Application of Photo-electrochemical Hydrogen Production for Autonomous Solar Based Electricity Supply

Jan Wingens, Gerhard Krost, *Member, IEEE*, Dieter Ostermann, Udo Damm and Jörg Hess

***Abstract*--Utilization of photovoltaic (PV) generated electricity in power systems detached from the public grid usually requires both short term storage for the compensation of day/night cycles as well as long term storage for smoothing the seasonal energy harvest distinctions. Prototype systems relying on an accumulator for short term and a hydrogen path - consisting of electrolyzer, hydrogen tank and hydrogen gas engine based generator (or alternatively a fuel cell) - as long term storage have proven well in various prototype plants. A disadvantage is the electricity based generation of hydrogen for the long term storage path; rather, direct solar hydrogen production using innovative photo-electrochemical (PEC) cells - which are newly available - eases and simplifies both plant design and operation. In the following these photo-electrochemical cells are briefly characterized and their potential exemplary application for the autonomous electricity supply of an industrial plant in several configuration variants is investigated.**

***Index Terms*—Autonomous electricity supply, Energy management, Energy storage, Hydrogen, Photo-electrochemical cells, Photovoltaic.**

I. Photo-electrochemical Cells

In 1972 an assembly was proposed which had the ability to directly electrolyze water by the influence of light [1]. This principle is currently further developed to marketing readiness of an innovative reaction cell for the photo-electrochemical production of hydrogen gas [2]. The cell consists of

- a housing which is filled with an aqueous electrolyte;
- one working electrode made of n-doped semiconductor (TiO_2) and
- a counter electrode made of metal (Pt) or an oppositely doped semiconductor,

see Figure 1. The pair of electrodes is electro-conductively connected and immersed in the electrolyte, thus subdividing the reaction cell in two chambers which are connected to each other in a liquid conducting manner. A light source irradiating the first electrode leads to formation of anodic and cathodic spaces next to the electrodes where the aqueous electrolyte is split to hydrogen gas in one and oxygen gas in the other chamber. Compression of the hydrogen gas allows for storage in long term range.

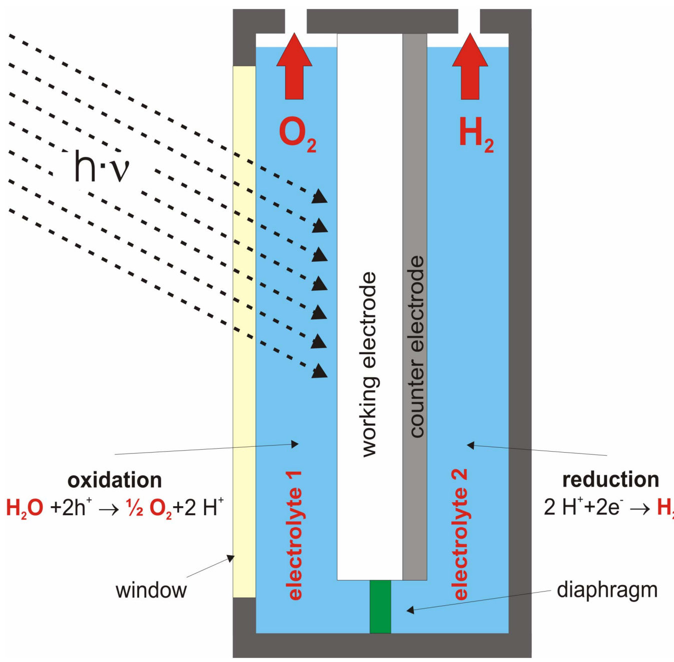

Fig. 1. Cross-section of photo-electrochemical cell.

The principle of photo-electrochemical (PEC) cells is seen advantageous especially for those solar applications where energy storage is needed, i.e. autonomous supply systems with no coupling to the electrical grid. In contrast to conventional photovoltaic (PV) plants, hydrogen as savable medium is directly generated – an electrolyzer as additional system component and cost factor is not needed.

II. Photo-electrochemical Cells vs. PV with Electrolyzer

In order to assess the potential of photo-electrochemical cells for practical application a measurement based comparison with conventional PV cells was conducted.

A. Physical performance

It was expected that the hydrogen output of photo-electrochemical cells is influenced by external physical parameters in similar way as the electrical output of PV cells. In order to procure concrete evidence, comparative measurements were performed in the lab, using a special HQI

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lamp with spectrum close to solar, mainly with respect to the impacts of light intensity, angle of incidence and cell temperatures. The investigations were made in a wide range of parameters considerably exceeding the standard measurement conditions (1.000 W/m², 25°C).
The connatural impact of solar irradiation intensity is depicted in Figure 2, left hand side. Disregarding the different capacities of test objects, the characteristic similarity of performance appears physically plausible.

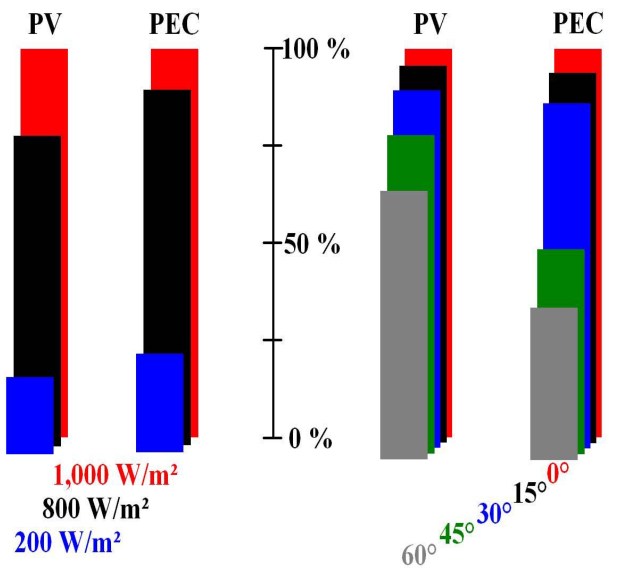

Fig. 2. Comparison of dependencies on irradiation intensity (left) and angle of incidence (right) for PEC and PV.

The angular dependency of PEC cells was measured to be stronger than that of conventional PV, Figure 2 right hand side. Even if it can be assumed that the respective semiconductor materials behave in similar way, the total refraction of light is different: in PV cells there is only one boundary layer (air / covering glassware), while in PEC cells light is fractured at both the external air / glassware as well as at the internal glassware / electrolyte boundary layers, thus lowering the refraction index in total. This finally leads to stronger decay of output especially for large angles of incidence.
The temperature coefficient of PEC cells in the temperature range 0…35 °C was found to be close to that of crystalline PV cells.

B. Efficiency

For given solar irradiation the efficiency of PEC hydrogen energetic output is lower than that of PV electrical output. To make things comparable – under the given fact that pure solar systems must comprise energy storage anyway – it seems reasonable to rely on hydrogen as storage medium which would require additional electrolysis in the case of conventional PV. The energy flow diagrams – including hydrogen compression for storage – are comparatively depicted in Figure 3, showing that PV overall efficiency (mono-crystalline cells) is in excess of that of PEC cells by a factor of 1.5 approximately.

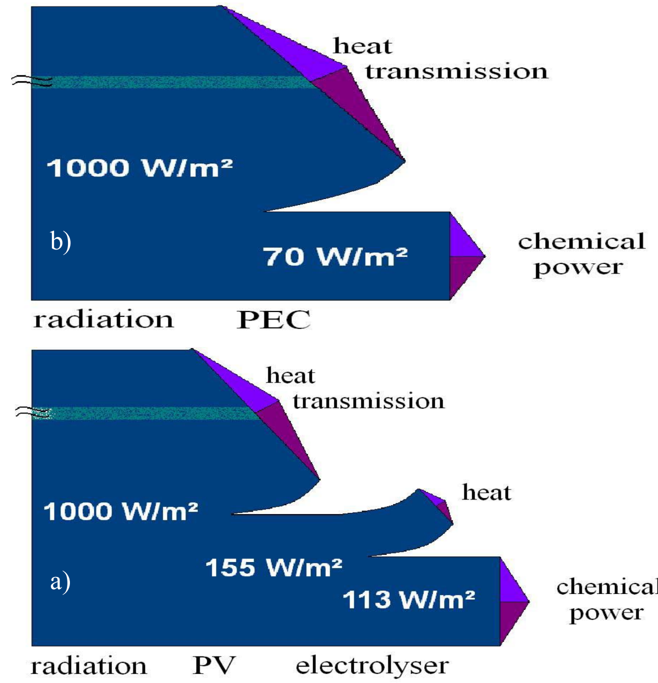

Fig. 3. Energy flow diagrams of conventional PV with electrolysis (a) and photo-electrochemical cells (b).

C. Cost considerations

Presently the cost level of PEC prototypes is approximately twice as high as that of commercially available mono-crystalline PV cells. This means – especially under the viewpoint of their lower efficiency – that photo-electrochemical cells are much more far away from economic reasonability even than conventional PV. On the other hand, nowadays PV has in fact seized a certain market segment after prices have significantly diminished by more than 80 % during first 20 years of commercial sales, see Figure 4.

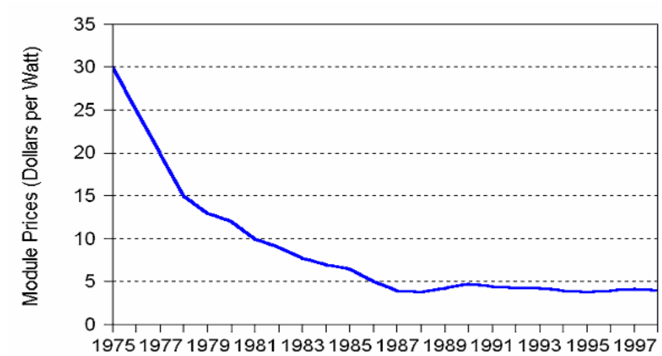

Fig. 4. Development of PV prices 1975 – 1998 [3].

In consequence of tremendously base raw material (natural TiO_2 instead of raised Si crystals in case of PV) and not yet established mass production, an at least likewise development of PEC prices can be expected for the future. Furthermore, the energetic amortization period of PEC cells is expected to be shorter than that of PV, and if hydrogen energy storage is considered in comparing investment cost of PV and PEC based systems, PEC is dispensed with electrolyzer cost. These perspectives encourage to explore the technical application potential of photo-electrochemical cells already now.

III. Investigation of Regenerative Supply of an Industrial Plant

From a weaving mill in Germany there was an incitation to investigate full solar based electricity supply of the plant – see Figure 5 –, making use of both

- conventional photovoltaic modules for direct load feed at day time and accumulator storage of electricity harvest surplus for night times, as well as
- innovative photo-electrochemical cells with long term hydrogen storage and gas engine driven generator for the seasonal compensation.
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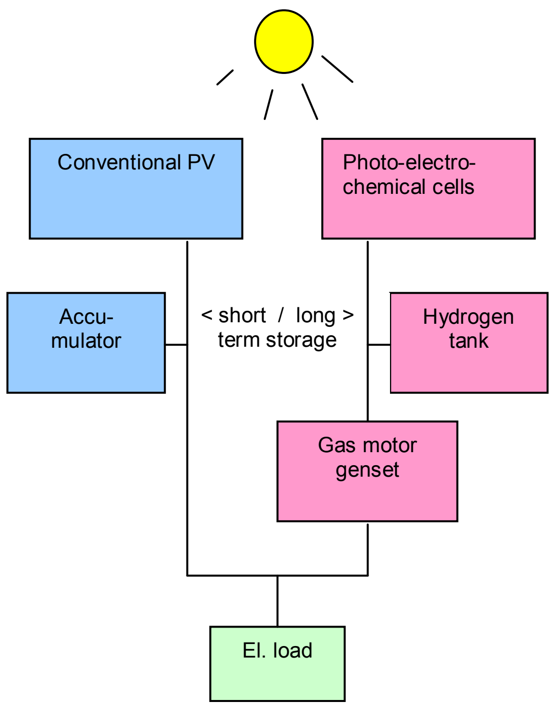

Fig. 5. Autonomous supply based on PV and photo-electrochemical cells.

The following study conducted for several variants of supply design was based on detailed operational simulation of the complete system in the Matlab/Simulink© environment, under application of given real yearly solar irradiation and load measurement data (Figure 6, both available in 15 min. resolution). Having moderate variations, the industrial load considered is approx. 1.3 MW peak with a yearly consumption of 6 GWh.

Regarding supply components, their boundary conditions such as minimal filling levels of storages as well as start up and minimum run times of devices were considered, as well as efficiencies, losses and controls. Types, data and cost of the particular components involved such as electrolyzer, accumulator, compressor, storage tank and photovoltaic panels were regarded as actually available on the market. Applying the above mentioned load and solar radiation measurement data the complete system including all situation dependent control interventions was simulated over one full year for each of the design variants compared in the following.

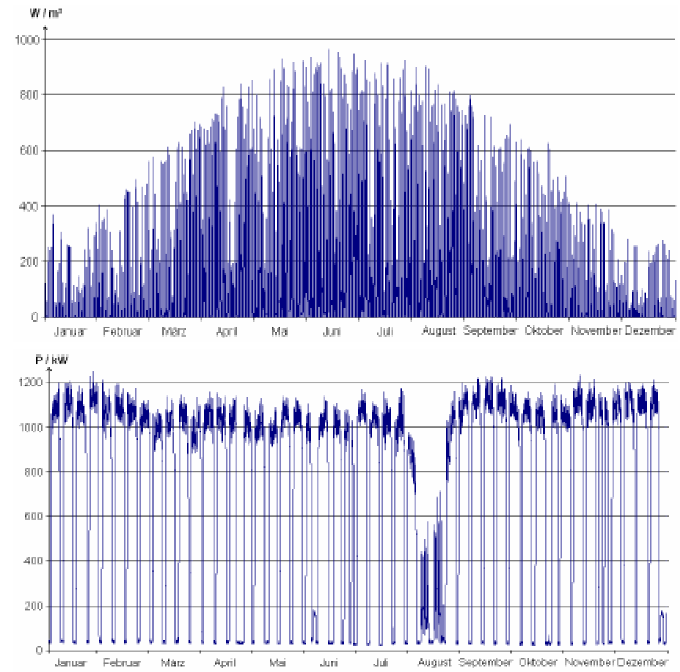

Fig. 6. Yearly shapes of solar irradiation (upper curve) and industrial load (lower curve).

A. Self-sustaining conventional PV based supply

As a first study, and for the purpose of later comparison with the intended PEC based approach, a solution purely relying on conventional PV as shown in Figure 7 was investigated.

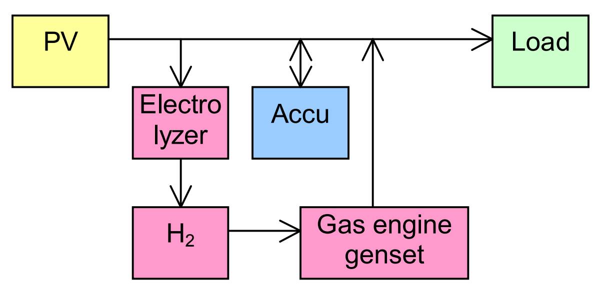

Fig. 7. Configuration principle of design variant *A*.

Optimization calculations led to a configuration of

- 6.73 MW conventional PV (39,100 m^2 of modules)
- 69.9 MWh lead acid accumulators (short term storage)
- 3.05 MW electrolyzer (alcalic)
- 150 kW compressor (50 bar)
- 2,290 MWh hydrogen tanks (long term storage)
- 1.3 MW hydrogen turbine driven generator set

altogether summing up to approx. 48 mill. €. Figure 8 shows the filling levels of both accumulator short term and hydrogen long term storages during the year under regard. Even if the yearly consumption is fully covered on a purely solar basis, the surface needed for PV modules placement would exceed the acreage available for that purpose. Furthermore, the size of the hydrogen storage required, comprising 170 tanks (50 bar, 763,000 m^3), is unreasonably large.

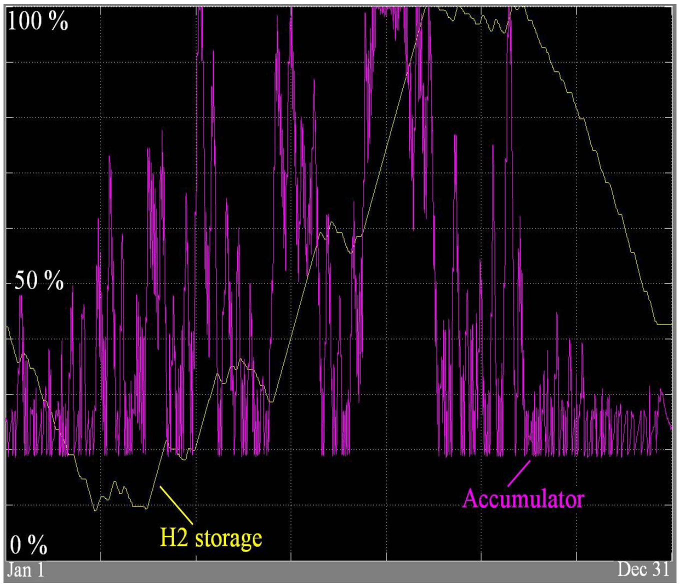

Fig. 8. Configuration *A*; filling levels of accumulator and hydrogen storages over one year.

B. Self-sustaining combined PV / PEC cells based supply

Concrete design optimization for the desired configuration principle based on both PV and PEC cells – see Figure 9 – yielded the following plant parameters:

- 9.72 MW conventional PV (56,500 m^2 of modules)
- 3.43 MW photo-electrochemical cells (49,000 m^2)
- 200 MWh lead acid accumulators (short term storage)
- 150 kW compressor (50 bar)
- 1,600 MWh hydrogen tanks (long term storage)
- 1.3 MW hydrogen turbine driven generator set

summing up to almost double the investment cost as in case *A*.

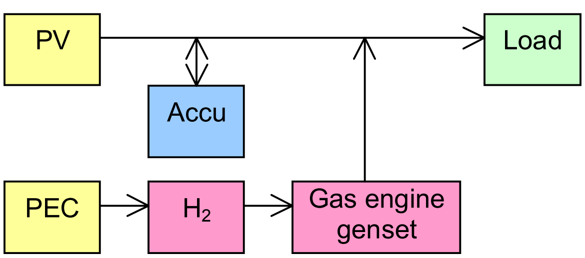

Fig. 9. Configuration principle of design variant *B*.

The filling levels over the year of both battery and hydrogen storage for this configuration are shown in Figure 10, proving that self-sustaining supply can be achieved with this configuration, too.

However, decoupling of the PV set from the long term storage path in this design variant *B* results in high PV capacity required, leading to extensive surplus generation during summer time – approximately half the amount of yearly harvest – as shown in Figure 11; but the PV capacity cannot be reduced in order to avoid critical undersupply during spring time.

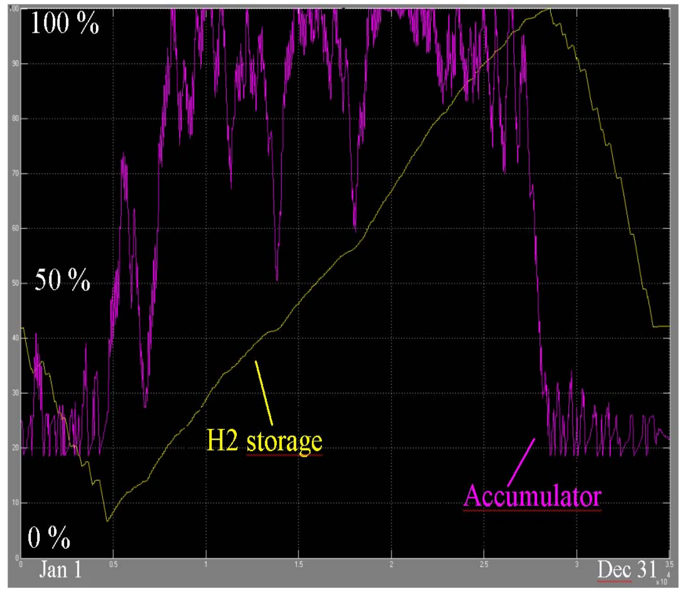

Fig. 10. Configuration *B*; filling levels of accumulator and hydrogen storages over one year.

Increase of the accumulator storage capacity by a factor of slightly above 3 to make use of this PV energy harvest – see Figure 11 – would be possible but leads to an unintended use of the accumulator as a second long term seasonal storage which is prohibited by cost reasons.

Furthermore, the required area for placement of both PV and photo-electrochemical modules would exceed the available acreage even considerably more than in the previous example *A*.

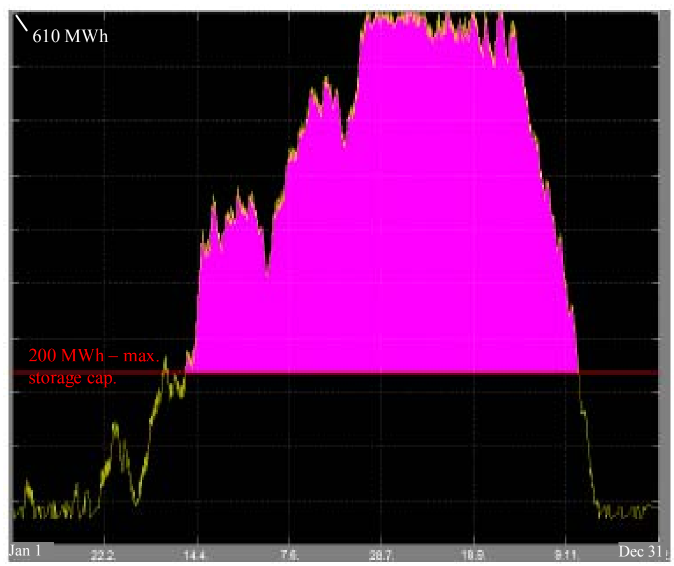

Fig. 11. PV surplus generation at summer time (configuration *B*).

In summary it must be stated that the proposed combined use of both PV and PEC cells for autonomous electricity supply as shown in Figures 5 and 9 respectively is not very well suited for the given industrial load profile. Therefore, other supply concepts should also be considered in the following.

C. Additional involvement of a wind converter

Decoupling of PV from long term storage is generally unfavorable if the source for long term storage is subject to the same temporal fluctuations as the PV / short term storage circuit. To avoid this disadvantage, the short term storage could, for instance, be supplied by a wind converter while the long term storage is further fed by photo-electrochemical cells, see Figure 12.

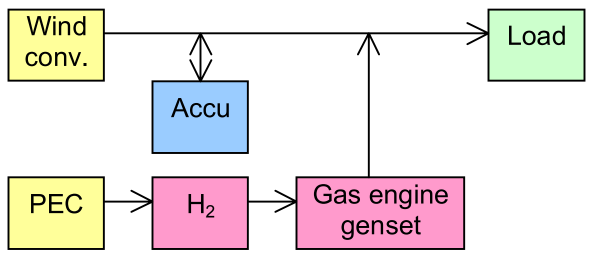

Fig. 12. Configuration principle of design variant *C*.

Calculations proved that this solution would require to even double the installed photo-electrochemical cells power, thus leading to investment cost as high as 2.4 times of those of reference case *A*.

D. Solution under consideration of investment cost and acreage available

In order to develop a solution which would provide full regenerative energetic autonomy with at the same time getting by with the given acreage (55.000 m^2) and minimal investment cost, optimization calculations procured that a configuration of

- 0.9 MW conventional PV (5.250 m^2 of modules)
- 250 MWh lead acid accumulators (short term storage)
- 3.9 MW electrolyzer (alcalic)
- 190 kW compressor (50 bar)
- 1,950 MWh hydrogen tanks (long term storage)
- 1.3 MW hydrogen turbine driven generator set
- wind converters (2 x Enercon E-82 [4]) 2 MW each

would limit the investment cost to 82 % of those in reference case *A*. The arrangement *D* is shown in Figure 13.

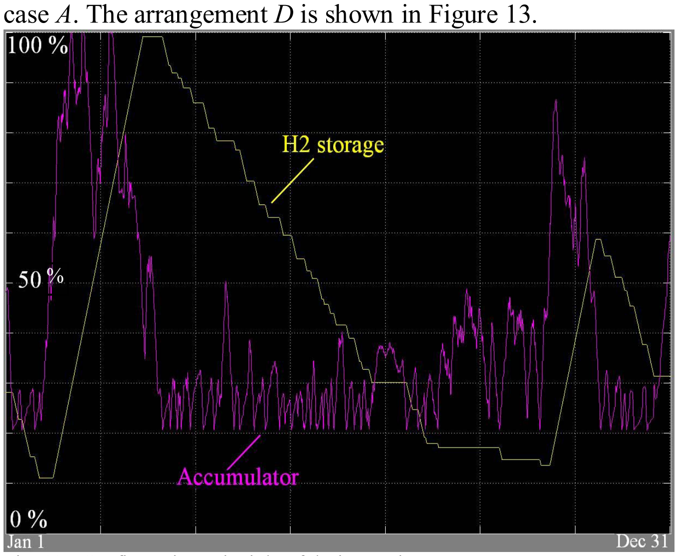

Fig. 13. Configuration principle of design variant *D*.

The (nowadays still) extremely expensive photo-electrochemical cells are not taking part in this approach, rather only those regenerative techniques which already have settled on the market were used. The yearly storage filling levels for this case are shown in Figure 14.

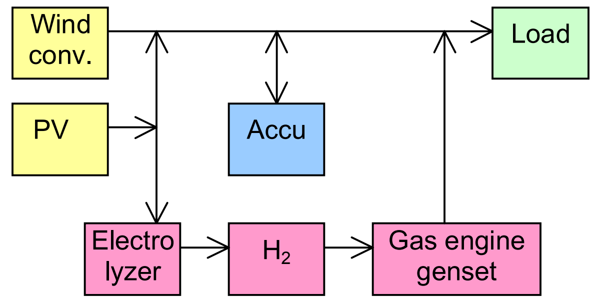

Fig. 14. Configuration *D*; filling levels of accumulator and hydrogen storages over one year.

It can be seen that also in this case the storages with their parameters as given above were designed appropriately, thus providing autonomous electrical supply of the industrial load all over the year. But, in consequence of the predominance of wind energy, the long term storage doesn't any longer compensate for the low solar harvest during winter time as to be seen in Figures 8 and 10, rather than the lower wind period during the summer months; PV is mainly related to short term storage.

IV. Summary and Outlook

Direct solar hydrogen production by innovative photo-electrochemical cells considerably simplifies the long term storage path of pure solar based electricity supply systems.

Comparative measurements proved that the performance of photo-electrochemical cells with regard to, e.g., dependency on intensity of light, angle of incidence etc. is similar to that of conventional PV. Their energetic efficiency is lower if generated H_2 energy contents is compared with PV electrical output, but taking into account the additional electrolysis needed for PV harvest storage it is more likely comparable.

The concrete components parameters as elaborated in the frame of an application study for full solar based electricity supply of an industrial plant yield tremendous requirement of both solar expanse and storage volume in several design variants investigated. Rather, additional employment of wind generation allows reducing solar and storage efforts.

As an even more promising application example, micro combined heat and power (CHP) supply of residential houses exploiting both gas engine generated electric power *and* waste heat [5] seems to be an interesting perspective for which the employment of PEC cells is currently being investigated. First results prove that for a typical single family house in Germany with up-to-date thermal insulation a share of approx. 9 % (1 MWh/year) of yearly natural gas consumption could be covered by hydrogen produced by 14 m^2 of photo-electrochemical cells installed on the roof. Rather, under present prototype conditions the investment cost required for this achievement would be unreasonably high, thus still being questionable under a pure economic aspect.

On the other hand it should be emphasized that photo-electrochemical cells are still at the very beginning of development phase which allows to suppose that their price can considerably be reduced in the future as it was experienced with conventional PV, too.

V. References

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