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Techno-economic study of NMMO pretreatment and biogas production from forest residues

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HIGHLIGHTS

- Biogas from co-digestion with pretreated forest residues was simulated and evaluated.
- Plant capacity of 50,000 tons per year forest residues and above is financially feasible.
- The cost of the NMMO was regarded as the largest operating expenditure.
- Biogas production was compared with the energy produced during incineration.

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ABSTRACT

Biogas is nowadays getting more attention as a means for converting wastes and lignocelluloses to green fuels for cars and electricity production. The process of biogas production from N-methylmorpholine oxide (NMMO) pretreated forest residues used in a co-digestion process was economically evaluated. The co-digestion occurs together with the organic fraction of municipal solid waste (OFMSW). The process simulated the milling of the lignocelluloses, NMMO pretreatment unit, washing and filtration of the feedstock, followed by an anaerobic co-digestion, upgrading of the biogas and de-watering of the digestate. The process also took into consideration the utilization of 100,000 DW (dried weight) tons of forest residues and 200,000 DW tons of OFMSW per year. It resulted in an internal rate of return (IRR) of 24.14% prior to taxes, which might be attractive economically. The cost of the chemical NMMO treatment was regarded as the most challenging operating cost, followed by the evaporation of the washing water. Sensitivity analysis was performed on different plant size capacities, treating and digesting between 25,000 and 400,000 DW tons forest residues per year. It shows that the minimum plant capacity of 50,000 DW tons forest residues per year is financially viable. Moreover, different co-digestion scenarios were evaluated. The co-digestion of forest residues together with sewage sludge instead of OFMSW, and the digestion of forest residues only were shown to be non-feasible solutions with too low IRR. Furthermore, biogas production from forest residues was compared with the energy produced during combustion.

1. Introduction

The global market and demand for biogas as a vehicle fuel, electricity production, and even as a heating energy source has had a positive trend. The biogas is produced in household digesters to provide cooking or lightening energy to replace kerosene or LPG, while the larger plants burn it in gas engines to produce electricity or upgrade it to almost pure methane to inject in the gas grids or compress it to CBG (compressed biogas) and sell as car fuel. The traditional substrates utilized for biogas production are municipal solid waste, organic wastes from industrial and agricultural activities, as well as high strength wastewater are. However, these sources are limited, and there is a demand for the development of new technologies utilizing other substrates. Lignocellulosic-rich materials have a great potential as an alternative feedstock for anaerobic digestion, since they are found in high abundance globally.

The degradation of lignocelluloses into biogas is a complicated process, since lignocelluloses have a recalcitrant structure which is naturally designed to prevent enzymatic degradation. Lignocelluloses are formed in a compact and crystalline structure and often contain a high amount of lignin. In order to permit degradation of these materials in an anaerobic digester, the structure has to open up and/or the lignin has to be degraded or removed. This can be performed by using different pretreatment methods [1], such as

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mechanically, e.g., by milling; physically by steam explosion or radiation; chemically by acids, bases or solvents; and biologically by enzymes or fungi [1–3].

Solvent pretreatment on lignocelluloses was shown to be an effective method due to the low degradation of the carbohydrates in the material under the applied, relatively mild conditions. Furthermore, pretreatment with a solvent does not require neutralization, and almost a complete recirculation of the treating chemical is possible [4]. The pretreatment using the solvent N-methylmorpholine oxide (NMMO) has previously been studied on bagasse [5] and on spruce [6] for ethanol production, and on spruce, rice, and triticale straws [7] as well as pure cellulose [8] for biogas production. NMMO is an organic solvent that interrupts inter- and intra-molecular bonds [9] in the lignocelluloses, making the carbohydrates of the material more accessible and thereby facilitating the enzymatic degradation. NMMO is an environmentally friendly cellulose solvent, and used in industrial scale in the lyocell process [10,11], where cellulose fibers are treated to produce textile. Since no toxic compounds are produced within the NMMO pretreatment and the recirculation of the solvent is possible [10,12], this process can be regarded as environmentally friendly.

Techno-economic analysis is a useful tool to examine the profitability and performance of a proposed process. Recently, Shafiei et al. [6] performed a techno-economical study on bioethanol production from NMMO pretreated wood. They found that the process is feasible when bioethanol production is combined with a subsequent biogas production utilizing the pentoses. Conversion of lignocellulosic pentoses to ethanol is one of the obstacles in the utilization of lignocelluloses to ethanol, since the ordinary industrial yeast species are unable to assimilate pentoses [13]. Furthermore, the production of biogas from lignocelluloses has several advantages compared to bioethanol production, since the overall energy efficiency is much higher in biogas production compared to that in ethanol production [14].

The focus of this study was therefore to develop a feasible industrial process for NMMO pretreatment and subsequent utilization of forest residues (branches, tops, barks, and needles) in anaerobic digestion. Forest residues were selected because they are the most abundant lignocellulosic waste stream in Sweden, and several other countries. In 2008, 1.6 M tons total solids (TS)/year of the tree tops and branches were delivered from the forests in Sweden, and this is expected to increase to 3.5 M tons total solids/year by 2018 [15]. Moreover, the total energy potential of bioenergy production from the forest is calculated as being 49 TW h [15]. An industrial scale process was designed and simulated using SuperPro Designer® 8.0 simulation software (Intelligen, Inc., NJ, USA) based on unpublished biomethane potential test (BMP) experimental data. A process including an NMMO pretreatment step with filtration, evaporation and recirculation of NMMO and washing water together with a following co-digestion step was evaluated to determine economic feasibility and profitability, such as capital costs for the total plant, annual operating costs, and unit costs. Finally, sensitivity analyses were performed on different scenarios, where effects of the plant size, different co-digestion setups as well as the methane price and the water consumption were evaluated.

2. Process development and financial analysis

2.1. Process description

A novel process of the NMMO pretreatment of forest residues prior to anaerobic digestion was developed. The process includes the feedstock handling, pretreatment by NMMO, anaerobic digestion, and upgrading of the biogas as well as the dewatering of the digestate. It is assumed that the plant is located close to a power plant, so that steam and electrical power are readily available. It is further assumed that the plant is situated in Sweden with a high availability of forest residues. The type of forest residues investigated in this study includes the rejected tops and branches.

The base case is constructed for 100,000 tons DW (dry weight) forest residues per year. However, capacities ranging from 25,000 to 400,000 tons DW forest residues/year were also studied. The plant is in operation for 7920 h/year, and the construction material was chosen to be stainless steel 304. The cost index was set at 2012.

2.2. Pretreatment unit

The forest residues arrive at the plant in truck trailers, where the price of the feedstock includes the handling all the way to the plant. The feedstock contains 42% carbohydrates, 44% lignin, 75% total solids (TS), and 64% volatile solids (VS) [17]. The forest residues have a C/N ratio of 325 [18]. The raw material is then placed into a grinder, which reduces the size of the biomass to 2 mm. After grinding, the biomass is conveyed to the pretreatment unit. The pretreatment is performed using 85% NMMO solution in water for 12 h at 90 °C. During the pretreatment, the lignocellulosic structure is opened up, resulting in less intra-molecular linkages and less cellulosic crystallinity [9]. The pretreated biomass is then washed with water and filtered using a rotary vacuum filtration unit (Figs. 1 and 2). The NMMO-solution is then evaporated back to 85% for reuse in the pretreatment unit. The recovery in the washing step is expected to be 99.5%. The use of the rotary vacuum filtration allows for a minimum usage of water during the washing, in order to save energy in the following evaporation unit. Previous experimental studies were performed with 500 mL washing water for 200 g NMMO/biomass mixture [16], where these conditions were applied in the base case of the simulation study. The evaporation unit was designed with a mechanical vapor design (MVR). The MVR design with two effects and two compressors was found to be the most energy efficient and an economically beneficial alternative for the evaporation of NMMO water solution in a previous investigation, focusing on NMMO pretreatment of spruce prior to ethanol production [6]. The same design for the evaporation step was applied in this study.

2.3. Biogas and digestate production

The washed and pretreated forest residues are mixed with the organic fraction of municipal waste (OFMSW, Figs. 1 and 2), in order to a achieve a C/N ratio of between 20 and 30 which is regarded as the optimum ratio [19]. Two-thirds of the OFMSW and one-third of the forest residues are used in the base case, which results in a C/N ratio of 30. The OFMSW in the simulation consist of 60% carbohydrates, 17% fats, 8% proteins based on the dried weight, and the water content was estimated to be 67% water. The cost of OFMSW is set to zero. The methane yield of similar substrate mix was 0.470 Nm^3/kg VS [20], which corresponds to a conversion rate of 86.7%. The methane production from forest residues is based on experimental results from lab scale BMP tests showing a yield of 0.137 Nm^3 CH_4 per kg total solids of forest residues, which corresponds to a conversion rate of 73.4%. The two fractions are together passed through a screw press prior to the anaerobic digester, together with extra water in order to reach a TS of 12% in the incoming stream. The digester runs at thermophilic conditions (55 °C) with a hydraulic retention time of 20 days. It is a fixed roof storage tank, which allows for mixing, constructed of stainless steel. The gas produced is a mixture of the main components methane and carbon dioxide, and trace amounts of some other