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Storage for Life

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Quantified optimization of the HESS system

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A Hybrid Energy Storage System (HESS) consists out of at least two different storage elements. In the NETfficient. To optimize the energy flow a power sharing algorithm has to decide which storage element should be used to satisfy the needs.

In the NETfficent project two kinds of HESS (Hybrid Energy Storage) power sharing algorithms were developed. One one hand Fraunhofer ISE developed a power sharing algorithm were no forecast is possible like grid disturbances and faults or fast changing demands in industry grids or micro grids. These algorithms share the power only based on the status of the storage systems and the actual power demand and power ramp.

On the other hand the partner UNICA developed and implemented a peak shaving algorithm were a forecast is available. This is the case in the energy systems in which generation and consumption can be planned through historical data and weather forecast. The results of this work were presented in chapter 4 of this document as well as in WP4 and different papers.

1. Theory of the power sharing algorithms without forecast

The power sharing algorithm developed by Fraunhofer is dedicated to the Medium Voltage HESS system used in the project. All the simulations are made for the system out of Li-Ion Battery and Supercap system. But the developed algorithms can also be used for other HESS systems with different technologies like battery system and thermal storage or battery system and redox flow.

Two different approaches – set point & Low pass - have been developed. As the storage element can get full or empty one have also consider a recharge strategy.

In the following chapters the storage element with larger amount of energy is called energy storage (in MV HESS case the battery) and the one with the smaller energy content is called power storage MV HESS: Supecap).

1.1 Set Point Approach (SP)

The set point approach is rather simple. At low power demand the energy storage element delivers the power. If the power demand reaches the set point the power element overtakes the power which is exceeds the set point. This approach is identical to the peak shaving in grids but here the approach takes place inside the HESS (see Figure 1).

But as the power element is limited in capacity this approach has to be combined with a recharge strategy out of chapter 1.1.3.

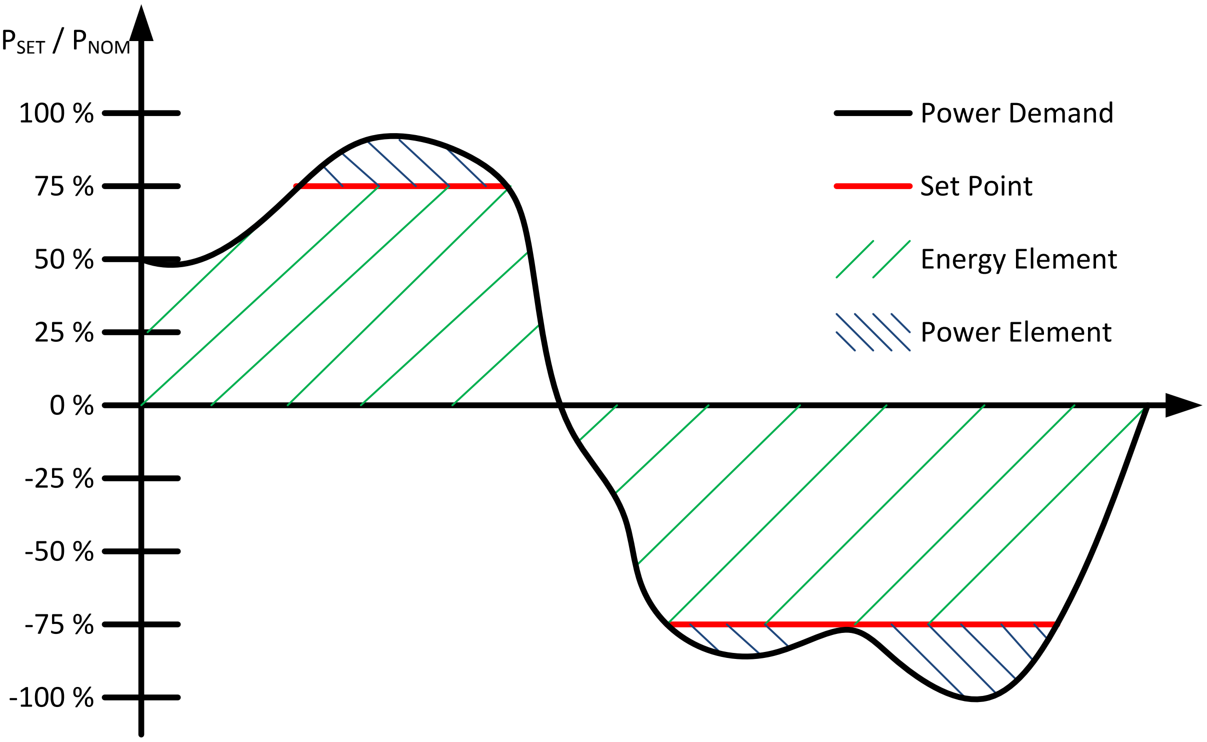


Figure 1: Set point approach

1.2 Low Pass Approach (LP)

In the low pass approach the Energy Management System is low pass filtering the power demand over the time. The low pass filtered curve is provided by the energy storage element and the difference between actual and low pass filtered value is supplied by the power element. In case of the MV HESS we get the following equations:

$$P_{INVERTER} = P_{DEMAND,Actual}$$

$$P_{SUPERCAP} = P_{DEMAND,LowPass}$$

$$P_{Battery} = P_{DEMAND,Actual} - P_{DEMAND,LowPass}$$

From the low pass approach we developed three variations.

In the first variation is the standard where the low pass approach is used all the time. The disadvantage here is that the power storage element is also used at low power demand. In case of the MV HESS this does not make sense as the power element supercap was used to extend the live time of the energy element battery. But aging of Li-Ion batteries is typically due to high charge rates, with low charge rates batteries can do much more cycles.

The second variation is a mixture of the low pass and the set point approach to avoid operation at low power demands. Here the low pass approach is only activate when the power demand is exceeding the set point limit.

In the third variation we tried to avoid a clear limit for the activation of the low pass filter. Therefore the filtering time of the low pass filter is adjusted to the height of the power demand. Then the low pass approach has a low effect at low power but is fully activated at high power peaks.

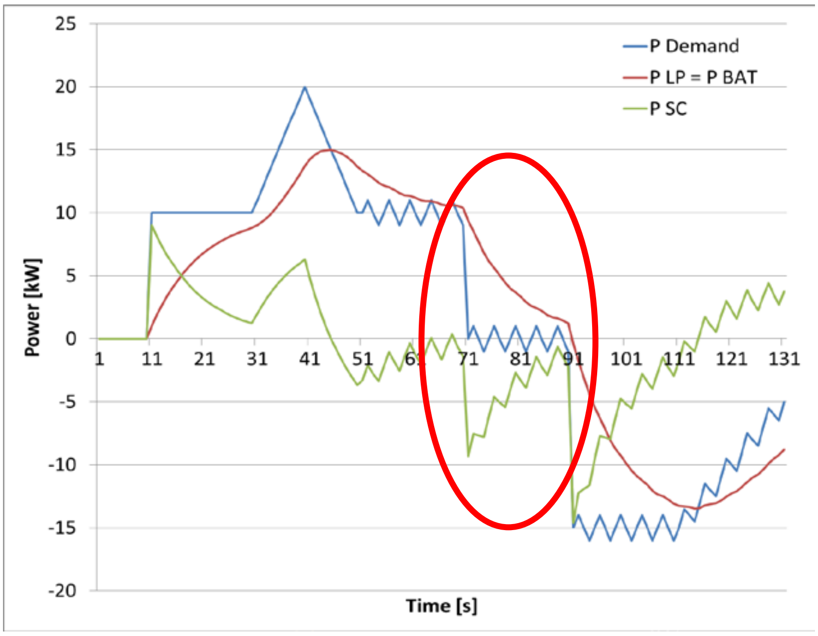


Figure 2: Low Pass Approach Variation 1 where Low Pass is always active

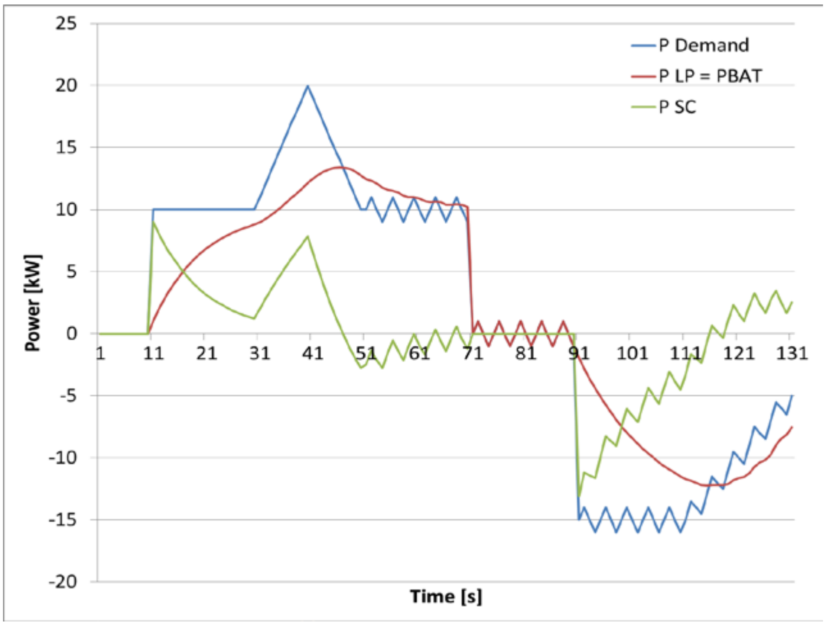


Figure 3: Low Pass Approach Variation 3 where the Low Pass time is adapted to power demand

As one can clearly see in Figure 2 inside of the red circle it is possible that energy is shifted from Battery to supercap even when there is a low demand. With the third (Figure 3) variation of the low pass approach with adjusted filtering time this drawback can be avoided.

1.3 Recharge Strategies

As the power element is limited in energy it makes sense to have a look at his state of charge (SOC) and consider a recharge strategy. Depending on the use case different recharge strategies should be considered.

First recharge strategy is to implement nothing. When there is a positive peak demand the power element will be discharged until it is empty. After a sign change and a negative power demand the element will be charged until it is full. This strategy makes sense when it is clear that after every positive peak comes a negative peak. Typical application would be a electrical motor with a load that has to be repetitive accelerated and braked.

Second recharge strategy is to make an intervention when the SOC of the power element is very high or low. For the MV HESS we decided that if the SOC of the supercap exceeds 95 % it will be discharged with partial load until 85 %. Also the supcercap will be charged to a SOC of 15 % as soon as the values fall below 5 %. This strategy makes sense when one can expect many short pulses in one or the other direction like at the connecting point of a production line with many pulsed drives.

The third recharge strategy is to prepare the power element in times of low demand for future power peaks. For the MV HESS we decided to balance the supercap with partial load as soon as the power demand is below 25 % of the nominal power of the system.

1.4 Combinations

The following combinations have been simulated

SP1: Use the Set Point Approach without balancing
SP1: Use the Set Point Approach recharge with partial load when SOC is high or low
SP1: Use the Set Point Approach recharge with partial load at low power demand
LP1: Use always the Low Pass Approach and recharge with partial load at low power demand
LP2: Use the Low Pass Approach at high power demand and recharge with partial load
LP3: Use the Low Pass Approach with adjusted time and recharge with partial load

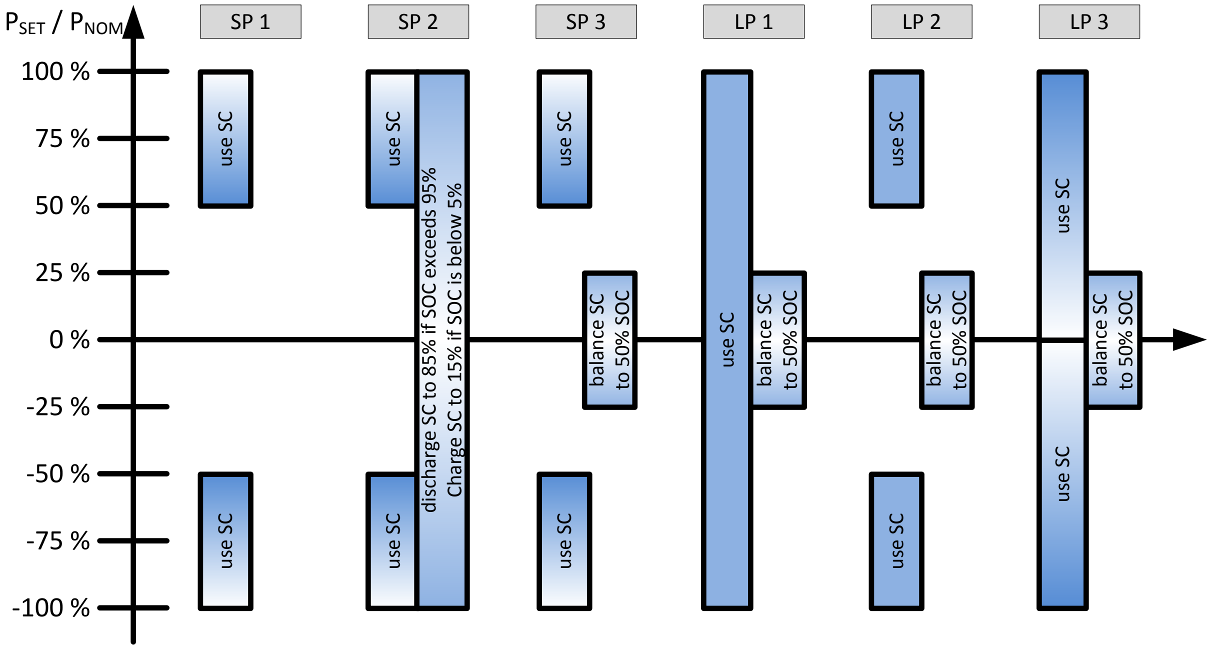


Figure 4: Overview of the Power Sharing Algorithms without forecast

2. Simulation of Power Sharing Algorithms without forecast

To compare the different power sharing algorithms and the recharge strategies a power profile of the use case primary reserve was chosen as it is the most typical application for stationary batteries in container size. Primary Reserve is not a heavy application with many cycles for a battery but data for use cases like industrial self consumption or micro grid were not available and differ strongly from application to application.

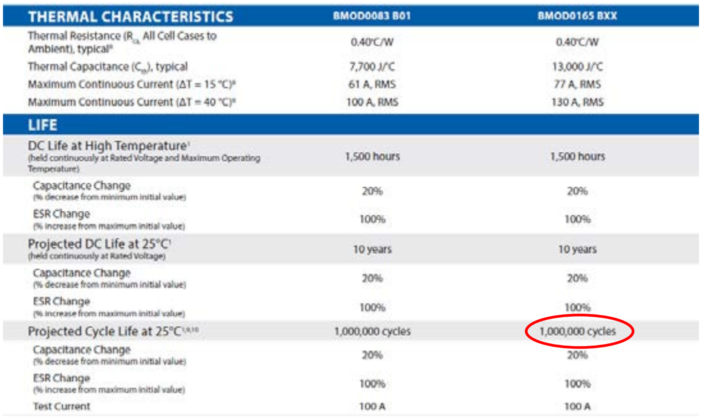
To compare the algorithms in the field test also makes no sense as the frequency change and therefore the power demand differs from day to day. Therefore the measurements of a typical day were used to determine the characteristics of the different approaches (04.05.2015).

Simulation Parameter

For the simulation the following parameters were used:

Battery Capacity	1000 kWh
Battery Power	1000 kW
Battery cost	750 €/kWh
Supercap Capacity	9000 Wh
Supercap Power	500 kW
Supercap cost	22,5 €/Wh
Set Point	500 kW
Partial Load recharge	200 kW
Start balancing	95 % and 5 % (SP2) for 10 %
Low pass	128 values (@ 500 ms sampling time)
Low pass adjustment	128 values @ 100 % and 1 value @ 0 %

To get the lifetime of the supercap we used the values out of the datasheet from Maxwell “BMOD0165P048”



THERMAL CHARACTERISTICS	BMOD0083 B01	BMOD0165 BXX
Thermal Resistance (R_{ca}, All Cell Cases to Ambient), typical[8]	0.40°C/W	0.40°C/W
Thermal Capacitance (C_{th}), typical	7,700 J/°C	13,000 J/°C
Maximum Continuous Current (ΔT = 15 °C)[8]	61 A, RMS	77 A, RMS
Maximum Continuous Current (ΔT = 40 °C)[8]	100 A, RMS	130 A, RMS
LIFE		
DC Life at High Temperature[1] (held continuously at Rated Voltage and Maximum Operating Temperature)	1,500 hours	1,500 hours
Capacitance Change (% decrease from minimum initial value)	20%	20%
ESR Change (% increase from maximum initial value)	100%	100%
Projected DC Life at 25°C[1] (held continuously at Rated Voltage)	10 years	10 years
Capacitance Change (% decrease from minimum initial value)	20%	20%
ESR Change (% increase from maximum initial value)	100%	100%
Projected Cycle Life at 25°C[1,9,10]	1,000,000 cycles	1,000,000 cycles
Capacitance Change (% decrease from minimum initial value)	20%	20%
ESR Change (% increase from maximum initial value)	100%	100%
Test Current	100 A	100 A

Figure 5: Part of the used supercap modul

For the lifetime of the battery the following data from the partner Powertech was used

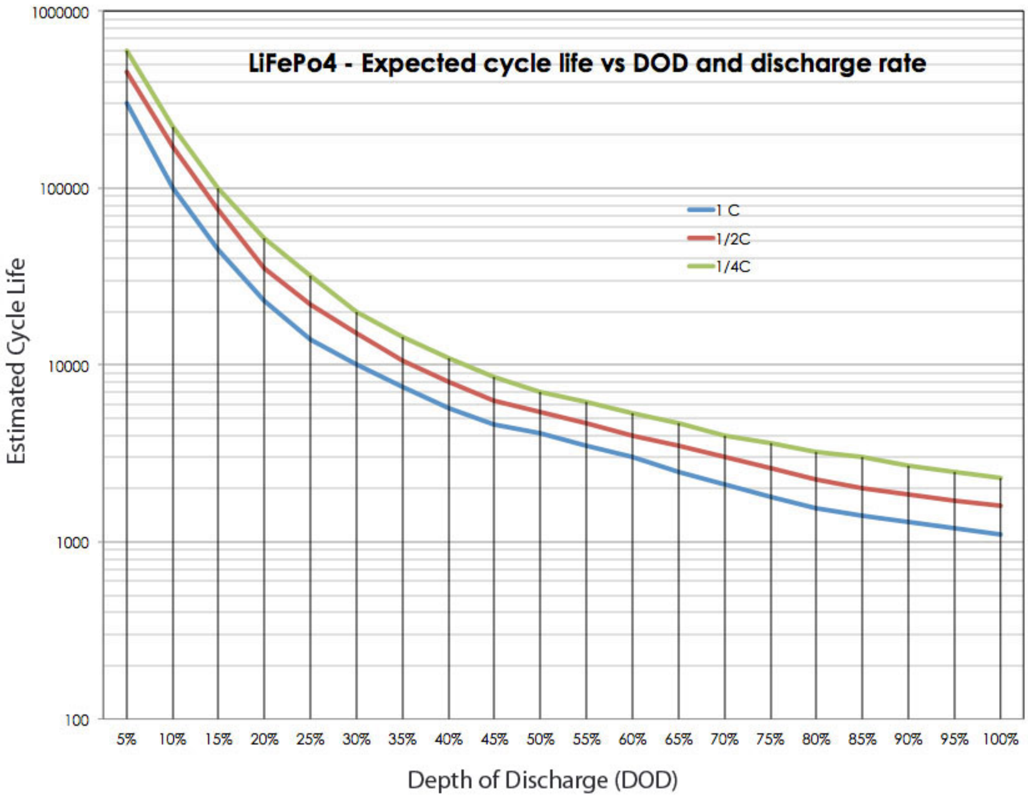


Figure 6: Available Battery Cycles of the used technolgy

Simulation Approach

The simulation approach consists of three steps

In the first step the power demand of the UseCase is calculated and one of the HESS Algorithm approaches including recharge strategy is chosen to get the power demand for the energy and power storage element.

In a second step the power demand curve is divided at every sign chance and the sections are classified in a table with the Power (C-Rate) in one axis and the Depth of Discharge (DoD) on the other axis.

In a third step a live time table of the battery with the same axis values is generated and multiplied with the results of the second step to get the aging per table cell (C-Rate & DoD pair). In the end all the cells of the table are added up to get the loss of lifetime.

This approach is adapted from the lifetime estimation of mechanical parts under stress with the axis bend and time.

2.1 Basic scenario - only Battery (BS)

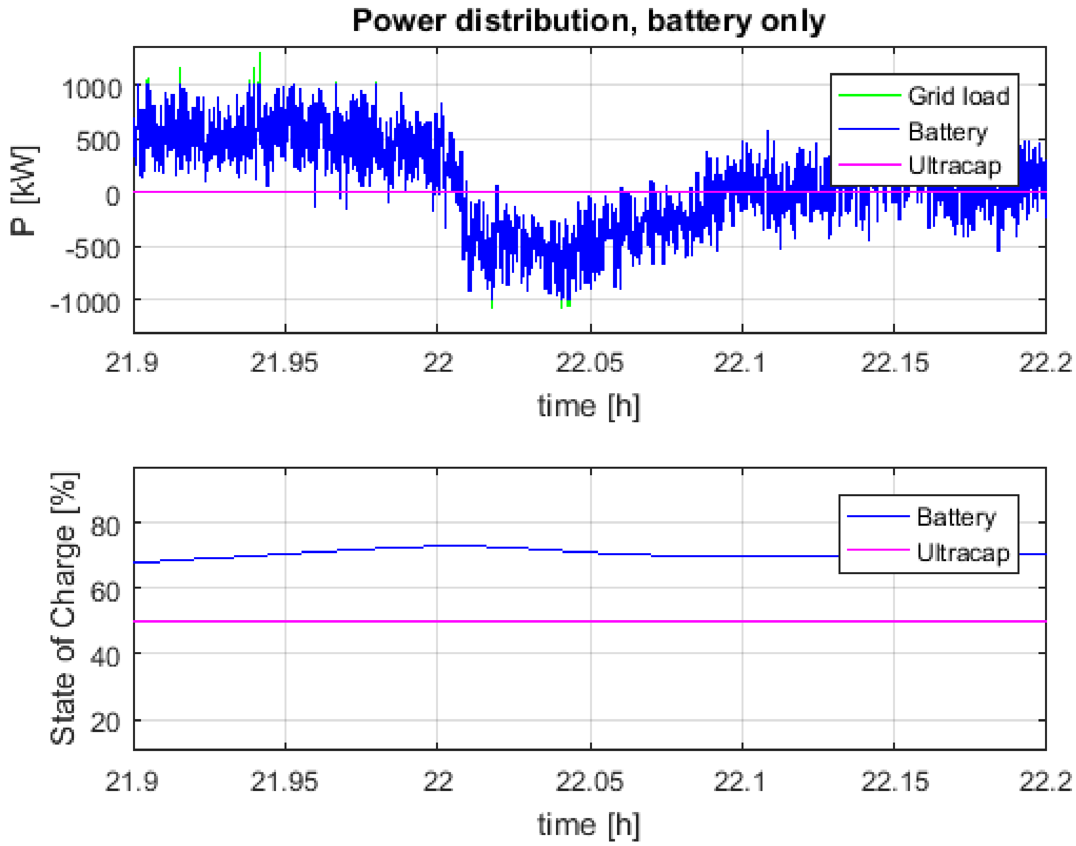


Figure 7: Basic Scenario – Power Flow

At the basic scenario the battery overtakes fully the demand (grid load) as there is no ultracap foreseen.

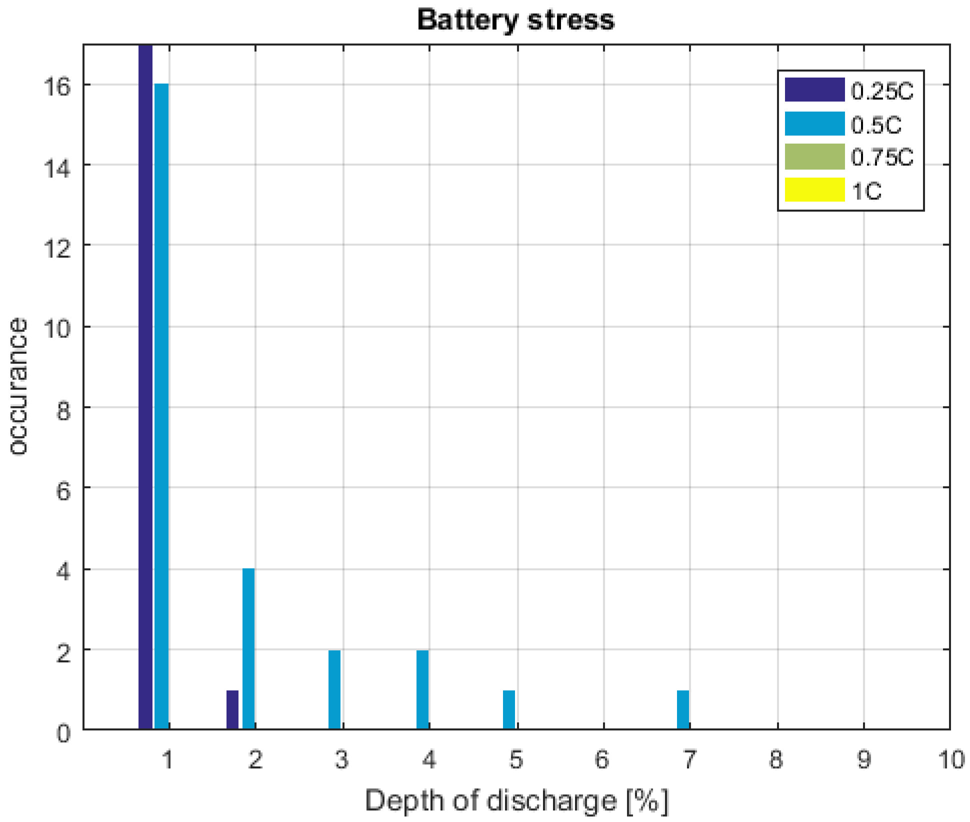


Figure 8: Basic Scenario – Battery stress

2.2 Set Point Approach with first recharge strategy (SP1)

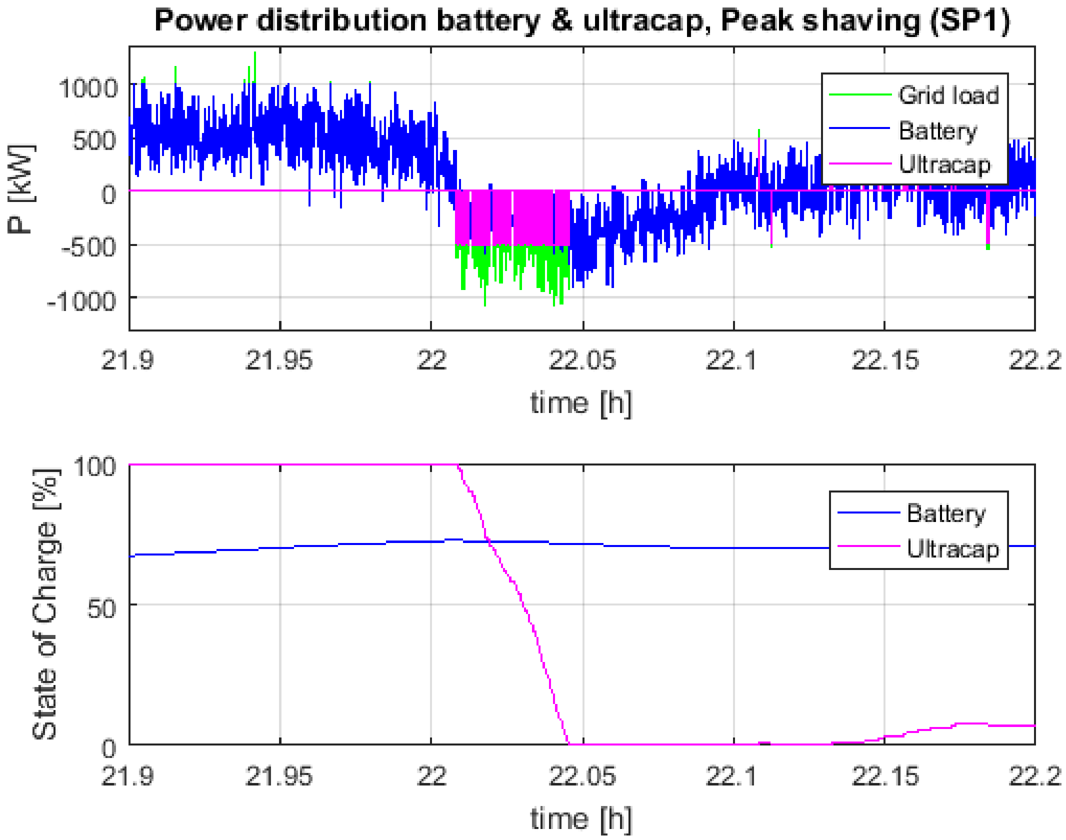


Figure 9: Set Point approach with first recharge strategy – Power Flow

According to the described algorithm the supercap is used when the power demand reaches the set point limit. Once the supercap is fully charged or discharged it cannot be used a second time until the power demand has a sign change. One can see that this approach is able to decrease the battery stress slightly by cutting off some high power peaks. The effect cannot take place when the power demand is positive or negative for too long, because the supercap is limited in energy.

Compared to the other approaches SP1 is the most economic, taking battery lifetime and supercap investment costs into account. But it is still more expensive than using only a battery without supercap.

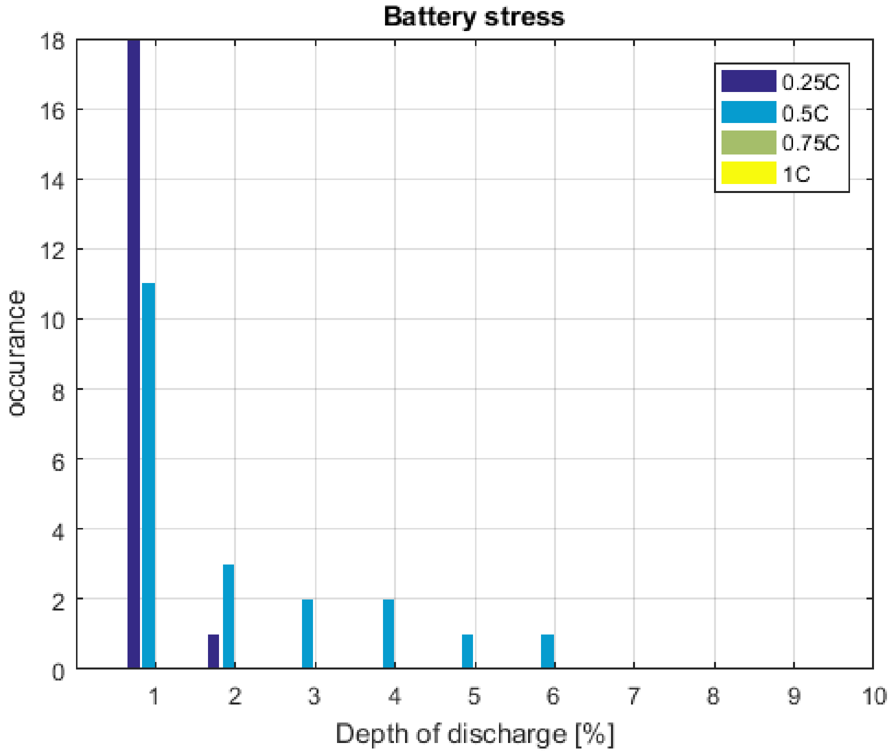


Figure 10: Set Point approach with first recharge strategy – Battery stress

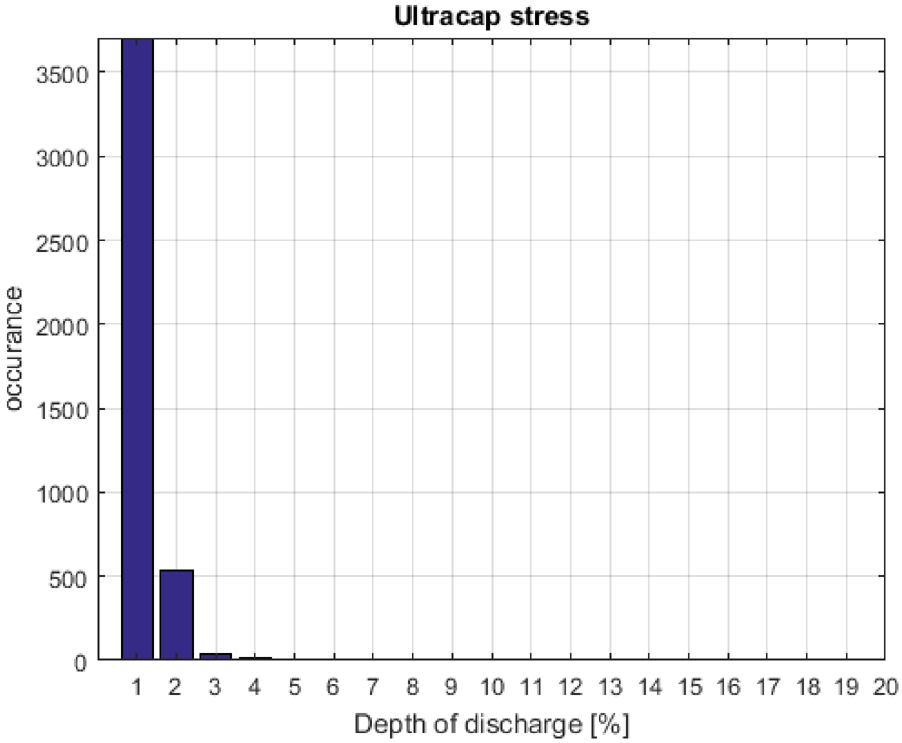


Figure 11: Set Point approach with first recharge strategy – Supercap stess

2.3 Set Point Approach with second recharge strategy (SP2)

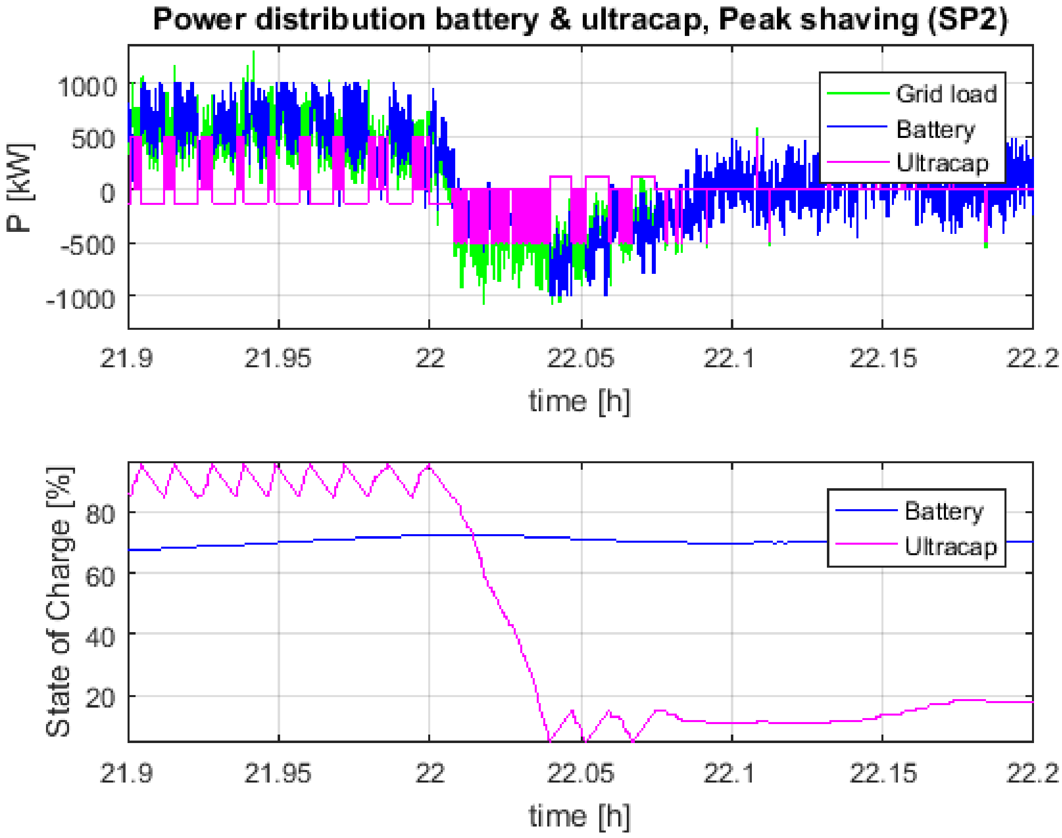


Figure 12: Set Point approach with second recharge strategy – Power Flow

Compared to SP1 now the balancing of the supercap SOC is visible. Whenever it reaches 95% it is forced to discharge by 10% with a partial load into battery or grid. Vice-versa the supercap is recharged by 10% whenever it falls below 5% SOC. Although this approach allows the supercap to absorb more power peaks, the battery stress actually becomes higher through the SOC balancing.

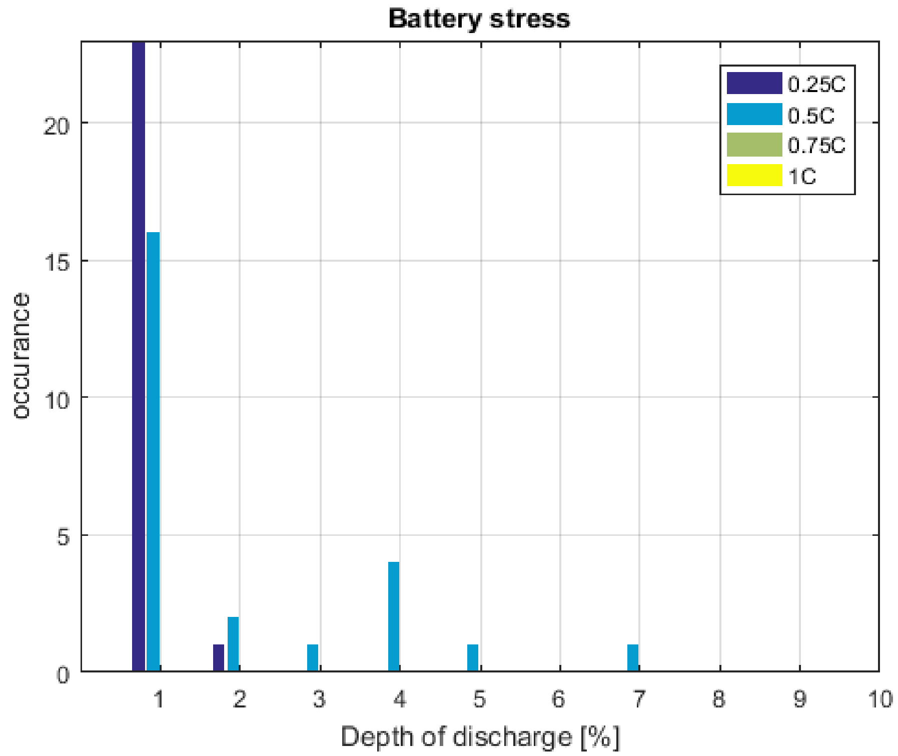


Figure 13: Set Point approach with second recharge strategy – Battery stress

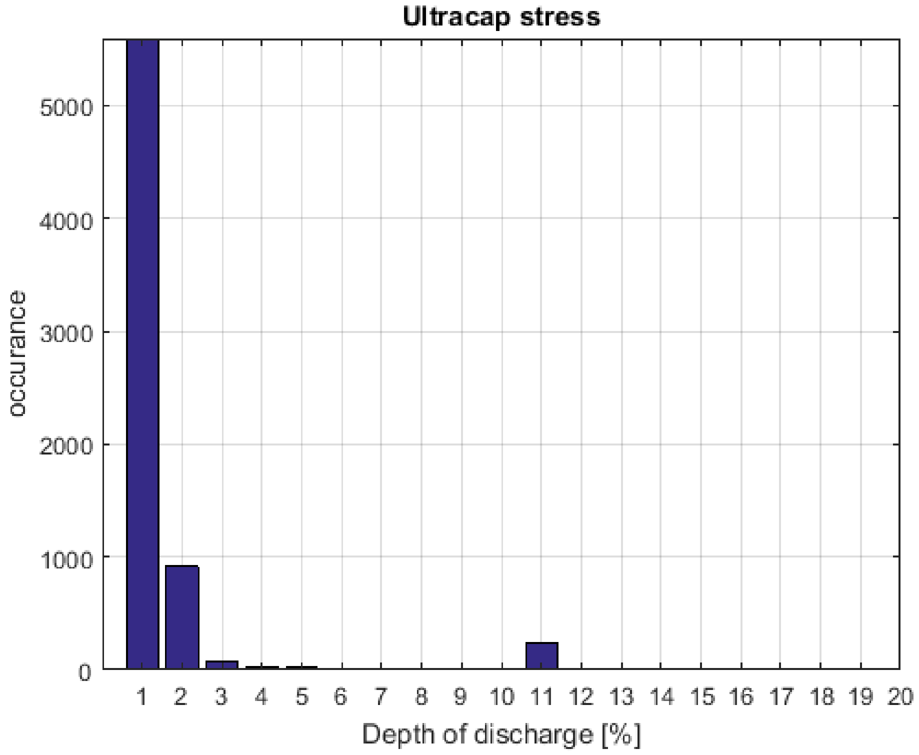


Figure 14: Set Point approach with second recharge strategy – Supercap stess

2.4 Set Point Approach with third recharge strategy (SP3)

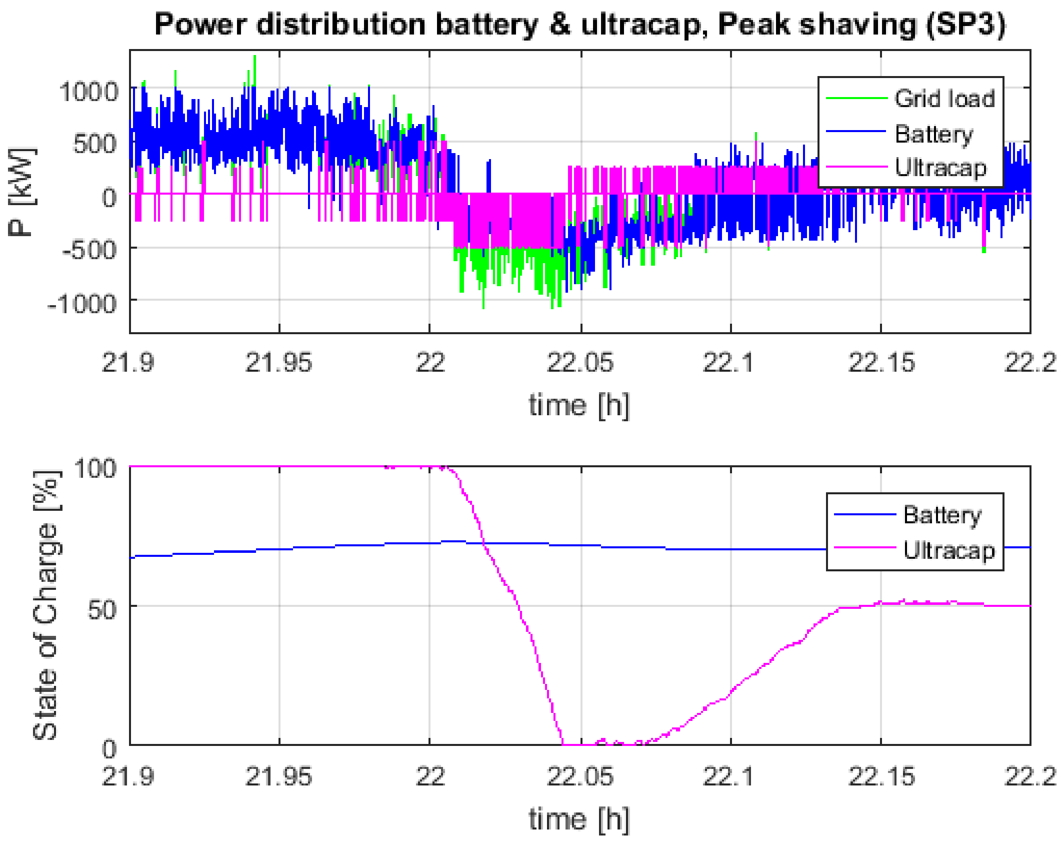


Figure 15: Set Point approach with third recharge strategy – Power Flow

In this approach the balancing of the supercap SOC to 50% during low power demands is visible. The supercap is now able to absorb many power peaks and to clearly reduce the battery stress. But due to the high investment costs of supercaps this comes with a price. In the investigated scenario the costs for supercap usage supersede the savings through extended battery lifetime.

Scenario SP3 can be made nearly as economic as as SP1 when choosing adequate parameter values. But again, it is more expensive than only using a battery.

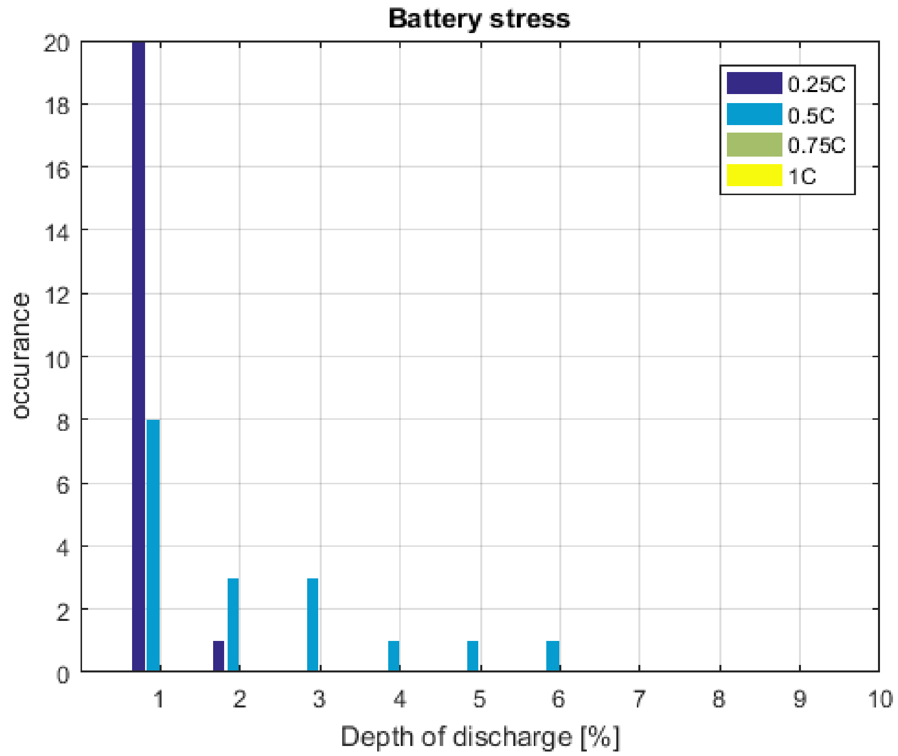


Figure 16: Set Point approach with third recharge strategy – Battery stress

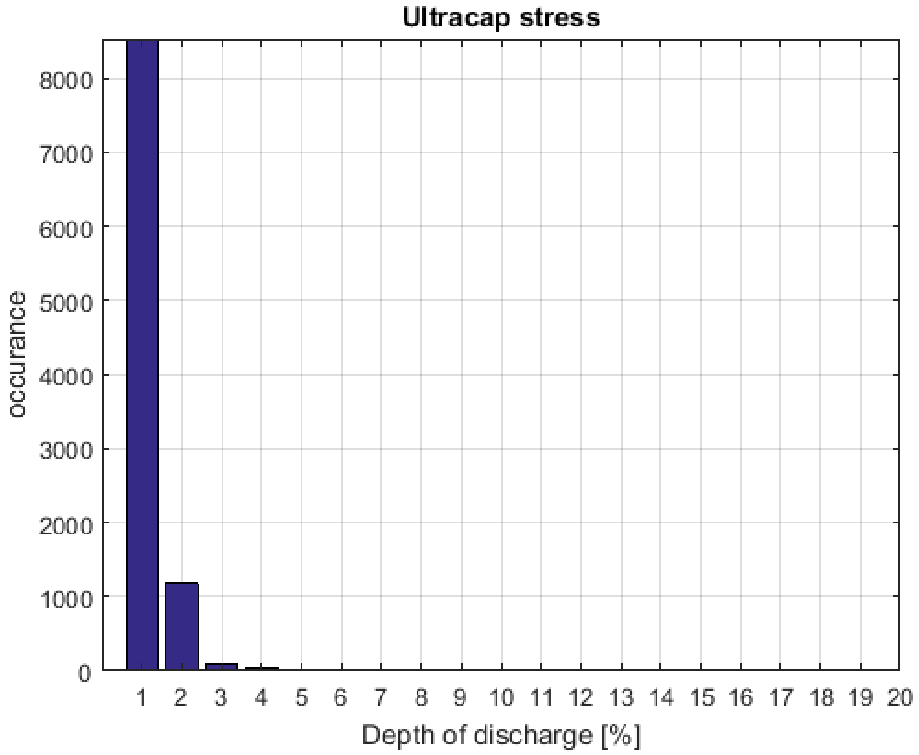


Figure 17: Set Point approach with third recharge strategy – Supercap stess

2.5 Low Pass Approach with third recharge strategy (LP1)

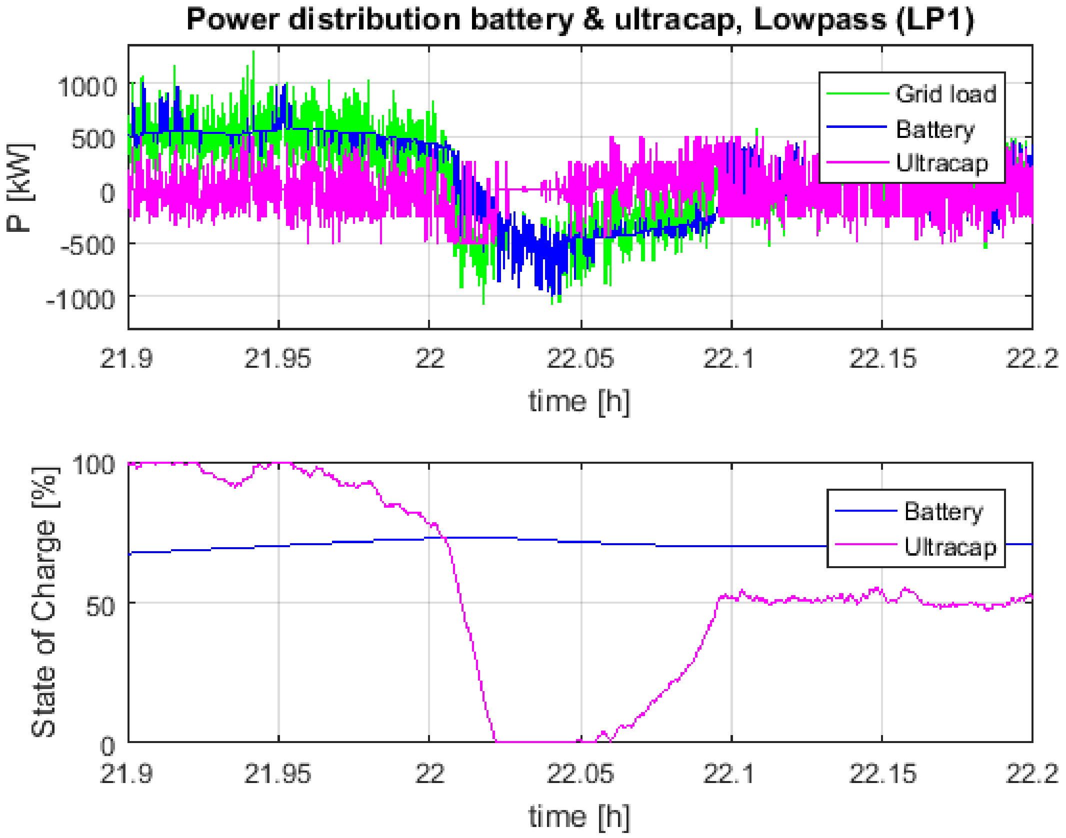


Figure 18: Low Pass approach with third recharge strategy – Power Flow

The low pass filtering of the power demand clearly reduces the energy flow through the battery. Due to the 50% SOC balancing the supercap is able to absorb most of the high frequency power demands. But the low pass filter also lengthens the time where the battery is charged at significant DoD rates and therefore increases the battery stress. Also the very high amount of supercap charging cycles is expensive. Therefore, this approach is not recommended.

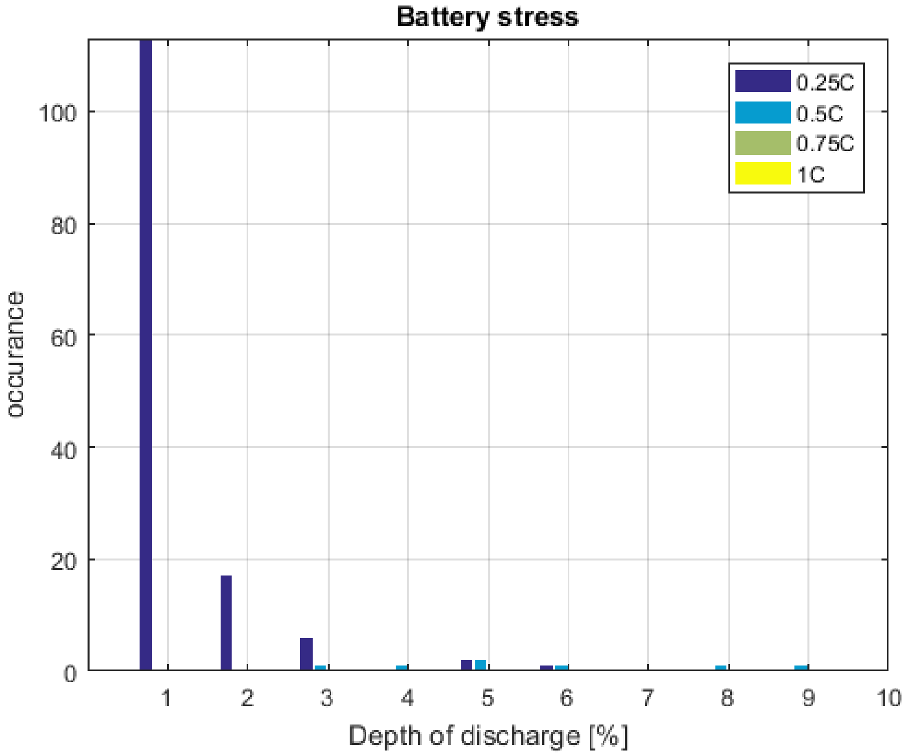


Figure 19: Low Pass approach with third recharge strategy – Battery stress

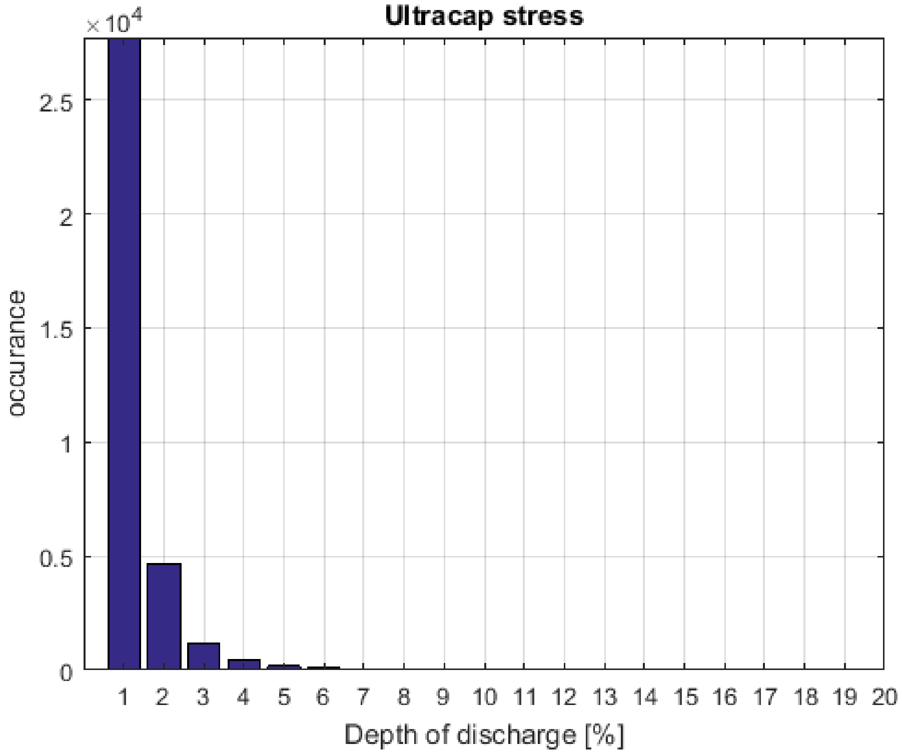


Figure 20: Low Pass approach with third recharge strategy – Supercap stess

2.6 Low Pass Approach with set point and third recharge strategy (LP2)

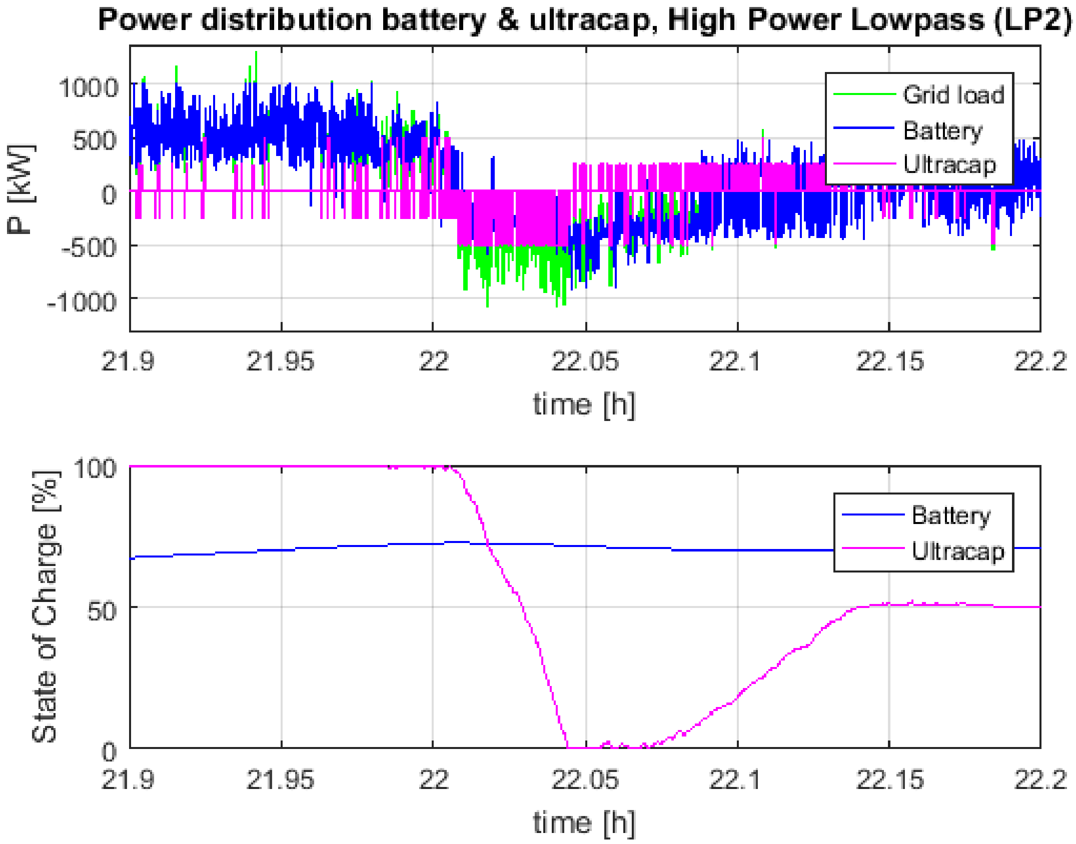


Figure 21: Low Pass approach with set point and third recharge strategy – Power Flow

In this approach the low pass filtered power demand is shifted to the supercap only when the set point is exceeded. Therefore the supercap power flow is reduced a lot compared to LP1. The results is very similar to the SP3 approach. The battery stress is clearly reduced compared to the reference scenario. But the cost savings due to longer battery lifetime do not compensate the investment costs for the supercap.

Scenario LP2 can be made nearly as economic as as SP1 when choosing adequate parameter values. But again, it is more expensive than only using a battery.

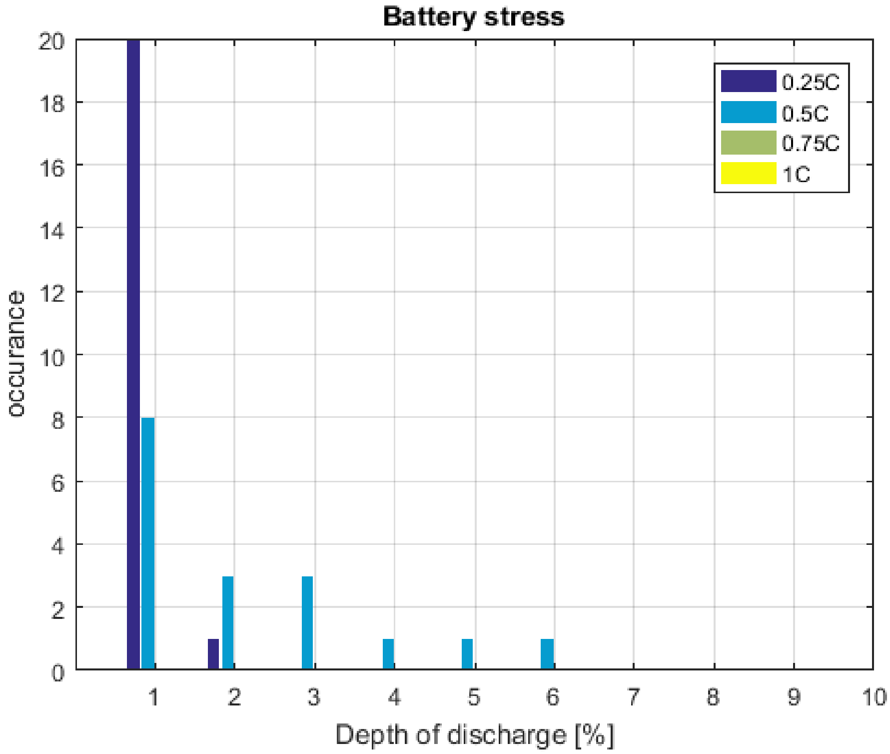


Figure 22: Low Pass approach with set point and third recharge strategy – Battery stress

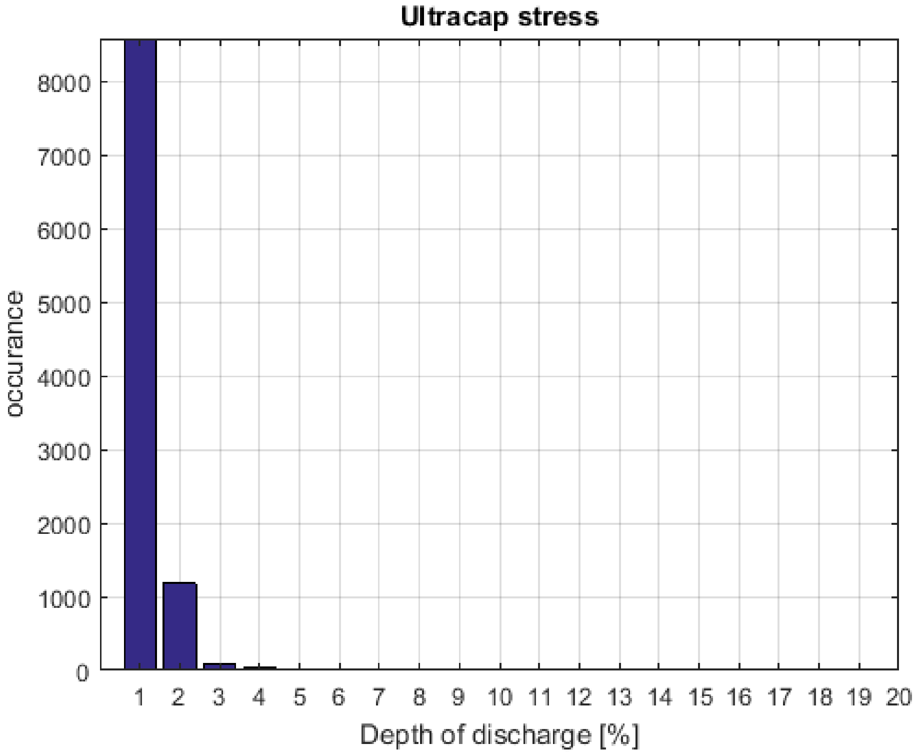


Figure 23: Low Pass approach with set point and third recharge strategy – Supercap stess

2.7 Weighted Low Pass Approach with third recharge strategy (LP3)

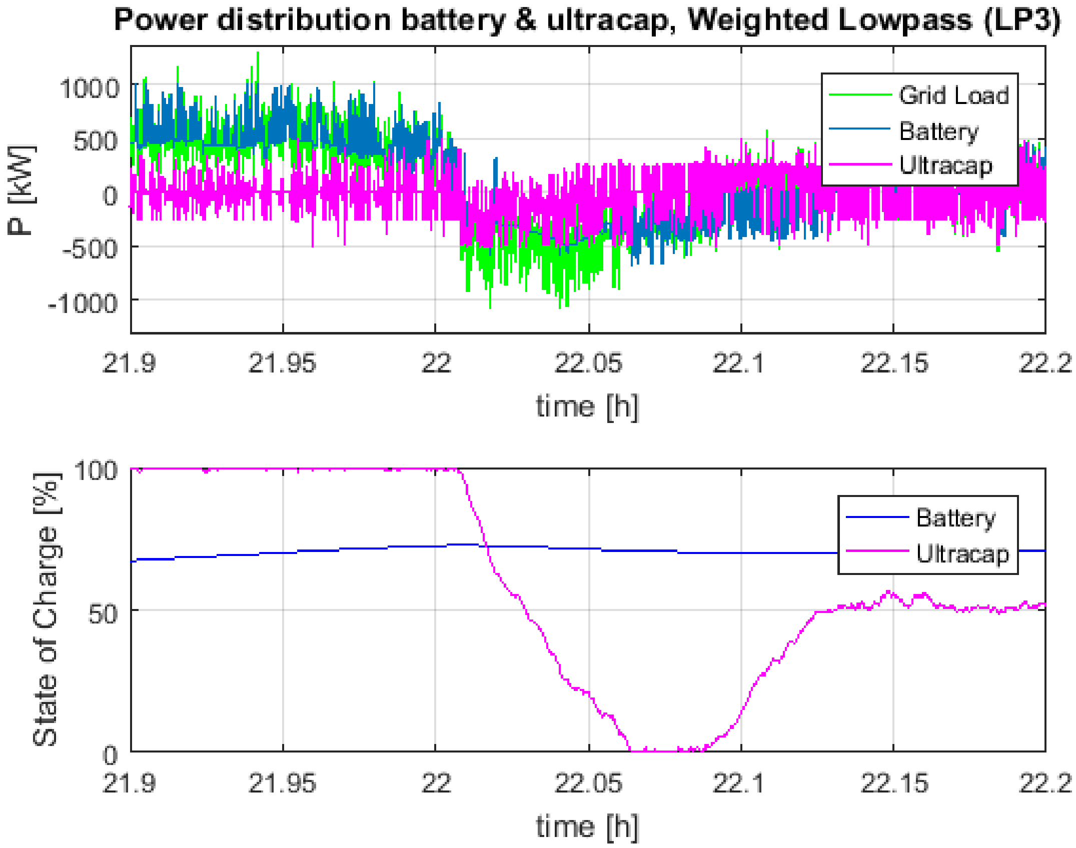


Figure 24: Weighted Low Pass approach with third recharge strategy – Power Flow

By weighting the low pass filter behaviour only quick AND high power demands are shifted to the supercap. This approach is the best to reduce the battery powerflow. Nevertheless, the battery stress increases due to the lengthened times of significant DoD rates. Within the investigated scenario also this approach cannot be recommended.

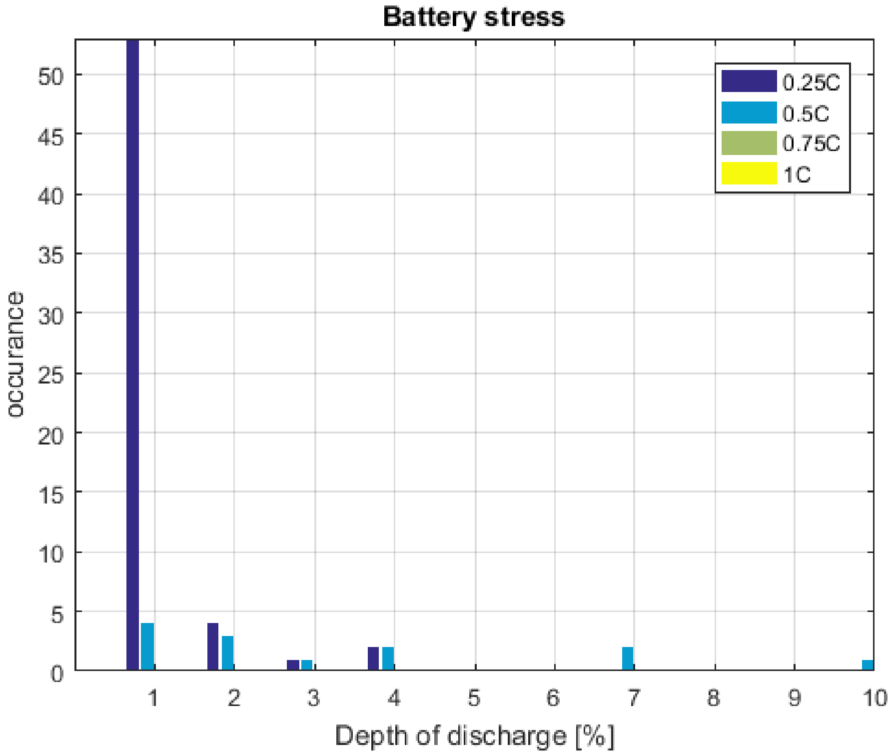


Figure 25: Weighted Low Pass approach with third recharge strategy – Battery stress

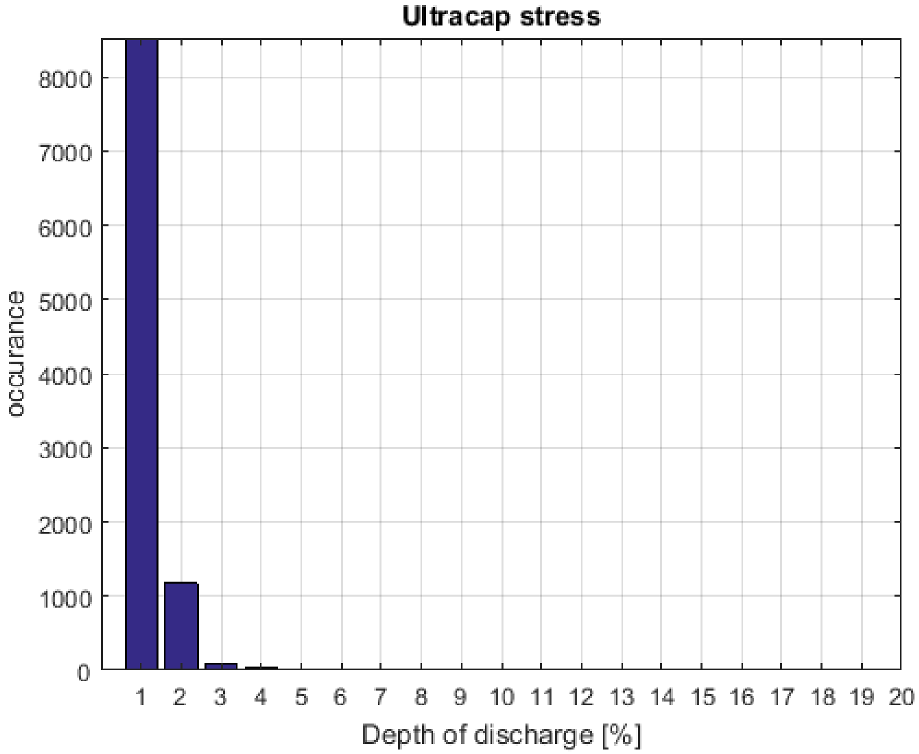


Figure 26: Weighted Low Pass approach with third recharge strategy – Supercap stess

3. Conclusion power sharing without forecast

Mode HESS_Algorithm	Energy Battery [kWh]	Energy UC [kWh]	Costs Battery [€]	Costs UC [€]	Sum Costs [€]	Lifetime Battery [y]	Lifetime UC [y]
Basic scenario only Battery [BS]	5231,51	0,00	37,34	0	37,34	55	0
Set Point - without recharge [SP1]	4863,14	368,72	32,27	10,31	42,58	63,6	53,8
Set Point - recharge @ low / high SOC [SP2]	4851,67	830,36	40,44	21,87	62,31	50,8	25,3
Set Point - recharge at low demand [SP3]	5128,97	1132,47	30,66	23,22	53,88	67	23,9
Low Pass always - recharge at low demand [LP1]	4198,24	4685,98	104,86	91,96	196,82	19,6	6
Low Pass @ high demand - recharge at low d.[LP2]	5126,41	1139,12	30,66	23,36	54,02	67	23,7
Low Pass weightend - recharge at low d. [LP3]	3518,62	4862,36	55,67	96,19	151,86	36,9	5,8

Table 1: Results of Power Sharing Algorithms

Most important results are:

- The calendar lifetime of Li-Ion batteries today is around 10 years. The simulated Use Case Primary Reserve leads to life time according to the cycles of around 55 years. Therefore it does not make sense to add a supcercap to the battery storage in this application.
- Good power sharing algorithms can reduce the energy flow up to 30% [LP3]
- To evaluate power sharing algorithms it is insufficient to look at the energy flow only; the costs of cyclical aging need to be taken into account.
- Longest battery lifetime could be reached with SetPoint [SP3] or Low Pass at high demand [LP2] combined with the recharge strategy at low power demand.
- Supercaps are nowadays by far too expensive to be used in a HESS in grid applications.
- Because of the high investment costs for supercaps up to now, none of the investigated scenarios was found to be more economic than a system with battery storage only

The above described results for a HESS out of Li-Ion battery and Supercap in primary reserve operation are not satisfying.

The developed algorithms could prove that a significant reduction of the energy flow in the energy storage element of a HESS is possible. Therefore the concept of HESS should be kept in mind for all applications were cycle aging is the limiting factor.

The described simulation approach can easily be adapted other use cases or HESS systems to find the cheapest combination of the selected hardware and algorithms.

4. Power Sharing Algorithms based on forecast

The algorithm developed by UNICA within the WP4 consists of driving the MV battery of the HESS in order to provide both peak shaving and reduced energy buffering of the island of Borkum with the mainland. Particularly, the aim of the algorithm is reducing the peak values of the residual power of the island of Borkum when it acts as either a generator or a load. Consequently, based on the residual power profile forecasted over a given time horizon, the UNICA's algorithm determines the most suitable battery power profile based on the actual battery state-of-charge (SoC). In this regard, it is worth noting that just MV battery is considered for the peak shaving service because ultracapacitors are weakly suited for providing this kind of energy service. Therefore, it is assumed that ultracapacitors can be managed locally for compensating for sudden power fluctuations and/or short term forecasting errors.

The results extrapolated from the case of a LONG time horizon (360 minutes) is reported in Figure 27 and Figure 28. Focusing on Figure 27 at first, it can be seen that the forecasted residual power (r) is negative almost all the time, meaning that the island of Borkum will act as a load for most of the time horizon considered for the test (about 210 minutes). Consequently, the MV battery will be driven in order to reduce the peak load power demand, leading to a smoother grid profile (g), as shown in Figure 27. The corresponding MV battery power and SoC evolutions are depicted in Figure 28; it can be seen that the MV battery is expected to increase the energy drawn in the first minutes of the time horizon in order to shave the peak occurring immediately after (within the first 30 minutes). Similar considerations go also for the subsequent evolution, namely the MV battery increase the load demand when it is relatively low; the energy drawn by the MV battery is then released for shaving the subsequent peak, thus revealing the effectiveness of the proposed algorithm. This effectiveness is revealed also by the SoC achieved by the MV battery at the end of the time horizon (35% at about 210 minutes); this value corresponds to the minimum allowed SoC value, thus meaning that MV battery energy capability has been fully exploited.

In order to better asses the performances of the peak shaving algorithm, reference can be made to both Figure 29 and Figure 30. Particularly, Figure 29 highlights that peak load power is shaved to almost 3 MW for about 60 minutes (right side of the graph), while load power is increased when it occurs at relatively low rates (left side of the graph). Similar considerations can be made by referring to Figure 30, which shows the number of hours for each power value during which the power demand is greater than the selected power value; this figure reveals that the number of hours characterized by high power rates drops significantly moving from r to g (right side of the graph), as expected due to the peak shaving action.

Considering now the case of the SHORT time horizon (60 minutes), the corresponding results are shown in Figure 31 and Figure 32. It can be seen that MV battery is fully discharged to 35% at the end of the considered time horizon in order to shave the load demand at the minimum possible constant level. As a result, the peak load demand is reduced to the maximum extent in accordance with both MV battery power and energy constraints. In this case, no Pareto diagrams have been considered due to monotonically evolution of the residual power, which makes them weakly informative.

In conclusion, the Key Performance Indexes (KPIs) that quantify peak shaving performance are resumed in Table 2 for both cases (LONG and SHORT time horizon).

Key Performance Index	LONG time horizon			SHORT time horizon		
	r	g	diff.	r	g	diff.
peak power (load)	3493 kW	2972 kW	–14.9%	2189 kW	2073 kW	–5.3%
peak power (gen)	15 kW	0 kW	–100%	-	-	-
“peak” time (load)	62 min	-	–62 min	60 min	-	–60 min
“peak” time (gen)	5 min	-	–5 min	0 min	-	-

Table 2: Key Performance Indexes (KPIs) of the peak shaving algorithm

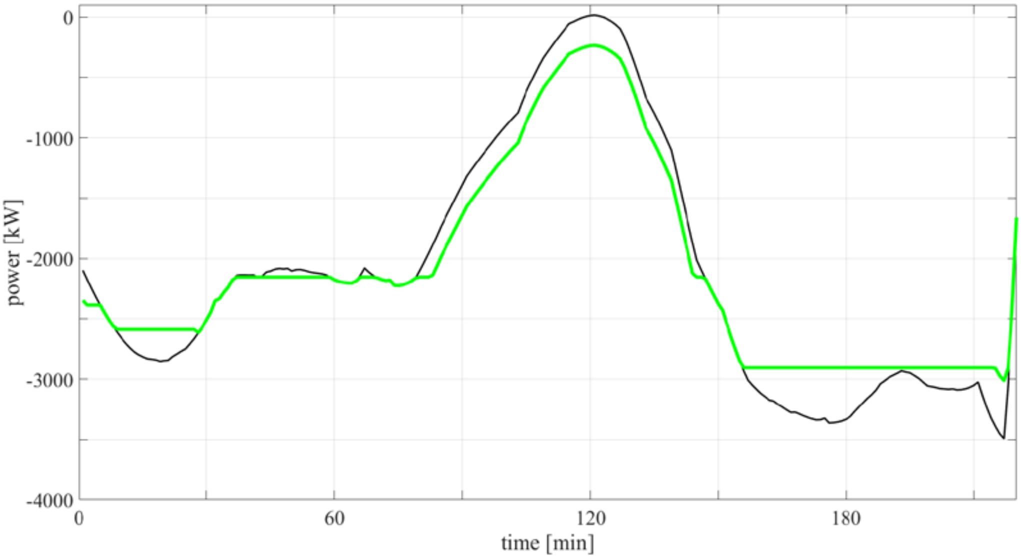


Figure 27: Time evolutions of residual power (r, in black) and grid power (g, in green) in the case of LONG time horizon

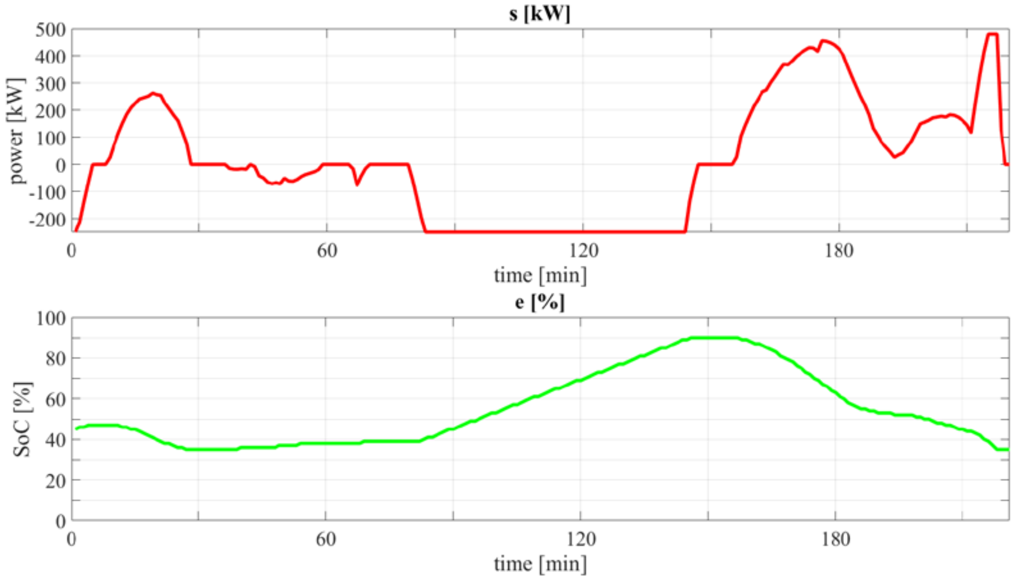


Figure 28: Time evolutions of MV battery power (s, in red) and SoC (e, in green) in the case of LONG time horizon

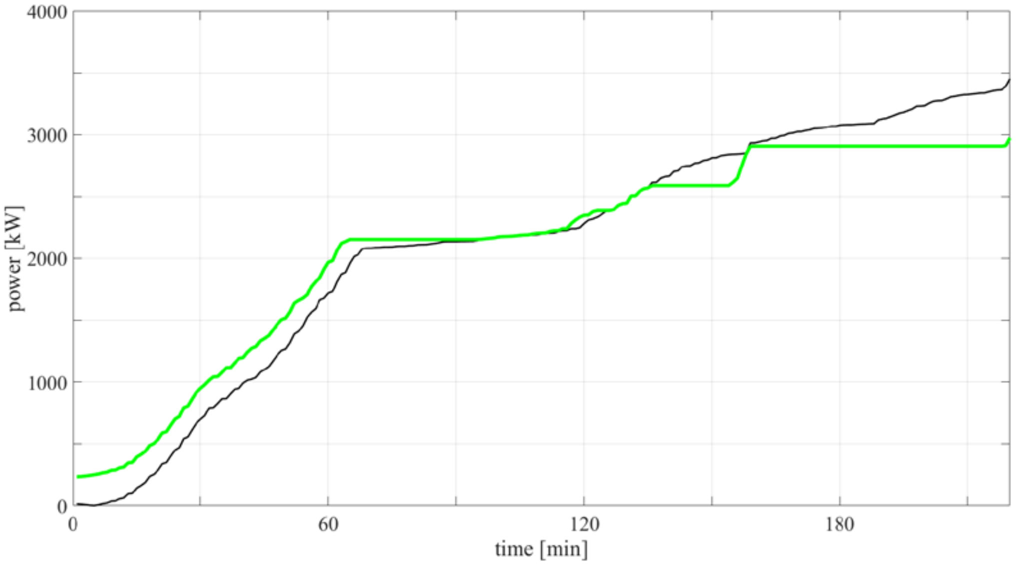


Figure 29: Pareto diagram of residual power (r, in black) and grid power (g, in green) in the case of LONG time horizon

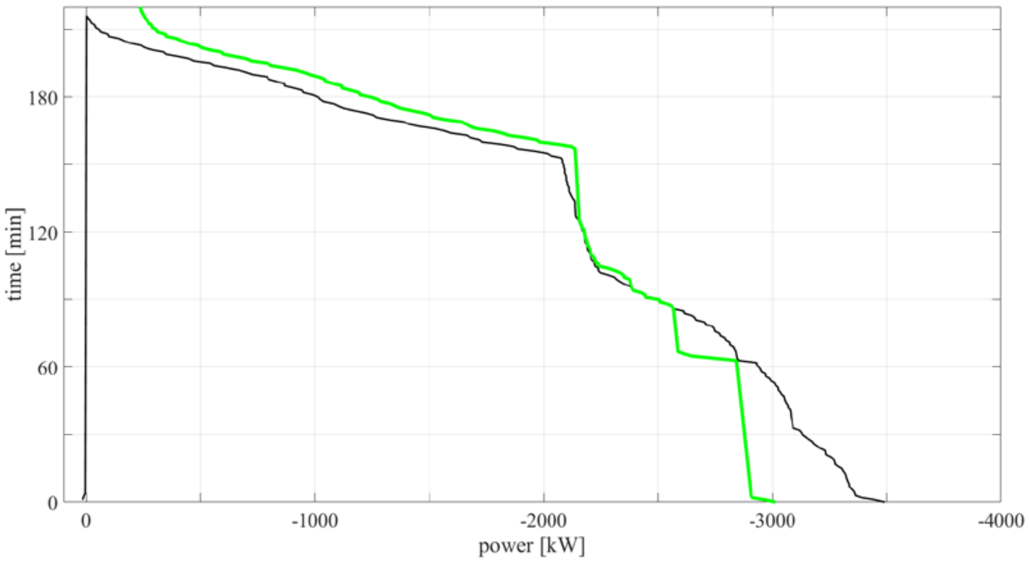


Figure 30: Pareto diagram that highlights, for each power value, the number of minutes for which the forecasted residual power (r, in black) and the grid power (g, in green) are greater than the selected power value

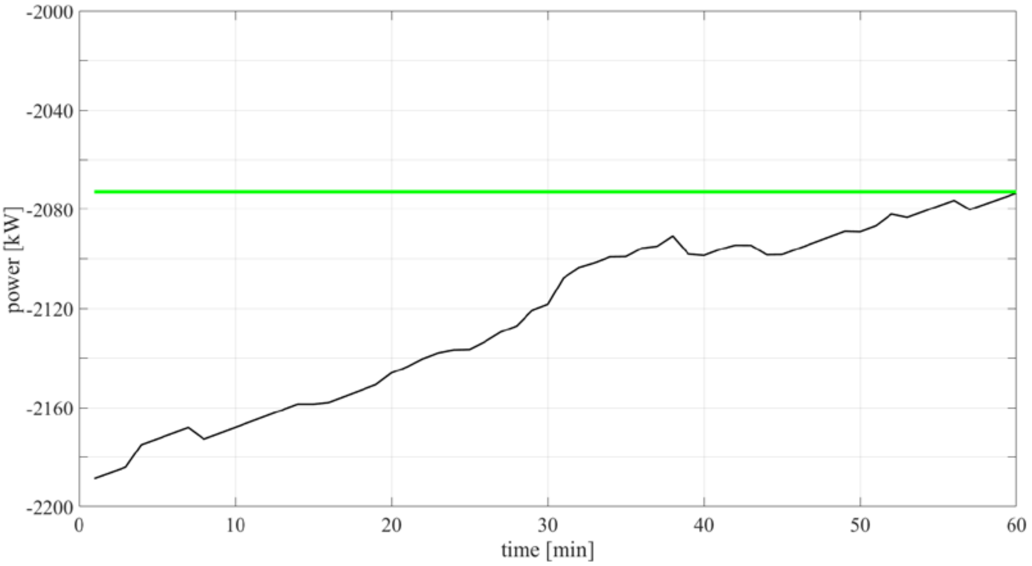


Figure 31: Time evolutions of residual power (r, in black) and grid power (g, in green) in the case of SHORT time horizon.

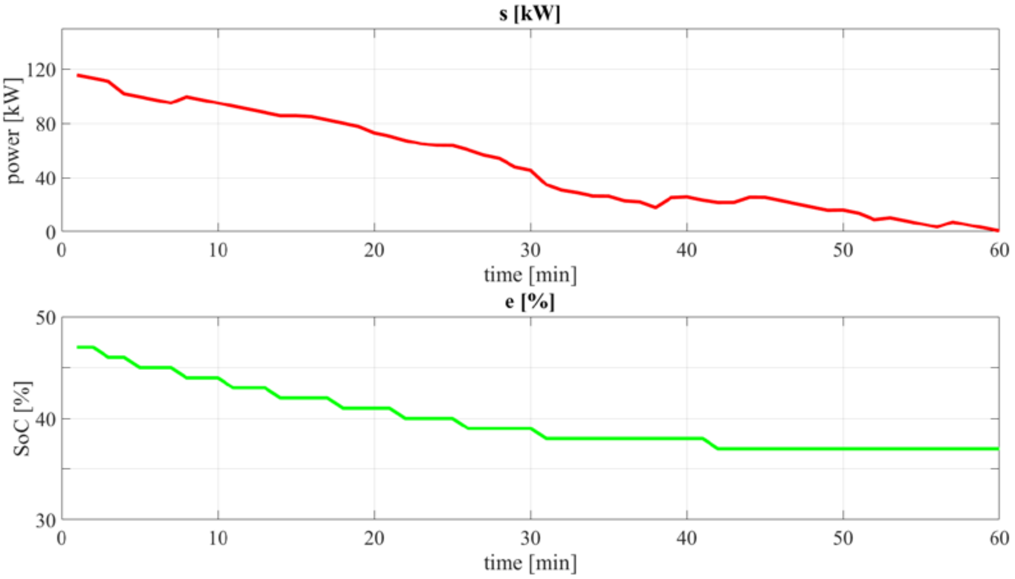


Figure 32: Time evolutions of MV battery power (s, in red) and SoC (e, in green) in the case of SHORT time horizon.

A1. Appendix: Index of figures and tables

A1.1. Index of figures

A1.2. Index of tables