RESelyser: System Concept for a combined RES-Electrolyser plant with optimised efficiency

Part 1 Review of electrolyser system with special emphasis on the HYSOLAR system

Project RESelyser

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Contents:

Quotes and Literature:

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/2/ e-mobil BW, “Energieträger der Zukunft – Potenzial der Wasserstofftechnik in Baden-Württemberg“, 2012, Kap. 4.1.1.1

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1 The Technique of Hydrogen Production with Alkaline Electrolysis

1.1 Principle of alkaline electrolysis

From cell to block /1/

The technical process with the highest potential for efficient large-scale hydrogen production with electrical energy from renewable sources is the electrolysis of water. It is a long-known method where in an electrolysis cell with two electrodes (negatively charged cathode and the positively charged anode) water is decomposed by electric energy in its gaseous components, hydrogen (cathode side) and oxygen (anode side). Between these electrode a membrane (called diaphragm) is located which prevents a direct mixing of the two gases. Two types of water electrolysis are technically used today, the so-called aqueous **A**lkaline **EL**ectrolysis (AEL), using a mixture of electrically conductive potassium hydroxide solution and water as fluid operating medium in the membrane at than 100°C of operating temperature, and the **P**olymer **E**lectrolyte **M**embrane electrolysis (PEM electrolyser) in which the electrolytic water is supplied on the anode side, and a polymer electrolyte membrane between anode and cathode as the electrically conductive operating medium is used. Due to the use of this membrane in the cell, this kind of electrolysis is called “dry electrolysis”. The operating temperature of the PEM electrolysis is maximum 100°C. Both types of electrolysis are operated with DC power or pulsating DC power.
Figure 1 shows the principle of a single alkaline electrolysis cell. By means of this figure the cells’ function can be simply explained below.

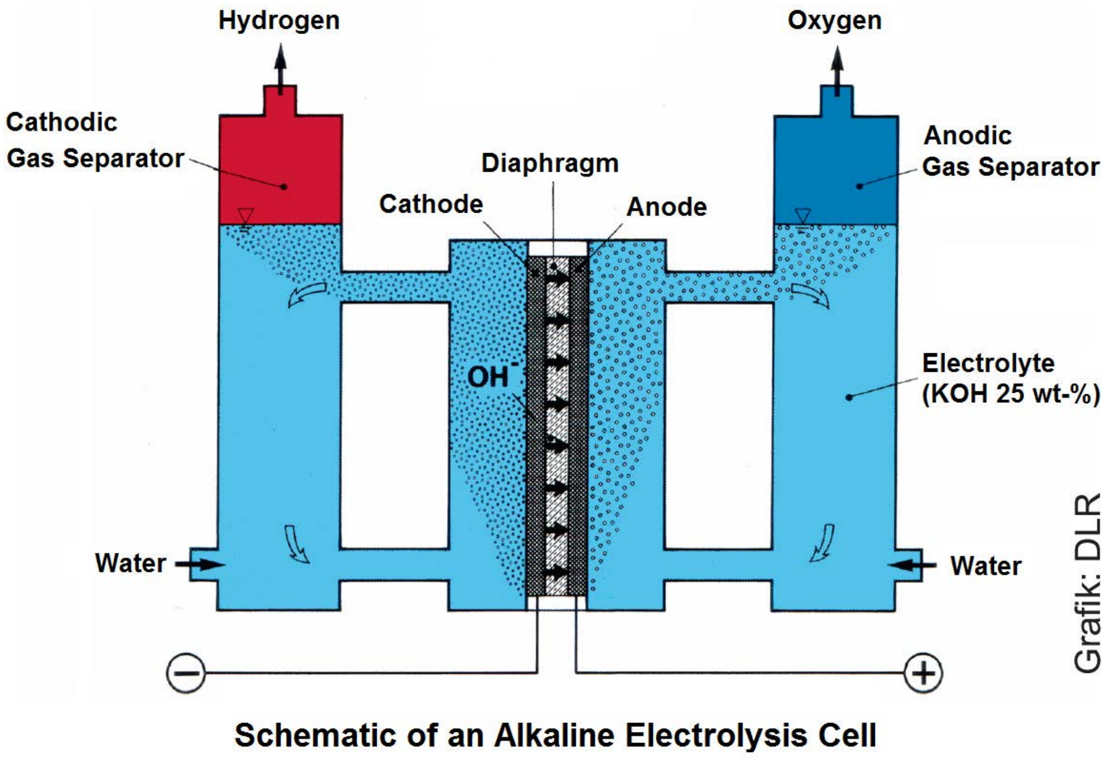

Figure 1: Functional principle of a single alkaline electrolysis cell

A power source is connected to the negative terminal (cathode) of the electrolytic cell and at its positive pole (anode). The cell is filled with a mixture of water and potassium hydroxide solution, the so-called electrolyte. Whenever the voltage of the power source is higher than the so-called electrochemical decomposition potential plus an overvoltage to overcome all the electrical connection resistances of the circuit, an electric current is flowing through the electrolysis cell. A hydrogen molecule is formed on the cathode side in a partial reaction from water molecules releasing an ion (OH_-ion) at the same time. Many gas molecules together form gas bubbles and pearl out from the water phase. The entire electrode surface produces fairly evenly hydrogen gas. As a result the gas content increases quite evenly from the bottom to the top of the electrode surface across the entire width of the electrode. At the cells bottom, the amount of liquid in the cell is high and at the top the foam portion (2-phase mixture of gas and liquid forming foam) is high.

The OH_-ions are transported by the applied operating voltage via the liquid through the diaphragm to the anode. Here they are recombined with hydrogen atoms of the water at the anode to form water again. Thereby oxygen atoms remain which are

also composed at the anode surface to oxygen molecules. Many of these molecules form on the anode side back together oxygen gas bubbles in the electrolyte liquid.
It is produced exactly twice the gas volume of the oxygen side on the hydrogen side.
Chemically this process is expressed as a total reaction like:

Cell reaction: $2\ H_2O(l) \xrightarrow[\text{Elektrolyse}]{} 2\ H_2(g) + O_2(g)$

Water is split by electric current into its gaseous constituents, hydrogen and oxygen.

At both electrodes, the product gases are produced on the front of the electrodes facing towards the diaphragm. To keep the electrical loss resistances are as small as possible, the electrodes are brought close together as possible. The minimum distance between the electrodes can thus be the thickness of the gas separating diaphragm as shown in Figure 1. In order to avoid direct gas production into the diaphragm and, consequently, mixing in thin diaphragms perforated plates are used as electrodes that allow the gases in small gas bubbles on both sides to escape directly to the backside of electrodes into the gas collection chamber. Both gases rise as two-phase mixture and are separated of the liquid in separate gas separators, which may be equipped partially with coolers, too. Pure, cooled and only water vapor saturated hydrogen and oxygen leave the gas separators. If many electrolysis cells are connected in series, the gases are collected in collecting ducts and leave the so-called electrolysis block through common outputs. This basic electrolysis principle is used for both, the non-pressurized electrolysis and for electrolysers with an operating pressure just above 30bar. For testing and in the lower power range electrolysers for pressure operation at 120 up to 200bar were realized and operated successfully. In an alkaline electrolysis system the water must be provided on the hydrogen side, as out of the water first hydrogen is produced and the remaining ions are transported on the oxygen side forming water and gas there..

Elektrolyser cell and electrolyser block /2/

In each electrolysis technology described above, gaseous hydrogen is generated on the cathode and oxygen on the anode side. Via Coulomb's law, the amount of gas produced is directly dependent on the electric charge to the electrolysis cell. To produce one mole of hydrogen (6.02 x 10^{23} atoms) from water a charge amount of 96485C (unit C = Coulomb) is required. The usable amount of charge per electrode area is limited. In today's industrial alkaline electrolysers, which have an electrode area of approximately $3m^2$ for unpressurized operation and less than $2m^2$ for pressurized electrolysis, gas volumes of approximately 2 - $3Nm^3/h$ per cell are produced on the hydrogen side. An increase in the electrode area is impractical or unreasonable for various technical reasons. In the PEM electrolysers the technical development is still in the range of about $1000cm^2$ of electrode area. The simple technical solution to the significantly increase the amount of producible gas per electrolyser is the combination of many electrolysis cells to an electrolysis block. There are two electrical wiring options for a plurality of cells which can form together in a block, the so-called Unipolar Interconnection, where all cells are connected in parallel, therefore the block voltage is equal to the cell voltage and block current is the sum of the individual cell currents, and there is existing the more popular so-called. Bipolar Connection with the serial connection of the cells in which the same block current through all cells and the block voltage is the sum of all single cell voltages. Except for a few special cases, the bipolar electrolysis interconnection of blocks and blocks of fuel cells has prevailed. Figure 2 shows the principle example of an electrolysis block consisting of three individual cells in a bipolar arrangement.

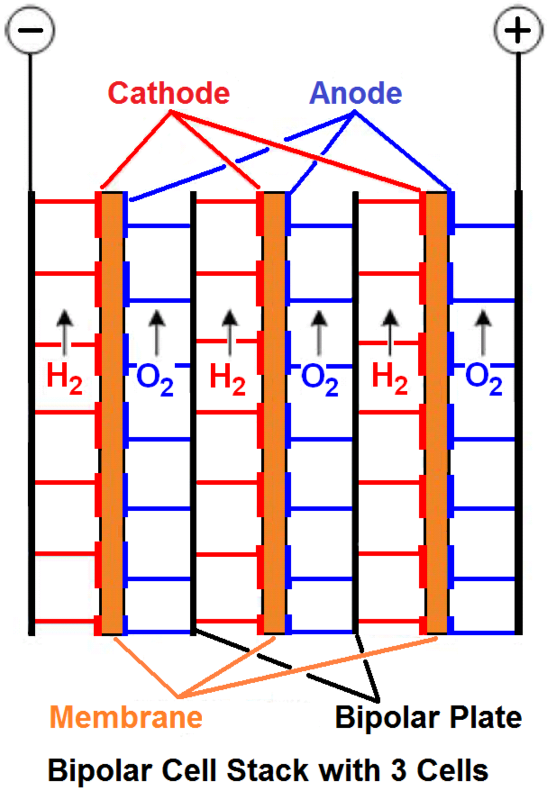

Figure 2: Principle scheme of a 3-cell electrolyser block in bipolar connection; source: A. Brinner, ZSW

The three cells in Figure°2 are stacked back to back with alternating electrical polarity (cathode cell 1 – anode cell 1; cathode cell 2 - anode cell 2; etc.). The highly electrically conductive and at the same time gas-tight connection between the different cell sides of the consecutive cells is ensured by the bipolar plates. In Figure°2, the most important measure to improve an electrolyser is also shown in principle. This is to minimize the gap between the electrodes in one cell. This measure is called zero-gap cell. In Figure°2 the anode and cathode are moved together to the extent that they are separated only by the gas-tight membrane. Since the product gases are produced on the membrane-facing electrodes fronts, and the gases shall not to be intentionally forced through the membrane, the electrodes have holes or slots through which the product gas bubbles can go directly to the backside of the electrodes into the so-called gas collecting volumes. Due to this specific electrode arrangement directly attached to the membrane but with a distance to their corresponding bipolar plates, this distance must be overcome with so-called current interconnectors. It is essential important for the block function that the bipolar plates are electrically well connected to the corresponding gas production electrodes. The current interconnectors can be inserted loosely or firmly connected to bipolar plates

and working electrodes. The method of interconnection varies from manufacturer to manufacturer.

The product gases are collected from the individual cells in common gas collection channels, as shown in Figure°3 in principle, for the 3-cell electrolysis block which is shown in Figure°2.

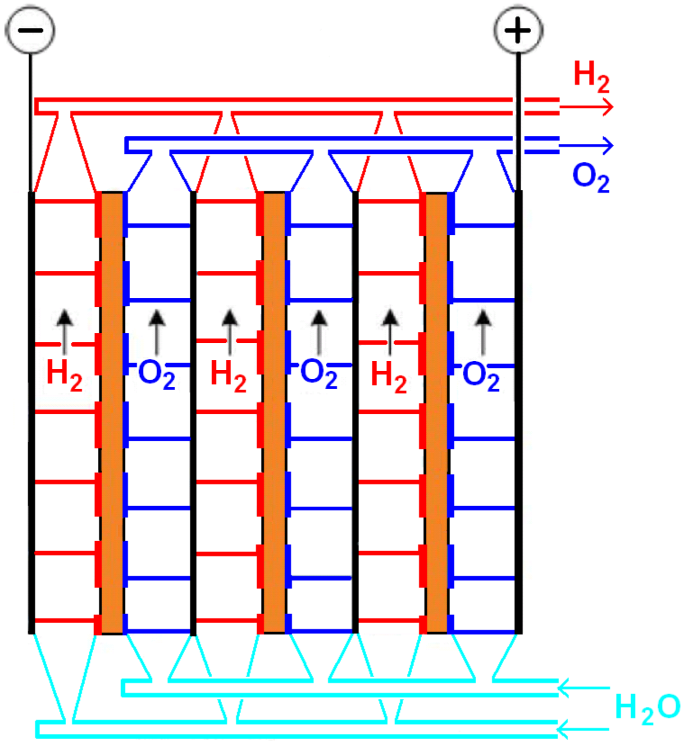

Figure 3: 3-cell electrolyser block with channels for collecting gas and electrolyte; source: A. Brinner, ZSW

At an alkaline electrolyser, the electrolyte (a mixture of potassium hydroxide solution and water) is supplied for the electrolysis process into the individual cells from separate collecting channels on the hydrogen and oxygen side and serves at the same time as a cooling medium, as shown in bottom of Figure°3 in principle.

The collecting channels can be both realized internally in the block as well as an external piping with separate branches into each cell. Both technical solutions are used. In pressure electrolysers only the principle with intra-block collection channels is used so far..

1.2 The technology of alkaline water electrolysis

From block to system /3/

Functional principle of an alkaline electrolyser with natural circulation

The electrolysis block is indeed the central component wherein water is decomposed into hydrogen and oxygen gas, but for proper function it requires a number of peripheral circuits, components and subsystems which fulfil the duties of:

- supply of new electrolyte,
- supply of fresh feed water,
- supply of electric power,
- dissipation of thermal energy,
- collection and separation of the product gas / electrolyte mixtures on both gas sides,
- supply of inert gas and
- electrolyte mixture circulation.

The summary of all subsystems in one functional unit is the electrolyser.
The addition of the functions:

- gas drying,
- monitoring of operational functions,
- monitoring of the apparatus and operational safety and
- control of the electrolysis operation

extends the electrolyser to an electrolysis system, which will be discussed in the next chapter.

The separation of functions between the electrolyser and electrolysis system makes sense, since some system functions can be fulfilled for several electrolysers in an electrolysis system simultaneously or jointly with common subsystems.

Figure°4 shows the cross-sectional drawing of an atmospheric electrolyser with external electrolyte collection channels and single-cell gas discharge into a common gas separator. Although the drawing shows only a very simple electrochemical apparatus which was developed several decades ago, it is - made from modern

materials with modern methods and equipped with catalytically active electrodes - still a low-cost hydrogen generator with high energy efficiency.

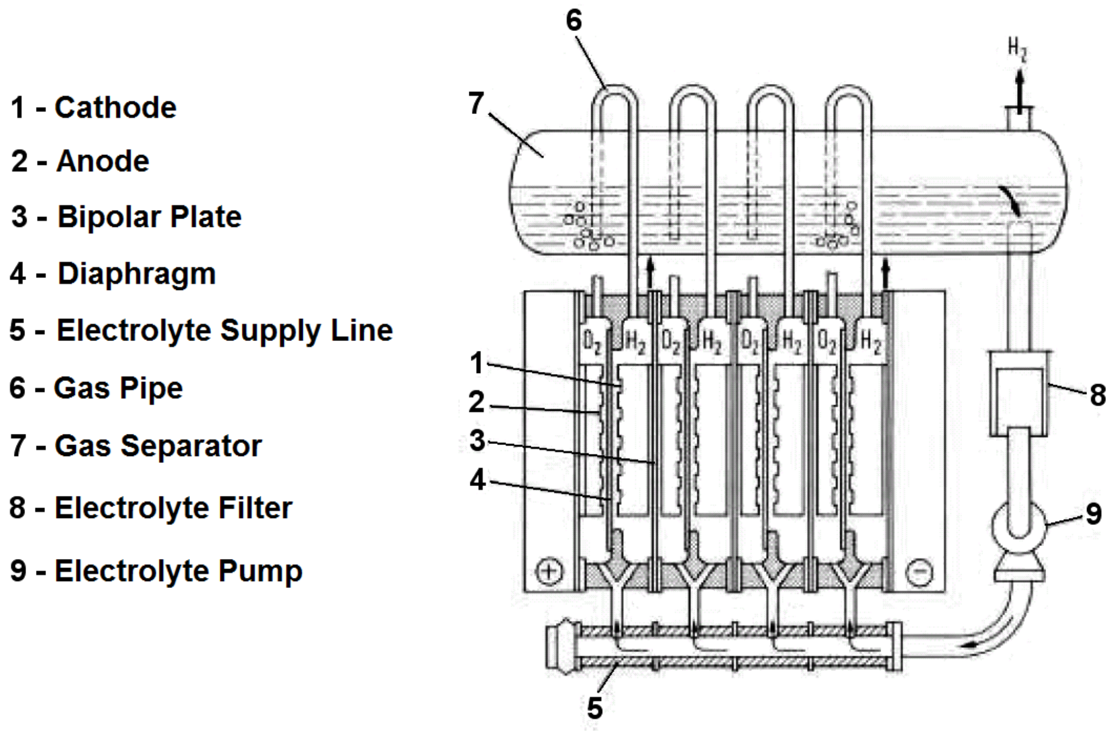

Figure 4: Atmospheric alkaline electrolyser basing on the so-called Oerlikon-principle; source: E. Hausmann, Krebskosmo

The electrolyser concept shown both with natural circulation as well as with pumped electrolyte circuit as shown in Figure°4, is built until today in a similar, more advanced form by at least four companies in the German-speaking countries until the power class of above 2MW.

Pressurised alkaline electrolyser (development of DLR) /4/

As to their process technology pressurised electrolysers are very similar to atmospheric electrolysers. Due to the necessary pressure regulation the high requirements for sealing leak tightness pressurised electrolysers need considerably more components for operation. On the other hand their construction can be kept very compact, depending on the level of operating pressure.

Figure 5 shows an advanced pressurised electrolyser naming the principal components. This electrolyser was designed for the directly coupled dynamic test operation with a photovoltaic field as electrical energy source. It could be operated for 15 years at different stages of remodelling at DLR.

The operation reliability of the first version of the electrolyser as shown in Figure°5, a commercial prototype, was insufficient during intermittent operation in its original layout. Problems with non-uniform cell stack temperature distribution, insufficient level and pressure controlling and a too small designed process technology caused many shut downs of the plant. Therefore a complete redesign of electrolyser 2 was realized which is presented in Figure 5.

Redesign of hardware components

To get detailed information about temperature and voltage distribution in the cell block measuring cell frames (MCF) have been developed. During disassembling of the cell stack for integrating these measuring cell frames, cracks have been observed in the area of top gas outlet and bottom electrolyte inlet of most cell frames. One of the reasons therefore was local overheating of the frames. Due to the insufficient natural circulation of electrolyte the produced heat could not be removed from the cell stack. Another reason for crack formation was a high content of water vapor in the polypropylene oxide (PPO) cell frame material enclosed during the injection molding process. Together with the manufacturer of the original cell stack (Metkon / Alyzer in Switzerland), it was decided to exchange all cell frames. In place of the PPO material the more temperature stable material poly-sulfone (PSU) was used. These frames enable operation under pressure up to 30bar when using additional fiber reinforcement rings. Furthermore, an electrolyte pump was installed, which promotes

the electrolyte circulation and the removal of waste heat. The electrolyte flow rate ranges between 10 and 250l/h. For standard investigations, the electrolyte flow rate was set to 200 l/h, therefore temperature difference over the stack decreases from 10 - 20K to about 2K. A reason for the many shut downs of first electrolyser version were the too small designed gas separators. As a consequence of the fast dynamic of solar insolation the levels in the gas separators and the pressure changed very strongly. The original level and pressure controller wasn't able to eliminate this oscillations and operation has to be stopped because limiting values were exceeded. These problems could be solved with newly designed gas separators. The total volume of the new gas separators with 31 liter is three times bigger than that of the original ones. A remotely controlled heating and cooling unit was integrated in the bottom of the gas separator unit which keeps the electrolyte temperature constant in the range of ± 2K. This is necessary for scientific experiments e.g. measurement of reproducible i-V-characteristics. The maximum pressure could be increased from 5 to 15bar.

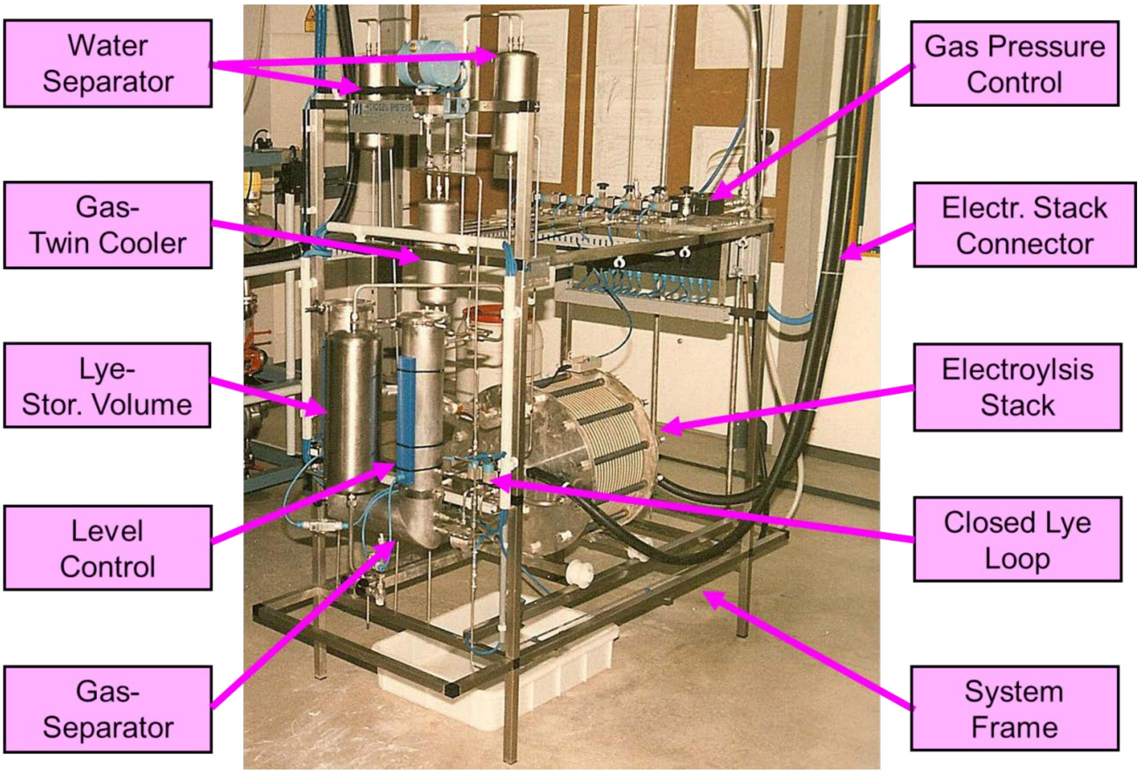

Figure 5: Alkaline pressurised electrolyser from DLR with 15 kW electric input power, designed for dynamic solar operation; source: DLR, ZSW

New design of pressure and level difference controlling

Due to insufficient controlling and subsequent shut downs of this electrolyser, the control circuits had to be designed completely new. For controlling of the release of the product gases two coupled control circuits are necessary. The pressure control circuit is responsible for the release of oxygen and the liquid level difference control circuit for hydrogen. By the contrary assignment (pressure to hydrogen side and level difference to oxygen side) the coupled control circuits could drive in a dead center position. This could happen when the value for level difference is negative and the pressure is lower than the set point. In this case, both expansion valves are closed. If the assignment of the control values to the expansion valves is correct, the different amount of gas production can balance the level difference and increase the pressure. Pressure differences in the gas separators can promote diffusion processes inside the cells, resulting in reduced purity of the product gases. For controlling of the release of the product gases in pressure electrolysers expansion valves are necessary. The influence of two different kinds of expansion valve / controller configurations on the gas impurities was investigated. Expansion valves are producing pressure peaks, which are flowing contrarily to the direction of the gas towards the cell stack and are supporting the migration of gas bubbles through the diaphragm. The production of pressure peaks is strongly influenced by the type of expansion valves and controllers. Originally, the electrolyser was equipped with discontinuously controlled expansion valves. Continuously controlled valves are producing less pressure peaks with lower amplitudes than discontinuously controlled ones. Systematic investigations of these phenomena are distinctly indicating that the gas impurities can be reduced by about 30% using continuously controlled expansion valves in combination with a PID controller compared to discontinuously controlled ones supported by a two position controller.

1.3 Advanced atmospheric industrial electrolyser /5/

As already said electrolysis today is operated as unpressurised electrolysis in the range 0.02 – 0.5bar above atmospheric pressure and as pressurised electrolysis at 30bar as s series device and up to 120bar as test system. Figure 6 shows an

atmospheric 111kW electrolyser of company Krebskosmo for a dynamic operation with a photovoltaics field. It was newly developed specially for the solar hydrogen project in Neunburg vorm Wald, Germany, and operated for years with a high availability.

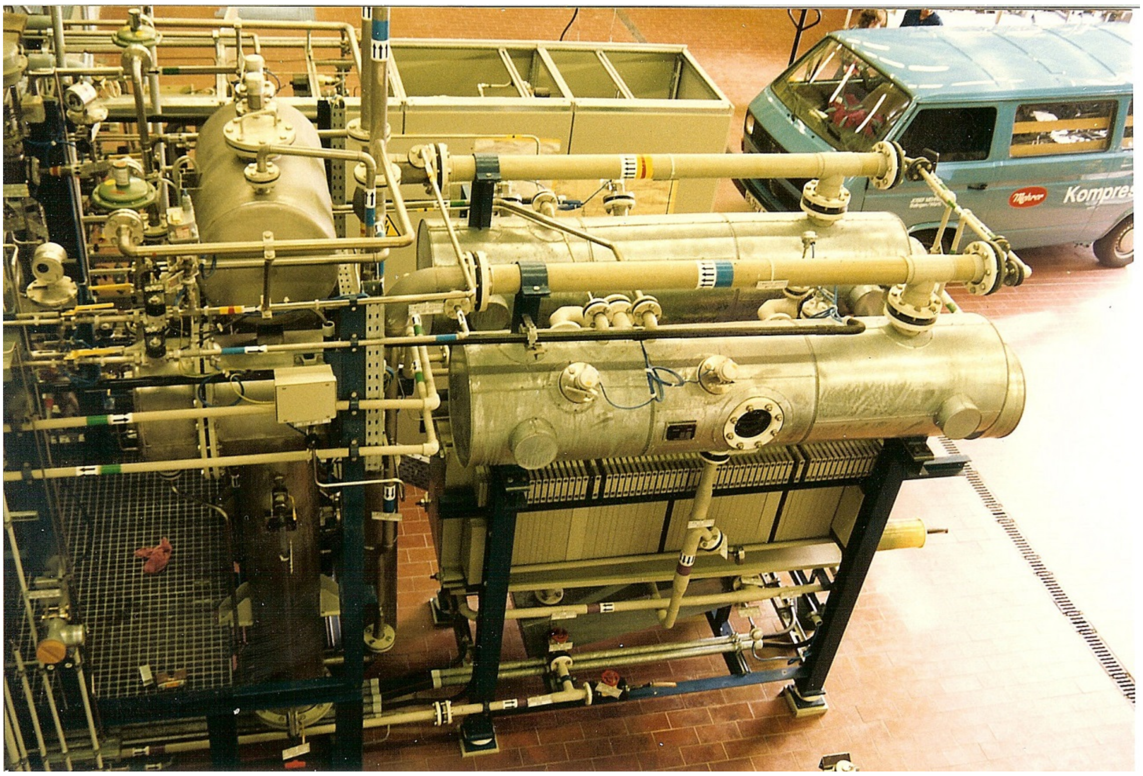

Figure 6: 111kW atmospheric alkaline water electrolyser; source: A. Brinner, ZSW

With this electrolyser for the first time research results of other parallel projects, e.g. HYSOLAR-Project (Acronym: **HY**drogen from **SOLAR** energy) were industrially realised. All cell frames of the electrolyser block were cast in plastic material. As a gastight membrane a polymer material, poly-sulfone (PSU), mechanically reinforced on the cathode side was used.

1.4 From electrolyser to hydrogen production system

The term ‘electrolyser’ only precisely describes the apparatus producing the two product gases hydrogen and oxygen by the process ‘electrochemical water dissociation’. This process engineering apparatus is schematically displayed in Figure 7 and will be furthermore denoted by ‘Electrolyser Core System’. To the process engineering of an electrolyser system providing hydrogen and oxygen at a

given gas quality, providing feed water at the requested purity, and conditioning waste heat and condensate such that a reuse in the electrolyser or use in another part of the facility is possible a more complex setup is necessary.
Images in report part B give an impression of further periphery devices which have to be added to the core electrolyser and electrolyte circuit.

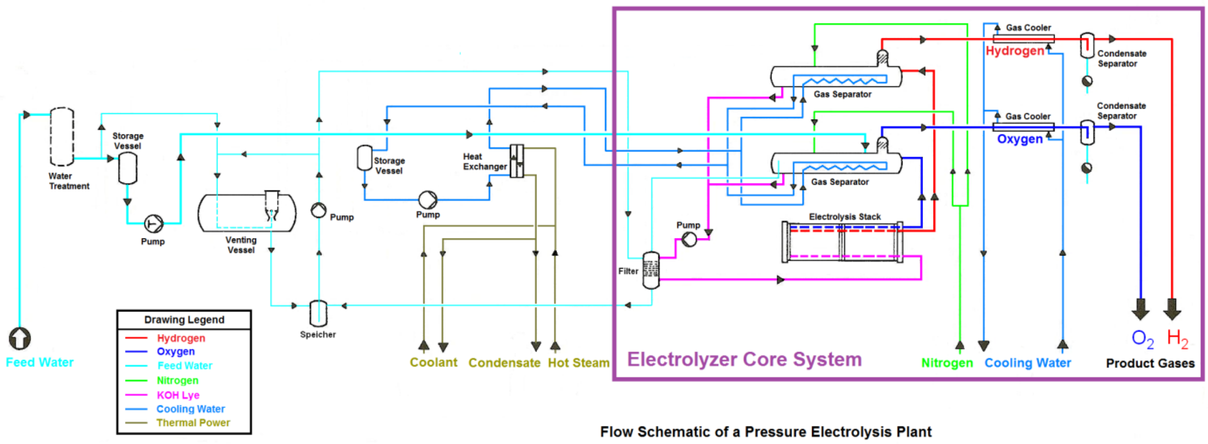

Figure 7: Flow chart of a pressurised electrolyser system with processing of both product gases; drawing: ZSW

Part of the core electrolyser system around the central electrolyser block are the electrolyte circuit with electrolyte preparation (violet in Figure°7), at the inlet side the water make-up (light blue) and the controlled feed of water (light blue). From the electrolyte with a closed primary cooling circuit (blue) large amounts of thermal power (grey-brown) can be extracted via a heat exchanger. These can be provided to other parts of the process or other systems of the facility. Via the two gas separators the product gas systems for hydrogen (red) and oxygen (dark blue) are linked to the electrolyte circuit. Part of the consecutive product gas systems are in every case a gas cooling and condensate separation that the extracted water and potassium hydroxide can be fed back into the electrolyte circuit. On the one hand this serves an optimisation of used process media, on the other hand it protects the subsequent gas systems from aggressive condensates.
For complete shutdown of the electrolyser system all components carrying gas and subsystems have to be flushed with inert gas, usually nitrogen until they contain no more explosive or flammable gas mixtures or components. This flushing system

(green in **Figure 7.**) feeds nitrogen either directly to the block gas outlets or to the gas separators and flushes also the gas tubes and components of the following subsystems. In modern electrolyser systems nitrogen flushing is not necessary after every interruption of operation or before every start of operation but only for servicing and repairs respectively after an emergency shutdown.

1.5 Facility with megawatt pressurised electrolyser from industrial application

Atmospheric alkaline electrolysers with pumped and natural circulation electrolyte are presently available at a rated power of up to 2 Megawatts.

To be able to reduce the investment costs as well as simultaneously the operating costs of an electrolytic hydrogen production facility the atmospheric electrolysis was further developed to a pressurised electrolysis. Connected to this development was the assumption that despite a larger wall thickness a compact electrolyser with small footprint should require smaller investment costs and in addition that providing pressurised hydrogen from electrolysis with many applications requiring higher pressure it reduces investment costs if an external compression step is dispensable. At the same time operating costs should go down by saving compression energy. For the stationary operation without or with only small electrical power variations already very large pressure electrolysers of close to 3.5 Megawatt power were realised. In Figure°7 an overview drawing of the 30bar alkaline large size electrolyser by Lurgi is shown. In the drawing a distance block is shown because this electrolyser is always built at the same power / number of cells by bridging missing cells in technical realisation with a distance block made from concrete without function. In the case of necessary later power increase this block can be replaced partially or completely by additional cells. This concept reduces invest costs because for any electrolyser block size the same system periphery can be used. Figure°8 shows two large size electrolysers installed next to each other for operation at a pressure of 30bar. Each of them has a production capacity of more than 480Nm^3/h of hydrogen gas.

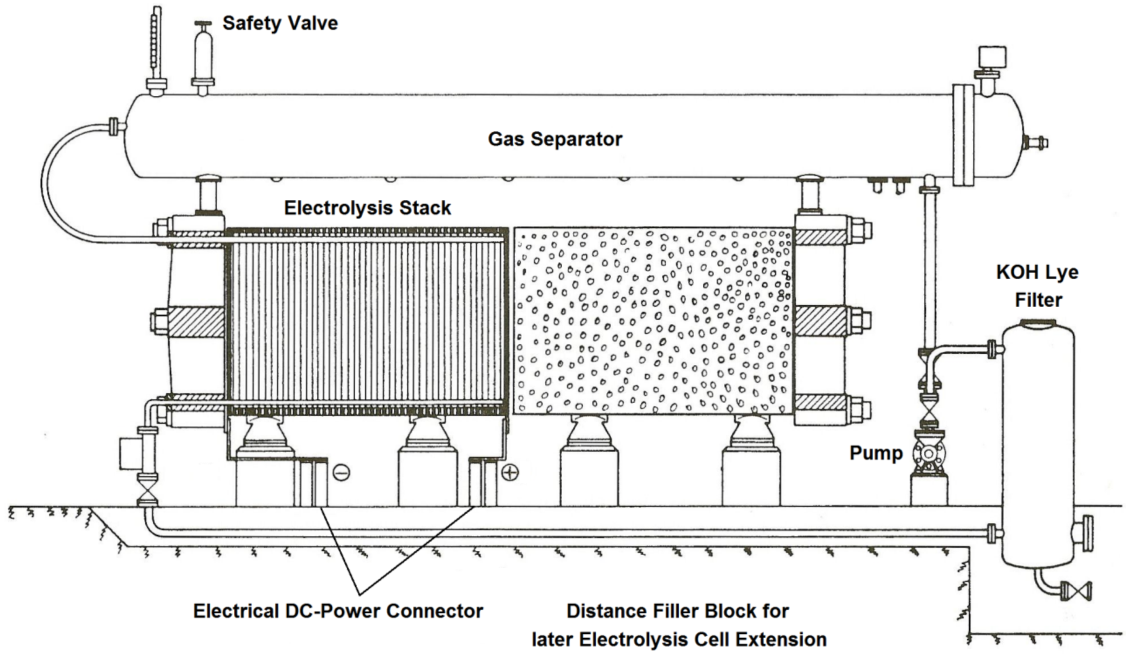

Figure 9: Overview drawing of an alkaline 30bar pressure electrolyser; source: Lurgi „Wasserstoff aus Wasser"

Figure 10: Two alkaline 30bar electrolysers with Lurgi design; source: ELT; www.elektrolyse.de

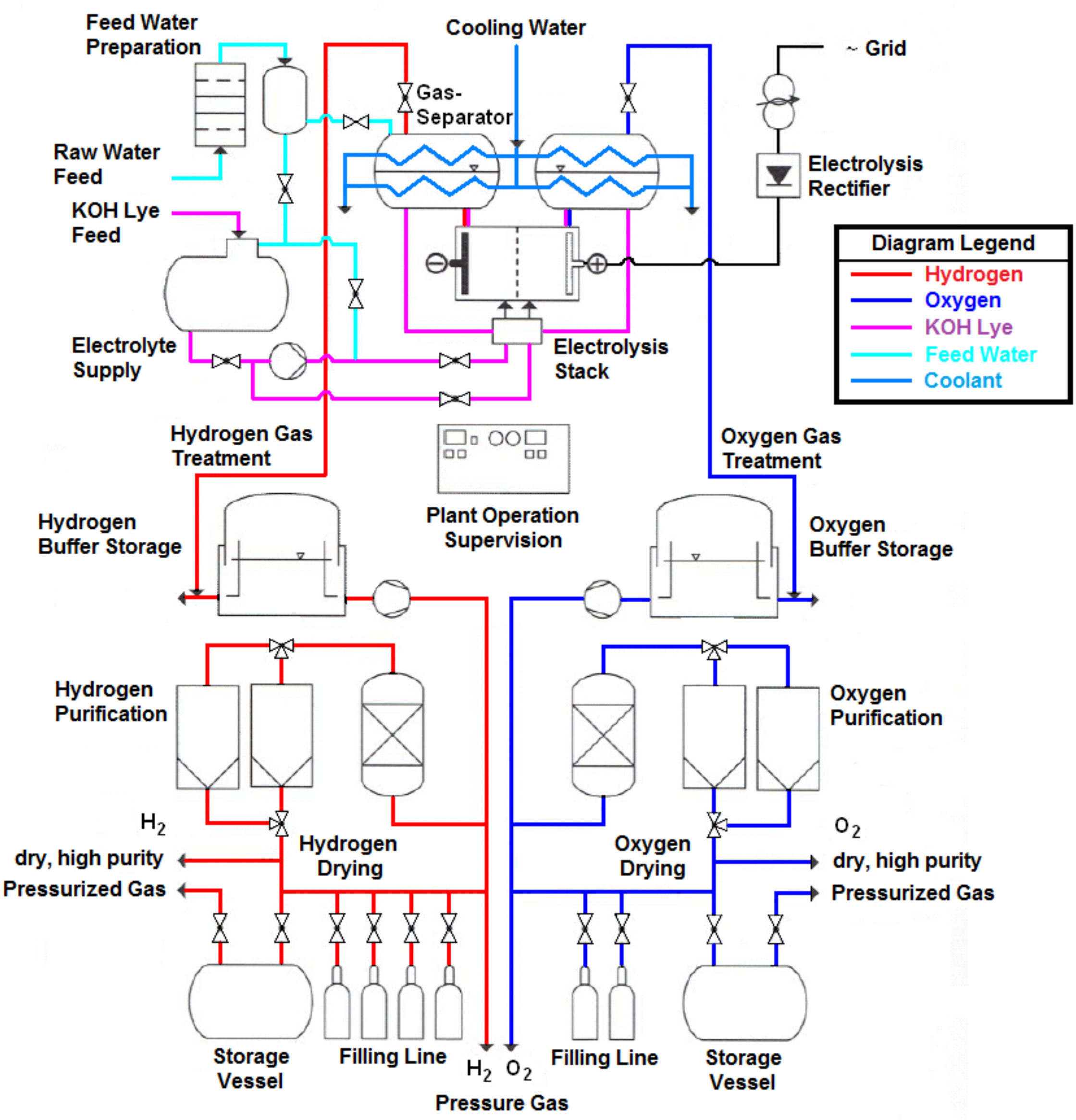

Figure 11: Principle of a hydrogen production system based on an electrolyser with delivery of hydrogen and oxygen; drawing: ZSW

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1.6 Using modules and pre-manufacturing of periphery exemplified by hydrogen post-treatment (cost reduction)

For providing hydrogen at a high purity and given pressure three more subsystems follow at the gas outlet. For a pressure electrolyser like the one presented in Figure 10 first residual oxygen and water is removed from hydrogen. In a purification step with an oxygen catalyst cartridge, as shown in Figure 12, the residual oxygen content, originally in the range of 0.1 - 0.3Vol-% is recombined with the respective amount of hydrogen to water. The gas with water vapour content is then cooled water vapour condenses and is separated. With this purification step a gas purity of 99.9% (Hydrogen 3.0) can be achieved.

Three examples:

Gas purification and drying

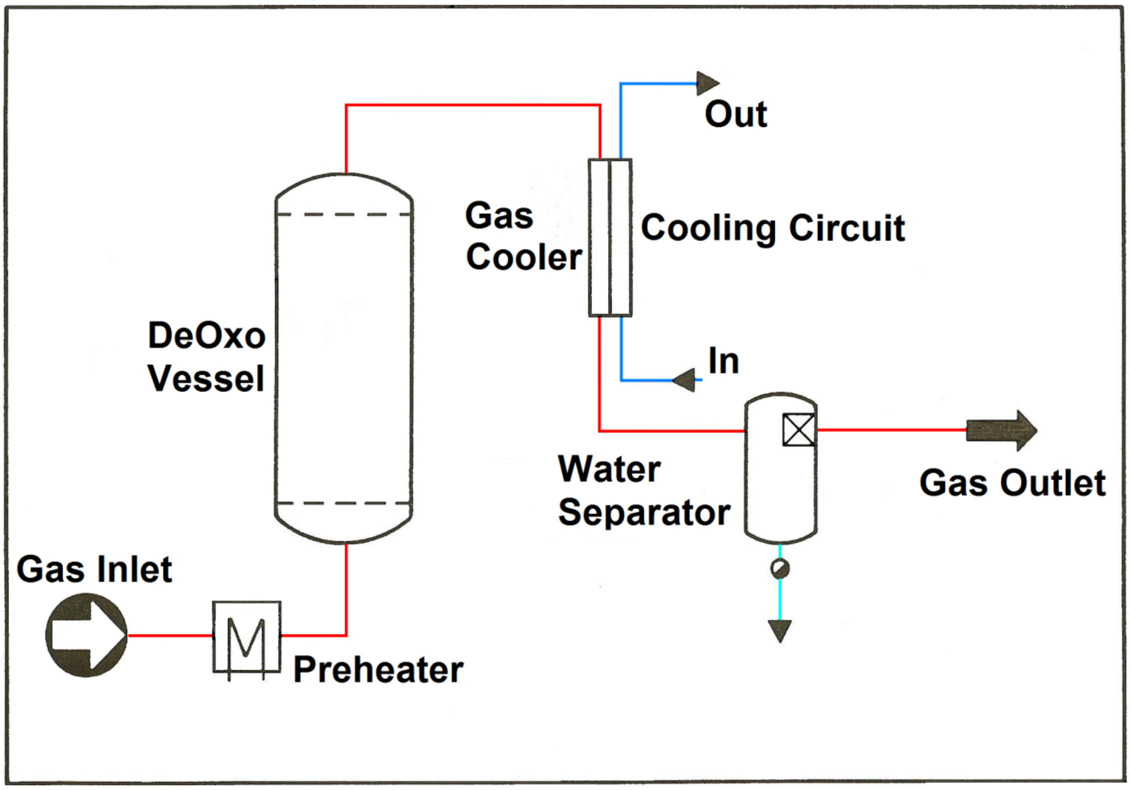

Figure 12: Recombination of residual oxygen for hydrogen purification; drawing: ZSW by Lurgi, “Wasserstoff aus Wasser“

Hydrogen from an electrolysis process with pre-purified water is free of high content of particles, hydrocarbons and other harmful content. Therefore after removing the residual oxygen content a purification facility as displayed in Figure°13 is sufficient. It is composed of gas preheating, pressure change adsorption and water separation to filter out the particles. By this the gas purity of 99.999Vol.-% (Hydrogen 5.0) is achieved. The two adsorber cartridges are used alternatingly. One cleans the fresh gas, in the other one adsorbed water is desorbed using dry hydrogen and transferred to the water separator.

Adsorption dryer to ensure the quality of the product

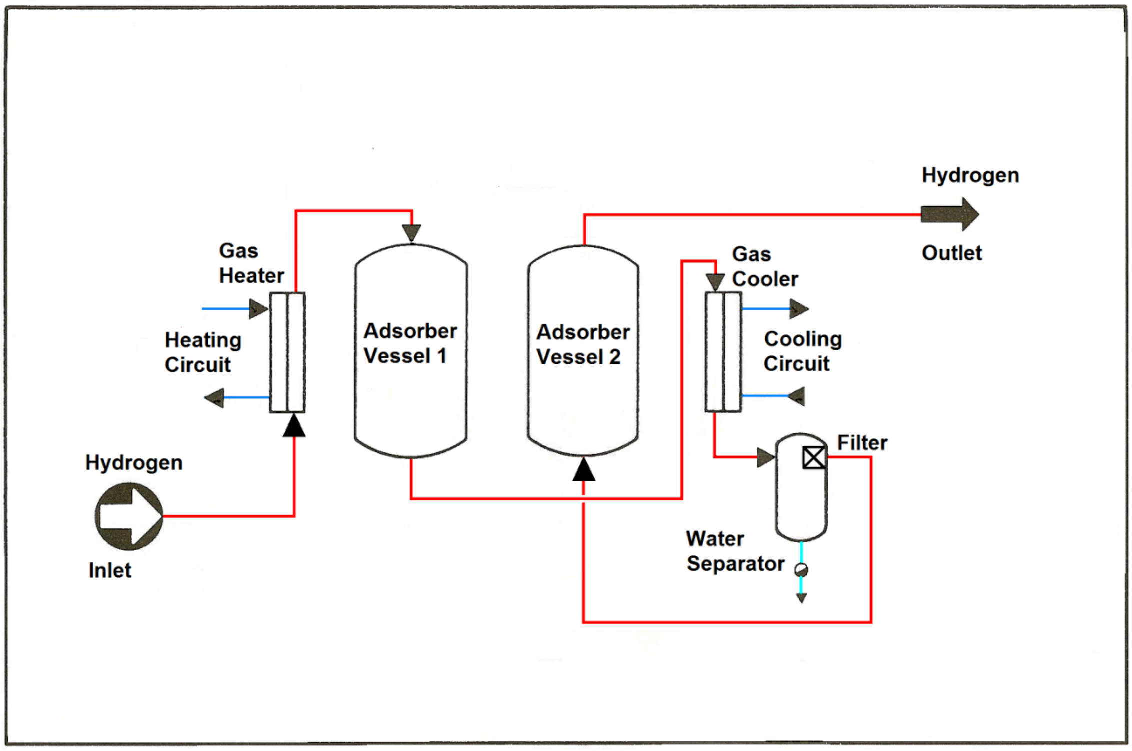

Figure 14: Adsorption dryer and water separation; drawing: ZSW by Lurgi, "Wasserstoff aus Wasser"

1.7 Compression

The last process step before gas delivery is the intermediate storage with an initial compressor to regulate the required pressure level for hydrogen delivery from the storage vessel. Alternatively the hydrogen volume is minimised by this step for gas transport in a transportable pressurised storage.

The storage subsystem with compressor is schematically displayed in Figure°15.

Gas compression

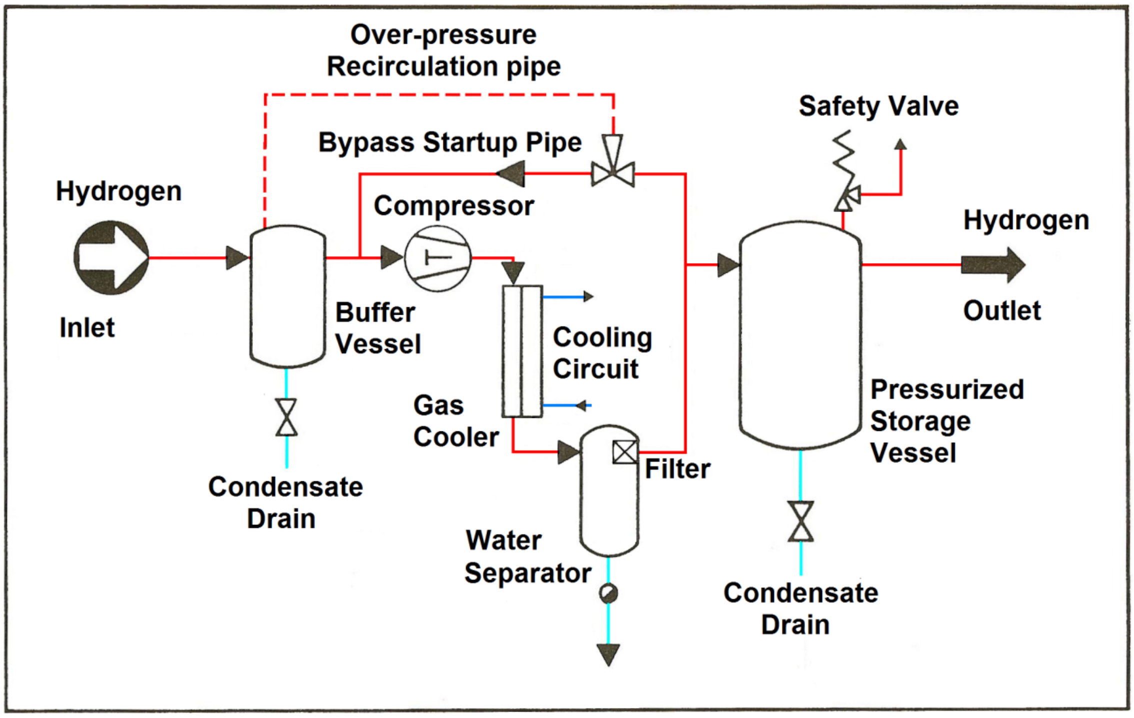

Figure 16: Compressor-storage subsystem for compressed, dry hydrogen; drawing: ZSW by Lurgi, "Wasserstoff aus Wasser"

If also oxygen with given purity requirements should be used as product of the electrolyser an analogous cleaning and storage system as Figure 12 to Figure 16 has to be built for oxygen.

Integrating all these subsystems together give a gas production facility as shown in Figure°17. This 'gas factory' includes all systems and components for educts, electrical energy and water up to an application-adapted delivery of hydrogen and oxygen.

2 From concept to realisation – example HYSOLAR-project

In the next chapters the principle setup with block diagram of an alkaline pressure electrolyser that can be operated autonomously is explained (state of the art 1990) by the example of the 350kW-PV-electrolysis facility. /6/

Figure 18 shows a solar powered pressure electrolyser of 350kW power and the connected PV concentrator field with two-axial tracking.

Figure 18: 350kW pressure electrolyser and PV field of the HYSOLAR-project in Riyadh, photos: A. Brinner

Within the frame of the so-called HYSOLAR program, a German-Saudi Arabian cooperation, a first completely solar-operated Photovoltaic-electrolysis hydrogen production demonstration facility was designed, installed and operated between 1989 and 1995 within the project and about 5 years more outside the co-operation. This plant was accompanied in design, installation and operation by the German safety authority TUEV and received its official operation permission after successful pass of plant inspection on-site Solar Village in September 1993.

In the next chapter a detailed technical plant description of the facility is given by hand of its block diagram in Figure 20 and the facility installation overview in Figure°19.

2.1 Plant Control Computer (PLC)

The PLC is a standard process computer based on the Siemens S5-series and has been equipped especially with certified potential-separation cards for all measurement sensors, valves and motors to separate the explosion-proof areas from the Utilities Room. The computer has three separate central processors for operation, communication with data acquisition/ printer and communication with the operator via

keyboard and monitor in the Utilities Room and in the PV-field control room. The PLC is supplied with power from the UPS system. For safety reasons the memories of the processors are additionally battery-buffered.

The PLC controls the complete facility operation including the connection of PV-sub fields. The operator can only give pre-defined commands to the PLC pressing the respective push buttons on a user-defined keyboard. For safety reasons it is not possible to change the program code during operation with the keyboard but only with an additional external programming device. All subsystems have their own subprogram code which can be operated completely automatically. For test purposes it is also possible to operate certain devices within the subsystems in the manual mode. As far as the manual operation does not collide with any safety requirements the manual operation of a subsystem is possible whilst others operate fully automatically.

Current, temperature and pressure of the hydrogen production can be pre-set and changed at any time during operation. Also the operator can select either hydrogen production to air or into the storage vessel at any time. But for safety reasons the computer cannot decide independently to store the hydrogen into the bottle racks with the compressor. A screen message is given to the operator to press the respective function key for hydrogen storage if the pressure limit of the hydrogen vessel is reached. If the operator does not decide to store the hydrogen for any reason the computer automatically changes to production to air. Thereby the vessel remains pressurized. Hydrogen production and storage are completely separated so that any disturbance of the storage subsystems does not interrupt the continuous test operation. This plant design including hardware and software design and realization on PLC-basis for safe and automatic operation was the starting point to use standard PLCs combined with approved safety subsystems and operating programs in the energetic hydrogen production supplied with renewable energies. For the first time a solar hydrogen production plant was designed and approved along German safety regulations which had to be followed consequently. The testing predecessor for plant design, safety concept and all formal works with respect to final acceptance and official hydrogen production and delivery allowance was a 10kW PV-electrolysis test facility located in Stuttgart.

2.2 Solar Power DC Supply / Transformer Rectifier

The power supply of the electrolysis block can be selected only during stop of production by means of a manual switch handle at a switch cabinet door in the Utility Skid.

The rectifier has been especially designed for the supply of the electrolysis block with a maximum input power of 500kW at a voltage level of 290V. The output current can be pre-set by the operator. The rectifier is self-supervising and can give certain malfunction signals to the PLC. The solar power supply is still controlled by its own original operation system for PV module tracking and delivered maximum 350kW peak power. But the connection of certain sub fields to the electrolysis block is under full control of the PLC via the so-called Master Control System (MCS) in the HPD DC. The number of connected PV-sub fields (1 – 8) depends on the current set point. Only a direct connection of PV-sub fields with the electrolysis block is actually possible so that the electrolyser fixes the common operation point.

2.3 Electrolyte Loop

The electrolysis block is the most important component of the electrolyte loop. It has 120 single cells in series with an electrode area of 0.25m^2. Besides the block, the electrolyte loop includes also an electrolyte pump with over pressure loop around the pump, an electrolyte cooler, two gas separators and the treated water supply. A more detailed overview about this essential part of the facility is given in Figure 20: Overview block diagram of HYSOLAR 350kW pressure electrolyser in Riyadh; source: DLR, ZSW. The operation limits of the electrolysis block with its plastic cell frames have fixed the layout of the whole facility. The following maximum operation limits have been fixed by the manufacturer and by TUEV Suedwest for continuous operation:

Considering these operation limits, measurement and release tolerances of the safety limiters and the control capabilities of the PLC the subsystems have been laid out. Compared to other electrolysers of this size a main step forward could be reached because no restriction concerning the change speed or absolute minimum level of the electric input power had to be fixed so that the electrolyser can directly operate from the PV-field without any electric buffer. Nevertheless the electrolyser is actually equipped only with pure Nickel-electrodes on the anodic side and sulphate-

activated electrodes on the cathodic side which increases the specific power consumption for hydrogen production compared to the operation with advanced activated electrodes.

2.4 Hydrogen & Oxygen Gas Treatment

When the product gases leave its gas separators saturated with water vapor they have to pass through its gas treatment units with separate gas cooler and condenser (demister) each. Despite of any block operation temperature the pure gas temperatures at the outlets are always held at a level around 10°C to decrease the water losses remarkably. Any condensate from the treatment loops is directly given back into the electrolyte loop separately on the hydrogen and oxygen side. At the outlet of the oxygen treatment the gas will be depressurized to ambient pressure and led directly to air through an outlet pipe on the roof of the Process Room. Depending on the selection of the operator or on the system availability the hydrogen is led either into the hydrogen storage vessel which can be pressurized up to 50kPa below the selected operating pressure or the gas is led to air after de pressurization through an outlet pipe with a detonation protector on the roof of the Gas Handling Room.

2.5 H_2 Intermediate Storage

This vessel has a geometrical volume of 4.78Nm^3. Its actual maximum operating pressure is always 50kPa below the hydrogen production pressure set point. The vessel is designed and certified for a maximum pressure of 800kPa. For safety reasons its minimum pressure has been fixed to 150kPa. The vessel is integrated into the hydrogen loop so that it operates as a bypass buffer. Therefore it is possible to feed the hydrogen compressor with continuously produced hydrogen from the electrolyzer whilst the vessel is depressurized by the compressor in parallel. Thereby the vessel pressure fixes start and stop of the compression procedure.

2.6 Hydrogen Compressor

The compressor is a usual two-stage membrane piston compressor with two high pressure outlets. Its inlet pressure can vary between one and eight bar. The maximum outlet pressure has been fixed to a limit of 15MPa which is the standard

gas bottle pressure for hydrogen in Saudi Arabia. The electric/ pneumatic equipment of the compressor has been designed to be fully integrated into the common facility operating system.

2.7 H_2 Storage Station 1 & 2

Two hydrogen standard bottles racks with twelve 50 liter standard gas bottles in a common housing each can be filled with hydrogen from the compressor one after the other. Always all 12 bottles of a rack will be filled in parallel. A full bottle rack can be exchanged against an empty one at any time. If both bottle racks are full and no exchange can be performed the PLC will pressurize the vessel at first and then automatically switch to hydrogen production to air without any interruption. The storage station 1 was also equipped to fill maximum 6 single bottles with one filling line in parallel.

2.8 Nitrogen Supply

The nitrogen supply system consists in two groups of three 50 liter bottles with separate pressure indicator/ limit switches for each bottle and 2 two-stage pressure reducers for the bottle groups. This subsystem is the main process safety system to purge electrolyser block, gas separators, coolers, demisters, hydrogen vessel, compressor and H_2, O_2 piping from pure gases or gas mixtures after any emergency shut down or before start up after a longer regular shut down. The system operates without any external power source and can therefore automatically purge the electrolysis facility in the case of any possible event. The nitrogen consumption for a regular purging procedure before start up comes to 2.3Nm^3. The system will be released by safety limiters of the HWSS by an alarm of the PLC or by any power failure which shuts down the pressurized air system.

2.9 Pressurized Air Supply

All valves inside the explosion-proof areas are operated with pressurized air. Therefore a subsystem with air compressor and main air vessel in the Utility Skid and buffer tanks in both operation rooms has been installed. All valves operate with two pressure levels, 140kPa as the control pressure and 600kPa as the actuation

pressure. It is possible to operate the facility 15 minutes only from the air buffers. Any malfunction of this system or mains power failure leads automatically to a regular shut down and de pressurization of the electrolysis facility. If no pressurized air is available no hydrogen production is possible.

2.10 Water Treatment

The facility has its own integrated water treatment facility to produce the water for the electrolysis facility with a minimum conductivity of 0.05 micro-Si. The system gets its raw water from a 50m^3 buffer tank and pressure pump system at the east side of the PVPS building. The water treatment unit has several consecutive components starting with a decalcifier / carbon filter combination then followed by a reverse osmosis module and at least an ion exchanger unit. The system has its own treated water buffer from where the water can be fed into the electrolyte loop at the electrolyte pump inlet at any operating pressure level with its own feed water pump. The water production and feed operates fully automatically depending on the water level in the buffer tank and the liquid levels in the gas separators. Also all procedures of subsystem and component cleaning are performed automatically depending on the capacity of filters or partly always once a day at midnight.

2.11 Radiator Cooling Circuit

In order to cool the electrolyte after the pump outlet a separate cooling loop with counter-flow electrolyte/ water heat exchanger in the process skid and pump, water/ air cooler outside the building has been installed. The air flow through the air cooler can be forced with three blower fans. The blower loop has its own control program which tries to hold the electrolyte temperature on its pre-set value. Nevertheless the control reacts independently of the pre-set value if the temperature difference between heat exchanger inlet and outlet falls below 9K to guarantee always a sufficient electrolyte cooling.

2.12 Forced Cooling Circuit

This cooling unit has three independent water cooling loops with independent pumps *tor* the water treatment system, commonly for the gas coolers and for the hydrogen

compressor. In the same rack as the blower air cooler a second coolant gas/ air cooler with forced fan ventilation has been installed for the three loops. An intermediate R12-coolant gas loop with three compressor coolers and water/ gas heat exchanger transports the heat power from the water loops to the coolant gas/ air cooler. Also this cooling loop has its own control program which can react independently to the cooling demand of the three loops.

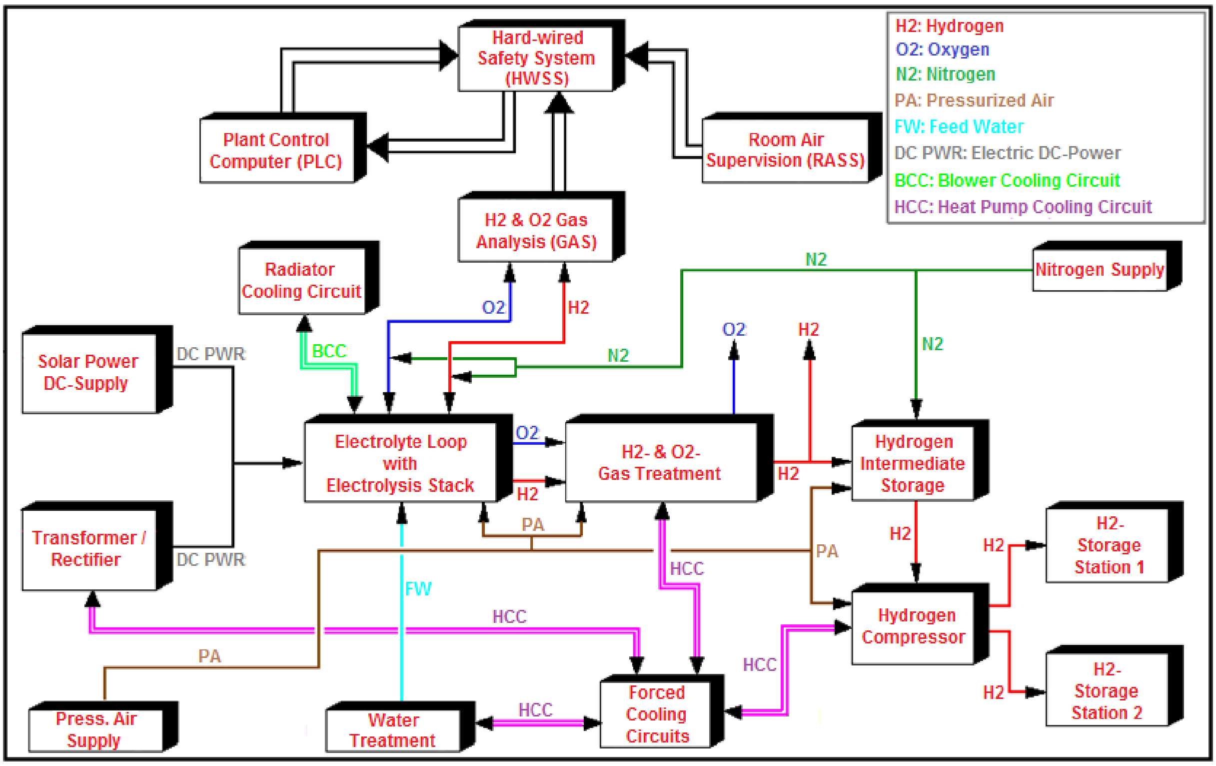

Figure 20: Overview block diagram of HYSOLAR 350kW pressure electrolyser in Riyadh; source: DLR, ZSW

Combination of system concept with container – safety concept to a system ready for certification

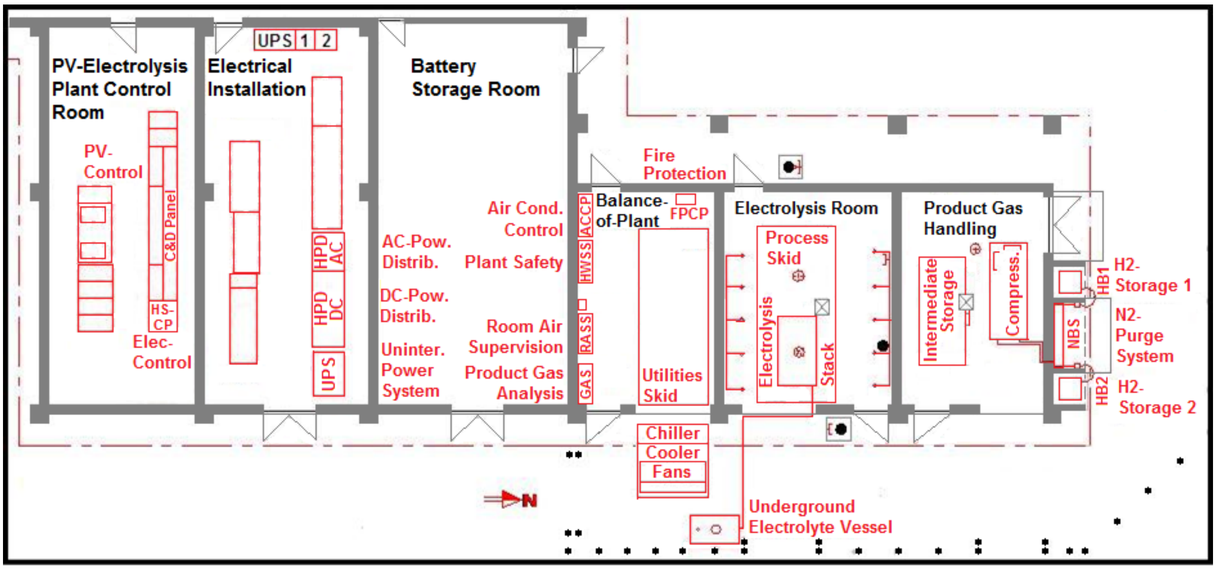

Figure 21: HYS 350 installations in the PVPS-building; source: A. Brinner, DLR

Figure 21 gives an overview about the ‘As Built’ installation of the electrolysis system and its external equipment showing a cut-out of the PVPS-building with the electrolysis operation areas, Utilities Room, Process Room and Gas Handling Room and the original rooms wherein new systems have been installed. Thereby the original equipment is also shown but without explanation.

Starting from left to right in the figure a new, second Electrolysis Control Panel (HS CP) has been installed in the Control Room besides the PV control board (C&D Panel). In the Electrical Room the two power distribution switch cabinets (HPD DC) for PV field connection and (HPD AC) for the supply with 480V AC from the grid and 110V AC from the uninterruptable power supply (UPS) have been installed. The Utilities Room is the new electrolysis control room housing the safety systems, Product Gas Analysis System (GAS), operation Room Air Supervision System (RASS), Hard-Wired Safety System (HWSS). Air Conditioning Control Panel (AC CP) and Fire Protection Control Panel (FPCP).

Within the utilities skid frame (US) the plant support systems for power supply of the electrolysis block via grid-connected rectifier or from the PV-field, water treatment system, power distribution panel, motor and valve control center and the operation control computer (PLC) are installed.

Outside this room on the east side another steel frame with the chiller and blower cooling systems and in front an underground electrolyte collection vessel are located. The Process Room houses a skid frame (PS) with the electrolysis block, electrolyte loop, gas separators, hydrogen and oxygen gas piping and its auxiliary subsystems. In the Gas Handling Room the intermediate hydrogen storage vessel and the

hydrogen compressor are installed. On the north side of this room a roofed outdoor area with the exchangeable Hydrogen Bottle racks (HB1, HB2) and the Nitrogen Bottling System (NBS) for purging has been erected. Process, Gas Handling Room and the roofed outdoor area have been designed and equipped completely explosion-proof to fulfil the German safety regulations (e.g. so-called UVV & TRB). In a distance of 3 meters around the operation rooms an area with access restriction has been formed with steel posts. The overview about the entire electrolysis installation including explanation of areas and main components is given in Figure°22.

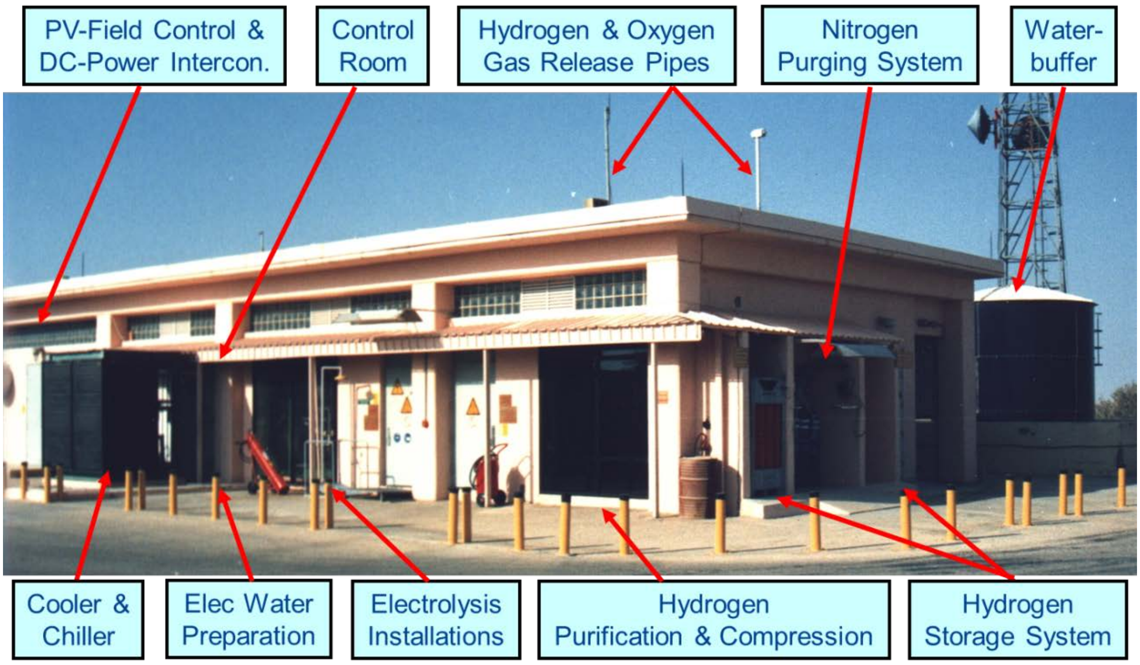

Figure 23: HYS 350 plant overview in the PVPS-building; source A. Brinner, DLR

2.13 Lesson learned

Modularisation is possible due to two important boundary conditions:

- Safe operation and operation permission by safety authority permission,
- Cost reduction by pre-assembly and standardisation.

3 Acknowledgement

Major parts of this report were composed by the ZSW departments of SYS and REG.