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Power to gas: Technological overview, systems analysis and economic assessment for a case study in Germany

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ABSTRACT

The issue of limited fossil fuels combined with the vast technological improvements in recent years has initiated numerous installations of renewable power production, particularly in form of photovoltaic cells and wind turbines. Since the volatile character of wind and solar radiation leads to a fluctuating power production, these renewables are incapable of providing reliable base load power. To enable the transition to a renewable energy system, large-scale energy storage is required to compensate for short-term and seasonal imbalances and to save temporary excess power. Due to the order of magnitude involved, this can best be achieved by converting electricity into hydrogen via electrolysis, a process that is also called "power to gas". Hereby, hydrogen can serve as a link combining the electricity, traffic and heating sector into one energy market. This paper presents the process chains of different power-to-gas paths, including different transformation technologies, which it evaluates with regard to their suitability for applications, the optional methanation step including the necessary production of CO_2, distribution options and geological storage options as well as end-user applications. Finally, the use of hydrogen and methane in transportation and reconversion to power are compared from the economic point of view.

Introduction

The impact of a fossil-based energy supply as well as the progressing scarcity of resources have already initiated a transition to a renewable energy system. For economic and technological reasons, this transition is based mainly on photovoltaic cells and wind turbines, both of which are characterized by volatile, weather-dependent power production. The worldwide in 2013 newly installed capacity of wind and photovoltaic power systems amounted to 34 GW [1] and 37 GW [2], respectively, and these values are expected to rise exponentially. Despite their ability to produce electric energy without consuming fossil resources, the inherent issue of these technologies is their dependency upon the weather, which leads to fluctuating power production. Hence, with an

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increasing share of renewables in the total power mix, the demand for storage technologies will increase. For example, in Germany a demand of 70 GWh for short-term storage (5 h) and 7.5 TWh for long-term storage (17 days) is predicted for the case of 80% renewable energy production in the electricity generation sector [3]. For this purpose, chemical energy carriers facilitate long-term storage with a high energy density and low storage costs.

The production of these chemical energy carriers using electric power during peak power production periods is termed "power to gas". The key technology for this concept is electrolysis, where electric energy is used to split water into hydrogen and oxygen.

In addition to large-scale long-term storage, power-to-gas facilitates the connection of the power sector to other energy sectors, i.e. heat and fuel supply. Electrolysis itself can help to integrate fluctuating power sources by providing grid services, such as balancing power, which may offer an additional source of income [4]. Even though power-to-gas offers a feasible solution in terms of energy storage and the integration of renewable energy, the efficiency and economic potential of this technology must be assessed in order to ascertain its competiveness compared to conventional fossil-based technologies and compared to other storage options.

In Germany, three alternative power-to-gas routes are currently being discussed (cf. Fig. 1) [5]:

- Use of hydrogen from renewable power (RPH) in a dedicated infrastructure for applications which require hydrogen, i.e. fuel-cell-based transportation and industrial processes.
- Direct feed-in of RPH into the natural gas grid with regard to the maximum allowable H_2 concentration.
- Methanation of the produced H_2 with CO_2 and subsequent feed-in of the renewable power methane (RPM) into the natural gas grid in unlimited quantities.

In this paper, the different technologies in the power-to-gas process chain are described together with related potential end-users. Based on this, a technological and economic assessment of the three routes in relation to the end-users is presented.

Water electrolysis

The conversion of electric into chemical energy is the core element of each power-to-gas concept and is performed in the process of water electrolysis. By applying an electric potential to two electrodes, water is split into its components hydrogen and oxygen, which are formed at the cathode and anode, respectively. In addition to the two electrodes, an electrolyzer is composed of an electrolyte, which is capable of conducting ions, and a diaphragm, which is an electric isolator and keeps the evolving gas streams separate in order to avoid a flammable mixture.

Electrolyzers in power-to-gas applications have special requirements:

- High efficiency to avoid unnecessary energy losses
- Highly dynamic behavior to follow the fluctuating power input of renewables
- Very low minimal load to allow for stand-by mode with low energy consumption
- Ideally, the ability to produce hydrogen at elevated pressure to reduce energy demand and investment costs for compressors
- Long lifetime and low investment costs to allow for cheap hydrogen production

Different types of electrolyzers can be distinguished according to their utilized electrolyte. Among these are alkaline water electrolysis with a liquid alkaline electrolyte, acidic proton exchange membrane (PEM) electrolysis with a proton-conducting polymer electrolyte membrane, and high-temperature electrolysis with a solid oxide electrolyte [6]. The respective technical principles as well as their characteristics will be described in the following subsections.

Alkaline water electrolysis

Alkaline water electrolysis has been commercially available for several decades with modules up to 2.5 MW_{el} and operating pressures up to 30 bar [7]. The electrolyte consists of aqueous potassium hydroxide with a concentration of

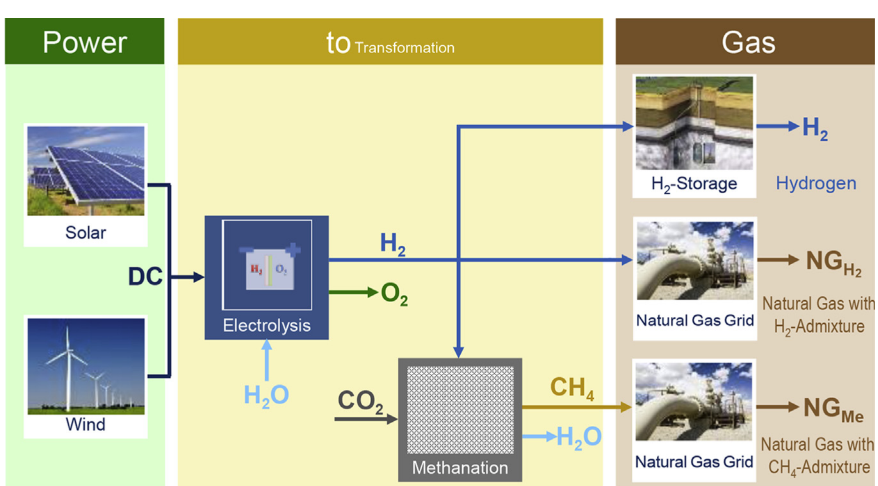

Fig. 1 – Principle of power-to-gas concept [5].