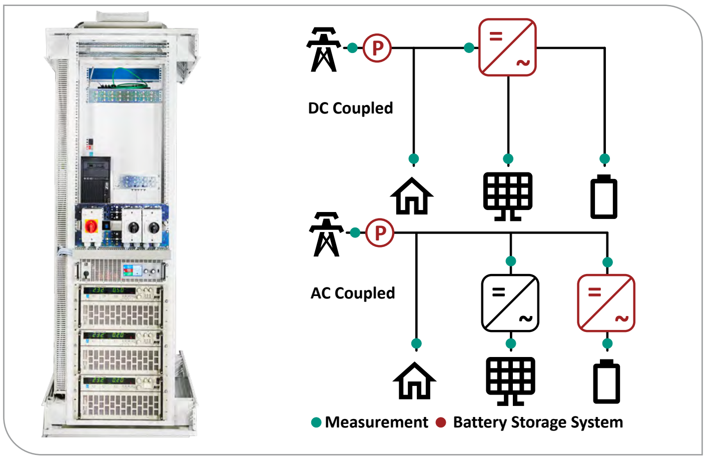
Karlsruhe Institute of Technology

# Performance Characterization of Energy Storage Systems

Energy storage systems are one of the key technologies of the energy transition. They can shift the supply of electricity from photovoltaic (PV) and wind power to match with consumer demand. More and more private households are using home storage systems to temporarily store electricity from PV systems and increase their own consumption of solar power. Instead of drawing electricity from the grid, households can supply themselves with self-generated renewable energy.

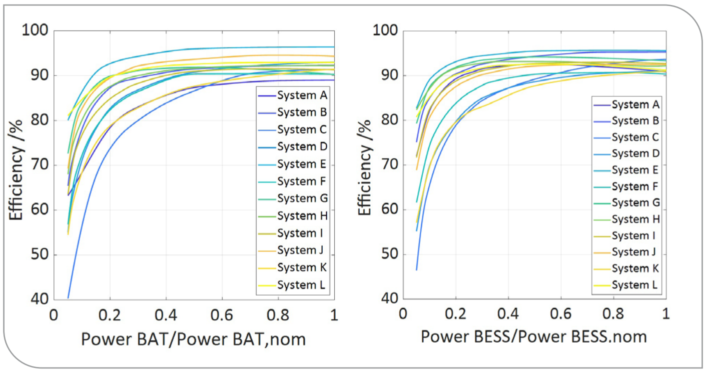



Test bench for home storage systems (left). Schematic structure of the systems in the test bench (right). (Source: KIT/Robert Schreier)

Not only the acquisition costs have a significant influence on the storage costs and therefore the economic viability, but also the quality and performance of the storage system during operation. The performance of the storage systems is influenced on one hand by the efficiency of the systems and the associated losses and on the other hand by the quality of the energy management of the PV storage systems.

## Efficiency of storage systems

Efficiency and the associated losses include efficiency losses of the power electronics and the battery, losses due to standby consumption as well as maximum power point tracking losses. Other characteristics such as control dynamics also have a direct impact on the economic efficiency of a system. As part of the 'Safety First' project (2015 - 2019), twenty different commercial home storage systems were operated in test benches under real conditions and analysed for the aforementioned aspects, among others. The results were incorporated to a large extent into the development of the efficiency guideline for PV storage systems, which in turn was further developed into DIN VDE V 0510-200. The project 'Testbench' (2020 - 2022), which focused in particular on the reproducibility and comparability of the measurement results on various test benches of the project partners, further contributed to this. The large number of storage systems that were tested at KIT as part of various projects and by industrial customers clearly shows that even today there are still major differences in quality between the systems available on the market. As an example, the charging and discharging efficiencies of 12 storage systems are shown below.




Efficiency of the power conversion path battery charging (left) and battery discharging (right) as a function of the rated output power. (Source: KIT/Nina Munzke)

## Quality of energy management

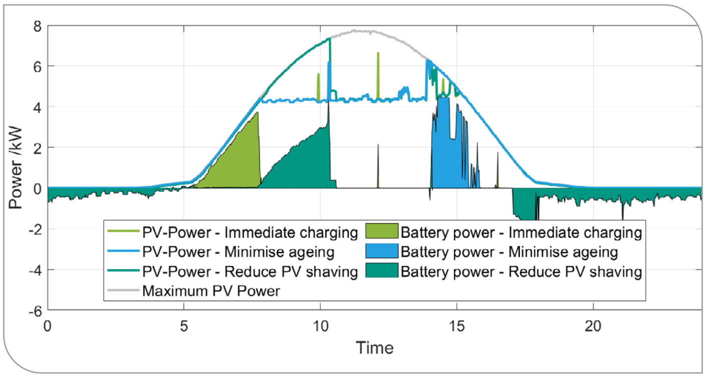
In addition to the efficiency of the systems, the quality of the energy management in particular has a decisive influence on the profitability of the systems. The basic function of the energy management is to increase the system operator's self-sufficiency. However, in order to increase the cost-effectiveness of the PV storage system, its intelligence plays a decisive role.

Most lithium-ion batteries age more quickly when their state of charge (SOC) is high. On sunny days excess energy should therefore not be stored in the battery right at the start of the day, as this can result in the battery remaining at a high SOC for a long time. Forecast-based energy management can charge the battery as late as possible. Delayed charging reduces the time spent in unfavourable SOC ranges. This can potentially extend the lifetime of the system by years.

Delayed charging of the battery also plays a decisive role when maximum feed-in power is available, as it is otherwise already fully charged at midday or at the time of maximum PV generation. Surplus energy can then no longer be stored and must be curtailed. Since February 2025, a feed-in limit of 60 % of the installed PV power has been in place in Germany.

The charging efficiency of the inverter or DCDC controller of the storage system can also be increased by operating the inverter in a more optimal operation point. To optimise one or more of the points mentioned a forecast-based energy management is necessary.

The following figure shows the different energy management strategies for the same load and PV curves:



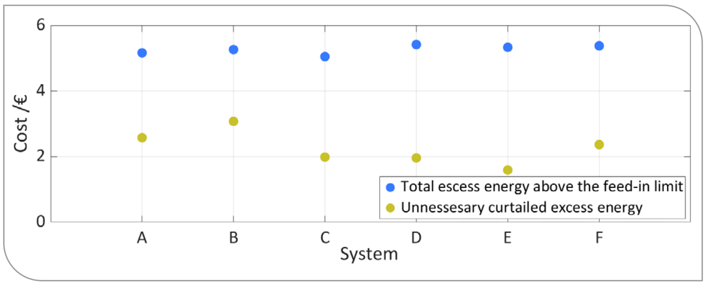

Typical daily profile of a household with a PV storage system. Depending on the energy management strategy, the battery is charged at different times. (Source: KIT/Robert Schreier)

**Immediate charging:** As soon as availablePV power is higher than electricity cunsumption within the household, the system starts charging the battery. This strategy is easy to implement as it does not require any forecasts. However, early charging means that the battery is already fully charged as soon as the PV power exceeds the feed-in limit and all PV energy above the feed-in limit must be curtailed. Due to the resulting long time spent in high SOC ranges, the lifetime of the battery is reduced.

**Minimise ageing:** A PV and load forecast is used to determine the time at which the PV is no longer sufficient to cover the households consumption (here approx. 17:00 o' clock). Charging of the battery is now started as late as possible so that it is not fully charged until 17:00 o' clock. This minimises the time the battery spends in high SOC ranges, which can significantly increase the lifetime of the battery. However, forecast errors may mean that the battery is not fully charged at the end of the day.

**Reduce PV shaving:** The aim of this strategy is to minimise the PV energy to be curtailed. A forecast is used to determine whether curtailment of the PV power is to be expected today. In such a case, charging of the battery is delayed until the point in time is reached at which the PV power would have to be curtailed. Errors in the forecast can lead to the battery being charged too early and PV energy still having to be curtailed or it being charged too late and the battery not being fully charged.

The evaluation of the implementation of the energy management was a crucial part of the 'Perform' project (2021 - 2025). For the first time, storage systems from different manufacturers, including systems with online forecasting were operated in test benches under identical conditions. A methodology for the evaluation of the energy management was developed. As an example, the following shows the energy surplus above the feed-in limit and the surplus that would not have had to be curtailed, if the battery had been perfectly controlled, for 10 summer days.




Costs for the total energy surplus as well as for the unnecessarily curtailed surplus energy with a 50 % feed-in limitation for 10 days in June. The results of 6 systems with a PV system size of 8 kW and an energy capacity between 6.9 and 10 kWh. (Source: KIT/Nina Munzke)

## Leistungsspektrum des KIT

In addition to the studies within research projects, KIT offers storage measurements for industry partners.

In the hardware-in-the-loop storage test environments, measurements are carried out according to efficiency guidelines, which can be used, among other things, to participate in the energy storage inspection.

Any number of scenarios can also be realised. For example, measurements with reference days, which are represented by a set of 10 representative PV and load profiles and with weighting factors, allow conclusions to be drawn about the system efficiency during operation over an entire year. By operating a system with realistic data, it is also possible to evaluate energy management with regard to various targets mentioned above

Special solutions for systems with high output power or special topologies, such as multilevel converters, can also be realised. By using mobile measurement systems, it is also possible to carry out efficiency measurements on large storage systems outside the KIT.

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