Applied Energy 218 (2018) 192–198

Contents lists available at ScienceDirect

Applied Energy

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

Energetically-optimal PEM electrolyzer pressure in power-to-gas plants

Geert Tjarks[a], Andrej Gibelhaus[b], Franz Lanzerath[b], Martin Müller[a,*], André Bardow[b], Detlef Stolten[a,c]

[a] Forschungszentrum Jülich GmbH, Institute of Energy and Climate Research, IEK-3: Electrochemical Process Engineering, Germany
[b] RWTH Aachen University, Chair of Technical Thermodynamics, Germany
[c] RWTH Aachen University, Chair of Fuel Cells, Germany

HIGHLIGHTS

- Efficiency of power-to-gas systems is mainly influenced by electrolysis overvoltages.
- The pressurized operation up to 20 bar reduces the total energy demand.
- Pressures > 20 bar increasing losses through permeation and lowering efficiency.
- Temperature-swing adsorption with recirculation reduces losses of gas drying process.
- In order to achieve the highest efficiency, each current density has an optimal operating pressure.

ARTICLE INFO

Keywords:
Hydrogen production
Hydrogen drying
Pressure operation
Polymer electrolyte membrane (PEM)
Hydrogen storage
System efficiency

ABSTRACT

Hydrogen production from renewable electricity in power-to-gas concepts is promising for future energy storage systems since hydrogen offers high energy density and can be used emission free. Economically viable power-to-gas applications require high efficiency and thus low specific energy demand of the hydrogen production. Energy is required for hydrogen production via water electrolysis, but also for gas conditioning. Gas conditioning includes mechanical gas compression to a defined storage pressure and gas drying to purify the raw hydrogen. The energy demand of gas conditioning can be reduced by operating pressurized electrolyzers. However, pressurized operation increases the energy demand of the electrolyzer. To determine the optimal operating pressure of the electrolyzer, the overall power-to-gas process has to be considered. In this paper, the energy demand of the overall power-to-gas plants is optimized considering compression and temperature swing adsorption (TSA)-drying of hydrogen. It is shown that an optimum pressure for each operating condition in the electrolyzer in relation to the efficiency exists. This optimal operating pressure depends on the current density in the stack and the hydrogen storage pressure. When operating the system with load adapted operating pressure efficiencies between 55% and 73% for the whole power-to-gas plant can be achieved.

1. Introduction

Hydrogen is considered a promising energy carrier for future energy storage systems [1]. This is due to the high energy density of compressed hydrogen and its emission free utilization [2,3], for example in fuel cells. The emission free production of hydrogen is also possible with water electrolysis powered by electricity of renewable energies. The produced hydrogen can be used directly for pressurized storage or as feed stock for synthetic fuels like methane [4]. The production of methane has to consider an additional production step and therefore a reduced efficiency of the complete process [5]. For the direct use of the produced hydrogen a subsequent compression has to be considered for the validation of the complete process, which is the scope of this paper. In addition to alkaline electrolysis, polymer-electrolyte-membrane (PEM) electrolysis has acquired an important role in hydrogen production in power-to-gas applications in recent years [6,7]. The economically and environmentally favorable use of renewable energy in power-to-gas technologies requires high efficiency and thus low specific energy demand of the hydrogen production [8]. Aside from the energy demand entailed in hydrogen production via water electrolysis, further process steps for gas conditioning are part of power-to-gas applications [7]. These steps include mechanical gas compression to a defined storage pressure and gas drying for the purification of the hydrogen produced [9].

---

[*] Corresponding author.
E-mail address: mar.mueller@fz-juelich.de (M. Müller).

https://doi.org/10.1016/j.apenergy.2018.02.155
Received 27 September 2017; Received in revised form 22 February 2018; Accepted 23 February 2018

The specific energy demand of the gas conditioning depends on the temperature and pressure of the hydrogen produced. In particular, the pressure of the produced hydrogen is an important design parameter, since the electrolyzer can be operated at a defined pressure level. To reduce the energy demand of the gas conditioning process, enhanced pressure levels in the electrolyzer are preferred [10]. Therefore, commercial electrolyzers are operated at pressure levels of up to 80 bar [11]. Suermann et al. have shown that the overvoltages apart from the current are dominated by the cell temperature and the influence of the operating pressure on the performance is low [12]. However, from a thermodynamic point of view the enhanced pressure levels reduce the electrolyzer efficiency due to the additional pressure-volume work and the increasing mass losses due to hydrogen and oxygen permeation through the membrane [13]. The dependence of hydrogen and oxygen permeation through perfluorosulfonic acid (PSFA) membranes on temperature, current density and operating pressure has been analyzed by Trinke et al. [14,15].

In order to determine the optimal pressure level of the electrolyzer, the whole process chain of power-to-gas plant must be considered. Recently, Bensmann et al. [16] showed that the energy demand of gas drying has a large impact on the energy demand of the whole process. To reduce these losses their analysis thus identified optimal pressure levels of the electrolyzer of up to 52 bar. Bensmann et al. considered pressure-swing adsorption (PSA) for gas drying leading to high energy demand due to hydrogen losses in the regeneration of the adsorber bed. Furthermore, the results reported by Bensmann et al. are based on a fixed operating point of the electrolyzer. Since the efficiency of the complete process is dominated by electrolysis, further investigation at different operating points of the electrolyzer is necessary.

In this paper, we investigate the specific energy demand of power-to-gas plants, considering hydrogen production with electrolysis, gas drying and gas compression. For gas drying thermal or temperature swing or pressure swing can be used [17], we consider temperature-swing adsorption (TSA), since it is thermodynamically more efficient for low adsorbate concentrations in the feed stream as shown in [18]. Thus, the TSA significantly reduces the energy demand for drying. Based on this, the system performance is analyzed for different storage pressures and operating points of electrolyzers. Based on the results, energetically optimal electrolyzer pressure levels for an efficient operation of the power-to-gas plant are presented. For this purpose, each process step is modelled to calculate the specific energy demand dependent on the pressure level. Afterwards, the process steps are combined to receive the specific energy demand of the complete process chain.

2. Modeling the hydrogen production process

For calculating the energy demand, a model is generated; calculations are conducted for varying pressure levels, operating points and storage pressures.

2.1. System

The system layout of the power-to-gas plant consists of three process steps: electrolysis, gas drying (condensation and adsorption drying with regeneration) and compression (see Fig. 1). The hydrogen storage is modelled as an ideal sink with constant pressure. In the following, we describe the modeling of the three main process steps in more detail.

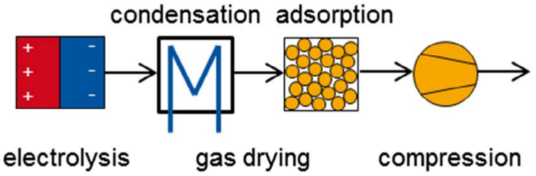

Fig. 1. System layout of the power-to-gas plant.

2.2. Electrolyzer

The model of the electrolyzer provides the specific energy demand of hydrogen production at a defined pressure and operating point. The specific energy demand includes the energy required for the ideal production of hydrogen and that for losses arising from electrolysis. The model corresponds to the characteristics of a PEM electrolyzer. The operating temperature is set to 80 °C. The operating point can be selected at current densities between 0.5 and 3 A cm^{-2}, while the cathodic pressure level can vary between 2 and 50 bar. The anode pressure is held constant at 2 bar. To calculate the specific energy demand, only the stack power is considered. It is assumed that the energy demand of other system components such as pumps and heaters is small compared to the energy demand of the stack [19,20]. This can be achieved by a stack design with a small pressure drop. The specific energy demand of the stack results from the polarization curves and the losses from permeation over the membrane.

The polarization curve describes the relationship between the cell voltage U_{ele} and the current density i. Since the current density directly corresponds to the production rate in accordance with Faraday's law, the polarization curve gives a correlation of the electric power and the production rate. For a constant operating temperature (here: 80 °C), the polarization curve depends only on the operating pressure. The modeling of the polarization curve is based on the model presented by Schalenbach [21]. The cell voltage U_{ele} results from the Nernst voltage U_{ner} and the overvoltages of the electrolysis reaction, embodied in Eq. (1):

$$U_{ele}(i) = U_{\mathrm{ner}} + \eta_{act} + \eta_{ohm} + \eta_{con} \tag{1}$$

The overvoltages are represented by η_{act} (activation overvoltage), η_{ohm} (ohmic losses) and η_{con} (concentration overvoltage). It is assumed that an appropriate cell design guarantees sufficient supply of water. In that case, concentration overvoltages are negligible in the analyzed operating range. Ohmic losses result from the ionic resistance of the membrane and of the cell components and their contact resistance. For this model, the membrane thickness is set to 200 µm, corresponding to a commercially available Nafion 117 membrane. The activation losses result from the applied catalyst and its characteristics. The relevant parameters for the model are determined by internal measurements at Forschungszentrum Jülich and by a comparison with results from Ayers et al. [22]. With a deviation of one percent, the simulated polarization curves correspond to the state of the art.

The calculated polarization curves for different pressure levels of the electrolyzer are shown in Fig. 2.

The permeation of the generated gases over the membrane leads to a loss in the amount of hydrogen produced. A direct reduction occurs as hydrogen permeates to the anode side. A further reduction results from

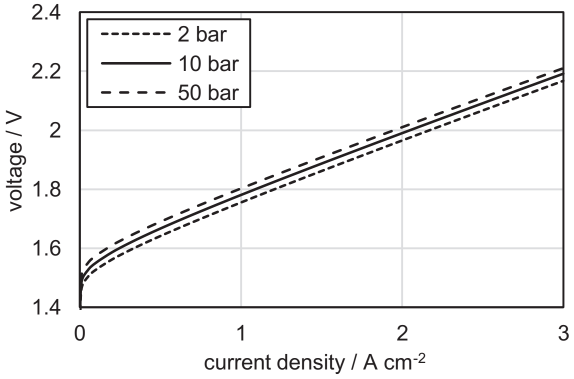

Fig. 2. Calculated polarization curves for different pressure levels of the electrolyzer.