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Techno-Economic Analysis of Dimethyl Ether Biofuel Production Plant Based on Sewage Sludge Gasification

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Bio-dimethyl ether (bio-DME) is an environmentally friendly alternative fuel for diesel engines that has several advantages over conventional fossil diesel fuel, such as lower emissions of particulate matter, hydrocarbons, carbon monoxide, and nitrogen oxides. The purpose of this paper is to perform a techno-economic analysis of a novel bio-DME production plant based on sewage sludge gasification. The first part of the work is centred around the modelling of a fixed bed, updraft gasification reactor, which is performed using a multi-scale, multi-phase methodology already tested and validated on biomass feedstock using the GasDS suite, a property package developed at Politecnico di Milano. The gas-solid kinetic model is coupled with a detailed gas-phase kinetic scheme including more than 200 species, and more than 2,000 reactions. The work then illustrates a new process scheme that undergoes techno-economic and sensitivity analyses to understand the most impacting parameters on the feasibility of the process. This procedure is useful to understand if sludge gasification could be considered as an alternative feedstock and a viable option for the future development of a sustainable supply chain for the production of bio-DME. The obtained results are promising, showing productivity of 19.3 kg/h of fuel-grade bio-DME from 100 kg/h of hydrochar with a market-competitive production cost ranging from -0.370 and 0.924 €/kgDME, and an average value of 0.277 €/kgDME.

1. Introduction

Dimethyl ether (DME) is the simplest ether (C_2H_6O). Once in the liquid state, it can be blended with gasoil up to around 20 wt.% to run diesel engines (Ying et al., 2008). DME is a cleaner fuel compared with gasoil since it produces lower emissions of particulate matter, hydrocarbons, carbon monoxide, nitrogen oxides (Makos et al., 2019), and carbon dioxide (Patten and McWha, 2015). Nowadays, worldwide DME production is based both on a two-step process in which methanol is firstly synthesized and then dehydrated (Fortin et al., 2020) and a one-step process in which DME synthesis is performed directly from syngas (Manenti et al., 2014). Both processes start from syngas, which is typically obtained from the reforming of light hydrocarbons and/or gasification of carbon-rich solid feedstock. It is possible to synthesize bio-DME by using syngas produced from non-fossil feedstock, such as biogas (Kralj and Hosnar, 2012), biomass (Chang et al., 2012), or sewage sludge (Malka et al., 2015). In the case of sewage sludge, it is possible to perform a pre-treatment of the slurry through the hydrothermal carbonization process (HTC). This step involves the treatment of sludge in water at 15 – 30 bar and 180 – 260 °C with a residence time from 10 min up to 12 h, resulting in the production of a type of char called hydrochar (Kambo and Dutta, 2015). Since dry hydrochar has a composition similar to that of coal (Knötig et al., 2021), it may be used as a feedstock for a gasification reactor, leading to the production of bio-syngas (Prifti et al., 2021). The aim of this work is to propose and investigate a novel route for bio-DME synthesis, starting from the conversion of sewage sludge to hydrochar, modelling its conversion to bio-syngas, and finally evaluating the economic feasibility of a bio-DME production plant. The results presented at the end of the paper are relevant since they show the feasibility of an innovative scheme for bio-DME production while also providing a low-cost and sustainable solution for the disposal of sewage sludge, a serious challenge of ever-increasing importance due to the rapid growth of the global population (Werle and Dudziak, 2019).

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2. Methods

This work deals with the design of a bio-DME plant based on sludge gasification by dividing the problem in two separate portions. First, the gasification of hydrochar is modeled by using the GasDS suite. Then, a process for the production of bio-DME is modeled in the commercial process simulation software Aspen HYSYS® V11.

2.1 Hydrochar gasification

Hydrochar produced by HBI Group srl was chosen as the feedstock for the plant to be designed in this work (HBI Group srl, 2022). The detailed gasification model contained in the GasDS suite exploits the chemical-physical data, the kinetic behaviour, and the mass-transfer properties of several types of biomass and coal. It is possible to express the hydrochar as a linear combination of known solids already present in the GasDS database. This is done by solving the atomic conservation balances for carbon, hydrogen, and oxygen while considering two types of coal (COAL1, COAL3) and the -CH_2- functional group as the components of the equivalent mixture. COAL1 and COAL3 describe anthracitic coals and lignitic coals. The utilisation of coal as the reference component is justified by the similarity between such solid and hydrochar itself (Prifti et al., 2021). A tailored package of kinetic and mass transfer models dedicated to coal gasification was implemented to analyze this system, as shown by Corbetta et al. (2015) in their work. The visualization of this linear combination process for the characterization of hydrochar is shown in Figure 1, where the hydrochar is represented by the point inside of the triangular region enclosed by COAL1, COAL3, and the -CH2- functional group. The hydrochar composition is close to the line connecting COAL1 and COAL3, meaning that is almost possible to express this substance as a linear combination of these two solids. The utilization of the -CH2- group to close the atomic balance is justified in this case despite it not being a real solid.

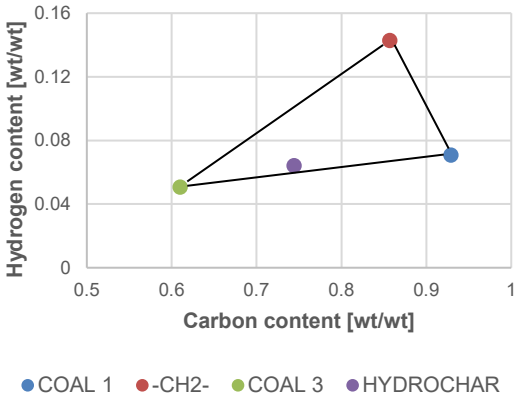

Figure 1: Visual representation of the linear combination procedure for the characterization of hydrochar

The modelling of hydrochar gasification is based on the discretization of both the solid particle and the gasification reactor. Each discrete volume is described by component-wise mass balances and an energy balance, both written with the hypothesis of perfect mixing, leading to homogeneous concentration and temperature in each volume (Ranzi et al., 2014). The reacting system modelled in this work is a fixed-bed, updraft, cylindrical gasifier with the following characteristics:

- Reactor height: 5 m
- Reactor diameter: 1 m
- Flowrate of gasification agent: 72 Nm^3/h
- Composition of gasifying agent: from 15 mol% O_2 / 85 mol% H_2O to 35 mol% O_2 / 65 mol% H_2O
- Temperature of gasifying agent at the inlet: 230 °C
- Counter-current configuration
- Initial temperature of gaseous feedstock for start-up: 930 °C
- Initial temperature of the system at the start-up: 25 °C
- Particle average diameter: 0.01 m
- Hydrochar feedstock flowrate: 100 kg/h
- Number of discrete volumes for the analysis of the solid particles: 2
- Number of discrete volumes for the analysis of the gasifier: 3

The GasDS suite has been used to study the produced bio-syngas depending on the composition of the gasifying agent used in the process, which is an O_2/H_2O binary mixture with oxygen content variating between 15 % and 35 % on a molar basis. It has been decided to proceed with the analysis by using the bio-syngas produced with the mixture having the following composition: 25 mol% O_2, 75 mol% H_2O.

2.2 Bio-DME process plant simulation

The Process Flow Diagram (PFD) of the bio-DME production plant is reported in Figure 2. The sewage sludge having a humidity content of 80 wt.% (Zhang et al., 2017) is pumped to 20 bar and 200 °C before entering the HTC unit. The reactor effluent is then flashed to 1.6 bar and the resulting steam is used for energy recovery (Knötig et al., 2021). The concentrated slurry exiting the flash unit then enters a filter-press, which reduces the humidity content to 60 wt.% (Qin et al., 2022), and finally it enters a drying unit working with hot air, which further reduces the water content to 10 wt.% (Vaxelaire and Cézac, 2004). The dry hydrochar flowrate (100 kg/h) is then fed to the previously modelled gasifier. The sour bio-syngas is processed in a chemical absorption section including an absorber that works with a 30 wt.% DEA solution, and a regeneration column. The H_2S contained in the acid gas captured in this section is then neutralized through a Claus unit (Ghahraloud et al., 2017). The sweetened bio-syngas having a residual H_2S content lower than 100 ppmv is compressed to 14 bar and mixed with steam at 15 bar, 199 °C before being pre-heated to 500 °C and entering a ZnO chemical guard for the complete removal of any H_2S traces. The mixture then enters a pre-reformer modelled as a thermodynamic reactor that converts any hydrocarbon to methane. The gas then enters a conventional fire-heated reformer modelled as a plug-flow reactor with kinetics from Xu and Froment (1989). The water content of the reformer effluent is condensed and recirculated to the reforming section, while the gas is compressed to 60 bar and sent to a water-based physical absorption unit for the removal of CO_2. This system tunes the CO_2 content of the process stream so that the Stoichiometric Number (SN) is equal to 2, a value that maximizes Methanol production (Ribeiro et al., 2012). The reacting system for the synthesis of Methanol is modelled as an isothermal, multi-tubular plug-flow reactor working at 250 °C with kinetics from Bisotti et al. (2021). The effluent is cooled to condense a methanol-rich phase and the un-reacted gas is recirculated, while 10 % of the stream is purged. The liquid effluent from the section is laminated to 11 bar and sent to a reboiled absorber for the removal of residual CO_2. The liquid exiting the bottom of the column is then heated and sent to the DME production section. The reacting system is modelled as an adiabatic plug-flow reactor with a stream entering at 240 °C and an effluent exiting at 348 °C with kinetics from Berčič and Levec (1992). The SRK package has been used to model the process except for the H_2S removal step, in which the Acid Gas - Chemical Solvents package was used. However, the ternary mixture exiting from the DME synthesis step has a strongly non-ideal behaviour which may result in the formation of two distinct liquid phases (Park et al., 2007). For this reason, the following separation section is modelled using the NRTL/SRK model for liquid/gas mixtures. The first column produces 19.3 kg/h of fuel-grade DME from the top, at a purity higher than 99.95 wt.% (Oguma, 2017). The liquid effluent from the bottom is laminated at 1.5 bar before entering a column for the separation of MeOH and H_2O. The MeOH from the top of the column is recirculated to the reactor for the DME synthesis, while the H_2O from the bottom of the column is recirculated to the reforming step. Recycling the water produced from this column allows sustaining the steam reforming section without any H_2O input, significantly reducing the freshwater consumption of the system. The tail gases are fed to the reforming furnace to reduce the overall natural gas consumption.

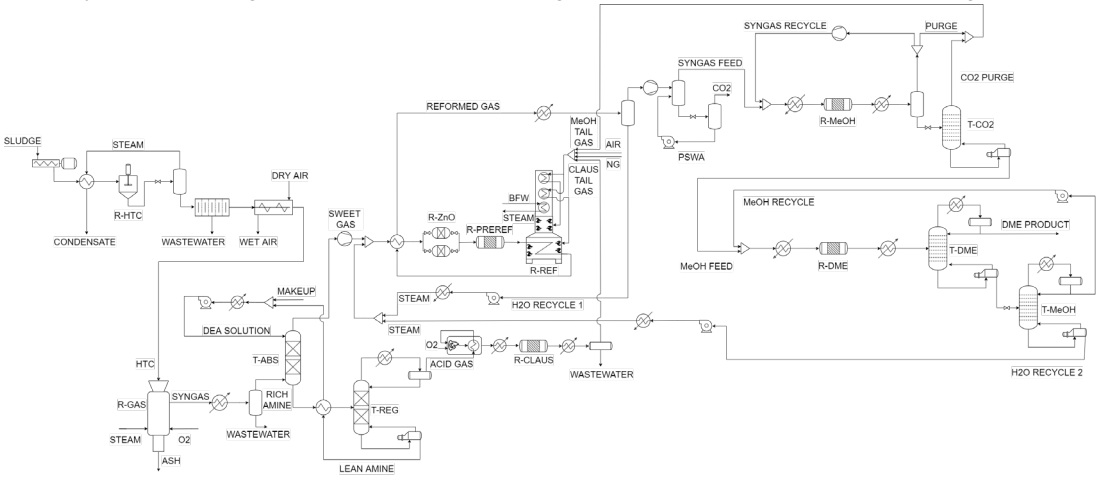

Figure 2: Process Flow Diagram of the bio-DME production plant

The Aspen HYSYS® V11 simulation included all the necessary information to perform a techno-economic analysis based on the calculation of the unit production cost in €/kgDME. Table 1 shows the unit prices for the utilities and feedstocks that have been used in the analysis. The negative cost shown by the sludge is due to the fact that the process plant is paid to dispose of this waste produced by third parties. The price refers to a sludge having 60 wt.% water content, as it is typically sold to treatment plants (CCAM, 2020).

Table 1: Unit prices for feedstock and utilities

Feedstock/Utility	Price	Reference
Demineralized Water	0.0022 €/kg	(Turton et al., 2020)
Cooling Water	0.0384 €/m^3	(Turton et al., 2020)
Electricity	0.2025 €/kWh	(ARERA, 2021)
Oxygen	0.1911 €/kg	(Dorris et al., 2016)
Natural gas	0.3380 €/Nm^3	(ARERA, 2021)
Sewage sludge	-0.1000 €/kg	(CCAM, 2020)

3. Results

This section shows the main results of the hydrochar gasification performed with GasDS and the techno-economic and sensitivity analysis operated on the data from the Aspen HYSYS® V11 simulation.

3.1 Bio-syngas composition and temperature

The temperature profile in the gasifier is shown in Figure 3a. As the O_2 content in the binary O_2/H_2O gasifying mixture increases, the temperatures along the reactor tend to increase as well, with T1 and T4 being the inlet and outlet gas temperatures. Figure 3b shows the bio-syngas dry composition at the reactor outlet. Higher O_2 content provides better syngas yield and leaves a lower quantity of heavy hydrocarbons in the final product but the gaseous product has a lower H_2/CO ratio, which is not optimal for bio-DME synthesis (Inayat et al., 2017). Vice versa, lower O_2 content leads to higher methane content, which can then be treated in the steam reforming unit, leading to both higher overall syngas productivity and a larger H_2/CO ratio. For these reasons, it has been decided to work with a gasifying mixture having a 25 mol% O_2 content since it leads to higher productivity of both the gasifier and the steam reformer and also leads to a rather high final H_2/CO content after the reforming section (larger than 3).

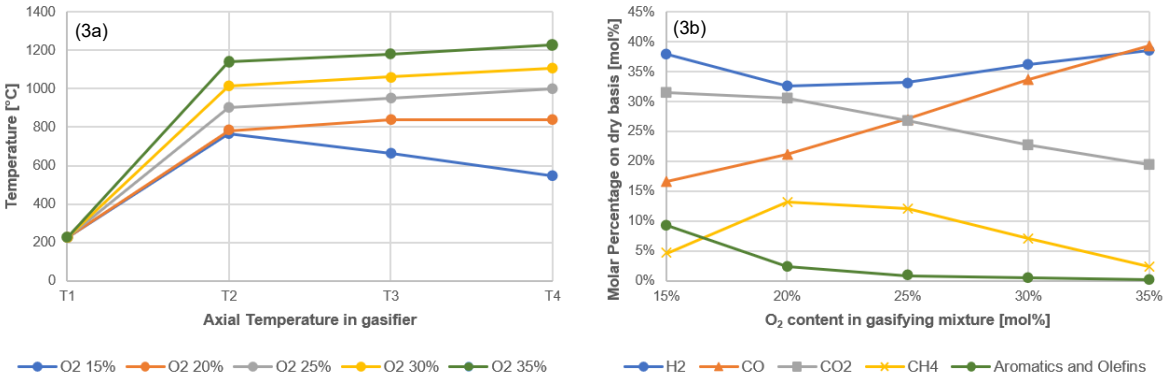

Figure 3: Results from the hydrochar gasification simulated with GasDS

3.2 Cost of production of bio-DME and sensitivity analysis

The unit cost of production resulting from the Aspen HYSYS® V11 simulation is equal to 0.277 €/kgDME, which is rather low due to the additional income coming from the disposal of sewage sludge produced by third parties. A sensitivity analysis is performed by both increasing and decreasing by ±50 % the unit cost of the terms previously reported in Table 1. The results are shown in Figure 4 highlight sewage sludge as the main factor in determining the unit cost of bio-DME, closely followed by natural gas. Oxygen, electricity, and cooling water all provide a smaller but still significant contribution to the cost of production. Demineralized water cost is almost negligible, mainly due to the recirculation of the water exiting the bio-DME separation columns back to the reforming section, leading to a significantly smaller demand for this utility. The trend shown by sewage sludge is opposite to that of the other terms since it has a negative cost. It is interesting to notice that both a low cost

of natural gas and a high cost of the sewage sludge (in absolute value) lead to a negative cost of production for bio-DME, meaning that the owner of the plant would benefit from a net profit just for processing the sludge, even without accounting for the bio-DME sales. As a final note, it is interesting to confront these results with the hypothetical sales price of bio-DME exiting this process plant. For the product to be competitive with conventional diesel fuel on the market, the two prices must be the same on an energy content basis. By considering that DME has roughly half the energy content of conventional gasoil on a volume basis (Patten and McWha, 2015) and by selecting a price of 1.5 €/L for gasoil, in line with the 2021 average value for Italy (Ministero della Transizione Ecologica, 2021), the resulting bio-DME sales price is equal to 1.243 €/kg. This value is higher than all the production costs shown in the sensitivity analysis, the maximum one being 0.924 €/kg. This means that a bio-DME production plant that starts from sewage sludge is potentially an extremely profitable business opportunity, and also shows low consumption of raw materials and an efficient disposal way for sewage sludge.

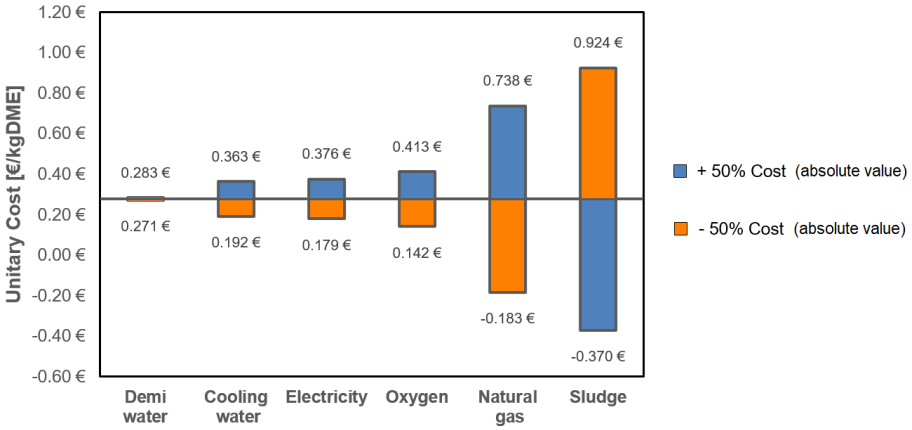

Figure 4: Sensitivity analysis of the bio-DME unit cost of production

4. Conclusions

The gasification of hydrochar produced by HBI Group srl (2022) was modelled through the GasDS package and the effect of the oxygen content in the binary O_2/H_2O gasifying mixture has been studied. The mixture containing 25 mol% oxygen has been selected as the most appropriate one, due to the increased overall syngas yield and its higher H_2/CO ratio. The process simulated in Aspen HYSYS® V11 includes a DEA-based syngas sweetening section, a steam reforming section for the conversion of methane, a methanol synthesis section, and a DME synthesis section through methanol dehydration. The economic analysis on the system highlighted a bio-DME cost of production which is very influenced by the price of both sewage sludge and natural gas. Comparing the cost of production with a hypothetical competitive price for bio-DME showed that the simulated process might be very promising from an economic standpoint. The proposed process shows a reduced consumption of raw materials, due to appropriate process design decisions. Specifically, the recirculation of the H_2O obtained from the bio-DME separation train back to the reforming section drastically reduced the freshwater consumption of the process and the utilization of the tail gas as fuel for the reforming furnace lowered the consumption of natural gas in the process. Finally, the process is inherently beneficial for the environment since it produces bio-DME, cleaner fuel for diesel engines, and provides an efficient disposal method for sewage sludge, common and problematic waste produced both by people and industries.

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