Applied Energy 170 (2016) 278–285

Contents lists available at ScienceDirect

Applied Energy

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

Modeling a power-to-renewable methane system for an assessment of power grid balancing options in the Baltic States' region

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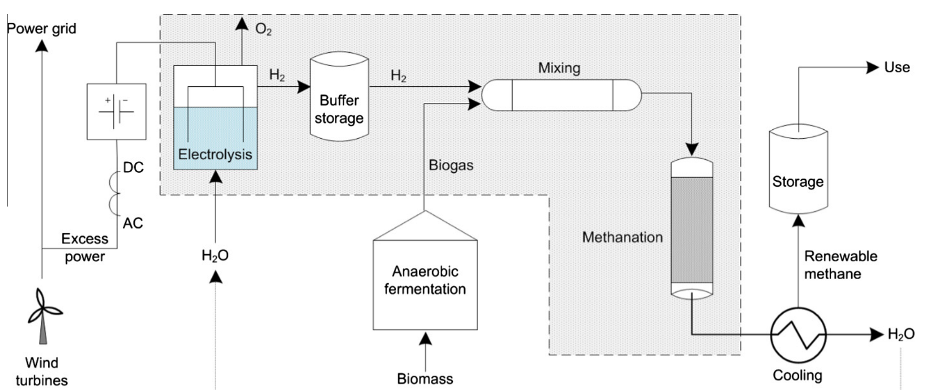
HIGHLIGHTS

- A mathematical modeling framework developed for assessing power-to-methane systems.
- An integrated system of wind power, electrolysis, biogas and methanation assessed.
- Power system is more stable with methanizing biogas with H_2 from excess wind power.
- Accumulation of H_2 limits production of renewable methane.
- Large potential for wind power development in the Baltic States.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 21 December 2015
Received in revised form 10 February 2016
Accepted 25 February 2016
Available online 7 March 2016

Keywords:
Excess power
Methanation
Power-to-gas
Power-to-methane
Renewable methane
Stochastic energy

ABSTRACT

The explicit tendency to increase the power generation from stochastic renewable resources forces to look for technological solutions of energy management and storage. In the recent years, the concept of power-to-gas, where the excess energy is converted into hydrogen and/or further methanized into renewable methane, is gaining high popularity among researchers. In this study, we assess the power-to-renewable methane system as the potential technology for power grid balancing. For the assessment, a mathematical model has been developed that assists in understanding of whether a power-to-renewable methane system can be developed in a region with specific installed and planned capacities of wind energy and biogas plants. Considering the varying amount of excess power available for H_2 production and the varying biogas quality, the aim of the model is to simulate the system to determine, if wind power generation meets the needs of biogas plants for storing the excess energy in the form of methane via the methanation process. For the case study, the Baltic States (Estonia, Latvia, and Lithuania) have been selected, as the region is characterized by high dependence on fossil energy sources and electricity import. The results show that with the wind power produced in the region it would be possible to increase the average CH_4 content in the methanized biogas by up to 48.4%. Yet, even with a positive H_2 net production rate, not in all cases the maximum possible quality of the renewable methane would be achieved, as at moments the necessary amount of H_2 for methanation would not be readily available, and the reaction would not be possible. Thus, in the region, the wind power capacities would not meet the biogas plant capacities nor now, nor until 2020. For the system's development, two potential pathways are seen as possible for balancing the regions' power grid.

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http://dx.doi.org/10.1016/j.apenergy.2016.02.137

1. Introduction

Power grid balancing becomes very essential as soon as stochastic energy generators, such as wind and solar power plants are introduced into power grid. Widely known methods for energy balancing through accumulation are CAES (compressed air energy storage systems), PHS (pumped hydro storage), batteries and water accumulation behind dams (profoundly reviewed by Akinyele and Rayudu [1] and Zhao et al. [2]). The trend to increase the power generation from renewable resources is strong: the total installed global wind capacity alone has increased from 17,400 MW in 2000 to 392,927 MW by mid-2015 [3]. Denmark with 34% and Spain with 21% are countries where wind energy has become the largest source of electrical energy. Large share of wind energy has also been reached in Portugal (>20%), Ireland (>16%) and Germany (9%) [3]. For now, the generated stochastic energy is managed by strong interconnections between countries or regions. E.g. in the case of Denmark, most of the energy is exported to Sweden and Norway, where the excess energy can be stored in water reservoirs, and imported when demand cannot be covered by the local resources [4]. Spain's average daily energy surplus is 22.38 GW h [5], and the interconnections to France and Portugal are essential for balancing the grid. Spain is also between the leaders in EU for the installed PHS capacity that in 2012 was 5.257 GW [6]. While in Germany, the PHS gross capacity adds up to 7.6 GW [7], and it also is one of the two countries in the world, where CAES is used – a 290 MW facility is built in Huntorf [8]. In the next few years, the installed PHS capacities are expected to double in Portugal where most of electricity is generated in large hydropower plants such as pumped-storage power plants, or simple storage power plants [9]. Whereas, Ireland sees smart grids as contributors to increasing the amount of stochastic renewable energy incorporated into the electricity system [10], as it has limited interconnections to other networks [11].

The presented cases show that the electricity grid can be successfully managed and varied depending on the available resources and technologies. Yet, they also indicate that the current balancing technologies will not be sufficient for fulfilling the future needs, and further development and research is required. In this context, power-to-gas is a relatively new concept, where the excess energy is converted into hydrogen (H_2) by water electrolysis or further to methane by methanation [12]. In the case of H_2, it is stored and, when necessary, reconverted into electricity by fuel cells [13]. Yet, the storage and utilization of the seemingly promising energy carrier poses several challenges. Properties of H_2 set specific requirements for its storage, such as high pressure, low temperatures and special materials to limit its diffusion and leakages [14]. While utilization of H_2 for energy production for now is limited as hardly any infrastructure for it exists [15]. Also, feeding H_2 into the natural gas grid involves several uncertainties, as the extent to which H_2 can be fed into the gas grid is unclear and the information on the related impacts and risks is very contradictory [14]. Therefore, currently, H_2 is mostly used as a chemical feedstock. Utilization of H_2 in methanation process is an alternative solution that in recent years has gained much attention [16].

Methanation (also known as hydrogenation) is a reaction where carbon oxides present in a gas react with H_2 to produce methane [17]. Reactions are present in a methanation reactor under controlled conditions and parameters, such as temperature, reactant ratios, gas composition, flow rate, pressure, and mass [18]. An external addition of a catalyst is needed to initiate the reaction [19]. Although the reaction itself was discovered more than a century ago, only in 2008, the first industrial methanation plant was launched [20]. The main industrial application of methanation reactions has been the removal of traces of CO from H_2-rich feed gases in ammonia plants [20]. In recent years, studies and industrial application of methanation is gaining popularity as a method for treating products from gasification and anaerobic digestion processes – syngas and biogas (e.g. in [18,21,22]). Increasingly, methanation is as well mentioned as part of a power-to-gas system (e.g. in [16,23,24]). A system, where biomass and irregular energy sources are integrated, allows for storing the excess power and upgrading, for example, biogas quality to biomethane, also referred to as renewable methane. Methanation differs from the other power grid balancing technologies, as the end product not necessarily has to be converted back to electrical energy. In addition, reconversion to electrical energy can have lower efficiency than conversion to gas or fuel. According to Sterner [24], efficiency of renewable power-to-methane generation is between 46% and 75% (on average 63%), while methane-to-power efficiency can reach up to 60%. Thus, the resulting efficiency of power-to-methane-to-power system is estimated around 36%. CH_4 requires 4–5 times less storage volume than H_2, thereof enhancing its economic viability as compared to H_2 storage [12]. The renewable CH_4 systems can use the existing natural gas infrastructure for distribution and storage. Accordingly, new infrastructure and technology for development of H_2 economy can be avoided [25]. Meanwhile the increased quality of biogas will prove economically viable to change biogas users from low-efficiency condensation power stations to the use of biomethane in transport and as an input to the natural gas grid.

During the last five years, the number of studies where system integration for power-to-gas generation is explored has considerably increased indicating the topicality of the subject. De Saint Jean et al. [16] have simulated a power-to-substitute-natural-gas system, where H_2 generated in a high-temperature electrolysis process and CO_2 from industrial capture process are inlet into a methanation reactor. In the study, authors make a process simulation with predefined process data. A reference case is described and afterwards sensitivity analysis is made by changing input parameters, where every scenario assumes that the input parameters are constants throughout the process. In contrary, the model described in our paper uses dynamic data as input, with varying quality of biogas and varying amount of power available for electrolysis. Schiebahn et al. [26] have reviewed the process chains of different power-to-gas paths, including different transformation technologies, the optional methanation step including the necessary production of CO_2, distribution options and geological storage options, as well as end-user applications. However, the study concentrates on economic analysis rather than technological process itself, and concludes that the economics are strongly connected to the individual market potential and competitive products. Reiter and Lindorfer [27] have evaluated different CO_2 sources concerning their potential utilization within the power-to-gas energy storage technology with regard to capture costs, specific energy requirement and CO_2 penalties. The case study of Austria indicates that CO_2 from biogas upgrading facilities and the bioethanol plants is best source due to low capture costs, low CO_2 penalties, biogenic origins of those sources and short distance to wind power plants in Austria. Meanwhile, Guandalini et al. [28] have assessed the energy and economic aspects of a wind power-to-gas system, where H_2 is directly injected into a natural gas grid. Quadrdan et al. [29] have investigated the power-to-gas concept by including the H_2 electrolysers within an operational energy model of Great Britain. Results show that simple payback of such system would be 10–14 years depending on the permissible H_2 limit in gas. The study emphasizes importance of power-to-gas system as a link between power and gas infrastructures, and indicates that such system can be a source of gas for local consumers, which in large systems would decrease the need of running compressors in