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M5BAT Large-Scale Battery Storage System Dataset: Evaluation Operation Report 04/2023

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Chair for Electrochemical Energy Conversion
and Storage Systems

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M5BAT: Executive Summary 04/2023

Dataset

- **April 2023**
- Logging frequency 1Hz
- System data
- 10x battery unit data



M5BAT operational

- Availability 2023: 99.84% (incl. maintenance)
- RTE 04.2023: ~78%
- FCR: 3MW operation



More

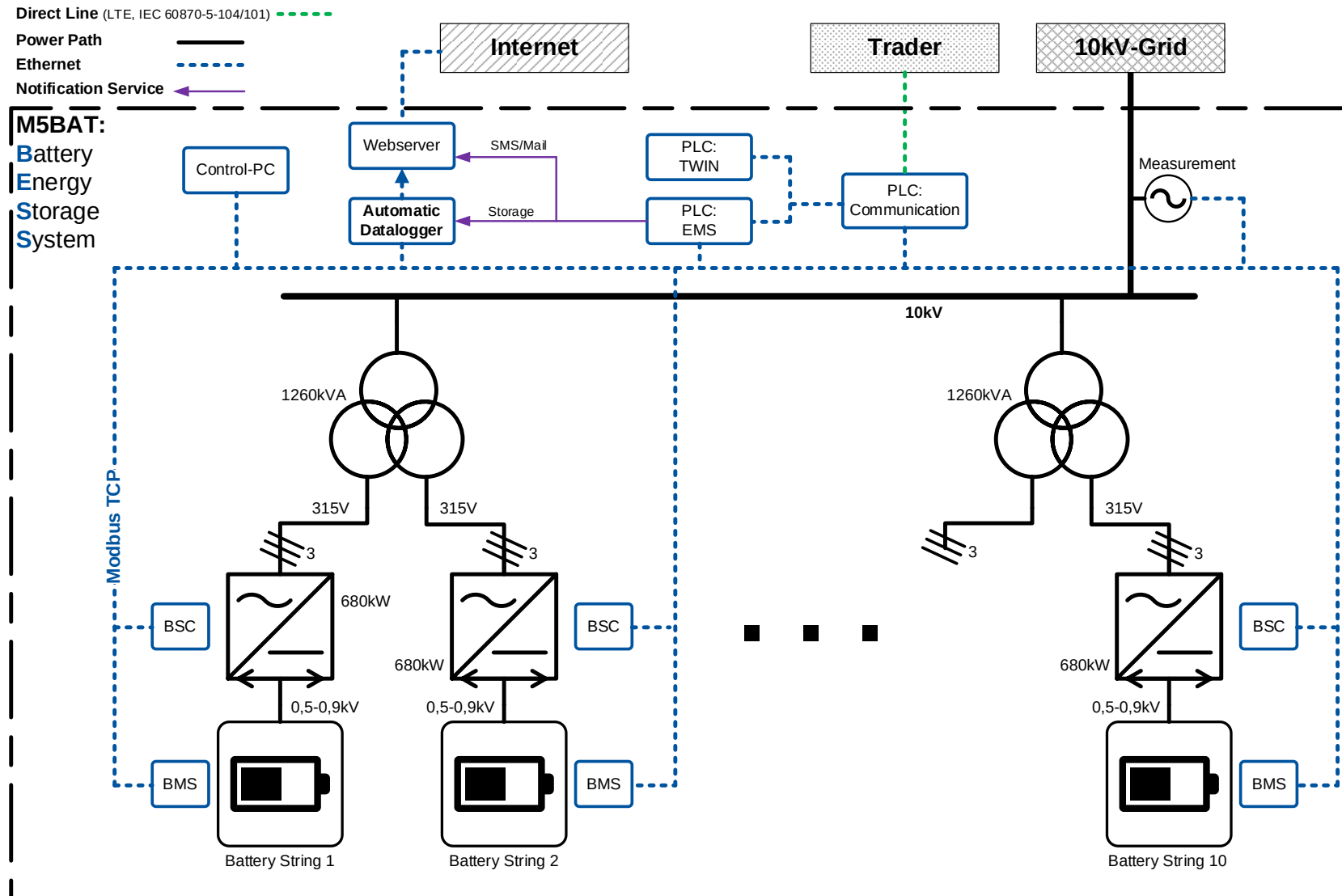
- M5BAT Live Website
- Publications
<https://m5bat.isea.rwth-aachen.de/Projekt/Forschungsergebnisse/>



M5BAT - Overview of technologies and parameters

Battery Technology	Number, Abbreviation	Nominal power / nominal energy	Nominal cycle number	Wiring	Nominal cell voltage
Lead-acid (OCSM)	1; Pb1	630 kW / 1066 kWh	1500	300s1p	2 V
Lead-acid (OCSM)	2; Pb2	630 kW / 1066 kWh	1500	300s1p	2 V
Lead-acid Gel (OPzV)	3; Pb3	630 kW / 843 kWh	2400	308s2p	2 V
Lead-acid Gel (OPzV)	4; Pb4	522 kW / 740 kWh	2400	306s1p	2 V
Lithium-Manganese-Oxide (LMO)	5; LMO1	630 kW / 774 kWh	6000	192s16p	3.7 V
Lithium-Manganese-Oxide (LMO)	6; LMO2	630 kW / 774 kWh	6000	192s16p	3.7 V
Lithium-Manganese-Oxide (LMO)	7; LMO3	630 kW / 774 kWh	6000	192s16p	3.7 V
Lithium-Manganese-Oxide (LMO)	8; LMO4	630 kW / 774 kWh	6000	192s16p	3.7 V
Lithium-Iron-Phosphate (LFP)	9; LFP	630 kW / 738 kWh (923 kWh)	5000	240s10p	3.2 V
Lithium-Titanate-Oxide (LTO)	10; LTO	630 kW / 230 kWh	<12.000	312s32p	2.3 V
Overall system (BESS / M5BAT)	M5BAT	6,19 MW / 7,78 MWh			

M5BAT - Connection scheme (status: Feb. 2023)



Events in April 2023

■ 01.04.2023

- LFP overvoltage error

■ 03.04.2023

- Maintenance work between 8:00 and 16:00 MESZ
- Maintenance work fire detection and extinguishing system
- 06:33:48 till 07:11:00 no frequency measurement available due to transformer shutdown

■ 08.04.2023 till 18.04.2023

- Pb3 problems with cell voltage measurement; no cell defects found after inspection
- 17.04.2023: Pb3 Inverter Error

■ 28.04.2023

- Fullcycle Pb1

■ 29.04.2023

- Fullcycle Pb3

Data Explanation Table BESS

Variable	Description	Unit
DateAndTime	Date and Time	UTC Timezone ('yyyy-MM-dd HH:mm:ss')
M5BAT_P	Active power of M5BAT measured at the network node	kW (- = charging; + = discharging)
M5BAT_Q	Reactive power of M5BAT measured at the network node	kVAr
Grid_frequency	Grid frequency measured at the network node	mHz
Temperature	Ambient temperature at M5BAT site	0.1°C
FCR_activated	Activation signal für FCR	True = FCR activated
FCR_P	Active Power for FCR (calculation)	kW (- = charging; + = discharging)
FCR_control	Control band for FCR	kW
SPA_ask_P	Request for active power for setpoint adjustment	kW (- = charging; + = discharging)
SPA_exec_P	Active power for setpoint adjustment	kW (- = charging; + = discharging)
SOC	State of Charge for M5BAT (calculated)	%
Interpolated	Interpolation signal for data evaluation	True = Value linear interpolated

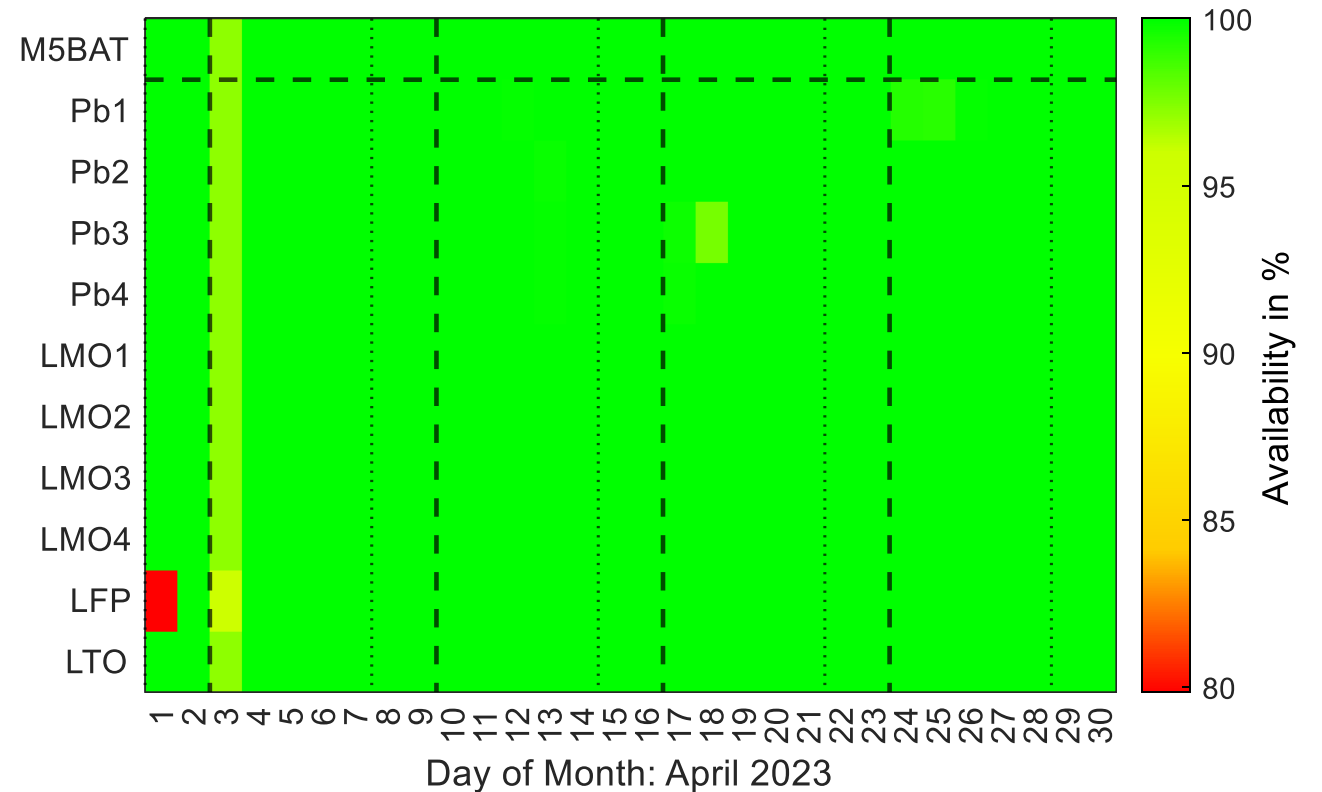
Data Explanation Table Battery unit

Variable	Description	Unit
DateAndTime	Date and Time	UTC Timezone ('yyyy-MM-dd HH:mm:ss')
P_AC_Set	Setpoint for active power of battery unit after the inverter	kW (- = charging; + = discharging)
Q_AC_Set	Setpoint for reactive power of battery unit after the inverter	kVAr
P_AC	Active power of battery unit after the inverter	kW (- = charging; + = discharging)
Q_AC	Reactive power of battery unit after the inverter	kVAr
SOC	State of Charge (BMS value)	0.1%
I_DC_Batt	Current measured at battery unit	0.1A
U_DC_Batt	Voltage measured at battery unit	0.1V
Mode_PQ	Inverter Mode (Power output)	True / False
Mode_Stop	Inverter Mode (Stop)	True / False
Mode_Silent	Inverter Mode (Silent)	True / False
Mode_Wait	Inverter Mode (Switching)	True / False
Interpolated	Interpolation signal for data evaluation	True = Value linear interpolated

M5BAT – Availability of Batteries

Explanation:

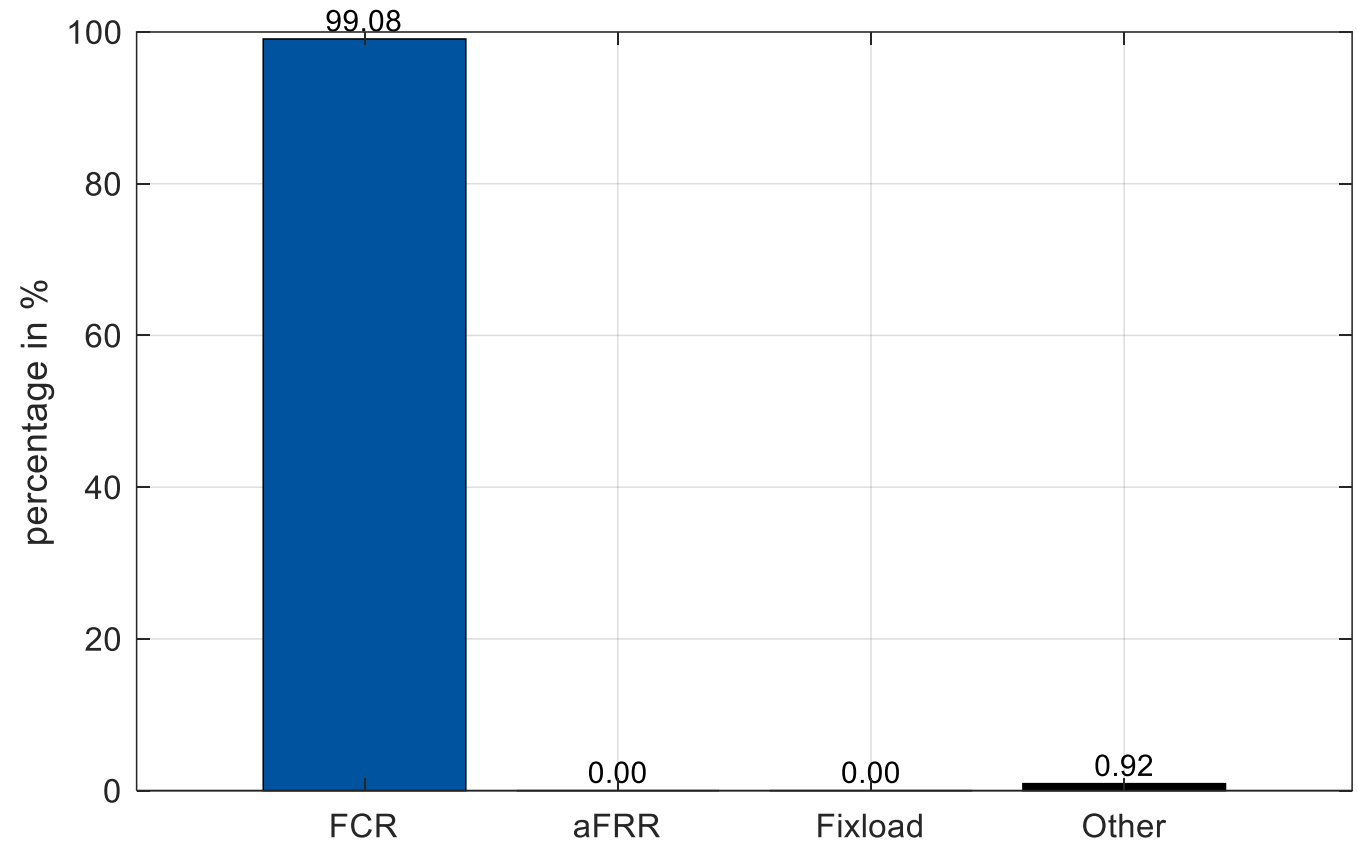
- Availability stands for M5BAT or the battery unit being in standby or actively providing power.
- M5BAT is available if one battery unit is available at this time
- 1st of April LFP outage due to voltage limit violation
- 3rd of April outage due to maintenance
- 18th of April: Pb3 outage due to inverter error



Dotted line to dashed line: weekend

Explanation:

- M5BAT is only prequalified for FCR service (3 MW) in April 2023
- 99.08 % of the time in April M5BAT is delivering FCR service
- 3rd of April no delivery due to maintenance → “Other”

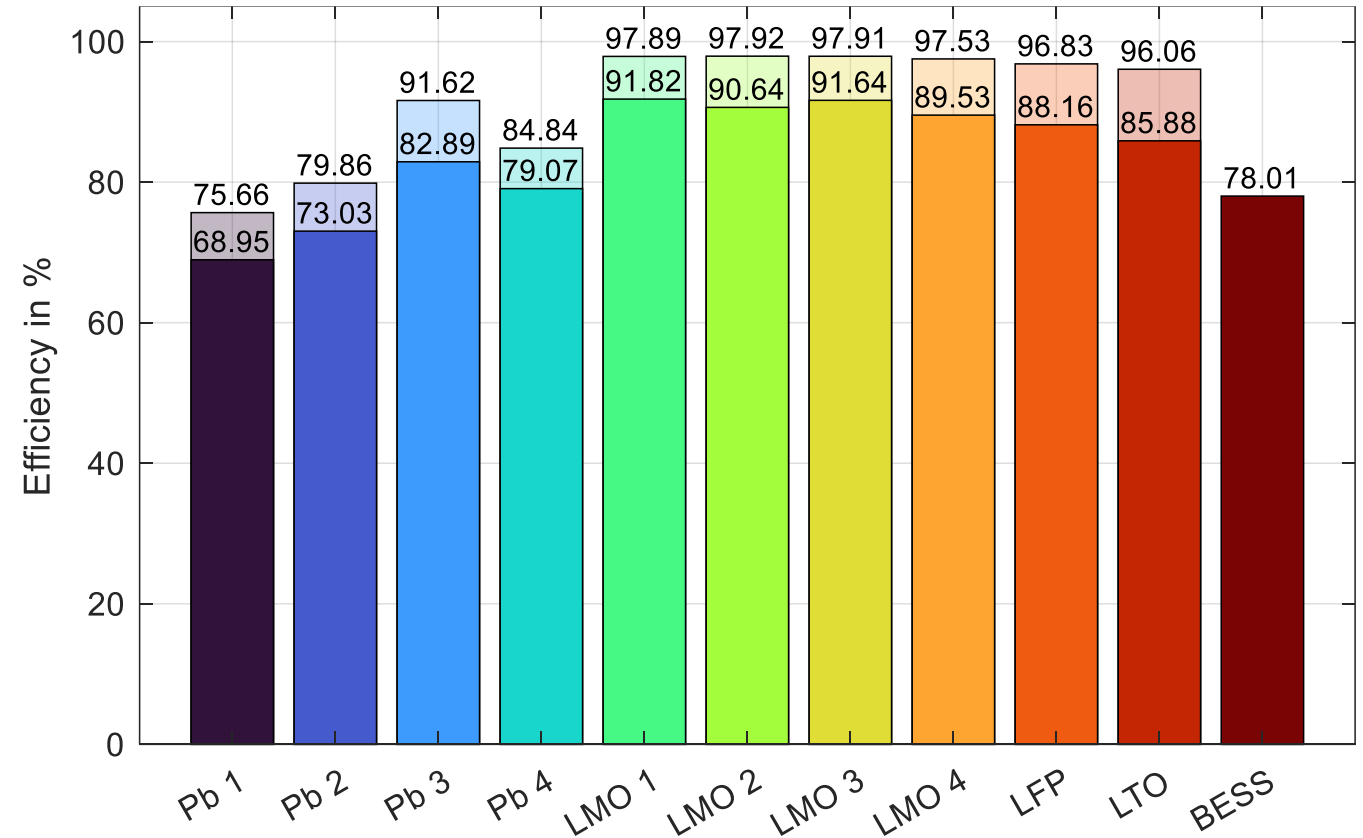


Abbreviation:

- FCR: Frequency Containment Reserve
- aFRR: automatic Frequency Restoration Reserve
- Fixload: Fixed load specified by Uniper Dispatching

Explanation:

- Efficiency calculation based on inverter measurements
- kWh-Efficiency of battery units in light color
 - Li-ion: 96%-98%
 - Pb Gel: 85-92%
 - Pb water: 75-80%
- kWh-efficiency of battery unit incl. inverter in intense color
 - 6-10% decrease in efficiency

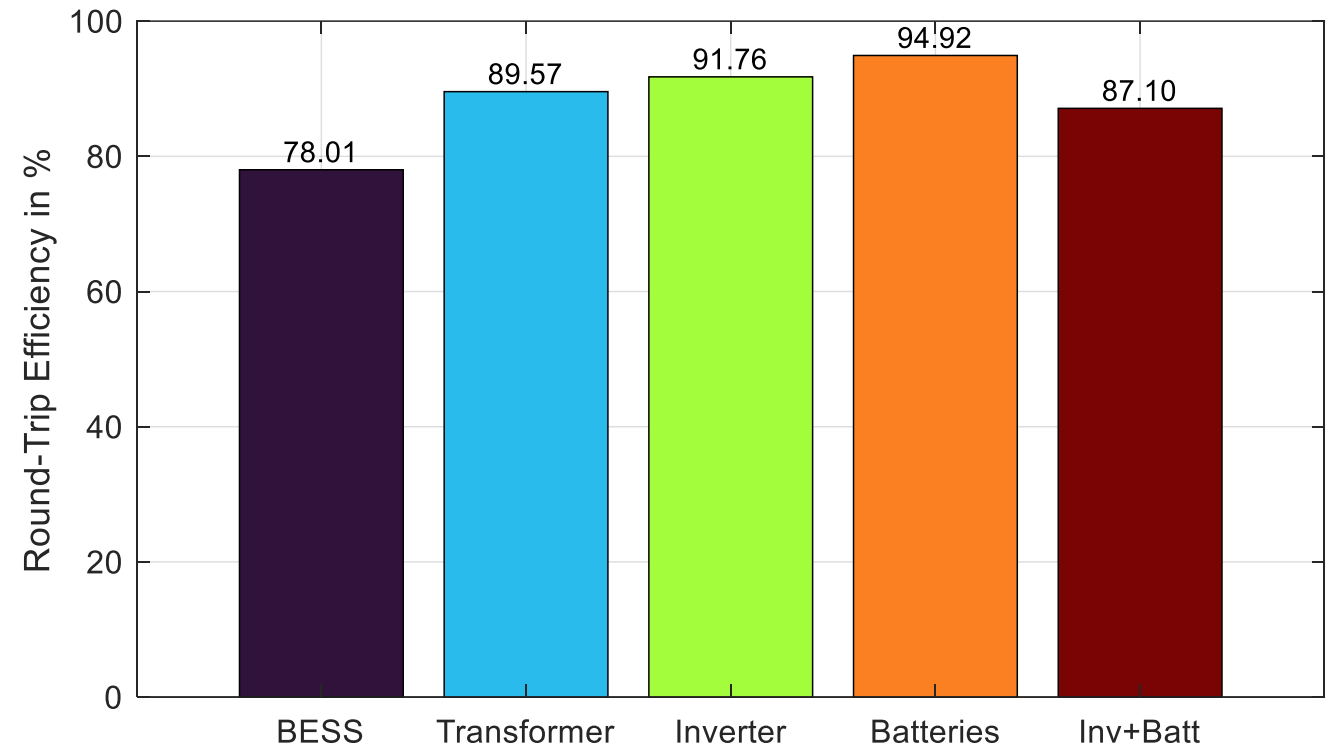


Hint:

- Light color: efficiency without inverter losses
- Intense color: efficiency including inverter losses
- BESS : Battery energy storage systems

Explanation:

- Components named, are the combination of all installed components of this kind
 - Batteries = all ten battery units of different technologies
- Most losses occur at transformer level, followed by inverters



Hint:

- BESS: Battery energy storage systems
- RTE: Round-Trip Efficiency
- PE: power efficiency

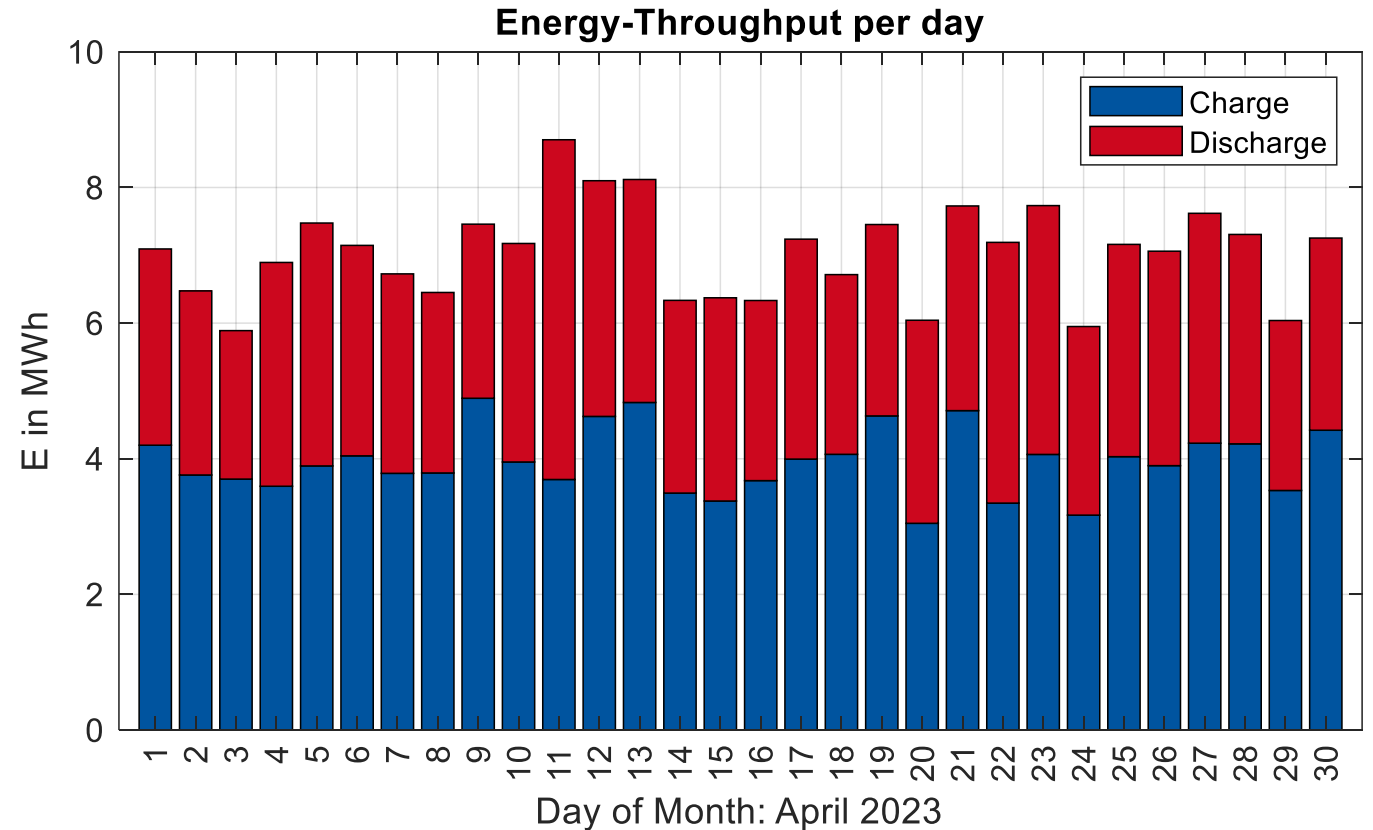
Calculation:

$$RTE_{BESS} = RTE_{Battery} \cdot PE_{Inverter}^2 \cdot PE_{Transformer}^2 = RTE_{Battery} \cdot RTE_{Inverter} \cdot RTE_{Transformer}$$

M5BAT – Energy throughput per day

Explanation:

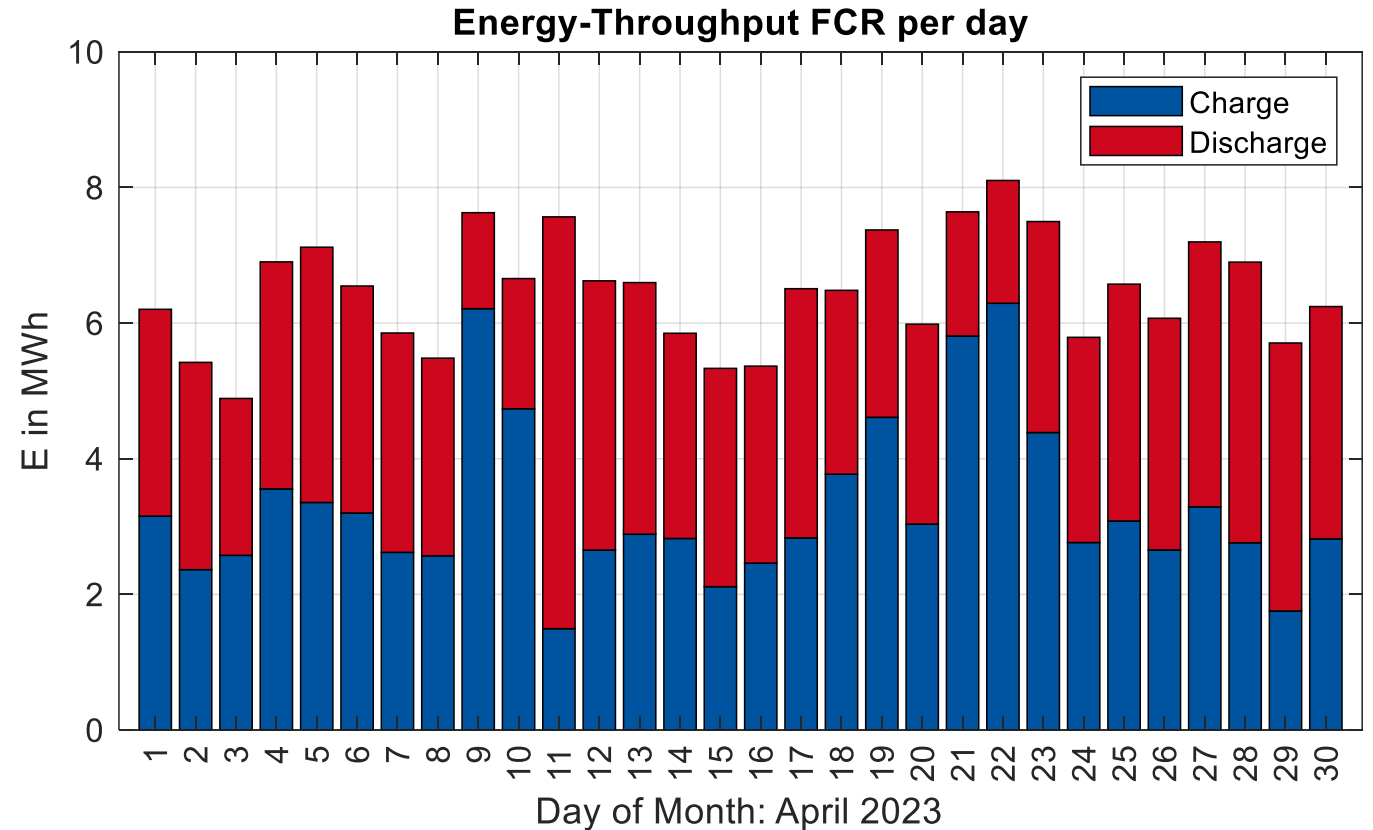
- Energy throughput measured at the grid node (medium voltage level)
- Energy throughput includes battery testing, FCR service, SOC-management, but different services can cancel out at grid node → higher energy throughput for addition of services possible
- Charged ~100 MWh
- Discharge ~79.5 MWh
- Transferring charge between battery units is not included → higher energy throughput for battery units possible



M5BAT – Energy throughput per month in FCR operation

Explanation:

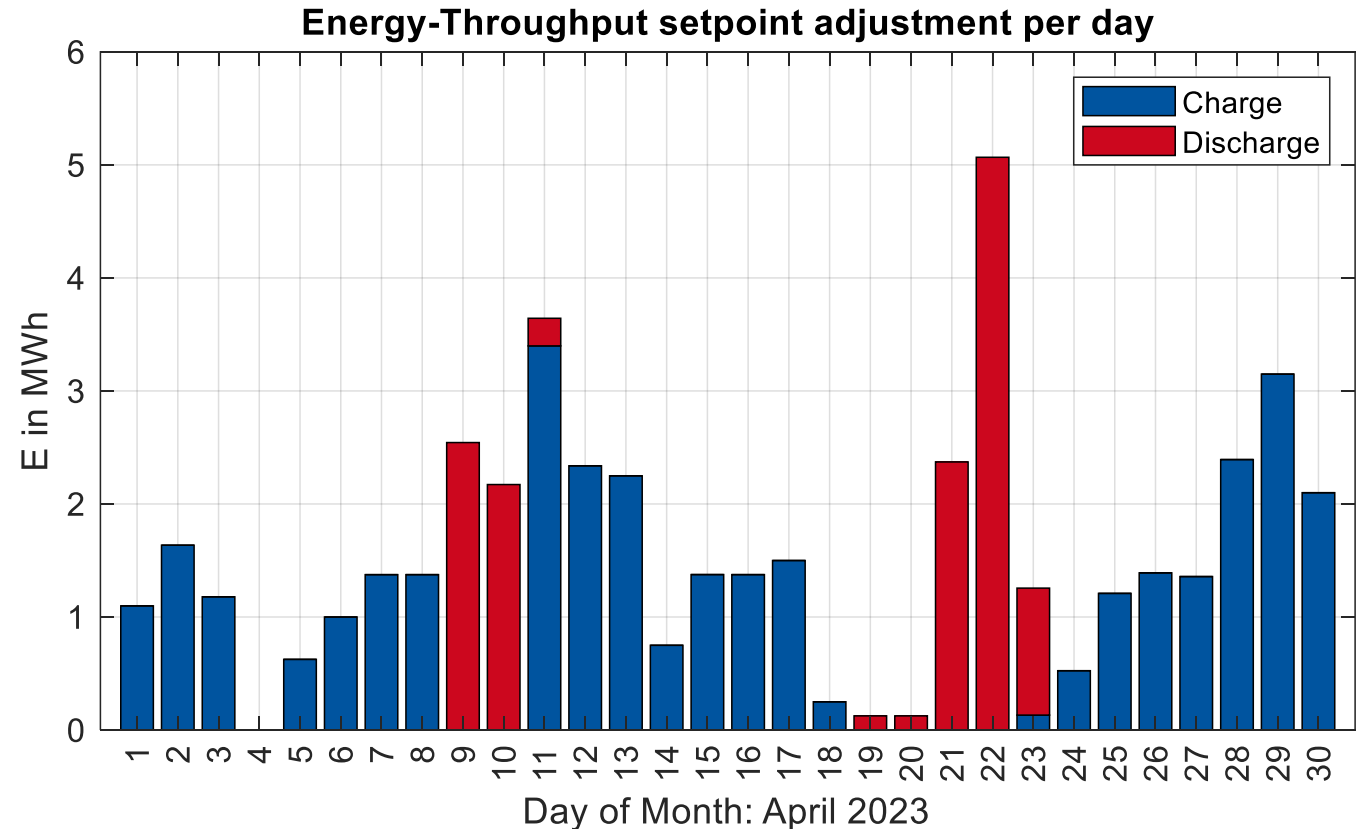
- Energy throughput for FCR service
 - Dependent on grid frequency



M5BAT – Energy throughput per month for operating point adjustment

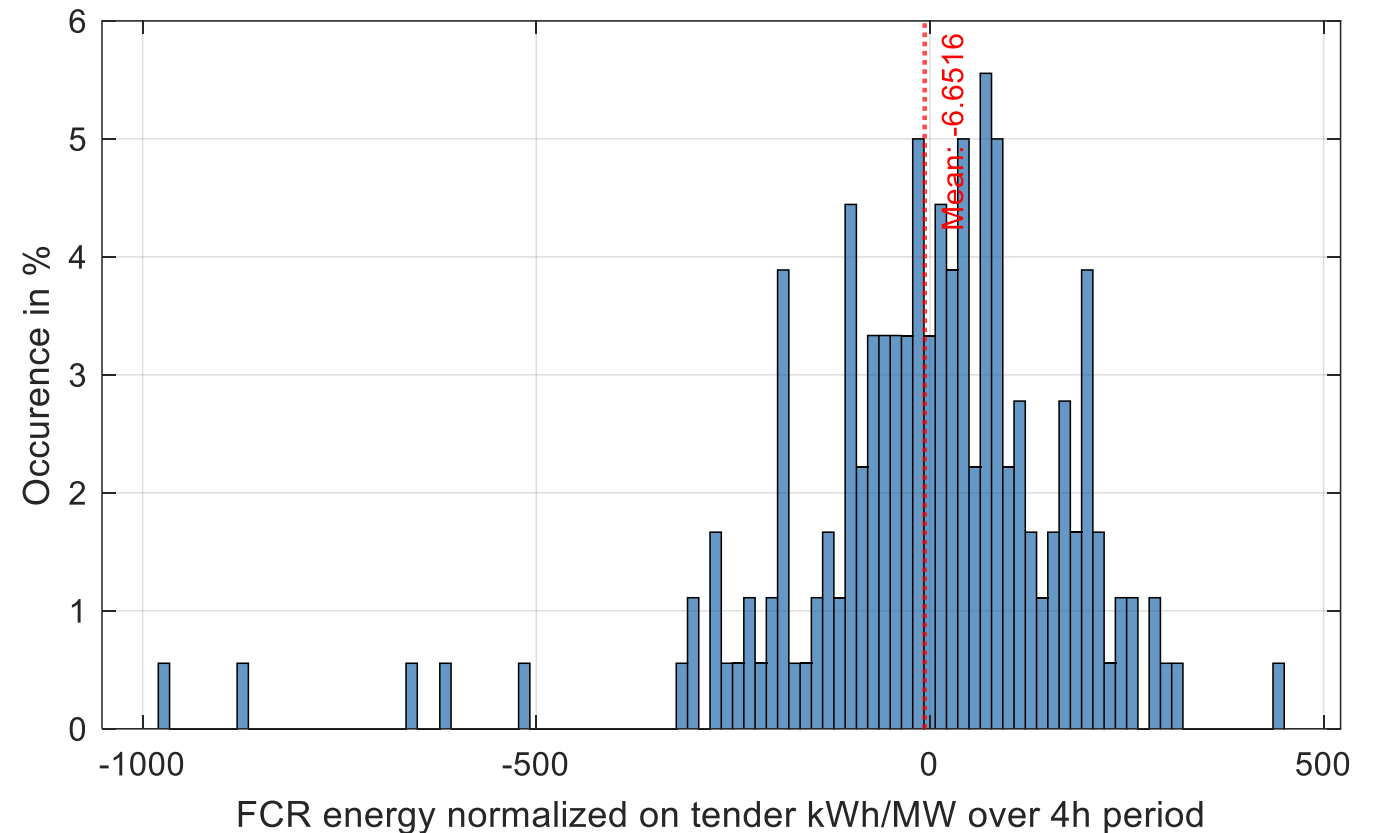
Explanation:

- Energy throughput for SOC-management (Setpoint adjustment (SPA))
- Energy is bought on the intraday continuous market (15min)
- Due to 78% efficiency mostly, recharging is necessary to maintain allowed SOC region for FCR-service



Explanation:

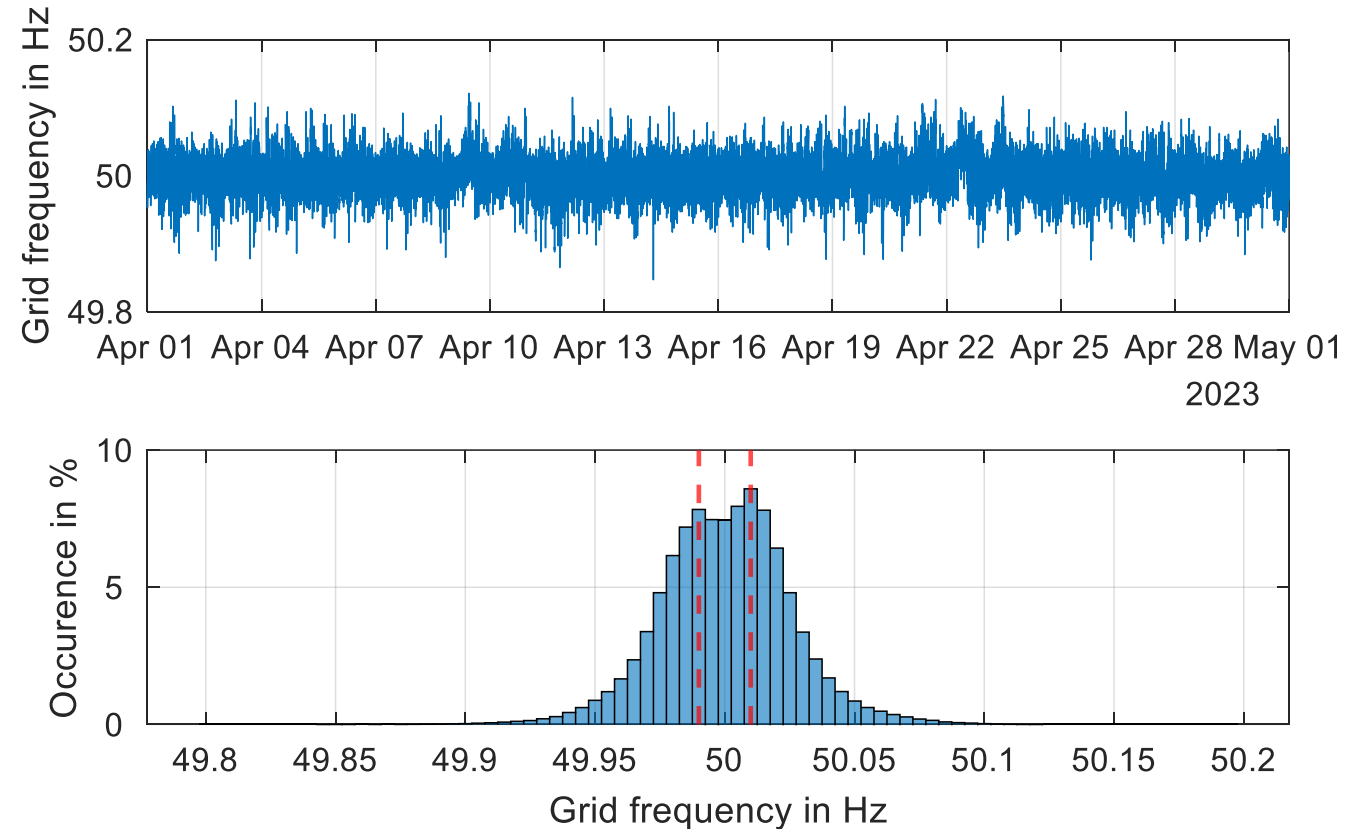
- FCR energy per 4h Block normalized on tender
- Degrees of freedom were not used



Grid frequency

Explanation:

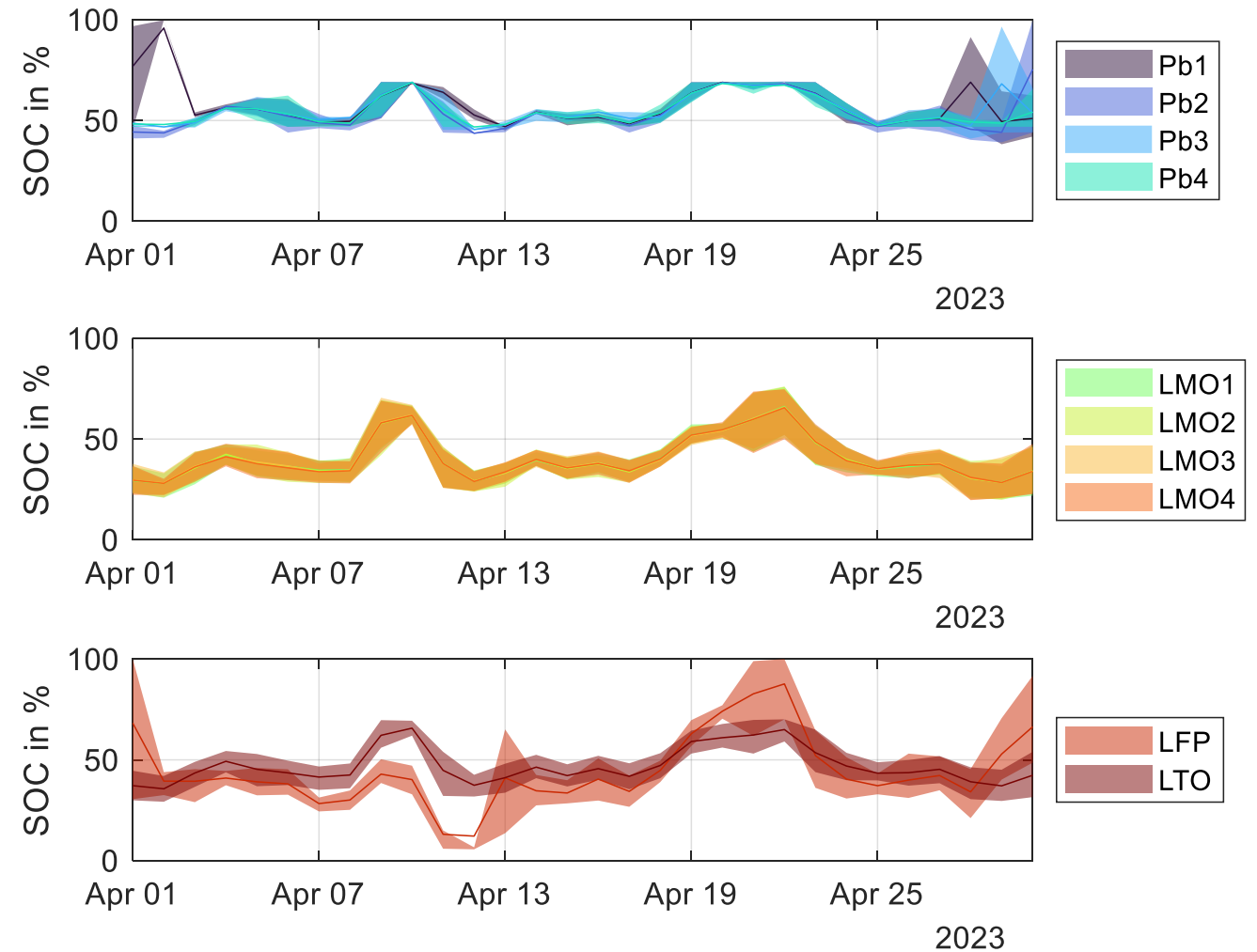
- Top graphic: measured grid frequency in April 2023
- Bottom graphic: grid frequency distribution
 - Red dashed lines: Deadband boundaries, within this area no FCR is necessary



M5BAT – Battery SOC

Explanation:

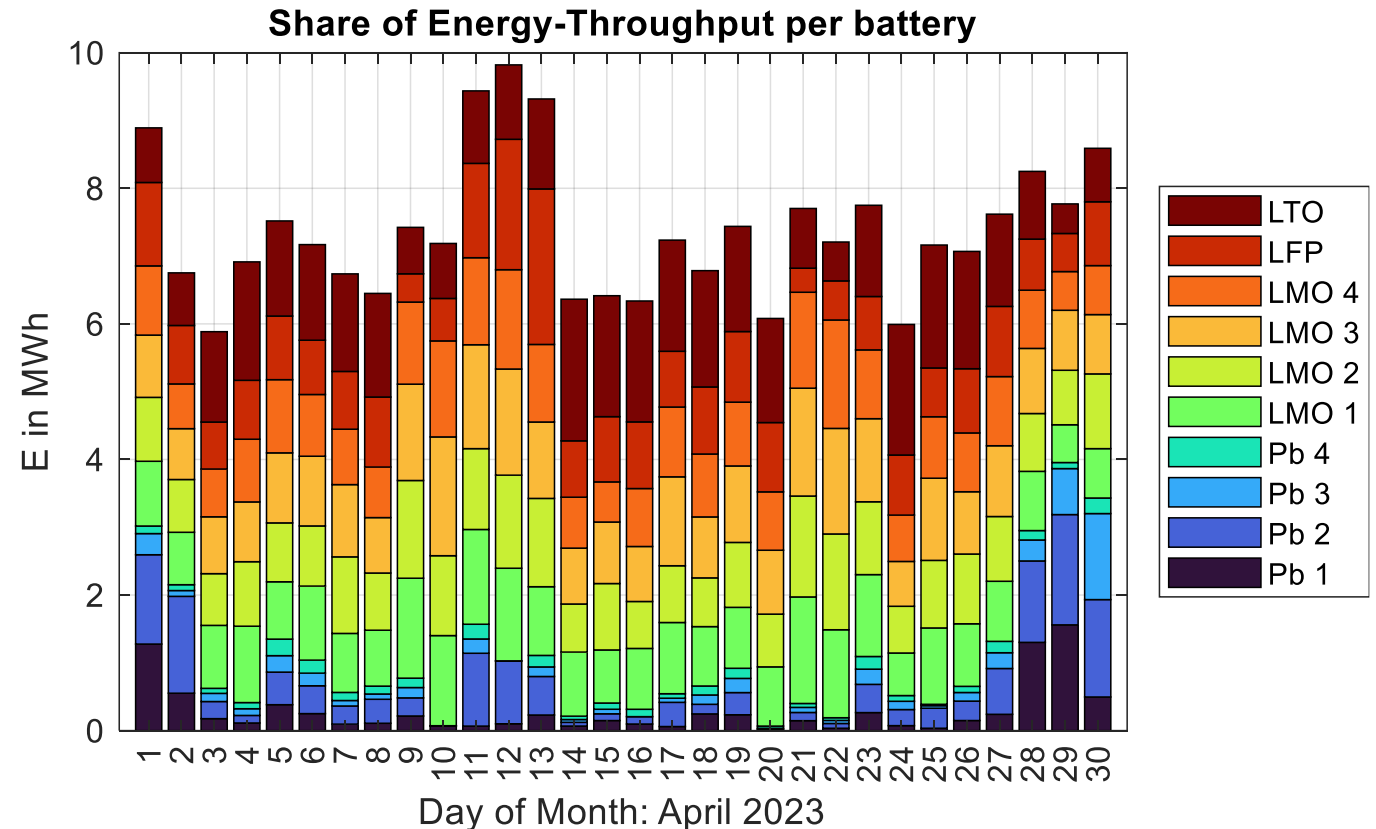
- SOC history for battery units
- Area describes 50% of SOC values per day; solid line represents daily mean SOC
- SOC rises to 100% at maintenance charges / procedures



M5BAT – Power distribution for 2023

Explanation:

- Energy throughput for lithium-ion batteries is intended to be higher due to higher cyclic stability
- Lead-acid batteries are used as backup
 - High energy throughput caused by maintenance charges or fullcycle tests

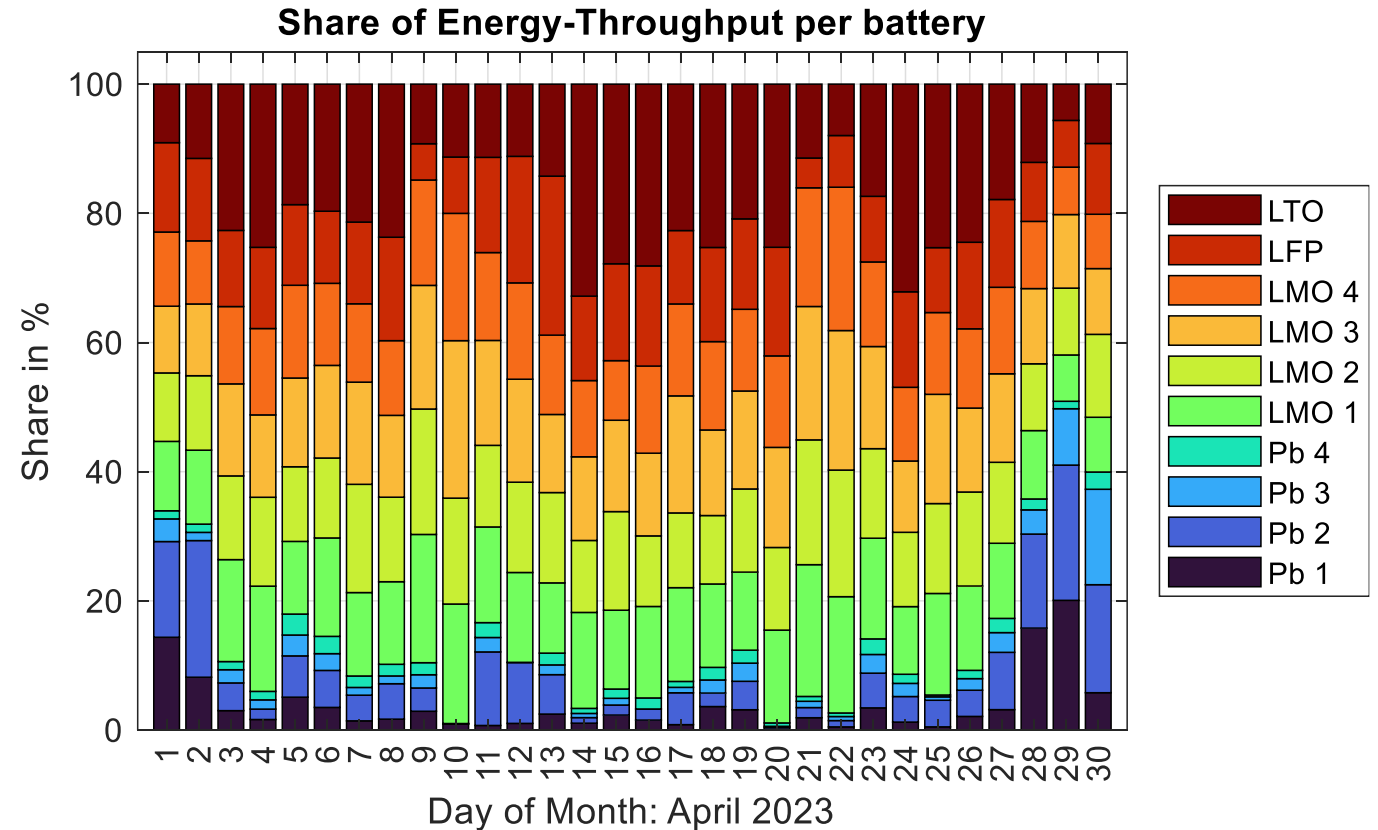


$$E_{throughput} = |E_{charge}| + |E_{discharge}|$$

M5BAT – Power distribution for 2023

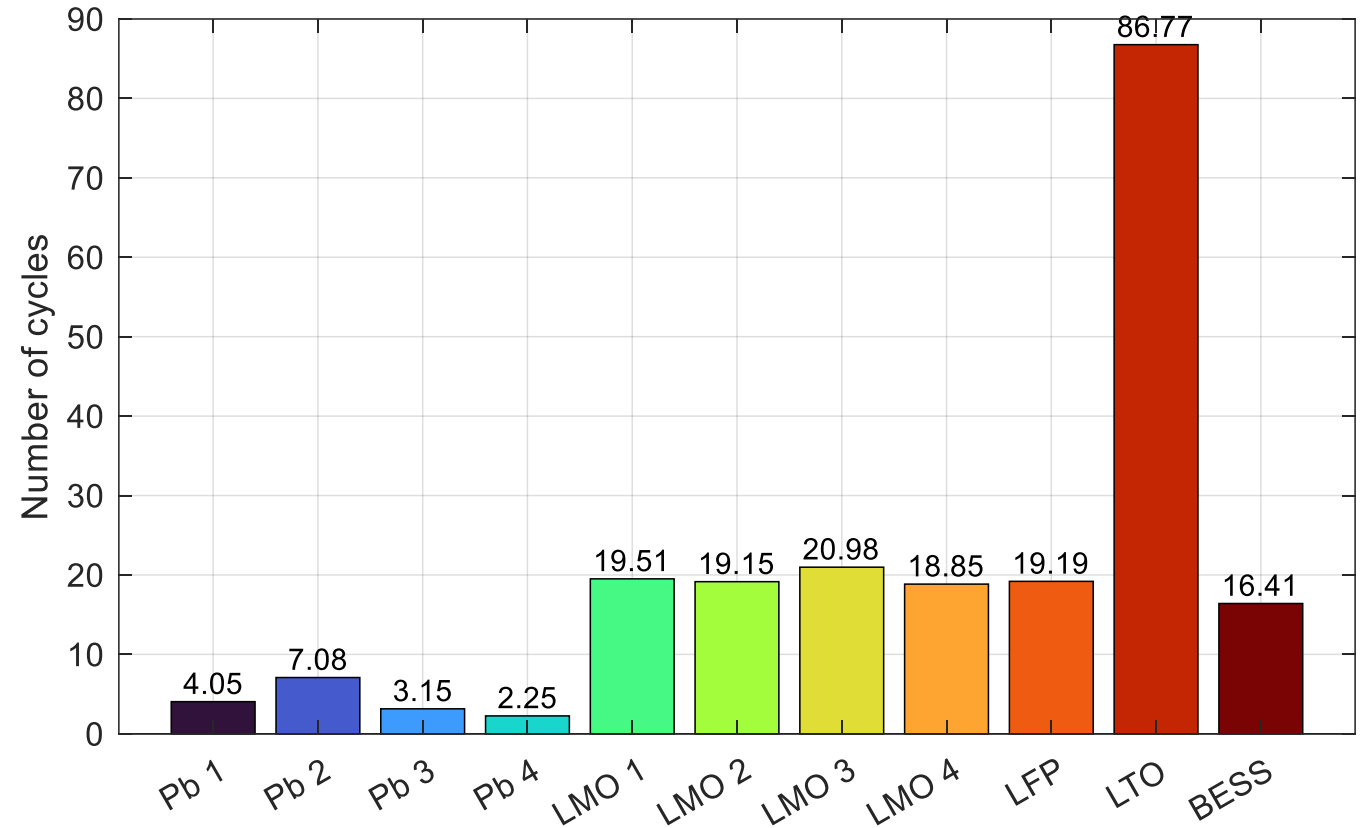
Explanation:

- Energy throughput for lithium-ion batteries is intended to be higher due to higher cyclic stability
- Lead-acid batteries are used as backup
 - High energy throughput caused by maintenance charges or fullcycle tests



Explanation:

- Mainly microcycles or partial cycles



$$\text{Cycles, Batt} = \frac{|E_{\text{charge, Batt}}| + |E_{\text{discharge, Batt}}|}{E_{\text{nominal, Batt}} \cdot 2}$$

M5BAT Publications 1/2

- L. Koltermann, M. Celi Cortés, J. Figgner, S. Zurmühlen, and D. U. Sauer, "Improved rule-based power distribution algorithm for hybrid battery storage systems and real-world validation," *Journal of Energy Storage*, vol. 86, p. 111360, 2024, doi: 10.1016/j.est.2024.111360.
- L. Koltermann, M. Celi Cortés, J. Figgner, S. Zurmühlen, and D. U. Sauer, "Power curves of megawatt-scale battery storage technologies for frequency regulation and energy trading," *Applied Energy*, vol. 347, p. 121428, 2023, doi: 10.1016/j.apenergy.2023.121428.
- L. Koltermann *et al.*, "Potential analysis of current battery storage systems for providing fast grid services like synthetic inertia – Case study on a 6 MW system," *Journal of Energy Storage*, vol. 57, p. 106190, 2023, doi: 10.1016/j.est.2022.106190.
- L. Koltermann, K. Jacqué, J. Figgner, S. Zurmühlen, and D. U. Sauer, "Operational Validation of a Power Distribution Algorithm for a Modular Megawatt Battery Storage System," *Batteries & Supercaps*, vol. 6, no. 3, 2023, doi: 10.1002/batt.202200414.
- K. Jacqué, L. Koltermann, J. Figgner, S. Zurmühlen, and D. U. Sauer, "The influence of frequency containment reserve on the cycles of a hybrid stationary large-scale storage system," *Journal of Energy Storage*, vol. 52, p. 105040, 2022, doi: 10.1016/j.est.2022.105040.
- K. Jacqué, L. Koltermann, J. Figgner, S. Zurmühlen, and D. U. Sauer, "The influence of frequency containment reserve on the efficiency of a hybrid stationary large-scale storage system," *Journal of Energy Storage*, vol. 52, p. 104961, 2022, doi: 10.1016/j.est.2022.104961.
- K. Jacqué, L. Koltermann, J. Figgner, S. Zurmühlen, and D. U. Sauer, "The Influence of Frequency Containment Reserve on the Operational Data and the State of Health of the Hybrid Stationary Large-Scale Storage System," *Energies*, vol. 15, no. 4, p. 1342, 2022, doi: 10.3390/en15041342.

M5BAT Publications 2/2

- T. Thien, H. Axelsen, M. Merten, and D. U. Sauer, "Energy management of stationary hybrid battery energy storage systems using the example of a real-world 5 MW hybrid battery storage project in Germany," *Journal of Energy Storage*, vol. 51, p. 104257, 2022, doi: 10.1016/j.est.2022.104257.
- M. Merten, C. Olk, I. Schoeneberger, and D. U. Sauer, "Bidding strategy for battery storage systems in the secondary control reserve market," *Applied Energy*, vol. 268, p. 114951, 2020, doi: 10.1016/j.apenergy.2020.114951.
- J. Munderlein, G. Ipers, M. Steinhoff, S. Zurmühlen, and D. U. Sauer, "Optimization of a hybrid storage system and evaluation of operation strategies," *International Journal of Electrical Power & Energy Systems*, vol. 119, p. 105887, 2020, doi: 10.1016/j.ijepes.2020.105887.
- J. Munderlein, M. Steinhoff, S. Zurmühlen, and D. U. Sauer, "Analysis and evaluation of operations strategies based on a large scale 5 MW and 5 MWh battery storage system," *Journal of Energy Storage*, vol. 24, p. 100778, 2019, doi: 10.1016/j.est.2019.100778.
- J. Munderlein, M. Steinhoff, H. Axelsen, and D. U. Sauer, "Planning, building, efficiency measurement and determination of forecast data of a grid-scale hybrid 5 MW / 5 MWh battery storage system," in *2017 IEEE International Telecommunications Energy Conference (INTELEC)*, Broadbeach, QLD, Oct. 2017 - Oct. 2017, pp. 314–320.
- T. Thien, D. Schweer, D. vom Stein, A. Moser, and D. U. Sauer, "Real-world operating strategy and sensitivity analysis of frequency containment reserve provision with battery energy storage systems in the german market," *Journal of Energy Storage*, vol. 13, pp. 143–163, 2017, doi: 10.1016/j.est.2017.06.012.
- D. Schweer, A. Maaz, and A. Moser, "Optimization of frequency containment reserve provision in M5BAT hybrid battery storage," *Journal of Energy Storage*, vol. 8, pp. 1–5, 2016, doi: 10.1109/EEM.2016.7521335.

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