

FUTURE DEVELOPMENTS OF THE PHOTOVOLTAIC TECHNOLOGIES IN GERMANY AND THEIR CONSEQUENCES IN THE POWER NETWORK STABILITY, THE SYSTEM SECURITY AND THE DEMAND OF CHEMICAL LONG-TERM STORAGE

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ABSTRACT

The Energy Transition in Germany fosters significant changes not only on the requirements for transmission networks but mainly in the conditions of the electricity distribution grids as well. These grids must not only distribute electricity to the consumer anymore. They must also be able to handle and transport more and more decentralized electricity generated in photovoltaic systems. The planned expansion of the photovoltaic systems until 2050 (when there is the target to supply 80% of the German electricity with renewable energy sources) is a key driver for the expansion of the networks and storage technologies, as this energy will be predominantly connected to the distribution network. By the end of 2013, 35GW of electricity generated from solar technologies (corresponding to 100%) were connected to the electricity distribution network. As part of the energy transition the construction of additional facilities will increase significantly. That means that the capacity of the distribution network will not be enough anymore to transport the surplus electricity generated from renewable energies. For this reason, storage technologies must be purposefully used to optimize the network operation. By using chemical long-term storage (power to gas) it could be possible to achieve a significant load removal and with it, a reduction in the net expansion demand [1, 2].

INTRODUCTION

With an increasing share of renewable energy sources, particularly photovoltaic electricity, the demand for electricity storage will also increase significantly. Even today, the electricity generated with photovoltaic technologies has reached such a magnitude that can lead to situations in which they can affect the entire power supply critically. For instance if there was a large oversupply of wind and solar power, this must first be integrated and distributed in the local network. This problem can be solved by chemically storing surplus electricity

in the form of hydrogen and thus temporally decoupling the generation and consumption of electrical energy. For that reason large energy conversion and storage capacities will be needed in the future. This applies to both: short-term storage, as well as daily, weekly or even seasonal energy storage. The storage must provide a high performance and capacity preferably over a very long period of time, while having only small losses and being economical to operate.

For this purpose the chemical storage of electrical energy in the form of hydrogen rises as a promising alternative. Within this context the Brandenburg University of Technology Cottbus-Senftenberg (BTU-CS) carries out research to investigate a hydrogen storage power plant for generating and having an intermediate storage of hydrogen exclusively from renewable sources. The BTU-CS has the know-how and the necessary technical resources for the research and development of the next generation pressure electrolysers. Within this context, the Hydrogen Research Center has been erected. In this center a 58bar pressure electrolysis prototype was installed to investigate the dynamic response of such plant types when exposed to intermittent load. A good dynamic behavior is a prerequisite for the use of the electrolyzer as a grid control component in the concept of the hybrid, hydrogen-based power plant system. Conventional electrolysis plants operate at a system pressure of about 30bars, whereby the generated hydrogen has to be compressed for its subsequent distribution using a compressor. Conventional electrolysers work at a system pressure of ca. 30bars, from which the hydrogen must be compressed with the help of a compressor for its subsequent distribution. However, in the prototype system, a system pressure of hydrogen of about 58bar is implemented to increase the overall efficiency of the system. Another focus of this study is to extend the load range. Thus, even small load peaks can be absorbed by the system whereby the annual full load hours of the system can increase significantly and the hydrogen from the

surplus solar energy can be economically produced and stored. In addition, the capability of storing the product gases and their impact on the control dynamics and the performance of the electrolyzer are investigated. In order to carry out theoretical research of the industrial alkaline electrolysis process, a single cell test rig was additionally designed and built to perform concrete research on electrochemical processes.

OVERVIEW

Efficiency of photovoltaic facilities in Germany

In the last years, the nominal efficiency of commercial wafer-based photovoltaic modules increased approximately 0.3% points per year to reach almost 16-20%. Each square meter of module provide a nominal power output of ca. 160W. Highly efficient modules reach up to 200W. The nominal efficiency of thin-film modules currently stands at 6-11% with its highest values being 12-13%. Photovoltaic facilities do not work with the nominal efficiency of the module because in real operation there are additional losses taking place. These effects can be described by means of the performance ratio. A photovoltaic facility intalled currently would reach in average during the year a performance ratio value of 80-90%, including all the loses through the real operating temperatures, the changing solar radiation conditions, occurring contaminants, pipe resistance and conversion losses of the inverter. The direct current supplied from the modules will be adapted for the net feeding by an alternating current coverter. The efficiency of new photovoltaic coverters is currently at about 98% [3]. In Germany, specific yields of up to 900-1000kWh/kWp can be achieved depending on solar radiation and and performance ratio. Per square meter of solar panel, this corresponds to approximately 150-180kWh. A German average four-person household consumes approximately 4400kWh in electricity, which corresponds to an annual yield of 30m² solar panels with average efficiency. The south-facing, moderately slope roof of a family house has been mathematically simulated and it was found that the energy generated by a photovoltaic system of 20 modules Sufficient could meet the annual electricity needs. For comparison, in the south of Spain or North Africa a specific yield of up to 1,600kWh /kWp could be reached.

Transmission and distribution of electricity generated from solar power

More than 98% of the approximately 1 million photovoltaic systems in Germany are connected to the decentralized low voltage power net and produce electricity to be used in close points. From all the megawatt range power plants in Germany photovoltaics account for only 15% of the total installed capacity. A high density of photovoltaic systems in a determined area of the low-voltage grid on sunny days can lead to the production of electricity surplus when compared to the power requirements by far. Transformers must then feed the excess power back into the medium-voltage network. At very high photovoltaic densities, the substations can reach their performance limits. A uniform distribution of photovoltaic installations via the network sections would significantly reduce the need for expansion. The decentralized, two-

dimensional character of the electricity generated through solar systems complies with a recording and distribution by the existing electricity network. Large photovoltaic power plants or local clusters of smaller plants in sparsely populated areas require the reinforcement of the distribution network and transformer stations and the future development of storage technologies. The further expansion of photovoltaics should be done consumption-based in order to facilitate the distribution of electricity generated from solar power. The generation of solar power is now very easy to plan thanks to reliable national weather predictions. Due to technical reasons, losses and inconsistent weather conditions in Germany, only very few days a year 70% of the installed capacity is achieved in reality. A limitation or down-regulation ("feed-in management") at the level of individual plants to 70% of their nominal power capacity leads to revenue losses estimated by 2-5%. A statutory provision which require this down-regulation for small installations entered into force in 2012 [4]. A balanced mix of electricity generation capacity from solar and wind would be superior and economically development. With an ever increasing performance phototvoltaics could be increasingly taken as a stabilizing control variable. The German Renewable Energy Law (EEG) amendment of the 1st January 2012, fosters the participation of facilities in the low voltage network to manage their energy feed through remote control by the network operator or automatic speed regulation at 70% of the active power [5].

DESCRIPTION OF BOTH PROTOTYPES FOR HYDROGEN PRODUCTION AT THE HYDROGEN RESEARCH CENTER COTTBUS

The Alkaline Electrolyzer Prototype

The alkaline pressure electrolysis prototype has a maximum production capacity of 30Nm³/h of hydrogen and a maximum pressure of 58bar. This test facility is the only one in Germany of this type and magnitude. The table 1below summarizes the most important system parameters of the pressure electrolyzer. The peripheral systems have also been included.

Table 1 Specifications of the 58bar pressurized electrolyzer prototype

| <u>Components</u> | <u>Specification</u> |
|-------------------|--|
| Rectifier | <ul style="list-style-type: none"> • Current range: 0-3000A • Voltage: 52V |

| | |
|--------------------------------|---|
| Stack | <ul style="list-style-type: none"> • Operating pressure: 1-58bar with external pressure vessel • Single cells: 24 • Electrode activation (cathode): VPS-coating • Cell surface of single electrode: 0.44m² • Maximum hydrogen production: 30Nm³/h • DC maximum current: 3000A • Specific energy consum: < 4.5kWh/Nm³ • Rated load range: < 10-150% • Operating Temperature: 75°C • Electrolyte concentration: 28 % KOH |
| Gas cleaning and drying | <ul style="list-style-type: none"> • KOH filters • Catalytic O₂ removal • Adsorber unit for gas drying • Gas quality of the hydrogen produced: 5.0 (99.999 Vol.-% H₂) |
| Storage tank | <ul style="list-style-type: none"> • Storage volume: 5 m³ geometrically • Pressure: 42bar |

The alkaline electrolysis technology provides advantages over the PEM electrolysis due to different factors, including the lower degradation of the electrodes, the technological availability of larger electrode surfaces and the greater electrolysis performance and better resource security by doing away with expensive noble metal catalysts. The electrolysis stack is integrated by 24 individual cells with an area of 0.44m² each. In order to reduce the over-voltage, the electrodes are catalytically activated coated on the cathode side with Vacuum Plasma Spraying [6]. The figure 1 below shows at the top the pressure capsule and the separators for the separation of the product gases.



Figure 1 The 58bar pressurized alkaline electrolyzer prototype

It is feasible that high pressure takes place due to the external electrolyzer pressure vessel that encloses the electrolyzer stack. The figure 2 shows this principle in 3D by illustrating the open pressure vessel. During normal operation the space between the pressure vessel and electrolyzer stack is filled with demineralized water, which is maintained by a special pressure control on the operating pressure of the electrolyzer. Consequently, the differential pressure between the internal volume of the stack and the surrounding volume within the pressure capsule is approximately zero. This construction principle allows the use of Polyoxymethylen (POM) materials for the construction of the stack frame. This is suitable due to the reduced demand on the compressive strength. The differential pressure between the cathode and anode compartments is controlled by the alkaline solution filling levels in the separators. This situation avoids an excessive differential pressure across the diaphragms of the electrolyzer stack caused by the different hydrogen and oxygen volumes produced. Especially during the dynamic operation of the electrolyzer, these pressure controls are subjected to high demands.

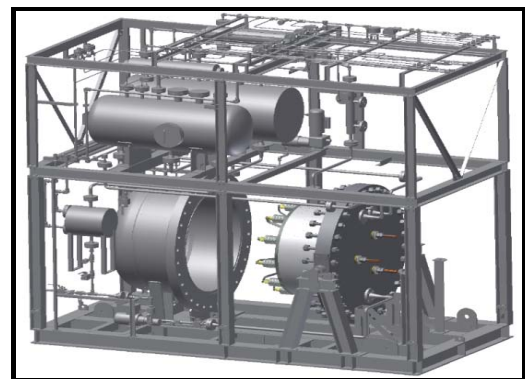


Figure 2 First conceptual 3D-construction layout of the 58bar pressurized alkaline electrolyzer with opened pressure vessel

The Single Cell Test Station

The 30 bar test rig enables, with its variable cellular structures, to carry out research on the pressurized alkaline electrolysis process. In addition, the rig makes possible the study of the widely used cell and spacing configurations in industrial practice. Some of the most important aspects to be mentioned are the zero gap alignment, the capillary gap and the minimum distance configuration. Figure 1 shows the single cell, the vacuum plasma spraying (VPS) electrode and the polyetheretherketone (PEEK) spacer frame. In addition, other suitable materials for the membranes and electrodes should be examined. This situation could allow a reduced lateral diffusion, but also, a mechanical. In addition, in the case of the electrode activation, a high chemical resistance can be shown. More research is still necessary in this regard [7].

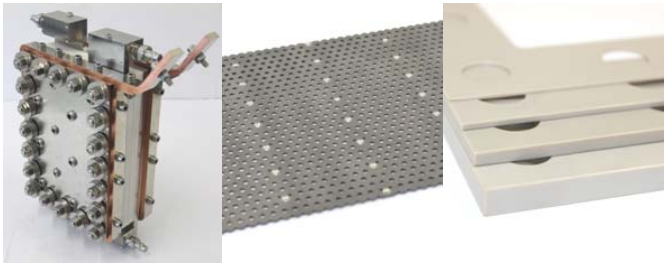


Figure 3 Single Cell, VPS-Electrode, PEEK-Distance frame

In table 2 below the limit or operating parameters of the pilot plant and process acquisition possibilities are presented.

Table 2 Basic system parameters of the 30bar Single Cell Test Station

| System parameter | Operating Range |
|---|--|
| Operating pressure | 1-30bar |
| Gas production | H ₂ 0.2-1Nm ³ /h O ₂ 0.1-0.5Nm ³ /h |
| Elektrolyte flow | 0-2.1m ³ /h |
| Temperature range | 25-120°C |
| Current density | <ul style="list-style-type: none"> Nominal load: 4'000A/m² =100% Constant operation: 6'000A/m² =150% Overload: 20'000A/m² =500% |
| Rated load range | <10-500% |
| Electrolyte concentration | 0-50-wt% KOH |
| Process recording/acquisition possibilities | <ul style="list-style-type: none"> Current measurement Voltage drop on bubble layer Distribution of current density Distribution of temperature Optical process observation |

The research focuses on finding the potentials to increase the efficiency of the alkaline electrolysis process. One approach is to determine the optimized distance between the membrane and the electrode and between the electrode and the end plate by using different membrane and electrode materials. After having found the optimal process-related distance between the membrane and electrodes, the effects of bubbles and fluid dynamics, and the resulting voltage drops within the dispersed liquid-gas mixture can be identified. The bubble size and the flow through the individual cells are dependent on the current-density, the cell temperature, the operating pressure, the electrolyte concentration and the electrolyte circulation.

Based on and through the combination of POM space frames (1, 2, 4, 8 and 30 mm) that have been specially designed for this study, investigations for distances with a step size of 1

mm between 1-15 mm and for 30 mm can take place. Moreover, other topics to be investigated include the influences of different coating processes and materials on the electrolysis process and the energy losses in the electrolytic production of hydrogen. Other topics investigated within the single-cell-test-station by setting different operating parameters (current, operating pressure, system temperature, flow rate and electrolyte concentration) include the industrially available material on the market as well as the test electrode materials and coating options. Hence, it is possible to determine the surplus voltage losses which occur depending on the electrode material used.

ADVANTAGE OF PRESSURIZED HYDROGEN PRODUCTION

When comparing electrolysis and the atmospheric pressure the advantage of the first one is the relatively low plant-engineering effort, based on the entire infrastructure necessary for a power-to-gas system. It is possible for the system to operate without additional compressors due to the process of internal electrochemical compression. At a pressure of about 58 bar, the hydrogen could for instance be fed directly into a standard 43 bar tank or a natural gas pipeline without additional compressor stages. The required energy needed for the mechanical compression is therefore eliminated. The current plant engineering and energy advantage is counterbalanced by the enlarged energy needed to carry out the pressure electrolysis, which manifests itself in a higher reversible cell voltage. It is possible to use the Nemst equation to calculate this increase in cell voltage as a function of system pressure [8]:

$$\Delta V_{rev} = \frac{R \cdot T}{2 \cdot F} \cdot \ln \left[\left(\frac{P_{H_2}}{P_0} \right) \cdot \left(\frac{P_{O_2}}{P_0} \right)^{1/2} \right] \quad (1)$$

Within the Equation (1) ΔV_{rev} is the increase in the reversible cell voltage due to a pressure increase from P_0 to P_{H_2} , R is the universal gas constant, T is the thermodynamic temperature and F the Faraday constant.

If only the compression of the hydrogen side took place this would result to:

$$\Delta V_{rev} = \frac{R \cdot T}{2 \cdot F} \cdot \ln \left(\frac{P_{H_2}}{P_0} \right) \quad (2)$$

Taking into account an electrical charge flow of $2 \cdot F$ Coulomb for the production of a mole of hydrogen, (2) follows for the additional work ΔW from the voltage increase ΔV_{rev} in the production of n moles of hydrogen:

$$\Delta W = Q \cdot \Delta V_{rev} \quad (3)$$

$$\Delta W = n \cdot 2 \cdot F \cdot \frac{R \cdot T}{2 \cdot F} \cdot \ln \left(\frac{P_{H_2}}{P_0} \right) \quad (4)$$

$$\Delta W = n \cdot R \cdot T \cdot \ln \left(\frac{P_{H_2}}{P_0} \right) \quad (5)$$

The same work would have to be done at the compression of hydrogen from P_0 to P_{H_2} in isothermal conditions. For a PEM

electrolyzer operating according to the principle of the one-sided pressure system on the hydrogen side, losses would take place because of the increased hydrogen diffusion through the membrane [9]. The formula (5) describes exclusively the additional work for the pressure build-up caused by the increase of the reversible cell voltage. In addition, irreversible effects must also be considered, which partially have counter-positive effects in terms of cell voltage reduction. These effects include the reduction of the resistance of the electrolyte caused by the smaller bubble diameter of the product gases and better electrode kinetics. Hence, the only way to obtain an accurate assessment of the influence of pressure is by means of measurements obtained on the real pressurized electrolyzer.

The effect of temperature on the voltage of the cell is easy to recognize. According to the temperature dependency of the change in the molar Gibbs energy ΔG as shown on the equations (6 and 7) a voltage reduction of 0.845 mV/K can be expected:

$$\frac{\partial V_{rev}}{\partial T} = \frac{1}{2 \cdot F} \cdot \frac{\partial \Delta G}{\partial T} = -\frac{\Delta S}{2 \cdot F} \quad (6)$$

$$\frac{\partial V_{rev}}{\partial T} = -\frac{163.25 \text{ J} \cdot \text{K}^{-1} \cdot \text{mol}^{-1}}{2 \cdot 96485 \text{ As} \cdot \text{mol}^{-1}} = -0.845 \frac{\text{mV}}{\text{K}} \quad (7)$$

Additional contributions to the cell voltage reduction are caused by increasing temperature resulting from the higher electrolyte conductivity with a lower voltage drop across the electrolyte as well as the lower activation surplus at the electrode surfaces. The measured values in real conditions at the prototypes provide a voltage loss of the single cell in the range of ca. 2 to 4 mV·K⁻¹ at a current density of 0.4 kA·m⁻². Other research works [10, 11] have reported a loss of 2.8 mV·K⁻¹ in the temperature range between 15°C and 65°C at 25 bar and also 0.4 kA·m⁻².

The measurements depending on the temperature also show, that with lower current densities there is an increase of the influence of temperature on the cell voltage.

EFFECT OF PRESSURE ON THE CELL VOLTAGE BASED ON REAL MEASURED DATA OF 58 BAR PROTOTYPES

The pressure effect on the cell voltage achieved by the electrolysis process is relatively low. In addition to the general increase of the cell voltage with increasing current density, it is possible to recognize the tendency that by increasing pressure at constant temperature also the cell voltage increases slightly whereas the cell surplus voltage slightly drops. The unique effects of the pressure influence could not be compared with the current density-cell voltage curves for the investigated pressures at the same temperature. Most of the curves are very close to one another and there are junctions in the course of the curves among themselves. The curves run accordingly in a narrow band where the curves with the lowest and highest pressures and the smallest or largest total voltage are not necessarily shown. To illustrate the size of the influence of a wide range of pressures, the differences between the maximum and minimum measured cell voltage were investigated in the pressure range between 10 and 55 bar at a constant temperature

depending on the current density in each case. From these figures it can be seen that the maximum effect of the pressure on the cell voltage in the range of 10 to 55 bar for all the parameters configurations considered of temperature and current density account for ca. 0.020 V in average per cell. The dependence of the pressure influence with the temperature or the current density cannot be clearly identified. The average difference of the cell surplus tension resulting from the measurement values over the different temperatures accounts approximately for 0.023 V. The graphical representations of the recorded current density-cell voltage characteristics for different pressures at constant temperatures of 50°C and 60°C are shown below.

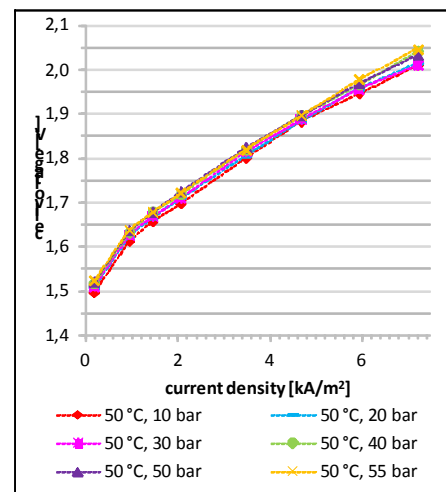


Figure 4 Current density-cell voltage curves for different pressures at 50°C

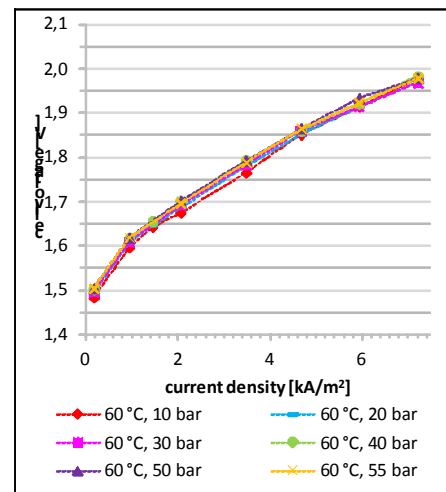


Figure 5 Current density-cell voltage curves for different pressures at 60°C

CHALLENGES OF HYDROGEN STORAGE

High-pressure gas storage has a number of challenges that need to be approached. Besides to safety issues, the effects of the

loading cycle on the tank lifetime need to be addressed [12]. In addition, according to the IEA the high cost of gaseous storage tanks and the energy penalty in compression remain the main problems [12]. Hydrogen has a relatively good energy density when considering its weight. Nevertheless, it has poor energy density when considering its volume when compared vis-à-vis with hydrocarbons. Therefore, hydrogen requires larger tanks to be stored. On the other hand, the energy density by volume can be improved by increasing the gas pressure [13]. When considering large scale compressed hydrogen storage alternatives, geological formations might be a suitable alternative. The underground storage of hydrogen in salt caverns could be used to meet both base and peak load demands such as it does with natural gas [14]. For small scale applications tanks for different pressures are commercially available (e.g. metal tanks with steel/aluminium, tanks made from composite material, fibreglass/aramid or carbon fiber, metal hydride storage tanks, etc.).

CONCLUSION

In order to obtain clearer results regarding the presented work, the experiments carried out have to be repeated and evaluated. For this purpose, the essential measurement points on the single-cell rig must be reproduced and the measured values have to be compared with the already calculated ones. Since the instrumentation of the single-cell test rig allows a higher resolution, more concrete evidence regarding the pressure dependence of the cell voltage and its implications can be derived. In order to provide demand matching surplus energy from photovoltaic systems in Germany and also to store it seasonally, the basic research carried out on Single Cell Test Station and the associated reduction of the general costs for the conversion from electrical surplus energy in hydrogen for chemical storage gain importance. The identified potential for the process control and the interaction of pressure, temperature and current density can provide a significant contribution to the efficient design of alkaline pressure electrolysis systems. Consequently energy could be stored in a more cost-effective way supporting significantly the energy transition in Germany.

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