An Experimental Study of Laboratory Hybrid Power System with the Hydrogen Technologies

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Abstract. *This paper presents very small laboratory hybrid photovoltaic-hydrogen power system. The system was primarily assembled to verify the operability of the control algorithms and practical deployment of available commercial hydrogen technologies that are directly usable for storage of electricity produced from renewable energy sources in a small island system. This energetic system was installed and tested in Laboratory of fuel cells that is located in the university campus of VSB–Technical University of Ostrava. The energetic system consists of several basic components: a photovoltaic field, accumulator's bank, water commercial electrolyzer and compact fuel cell system. The weather conditions recorded in two different weeks as model weather and solar conditions are used as case studies to test the energetic system and the results for two different cases are compared each other. The results show and illustrate selected behaviour curves of the power system and also average energy storage efficiency for accumulation subsystem based on hydrogen technologies or at the energetic system embedded components. On the basis of real measurement and its evaluation the ideal parameters of the photovoltaic field were calculated as well as the hydrogen technologies for supposed purpose and the power requirements.*

Keywords

Efficiency, electrolysis, energy conversion, energy storage, fuel cells, hybrid power system, hydrogen storage, photovoltaic, renewable energy sources.

1. Introduction

The planet Earth has no other resources besides those that evolved as a result of natural physical processes long before the arrival of human era. These materials include mainly fossil fuels, as the greatest contribution to the development of mankind, radioactive elements or hydrogen bonded in water. Since the deposits of the first two raw materials mentioned above are unfortunately limited and the whole world is still dependent on them, further technologies are appreciated for sustainable development and catering for increasing demand, while these enable utilization of other energy resources, including mainly energy from wind, water and the Sun. The problems associated with utilisation of the said energy resources address mainly their variability in time, substantial dependency on local conditions and low density of energetic flow from transformation equipment. Mankind has been using these energy resources for centuries, and the current state of the art equipment makes them a very prospective and interesting supply of energy. The technology of thermonuclear fusion, which is still in development, could solve most economic and environmental problems incidental to retrieval of energy. This technology would further enable a smooth transition to hydrogen technologies as it could be considered a hydrogen-based technology itself. Several optimistic prognoses say this technology should be launched in commercial practice within the "mere" period of 40–50 years. The transition period before full adoption of the thermonuclear fusion technology can be used for to proceed with retrieval of energy from the relatively familiar hydrogen technologies being developed and put into use. Just the combination of technologies for the utilization of energy from renewable sources and hydrogen technologies can help to remove mentioned deficiencies or at least improve the usability of renewable energies and generally expand the limits of acceptability of these sources into the power distribution system. Such hybrid power systems was also examined and tested by the authors in other studies [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17].

2. Description of Experimental Energy System

The basic idea of the whole project was to create a self-contained and self-sufficient source of electric energy to provide power supply into appliances within suitable premises with respect to the estimated output from the entire system. Premises suitable for this application would comprise a smaller leisure facility, remote buildings or facilities that are either impossible or very costly to connect into the grid. The system, designed here, could be also used as an alternate solution for power supply employing motor-driven generators. The system output should be ideally used to cover a certain permanent consumption of electric power for a defined period matching the duration of supply provided with an integrated hydrogen power supply unit as well.

The primary energy resource installed within the power system is, therefore, represented by an array of photovoltaic panels located on the laboratory roof. The photovoltaic system (further PVS only) is made of 12 pieces photovoltaic panels with the total installed power of 1.98 kWp.

The direct-current (DC) power is fed into the DC/DC converter (charger) and subsequently forwarded to the direct-current bus with nominal voltage of 48 V defined by the auxiliary accumulator storage bank linked with the bus. The nominal capacity of power storage bank that consist from four accumulators in series connection is 75 Ah, which defines its total power capacity of 3.6 kWh. The main function of the accumulator storage bank in the energetic system is accumulation of electrical energy produced by photovoltaic panels that does not directly cover consumption of a load (appliances connected by the user), consumption of the electrolyzer, transmission and also transformation losses of the system. Another benefit and unambiguously indispensable function of the accumulator power storage is the functionality as power "buffer" from which electrolyzer's consumption is covered under a defined temporal constraints of the photovoltaic system that are caused by immediate worsening of local meteorological situation.

The said direct-current bus is also provided with a stabilizing DC/DC converter for connection of one of the essential hydrogen technologies - a Polymer Electrolyte Membrane (PEM) type fuel cell. As the specific fuel cell was after several necessary adjustments its electronic systems used the Ballard's Nexa^{TM} Power Module readily available on the market.

Production of hydrogen in the system is handled by an electrolyzer (ELCLZR in diagram), which operated during the period of power surplus from photovoltaic source to store the power in hydrogen. The electrolyzer

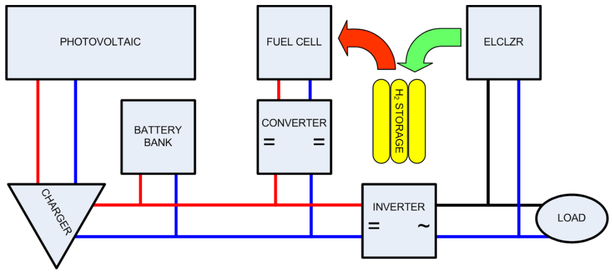

Fig. 1: Diagram of key components of tested energetic system [1].

available for production of hydrogen was the laboratory unit low temperature PEM type Hogen GC600 connected to the system via an alternating-current (AC) bus. The electrolyzer is able to supply approx. 0.6 Nl per minute of gaseous hydrogen at the pressure up to 13.8 bar.

The produced gaseous hydrogen was stored in three standard pressure vessels with water volume of 50 l used for capturing pure hydrogen gas (see Fig. 1). The total capacity of storage therefore equals to water volume of 150 l, which corresponds to approx. 2 Nm^3 (normal cubic meters; gas volume related to normal pressure 100 kPa and temperature 20 °C) of hydrogen gas in a bundle, i.e. which is approx. 650 Nl (normal liters) per one pressure vessel at the maximum pressure in electrolyzer. The system for storage and distribution of hydrogen is also equipped with a connection point for potential supply of hydrogen from an external supply of hydrogen gas from the laboratory hydrogen distribution. The fuel from external tanks is used in case the produced hydrogen stored in the primary and above mentioned tank for power system is depleted during the operation of the fuel cell and the whole power system faces the risk of complete shutdown.

The last essential element within the power system is a power inverter to ensure production of alternating voltage with standard parameters in the single-phase low voltage grid (230 V, 50 Hz) used to supply the alternating current bus. The alternating current bus was also employed to supply the load and electrolyzer as needed [1].

The power system also featured the control and independent measuring system. The measuring system was implemented to ensure measuring of non-electric and electric values of the whole power system, for digitalisation, processing, visualization and storage of data obtained by measurement and values monitored during operation of particular components of the power system. The whole power system is controlled and operated via a control system fitted with the main control unit in the form of a programmable logic controller (PLC) Siemens SIMATIC type S7-224XP with the relevant control and visualization peripheries. The user's interface and control algorithm were programmed to make the intended ideal operation of power system ensure mainly uninterrupted supply for the permanent design consumption of 200 W and the implemented hydrogen accumulation system with fuel cell was to balance overhang of the power produced by photovoltaic system or to supply electric power in case of production lack using renewable sources.

3. Analysis of Power System Operation Characteristics

Measurements further used as the basis for the relevant conclusions were run during first stage debugging of the power system during the autumn season. To serve the assessment purpose, model measuring was split into two periods differing mainly with respect to the nature of weather and solar radiation conditions. As far as sunshine power is concerned, the first period was below average, and the second period of measuring could be defined as very good [2].

The following figure (see Fig. 2) shows a fragment of data obtained by measurement over five days from 23.10. to 27.10.2010 representing behaviour of selected values within the power system. As the first behaviour curve clearly shows, depicting the power supplied by photovoltaic system (PPV value), this period was associated with solar power below average. The curve illustrates mainly two days with average solar power - 24. and 26.10 - plus one day with overcast condition (25.10.) and one model day (27.10.), when the electrolyzer was launched. Activation of the electrolyzer is evident from the second behaviour curve showing the course of power drain by inverter from the direct-current bus. As one can further see, besides deviations, the permanent load ranged around approx. 240 W corresponding with a permanently connected load of 200 W. The different in output values corresponds mainly with losses during transformation and transmissions losses in the distribution system.

To assess the operation of the power system, we will further deal with behaviour shown in Fig. 3 detailing the behaviour of six values in the power system. Values $I_{PV\ dc}$ and $U_{PV\ dc}$ relate to the photovoltaic system and define the current and voltage from the photovoltaic system. Measuring of values from the photovoltaic system was run on supply cables connected to input terminals of the charger. Further indicators of behaviour – $I_{ChAR\ dc}$ and $U_{BAT\ dc}$ - show the course of current at charger output and voltage from the power storage bank, which basically defines the voltage in direct-current bus. The values of $I_{ChAR\ dc}$ and $U_{BAT\ dc}$ are used to calculate the output power of the charger, which is further defined as the value $P_{ChAR\ dc}$. Values of $I_{ISL\ dc}$ and $U_{ISL\ dc}$ show the input current and voltage at inverter terminals. In case the system is connected to a single fuel cell only, values $I_{ISL\ dc}$ and $U_{ISL\ dc}$ show the current and voltage at the output from stabilizing converter fitted to the fuel cell.

Figure 3 shows ten time indicators, which highlight key moments in operation of the power system. In the beginning, the values shown to the left from indicator 1, the system was in operation, and the consumption of system and load was covered with the photovoltaic system. That was followed by gradual decrease of output from PVS up to the point, when the PVS was no longer able to cater for consumption. Coverage of power consumption was then launched with the assistance of the accumulator power storage bank. This is also reflected in the voltage behaviour captured in UBAT dc curve, which showing the clear drop in voltage from batteries. Once the insufficient capacity of batteries was assessed (indicator 2), the system was supported by the fuel cell to cover the system consumption in full. The fuel cell was in operation till dawn (indicator 3), when the supply from PVS was restored. However, the relatively low output of PVS during the particular day could not ensure sufficient re-charging of batteries resulting in inevitable re-connection to the fuel cell (indicator 4). The very next day was even less convenient in terms of solar power and indicators 5 and 6 show several attempts to shut the fuel cell down. The power system operation was similar on the subsequent day, with partial re-charging of the power storage bank. The fuel cell took over power production next night only. The last day in the description brought clear skies, which is also reflected by its operation data. As the behaviour indicators after assessment of sufficient power from the PVS (indicator 7) clearly show, the fuel cell has been disconnected. Batteries were re-charged to a sufficient level gradually to enable connection of the electrolyzer (indicator 8). It was in operation until cloudy conditions (indicator 9), when the control system interfered to disconnect it and regenerate the power storage bank, which is shown by increase of voltage within. Once the skies cleared up again, sufficient output from the photovoltaic system resumed and the production of hydrogen restarted. The production cycle terminated approx. 1 hour later and the power system began to utilize the power accumulated in batteries.

If we abstract from assessment of the very efficiency of photovoltaic panels, the first indicator in chain of power transformations may be represented by the efficiency of first converter (charger) that transforms power produced by PVS to parameters of the direct-current bus. This efficiency value has been calculated as a rate between the two values of energies i.e. energy measured on the charger output and energy value delivered on to charger input (9.756 kWh / 10.008 kWh)

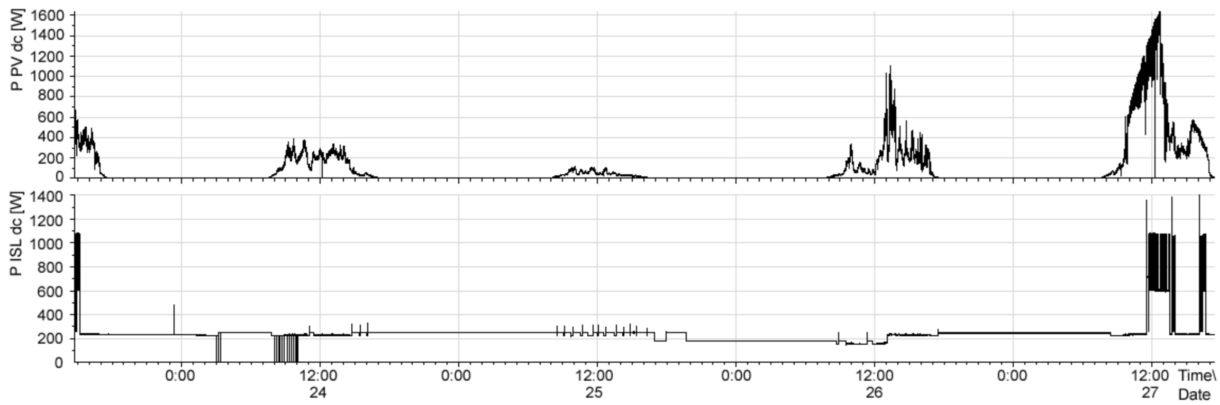

Fig. 2: Selected behaviour curves of the power system for a period of inconvenient solar and weather conditions. ($P_{PV\ dc}$ - power supplied by photovoltaic panels, $P_{ISL\ dc}$ - power drawn at inverter).

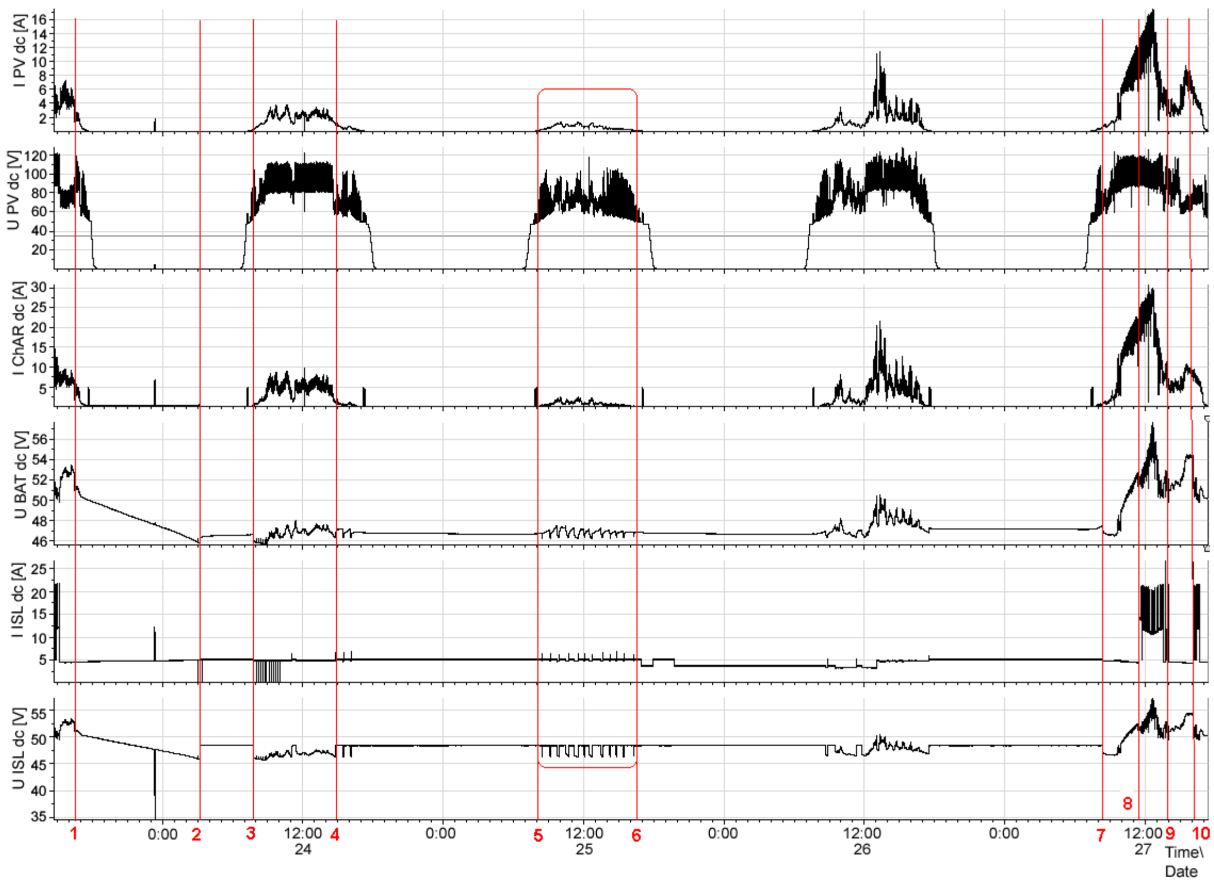

Fig. 3: Selected behaviour indicators of measured values in the power system for cloudy days ($I_{PV\ dc}$ - current in photovoltaic panels, $U_{PV\ dc}$ - voltage on photovoltaic panels, $I_{ChAR\ dc}$ - current at charger input, $U_{BAT\ dc}$ - voltage in power storage bank, $I_{ISL\ dc}$ - current at inverter input, $U_{ISL\ dc}$ - voltage at inverter input). All the power or efficiency indicators shown below have been calculated using the said behaviour indicators.

for overall operating time and it is equal to 97.48 %. Another important element in the system is the inverter whose overall average efficiency was calculated from the measured data as 81.18 %. Concretely, was for determine the efficiency of the inverter calculated the energies delivered to the inverter input with a value of 24.139 kWh and energy taken from the inverter output with value 19.596 kWh. This efficiency is relatively low and it can be justified by the fact that the inverter was not even near its operating scope of defined nominal output, which is 4.2 kW; and worked in the system under load from 0.24 kW to 1.1 kW only.

The most vital information about efficiency of the hydrogen power storage system is derived from data on consumption and production of hydrogen within the power system, resp. relevant amounts of electric power produced and consumed by hydrogen technologies. As far as these details are concerned, the total amount of hydrogen consumed by the fuel cell within the observed period was 12,631 Nl. Converted with respect to the maximum power utilization by PEM type fuel cell, this amount corresponded to 37.173 kWh of stored energy. The fuel cell supplied the system with 14.138 kWh, which corresponds with efficiency rating of transformation of power from hydrogen into electric power supplied to the direct-current bus equal to 38.03 %. This efficiency includes losses on the route from "stack" of fuel cell up to terminals on the inverter, i.e. losses in distribution lines, consumption within the fuel cell itself and losses during transformation of output using the stabilizing DC/DC converter, this is the net production efficiency of fuel cell in other words.

The reverse process - electrolysis - run in accordance with behaviour indicators described earlier, especially the data obtained on the last day (see Fig. 3 – between indicators 8 and 9, past 10 and partially even before indicator 1), consumed 1.575 kWh to supply the electrolyzer which produced 100.53 Nl of hydrogen. This amount of hydrogen gas corresponds to 0.296 kWh of energy usable by the fuel cell and the efficiency of electric power conversion into hydrogen equals to 18.8 %. Another fact worth mentioning is that the said efficiency value reflects rather the efficiency of subsystem for hydrogen production, not just the electrolyzer as a device, since this value is also affected by losses incurred during idle times, when no hydrogen was produced and the electrolyzer stayed in the operation initialization stage etc. The transformation efficiency during stable operation of the electrolyzer is equal to 24.8 %. In other words, the example of the electrolyzer operation shows a serious effect of settings made to the algorithm of the control system with impact to the overall efficiency of power system as a whole. The level of efficiency of transformation of the electric power is very low and that is mainly due to the design of implemented electrolyzer and definitely not due to the conversion efficiency of electrolysis as a electrochemical process. The most common value of the energy efficiency of electrolysis process which is achieved in practice on laboratory testing devices is in interval roughly between 60–80 % [5], [6], [8], depending on specific parameters of used equipment and its operational parameters.

Another measurement to be assessed has been taken with respect to the said period under the most convenient conditions possible. The first four days illustrated by the fragment of measured data shown in Fig. 4 brought absolutely clear skies, which is matched by achieved peaks of output from the photovoltaic system reaching values above 1.4 kW, i.e. 73 % (usage) of the installed capacity. As far as the operation characteristics of the power system are concerned, these four days are almost identical, and time indicators can be used to interpreter all the events observed, similarly to the previous case. The fifth day shown in behaviour indicators at the last one did not bring such convenient weather, compared to preceding days, and the course of output drawn by inverter shows the electrolyzer was not launched either. The power available from the photovoltaic system was used to re-charge the power storage bank only. Figure 5 shows almost ideal characteristics providing a clear demonstration of essential principles of the power system. The indicator 1 (as well as 8) shows the moment, when the capacity of batteries has been depleted, and the production of electric power in the fuel cell was initialized around one o'clock in the morning. The fuel cell was shut down, and the coverage of input for load was taken over by the photovoltaic system at the moment shown by indicator 2 (as well as 9). The time indicators 3 and 4 define a time interval (approx. 3 hrs.) of the electrolyzer operation. Termination of charging of the power storage bank and the beginning of its discharge is marked using the indicator 5 (as well as 7). The subsequent three days show repetition of the power system cycle at the same level of defined operation logic.

Power parameters and efficiency levels set for individual components of the power system determined using the data obtained by measurement during the said interval, i.e. from 27.10. to 1.11., have been summarized in Tab. 2.

Compared to the previous assessments, the converter efficiency has been determined at 89.68 % that is higher thanks to its improved utilization. The efficiency of the charger achieved a slightly lower level of 97.38 %, which is most likely due to measurement inaccuracy and subsequent calculation operations during processing of the measured data only. As far as the particular period is concerned, the amount of power produced by photovoltaic system reached 25.3 kWh and the charger supplied the system with 24.6 kWh. The amount of power supplied to the system by fuel cell was

Tab. 1: Summary of data on power system operation in the period of inconvenient solar and weather conditions.

Energy [kWh] Amount of H_2 [NL]	Supplied	Drawn	Efficiency of	%
Energy supplied from PVS [W_{PV}]	10.008	-		
Energy at charger output [W_{ChAR}]	9.756	-	Charger	97.48
Energy at inverter input [W_{ISL}]	24.139	-	Inverter	81.18
Energy drawn from the system [W_Z]	-	19.596		
Energy drawn by load [W_{LOAD}]	-	18.021		
Amount of hydrogen produced	-	100.53	Electrolyzer	18.78
Equivalent amount of energy in H_2	-	0.296		
Energy drawn by electrolyzer [W_{ELC}]	-	1.575		
Amount of hydrogen consumed	12 631.0	-	FC+Converter	38.03
Equivalent amount of energy in H_2	37.173	-		
Energy supplied by fuel cell [W_{FC}]	14.138	-		

Tab. 2: Summary of data on power system operation in the period of convenient solar and weather conditions.

Energy [kWh] Amount of H_2 [NL]	Supplied	Drawn	Efficiency of	%
Energy supplied from PVS [W_{PV}]	25.267	-		
Energy at charger output [W_{ChAR}]	24.605	-	Charger	97.38
Energy at inverter input [W_{ISL}]	34.081	-	Inverter	89.68
Energy drawn from the system [W_Z]	-	30.564		
Energy drawn by load [W_{LOAD}]	-	23.506		
Amount of hydrogen produced	-	465.12	Electrolyzer	19.39
Equivalent amount of energy in H_2	-	1.369		
Energy drawn by electrolyzer [W_{ELC}]	-	7.058		
Amount of hydrogen consumed	8 138.8	-	FC+Converter	37.20
Equivalent amount of energy in H_2	23.952	-		
Energy supplied by fuel cell [W_{FC}]	8.911	-		

8.9 kWh, which required more than 8 Nm^3 of hydrogen consumed. The generator block with fuel cell, i.e. the fuel cell and its stabilizing converter, worked with the total efficiency of fuel transformation equal to 37.2 %. The different between power supply efficiency of the fuel cell shown by the data obtained is not substantial and it is mainly caused by longer period, when the fuel cell operated outside the optimal operation conditions, compared to the total operation period. The previous assessment shows the fuel cell in operation basically throughout the entire period of measuring, which can be easily compared using behaviour indicators illustrated in Fig. 3 and Fig. 5.

Similar logic is implemented for reasoning of higher efficiency of hydrogen production reaching the level of 19.4 % in the second case of operation. This slight increase of operation efficiency of the electrolyzer is probably supported by the essentially stable operation of the electrolyzer without unnecessary warm-up stages compared to its total operation period. The amount of hydrogen produced throughout the entire period of measurement assessed was 465 Nl, which can be expressed by the power equivalent of 1.37 kWh.

4. Summary

The data and parameters mentioned above imply several important conclusions. It is absolutely evident that "the bottleneck" of the whole power system is represented by the specific electrolyzer employed. The very low efficiency (around 19 %) makes it totally unacceptable for similar installations. As already mentioned above, the minimum operation efficiency of regular PEM type electrolyzers available on the market ranges within the interval of 56–73 % [4], depending mainly on the volume of production capacity.

If the power system were to employ an electrolyzer technology with the same parameters (efficiency), the coverage of hydrogen consumption ensured by the fuel cell, properly quantified and determined for the first assessment period at approx. 12.6 Nm^3, would have to be catered by the total of 14 electrolyzers operated in parallel 5 hours a day for the total period of 5 days (all of the same type, i.e. Hogen GC 600). However, the power consumed by these devices would reach the level of 196 kWh, which in turn corresponds with the required absorbed power of approx. 7.8 kW. Considering the assessed efficiency of the charger, this would be matched by 60 % usage of photovoltaic producing 13 kWp, which requires an installation comprising 79 photovoltaic panels. Various variants of the above-mentioned modification with said parameters are summarized in Tab. 3.

Similar ideas may be elaborated for the second case too as it is based on values analyzed under relatively convenient weather conditions. This case should be considered with values matching the data from Tab. 3, obviously with the different quantity of hydrogen required by fuel cell. As implied by values summarized

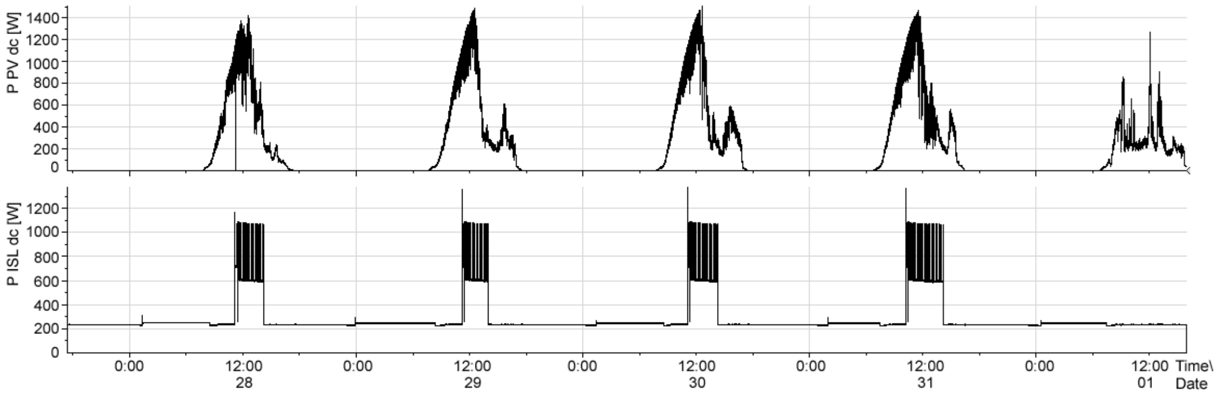

Fig. 4: Selected behaviour curves of the power system for a period of convenient solar and weather conditions. ($P_{PV\ dc}$ - power supplied by photovoltaic panels, $P_{ISL\ dc}$ - power drawn at inverter).

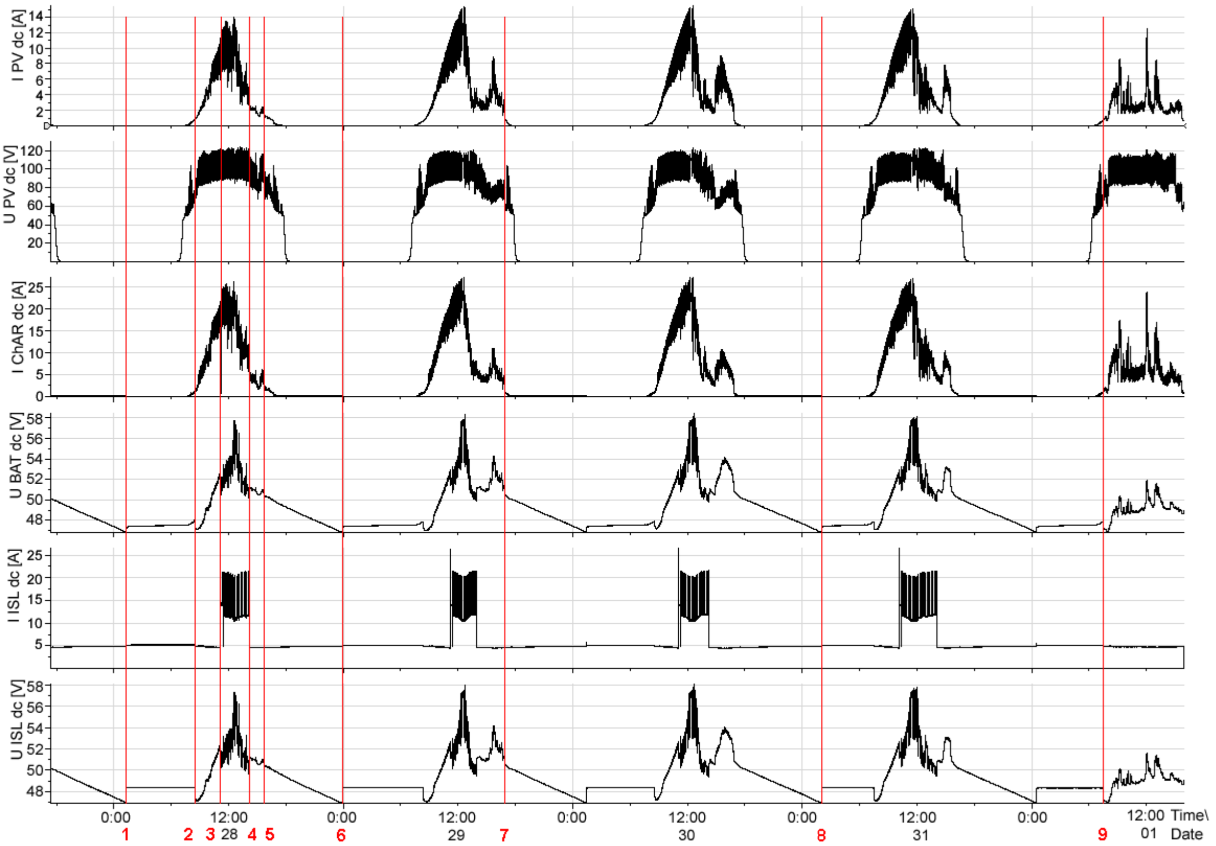

Fig. 5: Selected behaviour indicators of measured values in the power system for clear sky days. ($I_{PV\ dc}$ - current in photovoltaic panels, $U_{PV\ dc}$ - voltage on photovoltaic panels, $I_{ChAR\ dc}$ - current at charger input, $U_{BAT\ dc}$ - voltage in power storage bank, $I_{ISL\ dc}$ - current at inverter input, $U_{ISL\ dc}$ - voltage at inverter input .

Tab. 3: Summary of the intended substitution of equipment required to achieve the necessary hydrogen production levels in case of poor weather conditions.

Entered parameters		
Total amount of hydrogen required		12 631 Nl
Equivalent energy		37.173 kWh
Number of days of operation		5 days
Number of hours of operation per day		5 h
Efficiency of transformation		19.00 %
Charger efficiency		97.48 %
Electrolyzers production capacity		36 Nl/h
One PV panel output		165 Wp
Calculated parameters		
Number of electrolyzers		14 pcs
Energy consumed by electrolyzers		195.647 kWh
Electrolyzers power requirement		7.826 kW
Overall PVS system utilization	**Total installed capacity of PVS**	**Number of panels**
30%	26.086 kWp	158 pcs
40%	19.565 kWp	119 pcs
50%	15.652 kWp	95 pcs
60%	13.043 kWp	79 pcs
70%	11.180 kWp	68 pcs
80%	9.782 kWp	59 pcs
90%	8.695 kWp	53 pcs

Tab. 4: Summary of the intended substitution of equipment required to achieve the necessary hydrogen production levels in case of good weather conditions.

Entered parameters		
Total amount of hydrogen required		8 139 Nl
Equivalent energy		23.952 kWh
Number of days of operation		5 days
Number of hours of operation per day		5 h
Efficiency of transformation		19.00 %
Charger efficiency		97.48 %
Electrolyzers production capacity		36 Nl/h
One PV panel output		165 Wp
Calculated parameters		
Number of electrolyzers		9 pcs
Energy consumed by electrolyzers		126.063 kWh
Electrolyzers power requirement		5.043 kW
Overall PVS system utilization	**Total installed capacity of PVS**	**Number of panels**
30%	16.808 kWp	102 pcs
40%	12.606 kWp	76 pcs
50%	10.085 kWp	61 pcs
60%	8.404 kWp	51 pcs
70%	7.204 kWp	44 pcs
80%	6.303 kWp	38 pcs
90%	5.603 kWp	34 pcs

in the Tab. 4, the system would require 51 photovoltaic panels to produce approx. 8.1 Nm^3 of hydrogen with the power equivalent of 24 kWh, involving 9 electrolyzers used within the experimental power system.

Further components of the power system show very favourable efficiency parameters. The fuel cell worked as expected, with respect to the efficiency of stabilizing converter declared by its manufacturer at 90 %, with the average conversion efficiency of 41.8 %, which exactly corresponds with the value determined from the above mentioned independent measurements on the idle fuel cell within a power system.

The total efficiency of a completed hydrogen accumulation cycle within the experimental power system is determine when considering the average efficiency of key components. These partial efficiencies were determined for two observed periods with inconvenient and more convenient solar conditions and were calculated as its arithmetic averages, i.e. 37.62 % for generator production block with a fuel cell and 19.09 % for the electrolyzer. This total efficiency, therefore, reached the level of 7.18 %. Inclusion of the average charger efficiency of 97.43 % makes the overall efficiency of the hydrogen cycle equal to 7.0 %.

5. Conclusion

This paper deals with issues associated with integration of system for accumulation of electric power based on hydrogen technologies into power systems producing electric power from renewable energy sources.

The contents of this paper summarize results obtained through practical measurements on the built hybrid power system with accumulation of electric power by means of hydrogen technologies and especially the subsequent practical analysis of results produced by actual testing operation of this power system.

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