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# Performance of a hybrid battery energy storage system

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**Abstract**

The use of energy storage systems is inevitable in a power grid dominated by renewable generators. This paper presents a performance overview of a 100 kW/270 kWh, grid-connected, hybrid battery energy storage system. The hybrid system uses two types of battery chemistries, li-ion and lead–acid connected directly at the DC bus — without power electronic converters. After a brief introduction and a short technical description of the project, the paper presents a three year, 2019 to 2021, operational data set. The battery data is later split into individual charge/discharge cycles and analyzed in terms of power and strings current sharing, energy, round-trip efficiency and energy transfer between the strings. The analysis shows that the average round-trip energy efficiency of the system is 90% and depends on the depth of discharge. The energy transfer between the strings can happen during charge or discharge and the average values are 5.5% (during charge) and 2.47% (during discharge) of the total discharged energy. Minimum capacity loss was recorded for the lead–acid cells and practically no capacity degradation for the li-ion cells.


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*Keywords:* Battery energy storage; Hybrid energy storage; Dual chemistry; Lead–acid; Li-ion

## 1. Energy storage

The global renewable energy sector is rapidly changing by integrating more renewable generators. Between 2011 and 2020, the global renewable power generation more than doubled its installed capacity, from approximately 1331 GW to around 2802 GW. In 2011, around 80% of that was traditional hydropower, 1058 GW, however, in 2020 this dropped to around 48%, 1333 GW. This was mainly the result of fast growing wind and solar sectors. Wind power grew from 220 GW in 2011 to 731 GW in 2020 and solar power from 74 GW to 716 GW in the same interval. In terms of electricity production, in 2020, the global hydropower generated 3586 TWh, wind power 1412 TWh and solar power 693 TWh. This puts the average hydropower capacity factor at around 37%, wind at 22% and solar at 11% [1].

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This impressive growth of renewables is expected to continue for decades. However, as the share of renewables rises, the operation of power grids becomes a challenge because of the variable nature these power sources. The issues encountered in a power grid with high share of renewables are not only technical but economical and operational [2]. Energy storage can help address most of these problems by storing the electricity during periods of low demand and discharging it later to meet peak demand. Alongside a wide variety of energy storage technologies, hybrid storage is another promising option [3]. The overall idea of hybrid energy storage is based on taking advantage of the different storage system characteristics by linking high power, high cycle life technologies with high energy capacity systems to improve the overall performance. This paper presents the results of a hybrid li-ion (LI) and lead–acid (LA) storage system connected directly at the DC bus without any power converters.

## 2. GS Yuasa — hybrid battery system

The hybrid battery storage project presented in this paper is part of a wider UK micro-grid system developed in partnership with Innovate UK, University of Sheffield, GS Yuasa and Infinite Renewables. The project is located in the Ebbw Vale, Wales, next to the GS Yuasa manufacturing facilities. The high-level schematic for the entire system shown in Fig. 1. The micro-grid brings together a wind turbine, a small solar array and the energy storage unit. Additionally, the system monitors the factory low voltage electrical loads and based on this information the storage system is charged or discharged.

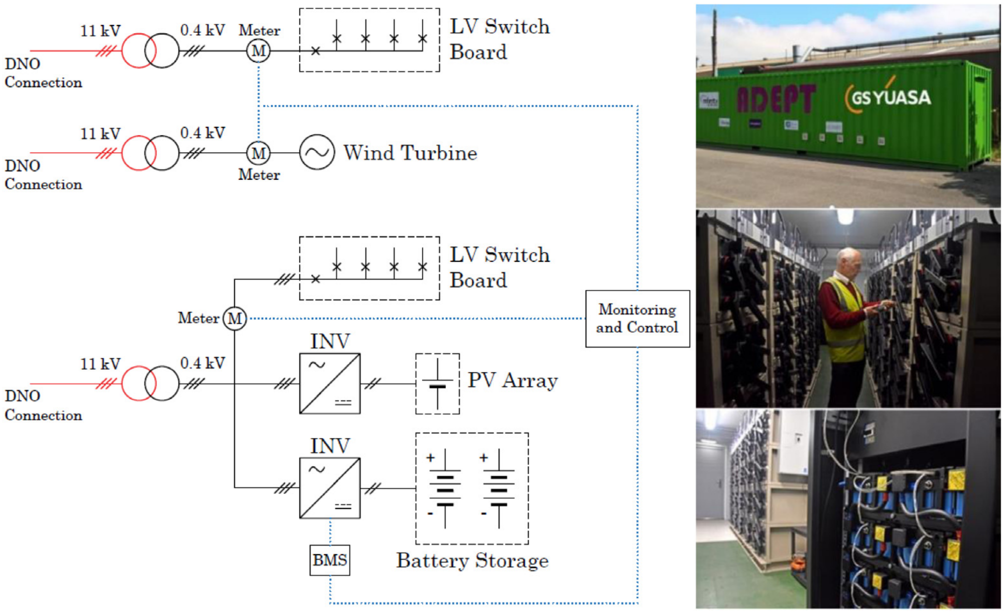


**Fig. 1.** GS-Yuasa ADEPT, Dual Chemistry Battery System.

The technology used for the energy storage system (ESS) is a hybrid combination of two different battery chemistries LA and LI provided by GS Yuasa. There are two main reasons why these chemistries are being used. First, they have complementary strengths, LI — (high cycle life, high discharge rate, partial SOC operation, high efficiency and high energy density) and LA — (sustainable & abundant materials, simple control, abuse tolerant, economical, low embodied energy). Second, the voltage profiles of the two chemistries allow the LI strings to be cycled before LA thus providing some control over the strings even when using a direct DC bus connection.

The project has been commissioned in the first months of 2019 and it is believed to be the first of its kind in the world. The entire system is controlled remotely via the internet using the ADEPT software platform.

The total storage capacity of the system is 270kWh with the energy split between three strings of LI and one string of LA. The cells are grouped in battery modules, LIM50Ah and SLR500Ah. The LI chemistry used is manganese oxide and the LA is of VRLA type. The system is connected to the grid using a HiT POWER, PS100, 100 kW bidirectional converter. The overall schematic of the dual chemistry system is indicated in Fig. 2.

Table 1 presents the battery modules technical data taken from the GS Yuasa manufacturing catalogues.

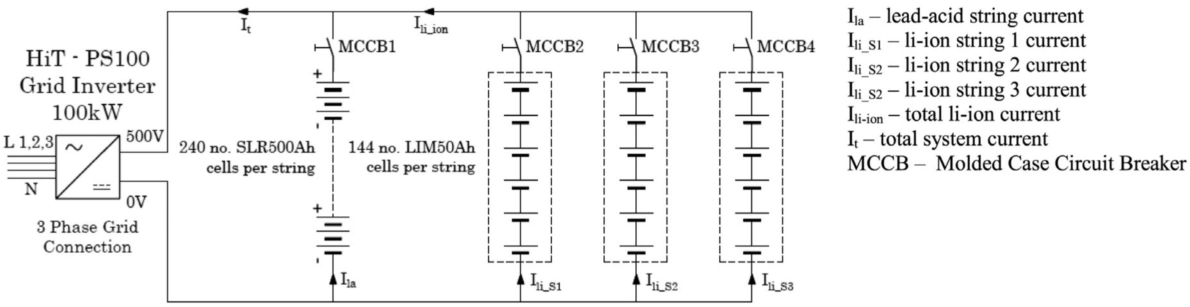


**Fig. 2.** Dual Chemistry System — Schematic.

**Table 1**. GS Yuasa Battery — Data.

| Battery/ Cell type | Nominal voltage [V] | Capacity [Ah] | Internal resistance [mΩ] |
|---|---|---|---|
| Lead–acid SWL3300 | 12 (max 13.6) | 100 (C/10 rate) | 5.64 |
| Li-ion Pack 6 x LEV50 | 3.75/ cell (max 4.1) | 50 (at 1C rate) | 0.5/ cell |

## 3. Performance analysis and results

The GS-Yuasa Hybrid ESS has been in operation since January 2019, with interruptions between October 2019–January 2020 and March–April 2020. During this time, the system was monitored using multiple BMS modules, one for each battery cabinet. The LI BMS systems provide comprehensive information up to the individual cell level but the LA monitoring system recorded data only at the pack level. The information was stored on SD cards and later transferred in stages to a laptop. The LI data was generally recorded at 30 s resolution and the LA at 15–30 s resolution. The final data time step resolution was set to 30 s as it is the most common among all data files.

The overall data set is shown in Figs. 3 and 4. Fig. 3 shows the information about the system voltage, total LA current ($I_{la}$ indicated in Fig. 2) and total LI current ($I_{li-ion}$ indicated in Fig. 2). The gaps in the data set are due to the interruptions of the system.

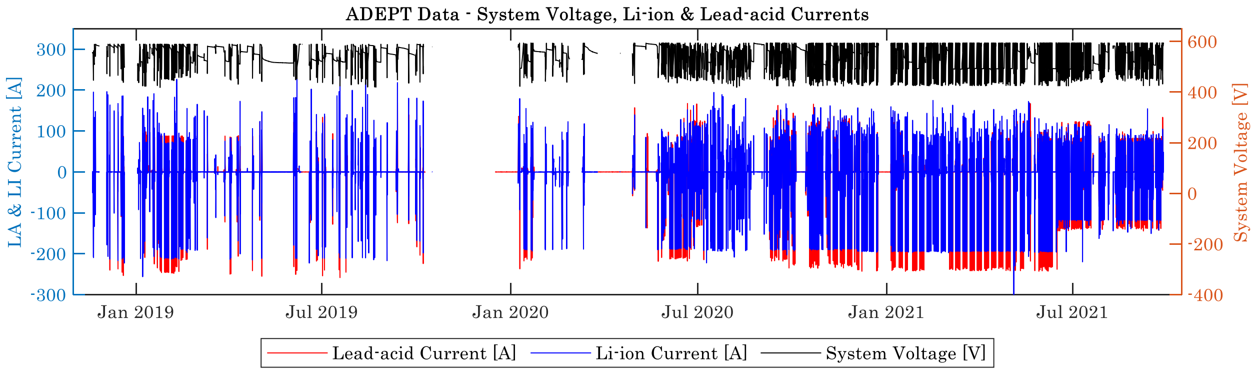


**Fig. 3.** Total ADEPT Data, System Voltage, LI & LA Currents.

Fig. 4 shows the state of charge (SOC) for the overall LI and LA strings as well as the temperatures of the battery modules. It can be seen that for the majority of the cycles, the LI strings have been charged/discharged from 100% to low SOC but the LA strings have generally been cycled between 100% and 50% SOC.

The data shown in Figs. 3 and 4 contains around 500 complete charge/discharge cycles of the entire system. Typical charge/discharge cycle waveforms are shown in Fig. 5, the LI and LA currents are the $I_{li-ion}$ and $I_{la}$ shown in Fig. 2.

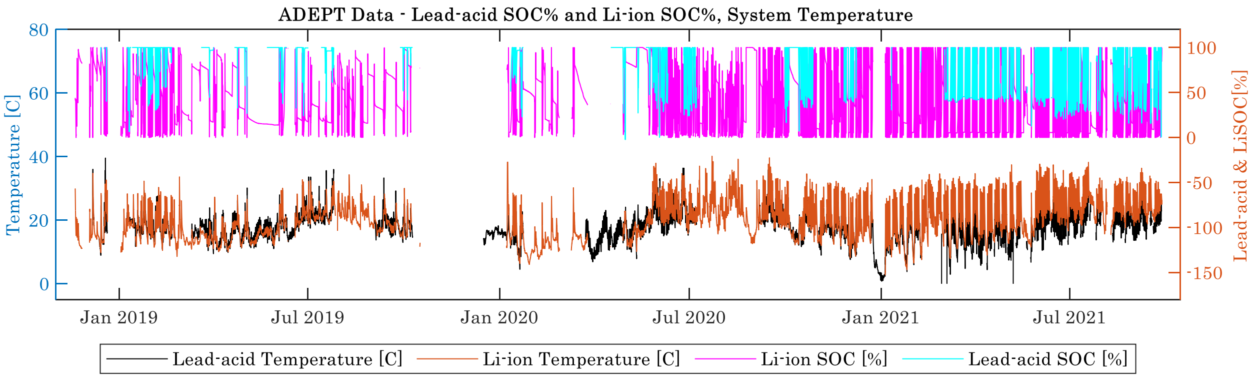


**Fig. 4.** Total ADEPT Data, LI & LA SOC, LI & LA temperatures.

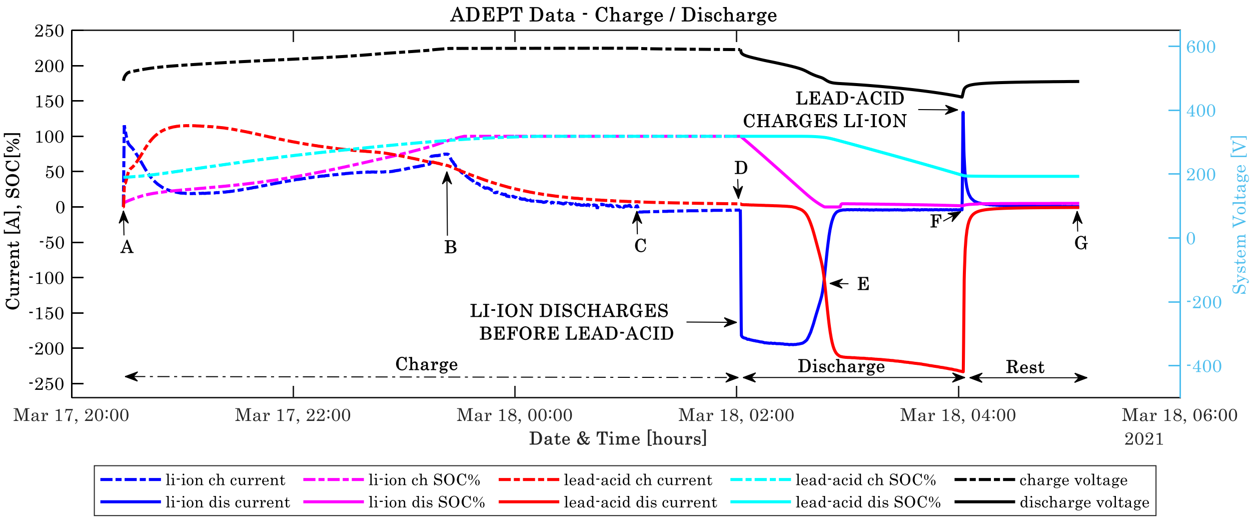


**Fig. 5.** Typical Daily Charge/ Discharge Cycle.

The general points of interest indicated in Fig. 5 are the following:

- **A–B:** Between the points A and B the system charges at constant power. There is an initial current & power spike on the LI strings as these react faster but after a brief period the LA starts to charge.
- **B–C:** At point B the system reaches nominal voltage and the charger changes to constant-voltage (CV) mode.
- **C–D:** At point C the CV charge is stopped. If the system is not charged completely, the LI strings slowly transfers the final top up charge to the LA string.
- **D–E:** The system starts to discharge at constant power at point D. Between points D and E the LI strings discharges, and there is no LA activity in the first 3/4 of this period. At point E the current and power provided by the LA and LI strings equalize.
- **E–F:** Between points E and F, the lead–acid string discharges at constant power. As it can be seen the LI activity is almost insignificant.
- **F–G:** At point F, the system stops the discharge process and rests between F and G. During this time (F–G), because of the different dynamic responses of the two strings, the lead–acid string charges the li-ion ones until the system reaches final equilibrium.

A total number of 140 such charge/discharge cycles have been analyzed (around 30% of the total performed so far) to obtain a general picture of how the system performs under real working conditions. The cycles have been randomly picked across the data timespan and no two charge/discharge cycles are identical.

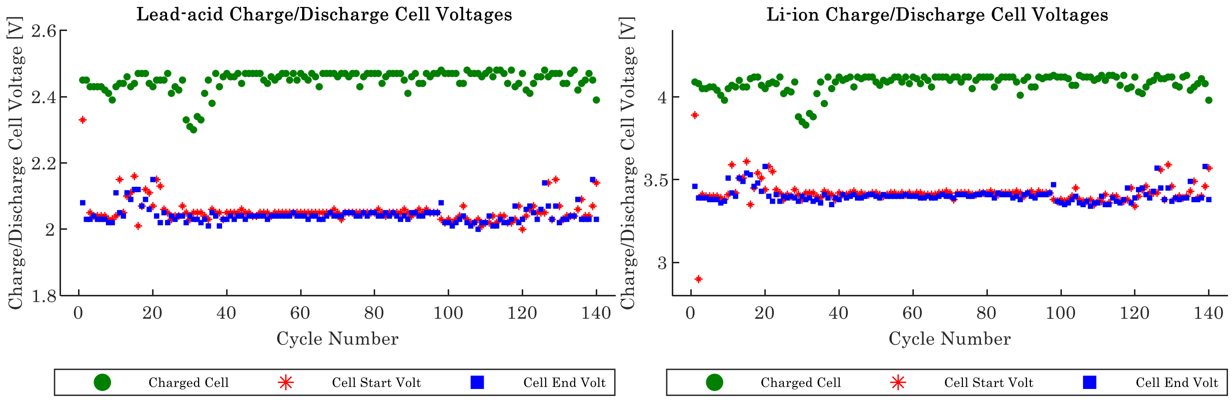


**Fig. 6.** LA & LI Charge/Discharge Cell Voltage Interval (LA — left and LI — right).

Fig. 6 shows the LA and LI cell voltages intervals for each cycle: the starting cell voltage, the final charged voltage and the final discharged cell voltage. It can be seen that the LA cells have generally been cycled between 2–2.41 V and LI between 3.4–4.1 V. This corresponds to the SOC charge/discharge intervals indicated in Fig. 7. Fig. 7 shows that the LA cells have generally not been discharged below 40% SOC. On the contrary, LI cells have been discharged to around 5.5% SOC.

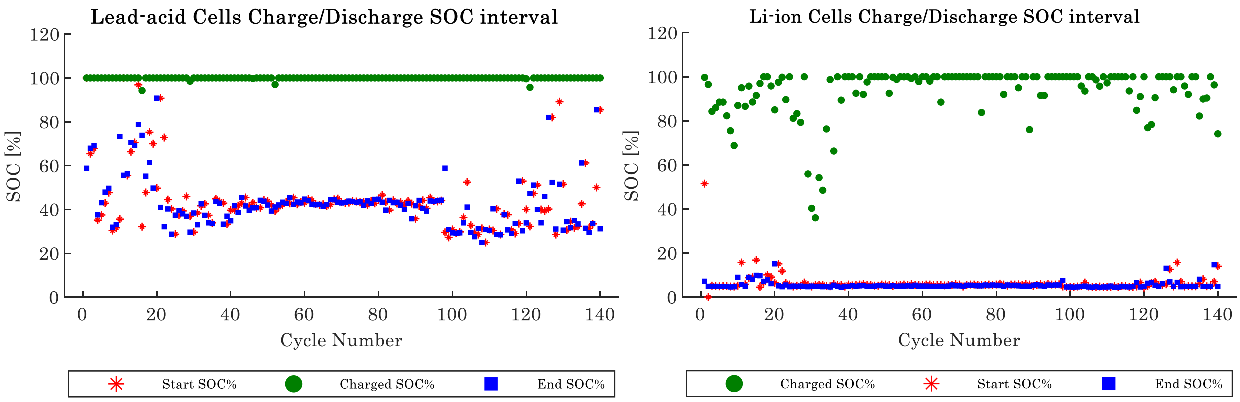


**Fig. 7.** LA & LI strings Charge/Discharge SOC Interval (LA — left and LI — right).

Fig. 8 (left) shows the total system discharged energy for each cycle as well as the energy discharged by each chemistry. The total average discharged energy is 210 kWh, 138 kWh by LA and 75 kWh by LI. The total available LA energy depends on the discharge current. Between cycle 100 and 140, the discharge power was set to 60 kW and this is reflected in the total available LA discharged energy.

Fig. 8 (right) shows the total energy transfer between the strings due to the different dynamic responses of the two chemistries. The energy transfer from LI to LA strings happens during charge, between points C–D indicated in Fig. 5. This only takes place if the charging process is stopped before both strings reach 100% SOC. As it can be seen, the total energy transfer varies significantly, from 0 kWh to 50 kWh, depending on the charge stopping point (point C, Fig. 5). For the analyzed cases, the average energy transferred from LI to LA strings is 13kWh. On the other hand, the energy transfer between LA to LI stings happens during discharge, points F–G indicated in Fig. 5. This is relatively constant across all discharge cycles and varies little with the discharged power or when the discharge process is stopped (point F, Fig. 5). The average energy transferred between LA to LI is 5.2 kWh or 3.7% of total LA discharged energy.

Fig. 9 shows the total energy discharged by the LI strings between D–E points, indicated in Fig. 5. This is crucial as it indicates the total energy the LI strings can discharge independent of the LA string. The average of this values,

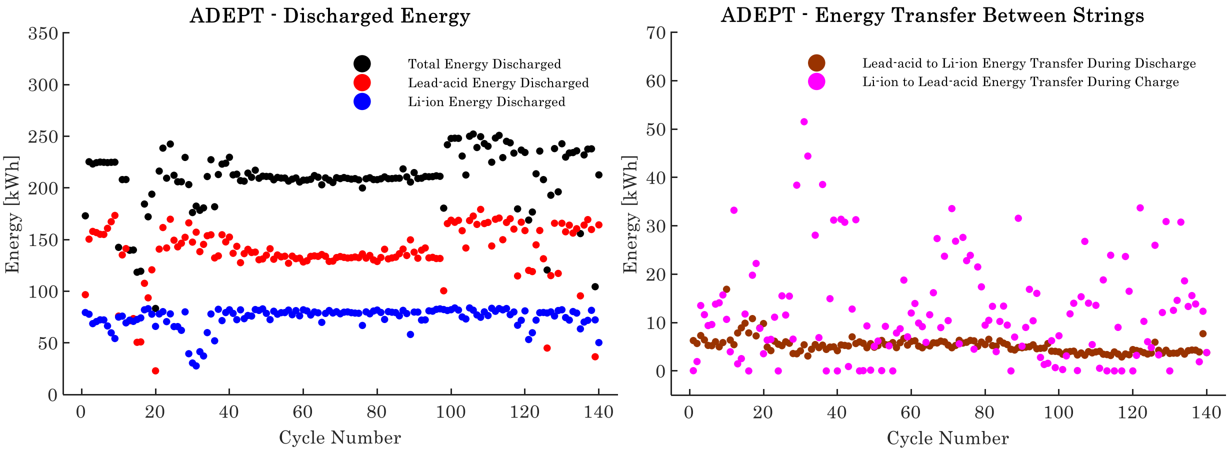


**Fig. 8.** ADEPT System Energy Flows, Total Energy (left) and Energy Transfer (right).

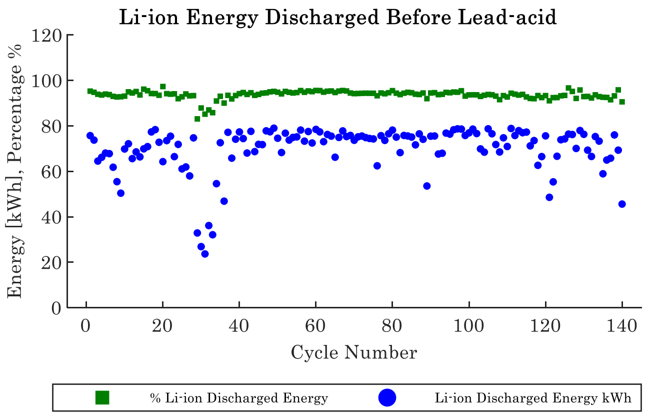


**Fig. 9.** ADEPT System Energy Discharged Between Points D–E..

across all 140 cycles is 70 kWh, which corresponds to 93% of the total LI discharged energy. This means that the LI stings reach around 7% SOC when the power share between the LI and LA stings equalize.

The average round-trip energy efficiency of the system was calculated to be around 90% with no capacity loss for the LI strings and less than 3% for the LA across the data set timespan.

## 4. Conclusions

The general data presented above shows that the dual chemistry LI and LA hybrid storage system is stable and can work successfully connected directly at the DC bus, without power converters. The interaction between the two chemistries shows that we can discharge the LI string independent of LA, thus providing semi-control of the strings.

The overall system round-trip efficiency depends on the ratio of LI to LA capacity and the depth of discharge of the overall system. The calculated average round-trip efficiency across the analyzed tests is 90%. The average energy discharged by the system was calculated to be 210 kWh, 138 kWh being delivered by LA and 75 kWh by the LI strings.

The energy transfer between the strings due to different time constants of the two chemistries depends on the charge stopping point C and to a lesser extent on the discharge point F. For the analyzed system, the average LI to LA energy transfer during the charge process is 13kWh, 5.5% of the total charged energy. The average LA to LI energy transfer during discharge is 5.2kWh, 2.47% of the total discharged energy.

During discharge the LI strings provide most of the power between points D–E. The data shows that around 93% of the total LI discharged energy takes place before the LA and LI power share equalize (point E). This is important as it allows the LI strings can take most of the short charge/discharge cycles thus protecting the LA ones.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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