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20 % Reduction of CO_2-Emissions with Power-to-Gas in WWTP

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Abstract – **The engineering company Witteveen+Bos and the Water Board Aa en Maas explored the potential of a new concept combining Power-to-Gas (PtG) and sludge digestion in Wastewater Treatment Plant (WWTP) Cuijck. This project aims to tackle two topical issues at once, which are respectively the need for increase of energy storage for renewable energy production and the need for reduction of greenhouse gas emissions. The main conclusion of this study shows that Power-to-Gas systems can reduce around 20 % of the carbon dioxide (CO_2) emissions and provide long term storage of 126.5 MWh/year (140 579 Nm^3 Synthetic Natural Gas/year) at the WWTP of Land van Cuijk.**

Keywords – **Power-to-Gas, Methanation, Hydrogen, CHP**

I. INTRODUCTION

The Netherlands, similar to many countries in Europe, develops its renewable energy sector in order to decrease the greenhouse gas emissions within its territory. By 2020, the Dutch government aims to increase the share of renewable energy to 14 % of the total energy production (4.5 % only in 2013). This renewable energy expansion is mainly based on the development of wind and solar energy, the cleanest and most used renewable energy sources. Despite their potential, the power production from both energy sources is not constant over time due to their high dependency on the weather conditions resulting in a mismatch between the electricity production and the electricity demand. The need for a higher and better utilization of renewable energy in the Dutch grid necessitates new innovative energy storage solutions.

In this energy context, Witteveen+Bos and Aa en Maas propose an innovative solution combining energy storage solution and CO_2eq emissions reduction. The concept is based on the conversion of renewable energy into Synthetic Natural Gas (SNG) or green gas, through the Power-to-Gas (PtG) process. On the one hand, the resulting green gas can be stored in the Dutch gas transmission grid for long-time energy storage. On the other hand, the CO_2 content of the biogas is converted into methane (CH_4) during the upgrading process, resulting in lower CO_2 emissions in the atmosphere compared to traditional gas upgrading technology.

II. POWER TO GAS INTEGRATED IN WWTP CUIJCK

Power-to-Gas (PtG) technology converts electrical power into hydrogen (H_2) gas and oxygen (O_2) by water electrolysis. Excess energy from renewable sources (sun, wind) can be used to power an electrolyzer. The resulting H_2 is either stored in pressure vessels or reacts with carbon dioxide to produce CH_4 (methanation reaction). Although energy is lost during both the electrolysis and methanation reaction, this concept is interesting for long term energy storage.

The current gas infrastructure is more suitable for long term energy storage than the electricity grid and injection of H_2 into the gas grid is limited to 0.02 vol % for safety reasons. [1] From an environmental point of view, the methanation reaction has shown to be an interesting option to achieve significant CO_2 emissions reduction in the Netherlands [2]. And although the O_2 stream is usually not used in Power-to-Gas processes, at the Wastewater Treatment Plant (WWTP) where there is a need for aeration the O_2 can be utilized, which represents a potential economic value [3].

At WWTP Cuijck, the CO_2 is present in biogas and air containing O_2 is used in the aeration system.

The H_2 stream produced by the electrolyzer and the CO_2 content of biogas are mixed and converted into CH_4, through the methanation reaction. The CH_4 from biogas is therefore increased from 65 % until the value higher than 90–95 %.

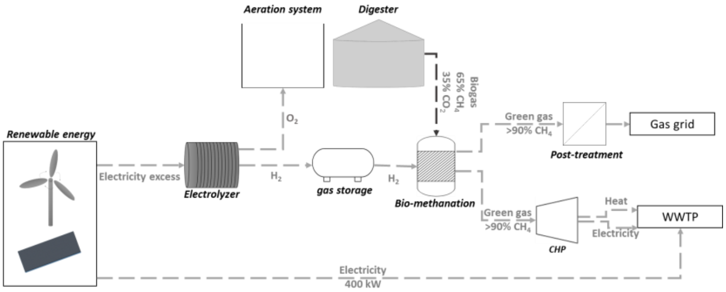

Fig. 1. Scheme of the PtG combined in WWTP.

Simultaneously, the O_2 stream generated by the electrolyzer is fed into the aeration basin. Injection of pure O_2 (100 % O_2) instead of air (21 %) reduces the volume of gas injected into the aeration basin leading to a decrease of the compressors electricity consumption by a factor of five.

As shown in Fig. 1, only the renewable energy production exceeding the WWTP electricity consumption is used in the electrolyzer. In fact, the renewable energy produced on-site has to meet the energy requirement of the WWTP before being stored. Therefore, the H_2 production follows the energy production pattern of solar and wind energy resulting in a discontinuous H_2 production. A gas storage tank and smart flow control ensure the transition between a discontinuous H_2 production to a continuous H_2 supply to the bio-methanation reactor. Within this configuration, H_2 can be mixed with the biogas constantly even if no renewable energy is produced.

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The upgraded biogas (or green gas) is either used in a cogeneration or combined heat and power installation if energy is needed on the WWTP (low renewable energy production) or post-treated and sent to the national transmission gas grid if no or less energy is needed.

III. TECHNICAL FEASIBILITY

Although the electrolyzer is a mature technology used for many years, the biological methanation is a rather new process not currently used in a WWTP. Three alternatives have been considered for mixing H_2 and biogas:

1. H_2 is injected into and mixed with the biogas inside the digester in one single step.
2. H_2 is injected and mixed with the biogas in a separate vessel.
3. H_2 is injected and mixed with the residual gas flow after CO_2 removal from the biogas. This gas flow is containing mainly CO_2 and depending on the removal technology a small amount of CH_4 content of the biogas obtained after a step.

The three alternatives are shown in Fig. 2.

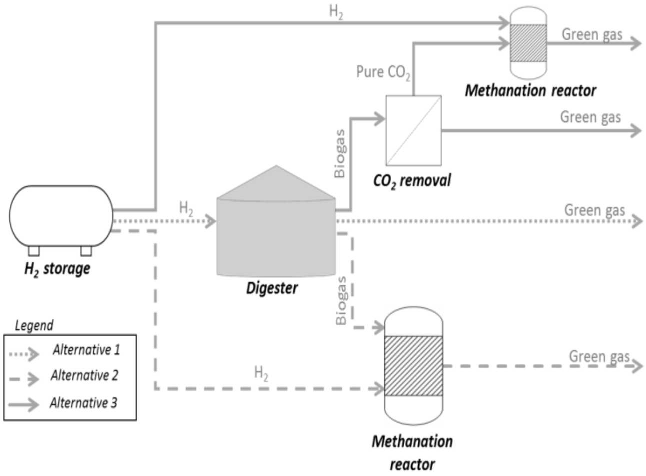

Fig. 2. Three different alternatives to upgrade biogas with H_2.

3.1 Direct Injection in the Digester (alternative 1)

During the anaerobic digestion process, H_2 is naturally released and converted into CH_4 with CO_2 during the last digestion step by *hydrogenetrophic methanogens*. Hence, the possibility of producing and upgrading biogas in one single step with injecting extra H_2 is considered. This configuration requires little extra equipment and makes use of existing equipment in the WWTP.

The methane production in the digester could potentially double with H_2 injection. Since the CO_2 is characterized by a lower solubility than CH_4 and H_2, a considerable amount of CO_2 is dissolved in the sludge. H_2 injections allow converting the dissolved CO_2 in CH_4, which increases the overall methane production in the biogas. Although the methane production increases with H_2 injection, biogas composed of 75 % CH_4 was obtained in average using classical gas diffuser (e.g. ceramic diffuser) [4] due to the hydrogen remaining in the effluent gas (20 % H_2). Thus, the H_2 gas-liquid mass transfer is a limitation on this system. Nevertheless, complete H_2 dissolution in the digester and high methane composition from the effluent biogas (>90 %) are potentially achievable with very fine bubble gas diffusers (e.g. hollow fiber) [5].

However, the H_2 injection in the digester tends to influence the anaerobic digestion process. For instance, increase of pH (until 8–8.3) was observed in laboratory experiments at high H_2 dissolved pressure [4]. The H_2 injected in the digester reacts with bicarbonate (HCO_3^-), a chemical compound known to buffer the pH. Thus, the HCO_3^- concentration drop leads to a pH increase. This phenomenon tends to inhibit the microbial degradation of acetate into biogas (CH_4 and CO_2), which represents more than 70 % [6] of the total biogas production in classical digesters without H_2 injection.

Moreover, high H2 dissolved pressure is known to inhibit the degradation of Volatile Fatty Acids (VFAs) into acetate, which represents 20 % [6] of the total biogas production Nevertheless, no obvious VFAs degradation inhibition was observed, which suggest that microbial flocs structures are able to protect the bacteria from the high H_2 concentration.

Overall, the simultaneous biogas production and upgrading in one single digester is possible but remains challenging due to the competition between the numerous chemical reactions involved and low H_2 solubility. For instance, high H_2 dissolution increases the dissolved CO_2 conversion into CH_4 but also increases the pH in the digester. Thus, research is still needed to extend our knowledge on these complex chemical interactions and a new innovative reactor design needs to be developed to optimize this process.

3.2 Injection in a Bioreactor with the Biogas (alternative 2)

The anaerobic digestion and the upgrading step are separated. H_2 is directly injected with the biogas into one reactor. Separating both processes avoids inhibition reactions and increases the reaction selectivity wanted. For instance, Electrochaea, the University of Chicago and the University of Cornell manage to upgrade biogas with H_2 using one single bacterial strain [5]. The bacteria strain was selected to convert exclusively H_2 into CH_4. The same research team observed that the H_2 mass transfer is the main limitation in this process. The higher is the H_2 retention time, the higher is the CH_4 conversion efficiency [7]. Methane production of 20 m^3 CH_4/m^3 reactor/day is achievable with low H_2 remaining in the effluent gas (<10 %).

3.3 Injection in a Bioreactor with Residual CO_2 Flow (alternative 3)

The H_2 conversion is faster when pure CO_2 is injected in the reactor instead of biogas [6]. The CH_4 content of the biogas reduces the H_2 partial pressure in the reactor and consequently decreases the H_2 mass transfer. Therefore, a lower retention time and lower reactor volume is needed when the H_2 is mixed with pure CO_2. Methane production of 22 m^3 CH_4/m^3 reactor/day has been obtained with low H_2 remaining in the effluent gas (<10 %).

Nevertheless, a CO_2 removal step is needed to separate the CO_2 from the biogas before mixing the H_2 and pure CO_2. This step requires a higher investment cost than the bioreactor itself. When using biogas to feed a CHP, this CO_2 removal is normally not needed.

The three different alternatives proposed in this paper show some pros and cons. Among them, the injection of H_2 downstream into a separate bioreactor with biogas (alternative 2) appears to be the best trade-off between financial and technical aspects nowadays.

On the one hand, mixing residual gas with high CO_2 content and H_2 is the most efficient methanation process. However, this system requires extra costly equipment (e.g CO_2 removal). On the other hand, direct H_2 injection in the digester shows the highest CH_4 potential production and the lowest costs. Nevertheless, this process is still in a research stage due to the H_2 influence on the acetate, VFAs degradation and the pH increase. The Biocat Project located in Denmark is currently testing the injection of H_2 downstream into a separate bioreactor with biogas under continuous full scale conditions.

IV. ENVIRONMENTAL BENEFITS

4.1Biogas

In general, the CO_2 content of biogas is emitted into the atmosphere either from a CHP unit (electricity generation) or from a CO_2 removal step (biogas upgrading). In the combined PtG and WWTP, the CO_2 is used to increase the calorific value of the biogas. Therefore, more energy is harvested in the CHP for the same amount of CO_2 emissions and almost no carbon is emitted in the WWTP during the upgrading of biogas in green gas. For instance, conventional biogas produces 2.9 KWh_e/Nm^3 of electricity, whereas upgraded biogas with H_2 can potentially produce 4.3 kWh_e/Nm^3 (48 % energy increase). Therefore, 673 gCO_2eq/kWh is emitted with conventional biogas compared to 430 gCO2eq/KWh for upgraded biogas using H_2. Thus, less electricity and less carbon is imported from the Dutch grid when the biogas is upgraded with H_2. The CO_2 emission factor for the electricity production in the Netherlands is evaluated to be around 410 g CO2eq/kWh [8]. Electricity generation from natural gas emits less CO_2 due to the higher efficiency of natural gas power plant (45–50 %) than CHP at WWTP (45 %).

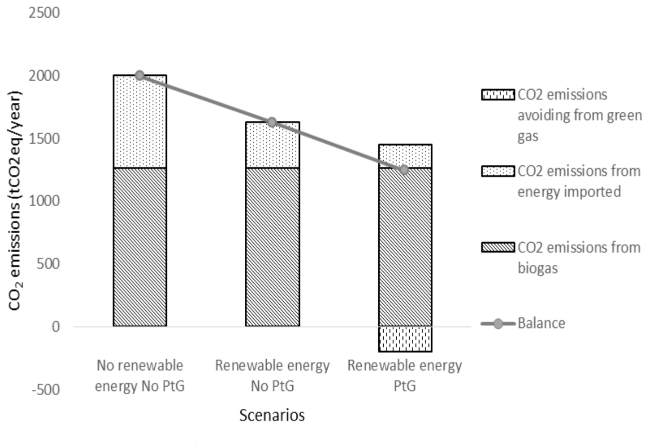

Fig. 3. CO_2 emissions for three different scenarios. PtG stands for Power-to-Gas.

The overall conversion of electricity in CH4 and the re-conversion in electricity (Power-to-Gas-to-Power) is rather low (20–30 %). Thus, the direct use of excess renewable energy by other end-consumers than the WWTP itself is always better than chemical storage from a CO2 emissions perspective. However, the Power-to-Gas has a positive impact on the CO2 emissions and overall availability of renewable energy when the excess renewable energy is not usable by other end-consumers, i.e. the supply of sustainable electricity exceeds the demand at a certain period. Fig. 3 shows the CO2 emissions of three different scenarios for the WWTP of Land van Cuijk, operated by Aa en Maas. In these calculations, we consider the excess of renewable energy on the WWTP not to be available for other consumers.

Application of PtG at the WWTP results in a decrease of the CO_2 from energy imported (electricity and gas) as well as the decrease of future CO_2 emissions from natural gas due to the long-term storage of green gas (CO_2 emissions avoiding). Overall, the CO_2 emissions of the WWTP decreases by almost 20 % with PtG compared to a system without PtG.

4.2 Financial Feasibility

Nowadays, the PEM-electrolyzer investment cost (hydrogen production) is too high to allow the PtG combined with WWTP to be financially feasible. Fig. 4 shows the green gas production cost for each alternative. Production costs investment and operational costs are the most sensitive factor on the total cost. Joined efforts of research institutes and manufacturers are constantly aimed at the decrease of the electrolyzer cost.

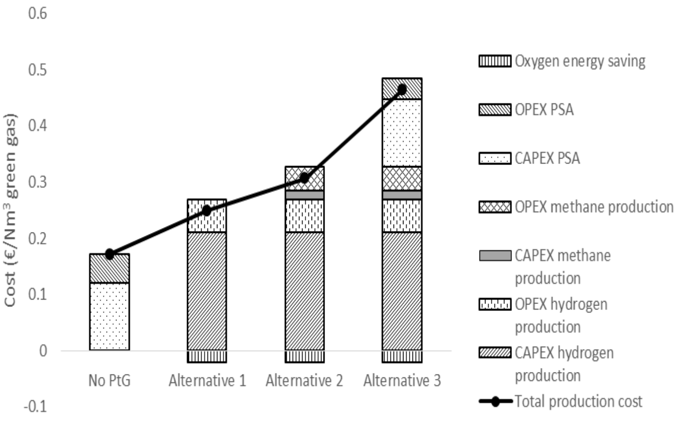

Fig. 4. Cost per Nm3 of green gas. PtG stands for Power-to-Gas (Electricity and storage cost are not included).

In contrast, the CH_4 production (methanation) costs are not significant compared to the H2 production costs (22 % of the H_2 production costs). The electricity saved from the O_2 steam decreases the green gas production costs with H_2. However, the energy cost saved from O_2 is much lower than the hydrogen production cost (10 % of the hydrogen costs).

The initial electrolyzer investment (CAPEX) is the most sensitive parameter on the green gas production costs (Fig. 5). For instance, a 20 % decrease of the electrolyzer costs leads to a total green gas production decrease of 14 %. In contrast, the CH_4 production CAPEX (methanation reaction) has the least impact on the total green gas production costs. The OPEX of the methane production and the electrolyzer are more or less similar. Besides the technology costs, improvement of the electrolyzer efficiency (currently around 70-80 %) can significantly decrease the H_2 production costs. An electrolyzer efficiency up to 95 % could decrease the total methane production costs until 12 %.

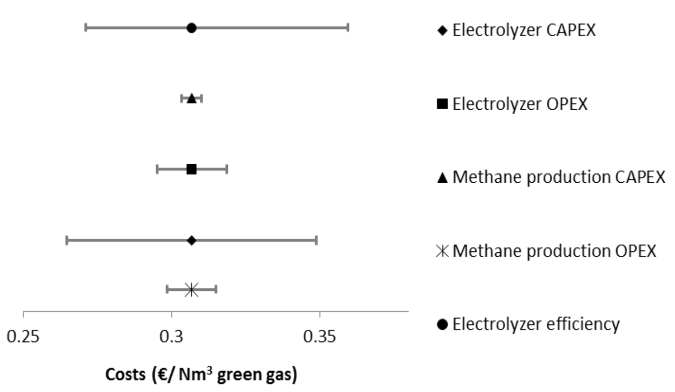

Fig. 5. Sensitivity analysis for the alternative 2 (+/− 20 % for each parameter).

To summarize, the electrolyzer investment costs and efficiency are two most sensitive parameters influencing the green gas production costs. Decrease of the efficiency losses and the technology costs are compulsory to increase the cost-competiveness of methane production from H_2 and CO_2. Nowadays, upgrading biogas with H_2 is not financially attractive in the Netherlands.

V. CONCLUSION

The green gas production from excess energy is a technical feasible solution for seasonal energy storage and reduction of CO_2 emissions in WWTP (around 20 %). The concept was successful in lab-scale but still further experiments are required to describe the efficiency of such a system in full scale condition and the best configuration. The alternative whereby the methanation reaction takes place with biogas and hydrogen in a separate reactor appears to be the best trade-off between technical and financial performance. However, upgrading biogas with H_2 (0.33 €/Nm^3 green gas) is almost twice more expensive than traditional biogas upgrading technology (0.17 €/Nm^3 green gas). From a financial point of view, the cost-effectiveness of the concept proposed strongly depends on the H_2 production technology costs. Breakthrough in the H_2 production field would have a great influence on the financial feasibility of this system.

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