Energy Conversion and Management 135 (2017) 297–307

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Potential of brown algae for sustainable electricity production through anaerobic digestion

Peyman Fasahati [a], Christopher M. Saffron [a], Hee Chul Woo [b], J. Jay Liu [b,*]

[a] Department of Biosystems and Agricultural Engineering, Michigan State University, East Lansing, MI 48824, USA
[b] Department of Chemical Engineering, Pukyong National University, 365 Sinseon-ro, Nam-gu, Busan 608-739, Republic of Korea

ARTICLE INFO

Article history:
Received 26 September 2016
Received in revised form 26 December 2016
Accepted 27 December 2016

Keywords:
Seaweed
Brown algae
Anaerobic digestion
Methane production
Electricity
Economic assessment

ABSTRACT

This paper assesses the economics of heat and power production from the anaerobic digestion (AD) of brown algae (*Laminaria japonica*) at a plant scale of 400,000 dry tons/year. The conversion process was simulated in Aspen Plus v.8.6 to obtain rigorous heat and material balance for energy assessments and the development of a techno-economic model. The breakeven electricity selling price (BESP) was found to be 18.81 ¢/kWh assuming 30 years of plant life and a 10% internal rate of return. The results show that the AD unit has the highest energy demand in the entire process and consumes approximately 14% of all electricity produced. In addition, the seaweed cost of 11.95 ¢/kWh is the largest cost component that contributes to the calculated BESP, which means that a reduction in the cost of seaweed cultivation can significantly decrease the electricity production cost. A sensitivity analysis was performed on the economic and process parameters in order to assess the impact of possible variations and uncertainties in these parameters. Results showed that solids loading, anaerobic digestion yield, and time, respectively, have the highest impact on BESP.

1. Introduction

Brown algae, as the third generation of biomass, has great potential as a renewable source of biomass for biofuel production. It requires no arable land, irrigation water, or fertilizer for cultivation, and has a higher photosynthetic efficiency of 6–8% compared to 1.8–2.2% for terrestrial biomass [1,2]. The lack of lignin in the cell walls of brown algae makes the manufacturing process relatively simple compared to that for lignocellulosic biomass for which costly pretreatment processes are required to separate the cellulose from the lignin [3,4].

The anaerobic digestion (AD) of biomass is biological decomposition of organic material to biogas by a mixture of microbes in the absence of oxygen [5]. The yield of the process is impacted by the type of digester selected, pretreatment process, hydraulic retention time (HRT), and source of inoculum [5,7–9]. Generally, anaerobic digesters are categorized into batch vs. continuous process modes, mesophilic (30–38 °C) vs. thermophilic (49–57 °C) temperature conditions, high vs. low solids loading, and single stage vs. multistage processes [10,11]. Several experimental, economic feasibility, and pilot-scale studies have shown the potential of using brown algae for methane production [5–9,12,13]. Rodriguez et al. [5] and Tedesco et al. [9] studied several pre-treatment techniques to improve the digestibility of seaweed for increased methane yield and reported that mechanical pretreatments results in higher methane yield in comparison to ultrasound and micro-wave, thermal, and chemical pretreatments. Some literature data show that brown algae can have an inhibitory impact on anaerobic digestion when it is considered for co-digestion with other types of biomass. Akunna and Hierholtzer [14] studied co-digestion of *Laminaria digitate* and green peas. Their results showed that when only 2% of feedstock of a reactor treating the green peas was replaced with the seaweed, methane production was disrupted and reactor stability was difficult to achieve thereafter. They concluded that certain seaweed constituents are inhibitory to the methanogens even at trace concentrations than to the other anaerobic digestion microbial groups. They recommended that appropriate adaptation strategy, involving initial low proportion of the seaweed relative to the total organic loading rate (OLR), and overall low OLR, is necessary to ensure effective adaptation of the microorganisms to the inhibitory constituents of seaweed. Sarker et al., [15] studied effect of variable feeding of *Laminaria digitata* for codigestion in a mesophilic and thermophilic digester with cattle manure. The study revealed that the variation in *Laminaria* feeding did not largely contribute to the average specific methane yield from the mesophilic co-digester. However, in thermophilic co-digester, seaweed addi-

* Corresponding author.
E-mail address: jayliu@pknu.ac.kr (J.J. Liu).

http://dx.doi.org/10.1016/j.enconman.2016.12.084
0196-8904/

tion enhanced the anaerobic digestion and boosted methane yield to a maximum of 39% at an average feeding rate of 24% VS of algae. Miura et al. [7,8] evaluated marine sediments as a microbial source for methane production from brown algae at the salinity of seawater. They identified that acetoclastic methanogenesis is the rate-limiting step in brown algae anaerobic digestion and the batch-fed cultivation of microbes could better acclimate the culture to predominantly produce methanogens. In addition, AD under saline conditions implies that wet brown algae, containing approximately 80–90 wt% water, can be utilized directly. This can substantially reduce the fresh water requirements of the process and allow the biomass drying and washing steps to be bypassed.

In the United States (U.S.) in 1968, a feasibility study on marine biomass was conducted for making substitute natural gas (SNG) from marine biomass using anaerobic digestion (AD) as a conversion process [16]. Chynoweth reported the results of the program for the types and yield of seaweed cultivation farms, anaerobic digesters, and the potential for co-digestion with wastes [16]. Results showed that marine biomass was the least developed resource resulting in high gas cost estimates of 3–6 times those for U.S. natural gas. The program ended in 1990, because of low energy prices in the U.S. and reduced emphasis on renewable energy. However, in recent years, interest in marine biomass has been rekindled by the threat of global warming due to greenhouse gases (GHGs) from combusting non-fossil energy resources. In a study performed in 2005 at the Energy Research Centre of the Netherlands (ECN), Reith et al. [17] studied the economic feasibility of biofuels from offshore seaweed cultivation envisioned by 2020 in the North Sea using 1000 km^2 of offshore wind farm infrastructure. Their results showed, at a scale of 100,000 dry tons/year, that biomass price must be decreased by 75% to allow for economical electricity production from AD of seaweed. They concluded that a scale of 500,000 tons/year would be more appropriate for the commercial production of biofuels. In 2010, Roesijadi et al. [18] performed preliminary resource, economic, and environmental analyses based on the results obtained by Reith et al. to assess the potential of seaweed for biomethane production in the United States. They concluded that the methane yield of 0.124 m^3/kg volatile solids (VS) considered by Reith et al. is very conservative compared to the yield of 0.22–0.30 m^3/kg VS reported in the literature [19,20] and, therefore, there are opportunities for improvement in the economics of methane from seaweed. Bruton et al. [21] also used the economic model of Reith et al. to evaluate the potential of aquatic biomass for biofuel production in Ireland. They concluded that the mass cultivation of seaweed should be prioritized to provide sufficient biomass to avoid the large-scale exploitation of wild seaweed stocks and its negative impact on supporting and maintaining marine biodiversity. In another study by Matsui et al. [12], a pilot plant at a scale of 1 ton/day was built in Japan for AD of drift seaweed, including *Ulva* and *Laminaria* species. The pilot plant operated successfully for over 150 days using two-stage AD and a mesophilic reactor temperature. The biogas was desulfurized and mixed with natural gas before use as fuel in a combined heat and power gas engine. The study showed that long-term and continuous operation of AD of seaweed is both possible and practical.

The production of electricity from brown algae has a high technology readiness level, based on the NASA (National Aeronautics and Space Administration) definition [22], considering the many AD trials with brown algae [5,7–9], the numerous pilot plants installed, and that AD has been previously practiced for many other biomass varieties. However, there has not been an accurate and comprehensive techno-economic analysis of industrial-scale biomethane production using brown algae as biomass in the literature. This study fills this gap by performing a detailed economic assessment of electricity production using AD of brown algae considering recent achievements and technology advances in the field. With an increasing annual brown algae production rate [2] and determination of the global community to find sustainable and economical sources of energy to substitute fossil fuels and reduce GHG emissions, this study aims to provide a strong basis for decision– and policy makers to understand the potentials, limitations, and challenges of brown algae for renewable electricity production. For this purpose, a comprehensive literature study was performed to understand the current technology status. Later, the production process is rigorously simulated in Aspen Plus v.8.6 to close energy and material balances, which are then used to determine the process energy demands and to calculate the operating and capital costs that are quoted by specialized vendors. The calculated costs are used to develop a discounted cash flow analysis to calculate the breakeven electricity selling price (BESP) of the process. It is also the objective of this study to understand the bottlenecks and quantify the impact of the most sensitive parameters on the economics of the process.

2. Material and methods

Brown algae *L. japonica* are the most cultivated type of seaweed with an annual world production of 5.998 million wet tons in 2013, having increased 1.8 million wet tons since 2000 [23]. Carbohydrates form approximately 60 wt% of dry mass and include laminaran (β-1,3-linked glucan, $(C_6H_{10}O_5)_n$); cellulose (β(1,4)-linked D-glucose, $(C_6H_{10}O_5)_n$); mannitol (sugar alcohol, $C_6H_{14}O_6$); alginate (an anionic polysaccharide composed of mannuronic and guluronic acids, $(C_6H_8O_6)_n$); and fucoidan (sulfated fucan) [15,18]. Table S-1 of the supplementary data shows the chemical composition, elemental analyses, and heating value of *L. japonica*. *Laminaria* products are used for industrial, medical, human consumption purposes, and as livestock fodder. The main industrial products extracted from *Laminaria* are iodine, algin, and mannitol [1,24]. Iodine is used as an additive to salt and other foods to prevent thyroid gland disorders and goiters. Algin is a hydrocolloid or phycocolloid made from extracted alginate or alginic acid that has the property of holding water in suspension. It is widely used as a binding agent in textile, printing, medical and food manufacturing industries. Mannitol is widely used in food and medical industries because of its medicinal properties. *L. japonica* contains approximately 88 wt% water in its wet form and 12 wt% total solids, of which 74 wt% are VS and 26 wt% is ash [15]. The high water (>80%) and ash content (~26% dry wt) of brown seaweed make it challenging for thermochemical pathways, like gasification and pyrolysis [25], but more appropriate for biochemical pathways, like AD and fermentation processes [18,26]. Generally, thermochemical pathways require biomass to be dried below 7% moisture content. This would require external source of heat since high heating value of seaweeds are relatively smaller than the one for lignocellulosic biomass [25]. In addition, high metal content of seaweeds compared to lignocellulosic biomass can potentially poison the bio-oil hydrotreating catalyst obtained from pyrolysis process [27]. Okoli et al. [25] studied the economics of butanol production from *Laminaria japonica* through gasification process. Their results showed that energy efficiency of a gasification process for brown algae to butanol process is about 12% less than the similar process for lignocellulosic biomass mainly because of higher ash content in brown algae. In addition, the minimum fuel selling price calculated for gasification of brown algae was about 2–3 times more than the MFSP calculated for a similar thermochemical and biochemical process using lignocellulosic biomass [25,28]. Fig. 1 shows a simplified process flow diagram for electricity production from brown algae. The conversion process include an AD unit, boiler/turbogenerator, and utilities. A detailed process flow diagram (PFD),