Journal of Cleaner Production 191 (2018) 87–98

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Environmental impact of the excess electricity conversion into methanol

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ARTICLE INFO

Article history:
Received 5 February 2018
Received in revised form
23 April 2018
Accepted 25 April 2018
Available online 26 April 2018

Handling Editor: Cecilia Maria Villas Bôas de Almeida

Keywords:
Excess electricity
Energy storage
Renewable methanol
CO_2 capture and utilization
Life cycle assessment
PtX

ABSTRACT

In this work, the impact on the environment of a renewable methanol production in combination with a wastewater treatment plant (WWTP) was analysed. Carbon dioxide from biogas and hydrogen from water electrolysis were used as resources for methanol synthesis. Additionally, it was decided to use the available excess of electricity and it was prepared for a small city in North-West of Germany (Emden) to have a realistic scenario. As a consequence, methanol plant was simulated with the use of ASPEN Plus software in order to calculate the mass balance and energy requirement. Subsequently a comparative life cycle assessment (cradle-to-gate) was conducted in order to compare renewable methanol with conventional process and also with methanol produced from biomass. In order to evaluate possible impact on the environment, 11 common impact categories were selected. Results showed that enough excess electricity was already available to utilize the whole CO_2 from WWTP in Emden. Subsequently it was found that the production of renewable methanol, without emissions related to windmill construction, has much lower impact on the environment than conventional production according to all impact categories. Furthermore, the combination of power-to-methanol plant with WWTP allowed utilization of the biogenic carbon dioxide and application of the produced via electrolysis oxygen. Therefore, thanks to substitution of air with produced oxygen, a reduction in electricity consumption for the aeration system could be possible. However, taking into account the emissions related to wind electricity, renewable methanol would cause lower emissions according to 5 impact categories (acidification potential, climate change, ozone layer depletion, photochemical oxidation, and primary energy demand from non-renewable resources) than natural gas or biomass based methanol.

1. Introduction

The further expansion of wind power (WP) in Germany is noticeable, because alone in 2016, 1288 new windmills were constructed, with net installed electricity capacity of over 4259 MW. Furthermore, new plants built in 2016 account for 4.7% of all plants (27 270) in operation on the 31st of December 2016 in Germany, which together have the net installed electricity capacity of over 45,910 MW electric power. Taking under consideration that German wind energy's market is already very mature, such a market growth is significant (Deutsche WindGuard GmbH, 2017). As a consequence, days like Sunday, the 8th of Mai 2016, when 87.6% of energy demand was covered with renewable energy (RE), are predicted to occur more often (WeltN24 GmbH, 2016). Furthermore, in Denmark already on Thursday, the 9th of July 2015 the electricity produced from windmills exceeded the domestic electricity demand (116%) (Neslen, 2015) and in Scotland also, the windmills covered the whole demand on Sunday, the 7th of August 2016 (The Guardian, 2016). However, further expansion of WP and other RE lead also to a situation when the grid is overloaded. Occasionally windmills or photovoltaic-plants (PV-plant) in Germany need to be switch off due to the grid overload, still obtaining reimbursement. Therefore initiatives like “switch over despite switch off” (German “*Umschalten statt Abschalten*”) from German Federal Association of Wind Energy are promoting alternative

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https://doi.org/10.1016/j.jclepro.2018.04.232
0959-6526/

usage of the excess electricity (German Federal Association of Wind Energy, 2015).

Currently there are many alternative storage options of the excess electricity, like e.g. production of hydrogen (Uusitalo et al., 2017), or alternative usages like e.g. production of ammonia (ISPT, 2017). Furthermore, even some of the possible energy storage solutions are actually utilizing carbon dioxide like conversion to methane, methanol (Uusitalo et al., 2017) or formic acid (Moret et al., 2014), hence allowing energy storage for a later usage. On the other hand, looking at the current findings about diesel emissions and its impact on premature deaths (Anenberg et al., 2017), conversion of excess of electricity into fuel, which is less toxic (Olah et al., 2009), would be very convenient. Moreover, its energy density at ambient conditions equals to 4.4 kWh/l (Chemie.de Information Service GmbH, 2017) and in contrast to hydrogen, which energy density at ambient conditions equals to 3 Wh/l and at 700 bar equals to 1.4 kWh/l (PLANET- Planungsgruppe Energie und Technik GbR, 2013), makes methanol an interesting alternative as an energy storage medium. As a consequence, methanol is an interesting option and could be applied as a fuel for vehicles (Bicer und Dincer, 2017a; Hao et al., 2017; Li et al., 2010; Shen et al., 2012; Trudewind et al., 2014a, 2014b; Zhen und Wang, 2015) aircrafts (Bicer und Dincer, 2017b) rail (Dincer und Zamfirescu, 2016) and ships (Brynolf et al., 2014; Strazza et al., 2010). According to IHS (Information Handling Services Markit), already in 2014 7000 thousand metric tons of methanol were directly used as a fuel out of 63,965 thousand metric tons produced worldwide (IHS Markit, 2017). Additionally, methanol is used for production of formaldehyde, MTBE (methyl tert-butyl ether), acetic acid (Olah et al., 2009; Van-Dal und Bouallou, 2013) and MTO (methanol to olefins, like ethylene and propylene), and is also possible application of it at the wastewater treatment plant for the denitrification process (Methanol Institute, 2017).

In order to ensure reduction in the environmental burden of e.g. new fuels before introducing them on a large scale, life cycle assessment (LCA) is a widely recognized method used for evaluation of possible environmental benefits over e.g. conventional production. Trudewind et al. prepared a life-cycle assessment and well-to-wheel analysis indicating that the photocatalytically produced methane has a lower ecological impact than photocatalytically produced methanol (Trudewind et al., 2014a, 2014b). Subsequently, an assessment of the methanol chemical synthesis from carbon dioxide and hydrogen together with comparison to conventional methanol production was conducted by Hoppe et al., where 3 parameters (global warming potential (GWI), total material requirement, raw material input) and the CO_2-source were analysed (Hoppe und Bringezu, 2016; Hoppe et al., 2017). In their system the German electricity mix was applied for production of methanol and wind energy was used for electrolysis. They included hydrogen production but produced oxygen was not further considered. One of the key findings is, that CO_2 from direct air capture is significantly increasing the environmental impact in means of all the three parameters analysed, due to excessive heat and electricity demand. Pérez-Fortes et al. analysed a net reduction of CO_2 emissions and a cost of methanol production. They indicated that a capital cost of methanol plant synthesized from hydrogen and captured carbon dioxide, not including electrolyser and carbon capture unit, is lower than for conventional plants. But the cost of resources (H_2 and CO_2) does not allow the project to be financially attractive, as long as the price of hydrogen would decrease almost 2.5 times or the price of methanol would be two times more expensive. Nevertheless, they also found that a very small reduction of carbon dioxide emissions could be achieved, but it needs to be kept in mind that they are operating the plant with electricity from a conventional pulverised coal plant as a worst case scenario (Pérez-Fortes et al., 2016). Matzen and Demirel prepared a fully comparative LCA (cradle-to-grave) of a very big scale methanol (96.7 tons per day) and dimethyl ether (68.5 tons per day) plants from renewable hydrogen and captured carbon dioxide. They included the production of CO_2 via ethanol plant, hence biomass growth, harvesting etc. was included in their system boundary along with construction of windmills. Authors also used the renewable electricity for operating the facility and for electrolysis. According to the five impact categories (Global Warming Potential, Acidification Potential, Photochemical Oxidation Formation, Particulate Matter Formation, Human Toxicity) analysed, renewable methanol production has lower impact on the environment compared to dimethyl ether or the conventional processes. However, according to the authors, methanol has a higher impact on the environment than dimethyl ether during combustion, Yet it is noteworthy that the largest environmental impact still was found to be related to the fuel production stage for both fuels (Matzen und Demirel, 2016). Finally Uusitalo et al., (2017) used the excess of electricity for production of hydrogen, methane and methanol and looked at the greenhouse gas (GHG) emission. Authors stated that the highest reduction on GHG was achieved with hydrogen, but all three options indicated high GHG reduction potential if applied in transportation (Uusitalo et al., 2017).

Consequently authors identify a need for a fully comparative methanol life cycle (cradle-to-gate) assessment, where production of the renewable methanol from the excess electricity will be compared to conventional process and to methanol from biomass. The comparison will be conducted according to 11 impact categories, in order to identify eventual impact of the methanol production. Finally, in this concept the power-to-methanol plant will be located at the wastewater treatment plant, which allows application of the produced via electrolysis oxygen, what is not considered in other LCA analysis. The whole methanol plant is simulated with ASPEN Plus® and for life cycle assessment GABI® software is employed.

2. Material and methods

2.1. Methanol production

The methanol production process is a catalytic conversion of carbon monoxide and carbon dioxide with hydrogen at elevated temperature (250 °C) and pressure (50 bar) in presence of e.g. CuO/ZnO/Al_2O_3 catalyst (Sahki et al., 2011). Obtaining those conditions would allow both exothermic reactions (eq. 1 and eq. 2) to take place (Van-Dal und Bouallou, 2013):

$$CO + 2H_2 \leftrightarrow CH_3OH \quad \Delta H = -128\,\frac{kJ}{mol}\ (298\,K)$$

Equation 1 Methanol synthesis from carbon monoxide (Van-Dal und Bouallou, 2013)

$$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O \quad \Delta H = -87\,\frac{kJ}{mol}\ (298\,K)$$

Equation 2 Methanol synthesis from carbon dioxide (Van-Dal und Bouallou, 2013).

The required gas mixture, so a synthesis gas, is obtained from natural gas for the conventional methanol production (Van-Dal und Bouallou, 2013). But the synthesis gas can also be obtained from the biomass (Cheng, 2009) or as the resources could directly serve the captured carbon dioxide and derived via electrolysis hydrogen (eq. 2) (Van-Dal und Bouallou, 2013).