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Power-to-gas in electricity markets dominated by renewables

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HIGHLIGHTS

- Power-to-gas plants are not profitable under current market conditions.
- There are currently not enough hours with sufficiently low electricity prices.
- To become profitable, power-to-gas plants need higher revenues and lower costs.
- An optimistic future scenario shows that power-to-gas plants can become profitable.

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ABSTRACT

This paper analyses the feasibility of power-to-gas in electricity markets dominated by renewables. The business case of a power-to-gas plant that is producing hydrogen is evaluated by determining the willingness to pay for electricity and by comparing this to the level and volatility of electricity prices in a number of European day-ahead markets. The short-term willingness to pay for electricity depends on the marginal costs and revenues of the plant while the long-term willingness to pay for electricity also takes into account investment and yearly fixed operational costs and therefore depends on the expected number of operating hours. The latter ultimately determines whether or not large-scale investments in the power-to-gas technology will take place.

We find that power-to-gas plants are not profitable under current market conditions: even under the most optimistic assumptions for the cost and revenue parameters, power-to-gas plants need to run for many hours during the year at very low prices (i.e. the long-term willingness to pay for electricity is very low) that do not currently exist in Europe. In an optimistic future scenario regarding investment costs, efficiency and revenues of power-to-gas, however, the long-term willingness to pay for electricity is higher than the lowest recently observed day-ahead electricity prices. When prices remain at this low level, investments in power-to-gas can thus become profitable.

1. Introduction

As part of their policies to reduce the emissions of greenhouse gases, many governments want to replace fossil energy systems by systems strongly based on renewable energy [1]. This transition coincides with several economic and social challenges. In electricity systems it creates a particular challenge due to the fact that generation from the renewable sources wind and sun is intermittent because it is related to weather conditions, while the electricity system requires a permanent balance between inflow and outflow (the so-called energy balance). An increasing supply of intermittent generation, hence, requires more flexibility within the system. At the same time, conventional fossil fuel power plants – currently the main providers of flexibility in many electricity systems – will be less available in future systems dominated by renewable energy. Such systems will therefore have a large demand for flexibility from other sources.

One option that could provide flexibility in a renewable energy dominated system is power-to-gas (PtG). In this technology, electricity is used to split water into hydrogen and oxygen using an electrolyser. PtG can offer three types of flexibility to the electricity system: flexibility with respect to time, location and end-use.

The time flexibility of PtG is that it is able to adapt the timing of using electricity and producing hydrogen. If a PtG plant is equipped with a facility to store the hydrogen, the timing of the production process can be fully adapted to the fluctuations of the electricity prices, while the storage ensures that the hydrogen can be delivered to the market at times the customers prefer this or when the prices of this gas are most beneficial.

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The location flexibility of PtG is that it enables alternative locations for electricity production by possibly reducing the energy transportation costs. Instead of transporting electricity produced by, for instance, offshore wind farms through an electricity grid, the electricity can be transformed into hydrogen close to the wind farm and transported directly to the consumers using ships or pipelines. Further conversion of the hydrogen into methane could allow usage of the already existing natural gas grid, which means that hardly additional transportation costs have to be made. Since high-voltage electricity grid lines are very capital intensive, this can lead to significant reductions in transportation costs of renewable energy, especially when it is generated at remote locations far from demand centres and distances are large.

The end-use flexibility of PtG is that it can be used to supply users other than electricity consumers with renewable energy without the need for these users to transform their own energy systems. Examples are the industrial and transportation sector. For this, the generated hydrogen can be used directly but could also be further converted into another substance such as methane, methanol or ammonia.

In this paper, we focus on the time flexibility of PtG. This flexibility may contribute to the need for extra flexibility in an electricity system with high shares of intermittent renewables. PtG can offer two types of time flexibility: it can serve as a real electricity storage technology where the produced hydrogen is reconverted back to electricity when required or as a demand side response technology where PtG becomes a flexible electricity consumer.

In the first time-flexibility option, PtG can be compared to other electricity storage technologies such as batteries, pumped hydro storage (PHS), flywheels or compressed air energy storage (CAES). PtG is able to store large amounts of electricity for a very long time, making it suitable for seasonal electricity storage. For this to be profitable, the spread between electricity prices in summer and winter needs to be sufficient to cover the investment. Although seasonal storage does not seem to be economically feasible in the near future, it could become very important in a fully renewable power system in the future. Heide et al. [2], for example, studied the storage needs in such a future power system based on 100% wind and solar power and concluded that the large need for storage can only be provided by a combination of PHS and PtG with underground hydrogen storage in salt caverns.

In the second time-flexibility option, PtG can be compared to other power consumers that can be flexible such as organised charging of a pool of electric vehicles or power-to-heat. Instead of using the hydrogen to generate electricity again, it is sold to the industrial or transportation sector. It is generally concluded that direct selling of hydrogen is economically much more beneficial than reconversion back to electricity due to the high revenues for hydrogen that can be achieved compared to those of electricity generation (e.g. [3–6]). Demand side response technologies can profit from low electricity prices during times of high (renewable) energy supply and low demand and avoid buying electricity at very high prices during times of low supply and high demand. Most power consumers need a stable supply of electricity, which means that it is costly for them to adapt to changing electricity prices in the short term. A PtG plant, however, can be operated in a flexible way, although additional investments are needed in the form of hydrogen storage to buffer the fluctuating production of hydrogen, which make the plant more expensive. Another factor making flexible operation of PtG more costly is the fact that it results in a lower equipment amortization: the available capacity is not fully utilized and needs to be expanded to be able to produce the same volumes in a flexible way. The business case of flexible operation of a PtG plant, therefore, depends on a trade-off between the lower electricity prices on the one hand and higher investment costs on the other hand per unit of hydrogen produced. For flexible PtG operation to be profitable, there need to be a sufficient number of hours in which the electricity price is sufficiently low.

In this paper we investigate to what extent PtG is a feasible option for providing time flexibility to the power system as a demand side response technology. Hereby we focus solely on the conversion of electricity into hydrogen (power-to-hydrogen). We analyse the market conditions (i.e. electricity prices) under which PtG is able to operate economically. This means that we analyse the maximum electricity price a PtG plant operator is willing to pay in case the investment in the installation (including storage facility) has already been made (short term) as well as when the investment still needs to be made (long term). Next, we explore the feasibility of these maximum prices under current and future electricity market conditions, taking into account the existence of other options for flexibility in the electricity system.

Operation of PtG plants in electricity markets has already been investigated by a large number of different studies (e.g. [5,7–9]). The contribution of our paper is that we develop and apply new economic metrics to assess the economic feasibility of PtG, which have not been used before in this field of research. Instead of calculating the hydrogen production costs, we perform a reverse analysis in which the price of hydrogen is fixed and the willingness to pay (WTP) for electricity is calculated. The WTP is then compared with the level and volatility of current European electricity prices in day-ahead and intraday markets to determine whether or not large-scale investments in the technology will be feasible. Our methodology allows for a thorough investigation of PtG plants in (future) electricity markets and puts the general thought that PtG plants can profit from low electricity prices in perspective. This approach enables us to explore systematically the economic potential of PtG in future electricity markets dominated by renewables.

The structure of the paper is as follows. In chapter 2 we describe the methods that are used. Chapter 3 presents the data that are used for the analysis: we describe the technology PtG and its current costs and revenues and we give an overview of the electricity system in four European countries (Germany, France, the Netherlands and Denmark) that differ significantly in their power system characteristics (including power generation portfolio, market structure, interconnection and electricity prices). Chapter 4 gives the results of the analysis and shows the maximum electricity prices a PtG plant operator is willing to pay and the feasibility of these prices for current as well as future market conditions. Chapter 5 finally discusses the results and concludes.

2. Method

Our methodology to assess the business case of PtG consists of two steps. First, we evaluate the costs and revenues of this technology and determine the maximum electricity price a PtG plant operator is able and, hence, willing to pay. In a second step, the feasibility of these maximum electricity prices is evaluated. The two-step procedure is first carried out for the current situation and afterwards for the future when the PtG technology is further developed and the electricity system contains higher shares of variable renewables.

2.1. Willingness to pay for electricity

To determine the willingness to pay (WTP) for electricity it is important to differentiate between the short-term and the long-term. In the short-term – when the plant has already been built and is operational – an operator only looks at the marginal costs and revenues to decide whether or not he will buy electricity during a specific hour to operate the plant. Besides electricity, water is the only feedstock of a PtG plant. The short-term WTP for electricity (in €/MWh) is therefore determined only by the costs for water (in €/kg H_2), the revenue of the hydrogen (in €/kg H_2) and the power consumption of the electrolyser (in MWh/kg H_2), following Eq. (1):

$$electricity\quad WTP_{short-term} = \frac{(revenue\quad H_2{-}costs\quad H_2O)}{Power\quad consumption\quad electrolyser} \tag{1}$$

The power consumption of the electrolyser depends on its efficiency, which is usually defined as a percentage using the higher heating value (HHV) of hydrogen. Eq. (2) shows how the power