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Gasification-based methanol production from biomass in industrial clusters: Characterisation of energy balances and greenhouse gas emissions

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ABSTRACT

This study evaluates the potential for reducing life cycle greenhouse gas (GHG) emissions of biomass gasification-based methanol production systems based on energy balances. Configurations which are process integrated with a chemical cluster have been compared to stand-alone units, i.e. units with no connection to any other industry but with the possibility to district heating connection. Two different uses of methanol are considered: the use as a vehicle fuel and the use for production of olefins *via* the methanol-to-olefins process. An added value of the integration can be the availability of excess hydrogen. For the studied case, the methanol production could be increased by 10% by using excess hydrogen from the cluster.

The results show that the integrated systems have greater potential to reduce GHG emissions than the stand-alone systems. The sensitivity analysis demonstrated that the references for electricity production and district heating production technology have important impacts on the outcomes. Using excess heat for district heating was found to have positive or negative impacts on GHG emissions depending on what heat production technologies it replaces.

The investigated olefins production systems resulted in GHG emissions reductions that were similar in magnitude to those of the investigated biofuel production systems.

1. Introduction

The gasification of biomass is a key technology for replacing fossil fuels in the transport sector and has potential for the production of green plastics. The technology is still not commercialised in full scale but several demonstration plants are under construction. The development and commercialisation of biomass gasification systems are dependent upon several factors, including the environmental performance and economic outcomes of the system. Influencing both these factors is the localisation of the plant, including the potential to integrate the process with industries and infrastructures that are already in place.

In the present study, the energy balance and the potential for reducing life cycle greenhouse gas (GHG) emissions (e.g., CO_2, CH_4, and N_2O) in commercial-scale, biomass gasification-based methanol production systems were examined (see Fig. 1 for an overview of the gasification system and individual process steps). Two different uses of methanol were considered: the use as a vehicle fuel and the use for olefins production *via* the methanol-to-olefins process. Stand-alone configurations, i.e. with no connections to other industry but with possibility to district heating connection and configurations integrated with a chemical cluster on the west coast of Sweden were compared. The investigated opportunities for process integration of the methanol production system and the chemical cluster included streams of recovered heat and selected material streams. The present study is a continuation of the previous published work of Holmgren et al. [1], in which a systematic

Abbreviations: CHP, combined heat and power; Bio CHP, biomass-fuelled combined heat and power; DH, district heating; DME, dimethyl ether; GHG, greenhouse gas; GWP, global warming potential; IGCC, integrated gasification combined cycle; LCA, life cycle assessment; LDPE, low density polyethylene; LHV, lower heating value; MTO, methanol-to-olefins; NGCC, natural gas combined cycle; NGCC CHP, natural gas combined cycle with combined heat and power production; RME, rapeseed methyl ester; TSA, total site analysis.

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analysis of interrelations between different process steps in the biomass gasification-based methanol production chain was made. Based on a review of previous studies analysing energy efficiencies of stand-alone biomass gasification-based methanol production systems Holmgren et al. [1] discussed in detail the choice of technology for the different process steps and the internal integration, i.e. rational use of heat within the whole gasification process system from incoming biomass to product. The energy balance of a technical solution for a stand-alone biomass gasification-based methanol production system was described. Previous studies had shown that heat recovery by a steam cycle is important for the energy balance and in addition Holmgren et al. [1] highlighted some other important system parameters; such as the internal biomass drying, the addition of hydrogen to the syngas, and the trade-off between the levels of produced methanol, electricity, and heat. Several factors important for the energy performance were found to be localisation-related. Co-localising a biomass gasification-based methanol production with a chemical cluster, as in the present study, could be advantageous for the energy performance based on many factors: large amounts of raw materials and products are being handled at the cluster; the infrastructure is already in place; and the presence of several industrial processes in one area increases the possibilities for process integration. However, there may be conditions that are disadvantageous for integrating the biomass gasification system to the cluster. For example, excess heat from the chemical industry may already be used for district heating in the nearby area, with consequent saturation of the heat demands of surrounding heat sinks.

2. Objectives

The objectives of the present study were to elucidate: (1) how the energy balance and the environmental performance (in terms of GHG emissions) are impacted when a biomass gasification unit with methanol production is thermally integrated with a chemical cluster, as compared with a stand-alone configuration; (2) how much will GHG emissions be reduced with such systems, as compared to the use of conventional (fossil-based) systems; and (3) how the extent of process integration influences these parameters.

For the stand-alone cases, with no integration to the chemical cluster, the possibility to connection to district heating was considered. Further, two sets of gasification-based methanol systems were studied, one where methanol was used as a biofuel (replacing propellants for vehicles), and one where the methanol was used in a methanol-to-olefins (MTO) process to produce olefins. In cases with olefin production, the MTO process was considered to be integrated with the methanol production system.

3. Earlier work

The description of related studies was here limited to biomass gasification systems using only woody biomass. Furthermore, biomass gasification-based systems with synthesis processes other than methanol synthesis; e.g., Fischer–Tropsch or methanation would have other biomass-to-fuel ratio, heat balances, electricity demands etc. and literature on such systems were only briefly commented in this article.

Several researchers have studied gasification-based methanol production from different viewpoints. The studies often include analysis of the energy performance and the economic performance of the systems. Peduzzi et al. [2] presented a thermo-economical evaluation of biomass gasification-based methanol production, and they concluded that energy integration, and in particular the Rankine/co-generation cycle, is crucial for the overall energy efficiency of the process. Peduzzi et al. [2] did not consider the possibility to deliver district heating. Very recently, Hannula and Kurkela [3] presented a thermo-economical study of different designs of biomass-to-liquid production routes including methanol, DME, Fischer–Tropsch fuels, and synthetic gasoline. The investigated systems had a size of 300 MW thermal and included different designs of the gasifier (different pressure levels), the heat recovering steam cycles (condensing or backpressure configuration) and different gas cleaning concepts. District heating connection was considered in the study by Hannula and Kurkela [3] but no other integration options were included. The results showed that some of the methanol production systems could be net exporters of electricity and heat, and that the methanol production systems resulted in the lowest production costs of the compared fuels. Hannula and Kurkela [3] did not estimate greenhouse gas emissions from the gasification systems and did not consider any replacement of existing district heating.

Van Rens et al. [4] evaluated the energy performance of biomass gasification-based production of methanol, DME and hydrogen, and reported the methanol case had the highest energy efficiency. In the economic evaluation conducted by Huisman et al. [5], the methanol route based on a new technology was found to be insensitive to the level of sold district heating (due to the lower level of excess heat). In contrast, Leduc et al. [6] who estimated the cost of the final product in relation to the location of a biomass gasification-based methanol production plant in northern Sweden, highlighted the importance of finding a heat sink that could use the excess heat from the methanol production process. Leduc et al. [7] explored the optimal localisation and size of biomass gasification-based methanol plants in Austria in terms of the biomass and methanol production and transport, the investments for the production plants and gas stations, and the impact of heat deliveries from the ethanol production plants to district heating nets or nearby industries. They discovered that the cost of the biomass had the greatest influence on the cost of the final products, and that heat recovery could reduce the fuel cost by 12%.

Previous work also includes the CO_2 emission performance of biomass gasification-based methanol (or other fuel) production systems. Natarajan et al. [8] studied the optimal localisation for biomass gasification-based methanol or CHP production in Eastern Finland using a geographically explicit mixed integer linear programming model to minimise the cost of the entire supply chain. The raw material used was woody biomass, and the cost and the CO_2 reduction potentials for both systems were evaluated. Although the methanol generation system had a higher potential for CO_2 emission reduction it only first became competitive at high CO_2 tax levels. Natarajan et al. [8], who used an attributional approach, obtained results that contradict those reported by Wetterlund et al. [9], who investigated the impact of policy instruments on biofuel production (including biomass gasification-based methanol production) in Europe and concluded that, in general, replacing heat or electricity results in greater reductions in CO_2 emissions than replacing transport fuels. Furthermore, Wetterlund et al. [9] demonstrated that CO_2 emissions were reduced to a greater extent in cases that involved high electricity production and co-production of heat. Berndes et al. [10] analysed the integration of biomass gasification-based biofuel production with DH systems in a European context, and they showed that integration through heat recovery from biofuel production could increase cost competitiveness, and given that much of the district heating production is fossil fuel-based there is also the possibility to decrease CO_2 emissions. However, their results confirmed that the potential for integration is highly dependent upon competitiveness, as compared with other heat supply systems, especially CHP. Schmidt et al. [11] presented a spatial explicit optimisation model that assessed new biomass conversion technologies for fuel, heat and