SOL-ION PV STORAGE SYSTEM: FIELD TRIAL RESULTS, SPREAD OF OPERATING CONDITIONS AND PERFORMANCE EVALUATION BASED ON FIELD DATA

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ABSTRACT: The French-German Research Project “Sol-ion” has developed a PV storage system based on Li-Ion batteries. The paper provides an update on the field test results up to August 2012. The data is analyzed with respect to the parameters critical to the economics of the system and with respect to non-monetary values provided by local self-sufficiency (autonomy) and back-up capability in case of grid failure. A black-box approach is proposed and applied to calculate the efficiency of the PV storage system during operation from logged traces of PV energy fed into the system and energy delivered from the system. Benefit of this approach is to allow collection performance parameters of PV storage systems from field data, without need for measurements at internal interfaces.
Keywords: Implementation, Battery Storage and Control, Grid-connected PV Systems, Stand-alone PV Systems

1 INTRODUCTION

With PV generated electricity reaching grid parity, local use of this electricity provides economic benefit to home owners. Combining storage capacity through Lithium-Ion batteries with the PV installation can help to increase the local benefit, by improving the balancing between generation and load at the site of electricity generation and thus increasing self-consumption [1-4]. Furthermore the impact of PV generation on the grid can be reduced by local storage and suitable charge control mechanisms [5, 6]. Suitable sizing of PV installation and battery capacity, adapted to the respective solar radiation patterns of the specific location, can lead to full self-sufficiency in off-grid systems [7].

As part of the French-German research Project Sol-Ion, prototypes of PV-Storage Systems have been developed with storage capacity of 8.8 to 13.2 kWh [8].

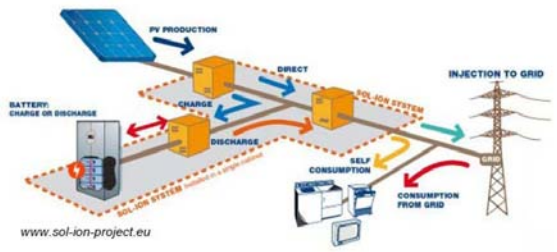
Important goals of the Sol-ion Project are to demonstrate improvements for grid and user brought by the system in various cases and to also generate data that enables the creation of economic scenarios for the deployment of such systems. Thus the systems are operated in different modes, to gather data on the performance as it varies with load and generation condition and on the requirements put onto the battery in those modes. The test devices installed in France are optimised with the aim of ensuring operation in case of a power failure. The goal in Germany is to increase grid-connected selfconsumption.

This paper focusses on the results of the field trial with the equipment being in self-consumption mode, while a concurrent publication reports on findings during operation in island mode [7]

3 FIELD TRIAL DESIGN

The Sol-ion system can be operated either connected to the grid or stand-alone, as shown in Fig. 1. Transition between the two modes is done automatically, depending on the presence or absence of the grid.

(a) connected to the grid / optimize self-consumption



(b) stand-alone / back-up for grid failure

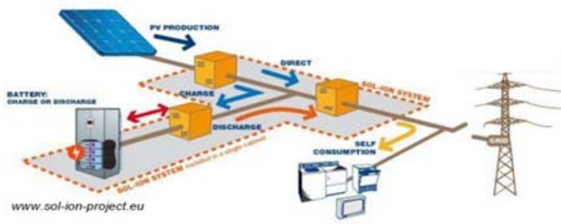


Figure 1: Sol-ion system with two DC/DC convertors towards PV generator and battery and one AC/DC convertor to connect to 235 V output line. The system is shown in two operation modes, connected to the grid and stand-alone.

To realize both operation modes, the Sol-ion system has two “line-out” terminals. The first single-phase output is designed for connection to any phase of the grid-connected power-bus bar of a home installation. Upon grid failure, this first output terminal will go into “listen” mode to detect re-appearance of the grid supply. During grid failure, Sol-Ion supplies power from the battery to a second terminal for back-up / stand-alone operation.

Sol-ion supplies a low-voltage DC-signal to control a user-supplied power relay, to switch-over the house wiring from the grid connected power-bus bar to Sol-ion´s back-up terminals. Single-phase house wiring simplifies switch-over for the complete load of the house within the output power specifications of the Sol-ion system. For a three-phase connection of the house wiring to the grid, the customer typically has to choose, which of the three phases he wants to provide with back-up functionality and put all critical loads onto this one phase.

The mode “optimize self-consumption” is being tested in the German field trial of the Sol-ion system at customer locations of E.ON Bayern AG and at the research institutes Fraunhofer IWES, ISEA RWTH Aachen and ZSW. The “Back-up and Island Mode” is focus of the work at the research institut INES-CEA, at Tenesol and at customer location in French mainland and Overseas Departments, where single-phase wiring is predominant. The difference from a battery management point of view between the modes is that in “German Self-consumption mode” the system will try use up the battery capacity to optimize self-consumption and stop only at discharged state, whereas in “French back-up mode” the battery is kept charged to a configurable level, to allow for maximum autonomy during grid failure.

Figure 2 shows the PV storage system as developed by voltwerk electronics within the Sol-ion project. The system is equipped in the field trials with 4 modules of Li-Ion batteries of SAFT

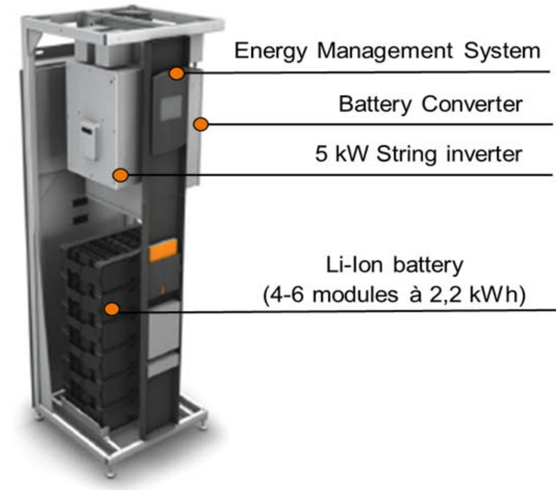


Figure 2: PV storage system as developed by voltwerk electronics within the Sol-ion project. The system can be equipped 4-6 modules of Li-Ion batteries of SAFT, each having 2.2 kWh nominal capacity and consisting of 14 cells type VL45E.

2 SPREAD OF OPERATING CONDITIONS

To describe self-consumption *SC* and autonomy *AUT* the following quantities must be compared for a chosen observation time:

- Local electrical energy demand: E_{load}
- Locally produced PV energy: E_{PV}
- Part of the PV energy used locally: $E_{PV,sc}$
- Self-consumption: $SC = E_{PV,sc} / E_{PV}$
- Rate of Local Generation: $RLG = E_{PV} / E_{load}$
- Autonomy: $AUT = E_{PV,sc} / E_{load}$

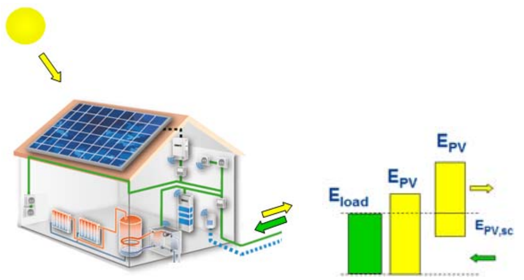


Figure 3: Schematic depiction of the local load, PV production and time coincidence, which allows for self-consumption $E_{PV,sc}$.

Taking the measured load profile of 89 households for one year and correlating them with the PV generation profile, resulting from a typical irradation profile of the location Kassel, Germany, the self-consumption and automony levels shown of Figure 4 can be calculated for a PV system without storage and for a PV storage system using 4 to 6 modules of the batteries used in the Sol-ion system. The calculations are based on a preliminary theoretical description of the system. The resulting *SC* and *AUT* levels depend strongly on the PV installation size (5 kWp in Figure 4), on the local yearly load and within those parameters on the load profile of the household. The improvement in *SC* and *AUT* achievable saturates, as the number of battery modules is increased. For 4 modules it amounts to 20-30 percent for the shown PV installation size and yearly consumption in the range of 2 to 8 MWh/y.

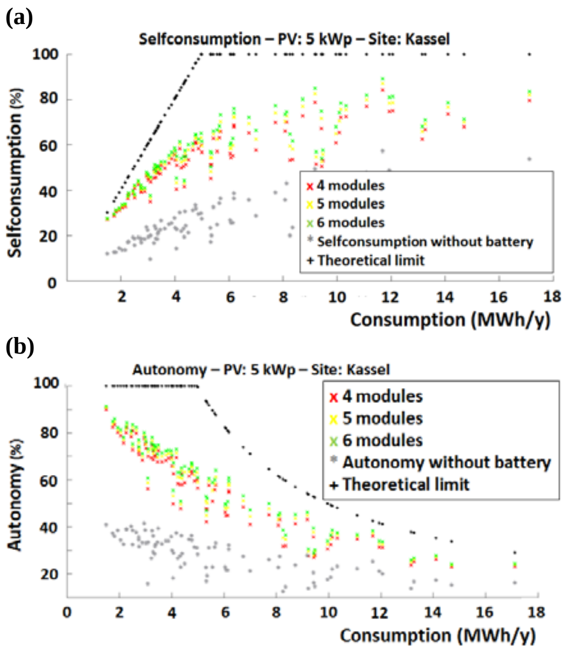


Figure 4: Levels of self-consumption and autonomy based on simulations with different battery sizes, a synthetic radiation profile for Kassel, Germany, and based on measured load profiles from 89 households.

A field trial with a PV storage system will generate for each year one single point in the above chart. From the measured PV generation and load profile of that year a second point can be calculated, which reflects the SC and AUT without battery, by taking the coincidents of generation and demand into account. With a limited amount of equipment, it is not possible to generate from a field trial the 356 data points of the charts in Figure 4. However, it will be possible to verify, whether the measured values for one year of each field trial system do fit into the chart. The main goals of the field trial will be to verify and measure the response of the system to the available PV production and load conditions, improve the system response by modifying the internal control algorithms and finally improve the theoretical modell of the PV storage system. The later will in turn allow rerun the calculations of Figure 4.

4 RESULTS OF FIELD TRIAL

Sol-ion test systems have been built and are under evaluation in the test labs of the industrial and research partners of the Sol-ion project. Installation on the ZSW field test site has been in August 2011 with continuous operation of the system starting in November 2011 and continuing to this day. Installations at customer location in the German field trial have started in December 2011.

All of the following graphs show results of the ZSW field test site, as those recordings have been running for the longest time and therefore show seasonal changes of the properties best.

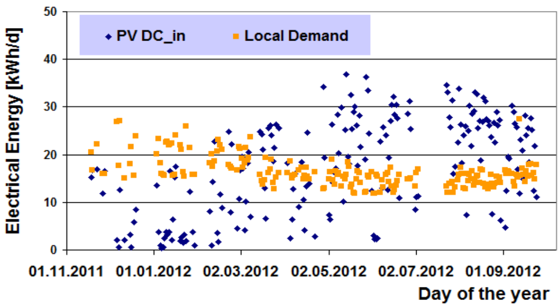


Figure 5: Daily values of DC Input power to the PV storage system from the PV generator of 5.145 kWp and local demand as measured for the system installed at the ZSW field test site. The local demand is created by a small office building at that test site.

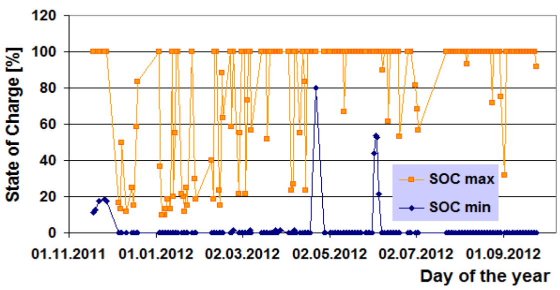


Figure 6: Daily cycling of the battery state of charge (SOC).

Figure 5 shows the input power to the Sol-ion System from the PV generator and the local load each in kWh for each day. As a sum over the year both values reach approximately 5 MWh/y and are balanced. The resulting battery cycling through the seasons in Figure 6 shows almost daily full cycling during the summer and even occasional full cycling during sunny days of winter. However during the “dark days” of winter low charging of the battery is predominant.

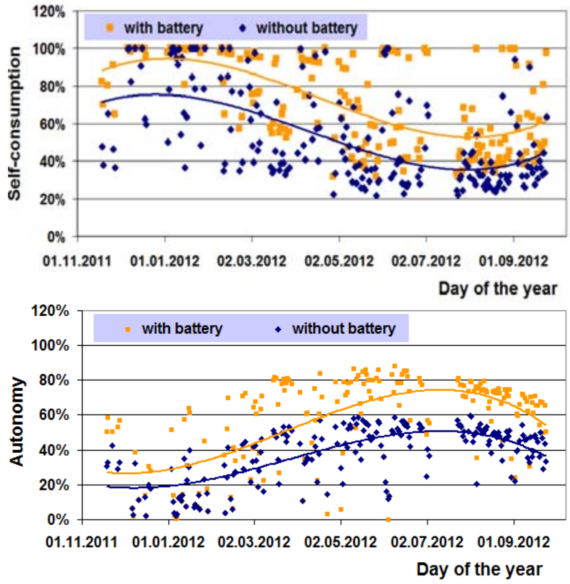


Figure 7: Self-consumption and autonomy calculated on a daily basis

The resulting measured self-consumption rates and autonomy with battery are shown in Figure 7. Also shown are the calculated values of self-consumption and autonomy based on the measured generation and load profile of the respective days, to show the improvement as a result of the battery storage. The self-consumption is raised through the battery by 20 - 30% per day. For the 10-month period of measurements the self-consumption is raised from calculated 38 % without battery to measured 57% with 4 battery modules. The autonomy is raised by 10 – 30% per day, with >70% of autonomy reached for many days from June through to August. The 10 month value of the autonomy is increased from calculated 37 % to 55 %.

5 PV AND PV STORAGE SYSTEM

PV inverters can be characterized by the efficiency of the inverter, which is calculated from the ratio of input to output power P_{PV_in} / $P_{AC\_out.}$

For a PV storage system however, the output power is not strictly following the input power, due to the possibility to store energy in the battery. Depending on the mode of operation, the battery SOC is cycled. In the mode “optimize self-consumption”, the output follows the local demand, as long as there is room in the battery to store surplus energy or room to discharge the battery, in case the PV generation is zero or below the local demand (Figure 9).

Integration of the energy flow at the input E_{PV_in} and output $E_{AC\_out.}$ during one battery cycle, i.e. in the case of self-consumption mode over one day, leads to the energy efficiency E_{PV} / $E_{AC\_out.}$ for one day. The resulting efficiency will be dependant on the amount of energy stored during this day in the battery, since the path taken for the stored energy is prone to increased losses due to the battery charge converter and the battery itself. However the energy efficiency per day is independent of, for an outside observer non disclosed power flow into and out of the battery at any given instant in time.

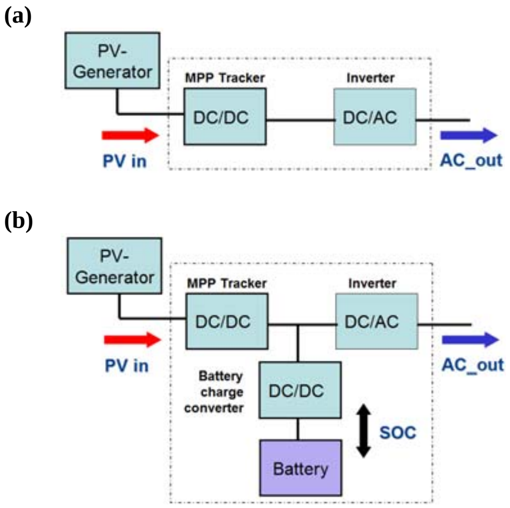


Figure 8: Schematic depiction of the building blocks of a PV inverter and a PV storage system, with DC-coupled battery as part of the inverter system.

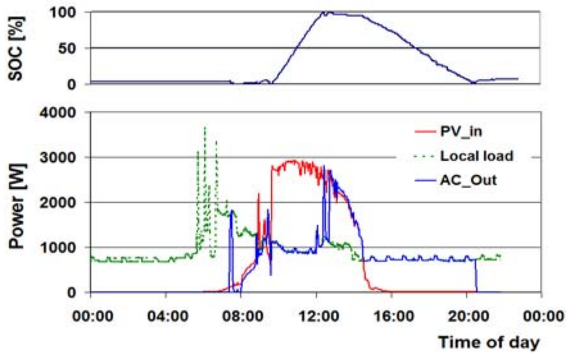


Figure 9: Traces of input power PV_in, output power AC_Out, local load and state of charge (SOC) of the battery for a PV storage system which follows the algorithm to optimize self-consumption.

The measured energy efficiencies per day (Figure 10) are dependant on the energy throughput of the PV storage system on that day and on the battery cycling that has happened during that day. As the energy delivery per day from the PV generator approaches the local demand per day, the battery is reliably charged during sun-shine hours and discharges during the evening hours. This was true for the load profile of the ZSW test site and will happen for a typical load profile of a household as well. Integration time was chosen from 4.00 a.m. to 4.00 a.m. of the following day since this time garuanteed best to have the battery at discharged state at the beginning and end of the integration time.

For low daily energy delivery into the PV storage systems, the amount of charging depends on the profile of sunshine. Continuous overcast days can lead to immediate consumption of PV production, without much charging of the battery (e.g. SOC > 25% in Figure 10). For low charging of the battery, and connected short operation of the equipment in the evening hours, the daily efficiency is high compared to days with partial sunshine, and following strong clouds, which in sum creates the same daily sum of E_{PV_in} but is causing overproduction compared to local demand during long enough times to fully charge the battery. As a consequence a large amount of power is passed through the battery and the equipment operates longer in the evening hours, which decreases the overall daily efficiency.

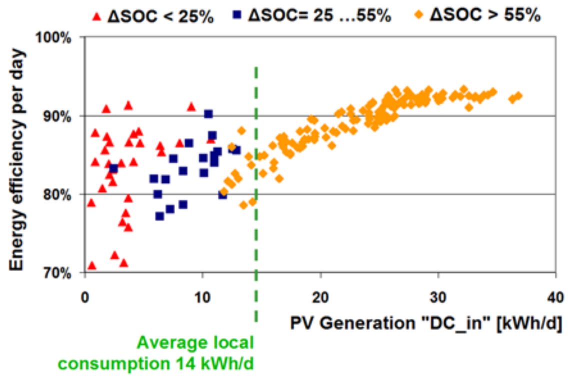


Figure 10: Energy efficiency per day sorted and plotted against the input energy per day to the PV storage system. The values are a result of the integration of the measured power flow over one day at the input and ouput of the Sol-ion system at the ZSW field test site.

The efficiencies measured for a PV storage system are not surprisingly lower, than the values for straight PV inverters. Reasons are the added components of the battery charge converter, the added system and battery management functions and the loss created due to battery charging and discharging. In addition the equipment is running for longer hours than a PV inverter, since it supports the local demand during evening hours.

However the value of the PV storage system is created by the possibility ot increase self-consumption and allow for back-up or for operation in island mode. The moderate decrease in efficiency can be compensated by increasing the dimensioning of the PV generator, such that the same output energy is delivered from the PV storage system compared to a straight PV inverter.

6 CONCLUSION

The Sol-ion PV storage system has been deployed in field test sites and has been delivering data for 3-10 months from various locations. Simulations based on measured load profiles of 89 households show strong dependance of the self-consumption and autonomy on the load profile. The field trial data does match results of simulations within those variances.

Due to the storage mechanism, the efficiency of a PV storage system cannot be measured at an instance in time as „power efficiency“, but instead has to be measured as „energy efficiency per day“ by comparing input and output energy delivered during one battery cycle, which is typically during a period of one day in “self-consumption mode”.

The „energy efficiency per day“ depends on total throughput, relation of throughput to local load and on the battery cycling during that day.

7 ACKNOWLEDGEMENT

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