TECHNISCHE UNIVERSITÄT DRESDEN

Chair of Energy Storage Systems

Hierarchical Energy Management of Hybrid Battery Storage Systems for PV Capacity Firming and Spot Market Trading Considering Degradation Costs

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Chair of Energy Storage Systems

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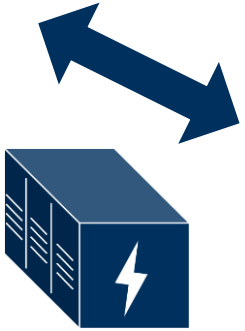
Introduction

Integration of renewable energies into existing energy systems

Photograph: Suvra Kanti Das/ The Guardian

greentechmedia.com



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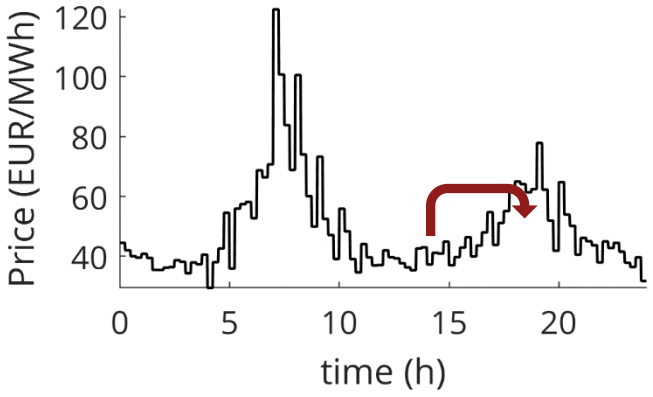
1. Introduction

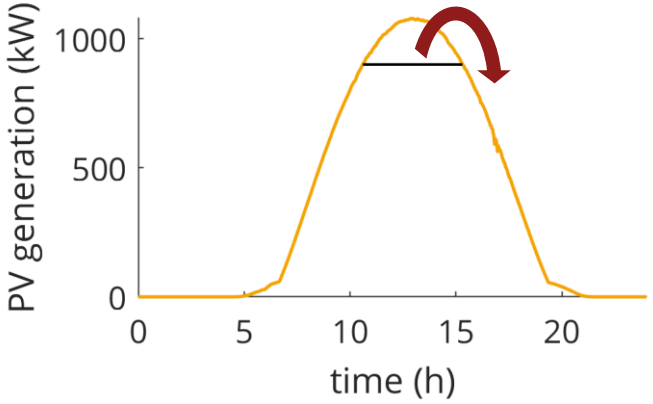
PV + Battery storage: Multi-use services

Energy Time Shift

Spot market trading

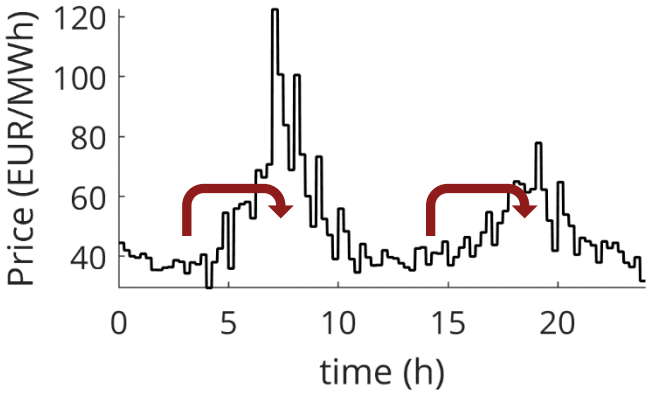


Peakshaving

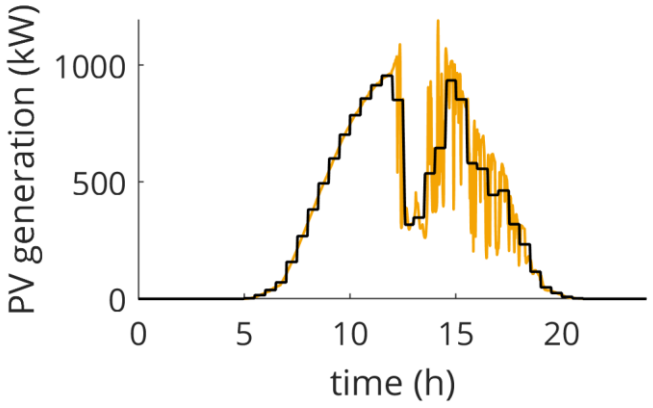


Energy Arbitrage

Spot market trading with grid supply

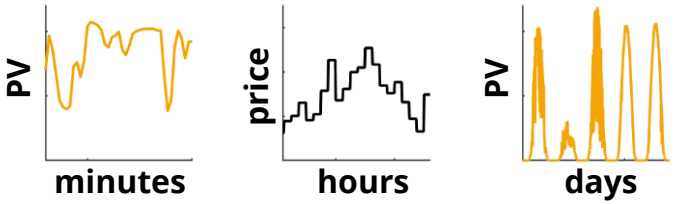


Capacity Firming

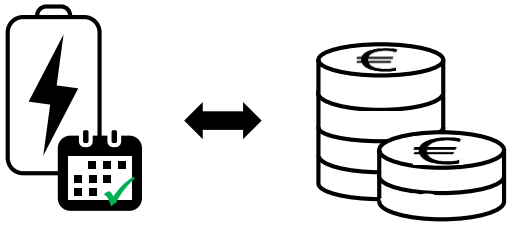


- Smoothing fluctuations
- Ramp rate control
- Complying with settled grid power

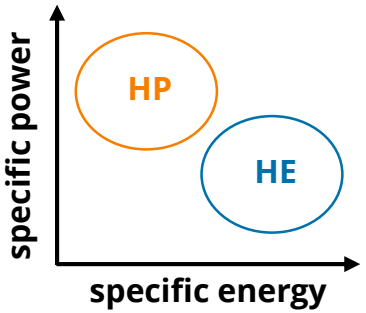
1. Introduction
Research questions



- How can the different temporal scales of the multi-use applications be addressed?



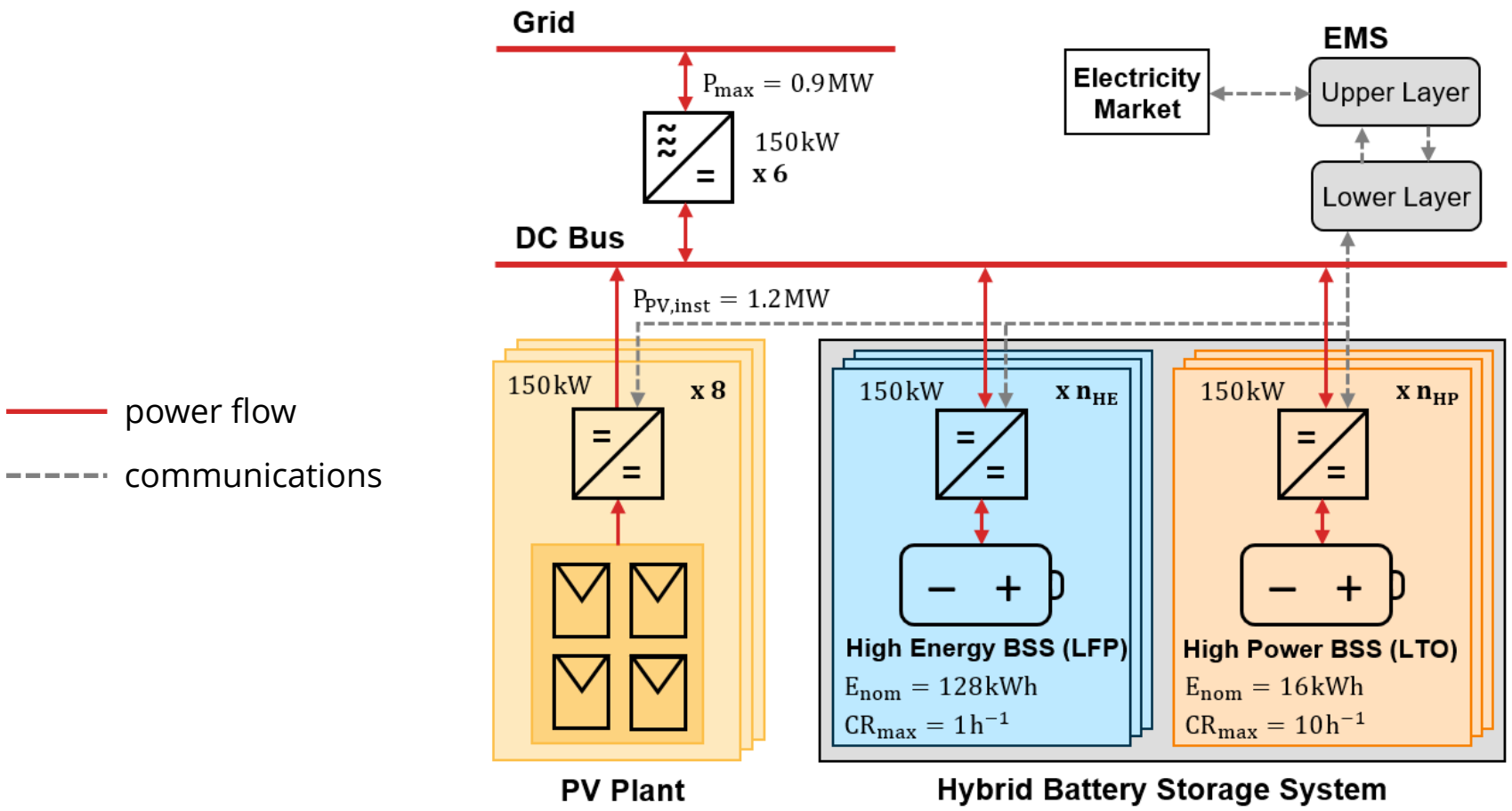
- Considering battery degradation, how can the benefits of the storage over its lifetime be maximized?



- Is there any advantage to battery hybridization for the given application, and how should the power be allocated?

1. Introduction

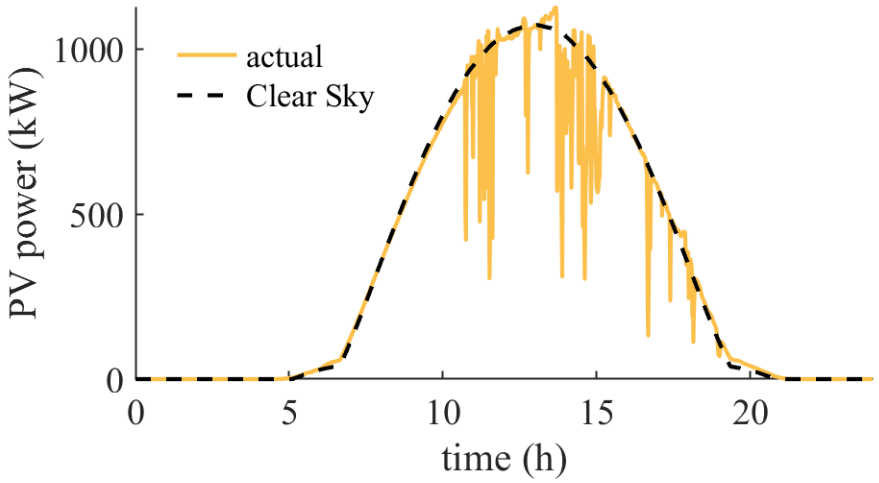
PV plant with Hybrid Battery Storage System



2. System Description

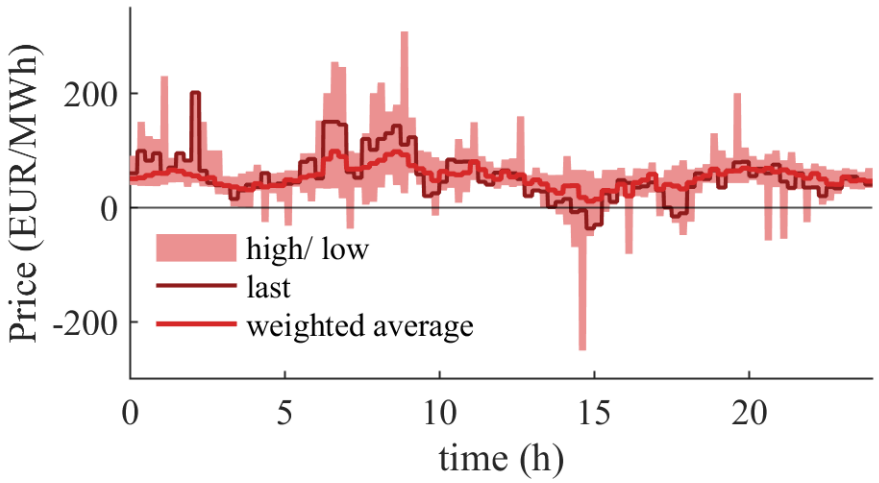
PV generation and price signal time series

PV generation



- Modeled using 1 min mean values of solar radiation (DWD[1])
- Lindenberg, Germany, 2018
- Forecast of 15 min mean values, horizon 24 h with Clear Sky model

Price signal



- Continuous 15 min Intraday Market (EPEX SPOT)
- Historical data, Germany, 2018
- Assumptions: fixed prices, perfect forecast

[1] S.Wacker. *Basic and other measurements of radiation at station Lindenberg.* DWD 2018. DOI: 10.1594/PANGAEA.669521

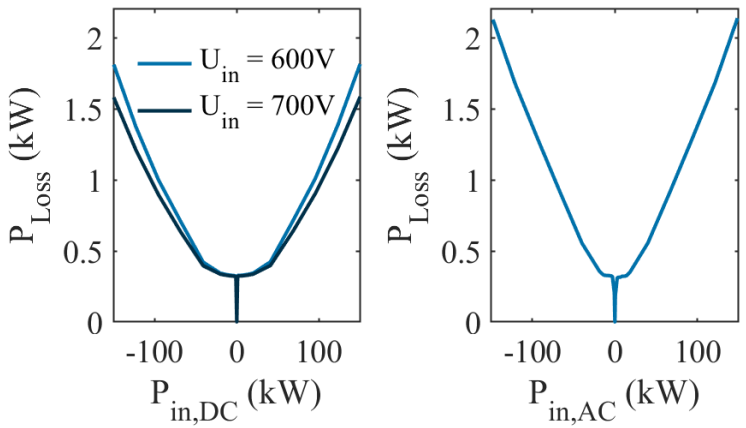
2. System Description

Battery modeling and power electronics

Parameters of the battery modules

Description	LFP High Energy [1]	LTO High Power [2]
Cells serial; cells parallel	190; 2	255; 9
Energy	128 kWh	16 kWh
Max. continuous C-rate	1 h^{-1}	10 h^{-1}
Nominal voltage	608 V	612 V
Cycle Life	ca. 3500 cycles @ 25°C, 1C/1C, 100% DoC	ca. 60000 @ 25°C, 10C/10C, 100% DoC
Specific Costs	230 EUR/kWh	600 EUR/kWh

Losses of the power electronics [3]



[1] EVE Energy. Product Specification 2019.

[2] T. Nemeth et al., *„Lithium titanate oxide battery cells for high-power automotive applications – Electrothermal properties, aging behavior and cost considerations,"* Journal of Energy Storage, vol. 31, no. 5, 2020, DOI: 10.1016/j.est.2020.101656.

[3] Fraunhofer ISE (HYBAT research project)

2. System Description
Battery aging modeling

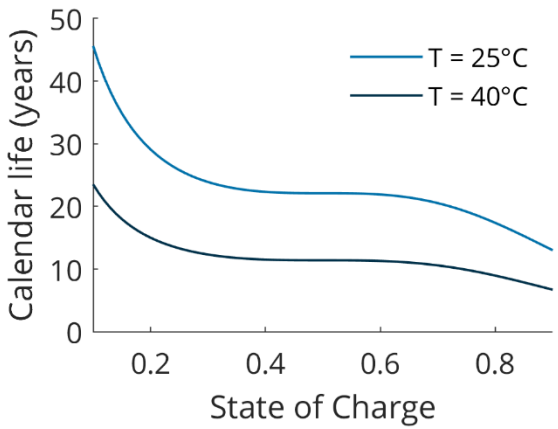
Semi-empirical aging model for LFP battery

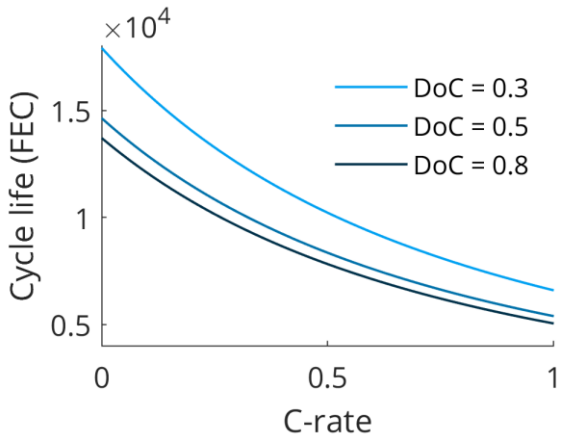
$$Q_{loss} = Q_{loss,cal} + Q_{loss,cyc}$$

$$Q_{loss,cal} = a \cdot e^{-\frac{E_A}{R}\cdot\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)} \cdot [b \cdot (SoC - 0.5)^3 + c] \cdot \sqrt{t} \qquad [t] = s$$

$$Q_{loss,cyc} = \{(a \cdot CR + b) \cdot [c \cdot (DoC - 0.6)^3 + d] \cdot \sqrt{FEC}\}/k_{scal}$$

t	Time
SoC	State of Charge
T	Temperature
FEC	Full Equivalent Cycles
CR	C-rate
DoC	Depth of Cycle
k_{scal}	Scaling to data sheet specifications



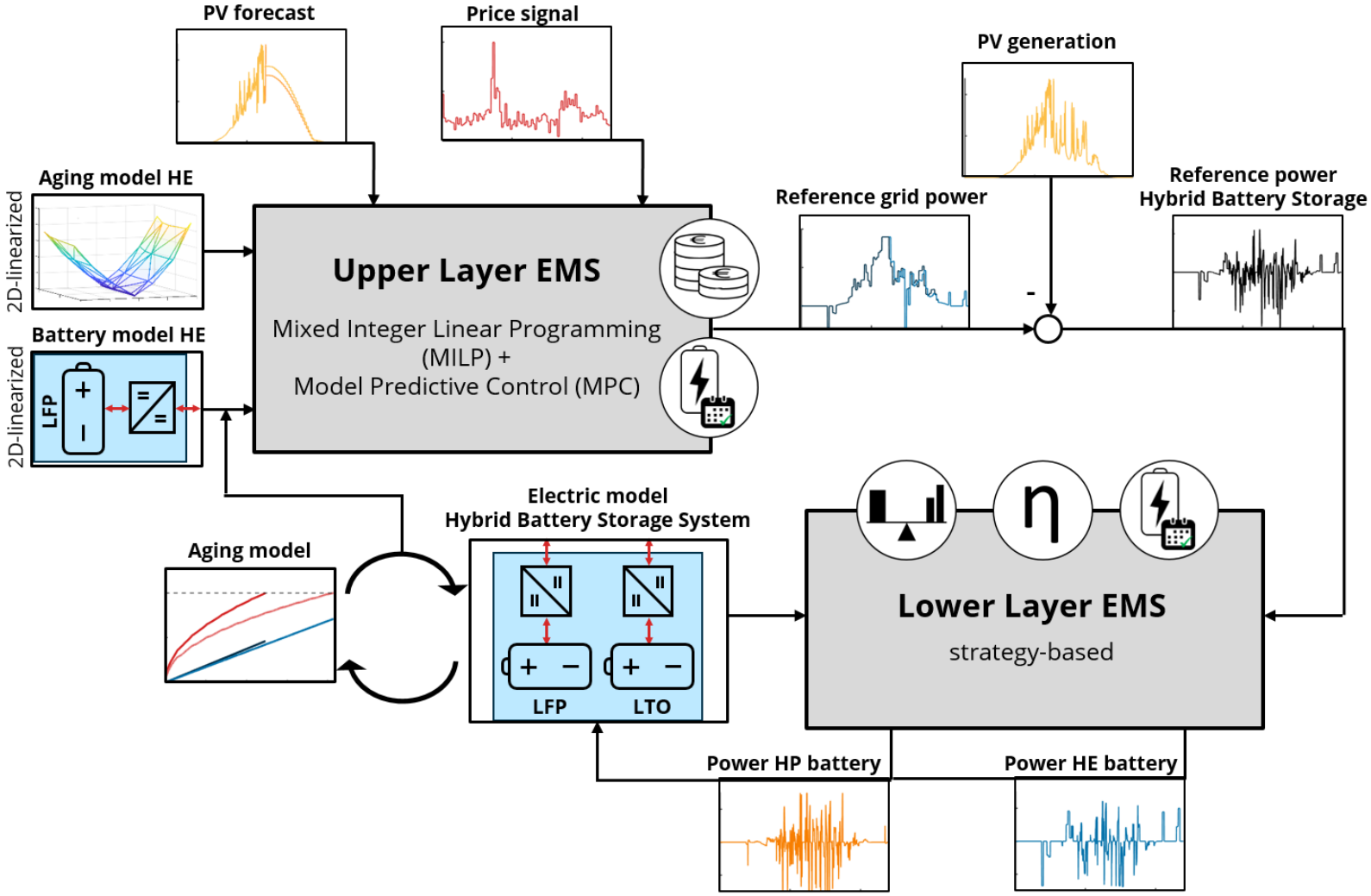


M. Naumann *et al*. *„Analysis and modeling of calendar aging of a commercial LiFePO4/graphite cell“*. Journal of Energy Storage 17 (2018). DOI: 10.1016/j.est.2018.01.019

M. Naumann, F. B. Spingler and A. Jossen. *„Analysis and modeling of cycle aging of a commercial LiFePO4/graphite cell“*. Journal of Power Sources 451 (2020). DOI: 10.1016/J.JPOWSOUR.2019.227666

3. Energy Management System

Hierarchical energy management



3. Energy Management System
Upper layer

Objective function

$$J = \min \sum_{t=t_{MPC}}^{T} \Delta t \cdot \left[-c_{spot}(t) \cdot \left(P_{grid,in}(t) + P_{grid,sup}(t) \right) + \sum_{i=1}^{N_P} \sum_{j=1}^{N_{SoC}} \lambda(i,j,t) \cdot c_{degr}(i,j) \right]$$

Spot market trading

Battery degradation costs

Power at the DC Bus

$$\frac{1}{\eta_{DCAC}} \cdot P_{grid,in}(t) + \eta_{DCAC} \cdot P_{grid,sup}(t) - P_{bat}(t) + P_{l,DCDC}(t) + P_{ct}(t) = \hat{P}_{PV}(t)$$

State of Charge

$$SoC(t+1) = SoC(t) - \Delta t \cdot CR(t) \cdot \frac{1}{SoH(t)}$$

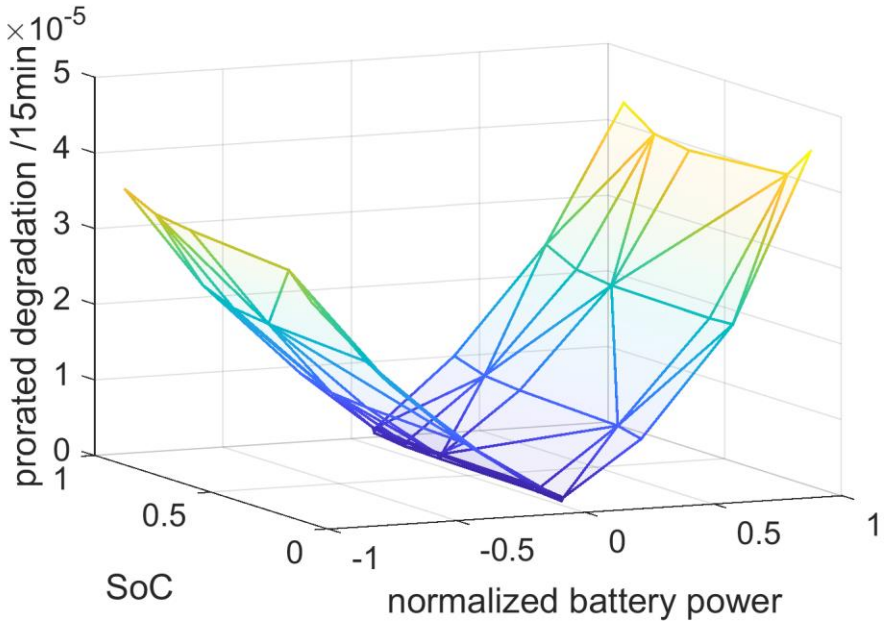
Δt	Time interval (15 min)
c_{spot}	Spot market price in €/(W·15 min)
$P_{grid,in}$ $P_{grid,sup}$	Grid power feed-in and supply
N_P N_{SoC}	Number of vertices for 2D PWA linearization ($N_P = 9$, $N_{SoC} = 5$)
$\lambda(i,j)$	Weight of vertex (i,j), $0 \leq \lambda \leq 1$
$c_{degr}(i,j)$	Degradation cost at vertex (i,j) in €/15min
$P_{l,DCDC}$	Losses of DC-to-DC converters
P_{ct}	PV power curtailment
$\hat{P}_{PV}$	PV power forecast
CR	C-rate
SoH	State of Health

3. Energy Management System
Upper layer

Prorated degradation per time interval

- Conversion of LFP aging model, depending on the time to reach End of Life at 80 % remaining capacity
- T and DoC set as constant → 2D function of battery power and SoC

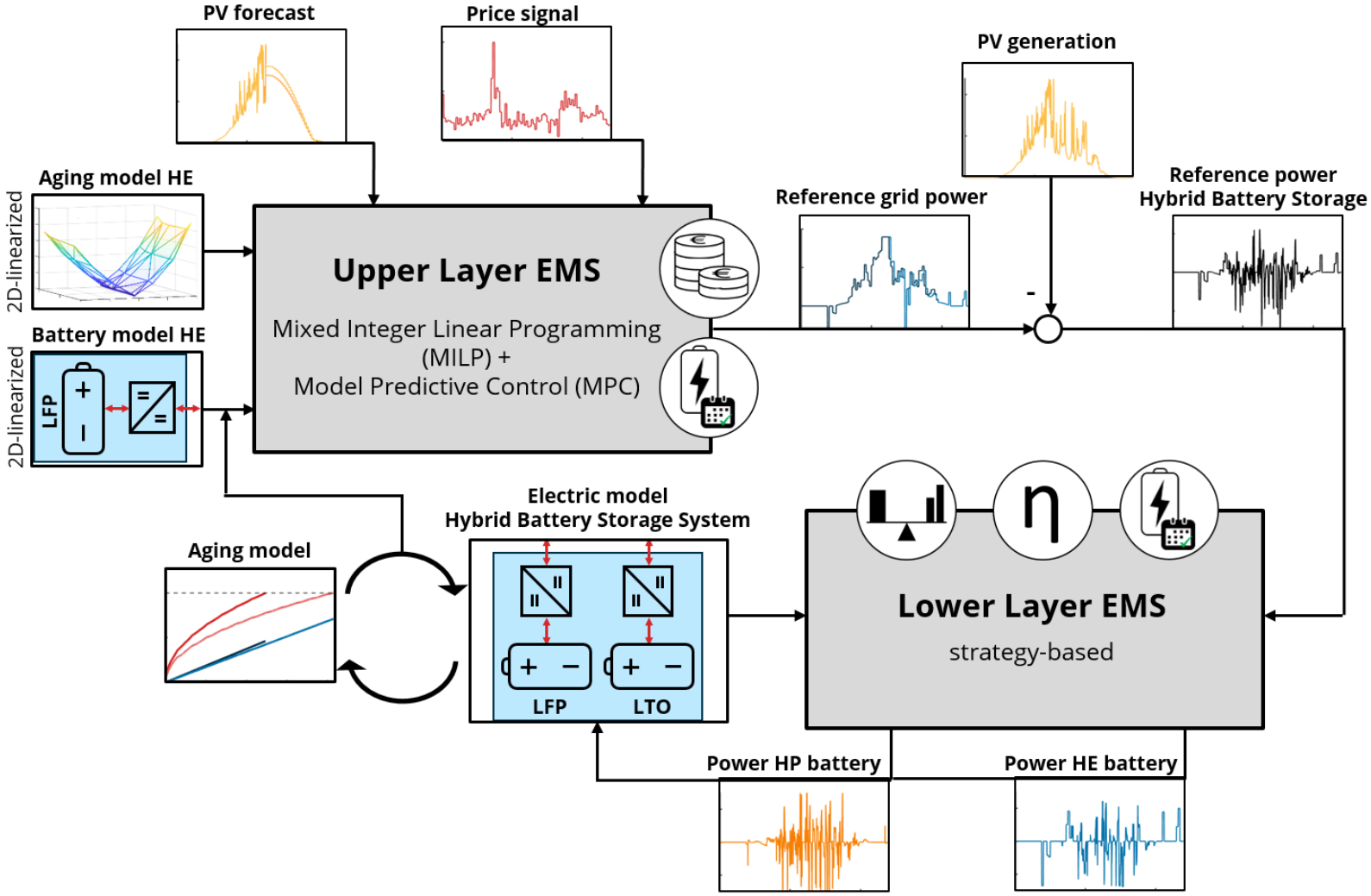
2D PWA linearization of prorated degradation



- MILP compatibility → piecewise-affine (PWA) linearization
- Logarithmic approach: 64 triangles ≙ 6 binary variables
- Same grid for degradation costs, converter losses and C-rate
- Vertices co-optimized to reduce linearization error

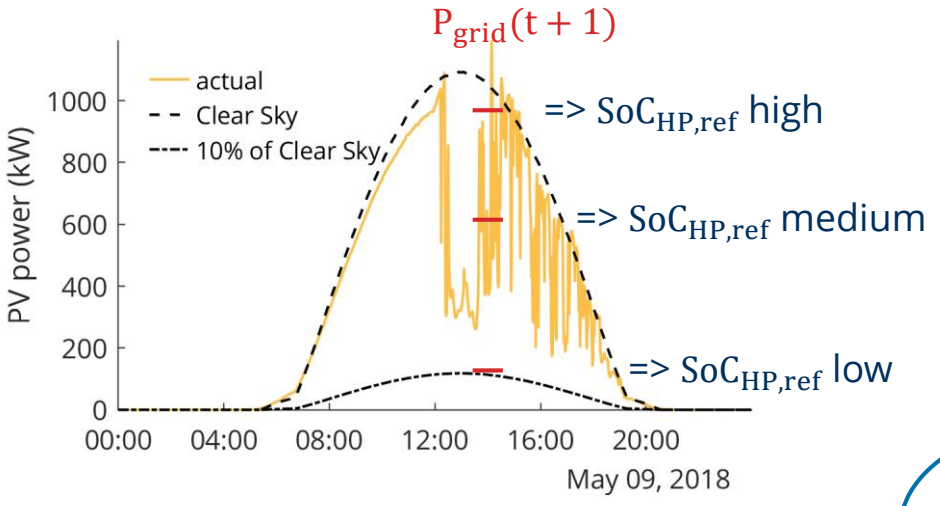
3. Energy Management System

Hierarchical energy management

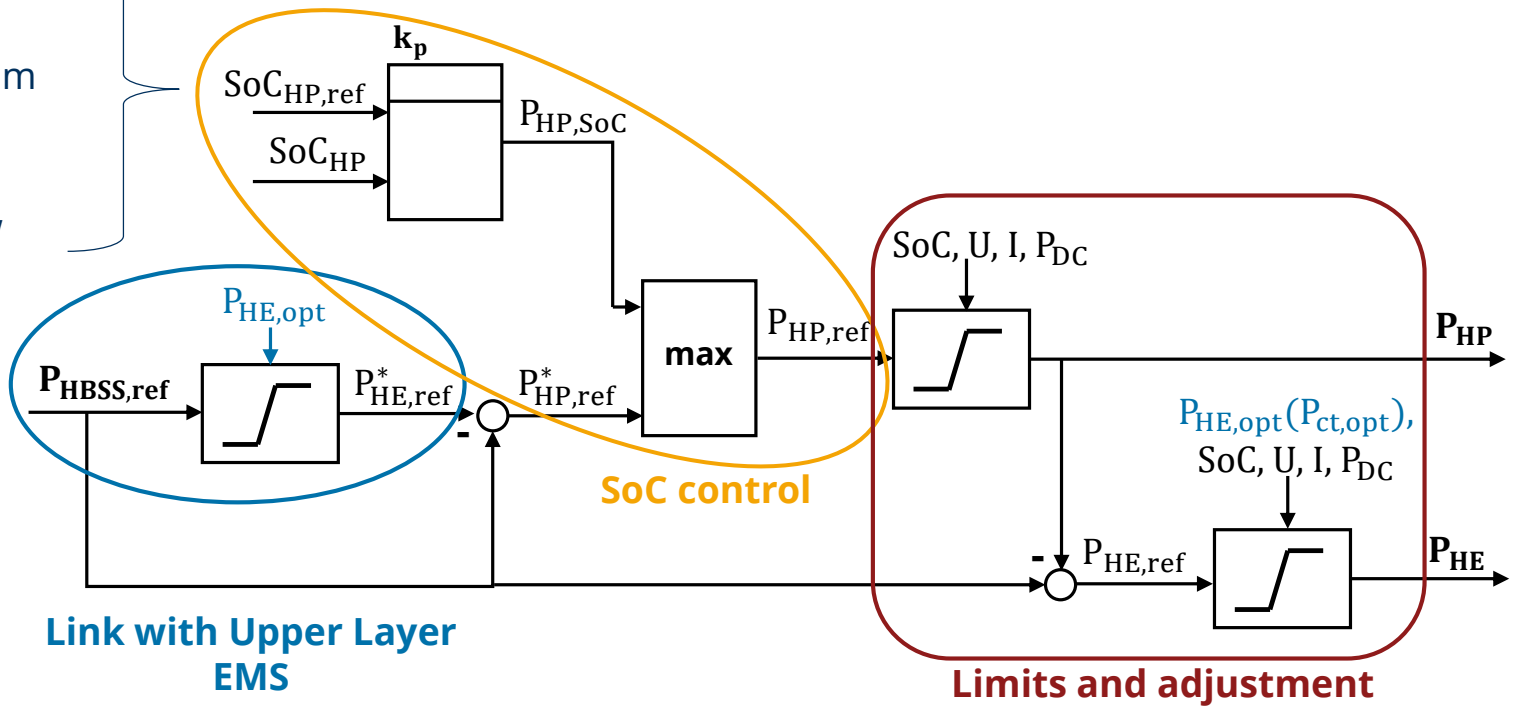


3. Energy Management System
Lower layer

Calculation of reference SoC for high power battery



Block diagram for allocation of hybrid battery power $P_{HBSS,ref}$



4. Results and Discussion

Case studies

Case 1: 2D MILP with Hybrid BSS

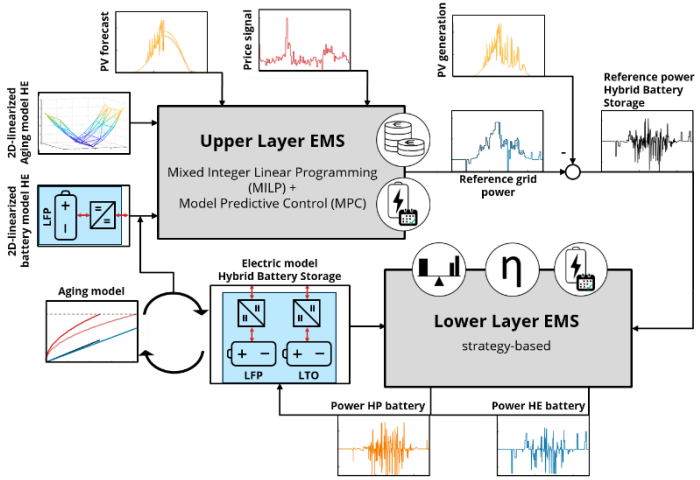
- ➢ Proposed configuration
- 2D MILP
- 2x HE battery modules + 2x HP battery modules

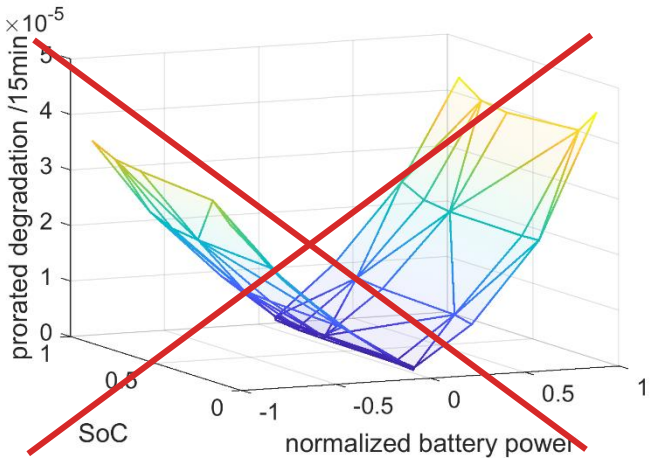
Case 2: No PWA linearization

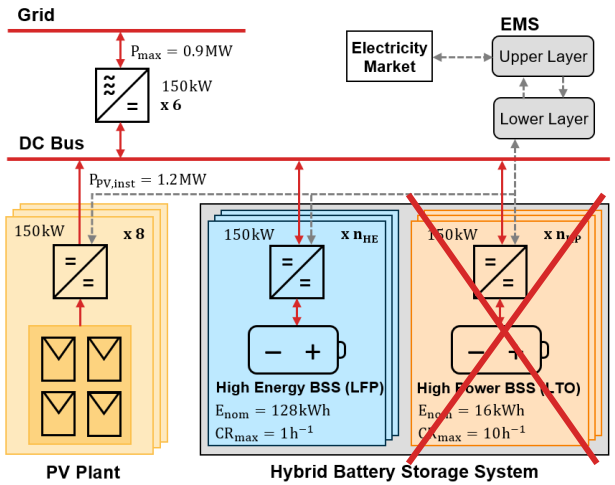
- ➢ Impact of sophisticated problem formulation
- Constant degradation costs
- Constant battery and DC-to-DC converter efficiency
- 2x HE battery modules + 2x HP battery modules

Case 3: Single storage system

- ➢ Impact of hybridization
- 2D MILP
- 3x HE battery modules

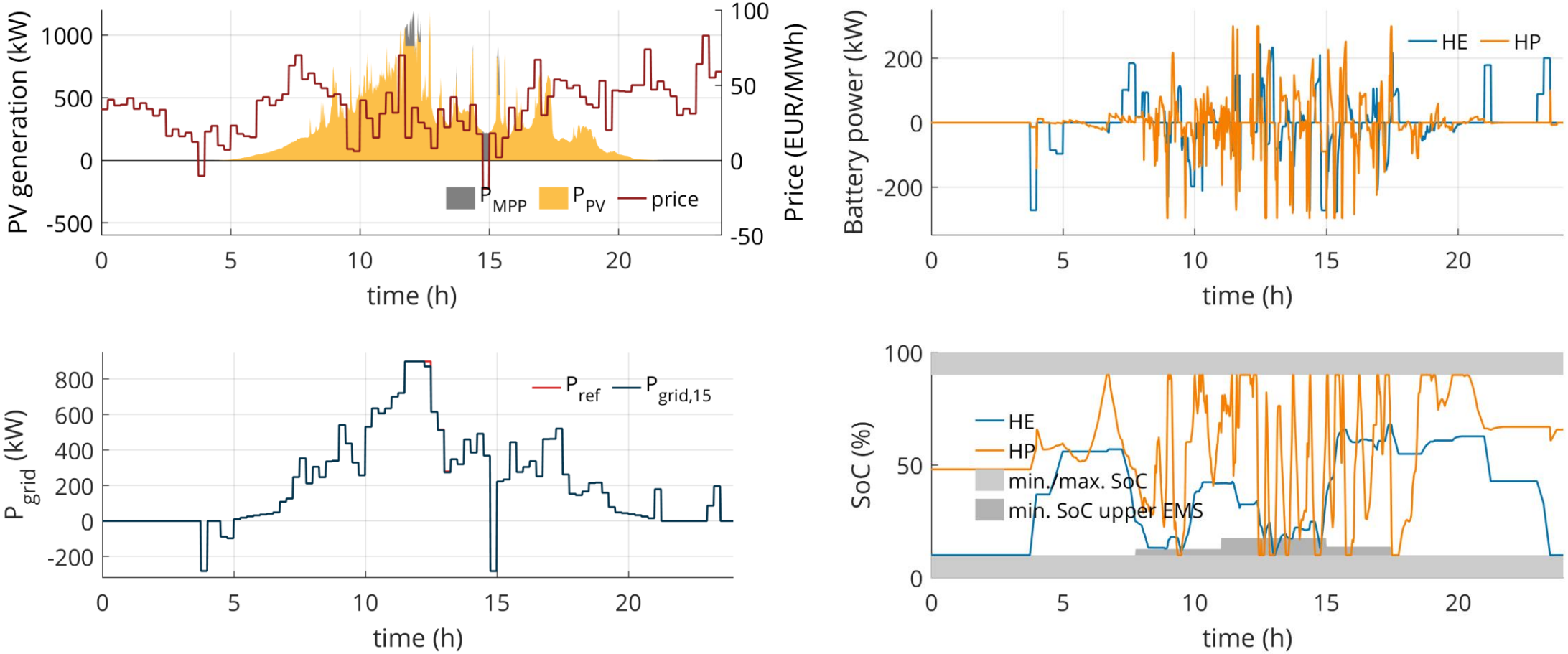






4. Results and Discussion

Illustration of system behavior (Case 1)

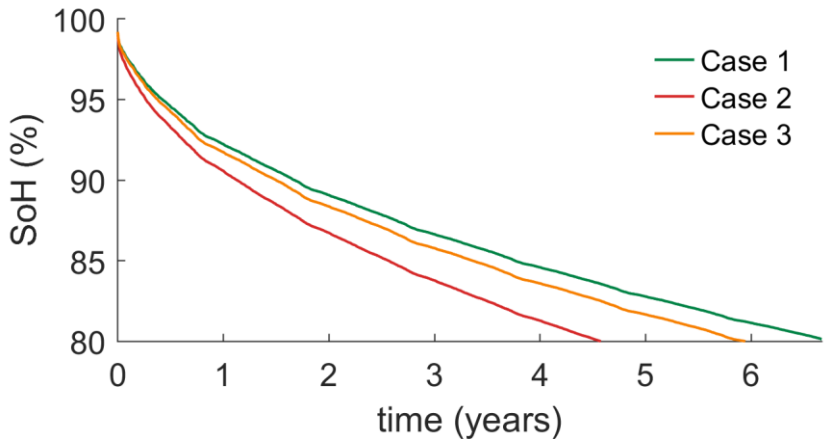


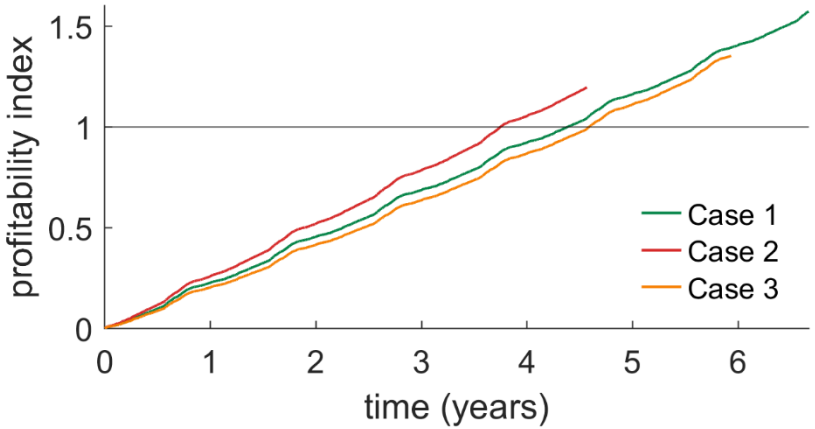
4. Results and Discussion

Long-term effects of energy management decisions

- Extrapolation of 1 year simulation
- Profit defined as margin compared to a PV plant with 3 high power battery modules for ramp rate control only
- Assumptions for profitability index:
  - high power batteries and power electronics are replaced once within PV module lifetime
  - Interest rate i = 0 %

	Case 1	Case 2	Case 3
Description	2D-MILP, Hybrid BSS	No PWA linearization, Hybrid BSS	2D-MILP, single storage (3x HE)
Profitability index	1.59	1.22	1.36
Storage losses (mean)	4.7 %	5.4 %	5.2 %
Non-compliance (mean)	0.6 %	1.6 %	0.8 %



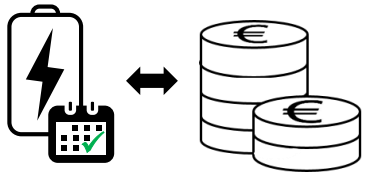


5. Conclusion and Outlook

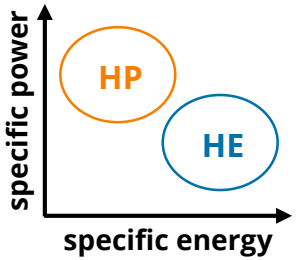
Conclusion

✓ Novel EMS for a hybrid li-ion battery storage that supports the grid integration of a PV plant

✓ Different temporal scales are successfully accounted for with a hierarchical energy management

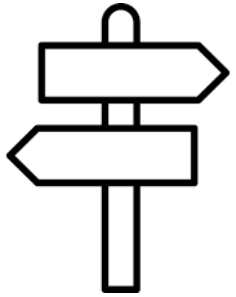


✓ Detailed implementation of aging behavior into the optimization leads to significantly higher benefit over lifetime



✓ For this configuration, the hybrid storage shows a clear advantage in terms of benefit over lifetime, efficiency and compliance with the settled grid power

5. Conclusion and Outlook
Outlook



- Realistic market model for economic evaluation
- Battery temperature model
- Additional layers: Higher layer for day-ahead market, lower layer for battery management system and power electronics control

Thank you!

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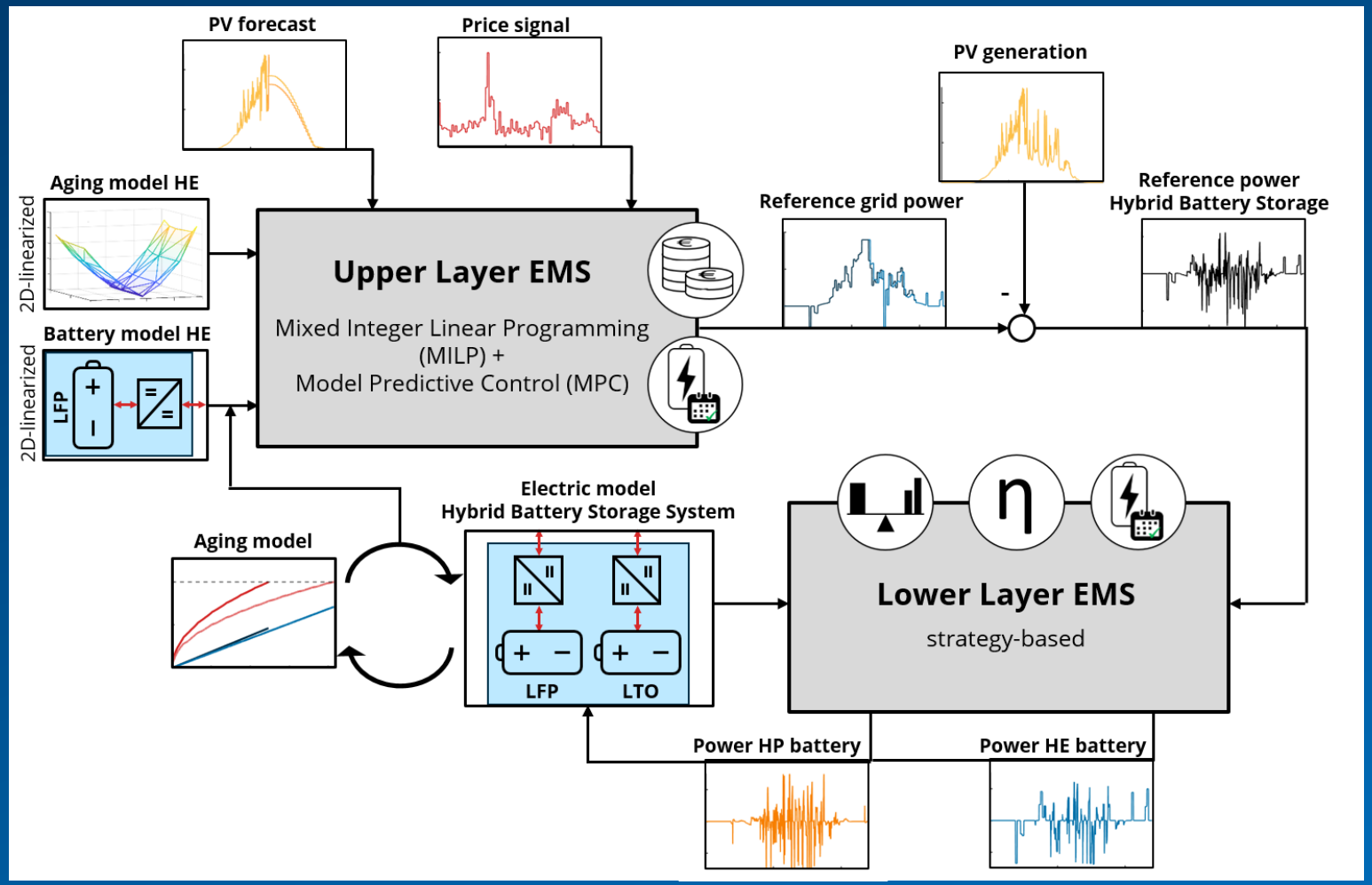

Federal Ministry for Economic Affairs and Climate Action

Based on results of the research project “HYBAT – Hybrid lithium-ion battery storage solution with 1500 V system technology, innovative thermal management and optimized system management”, supported by the Federal Ministry of Economic Affairs and Climate Action (funding code: 03EI3009C)