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

Part 2 Modern electrolyser systems and aspects of connecting to Renewable Energy sources

Project RESelyser

2015

Regine Reissner

Jan Vaes

Seyed Schwan Hosseiny

Contents:

Quotes and Literature:

/1/ e-mobil BW, “Energieträger der Zukunft – Potenzial der Wasserstofftechnik in Baden-Württemberg“, 2012, Kap. 3.1.2.2

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

/3/ e-mobil BW, “Energieträger der Zukunft – Potenzial der Wasserstofftechnik in Baden-Württemberg“, 2012, Kap. 4.1.1.2, 4.1.1.3

/4/ DLR, KACST, “HYSOLAR Report phase II 1992-1995”, 1996, Kap. 2.2.2.1

/5/ e-mobil BW, “Energieträger der Zukunft – Potenzial der Wasserstofftechnik in Baden-Württemberg“, 2012, Kap. 4.1.1.

/6/ A. Brinner, Y. Al-Saedi, „HYSOLAR II – Installation, Startup and Test of the 350 kW Solar Hydrogen Production Plant, Solar Village near Riyadh, KSA“, December 1993, Kap. 3.1

/7/ W. Grasse, H. AbaOud (eds.), “HYSOLAR - German/Saudi Joint Program on Solar Hydrogen Production and Utilization (1986 - 1991)”, October 1992, Kap. 4.4.1

/8/ W. Grasse, H. AbaOud (eds.), “HYSOLAR - German/Saudi Joint Program on Solar Hydrogen Production and Utilization (1986 - 1991)”, October 1992, Kap. 4.4.1.1

/9/ W. Grasse, H. AbaOud (eds.), “HYSOLAR - German/Saudi Joint Program on Solar Hydrogen Production and Utilization (1986 - 1991)”, October 1992, Kap. 4.2, 4.3.1

/10/ W. Grasse, H. AbaOud (eds.), “HYSOLAR - German/Saudi Joint Program on Solar Hydrogen Production and Utilization (1986 - 1991)”, October 1992, Kap. 4.4.1.2

/11/ W. Hug, H. Dienhart, “Technology and Economics of Wind-Hydrogen Production”, Project Report JOU2-CT93-0413, 1997

/12/ W. Grasse, H. AbaOud (eds.), “HYSOLAR - German/Saudi Joint Program on Solar Hydrogen Production and Utilization (1986 - 1991)”, October 1992, Kap. 4.4.1.3

/13/ ZSW, FhG-IWES, Etogas, “Abschlussbericht PtG 250, Verbundprojekt Power-to-Gas“, September 2014, Kap. II.1.4.1, Abb. 17

/14/ A. Brinner, „Wasserstoff als Sekundärenergieträger – Herstellung und Entwicklungsstand“, BBA-BW-Treffpunkt Brennstoffzelle und Batterie, Wasserstoff-Sekundärenergieträger der Zukunft, 16.01.2012

1 State of the art system concept

The electrolysis facility described above with its gas-treatment steps is the central system of a hydrogen production facility. However a number of further peripheral systems and components are also necessary for the safe operation of an electrolysis facility.

Figure°18 shows a block diagram of a hydrogen production facility. The block diagram also shows how the many electrical and process technological functions can be grouped to functional groups and subsystems. These can be assembled by specialized deliverers, started up and adjusted before system installation. Finally they are assembled to a hydrogen production facility at the final location and connected where relevant.

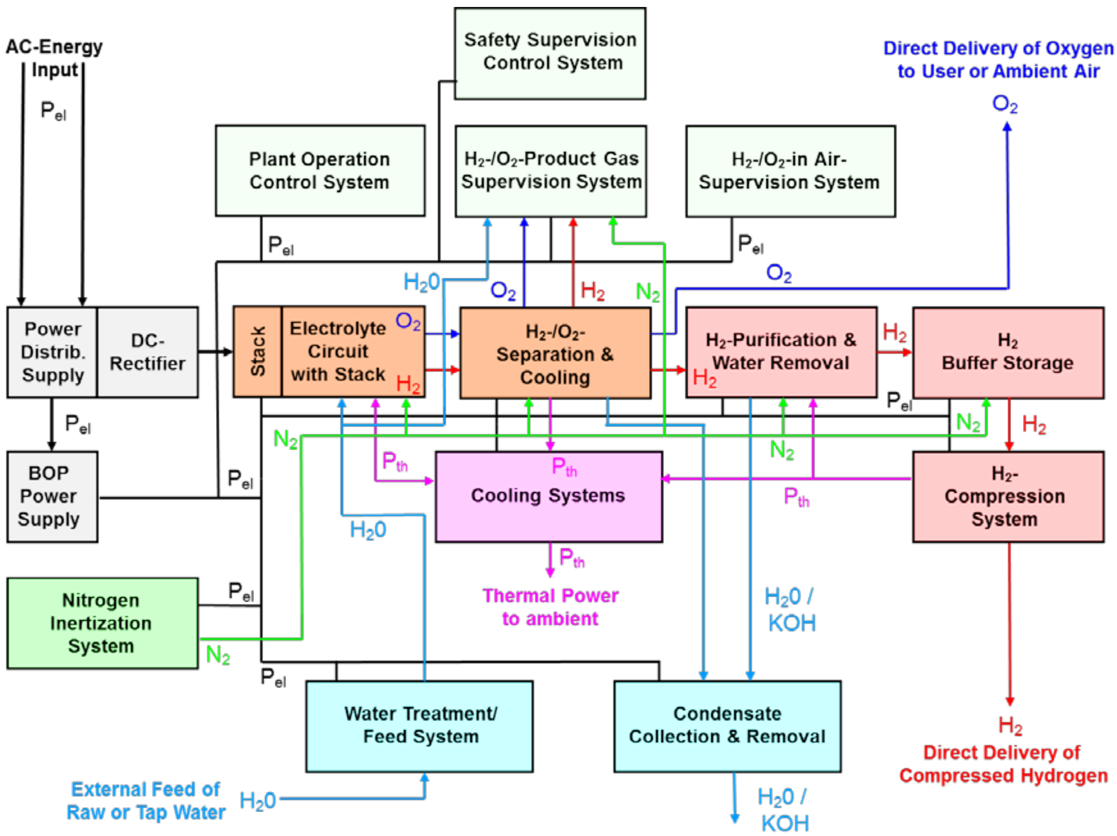


Figure 1: Block diagram of a state-of-the-art hydrogen production plant; source: ZSW

The electrolyser facility described above comprises in the block diagram Figure°18 only the chain of blocks (1) ‘electrolyte circuit with electrolyser stack’, (2) ‘H_2/O_2-Gas separation and cooling’ and (3) ‘H_2-purification and water removal’. In this block diagram no use of the oxygen is planned but after gas cooling and condensate separation. It is vented to the ambience.

On the electrical side the hydrogen production facility is supplied by the ‘AC energy input P_{el}’. This can be taken from the grid as well as by a single energy transformer like e.g. a wind turbine or a photovoltaics field. The major portion of electrical power input is supplied to a controllable rectifier or converter in the partial system ‘electrical power processing’. This is directly coupled to the electrolyser block and provides the electrical DC power for the electrolyser process. A smaller portion of facility power is used for the operation of all electrical and electro-mechanical components and systems of the facility itself. This is the internal consumption which is distributed to all subsystems and components via the partial system ‘BOP power supply’. At the advanced design hydrogen production facility which was for the first time built as 350 kW solar hydrogen production demonstration facility within the HYSOLAR project the system internal consumption was only 8.1% at a yearly average. With conventional electrolyser facilities designed for industrial use the internal consumption can grow up to more than 12%.

The purified water for the electrolysis process is usually supplied via another partial system ‘water treatment / feed system’ from the natural water available at the installation site. It is supplied to the partial system ‘electrolyte circuit’. The purified water must meet the high requirements of a low conductivity (few micro-Siemens), filtering of all dirt components and removal of all ions harmful to the electrolysis process. In Germany it is enough to use a simple filter and a commercial ion exchanger cartridge when using drinking water or rain water. For more heavily contaminated water up to use or salt water or waste water the more complex water treatment facility can also comprise several treatment steps, filtering, reverse osmosis, deodorisation, active coal filtering, and UV treatment. Per cubic meter of hydrogen gas supplied at approximately 20°C gas temperature approximately 0.8 liter of purified water have to be supplied to the electrolyser.

Part of the integral system is also a nitrogen supply for flushing all gas-filled parts of the facility to remove the product gases hydrogen and oxygen. This flushing step is

called inertisation. This partial system is called ‘nitrogen inertisation system’ in the block diagram. For safety reasons such a nitrogen inertisation is necessary before any opening of gas containing parts of the facility or works on such parts.

A further peripheral subsystem that can be constructed more or less complex is the partial system ‘pressurised air supply’. Especially in the partial systems of the hydrogen production facility where hydrogen and oxygen gas are present for safety reasons up to now often actors operated with pressurised air are used. To cover the need of pressurised air also a pressurised air supply must be integrated into the hydrogen production facility. The requirements on pressurised air quality are the same as in other chemical facilities having pressurised air-operated systems. However for cost and reliability reasons the trend is to reduce the pressurised air-operated parts in the gas partial systems in favour of the use of fast, efficient electrical actors.

For the subsystem ‘cooling systems’ efficient standard systems at the present state of the art can be used, usually. The tasks are to remove heat from the electrolyte circuit and the partial systems gas cooling, water condensation, gas purification, gas drying and gas compression. Developing the electrolyser technology for dynamic and intermittent operation with renewable energy supply especially the cooling systems have to be further developed for the special application, temperature range, energy efficient, low maintenance and non-supervised operation.

The subsystems ‘H_2/O_2 product gas supervision system’ and ‘H_2/O_2 in-air supervision system’ can also be proven standard systems which have an excellent technical state of the art. Also here with further development of the complete facility a separate development towards automatic operation, longer intervals for tests and certification for a cost-efficient operation will be important.

The air-in-the-room supervision system supervises the operating rooms of the facility for their hydrogen- and oxygen-in-air content. In case of leaks of the electrolyser system both product gases can be released into the operating rooms. On time before reaching the pre-set concentrations the measurement will induce an automatic shutdown of the electrolyser system. Limits for shut down are very narrow. Normally

exceeding 1.6Vol.-% of hydrogen in air or 25Vol.-% of oxygen in air will induce a shut down.

The product gas supervision system supervises continuously the produced product gases right at the exit of the electrolyser for mutual impurities. It is normal and without any problems if a minimal content of the respective other gas in the range of approximately 0.1 - 0.2Vol.-% is measured. Up to 4Vol.-% of hydrogen in oxygen or oxygen in hydrogen no ignition is possible for a dry gas mixture. Also in this case the limits for shutdown are set in a narrow range. At or above 2Vol.-% of hydrogen in oxygen or oxygen in hydrogen the electrolyser operation must be stopped. As long as the product gases have a high content of humidity, above 50% relative humidity, no ignition is possible. Therefore an alkaline electrolyser which contains only water vapour saturated product gases is not dangerous.

Product gas supervision systems and H_2/O_2 in-air supervision systems are essential elements of the facility safety strategy and therefore are subject to strict criteria of maintenance and certification.

The ‘plant operation control system’ and ‘safety supervision control system’ controls the operation of the hydrogen production facility. Due to its simultaneous function as process control system for normal operation and as safety system for safe handling of errors in the facility, e.g. controlled fast shutdown of operation, very high requirements and strict selection criteria are set to system technique and programming. Two realisation possibilities are permitted for the plant control system: separate systems of control and safety system with separate sensors and programming respectively wiring or the integrated setup of control- and safety system with special, certified freely programmable controls.

The electrolyser facility concept displayed in Figure°2 is presently further developed especially with the purpose of increasing the cost efficiency of CAPEX and OPEX costs. Similar facility concepts are optimised in other presently running projects like e.g. the project ‘P2G-Electrolysis’. The system concept of this development is displayed in Figure°3. Comparing to the original concept the following development steps were performed:

- Clear separation of power supply to the electrolyser process and to supply of the BOP,

- Development and use of an advanced, highly efficient rectifier with its own power supply connection to the grid with no influence on the facility power supply concept,
- Use of a further developed facility control with verifiable integration of all safety functions,
- Independent placement of the electrolyser block and the BOP,
- Transition to more flexible BOP functions such that different electrolyser blocks of various suppliers can be connected without changes to the BOP-hardware,
- Integration of an independent connecting module to transfer waste heat power to an external user,
- Consequent collection of condensate and purification for reuse in the electrolyte circuit,
- No regular inertisation of the hydrogen circuit before start of operation.

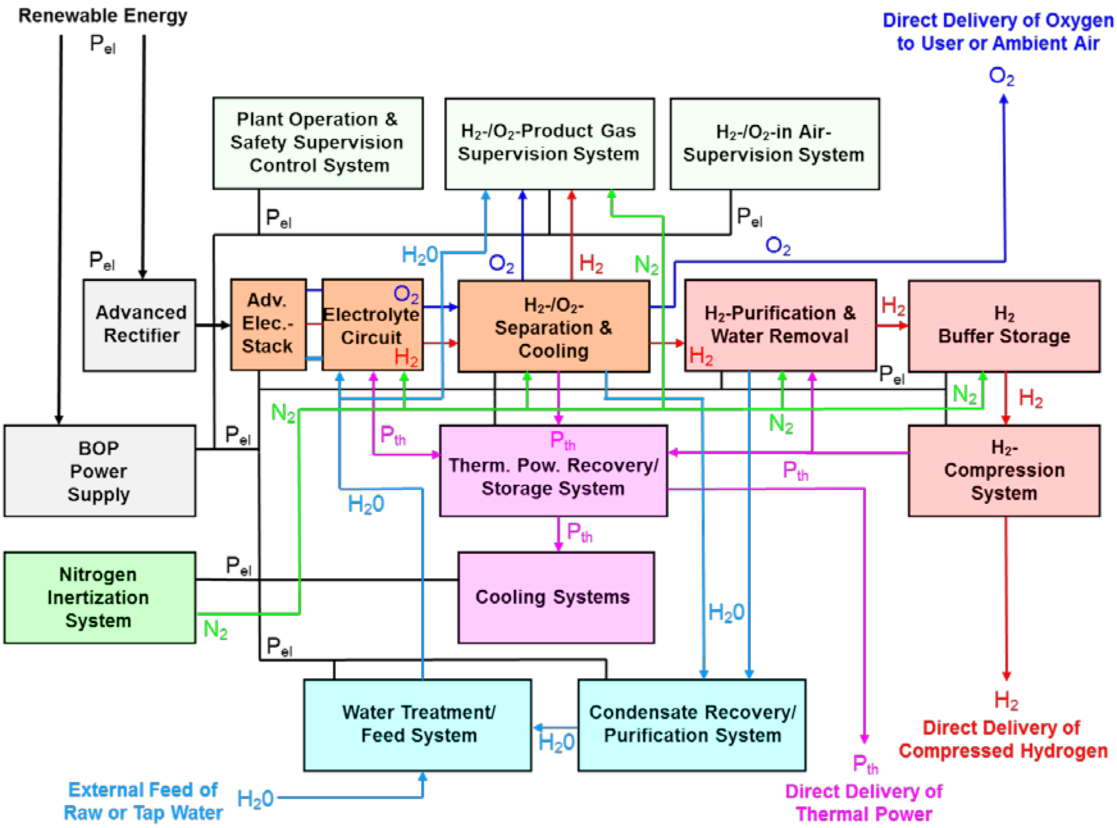


Figure 4: Block diagram of an advanced hydrogen production plant; source: ZSW

1.1 Cost reduction by serial production

Costs of electrolyser systems are at a rather high level today because the level of automation and series production is still low. Some economic considerations on introducing series production are given here.

Basis for state of the art analysis are sales of electrolyser systems of 15 MW per year. This generates a turnover of 20 million € per year at a cost of goods sold (COGS) of 15 million €. Many components in the supply chain are still made manually or semi-automatic.

Full automatisation and supply chain development (requiring a higher volume) is expected to decrease the cost by a factor of 1.5. Investment needed for a full automatic plan is estimated about 17 million € (of which membrane: 1 m€, electrode production: 4 m€, injection molding: existing, stack mounting: 2 m€, in line assembly of units (car-like): 4 m€, varia/footprint: 6 m€). 2 years of plant build-up and 10 million € to invest over two years would cover the expense of full automatisation.

When implementing the resulting COGS at the same market volume and price settings would be 10 million €/year. This 15% cost reduction is expected to generate a 1.5x turnover and an increase of the cross margin from 5 to 12 million € per year: with a price reduction to increase the market share 30 million € per year turnover could be achieved at COGS of 18 million € (27 MW/year sales).

To achieve this increase in turnover and cross margin by full automation, however, the sales network, customer and market intelligence must be there from the start. Every one of four one of four consecutive years a significant part of the market needs to be conquered. The total market at this point is estimated to be at 100 million € (world wide).

These numbers are illustrated in Figure 19b.

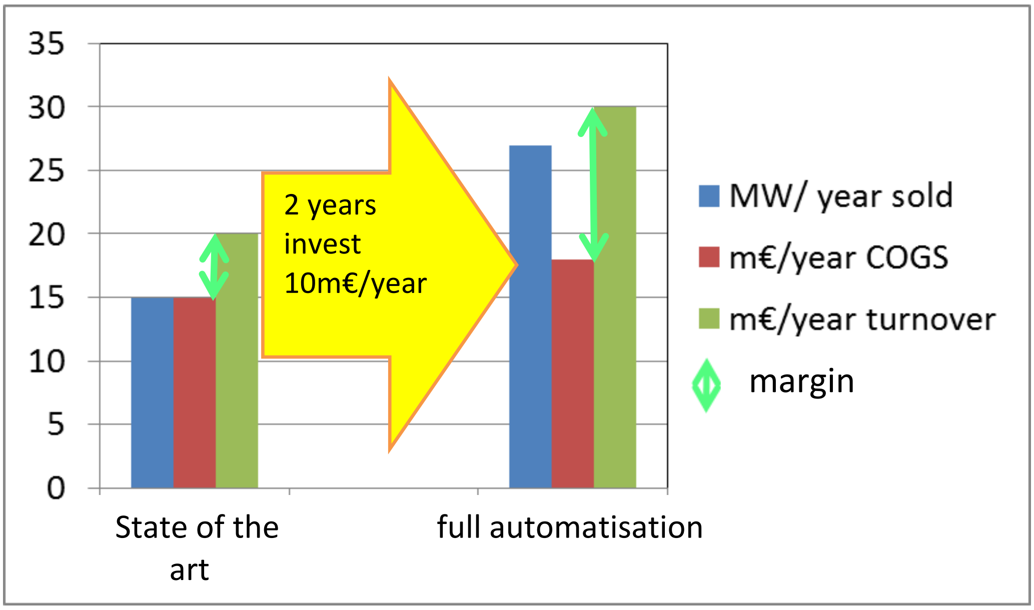


Figure 5b: Cost reduction by serial production

2 Coupling of renewable energy transformers with alkaline electrolysis

2.1 PV-electrolysis

To obtain experimental results for the overall system evaluation, the combined and interactive operation of the following essential plant components: PV-Generator, power conditioning unit electrolysers and hydrogen storage subsystem, has to be investigated during routine' solar operation under the greatest possible variety of meteorological conditions. /7/

This procedure has to be supported by specific experiments such as measurements of component efficiencies.

As power matching is one of the key objectives of the 10kW task, it has been decided to perform a solar year with the following constraints:

- cyclic use of all PV power conditioning modes,
- no basic change of subsystems, exclusive use of always the same electrolyser without improvements during the test phase,
- statistical use of all power conditioning modes,
- operation from sunrise to sunset.

The solar year started on April 6th, 1989. Until the end of December 1989, the system was operated during more than 120 whole solar days. During the remaining working clays no solar operation was performed because of experiments with

components, failures and repairs in subsystems, failures of the data acquisition system and failures of the HYSOLAR building support technique. On all solar days, consistent data sets have been collected in time intervals of five seconds.

The subsequent data evaluation takes place in three steps:

- Online data verification prior to storage on magnetic disc and tape,
- Data evaluation by standardized procedures and plots as presented e.g. in Figure°20,
- Offline data evaluation with respect to specific questioning as given in Figure 22 as an example.

A data base system (KOSMA), modified for HYSOLAR, allowed to use any set of data from any time interval in nearly any given mathematical combination. Due to newly arising questions of the data, the development of KOSMA was continuously progressing. Complete analysis of the first solar year was possible after it ended in April 1990. Results of the solar operation are given for selected days in the following sections.

System behavior during typical days /8/

System data of May 19th, 1989, a cloudy summer day with a very dynamic insolation profile, is given in Figure°20. PV power conditioning mode was Direct Connection, 45.0V; the solar day lasted from 5:00 a.m. to 8:00 p.m. local standard time.

Plant start-up and shut-down is not limited by solar insolation but by the concentration of hydrogen in oxygen product gas where the critical impurity level for shutdown is 2Vol.-% H_2 in O_2, Current and voltage fluctuations follow precisely the insolation path due to direct connection operation. No retarded reaction of the electrolyser is observed - even in plots with a higher time resolution. The electrolysis temperature also follows the insolation but in a very smooth curve shape that is caused by the large thermal mass of the cell block. A maximum temperature of only 50°C is reached.

Another typical example of solar operation is presented also in Figure°20 with data of September 19th, 1989, a very cloudy day with low and diffuse insolation. The PV power conditioning mode was Bypass DC/DC, 45V/36V; sunrise at 6:00 a.m. and sunset at 6:30 p.m. local standard time. Due to the low insolation level, plant start-up

was at 6:40 a.m. and shut-down at 5:42 p.m. In principle, the data showed the same operational behavior as on July 14th but on a lower level. Even the most critical value, H_2 in 0_2-content clearly indicates that the system is operable the whole day at very low insolation levels and only start-up and shut-down times are affected by the 2Vol.-% limit.

In the same Figure°20 also the system operation on a day with ideal sinewave solar power insolation is shown, which was October 27th, 1989. But such days are rarely to find even in summer time the normal days is more similar to the dynamic operation day, May 19th, 1989 under South German weather conditions.

2.2 Solar operation /8/

Various electrolyser versions were tested at the HYSOLAR 10 kW PV-electrolysis test facility. As no shut-offs caused by malfunctions of one specific electrolyser occurred during these experiments (only the electrolyte pump drive had to be repaired once) and no degradation of the electrochemical performance could be detected, it was decided to use the electrolyser (made by Forschungszentrum Juelich and DLR) as the reference load throughout a meteorological year.

The normal solar operation started at sunrise and ended in the evening when a hydrogen content of 2Vol.-% in oxygen was reached. On days with few or no clouds, the electrolyser was shut off 15 to 20 minutes before sunset. During operation, the nominal current density of 500mA/ cm^2 was reached whereas the electrolyte temperature did not exceed 65°C. Figure°20 shows the daily course of insolation and the electrolyser response for three typical operation days of the a.m. solar operation year. Solar operation of this electrolyser was going from April 1989 on until May 1990 with regular interruptions for performance measurements.

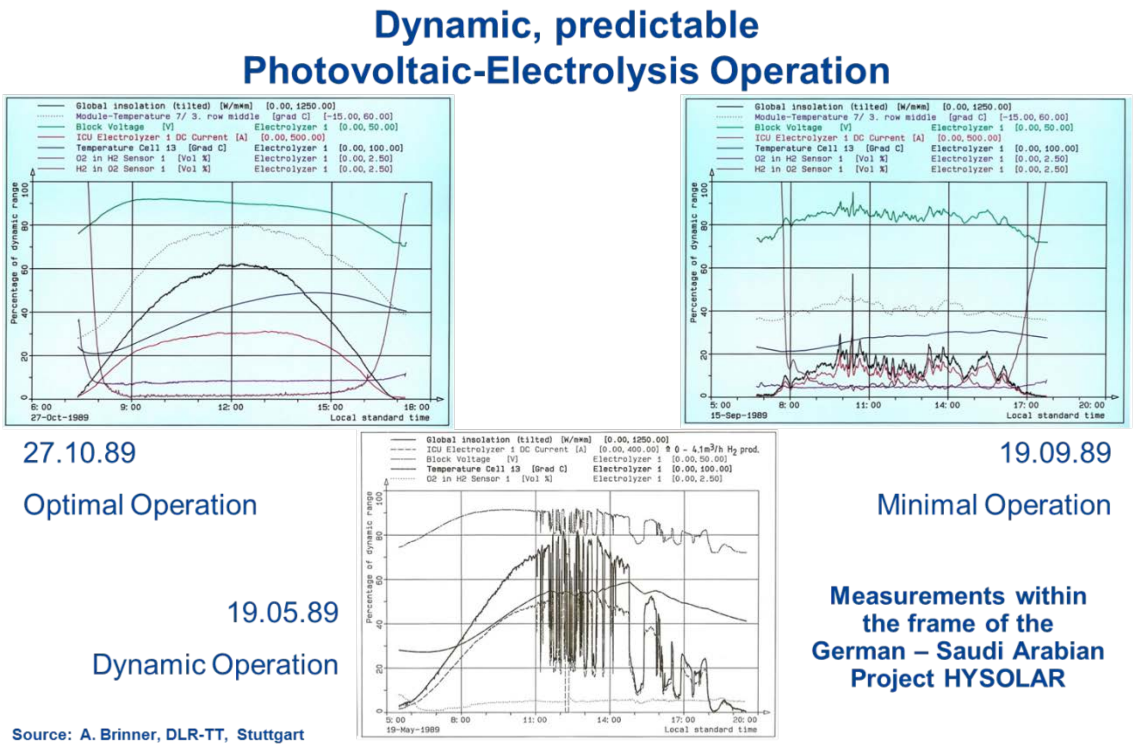


Figure 20: Typical Solar Operation Days with the 10kW PV-electrolysis facility in Stuttgart; source: A. Brinner, DLR

2.3 PV-Electrolysis Power Matching Concepts /9/

Different power matching concepts between Photovoltaic and electrolysis at different at different voltage levels as shown in Figure°21 have been examined with regard to the following aspects:

- comparison of voltage levels and power ratios within a concept
- comparison of concepts at the same voltage level
- concept influences on the system efficiency.

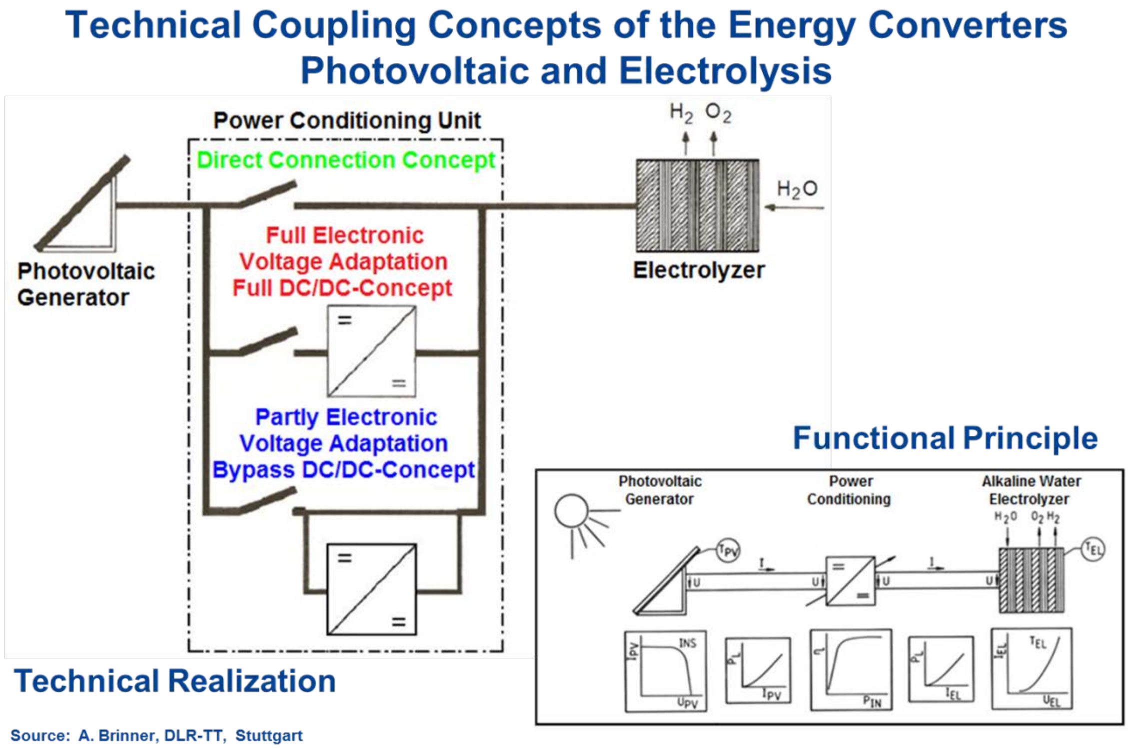


Figure 21: Photovoltaic-electrolysis coupling concepts for electric energy; source: A. Brinner, DLR

These power matching modes are:

Direct Connection concept: The PV-field is directly connected to the electrolyser. As in this case PV-field and electrolyser have only discrete fixed operation points, the layout of the PV-field has to be designed carefully in order to match the electrolyser characteristic in such a way that it produces the lowest possible losses. Three different voltage levels (Operation mode A1 – A3) have been examined in direct coupled operation with an electrolyser.

Full DC/DC concept: The PV-field is connected to a low-setting DC/DC converter. The field output voltage can be adapted continuously in a wide range (Operation mode B).
Two parallel operating buck converters (impedance coupled, choke-coil self-inductive) of the power conditioning unit transform the input power continuously (input voltage band 20 - 100 V DC) to the demand of the connected electrolyser (output voltage 48 ± 10V). At the same time, they track the PV-field at its MPP by varying their input voltage and input current. This MPP tracking can be done either internally by the converters or by an external program code. Optionally, a fixed input voltage

can be adjusted to do experiments for which no MPP tracking is desired. The two basic loss mechanisms (internal power consumption, conversion lasses) are summarized in the converter efficiency (output power/input power).
Three boundary conditions can restrict the operability of DC/DC-converters:

- A minimum retaining current is necessary at start-up in order to perform the internal power part check and, thus, must be overcome at startup.
- The converters cannot track at MPP below a minimum insolation of e.g. 50°W/m^2 because the I-V characteristic is then too flat for detection.
- The MPP tracking cannot follow fast fluctuations of solar insolation because, sometimes the control speed is restricted for technical reasons to a given voltage change speed.

Bypass DC/DC concept: The PV-field is subdivided into a main field (MF) and a bypass field (BF), the latter connected to a high-setting DC/DC converter. MF and converter output are connected in parallel to the electrolyser. The common output voltage of MF and BF can be adapted continuously in a small range.
In the bypass DC/DC operation mode, the BF power is transformed continuously by a high setting converter and added in parallel to the MF power which is coupled directly to an electrolyser. The BF is always operated at its MPP whilst the MF operating points are influenced by converter output and electrolyser. Four different power rations between directly coupled main field (MF and DC/DC-coupled bypass field (BF) and four voltage levels of the directly coupled PV-part have been examined (Operation mode C1 – C4).

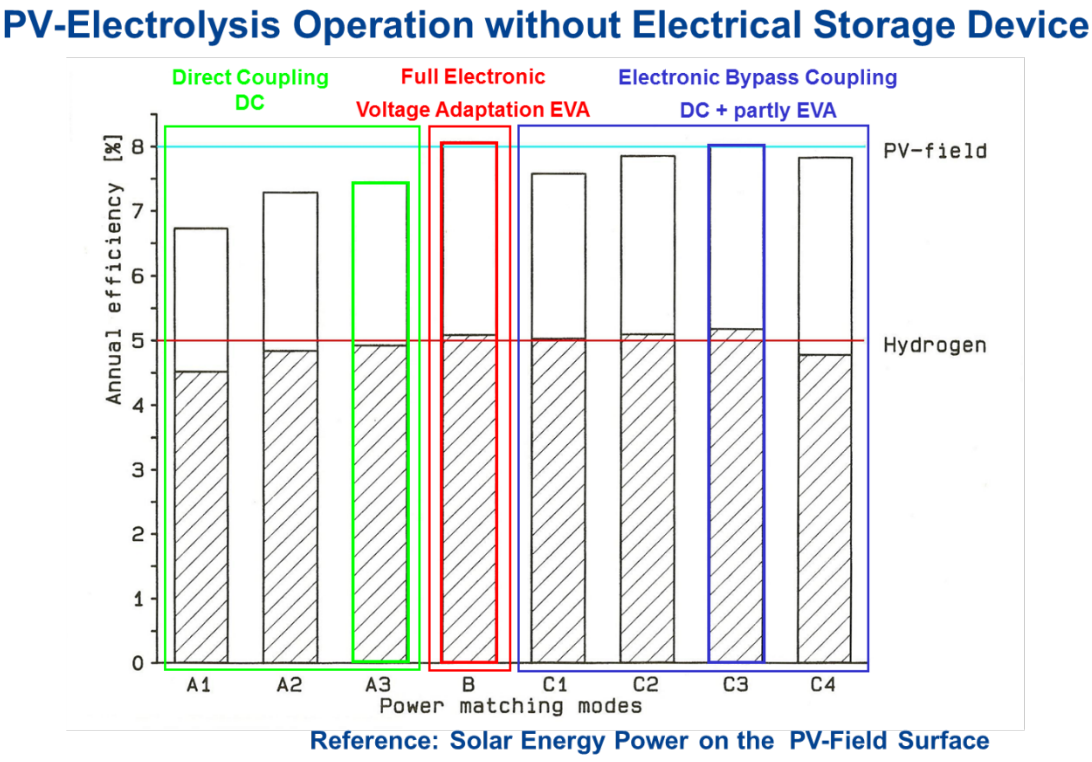
2.4 Comparison of Power Matching Concepts /10/

The data gained during the solar year have been evaluated with respect to energy relations of components and total system as well as to their yearly efficiencies. 155 days have been considered for evaluation with consistent data sets from sunrise to sunset. Each power matching mode A1 - A3, B, C1 - C4 has been operated for about 19 days.
The examination of the PV output energy as a function of insolated energy (as illustrated in Figure°22 for modes A1 - A3 and B) has shown that the output curves of A1 - A3 and C1 - C3 approach that of mode B with voltage levels up to 54 V. The

curve of C4 deviates again with a voltage of 58.5V and remains below the A3 curve. This effect is caused by the electrolyser characteristics. Generally the curves of C1 - C3 are about 4% above the corresponding curves of A1 - A3. Since A3 is the best Direct Connection mode in Figure 22 now the modes A3, B, C3 are compared with its PV- and electrolyzer output energy curves. As obvious in Figure 22 the PV output energy of A3 is lower than that of Band C3. But at the electrolyser output the advance shrinks to 3.3% (C3) and 4.1% (B) due to the converter losses in the DC/DC-modes.

The maximum values of the curves are not decisive for the examination because they depend on the weather conditions but not on the PV-generator. The comparison of the yearly efficiencies is only possible by taking the PV-generator energy output as a reference. Generally the system loses energy in the power lines and the electrolyser. Additional losses of the power conditioning have to be considered for B and C3. The yearly efficiencies of the above mentioned components are included in Figure°22.

Looking for energy conversion efficiency only and, consequently, not considering the PV-efficiency but setting the PV-generator output as the 100% reference, the Direct Connection mode A3 has the highest system efficiency with 66.2% compared to the Bypass DC/DC mode C 3 with 64.5% and the Full DC/DC mode B with 63%. From this point of view the well-adapted Direct Connection concept is the best. But on the other hand the MPP-tracking concepts gain more energy frame the PV-generator. If one takes the PY -generator output of A3 as the 100% reference and considers the energy gains of B with 7.7% and of C3 with 4.3% it is possible to calculate new system efficiencies of B with 67.9% and of C3 with 67.3%. So the concept B has an efficiency advantage of 1.7% compared to A3. The difference of A3 and C3 is insignificant due to the standard deviation included in the calculation. Therefore the Bypass DC/DC concept has no advantage on system efficiency.



Source: A. Brinner, DLR-TT, Stuttgart

Figure 22: Comparison of annual PV-electrolysis operation efficiencies gained with different electrical coupling concepts

Coupling of wind turbines with electrolysers /11/

Coupling of **W**ind **P**ower **P**lants (WPP) with electrolysers has also already been realised and was investigated in detail.

Figure°23 shows the two most common electrical coupling concepts between the principal systems of WPP and electrolyser block. Top left shows a system where the wind power plant supplies electrical energy to the electrical power grid from which the electrolyser block is supplied with DC energy via a controllable rectifier. The system bottom right is based on a direct DC intermediate circuit. The electrolyser block is electrically supplied via a DC converter. Via an additional grid-rectifier combination the electrolyser block can alternatively also be operated on grid energy. In the top case the WPP and the electrolyser need not be locally close. In the bottom case of DC current net coupling at low voltage the two systems must be close to each other to minimise the electrical losses.

Even though wind energy is a non-predictable form of energy the successful direct coupling operation, as shown in Figure°24 for a 3 days test operation, is no surprise. The 10kW pressure electrolyser originally optimised for dynamic solar operation could also manage without problems or incidents the dynamic operating conditions coupled to a WPP.

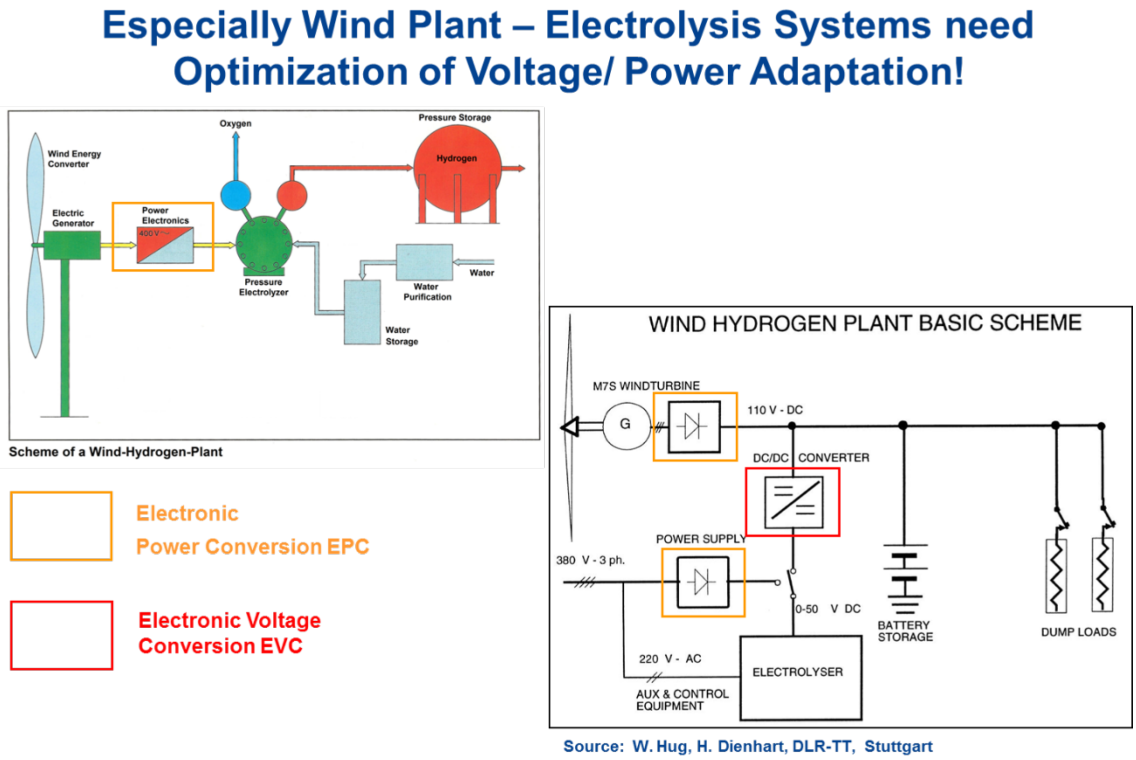


Figure 23: Technically realised electrical coupling concepts for wind turbine and electrolyser systems

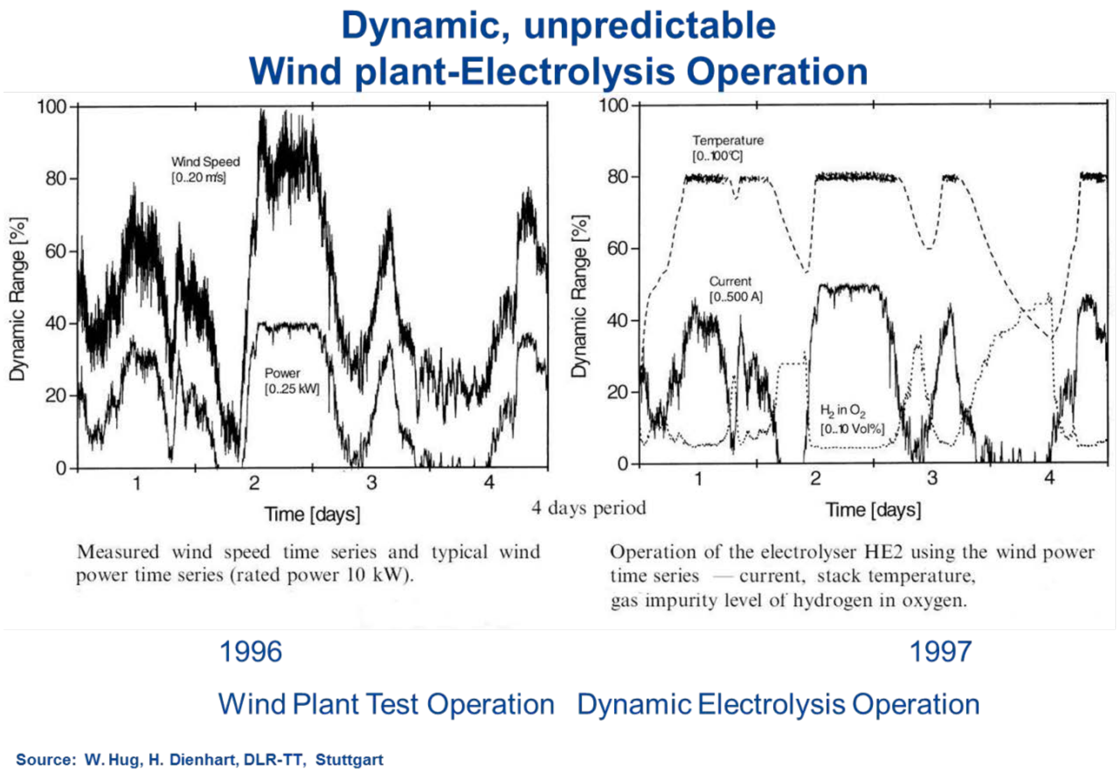


Figure 24: 3-day test operation of a 10kW electrolyser system with real dynamic power profiles of a wind turbine in southern Germany (Schwäbische Alb)

3 Consequences from the coupling of fluctuating renewable energies on electrolyser development

It has been found out that within the solar year the mean daily efficiency of the parallel operated buck converters was 92.5% with a standard deviation of ± 2.8%. The corresponding values for the single boost converter are 94.5% ± 0.8%. The electrolyser has been operated during the solar year with a mean daily efficiency of 72.4% nearly independent of all variations of energy input. Figure 25 illustrates this behavior presenting electrolyser efficiencies per day and the corresponding daily sums of the input energies. That means that the electrolyser operation is nearly independent of the daily insolation energy and the power matching. /12/

The reason for this behavior is very simple to explain along the principle current-voltage behavior of an alkaline electrolysis, see Figure°30 as an example. Operation at high power level results in an operating point at high current (I) and voltage (V). Voltage and specific energy consumption of a cell are directly related through the **E**lectro **C**hemical **D**ecomposition **P**otential (ECDP) or **T**hermo-**N**eutral **D**ecomposition **V**oltage (TNDV). The difference between operating voltage and TNDV multiplied with the current and time interval is the thermal loss. The thermal loss leads to higher

operating temperature. The higher the temperature is at the same current level, the lower is the operating voltage and the corresponding specific energy consumption.
At a low energy input level for the electrolysis the current/ voltage- operating point, operating temperature and thus the specific energy consumption is low. Since the current-voltage-characteristic of an electrolysis cell is relatively flat, a high change of current results in a small increase of voltage. As a result of the flat I-V-characteristic the differences of specific energy consumption/ efficiency between high input/ high temperature and low input power/ low temperature operating points are compensated.

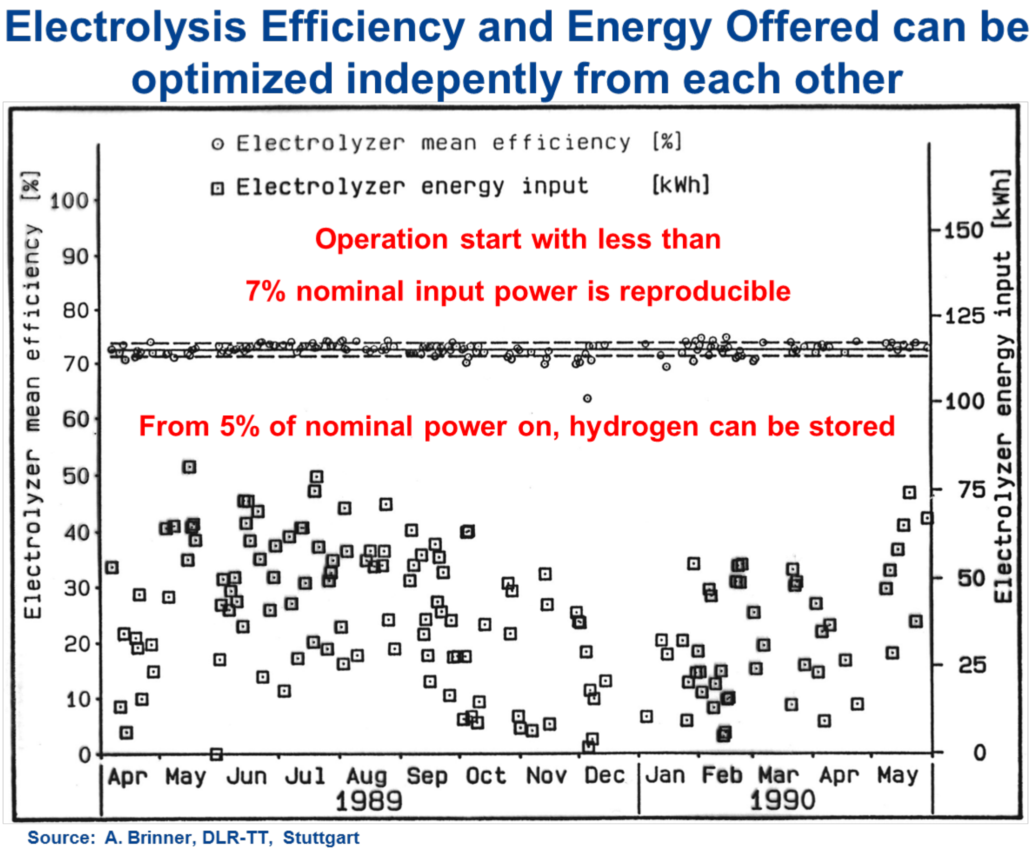


Figure 25: Long-term evaluation of electrolysis input power efficiency behavior during solar operation

Electrolysis can therefore be optimised for cost and efficiency without respect for a fluctuating energy supply. No adaptation of the electrolyser system to the specific energy source is necessary; matching can be done on facility level.

Modern alkaline atmospheric and pressure electrolysers are by their functional principle or electrochemically not limited in their possibilities of dynamical or intermittent operation. Also the electrical load shedding from full load is no problem

for a modern electrolyser. Due to construction and depending on the manufacturer for some models, boundary conditions exist which limit operation. These can be summarized as follows:

- Minimum temperature must be sustained in off-mode especially for large electrolyser blocks, e.g. to ensure the leak tightness of the electrolyser block,
- Minimum pressure must be kept in off-mode especially for pressure electrolysers to ensure that no ambient oxygen will get to the hydrogen side,
- Limitation of the current slope to protect the semiconductor electronic components of the rectifiers,
- Limitation of the gas pressure increase vs. time by limiting the electrical input power to guarantee a controlled pressure rise without oscillations or increased internal pressure losses,
- Limitation of the rise of electrical input power vs. time at low temperatures to ensure the stack and system leak tightness and to minimise mechanical stress to the system due to rise of operating temperature.

Within the given limits for temperature, pressure and electrical power dynamic load changes or interrupts of operation are no problem for modern electrolyser facilities. Figure°26 shows as an example a daily operation of a 0.3MW pressure electrolyser by Hydrogenics with a test cycle of various temperature and pressure levels with step functions from minimum load to full load. After each test a load shedding from full load to minimum load was performed and in-between the temperature and pressure level tests a 90 minutes interruption of operation was included. /13/

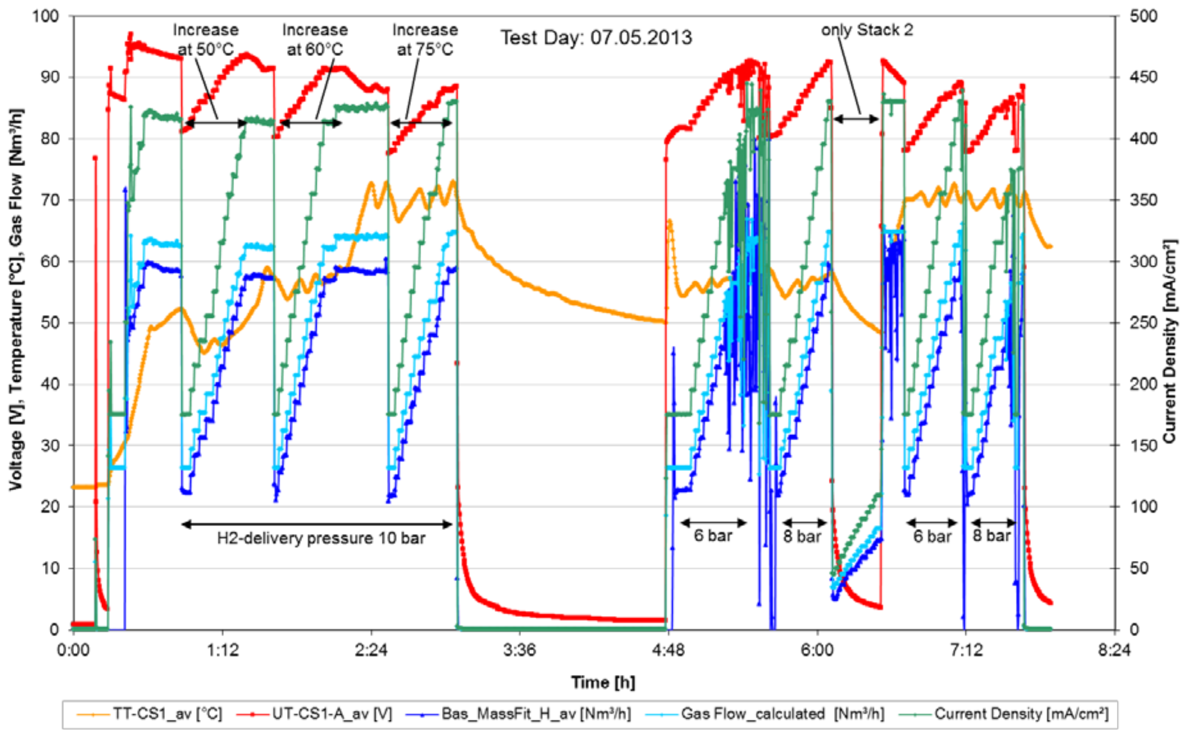


Figure 26: Test operation of a 0.3MW pressure electrolyser with varying temperature-, pressure and power profiles, source: ZSW

4 Need for technical development with respect to efficiency optimisation of (RES-) electrolyser systems

The international agreements on reach the so-called 2°K-target (limitation of the global warming to a maximum of 2°K) can only be reached by a decarbonisation strategy for the energy sector as well as the industrial production. Part of this is a massive development of renewable energies for electrical energy production mostly based on the use of fluctuating wind energy on land and on sea as well as photovoltaics. The potentials of controllable production from renewable energies are marginal. Increasing flexibility of the energy system is necessary with increasing proportions of renewable energy. Also seasonal storage of electrical energy is needed – most likely only possible via the chemical energy carriers such as hydrogen and methane-, and industrial processes have to change. Part of this change is especially the shift of hydrogen production from methane reforming to decentralised electrolysis technique.

As Figure°27 shows that the demand for hydrogen will strongly increase in the next years by the factors named above. Especially hydrogen demand in transportation will increase considerably.

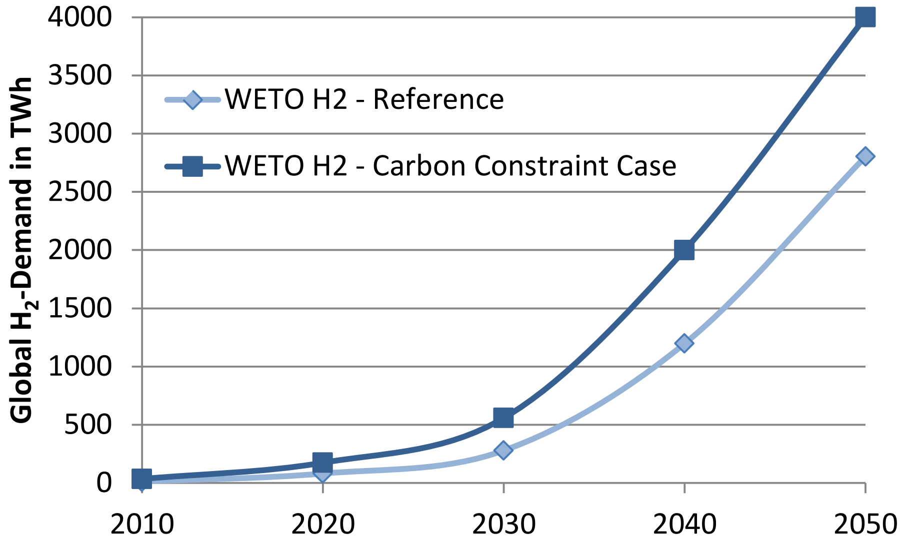


Figure 27: Global demand for H_2 according to WETO H_2 (World Energy Technology Outlook - 2050. WETO H_2"; European Commission 2006)

Development of this market for new applications of hydrogen requires not only technology development on the demand side but also that the costs will decrease substantially. Average costs of 1,100€/kW (5,700€/(Nm^3/h plant capacity)) in 2010 have to be reduced up to the target year 2050 by 75% to about 270€/kW, see Figure°28.

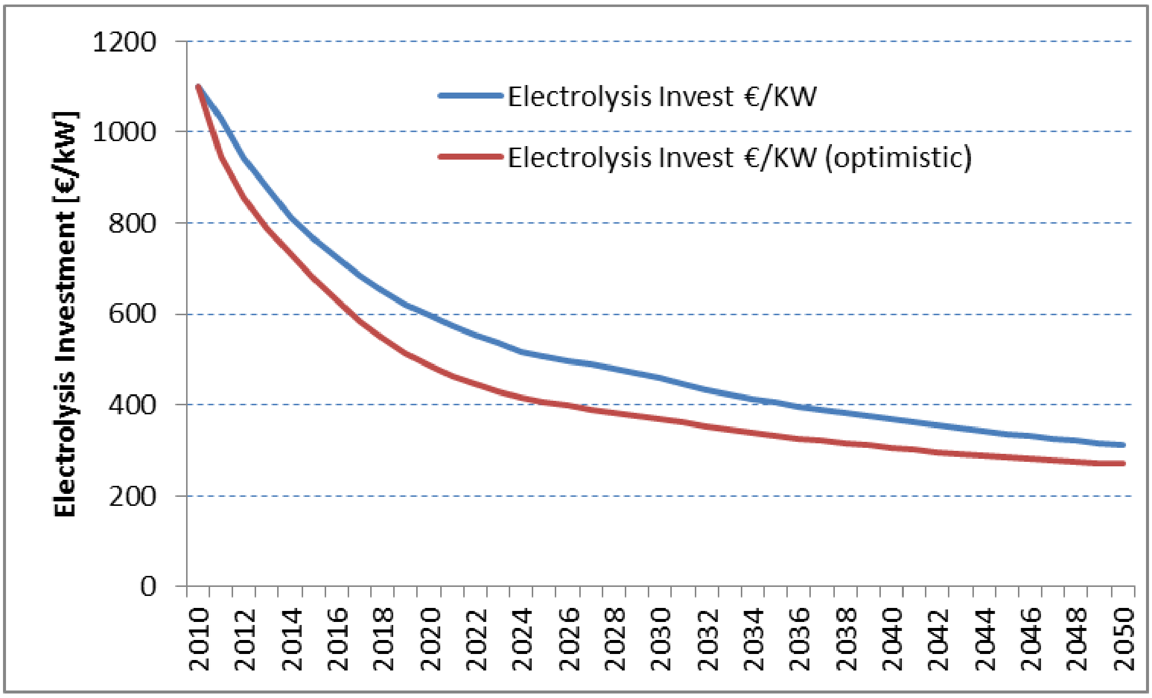


Figure 28: Necessary cost development for electrolysers according to ZSW (HYDROGEN IN BADEN-WÜRTTEMBERG – STATUS QUO; emobil, 2012)

The largest cost reduction potentials must and will be realised in the next years. Then simultaneously with the cost reduction effect by technology development also the increasing numbers of electrolysers produced will give an economy-of-scale effect. However this will not happen without stimulation. It requires the demand for low-priced electrolyser units. This demand can be stimulated by favourable political measures.

Until now electrolysers are designed and built for the production of hydrogen as chemical feedstock for industrial applications where the delivery of hydrogen as gas or liquid is too expensive. In these cases the electrolytic production had to compete with hydrogen produced from fossil energy carriers at lowest production but high distribution costs. If based on current from renewable energies electrochemically produced hydrogen has to compete in costs with a fossil energy carrier today's electrolyser plants have to be consequently refined. Figure°29 summarizes the technical R&D areas thematically by the key words efficiency (of plant operation), CAPEX-costs (plant investments), application (operation and product aspects), autonomy (energy source dependency), OPEX costs (production costs) und availability (industrial system availability at cost goals) /14/.

R&D-Areas

EFFICIENCY **Improved materials for cell frames, membranes, electrodes**
- Operation temperature rise up to 150°C
- Pressure rise above 30bar
- Minimization of ionic resistance & electrochemical specific energy consumption
- Rise of resistivity against differential pressure

CAPEX-COSTS **Simplification of process balance of plant**
- Rise of usage of plastic materials
- Simplification, functional integration, minimization of the number of subsystems
- Reduction of the number of components

APPLICATION **Operation areas, product gas quality, feed media tolerance**
- Intermittierent operation (Startup/Stopp from cold and standby status
- Dynamic operation (optimal use of fluctuating energy offer))
- Rise in product gas qualitiy during dynamic operation
- Rise in tolerance towards a fluctuating raw water quality (e.g. use of salt water & brakish water)

AUTONOMY **Optimization of plant operation**
- Plant operation completely from fluctuating energy offer (grid autonomy)
- Minimization of plant energy demand

OPEX-COSTS **Optimization of plant operation & of maintenance costs**

AVAILABILITY **Industrialization of development results**

Figure 29: Research and development areas for electrolysis operation to use hydrogen as an energy storage medium, Source: ZSW

In principle, like for any new technology, the efficiency should be increased towards the theoretically feasible respectively the energy consumption reduced to a technical minimum before market penetration. Costs have to be lowered by system simplification, series production and low cost materials, a safe operation with minimised manpower requirements at maximised product quality and a minimisation of operating costs. This requires at all levels from material selection up to facility concept planning scientific, technical and economic development. Only then the electrolysis can leave its present niche application and additional fields of application can be made accessible.

Development trends today

Due to the increased demand for seasonal energy storage for renewable energy, supply of renewable fuel for mobility and the demand for industrially used hydrogen from renewable sources the development of hydrogen production facilities and electrolysers has gained more dynamics. Priority have not only the technical and operational feasibility with renewable energies but especially reaching the cost targets, industrial realisation and the technical and economic feasibility of a wide range of power (0.1 - 10MW).

The most important aspect of development is reduction of the specific electrolysers and facility energy consumption. Figure°30 shows as an example the scientifically and in small scale technically feasible in energy consumption of specially developed electrode coatings at DLR in the 1990s. By these the energy consumption for electrochemical water dissociation could be reduced by 22% without changes to the electrolyser system concept or the technical periphery system. These good results now have to be realised in large power scale and a series production coating technique /14/.

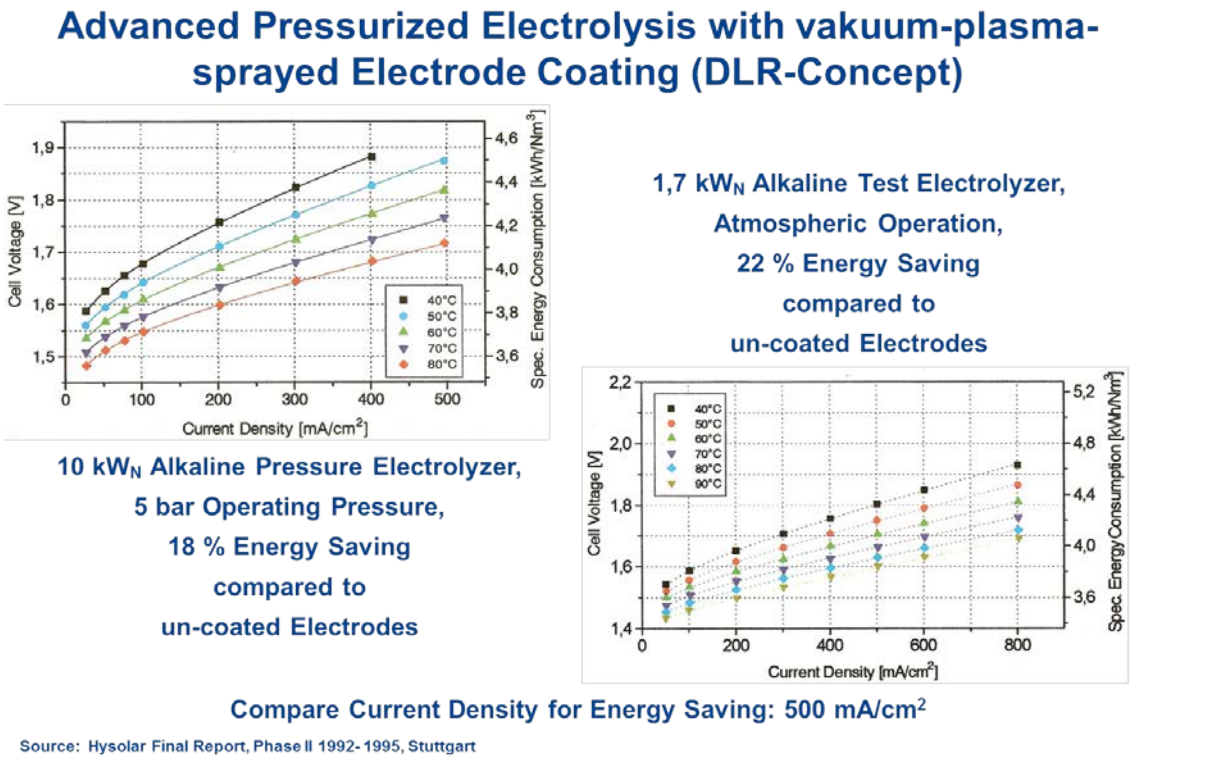


Figure 30: Scientific advance in reduction of the specific energy consumption

A new approach in development aims at minimising the system costs by modularising the complete system in pre-fabricated subsystems and by their serial production. Also minimisation of the installation costs can be achieved by a compact container-integrated system construction without solid building) as presented in the latest version of the company Hydrogenics in Figure°31. Container-integration of pre-manufactured subsystems requests initially a high effort in concept development as well as coordination with subsystem deliverers and container constructors. However it pays off by the possibility of direct transition from single system production to small-series manufacturing. Also it offers a high flexibility to adaptations to costumer requests. With the hydrogen production system displayed in Figure°31 Hydrogenics achieved a footprint of 50% in size as compared to the previous model.

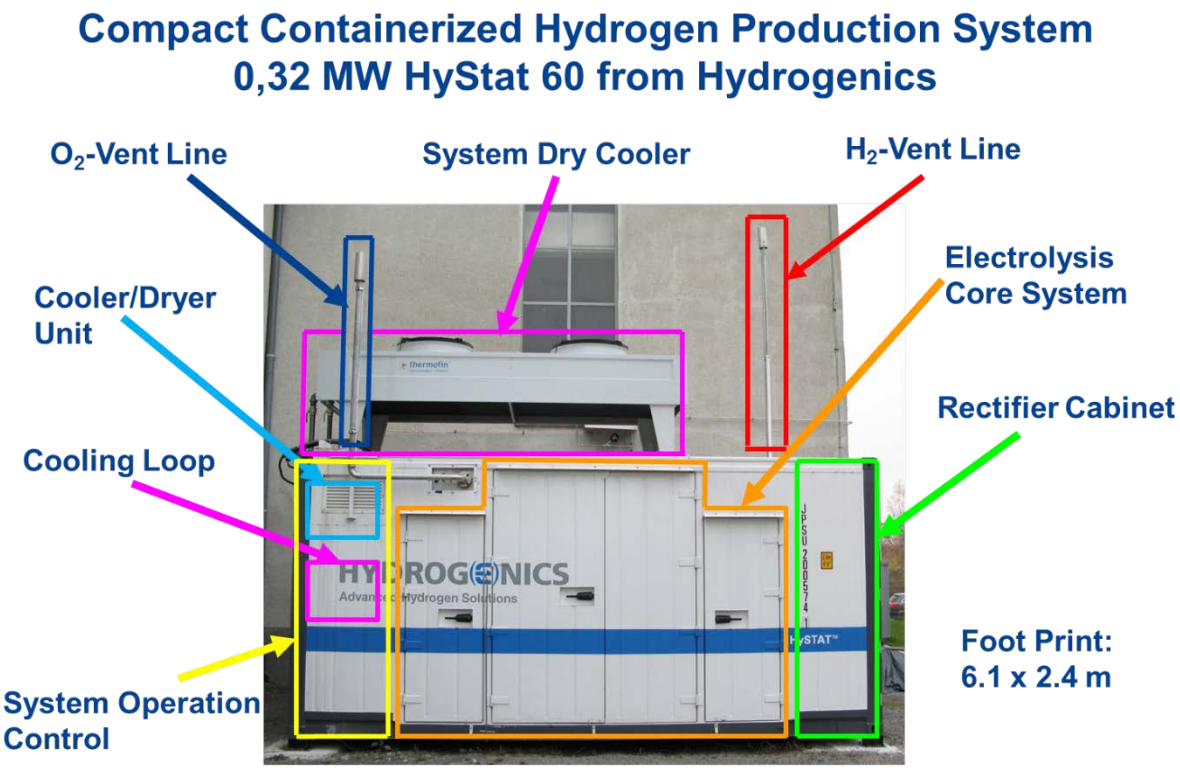


Figure 31: Compact containerized hydrogen production plant HyStat 60 from Hydrogenics; source: ZSW

Other manufacturers also offer container-based compact systems of comparable power based on the same 20ft standard container size. More powerful container-based systems are in development and were shown as detailed plans and 3D-models. It can be observed that the footprint-/volume need grows less than proportional to system power. A pressure electrolyser concept presented at Hannover Fair 2013 of 1.2MW electrical power needs no more than three 20ft containers.

5 Acknowledgement

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