biocrude production. This phenomena and detailed mechanism need to be further studied to understand the effects of internal supply of hydrogen on the biocrude and simultaneous evolution of CO_2 and H_2O better during cellulose decomposition.

2.3. Case C: Pyrobiomethane process for biochar, algae, biomethane and fertilizer

In case C, shown in Fig. 3, a co-pyrolysis process is coupled to a biogas digester and algae production. Process modelling is implemented in the SuperPro bioprocess design process simulation software. Here a combination of Aspen Plus product yields is implemented in SuperPro. The advantage of using SuperPro is availability of kinetic modelling of biodigesters reactors and aerobic ponds for algae production. Aquous phase enriched with acids portion is separted from the biooil to avoid toxicity in the digester. The aquous portion is sent to two stage digester consisting acedogenesis phase digester and methonogenesis. This is due to fluxibility of handling various feedstocks and provide enough residence time for biomethanation. The the acids digesgted in the first phase split into two portions one portion of the effluents is fed to aerobic oxidation ponds for algae production based on mixotropic culture.The algae effluents cultivated from aerobic ponds are dried by froth floatation and further dried by tray dryer as algae product.

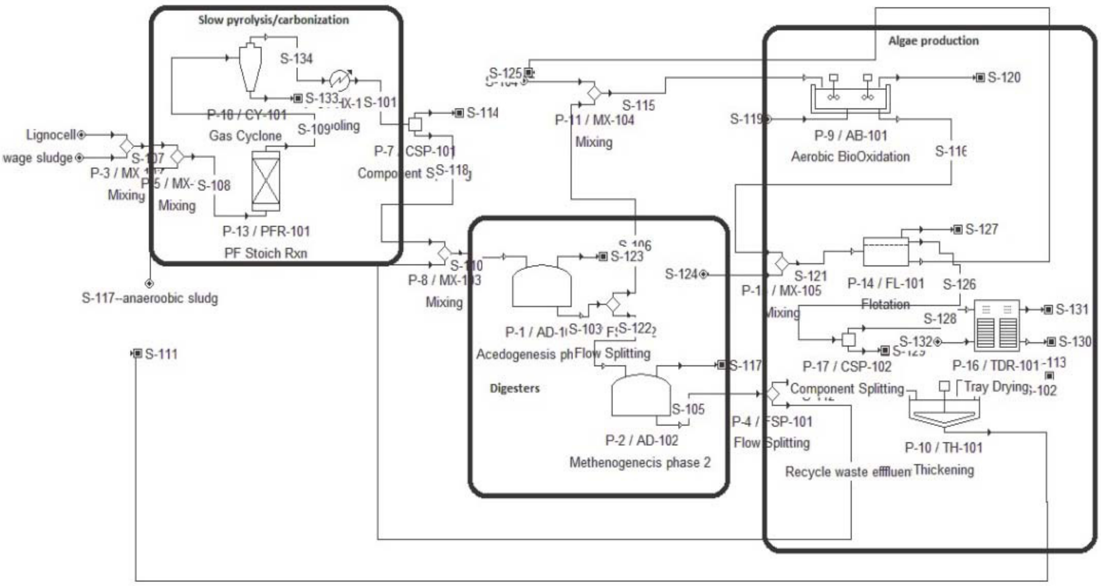

Fig. 3. Biocarbonization process integration for biomethane and algae

3. Results and discussion

As shown in Fig. 4, the model predicts high biocarbon efficiency in the low temperature carbonization range, however the quality of the biocarbon (Fig. 5) mimics torrefaction quality, i.e. below 66% fixed carbon content. A higher temperature range of 400-500 °C achieves fixed carbon contents up to 81% [17]. Increasing the pressure slightly increase the biocarbon efficiency. This means that the carbonization operating temperature and pressure regime at elevated pressure not only increase the biocarbon yield but also the fixed carbon content, which is suitable for metal industry. However capital cost increases with increased pressurization but cost of biocarbon decreases due to improved yield (Fig. 6). As well, district heat hot water production efficiency increased with pressurization (Fig. 7). Blended feedstocks of wood and algae increased the biooil efficiency as shown in Fig. 8. As well, sensitivity analysis as shown in Fig. 9 for biocarbon production shows that investment cost and feedstock price are the dominating factors under Norwegian conditions. Table 2 shows the economic viability for case C for algae production integrated in the biocarbon value chain.

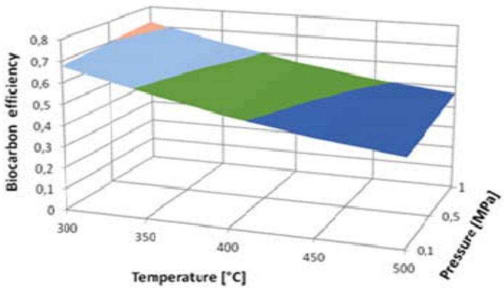

Fig. 4. Biocarbon efficiency

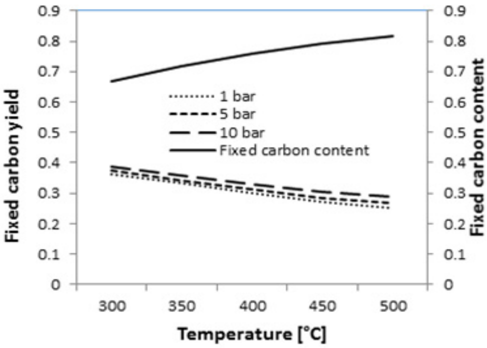

Fig. 5. Fixed carbon yield and content

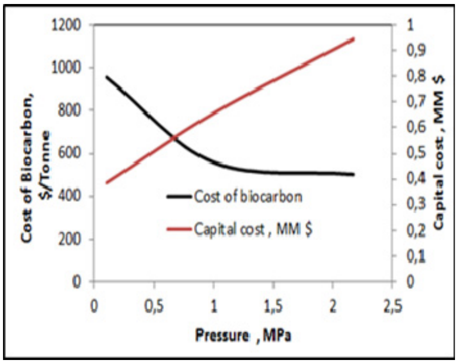

Fig. 6. Capital cost vs cost of biocarbon

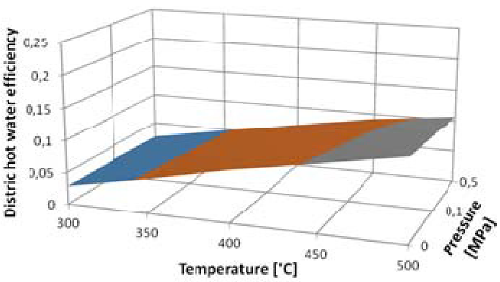

Fig. 7. Distric heat hot water production efficiency

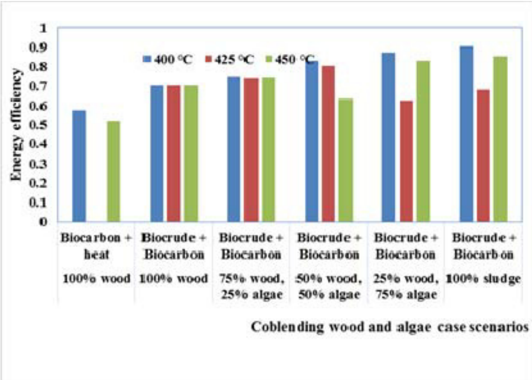

Fig. 8. Energy efficiency

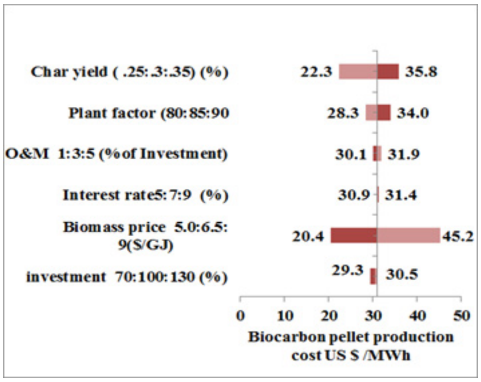

Fig. 9. Biocarbon pellet cost sensitivity

Table 2. Case C economic viability of algae production

Investment, MM $	Algae production cost, $/kg	OPEX, MM $	Production rate tons/year
5.5	20.28	4.04	199

4. Conclusions

Case designs for enabling biocarbon production for metallurgical industry are proposed. Marketable products such as biocarbon, biooil, heat, and biofertilizer can be potential coproducts in the biocarbon value chain. Techno-economic cases were designed in detail by modelling various sub-processes using empirical and semi-empirical techniques. A multifunctional modelling approach has been proposed to model the carbonization product yields as a function of the most influential parameters; pressure, temperature and particle size. Small Integrated Process Systems (SIPS) that is combining co-carbonization coupled with biochemical routes are favoured in terms of economic viability by using more sustainable production approaches. Further work is required to enable the biocarbon value chain in the context of viable market products, e.g. ammonium bicarbonate or biohythane. As demonstrated in this work, techno-economic analysis and integral system analysis are effective tools to assess the feasibility of processes at various TRL levels.

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Biography

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