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# The future role of Power-to-Gas in the energy transition: Regional and local techno-economic analyses in Baden-Württemberg

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## HIGHLIGHTS

- Techno-economic potential for Power-to-Gas in Baden-Württemberg, Germany, to 2040.
- Federal state and four different model regions analysed at high resolution.
- High residual loads by 2040 in the north-east imply high PtG potentials.
- Gas network restricts hydrogen feed in and requires upgrade to methane.
- Existing $CO_2$ sources are abundant but not located near to the potential PtG plants.

## ARTICLE INFO

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## ABSTRACT

This paper analyses the potential of the Power-to-Gas (PtG) concept in Baden-Württemberg (BW), south west Germany. A macroeconomic analysis shows that a cost-covering operation of PtG for hydrogen production is first possible under our assumptions in 2030. Previous model-based analyses for Germany identified locations, mainly in north-west Germany, where these plants could achieve these full load hours and thus be economical in the future energy system by 2040. Importantly, although some short-term storage devices (batteries) are installed in BW in this scenario, no PtG plants are seen at the level of the transport network. A more detailed analysis for BW at the municipality level develops residual load profiles for individual 110 kV transformers and municipalities. A very large increase in the residual load profiles in the north-east of Baden-Württemberg by 2040 is encountered, suggesting a requirement for network strengthening and local storage, including PtG, in this area. Four very different and representative model regions are further analysed, whereby only Aalen, a region with large wind potentials in the north east of BW, is identified as having significant potentials for PtG by 2040 (between 69 and 155 MWel). The current restrictions for injecting hydrogen into the gas network (2–10% by volume) mean that these PtG plants would have to incorporate a methanation step in order to upgrade and feed in SNG. The generation of SNG on a local level is therefore expected to be an option by about 2040, if the development of renewable energy generation proceeds as quickly as expected in the current energy-political scenario explored here. The existing $CO_2$ sources for methanation are not located in the vicinity of the expected PtG plants, so that a $CO_2$ separation from the air and/or a liquefied transport could be most economical. Further work is required to consider the local energy infrastructure, especially electrical and gas distribution networks.

## 1. Introduction

The continued expansion of renewable energy technology (RET) capacities and generation presents significant challenges for the energy system. Germany already generates 30% of electricity with RETs in 2016 [1], including around 50 GW of wind (on- and offshore), about 7 GW of bioenergy and 40 GW and over 1 million photovoltaic (PV) plants [2], whereby around 98% of these PV plants are connected to the low voltage distribution networks [3]. The low energy density of renewable energy resources means that they are typically exploited in a

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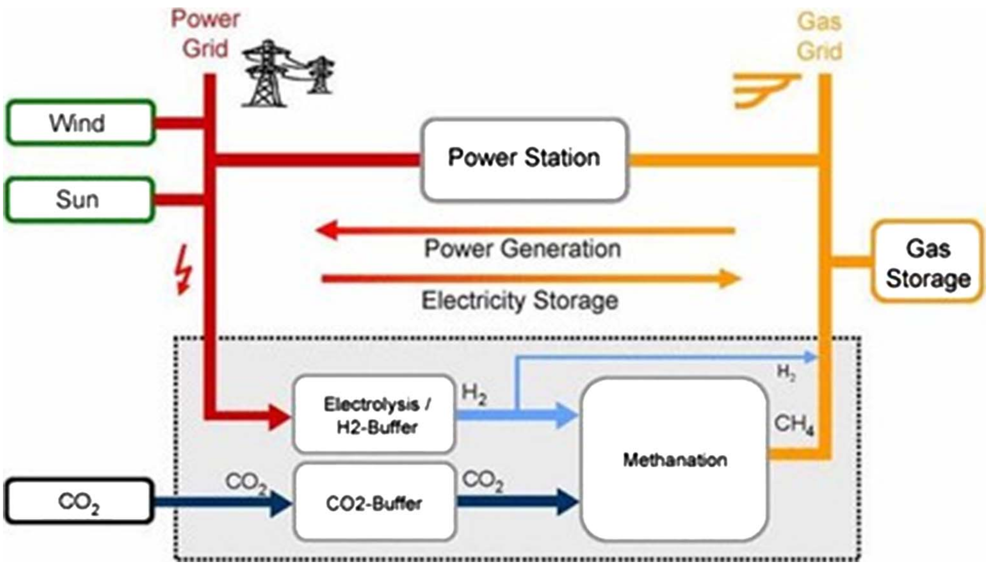


**Fig. 1.** Schematic of Power-to-Gas processes [72].

decentralised way, compared to the historically centralised electricity system. Some RETs, such as hydropower and bioenergy [4], enable the decoupling of energy supply and demand and are thus suitable for demand-oriented flexible operation. Other supply-oriented RETs such as wind and solar technologies are subject to strong spatial and temporal fluctuations, which means so-called integration measures are required in order to successfully integrate them into the energy system. These include network expansion and strengthening, flexible operation of existing power plants and infrastructure, smart grid approaches, and increased storage capacities.

One of the storage options that has gathered increased attention in recent years is sector coupling. This is the idea that previously distinct sectors such as mobility and industry, as well as energy vectors, such as heat, power and gas, should be integrated [5]. Whereas conventionally these sectors and vectors were considered in isolation, through their coupling it is possible to exploit existing and future flexibilities within the energy system. Power-to-Gas (PtG) is one such approach that couples the power and gas sectors, which had previously only been coupled in one direction, i.e. from gas to power in gas-fired power plants (Fig. 1). The generated gaseous chemical energy carrier can be stored for long periods as hydrogen or methane within the existing gas transport and distribution infrastructure and employed across all end-use sectors when required for heat, power and/or electrical applications, or as a feedstock in the chemical industry. The regional use of PtG promises to result in a significant reduction in the otherwise necessary power grid expansion on all levels (cf. [6]). In addition, the coupling of sectors thus enables the use of regenerative gases for heat supply, which is significantly more cost-efficient than very ambitious thermal insulation measures, e.g. according to the Integrated Energy and Climate Concept (IEKK, section 4.1, cf. [7]). The PtG concept is illustrated in Fig. 1 below, which shows how excess RET electricity generation is utilized to generate methane and/or hydrogen.

By utilizing excess electricity generation from RETs, hydrogen can be produced through electrolysis (Eq. (1)).

$$H_2O(l) \xrightarrow{\text{electrolysis}} H_2(g) + O^{2-}(g) \quad (1)$$

The currently permissible upper limit for the hydrogen concentration in the German gas network is 2–10% by volume (cf. Section 4.6), whereby the lower limit is dictated by the presence of filling stations or large consumers downstream in the distribution network [8]. Due to this limit, methanation is often carried out in order to obtain the gas quality that is necessary for feeding into the gas network, i.e. synthetic natural gas (SNG, cf. [9,10]). The educt gases hydrogen ($H_2$) and carbon dioxide ($CO_2$) can be catalytically converted into methane ($CH_4$) and water ($H_2O$) by means of a variant of the Sabatier process, as shown in Eq. (2) [11].

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O \quad (2)$$

These two processes are distinguished in the remainder of this paper by referring to Power-to-Hydrogen (PtH) or Power-to-SNG (PtSNG) respectively.

Based on the literature review in Section 2, the main objective of this paper is to analyse the potentials for PtG (including PtH and PtSNG) in Baden-Württemberg based on the current energy concept of the Federal state government [12]. This is achieved by a combination of different techno-economic methods of model-based energy system analysis, as presented in the following sections. The novelty thereby lies in the decentralised analysis of a whole region and the detailed examination of four case studies (model regions), as well as possible sources of $CO_2$. The work presented here was undertaken in the context of the BWPLUS project 'Power-to-Gas concepts with high social acceptance for an efficient and flexible storage and energy infrastructure for the integration of renewable energies in Baden-Württemberg' in the period 2013–2016, for details refer to the acknowledgements.

The paper is structured as follows. The subsequent section presents a literature review of previous research on PtG. Then Section 3 presents a macroeconomic analysis of the PtG technology in the context of electricity markets, deriving key parameters for the following analysis. Section 4 then presents the analysis of the PtG potentials in Baden-Württemberg, before Section 5 discusses the results and the method. The paper closes with a summary and conclusions in Section 6.

## 2. Literature review

This section gives a brief overview of relevant literature on PtG. For a review of PtG plants for stationary applications, the reader is referred to Gahleitner [13]. More recently, Götz et al. [14] reviewed the technological and economic aspects of three water electrolysis technologies for PtG, namely alkaline electrolysis, polymer electrolyte membrane (PEM) electrolysis and solid oxide electrolysis. Whilst the former is the most economical technology, the authors see future potentials for both of the other two technologies. They also highlight the suitability of biogas plants for providing $CO_2$ for PtG plants, due to their highly distributed nature and the relatively small gas flow rates.

Many contributions assess the PtG technology with technical, economic and/or environmental criteria. For example, Gillessen et al. [15] model PtG systems in combination with battery storage to achieve autonomous off-grid energy systems based on a cost-minimisation

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