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PALE:

**P&D LABORATORY
ALKALINE ELECTROLYSER TEST BENCH
FOR HIGH PRESSURE AND TEMPERATURE**

Final Report 2015 --- public version

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Zusammenfassung

In dem P&D Projekt PALE wurde von Nitidor, Italien, nach Vorgaben von Empa eine massgefertigte Pilotanlage für alkalische Elektrolyse bei hohen Temperaturen und Drücken (z.B. 85°C, 30 bar) entwickelt und an der Empa in Betrieb genommen. Dieser Prototyp überbrückt die Kluft zwischen Industrieanwendungen und wissenschaftlichen Laborexperimenten im Bereich alkalischer Elektrolyse. Mithilfe zusätzlicher Analysegeräte können optimierte Zellgestaltungen sowie neu entwickelte Komponenten und Materialien wie Separatoren und Elektroden unter realistischen Bedingungen getestet werden.

Der Aufbau einer solchen Pilotanlage stellte sich als technische Herausforderung heraus, da sich die Skalierung auf Laborgrösse bezüglich Druck- und Füllstands-Regelung des Systems als sehr kompliziert herausstellte. Auch wenn einige Probleme bezüglich der Gasanalysen sowie des präzisen Regels der Prozesstemperatur verbleiben, so ist dieser Pilot-Elektrolyseur doch einzigartig, in der Schweiz und Europa sind keine weiteren Elektrolyseure dieses Prototyps bekannt. Die damit erhobenen Daten können helfen, den technischen Stand der alkalischen Elektrolyse voran zu bringen, insbesondere im Hinblick auf die Speicherung unregelmässig auftretender erneuerbarer Energien. Die Verwendung von Wasserstoff als Energieträger für die Thematik „Power to Gas“ (direkt oder nach Weiterverarbeitung z.B. zu Kohlenwasserstoffen) ist auch im Zusammenhang mit der Senkung CO₂ basierter Emissionen und der Schweizer Energiestrategie 2050 von hoher Bedeutung und Wichtigkeit.

Résumé

Dans le projet P&D PALE, un système pilot pour la production d'hydrogène par électrolyse alcaline à haute température et pression (p.ex. 85°C, 30 bar) a été développé et installé à l'Empa. Cette unité prototype remplit le gap entre l'application industrielle et la recherche au laboratoire. En simulant des conditions réelles, l'électrolyseur pilot met à disposition des outils de caractérisation supplémentaires qui permettent de déterminer la performance d'architecture de cellules optimisées et de composants et matériaux nouveaux, p.ex. membranes de séparation de gaz et électrodes.

La construction d'un tel électrolyseur s'avère d'être un défi technique considérable, puisque la réduction en taille complique la gestion de la pression et les routines qui contrôlent le niveau de remplissage dans le système. Bien que plusieurs difficultés associées avec l'analyse des gaz et avec le contrôle de température restent non-résolues, cet électrolyseur pilot reste le seul instrument de ce type en Suisse et en Europe. Des données acquises avec ce système aideront à avancer la technologie d'électrolyse alcaline, en particulier en vue de stockage d'énergies renouvelables intermittentes. L'utilisation d'hydrogène comme porteur d'énergie (soit avant, soit après conversion p.ex. en hydrocarbure) est aussi d'importance majeure dans le contexte de réduction de l'émission de CO₂ et de la stratégie énergétique Suisse 2050.

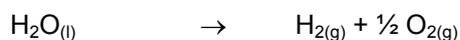
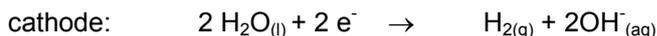
Abstract

In the P&D project PALE, a custom-made pilot alkaline electrolyzer working at high temperature and pressure (e.g. 85°C, 30 bar) was developed at Nitidor, Italy, according to specifications from Empa, where it was also set up. This prototype unit bridges the gap between industrial application and laboratory-scale research on alkaline electrolysis. While simulating realistic conditions, the pilot electrolyzer features additional characterization tools which allow assessing optimized cell designs and newly developed components and materials such as separators and electrodes.

Building up such a pilot electrolyzer turned out to be technically challenging, as downscaling complicates the pressure management and leveling routines in the system. Although several issues remain with gas analyses and accurate control of the process temperature, this pilot electrolyzer is the only one available of this kind in Switzerland and Europe. Data collected with this device will help to advance the alkaline electrolysis technology, in particular with respect to storage of intermittent renewable energy sources (power to gas). Application of hydrogen as an energy carrier (directly or after conversion e.g. to hydrocarbons) is also of high importance in the context of reducing CO₂ emissions and of the Swiss energy strategy 2050.

Initial position

Although the process of water electrolysis has been known for over two hundred years [1, 2], it is gaining increased attention as a means of energy storage from strongly fluctuating renewable sources in periods of excess energy production. Due to long-term experience with electrolyzers over 30 years, their robustness, and the absence of noble metal catalysts, high pressure alkaline water electrolysis is a mature technology [1] to produce CO₂-neutral hydrogen on a MW scale. The process is based on the following reactions:



To become cost-efficient and to decrease the total cost of hydrogen produced by this technique, the system and material costs need to be decreased, while the efficiency of the alkaline electrolysis process should be increased. This may be achieved by improving the electrolysis cell itself, the system design, the power electronics, and the balance of plant.

In order to improve the electrolysis cell, a pilot electrolyzer working at industrially relevant conditions is essential. Only under such conditions, e.g. in 25wt% KOH at 85°C and 30 bar pressure, can the influence of optimized cell designs, newly developed electrode and separator materials and their (micro-)structure be studied. While Lurgi-Zdansky type high-pressure alkaline electrolyzer systems with more than 500 bipolar cells and a maximum production of 760 Nm³/h hydrogen have been operated at industrial sites for decades [3], small-scale systems with extended characterization capabilities are not available so far.

Goal of the project

In this applied pilot and demonstrator (P&D) project a pilot electrolyzer working at 25wt% KOH, 85°C and 30 bar pressure was set up at Empa. The electrolyzer was used to test separators developed in the complementary EU project ELYGRID (No. 278824) and a *swisselectric research* project (Alkaline Electrolysis for Renewable Energy Generation: Membrane Development for Industrial Electrolyzers) to assure their stability for safe operation also in larger electrolysis systems. Stack tests were performed with the aim to characterize the separators' durability and their influence on efficiency, cell voltage and power consumption of the alkaline electrolysis process.

Procedure / method

Build-up of a pilot electrolyzer at Empa

As pilot electrolyzer systems with extended characterization capabilities are not available on the market, an **equipment specification** for an electrolysis test bench was developed and a pilot electrolyzer was ordered from Nitidor, Italy. The pilot electrolyzer was commissioned in October 2014. As a prototype, however, the system is very delicate and needs close supervision during operation. Malfunctions and system instabilities which are prone to lead to leakages or flooding of parts in the gas lines with electrolyte lye still do not allow regular operation resulting in frequent repairs and downtimes.

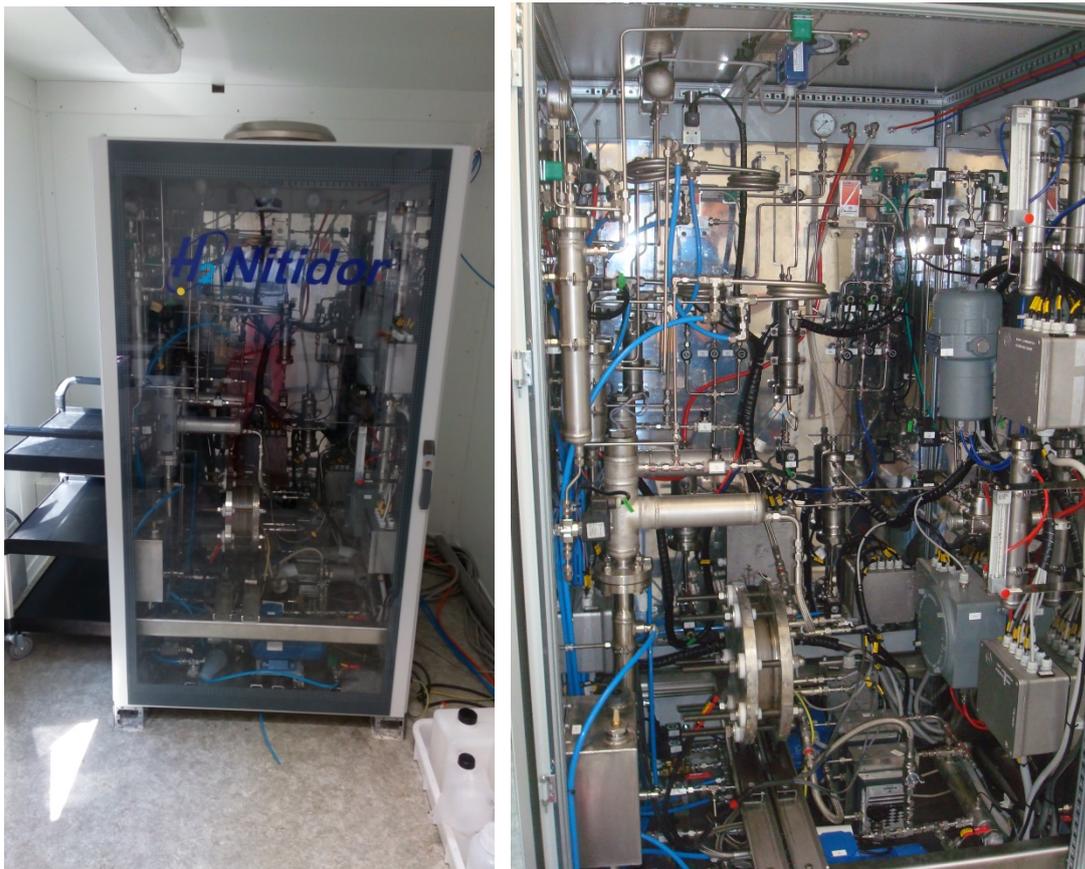


Figure 1 Main electrolysis unit VOLTIANA at Empa, Dübendorf: outside/ inside view.

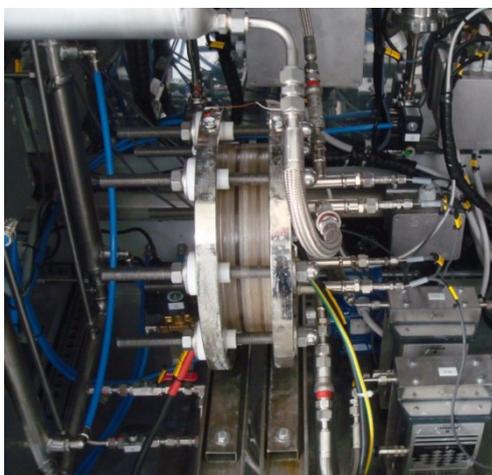


Figure 2 Electrolysis stack in VOLTIANA with 7 cells of 100 cm² each.

Current—voltage measurements

Current—voltage analyses are widely applied to characterize electrochemical systems. This approach is also feasible for industrially relevant zero-gap electrolyzers [4] operating at increased temperature and pressure. The cell potential E_{cell} is generally expressed by [1, 2, 5, 6, 7]:

$$(1) \quad E_{cell} = E_{rev} + |\eta_a| + |\eta_c| + \Delta U_{\Omega}$$

Here, $E_{rev} = \frac{-\Delta G_f}{zF} = E_c^0 - E_a^0 = 1.23V$ is the reversible cell potential (with the Gibbs free energy ΔG_f , the number of electrons involved in the reaction z , the Faraday constant F , and the equilibrium potentials of the cathode and anode reaction E_c^0 and E_a^0); η_a and η_c are the anodic and cathodic overpotentials, and $\Delta U_{\Omega} = i \cdot R_{\Omega}$ includes the ohmic potential drop through the whole system including the cell. The energy dissipation related to the ohmic system resistance R_{Ω} comprises the ion transport in electrolyte and separator (including the formation of gas bubbles and effects of concentration polarization) as well as all other ohmic resistances from system components like electrodes, current collectors, and wiring [1, 2, 7].

With the exception of E_{rev} , all factors on the right-hand side of Equation (1) depend on the current density. The electrode overpotentials comprise both charge transfer (η_{trans}) and concentration (η_{conc}) overpotentials, the latter of which are usually deemed negligible [4]. The charge transfer overpotential η_{trans} is correlated with the current density i according to the Butler-Volmer equation [6]

$$(2) \quad i = i_0 \left[\exp\left(\frac{\alpha_a zF}{RT} \eta_{trans,a}\right) - \exp\left(-\frac{\alpha_c zF}{RT} \eta_{trans,c}\right) \right]$$

where α_a, α_c are the anodic and cathodic charge transfer coefficients ($\alpha_c = 1 - \alpha_a$), R is the ideal gas constant, and T the process temperature. For high overpotentials, this equation can be transferred into the Tafel equation (e.g. for $\eta_{trans,a} > 0$):

$$(3) \quad \eta_{trans,a} = \frac{RT}{\alpha_a \cdot zF} \cdot \ln \frac{i}{i_{0,a}}$$

with the Tafel slope $b_a = \frac{RT}{\alpha_a \cdot zF}$.

Accordingly, the cell potential is expressed by [4, 8, 9, 10]

$$(4) \quad E_{cell} = E_{rev} + b_a \ln \frac{i}{i_{0,a}} + b_c \ln \frac{i}{i_{0,c}} + \Delta U_{cell}$$

with the Tafel slopes b_a, b_c and current density factors $i_{0,a}, i_{0,c}$ for anodic and cathodic processes.

This is also shown schematically in a conceptual current—voltage curve constructed and published in 1978 [7]/ 1979 [4], which is still the basis for more recent introductions and reviews to alkaline electrolysis [2]. In practice, the cell voltage – current density correlation is often reported to permit the use of a

linear approximation for higher current densities according to $E_{cell} \approx E_{crit}^* + i \cdot R_{\Omega}$, where E_{crit}^* is the apparent decomposition potential [6], and the overpotentials are included in $E_{crit}^* \approx E_{rev} + |\eta_a| + |\eta_c|$ as constant values.

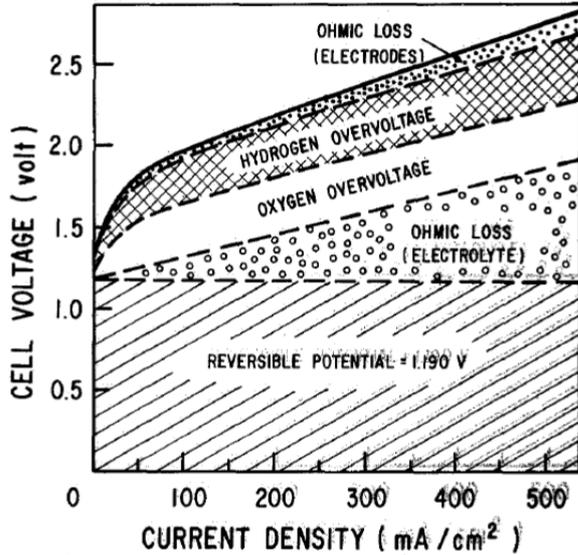


Figure 3 Typical current—voltage characteristics introduced in 1978 [7]/ 1979 [4].

Measurements at constant-current conditions

State-of-the-art industrial electrolyzers are designed to operate at constant-current conditions without repairs at the stack level for several decades. The long-term stability of newly developed components, e.g. separators, is of paramount importance. While the chemical stability can be assessed by ex-situ experiments (e.g. as described in our recent publication [12]), experiments under realistic operating conditions are essential to determine their gas separation properties as well as their electrochemical and mechanical stability at operating conditions.

Results / findings

Current—voltage measurements acquired with VOLTIANA

In order to characterize different newly developed and state-of-the-art separators, current—voltage curves were acquired at different gas pressures and cell temperatures using **standard Ni electrodes**. In November and December 2014, six different types of separators prepared at Empa (B41, B44, B48), by our ELYGRID project partner VITO (V27, V37), and commercially available from Agfa (Zirfon utp) were characterized in the new pilot electrolyzer VOLTIANA in stacks of **7 cells** (comprising 7 separators of the same type). On each type of separator, electrolysis experiments and measurements were performed during one work day using **33 wt% aqueous KOH** solutions as electrolyte.

A first experimental series aimed at characterizing the individual separators by means of current-voltage curves, as shortly reported in the PALE Annual Report 2014. In order to record comparable results for the different separators, constant pressure and temperature conditions of 30 bar and 85°C were targeted. A constant pressure of 30 ± 1 bar was obtained during all measurements. The recorded temperatures, however, varied both during one measurement and between the different separators. Despite the short measurement time of few minutes, the maximum temperature varied up to 5°C during one measurement. For the different stacks, temperatures between 83°C and 97°C were recorded. Uncertainties concerning the process temperature are very problematic when comparing the cell voltage of different stacks. For an increase in outlet temperatures from 75°C to 85°C, the cell voltage decreased by approximately $\Delta U = 17$ mV ($\Delta U/\Delta T \approx -2$ mV/°C) in a reference measurement. This has a strong influence when comparing current—voltage curves measured for different stacks, as accurately controlling the process temperature is not easy. The influence of **system pressure** is not that strong. The cell voltage at $\approx 85^\circ$ and at 400 mA/cm^2 increases from 2.089 V at 10 bar, to 2.095 V at 20 bar, and to 2.110 V at 30 bar. Around the target pressure of 30 bar, pressure variations of few bar therefore do not significantly influence the cell voltage. As a result of the different process conditions, it is difficult to relate the current—voltage curves determined for different stacks to the influence of separators. Voltage differences of up to $\Delta U \approx 30$ mV as determined at 400 mA/cm^2 for the different stacks could be insignificant when considering the large variation in temperature conditions, the influence of current ramping, and the sensitivity of the voltage drop to these variations.

Measurements at constant-current conditions acquired with VOLTIANA

In order to assess the gas separation properties of separators as well as their electrochemical and mechanical stability at operation conditions, long-term measurements at constant-current conditions are of high importance. In a first test, a stack of **commercial Zirfon membranes (7 cells)** was installed and measurements were performed in **33 wt% KOH** during working hours over two weeks (2015-03-16 to 2015-03-27) targeting **30 bar** pressure at **85°C**. Due to frequent instabilities in operation of the pilot electrolyzer VOLTIANA (potentially leading to flooding of the gas lines), the system could not be operated unattended. Overnight the electrolyzer was therefore put on standby. For the constant-current measurements, the pressure regulation was set to a range of ± 2 bars in order to avoid frequent depressurization events (which entail flushing the gas analysis lines with nitrogen for safety reasons as described above).

While it generally took 1 to 2 h to ramp up the electrolysis system to 400 mA/cm^2 and ≈ 30 bar during one day of operation, 5 to 7 h were required to obtain reasonably **constant temperature** conditions

due to thermal losses to the environment. Even after this **equilibration time**, the temperature of $72 \pm 7^\circ\text{C}$ at the heater decreased to $55 \pm 5^\circ\text{C}$ at the inlet of the stack. This may indicate that the electrolyte did not reach the heater temperature at the given flow rate. The stack outlet temperature on the H_2 side reached values between 85°C and 90°C , which remained constant within $\pm 2^\circ\text{C}$ after equilibration. The outlet temperature on the O_2 side, however, featured significantly lower temperatures. The **temperature difference** for the different electrode compartments became more and more pronounced, mainly the outlet temperature of the O_2 side accounting for this variation. This temperature difference evolved from $\Delta T \approx 7^\circ\text{C}$ at the first to $\Delta T \approx 25^\circ\text{C}$ at the fifth measurement day, when the recorded oxygen outlet temperature even took values well below the heater temperature. The outlet temperature on the O_2 side further showed oscillations similar to those of the system pressure and the KOH flow.

After each change in current density, the cell voltage featured spikes which overshoot the **cell voltage** after an equilibration time of around 10 min by up to 0.1 V. Longer measurement times, however, are expected to entail a temperature increase corresponding to a decrease in cell voltage, which needs to be taken into account. Interestingly, such a temperature increase was not always, and sometimes the measured gas outlet temperatures even decreased towards the end of one measurement day (especially for the oxygen side). At equilibrated conditions, a cell voltage of 2.03 ± 0.01 V was determined for alkaline electrolysis in 33 wt% KOH at 28 ± 2 bars and $88 \pm 2^\circ\text{C}$ H_2 outlet temperature from the current data set.

As described above, the gas purity could only be assessed in certain time intervals. In VOLTIANA, gases for analysis are probed from the main production line only after a certain target pressure is reached. After that, the readout of the gas analyzer requires a certain time to flush the lines and obtain stable readings. According to our measurements, this took approximately 10 min in the current conditions. However, as soon as the system pressure exceeded a certain limit and pressure was released to regulate the system, the gas analysis lines were flushed with nitrogen for safety reasons. Depending on the manual adjustments to the flow meters at the gas analysis lines, intervals of up to 50 min were achieved until the target pressure of 30 bars was reached and depressurization and nitrogen flushing were initiated. As a result, reasonable gas analyses reflecting the gases produced could only be obtained periodically. The O_2 content in H_2 was in the range of 0.2 ± 0.1 % throughout the measurements. Due to frequent interruptions of the gas measurements, more detailed observations are not possible from the current measurements.

Discussion / appraisal of the results / findings

System design of pilot electrolyzer (VOLTIANA)

Acquisition and commissioning of the pilot electrolyzer turned out much more complicated than expected. Most problems were related to **down-scaling** an alkaline electrolysis system from industrial into laboratory scale, which makes the handling of liquids and gases at increased temperatures and pressures rather challenging. As a result, intensive work was required at Empa until the system design allowed operation of the pilot electrolyzer VOLTIANA. Although many modifications have been implemented by now, several points could still be improved.

One important topic is the **process temperature**, which needs to be precisely controlled in order to allow scientific conclusions. The KOH temperature of the hydrogen side at the stack outlet is generally used to assess the relevant process temperature. In order to obtain measurements at constant

conditions, this temperature should be directly regulated to a target temperature by the control unit (instead of regulating the heater temperature). In order to avoid overheating of the electrolyte at any point, a maximum heater temperature could be implemented. This is also of importance when daytime and seasonal fluctuations of the ambient temperature play a role, as the setup is situated in a container unit without air-conditioning or heating. Accurately controlling the process conditions is difficult also due to the **stack design**. In the current setup, the KOH flow is divided into a cathode and an anode line. From these inlets, branches lead to one side of each single cell. After passing the cells, the electrolyte branches from the different cells are combined again. In this design, only the total electrolyte flow which is pumped through the whole stack is measured. Also the temperature measurements take place in the common electrolyte lines at the stack inlet and outlet. Temperature inhomogeneities within one cell and between different cells are therefore not assessed. Such effects could be quite substantial, as the inlet and outlet cavities for electrolyte branches to the single cell sides are quite narrow (≈ 2 mm in diameter). Constrictions at in- or outlets of the cells, e.g. by the swelling of separators as well as undulations in or warping of the electrodes and current collectors, may thus lead to decreased flow rates through some of the branches in the zero-gap cells, while the flow could be increased through other cells. As a result, the **temperature distribution** within one cell and between different cells may differ significantly. Inhomogeneities in KOH flow and temperature distribution would further influence the distribution of gas bubbles and current density, which could boost inhomogeneities even more.

Another point concerns the **purity of produced hydrogen and oxygen gases**. In VOLTIANA, two separate lines are available for the product gases; the KOH electrolyte from both electrode compartments, however, is remixed after liquid—gas separation and pumped back to the stack. This design is common for industrial electrolyzers. As a result, gases dissolved in the electrolyte are transported back to both sides of the cells, where they can be released leading to decreased gas purities. As a result, the gas purities may also depend on the electrolyte pump speed in such systems. To avoid gas impurities from the electrolyte, **two separate electrolyte cycles** (with two electrolyte pumps) could be installed. Of course the gas purities are also influenced by the **stack**, where **leakages** may occur through the separators or through sealants. Apart from the development of efficient separator materials, the quality of cell frames, sealing bands, compacting pressure and the accuracy in cell assemblage are important parameters in this context.

Maintaining a constant **KOH concentration** by refilling with water is also an important issue. In the current design, the electrolyte from both electrode sides is remixed after passing the stack. The molar content of water in the electrolyte therefore decreases with the production of hydrogen, which can be assessed by Faraday's law $n = \frac{Q}{F} \cdot \frac{1}{z}$ with electric charge Q , Faraday constant F , and valency z . In constant-current conditions, $Q = I \cdot t$ (current I , time t). Accordingly, the production of H_2 and the consumption of water would amount to ≈ 0.75 mol/h/cell in VOLTIANA at 400 mA/cm^2 ($A = 100 \text{ cm}^2$, $I = 40 \text{ A}$). For a stack of 7 cells, this would correspond to hydrogen production of ≈ 2 NI/min (at 273.15K, 101325 Pa) and a water consumption of ≈ 94 ml/min. In VOLTIANA, the electrolyte solution is replenished with water when the buoyancy sensors fall below a certain level in the gas—liquid separators. This procedure is expected to entail variations in KOH concentration and OH^- conductivity, which are not taken into account for the current measurements. The refilling procedure for water would become even more significant if two separate electrolyte cycles would be implemented: per mol H_2 , 2 mol H_2O would be consumed on the cathode side, while 1 mol H_2O would be produced at the anode. In order to maintain constant electrolyte concentrations, their conductivity could be measured in order to refill H_2O or KOH, or the refilling procedure could be based on the current applied to the system.

Despite many unforeseen issues and delays with the pilot electrolyzer VOLTIANA, measurements with

different types of separators could be performed. After further modifications to the system, **constant-current experiments** were conducted **over a time span of two weeks**, even if electrolysis had to be switched off overnight due to safety concerns.

Current—voltage measurements

Taking into account the large variations in temperature conditions and the sensitivity of the voltage drop to these variations, differences perceived when comparing different separators are insignificant for the current set of data. This also becomes clear when the ohmic contribution of the separator to the voltage drop is estimated: In absence of a separator, the ohmic contribution of 33 wt% KOH at 85°C (0.707 Ωcm [11]) in a cell with 0.5 mm electrode spacing would result in a voltage drop of $\Delta U = 14$ mV at a current density of 400 mA/cm² ($\Delta U/\Delta T \approx -0.2$ mV/°C at around 80°C [11]). According to zero-bias resistivity measurements, typical separators have resistivities which are ≈ 3 times higher than that of pure KOH lye [12]. As a result, an ohmic contribution of around $\Delta U = 45$ mV is estimated for separators of 0.5 mm thickness at 400 mA/cm² in a first approximation. Typical cell voltages measured for the same conditions are around 2.03 V; the total voltage drop relative to the reversible cell voltage $E_{\text{rev}} = 1.23$ V amounts to around $\Delta U = 800$ mV, which would be mainly related to overpotentials at the standard Ni electrodes.

Also the measurement protocol in terms of increasing the current density is important for meaningful analyses. Due to the nucleation of gas bubbles together with the heat generated from over-voltages at the electrodes, a certain time is required for an electrolyzer to equilibrate at the given operating conditions. The equilibration time depends on both the operating conditions and the electrolyzer geometry, and may range from seconds for small-scale test electrolyzers to hours in larger systems. Due to disturbances of the system, e.g. by gas bubble formation, it is technically difficult to obtain such constant conditions, and longer measurements are required for each point. Nevertheless, optimizations of the stack flow geometry together with improved measurement protocols may allow a more detailed analysis in the future.

Measurements at constant-current conditions

Even if the ohmic contribution of thin separators to the cell voltage and the process efficiency cannot be assessed in detail, the prototype pilot electrolyzer VOLTIANA offers unique possibilities to test the electrochemical and mechanical stability of separators in industrially relevant conditions. Measurements at constant conditions (current density, pressure, temperature) are therefore a main purpose of the pilot electrolyzer. Systems like VOLTIANA are the only available means to assess the influence of the separator on the gas purity during electrolysis at increased temperature and pressure, even if contributions from the electrolyte flow and from the sealing of cells also contribute to the results. The results obtained with VOLTIANA were also of significant interest for two other projects on alkaline electrolysis (EU project ELYGRID, *swisselectric research* project). In this context, the microstructural and transport properties of separators were investigated before and after electrolysis by zero-bias resistivity measurements, capillary flow porometry, and microscopy. As significant differences in stability or transport properties were not observed, the newly developed separators are deemed suitable for alkaline electrolysis under industrial conditions. Nevertheless, pressure and temperature regulation as well as the gas analysis in VOLTIANA need to be improved in order to allow continuous measurements in the future.

Conclusions, outlook, next steps after closure of the project

Our experiments have revealed the alkaline electrolysis process to be limited by electrode processes in the current conditions. The cell voltage and thus the process efficiency is strongly temperature dependent; operation at high temperatures is thus of advantage.

Fast current increases with 2 to 3 mA/sec have turned out to disturb the voltage measurements in current—voltage analyses. While short measurement times may be advantageous not to disturb the temperature profile during one measurement, they were found to result in overestimated cell voltages, which need a certain time to equilibrate. Apart from influencing the accuracy of current—voltage measurements, this behavior is of great importance with respect to fluctuating renewable energy sources. In order to balance the electricity grid, electrolysis systems should ideally be able to directly take in the variable current produced by renewable energy sources. According to our measurements, however, strongly fluctuating currents significantly increase the cell voltage, thus decreasing the efficiency. This behavior may be related to the fact that alkaline electrolysis is based on the production of gases at liquid—solid interfaces between electrolyte and electrodes. In this system, gas bubbles are prone to adhere to the electrochemically relevant interfaces. In order to be transported away from the cell, they have to locally replace the liquid electrolyte.

In future experiments, the performance of electrodes will be increased in order to improve the process efficiency, e.g. by introducing electrodes with higher surface areas and improved catalyst materials for the different reactions. These electrodes will then be characterized by current—voltage experiments (using standard separator materials). For more accurate measurements of the cell voltage, the current will be increased in steps followed by sufficient equilibration times. Special care will be taken to regulate constant temperatures for all measurements.

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Dissemination

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