PV BATTERY SYSTEM TESTED WITH REAL-LIFE CONSUMPTION DATA

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ABSTRACT: With a decrease in feed-in tariffs for photovoltaic (PV) systems in Europe and a decrease in the cost of Li-ion batteries, PV battery systems for increased self-consumption are becoming of increasing interest. A 4.8 kWh PV battery system with lithium iron phosphate ($LiFePO_4$) batteries was designed. The battery pack was installed with the commercially available LiTHIUM BALANCE A/S battery management system that manages the battery cells for achieving higher yield and increased service life of the battery packs.
The PV battery system was installed in the EnergyFlexHouse at Danish Technological Institute, a full-scale flexible measurement platform for construction and installation technology. This gave the possibility to test the PV battery system in a single-family house environment. The PV battery system was connected to a PV array of 3.5 kWp. High resolution consumptions data for typical single family households was used for minute by minute load simulation in the tested PV battery system. Economic calculations based on Danish feed in tariffs are calculated for a PV battery system and a PV system without battery to clarify if it is profitable for a Danish consumer to install a PV battery. Economic calculations shows that a PV battery system could potentially stimulate the demand for PV systems despite decreasing feed in tariffs.
Keywords: Battery, Load, Control system, On-grid PV, Efficiency

1 INTRODUCTION

Like in many other countries, the financial viability of Danish on-grid PV plants are being challenged by decreasing feed in tariffs [1] and new fees for grid connection. A few years ago the consumers could use a simple annual net metering, while today it is, at best, reduced to hourly net metering and export at a tariff less than half of the retail electricity price. In some cases PV self-consumption is even only possible if the production can be absorbed immediately and on the correct phase of the electric system. Batteries could be the obvious solution to this, in particular lithium based batteries, due to higher available state of charge range, more cycles and no evaporation of hydrogen and oxygen compared to lead acid batteries [2, 3]. LiTHIUM BALANCE A/S is an expert in lithium-ion batteries and battery management systems (BMS) in connection with these. It is the aim of this work to demonstrate the operation of a battery system in order to gain practical experience, document the efficiency, and to fine-tune the battery management system while operating in a typical PV system. It is expected that LiTHIUM BALANCE A/S will have two commercially available storage system solutions ready for the Danish PV market within a year.

2 EXPERIMENTS

2.1 EnergyFlexHouse and PV system

The physical location of the system is the EnergyFlexHouse at Danish Technological Institute in Taastrup, Denmark. This house was built in 2010 as a full-size experimental platform for new construction and energy technologies. A picture of the EnergyFlexHouse is shown in Figure 1. PV panels from First Solar and a small solar thermal system cover the entire south facing roof. The PV system is divided in two strings, so that the two halves of the system can run independently, and the house is therefore ideal for side by side testing of system solutions. Each string has a rated power of approximately 3.5 kWp corresponding to a small household PV system. Each PV string is connected to a Danfoss ULX inverter.

Figure 1: EnergyFlexHouse with PV panels on the roof. Left house: The test house in use. Right house: Identical house occupied by a single family.

2.2 System Diagram

Figure 2 shows the system diagram of the PV battery system. The 3.5 kW PV modules deliver power to the Danfoss ULX inverter that converts the PV power to single phase AC. When there is excess electricity from the PV modules the battery inverter charge the battery pack and when the power is needed the battery inverter discharge the battery pack. The battery cells in the pack are managed by the BMS to ensure proper charging and discharging for achiving higher yield and service life. The battery system monitoring are done on a PC with PC diagnostic software. A computer with consumption profiles together with a load controller and a resistive load simulate the load comsumption of the household.

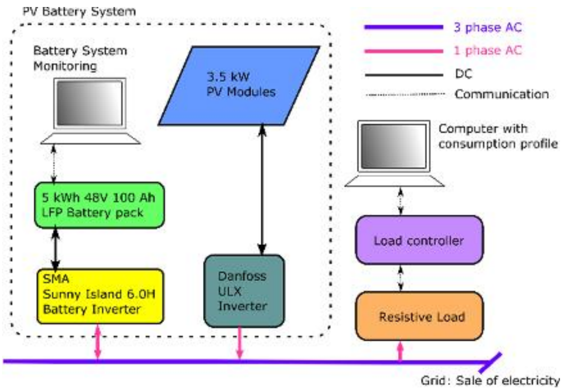

Figure 2: System diagram of the PV battery system and load controller.

2.3 Consumption profiles

The main objective of the PV battery systems test was to evaluate the behavior of a battery storage solution under realistic operating conditions. For this, consumption profiles for a single family with high resolution (1-minute) was needed. It turned out to be very difficult to find representative Danish data for a single family, instead a standard series for typical days was acquired from German VDI [4]. The climates in Northern Germany and Denmark are very comparable, so possible errors can be neglected. The data was scaled to fit an annual consumption of 4000 kWh, representing a single family house without electric heating. The simulated consumption profile for a week day is shown in Figure 2. The daily load curve for a summer week day shows a remarkably fluctuating pattern compared with the often used hourly load profiles.

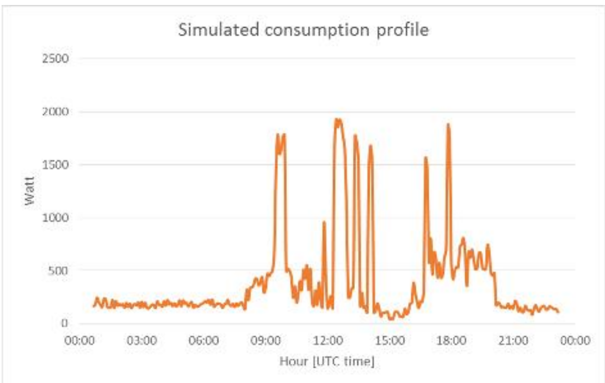

Figure 2: Minute based power consumption scaled for a single family with an annual consumption of 4000 kWh.

2.4 Load controller

The simulated household load is controlled by an electronic ohmic load made of simple and inexpensive components:

- An electric heater with fan
- A dimmer switch for industrial lighting
- A D/A controller connected to a laptop with LabView software.

The 3-phase heating element is connected to the lighting controller, which continuously controls the load power. The signal is calculated by calibration of the output power versus input voltage. In this way, the load profile can be repeated day after day. The computer with consumption profile, the load controller and the electronic AC load are shown at the system diagram in Figure 3.

2.5 Battery Energy Storage System

A 4.8kWh PV battery system with lithium iron phosphate (LiFePO4) was designed and tested with a SMA Sunny Island 6.0H battery inverter. The battery pack was installed with 16 CALB CA100 100Ah rechargeable LiFePO4 battery cells (fulfill UN38.3 [5]) connected in series, The battery pack was installed with the commercially available LiTHIUM BALANCE A/S s-BMS that manage the battery cells for achieving higher yield and increased service life of the battery packs. For safe operation of the battery pack a mid-pack fuse and a load fuse was installed together with two electromechanical normally open DC relays for redundant disconnection of the battery. For temperature monitoring of the battery cells 4 temperature sensors are strategically placed in the array of battery cells.

The BMS consist of one Battery Management Control Unit (BMCU) and two Local Monitoring Units (LMU). A single LMU monitors up to 8 cells in series with a balancing performance of 800 mA/cell. Up to 64 LMUs can be connected in series for total monitoring of 512 cells with a maximum limit of 1000 V. The BMS communicates with the battery inverter (SMA Sunny Island 6.0H) through CAN bus communication. Values and parameters from the BMS was monitored through the PC Diagnostic interface provided by LiTHIUM BALANCE A/S.

Figure 4: View of the battery pack prototype with the battery management system together with fuses and relays for redundant disconnection.

3 RESULTS

3.1 Efficiencies

The preliminary results indicate that the battery pack including the BMS system has a cycle efficiency of more than 95% when operating between 20 and 100% state of charge. The total system losses are, however, much higher than 5% due to the conversion losses from AC to DC and back to AC. For a sufficiently long period of time the difference in state of charge at start and end can be neglected, so the total efficiency can simply be calculated as:

$$\eta = \sum Eo \Big/ \sum Ein$$

The preliminary analysis shows a total round trip efficiency of 75-77%. The power conversions losses can be expressed as a constant loss when the converter is on (idle losses) plus a conversion loss that depends on the square of the converted power:

$$P_{loss} = a*P^2 + b*P + c$$

The converter switches off (automatic sleep mode) when the load becomes lower than a certain threshold value. The actual measured power distribution curves for charge and discharge are shown in Figure 5. The figure shows that most of the time the bi-directional battery inverter is in sleep or standby mode. There are very few hours exceeding a 3 kW charge or discharge power. The maximum output power of the battery inverter is 6 kW. A detailed analysis of the measured losses shows that approximately 30% of the energy is lost in standby or sleep mode. Table 1 shows the efficiencies on monthly basis from March to August 2015. The demonstrated efficiency of the battery pack in August was 99%.

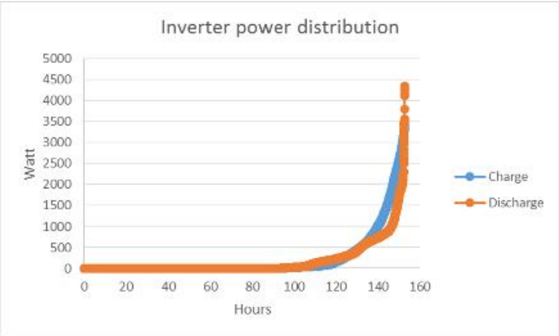

Figure 5: Measured distribution curve of the battery inverter power in May. It appears that there are very few operating hours above 3 kW which is only half of the maximum output power of the battery inverter.

	Battery	Converter	Total
March	96%	64%	61%
April	97%	77%	75%
May	98%	79%	77%
June	97%	60%	58%
July	89%	84%	75%
August	99%	75%	75%

Table 1: Table of monthly efficiencies. In March and June, the operation was irregular resulting in apparently high losses.

3.2 Power flow

The controller in the SMA Sunny Island 6.0H inverter should ensure that as much PV electricity as possible is consumed directly. Figure 6 shows how the system works in practice for a sunny day in Figure 6 and for a cloudy day in Figure 7. The dynamic minute based load profile show that the SMA Sunny Island respond to ensure maximum self-consumption of the PV power.

For a sunny day as shown in Figure 6 the battery is rapidly charged in the morning and hereafter PV power is exported (negative power flow). In the evening, the stored power is gradually released so import/export is balanced at almost zero. On cloudy days as shown in Figure 7 the battery pack is used during the consumption peaks and thereby minimizing the import of electricity. This would not have been a clear conclusion if 15 minutes or hour based consumption profiles were used.

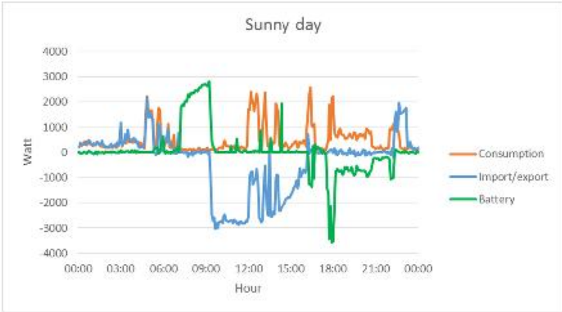

Figure 6: Power flow on a sunny day.

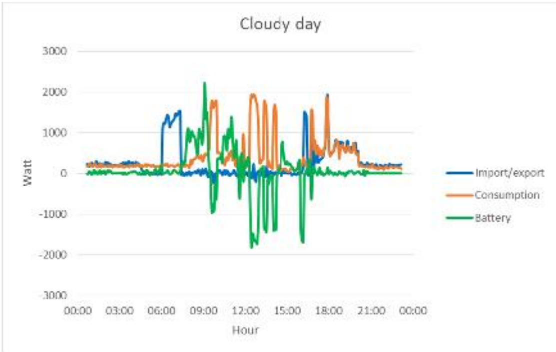

Figure 7: Power flow on a cloudy day.

3.3 Economy

Figure 8 shows the net present value (NPV) of the investment for a 6kWp PV system with a 5kWh battery pack with a high price (940€/kWh) and a battery pack with a low price (535€/kWh) compared to not having a battery in combination with a PV system. The calculations are done with Danish feed in tariff scheme. Any NPV above 0 is a good investment. Figure 8 shows that the NPV for PV system in combination with a battery pack is much better compared to PV system without battery pack.

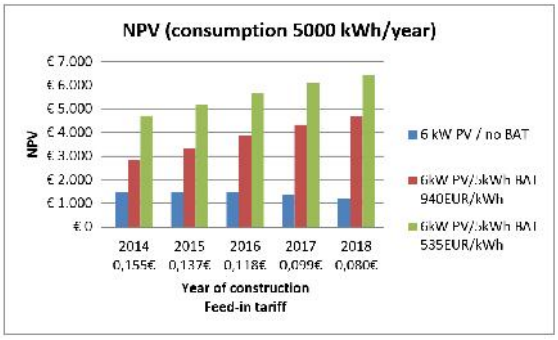

Figure 8: Net present value (NPV) of the investment of a 6 kWp PV sytem with a 5 kWh battery pack with an annual electricity consumption of 5000 kWh/year.

Figure 9 shows the payback time of the investment in years of a 6kWp PV system with a 5 kWh battery pack with a high price (940€/kWh) and a battery pack with a low price (535€/kWh) compared to not having a battery in combination with a PV system. The calculations shows that the payback time of investment is reduced significantly with a battery pack and reduce payback time for the overall PV system (i.e. to increase motivation to invest) if the battery price is in the low range. Even at the high price range a battery pack makes the PV system a much better investment than without a battery pack under the Danish feed-in tariff scheme.

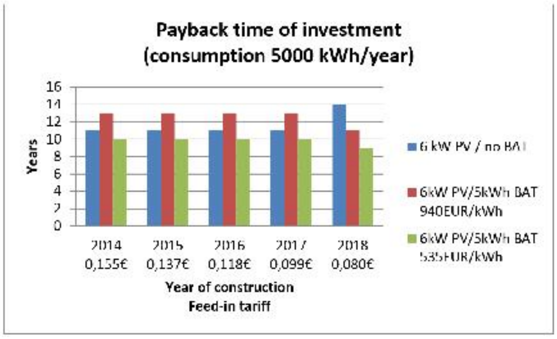

Figure 9: Payback of the investment in years of a 6 kWp PV sytem with a 5 kWh battery pack with an annual electricity consumption of 5000 kWh/year.

The last two years the price of battery packs for PV applications decreased considerably but based on LiTHIUM BALANCE A/S experience, the market prices for PV battery systems are still high compared to battery pack prices for automotive and industrial applications.

The expected price for a Lithium Balance A/S PV battery system is 740 €/kWh with current battery prices including VAT, distribution and installation cost. It is expected that the prices of lithium-ion batteries will continue to decrease the next ten years [6]. We expect that the battery pack prices decreases with the decreasing battery prices.

The economic calculations are on hour based consumption data. Our presumption from the present test of the PV battery system is that it become even more attractive when economic calculations are done on minute based consumption data.

4 CONCLUSION

A PV battery system was successfully tested in a full-size experimental platform called EnergyFlexHouse. The battery pack shows relative high efficiencies (up to 99%) in the test period.

The dynamic minute based consumption profile show that the battery inverter respond to ensure maximum self-consumption of the PV power. When evaluating PV battery systems it is important to use minute based consumption profiles since it will make the utilization of the battery pack more visible.

The economic calculations showed that the net present value was much better with a PV battery system with Danish feed in tariffs than having a PV system without a battery pack.

5 FUTURE WORK

It is the ambition to develop a battery pack ready for sale that fulfill the recommendations for safety standards from [7] and the complete checklist for Li-ion home storage systems recommended by Karlsruhe Institute of Technology [8].

The battery pack will include a newly developed BMS from LiTHIUM BALANCE A/S with temperature monitoring on every battery cell in the battery pack. The new battery management system are designed based on the principles from IEC 61508 with a high level of integrated functional safety.

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