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Energy and economic analyses of models developed for sustainable hydrogen production from biogas-based electricity and sewage sludge

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ABSTRACT

Five models were developed for the use of biogas-based electricity and sewage sludge obtained from a municipal wastewater treatment plant for hydrogen production. These models included alkaline, PEM, high temperature water electrolysis, alkaline hydrogen sulfide electrolysis and dark fermentation biohydrogen production processes. Energy and economic analyses were performed on the models by applying thermodynamic procedures and the results were compared. The daily hydrogen production rates of the models were calculated as 594, 625.4, 868.6, 10.8 and 56.74 kg for models 1, 2, 3, 4 and 5, respectively. The electricity costs of the models were calculated as 3.60, 3.43, 2.47, 1.16 and 6.7 \$/kg-H_2, for models 1, 2, 3, 4 and 5, respectively. In terms of the hydrogen production rate, the high temperature electrolysis process was found to be superior to the other models, followed by the PEM electrolysis process, whereas, in terms of the hydrogen production cost, hydrogen sulfide electrolysis was found to be superior to the other models. This paper aimed to determine the most appropriate model for a wastewater treatment plant among the considered models in terms of both hydrogen production and hydrogen production cost.

Introduction

Hydrogen is an energy carrier and it is proposed as an alternative energy source at present and in the future. Several hydrogen production processes exist, including steam methane reforming, partial oxidation of methane, autothermal reforming of methane, coal gasification, biomass pyrolysis and gasification, electrolysis, the sulfur–iodine cycle, photo-synthetic/photo-biological water splitting, and direct photocatalytic water splitting [1]. Each technology is at a different stage of development, and each offers unique opportunities, benefits and challenges [2]. As of today, most produced hydrogen (80–85%) is obtained by the steam reforming and gasification processes [3]. Although these preferred hydrogen production methods are considered more economical compared to the others, they are non-sustainable and not eco-friendly. In the long run, hydrogen should preferably be produced from renewable sources such as the electrolysis of water with renewable electricity or by means of biological hydrogen production [4].

The main task of a wastewater treatment plant (WWTP) is to treat wastewater to an extent that it can be discharged into a natural water body after minimizing the harmful impact on natural water quality. The wastewater treatment process

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requires large amounts of energy. However, wastewater sludge can be used as a renewable energy source. As a result of the anaerobic digestion process, sludge is degraded to produce biogas which consists of 60–70% CH_4, 30–35% CO_2, 1–2% H_2S, and 0.3–3% N_2 with various minor impurities, notably NH_3 and halides. This biogas can be used to produce heat and electricity onsite [5]. Electricity produced by the cogeneration facilities of a WWTP can be used as work input to the installed water electrolysis unit for hydrogen production. This hydrogen production method, in which biogas is used as a renewable energy source, can be considered as an eco-friendly or green process. The importance of electricity obtained from renewable energy sources is increased for the production of hydrogen [6].

In the electrolysis process, electricity is used to decompose water into its elemental components: hydrogen and oxygen. Electrolysis is often seen as the preferred method of hydrogen production, as it is the only process which does not rely on fossil fuels. It also provides high product purity, and is feasible for both small and large scale hydrogen production. Many different types of electrolysis cells have been proposed and constructed such as alkaline, PEM and high temperature steam electrolysis processes [7]. Another option is biohydrogen production from bio-renewables. Biohydrogen is a renewable biofuel produced from bio-renewable feedstocks by chemical, thermochemical, biological, biochemical, and biophotolytic methods. Processes for biological hydrogen production mostly operate at ambient temperature and pressure, and are expected to be less energy intensive than thermochemical hydrogen production methods. These processes can use a variety of feed stocks as carbon sources, such as organic waste materials, which facilitate waste recycling. Since activated sludge waste obtained from municipal WWTPs contains high levels of organic matter, it can be used as a carbon source and is considered a potential substrate for hydrogen production. Direct and indirect bio-photolysis, photo-fermentation, dark fermentation and integrated dark and photo-fermentation can be given as some examples of biohydrogen production processes [8–10].

Numerous studies have been undertaken to conduct water electrolysis and biohydrogen production [11–17]. However, only a few of these studies have been directly related to biogas-based hydrogen production and biohydrogen production from sewage sludge. Coskun et al. [6] performed an energy analysis of hydrogen production with biogas-based electricity. In their study, a facility generating its own electricity from biogas obtained from a WWTP was considered for investigation. The hydrogen production process conducted using biogas-based electricity was examined by three methods of electrolysis and PEM electrolyzing system was found as having higher overall system efficiencies of the other two electrolyzing systems. Pandu and Joseph [18] reviewed biohydrogen production processes and stated that the major biological processes discussed for hydrogen production were bio-photolysis of water by algae, dark fermentation, photo-fermentation of organic materials and sequential dark and photo-fermentation processes. Genc [19] reviewed biohydrogen production from wastewater sludge and emphasized the importance of sludge pretreatment due to the low sludge yield of fermentative hydrogen production methods. Wang et al. [10] presented a study on biohydrogen production from wastewater sludge by *Clostridium bifermentans*. This work examined the anaerobic digestion of wastewater sludge using a *Clostridium* strain isolated from the sludge as the inoculum.

Despite the existence of numerous studies on hydrogen production from renewable energy sources, hydrogen production from biogas-based electricity and sewage sludge are very limited in the open literature, to the best of our knowledge. In this study, five different hydrogen production models were developed based on the outputs of an actual municipal WWTP. These five models include alkaline, PEM, high temperature water electrolysis, hydrogen sulfur alkaline electrolysis and dark fermentation hydrogen production processes. The energy relations and economic analyses of the models were performed using the data provided from the plant management and previously published works [5,20] of the authors. The significance of the models presented in this paper is that they can be used to predict the hydrogen production potential of any municipal wastewater treatment plant since these plants have more or less similar processes and outputs such as biogas, sewage sludge, electricity, etc.

Model descriptions

The GASKI WWTP is a municipal wastewater treatment plant located in the city of Gaziantep, Turkey, and the flow schematic of the facility is given in Fig. 1. The plant treats nearly 222,000 m^3/day of domestic wastewater using primary, secondary (biological) and tertiary (anaerobic sludge digestion) treatments. The daily biogas production is nearly 15,200 m^3, as a result of the sludge stabilization process which takes place in the anaerobic digesters of the plant. 61% (9275 m^3/day) of the total biogas produced in the anaerobic digestion system is used as a fuel for the installed gas engine powered cogeneration facility on the campus of the WWTP. The remaining part (5925 m^3/day) is reserved in the biogas storage tank. The electricity production of the cogeneration plant is 1000 kWh. The digested sludge is sent to the de-watering unit of the WWTP to increase the dry matter content to 22%. The mass flow rate of the digested sludge is reduced to 2.48 kg/s as it exists the de-watering stage. In this study, five models were developed for the use of actual WWTP outputs (biogas, electricity and sewage sludge) for hydrogen production. The models are described in detail below.

In model 1 (see Fig. 2), an alkaline electrolysis process was considered for hydrogen production. In this model, the work output of the biogas engine powered cogeneration plant, 1000 kWh, is used as the work input to the electrolysis process. Water is heated before entering the electrolysis stage. For the process of heating water, there are two different options at the plant. The first involves the use of a very small amount of reserved biogas (about 0.001 kg/s) in a boiler (see Fig. 1a); the second option is to use the waste heat of the exhaust gas from the cogeneration plant by means of an exhaust gas heat exchanger (see Fig. 1b). The mass flow rate of the water entering the electrolysis process is taken as 0.062 kg/s. The temperature and pressure of preheated water by the boiler are 80 °C and 1 bar, respectively.