Electric energy module for energy-autarkic living

Picture of the energy storage module with PV on the roof and a large side door for easy access.

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Zusammenfassung Abstract

Wenn, wie durch das BFE (Bundesamt für Energie) vorausgesagt, der Anteil an erneuerbarer Energie im Stromnetz steigt, dann wächst auch der Bedarf an Energiespeicher. Lokale Energiespeicher in Form von Wärmespeicher und Stromspeicher können die durch erneuerbare Energie verursachte Leistungsfluktuationen minimieren. Zukünftige Energiespeicher müssen aber nicht nur als Tagesspeicher dienen, sondern auch in der Lage sein, saisonale Überbrückungen zu ermöglichen. Meist sind diese beiden Funktionen nicht durch eine Technologie umsetzbar. Für das von der EMPA entwickelte und gebaute autarke Gebäude SELF wurde ein Prototyp eines Hybridspeichers realisiert. Dieses Speichersystem besteht aus einem Block Lithiumionen- Batterien für die Tagesspeicherung und einem Wasserstoffspeicher bestehend aus Wasserstoffgenerator, Metallhydridtanks und Brennstoffzelle als Saisonspeicher. Das System wird durch PV Generatoren geladen und versorgt das SELF Gebäude mit Strom und Wasserstoff.

If the fraction of renewable energy is increased, as proposed by SFOE (Swiss Federal Office of Energy), energy storage becomes an essential component in the electric grid. Local and cluster energy storage systems for heat and electricity can strongly decrease grid load fluctuation and thus improve grid stability. In order to reach maximum annual impact energy storage must consist not only of short term but also of long term storage solutions. These are often not one and the same storage type. For the EMPA self sufficient building SELF a prototype hybrid storage was developed. This system consists of lithium ion battery storage for diurnal storage and hydrogen storage consisting of hydrogen generator, metal hydride and fuel cell for annual storage. The complete system functions as a mini energy hub. It is powered by two PV generators and supplies the SELF building facility with electric power and hydrogen.

1. Scope

In the frame of the development of the Empa self sufficient building SELF the step to build a hybrid electric storage was taken. The goal was to enable diurnal and annual storage [1]. SELF is to function all year round independent of the momentary state of solar radiation. In late spring, summer and early autumn diurnal storage is sufficient. Nevertheless during winter, where short days and high fog strongly reduce PV power, seasonal or annual storage is required.

Figure 1: Picture of the SELF building with the energy module on the right side (small silver building).

Diurnal and annual storage require highly varying profiles. The main concerns are: conversion at high efficiency for diurnal storage and no energy loss for annual storage. For this reason, batteries showing high conversion efficiency are implemented for diurnal storage. Lithium iron manganese phosphate batteries ($LiFeMgPO_4$) are used due to their high energy density and good safety features. With these batteries a charging to discharging efficiency of well above 90 % is possible. Nevertheless, lithium batteries suffer monthly internal discharging of up to 5 % of their nominal capacity. This, and their relatively high price, make batteries unattractive for seasonal storage. For seasonal storage hydrogen is chosen. Hydrogen stored under pressure or bonded to metal hydrate suffers no loss during storage. This makes hydrogen storage favorable for long term storage. Nevertheless, the electrical efficiency from charging to discharging is limited to approximately 30 %.

The battery storage subsystem is built of 6 parallel strings by 4 batteries in series. The nominal voltage is 51.2 V and the total capacity is 660 Ah. The batteries used are of the type U24-12XP from Valence. The hydrogen storage subsystem consists of a metal hydrate cylinder assembly of 10 cylinders, each with a volume of 10 l. The cylinders are able to store 4 kg of hydrogen, or 130 kWh of energy equivalent in respect to the lower heating value of hydrogen. The metal hydride used is alloy AB5 from JMC. Standard pressure cylinders were filled with the metal hydrate at Empa. A hydrogen generator from the Swiss company Schmidlin is used for charging. The generator has a maximum hydrogen output of 1 Nl/min (norm liter / minute). For reconverting hydrogen to electricity a 1 kW PEM fuel cell from the Swiss company MES is used. Figure 2 shows the system assembly, with batteries and inverters on the left and the hydrogen system on the right.

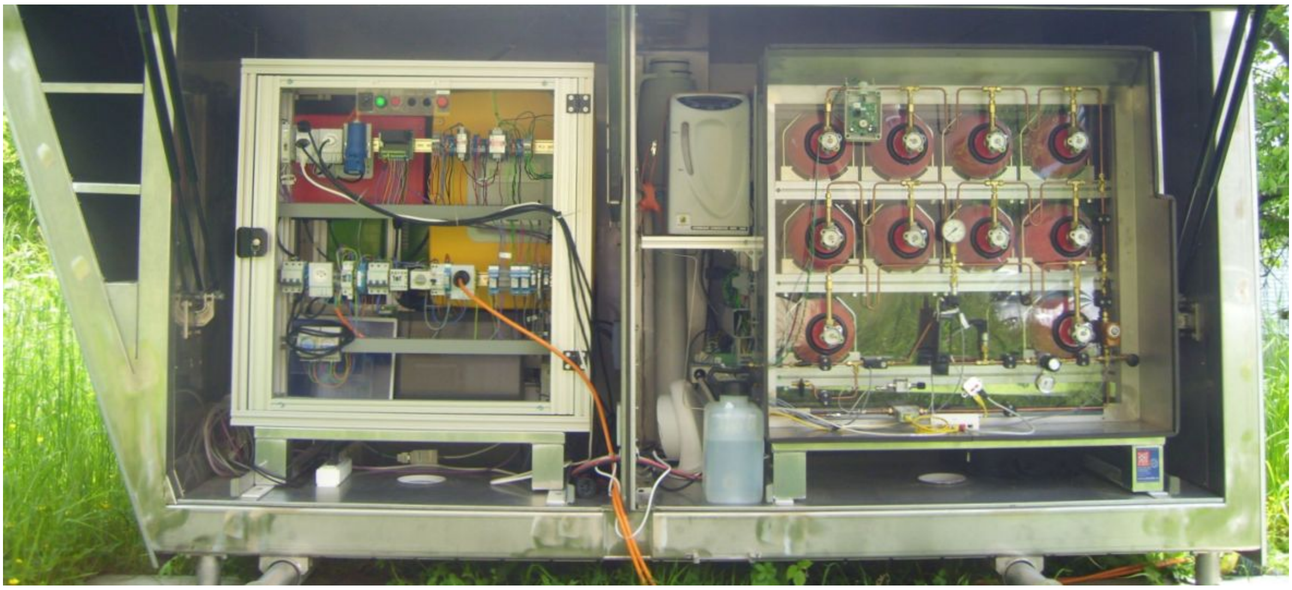

Figure 2: Picture of the energy module with the battery storage on the left and the hydrogen storage on the right.

Built as a mobile unit, the energy module is the ideal demonstrator for field testing under varying real supply and demand profiles. The module operates completely autonomous and allows monitoring of all valid parameters.

An 880 W_p PV generator is mounted on the embodiment roof. Any other renewable electric energy source can be added. In the momentary setup, SELF is connected to the storage system with its 3750 W_p PV generator. Proportions of battery storage to hydrogen storage are roughly dimensioned in order to sufficiently supply the Empa SELF building. Nevertheless, the energy module can be connected to any autarkic source and load.

2. Operation

The PV direct current is converted to alternating current by the Sunny Boy® inverter and supplied to the SELF micro grid. The Sunny Island® keeps this grid stable in frequency and power using the battery as energy buffer. Once the battery has reached an upper set point of state of charge (SOC), the hydrogen generator is automatically turned on. The hydrogen generator is connected to the SELF grid and has a power consumption of approximately 400 W. It then operates continuously as long as the battery SOC is above a medium set point. This is done to prevent limitations in solar harvesting due to lack of battery capacity. If the battery reaches a low SOC the fuel cell turns on to support the battery, by converting the stored hydrogen to electricity. Figure 3 shows the principal schematics of the system energy flows.

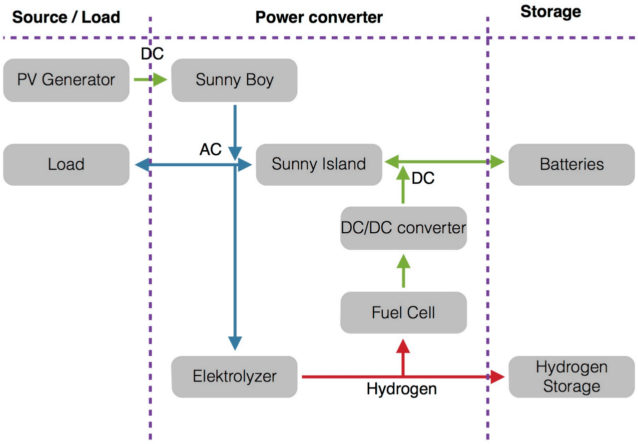

Figure 3: Diagram of the major energy flows with indications to direct current, alternating current and hydrogen.

The energy module was connected to SELF on the 29th of March 2014 and has remained in continuous operation. It is supplied from the SELF PV generator and the energy module PV generator. Varying states of operation have been examined. System operation is logged every 15 minutes.

Due to issues concerning the battery SOC indication discussed under the chapter Results, battery voltage was resorted to for controlling. Initially the voltage level to turn on the hydrogen generator was set to 54 V. This resulted in only minor hydrogen generator operation. In turn the batteries were often fully charged by noon, as can be seen in figure 4 where the inverter frequency increases from 50 Hz to 52 Hz. This greatly reduced the maximum possible solar harvesting, for even though the hydrogen generator is then on, its low power consumption of 400 W is far from able to adequately discharge the battery. For this reason the voltage level was reduced to 52 V. This increased the hydrogen generator time of operation and improved solar harvesting.

In operation there were difficulties with the hydrogen generator, and it often did not operate. This is indicated in figure 4 towards the end of the displayed operation sequence.

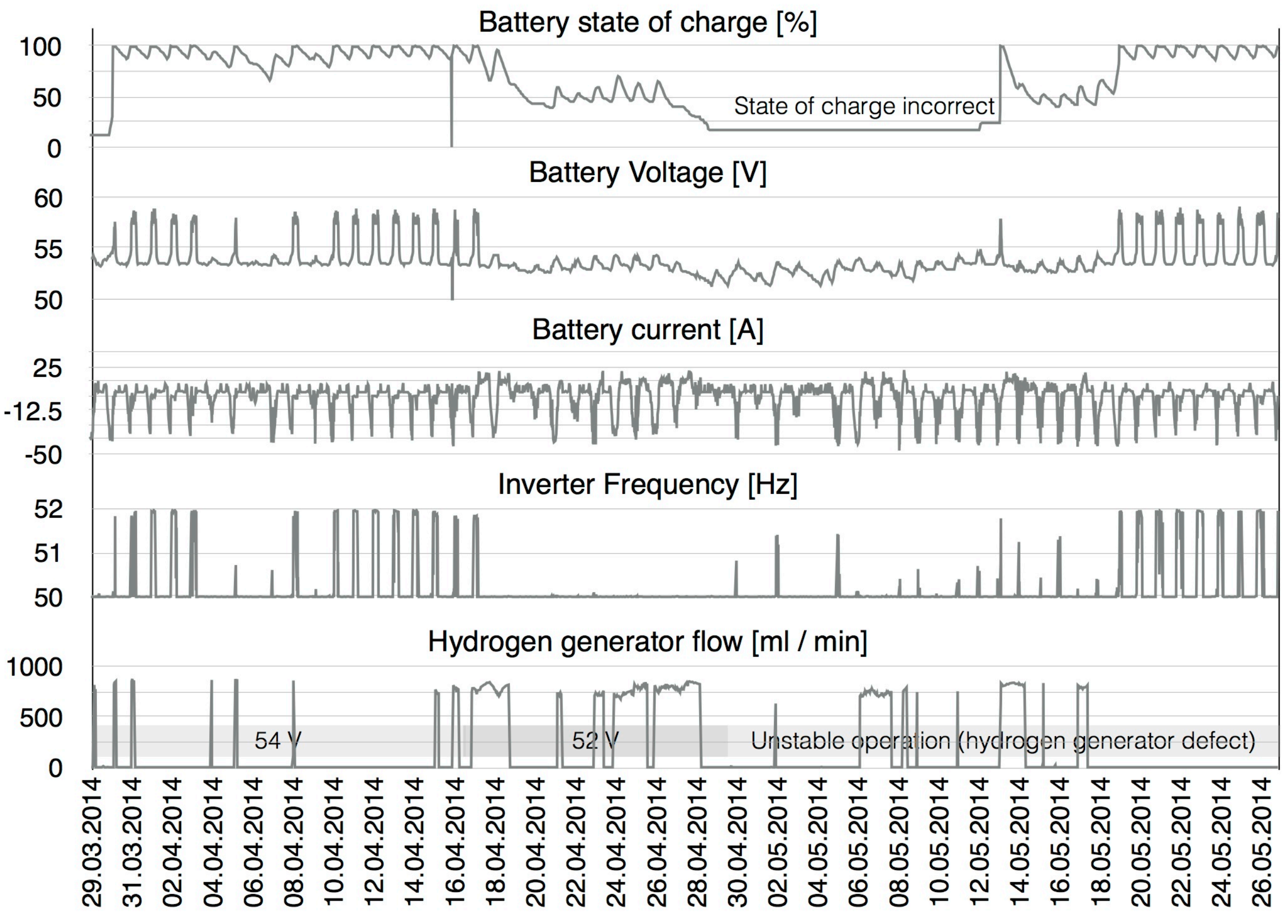

Figure 4: *Main operation parameters of the energy module from the 29th of March to the 26th of May. Indicated are varying settings for hydrogen generator operation as well as battery SOC error.*

3. Results

Battery efficiency and capacity

In cycling the complete battery module from a SOC of 100 % to 0 % with a load of 2000 W the accessible capacity was 639 Ah or approximately 32.7 kWh. Recharging to SOC 100 % required 682.7 Ah. It follows that the battery efficiency is 93 %.

Hydrogen storage efficiency and capacity

The fuel cell has a power output of 790 W when set to operate at maximum efficiency. When including the DC / DC converter 750 W remain. The resulting accessible output per norm liter of hydrogen is 1.29 Wh. In respect to the lower heating value, the energy capacity of hydrogen is 2.97 Wh / Nl. The fuel cell efficiency including the DC / DC converter is thus 44 %. It follows that the metal hydrate storage tanks have a total electrical output of 57 kWh.

The hydrogen generator runs on an average of 400 W. It produces 45.5 Nl of hydrogen per hour resulting in an energy consumption of 8.77 Wh / Nl of hydrogen. The hydrogen generator thus has an efficiency of 34 % in respect to the lower heating value of hydrogen. The resulting efficiency of the seasonal storage is approximately 15 % from electric input to electric output. Even though this may seem low, the measure of importance is the fuel cell efficiency. Storage capacity is more limiting then the ability to charge the hydrogen storage. In summer there is sufficient energy available to cope with low hydrogen conversion efficiency. The efficiency in reconverting hydrogen to electricity is the greater measure of importance. Naturally, this is in respect to the presented application.

Parasitic energy consumption

One of the major challenges in the energy module development was the parasitic energy consumption. This turned out to be much more critical then the battery discharging rate. In normal battery operation, not including the hydrogen storage, the parasitic power consumption of the system is 47.6 W. This is continuous, resulting in an energy consumption of 1152 Wh per day. The parasitic power consumption is composed of the Sunny Island® inverter with 29.2 W and other system components such as the PLC, safety relays, and BMS resulting in 18.4 W. When operating the hydrogen storage system a further 13 W for valves must be included. Without electrical input the battery (32.7 kWh) is thus discharged in 29 days.

4. Discussion

When charging the battery with a low power supply below 3 kW the BMS does not sense the charging process and the SOC is not increased. Thus the indicated SOC from the BMS is not adequate for controlling purposes (see figure 4 between 28.04 and 12.05). In operation the battery voltage was resorted to as an indication of SOC. This is not ideal though, due to the generally constant battery voltage in a large scope of actual battery SOC.

An issue was encountered in respect to the battery management system (BMS) indication of the SOC. The implemented batteries have an integrated battery management system (BMS) including a state of charge (SOC) indication. In operation the SOC indication was found to be unreliable. Due to the low charging and discharging currents given by the source and load in this application, the SOC counter was not able to detect the current and thus the indication did not react until the maximum cell voltage was reached and the BMS reset the SOC to 100 % (see figure 4). For this reason it was not possible to operate the hydrogen storage in dependence of the battery state of charge. In the momentary operation the hydrogen generator and the fuel cell are controlled in respect to the battery voltage. This is not ideal, due to the very constant battery voltage independent of the battery SOC.

Battery balancing is a further unresolved issue. It is common to impose active or most of the time passive balancing during the final battery charging phase. This is practical for batteries that are usually fully charged before use. Nevertheless for a renewable application this is not the case. The battery should never be completely charged, but always have the ability to receive the maximum energy output from the renewable source such as the PV generator in this application. The battery must be kept at a SOC of approximately 50 %. This is also favorable for battery life, another very important feature effecting operation costs and price per energy stored. If battery balancing is not permitted, in other words the batteries are never fully charged, then the individual state of charge of the batteries will drift apart and some will loose capacity. This greatly reduces the total battery capacity and will lead to battery failure. As the batteries are discharged, the weakest battery will hinder further discharging of the rest of the batteries connected in series.

For the described application no optimized solution was yet found. For this reason the battery is periodically completely charged so that battery balancing is activated. The consequence is reduced solar harvesting during this process. The hydrogen generator is deactivated until the batteries have reached a final and balanced state of charge.

In order to increase system simplicity and reach high energy density while preventing extra energetic effort for hydrogen compression, metal hydrate was used to store hydrogen. The hydrogen generator is able to directly fill the tanks without requiring an extra compressor. Due to the large quantity of metal hydrate the accompanying temperature increase in charging and decrease during discharging was not critical. Nevertheless the cylinders have to be placed in a thermally insulated containment. This must be considered in respect to safety issues regarding hydrogen leakage.

The state of charge of the metal hydrate tanks cannot be verified in respect to hydrogen pressure. For this reason the hydrogen flow to and from the hydrogen storage unit is measured and quantified.

5. Perspectives

Two possible solutions concerning balancing could be approached. The battery storage can be divided into two separate units, where each unit is able to charge with the peek power output of the renewable energy source. As such one unit can be completely charged to undergo battery balancing while the other is yet capable of charging with the remaining available energy. The other approach is to model the battery with an equivalent circuit diagram in order to determine the state of charge in respect to the momentary battery voltage and current. This feature and the ability of active balancing would enable battery balancing at any battery SOC.

6. Conclusion and outlook

The grid can only supply what is momentarily harvested or what has been stored. With this observation it becomes clear that hybrid energy storage for electricity as well as heat is a highly vital component in the renewable energy society. Small local all year round storage will thus play an important role in the overall renewable energy storage strategy. It will reduce stress on the energy grid by reducing energy transport, reduce energy loss in transport and improve efficiency by increasing capacity for fluctuating local energy supply and demand.

7. Acknowledgements

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References

[1] M. Bielmann, U.F. Vogt, M. Zimmermann, A. Zuettel; Seasonal energy storage system based on hydrogen for the self sufficient living unit (SELF), Journal of Power Sources (electronically published 12-2010)