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Techno-economic assessment of thermal co-pretreatment and co-digestion of food wastes and sewage sludge for heat, power and biochar production

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Abstract

This study deals with techno-economic assessments of three system scenarios combining various conversion technologies including co-digestion, hydro-methanation, syngas production and integration, thermodynamic and electrochemical aspects of a solid oxide fuel cell (SOFC) system, as well as solving the problem of chemical equilibrium in complex systems. Aspen Plus and SuperPro software packages are used as simulation and optimization tools. The optimized results are compared with other studies and reveals that thermal co-treatment integrated with a two-stage bio-thermal process involving anaerobic digestion and hydrogasification can produce good quality biofuels for a SOFC system. The economics of the final selected thermal co-treatment hybrid process for processing 30000 tons per annum of dry solids is feasible at an electricity selling cost of 0.3 \$/kWh, providing project benefits such as an IRR of 29.7%, a benefit to cost ratio of 1.38 and a net present value of 123 million \$. This innovative scheme not only reduces CO_2 but also improves the economic return and reduces the waste discharge.

Keywords: Thermal co-treatment, Anaerobic digestion, Bio-gasification, CHP, Process modelling and simulation, Techno-economics

1. Introduction

Anaerobic digestion (AD) can process a wide range of municipal, industry and organic wastes with high moisture content and heterogeneous compositions. The dry mass conversion yield to gas for these wastes

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can vary between 40 and 60% and the moisture content of the wastes can be above 40 wt.% [1]. The residues after biogas production are usually referred to as digestate and are usually disposed of by incineration, landfilling, or used as organic fertilizer due to the high contents of nitrogen, phosphorous and micronutrients. However, a challenge concerning the utilization of digestate as fertilizer is the fact that it normally requires long storage periods, which translates into increased greenhouse gas emissions due to the continuous biological degradation. There are also other limitations for biodigesters themselves. Biomass consists of cellulose, hemicellulose and lignin along with extractives. Hydrolyzing the cellulose to biogas have limited accessibility due to low surface area, cellulose fiber crystallinity, as well as these are bonded by lignin and hemicellulose [2]. The lignin and hemicellulose makes it difficult to access for cellulase enzymes, thus reducing the efficiency of the biodigesters. Lignin in these wastes are refractory under anaerobic conditions and inhibits the process. Inhibitors in biodigesters include ammonia, sulfide, light metal ions, heavy metals, and organics. There are various attempts to improve the anaerobic digestion process by improved co-digestion with other wastes to optimize the process conditions, such as the C/N ratio and feedstock size. In this context, the anaerobic digestion process could benefit if combined with thermochemical conversion, to enhance overall methane production. There are a few studies on digested residues conversion via hybrid gasification using water-gas shift followed by methanation, which can also be a good alternative [3]. Another concept proposed recently is a combination of AD with thermal gasification of the digestate for syngas production [4]. Also, utilization of the digestate for production of syngas, biooil and char has been proposed [5, 6]. Also hydrothermal carbonization for char production and phosphorous recovery is being investigated [7]. Numerous pilot scale studies on hydrothermal gasification for syngas and fertilizer production in the VERENA pilot plant have also been reported [8]. There are also some attempts at post phosphorus recovery from combustion and gasification ash from sewage sludge [9]. In this context, a study on hybrid systems is suggested for zero-waste discharge under Norwegian conditions, which is the objective of the present work.

2. Approach and Methods

The process system study in this work is carried out by using process simulation in combination with data and correlations derived from literature and patents, and includes overall mass balance, energy balance and economic calculations. Three case scenarios are proposed: Scenario 1: Hydrothermal/thermal hydrolysis pretreatment followed by co-digestion for CHP; Scenario 2: Hybrid thermal co-treatment for heat, power and activated char; Scenario 3: Hybrid co-thermal treatment and CHP. Our approach involves tailor made process models developed based on an empirical/semi-empirical technique. Process plant design is carried out with the commercial softwares Aspen Plus and SuperPro, supported by Fortran programming to establish mass and energy balances and process sizing. A customized spreadsheet model for estimating capital expenditures and operating expenses is used. The methodology of techno-economic analysis is explained in details elsewhere in our literatures [10, 11].

2.1 Co-digestion based process system scenario

Scenario 1: CAMBI [12] thermal hydrolysis as a pretreatment followed by co-digestion for CHP: A process case of the Ecopro AS [13] plant located in Verdal municipality north of Trondheim in Norway is considered as Scenario 1. The details of the process scheme is shown in Fig. 1. The plant treats organic wastes from 41 municipalities representing a population of 350000-400000. The system is developed by Cambi AS and can handle many different types of organic bio-degradable wastes such as source separated household waste, organic waste from catering kitchens, canteens and restaurants, fish waste, organic residues from industrial manufacture of foods, fat and other similar residues, slaughterhouse animal waste, solid organics, biological sludge and sewage sludge. Ecopro is owned by five municipal waste management companies, representing the 41 municipalities. The annual capacity is in the range of 30,000

- 50,000 tons/year. The conventional case can generate a yearly biogas yield equivalent to 20-30 GWh. The base case consists of thermal hydrolysis/hydrothermal pretreatment, whereafter pretreated biomass wastes are fed to the anaerobic digester, and the unconverted solid residues from the biogas plant are dewatered by a screw press and transported to farm facilities as fertilizer. The biogas is combusted in gas engines to produce electricity, with the installed capacity of 3 MW. The waste heat from the gas engines at 550 °C is recovered through the exhaust gas boiler to produce steam.

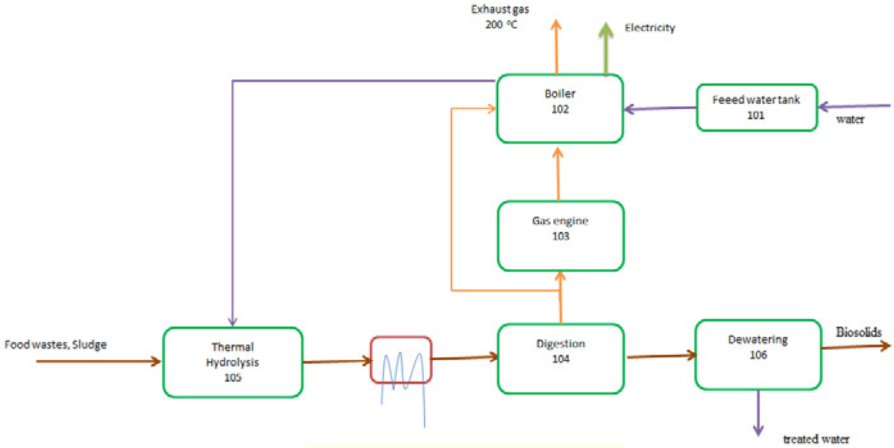

Fig. 1: CAMBI thermal hydrolysis process

Scenario 2: Hybrid system based on thermal co-treatment and CHP: The process proposed as shown in Fig. 2, mainly consists of a low temperature carbonization process (slow pyrolysis, S100), where the carbonization process can be atmospheric or pressurized. The main products are "pyroligneous acids", char and pyrogas. Pyroligneous acids are consisting of organic acids (such as acetic acid), alcohols (principally methanol) and other organic compounds. The gas stream (pyrogas) contains methane, carbon dioxide, and hydrogen. Water is fed to the two-stage AD process (S200 and S300). The hydrogasification process (S400) is an entrained flow reactor for production of methane enriched gas, and in this reactor charcoal, anaerobic digester gas products (CH_4, CO_2) and partly unconverted SOFC anode exhaust gases (H_2, CO, CO_2 and H_2O) are gasified/reacting to produce methane enriched gases. The advantage of co-mixing with the partly unconverted anode exhaust gases from the SOFC is to increase the H_2/CO_2 ratio for enhanced methane production on the solid char surface. Gas cleaning is done using conventional process trains and the gas is then fed to the SOFC for power generation and heat integration (S700). The characteristic features of the innovative Scenario 2 is that it is energy neutral in recycling the anode exhaust's H_2 gas to the pyrolysis, so that no external heat source is needed to maintain the required pyrolysis process temperature.

Scenario 3: Hybrid co-thermal treatment and CHP: In this scenario, the process is similar to Scenario 2, except that one equipment, the SOFC, is replaced by an IC engine. The advantage of replacing the SOFC by an IC engine is that high quality gas cleaning requirements can be avoided. The hot exhaust gas from the IC engine is indirectly heating up the pyrolysis reactor, similar to the SOFC case. The theoretical energetic value of the biogas with 60% methane content is 5.56-6.64 kWh/m^3; in general the value can be set to 6.5 kWh/m^3. The overall process efficiency can be taken as 30% and the energetic value of the biogas in terms of electrical energy is 1.95 kWh/m^3.

2.2 Process modelling

Low temperature carbonization: Experimental datas of various literature resources [14-18] are gathered and developed using a multivariable model as a function of temperature, pressure and particle size. The Box-Behnken approach [19] is used for curve fitting of the experimental data. The equation below is used for char yield (y^*) prediction.

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

Biocarbon CHO composition (weight fractions) is based on the empirical equations developed by Neves et al. [20]. The gas yield (kg/kg daf biomass) function is also based on an empirical equation, which is a function of temperature (T in °C) according to Neves et al. [20]. 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 the biooil contains several compounds, to reduce the complexity of modelling and to close the CHO balance, we assumed a biooil composition having phenol and acetic acid as model compounds.

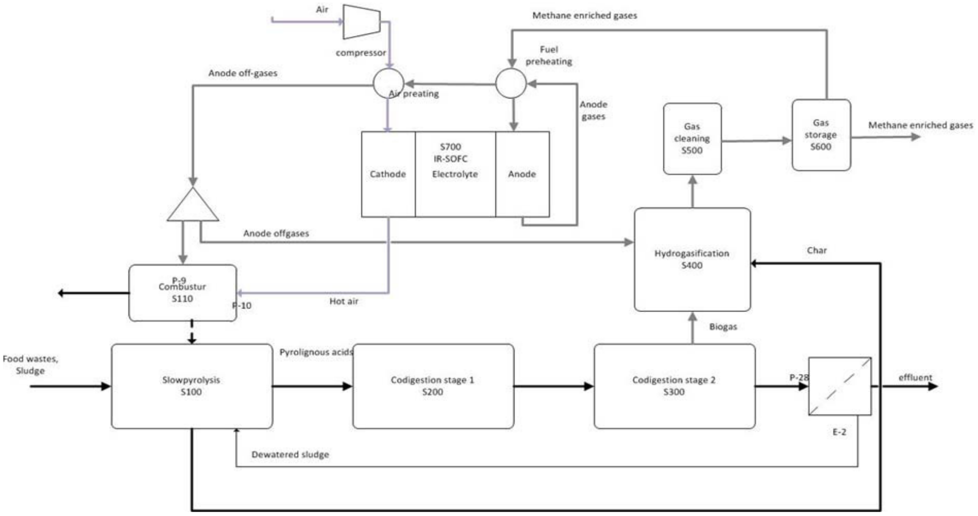

Fig. 2: Hybrid thermal co-treatment and SOFC integration

Anaerobic co-digestion process: There are several mathematical models and simulation tools for modelling anaerobic digestion and its details were extensively reviewed recently by Lauwers et al. [21]. Here, the simulation of anaerobic digestion by SuperPro is briefly explained. Kinetic constants varies in the range of K = 0.010 - 0.020 1/h (for hydrolytic and catabolic reactions). The yield coefficient, Y [g biomass, (B)/g substrate, (S)] is usually in the range of 0.04 - 0.06. This information is useful in specifying the stoichiometry of a degradation reaction.

SOFC electrochemical model: The SOFC has been modelled according to the publications of Kempegowda et al. [22]. The SOFC model has been decomposed into an anode and a cathode reactor. The reactions and the modelling details are provided below. The anode reactor is assumed as an equilibrium reactor and the cathode reactor is modelled as a simple stoichiometric reactor. Best operating conditions voltage performance and current density are given elsewhere, in the publications of Kempegowda et al. [22] for coupling a gasifier with a SOFC. The best operating conditions simulated in the previous paper is used as an input condition in this paper. The best operating conditions are a current density of 4000 A/m^2, a voltage of 0.7 volt, and a SOFC temperature of 900^{o}C.

3. Results and discussion

Comparative results for conventional pretreatment and thermal co-treatment are shown in Table 1. Net volatile conversion improved to up to 85% in the case of thermal co-treatment as compared to the conventional hydrolysis process. The electricity production increased by 137% and 108% with the SOFC and gas engine CHP configuration, respectively. The economic results indicates that the option of thermal co-treatment is economically feasible (Table 2), with a benefit to cost ratio above 1 at an electricity selling price of 0.3 $/kWh. However CO_2 emissions reductions and avoided CO_2 emissions cost are excluded here.

Table 1: Performance, comparative results

Particulars	Scenario 1	Scenario 2 With SOFC	Scenario 3 With gas engine
Input (tons/annum), dry solids	30000	30000	30000
Annual hours of operation	8400	8400	8400
Input (kg/h)	3571	3571	3571
Volatile solids (kg/h)	2357.1	2357.1	2357.1
Non-volatile solids (kg/h)	1214.3	1214.3	1214.3
Pretreatment process	thermal hydrolysis	carbonization	carbonizaiton
Pyrogas (kg/h)	-	381.69	381.69
Condensed pyroligneous acids (kg/h)	-	924.99	924.98
Ash (kg/h)	-	769.54	769.54
Char (kg/h)	-	127.74	127.74
Biogas yield (kg/h)	1414.3	1532.1	1532.1
Net volatile solid conversion (kg/h)	60%	85%	85%
Ungasified volatile solids (kg/h)	942.9	825.0	825.0
Methane (kg/h)	570.1	617.6	617.6
Dewatered undigested biosolids (kg/h)	2332	2205	2205
Maximum electrical output (MW)	2.8	3.80	3.0
Maximum electricity production per annum (GWh)	16.3	22.3	17.7

Table 2: Economic viability analysis

Electricity selling price $/kWh	NPV (1000 $)	IRR %	Benefit to cost ratio
0.2	84 996	22.2	0.07
0.25	88 492	22.8	0.18
0.25	106 389	26.3	0.79
0.3	123 650	29.7	1.38

4. Conclusions

Three scenarios based on carbonization value chains have been proposed and studied. The techno-economic analysis shows that Scenario 2 - hybrid process with thermal co-treatment option for processing 30000 tons per annum of dry solids, is feasible at an electricity selling price of 0.3 $/kWh, providing project benefits such as an IRR of 29.7%, a benefit to cost ratio of 1.38, and a net present value (NPV) of 123 million $. This innovative scheme not only reduces CO_2 but also improves the economic return and reduces the waste discharge.

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