Techno-economic evaluation of integrating torrefaction with anaerobic digestion

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HIGHLIGHTS

- Integrating torrefaction with anaerobic digestion has better process economics.
- Selling price of torrefied pellets reduced with proposed process integration.
- Pellets selling price reduced by 15 €/t with proposed process integration.
- Torrefaction process economics are significantly influenced by feedstock price.

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ABSTRACT

In recent days, the interest on torrefaction is increasing owing to its ability to improve biomass properties to a level of competing with coal. However, its techno-economic feasibility still need to be optimized. Integrating torrefaction with other thermochemical and biochemical processes could be a feasible option to improve the performance of the torrefaction process. In that regard, this study evaluates the techno-economic feasibility of integrating the torrefaction with anaerobic digestion (AD). In addition, new process configurations were studied to identify the possible heat energy recovery options. Technical feasibility was tested through mass and energy balance at each process unit. The economic indicators such as net present value (€), minimum selling price and internal rate on return (%) were used to evaluate the economic performance. At 10 t/h of torrefied biomass pellets production capacity, the estimated bio-methane production from AD was 369 m^3/h. The economic evaluation shows that the minimum selling price of the torrefied biomass to reach the breakeven could be reduced from 199 €/t for standalone torrefaction to 185 €/t in case of torrefaction integrated with AD. The sensitivity analysis shows that feedstock and total capital investment were the most sensitive input parameters. This study shows that integrating the torrefaction with AD has better technical and economic feasibility than standalone torrefaction.

1. Introduction

The main aim of the Paris climate change agreement was maintaining the global average temperature 2 °C below the pre-industrial level and reducing the greenhouse gas emissions by 40% compared with 1990 level by 2030 [1]. At the same time the European union energy targets are, 20% of the primary energy consumption from renewable resources by 2020 and 27% by 2030 [2]. By 2014, fossil fuels (i.e. coal, oil and natural gas) are accounted for 80% of world primary energy supply [3]. Among the other fuels, coal combustion is the major source of CO_2 emissions, and according to IEA statistics, 45% of the global CO_2 emissions are from coal combustion in 2014 [3]. Replacing

or reducing the coal with renewable materials in the industrial applications and electrical energy production could be one option to achieve the above said environmental and energy targets.

Biomass could be one such a renewable material, which can be considered as an alternative to coal. However, biomass has several challenges like high moisture content, fibrous, hydrophilic nature and low heating value [4]. To overcome these issues, biomass should be pretreated. Several pretreatment methods have been proposed, torrefaction being one of them [2]. During torrefaction, the biomass is heated slowly in the temperature range of 200–300 °C in an inert environment. Torrefaction treatment allows biomass to compete with coal by altering its physiochemical properties for example, energy density

and hydrophobicity [5]. In the recent days the research interest and commercial demand on the torrefied biomass is increasing globally. The market forecast shows that global demand for torrefied wood pellets will be around 70 million tons a year by 2020 [6].

However, the techno-economic optimization of the torrefaction process is required to remain competitive with conventional wood pellets production. According Koppejan et al. [5], the two major technical challenges to the commercialization of torrefaction technology are handling the volatile gases and energy integration within the process. According to Batidzirai et al. [7], torrefaction process still need to be optimized with respect to heat integration and waste heat utilization. Thus, the integration of torrefaction process with other thermochemical and/or biochemical processes could be useful for the improved technical and economic performance. Previously, Ekaterina et al. [8] studied the integration of torrefaction with combined heat and power (CHP) plant and reported that higher utilization of CHP boiler was achieved during part-load operations. In other study, Kumar et al. [9] studied the integration of torrefaction as a downstream operation in a conventional biomass pelletization process. The results show that capital investment can be reduced in an integrated approach in comparison with standalone torrefaction process. Clausen [10] studied the integration of torrefaction with gasification through thermodynamic modeling and reported that the biomass to syngas conversion efficiency increased from 63 to 86% in an integrated approach. Arpiainen et al. [11] analyzed the feasibility of integrating the torrefaction with CHP, saw mill and pulp and paper industry and concluded that integrating the torrefaction with CHP does not reduced the costs significantly. However, these studies were mainly focused on the integration of torrefaction with thermochemical processes. Fagernas et al. [12] studied the possibility of condensing the volatiles and selling the torrefaction condensate as a feedstock for pesticides production, and reported that the increased selling price of the torrefaction condensate reduces the selling price of the torrefied biomass.

Previously, Doddapaneni et al. [13] and Liaw et al. [14] studied the integration of torrefaction process with anaerobic digestion (AD) for the effective utilization of torrefaction condensate. The results from these studied [13,14] shows that torrefaction condensate can be effectively converted into biogas though AD. Although, the experimental results are promising, the techno-economic analysis and process modeling at an industrial scale operation, is required to better-understand the feasibility of such a process.

This study focuses on analyzing the operational and economic feasibility of integrating the torrefaction with AD. In addition, the possible heat energy recovery options from torrefaction process were also studied. The techno-economic performance of the standalone torrefaction process was compared with two different integrated process configurations. These two process configurations are using the biogas in a gas engine to produce electrical and heat energy and biogas upgrading into bio-methane using high-pressure water scrubbing (HPWS) and pressure swing adsorption (PSA). The technical feasibility of the process was analyzed through energy and mass balance at each process step. The comparative economic analysis between different process configurations was studied in terms of minimum selling price, net present value (NPV) and internal rate of return (IRR). A sensitivity analysis was carried out in order to understand the influence of different input values of the operating parameters on the economics of the studied process configurations. To the best of our knowledge, this is the first study on the techno-economic analysis of torrefaction process integrating with AD.

2. Methods

2.1. Process description

Fig. 1 shows three different process configurations considered in this study. The major difference between different cases presented in

Fig. 1 are given below.

Case 1: This case represents the standalone torrefaction process, where the volatiles from the torrefaction process were combusted along with wood chips to meet the heat energy demand.
Case 2: In this case, the condensation of torrefaction volatiles to produce torrefaction condensate and later, the AD of torrefaction condensate to produce biogas was considered. Finally, utilizing the biogas in a biogas engine to produce electrical energy was also considered in this case.
Case 3: The difference between case 2 and case 3 was with the application of produced biogas. In contrast to case 2, the biogas upgrading to bio-methane using high-pressure water scrubbing (HPWS) and pressure swing adsorption (PSA) was considered in case 3.

The pellets production process was common for all the cases. In case 2 and case 3, it was assumed that, the uncondensed gases are combusted along with wood chips to produce the heat energy required for drying and torrefaction units. For all the cases, the possibilities for heat energy recovery was also studied.

2.2. Process parameters

The mass and energy balances for torrefaction and AD were carried out based on the experimental results from our previous study [13]. A plant capacity of 10 ton/h of torrefied biomass pellets production was considered for all the cases presented in Fig. 1.

2.2.1. Drying and torrefaction process

Operating conditions of drying and torrefaction units are presented in Table 1. The forestry wood chips with a moisture content of 40% and heating value of 10 MJ/kg were considered as feedstock material [8]. It was assumed that in the drying section, moisture content of the wood chips is reduced from 40 to 10% and the products i.e. dried wood chips and water vapor leaves the dryer at its operating temperature (i.e. 150 °C). The energy required at drying unit was calculated from the latent heat of evaporation of water (2260 kJ/kg) and the sensible heat of wood chips (kJ/kg) at dryer operating temperature.

The torrefaction temperature was selected as 300 °C. The product flow information of the torrefaction unit was selected from our previous experimental data [13] which represents the mass yield of 0.55 and 0.45 kg/kg of dry wood chips for torrefied biomass and torrefaction volatiles, respectively. The energy required for torrefaction process was calculated by using Eq. (1), which represents the overall energy balance between input and output energy flows [7].

$$[m_{DB} \times (LHV_{DB} + (Cp_{DB} \times T_{DB}))] + Q_{in}$$
$$= [m_{TB} \times (LHV_{TB} + (Cp_{TB} \times T_{TB}))] + [m_{TV} \times (LHV_{TV}$$
$$+ (Cp_{TV} \times T_{TV}))] + Q_{loss} \qquad (1)$$

where m, LHV, C_p and T are the mass, lower heating value, specific heat capacity and temperature and DB, TB and TV are the dried biomass, torrefied biomass and torrefaction volatiles respectively. Q_{in} is the heat energy input to the torrefaction reactor and Q_{loss} is the heat energy loss from the torrefaction reactor. In this study, the radiative heat loss was considered as 3% on the LHV of the dried biomass [15]. The specific heating values for dried biomass (Cp_{TB}) and torrefied biomass (Cp_{DB}) was selected as 1.2 and 1.4 kJ/kg·K respectively [16]. The thermal properties of the torrefaction volatiles selected from [17] and National Institute of Standards and Technology's web directory [18] was used in Eq. (1).

2.2.2. Product properties

The heating value of the torrefied biomass varies between 19 and 24 MJ/kg depending on the severity of torrefaction [8] and in this study