Digital twin of an LMO-based UPS battery energy storage system with combined operation for backup reliability and grid support

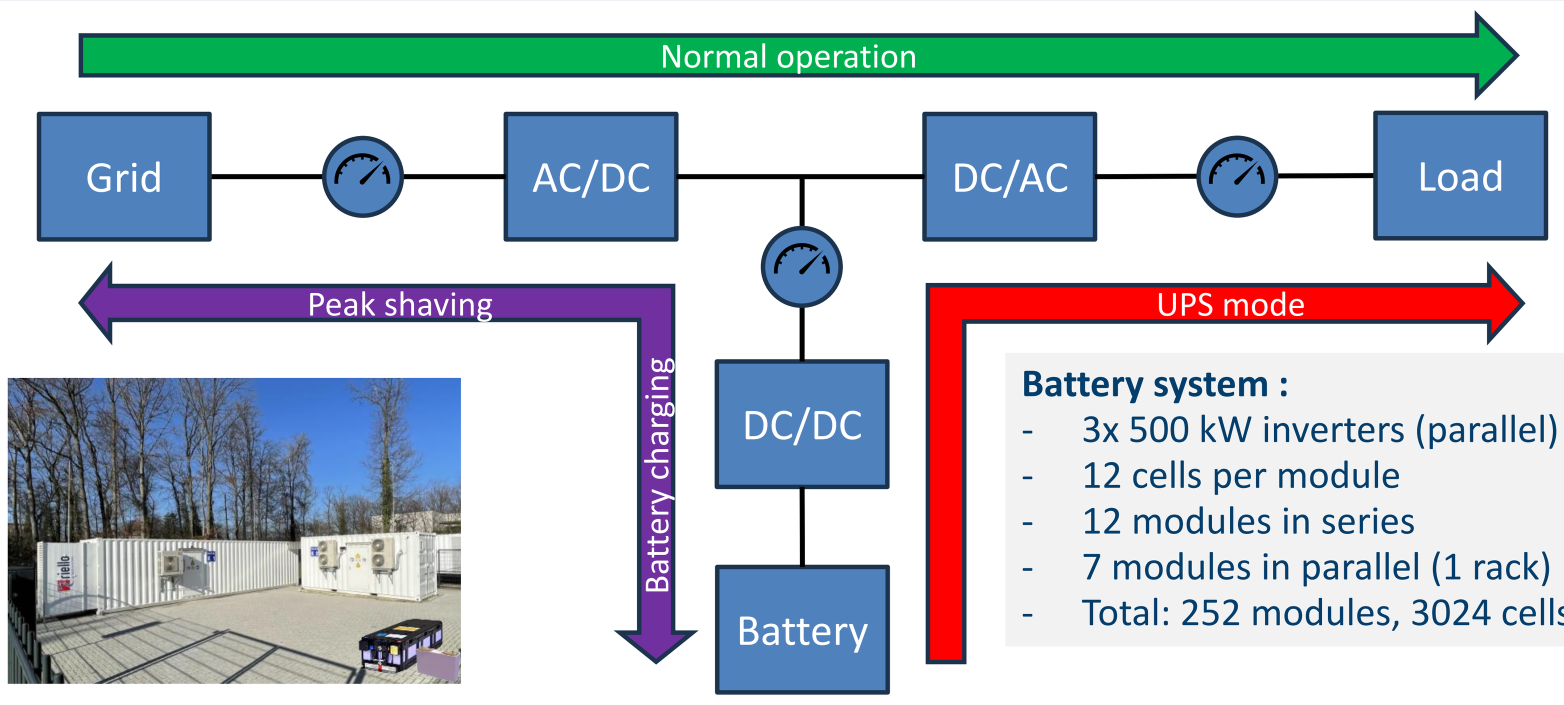
Luc Raijmakers [a], Muhammad Tayyab [a], Gregory Arnstein [a], Anna Windmueller [a], Rüdiger-A. Eichel [a,b]

[a] Forschungszentrum Jülich GmbH, Institute of Energy Technologies (IET-1), 52428 Jülich, Germany
[b] RWTH Aachen University, Institute of Physical Chemistry, Templergraben 55, 52074 Aachen, Germany

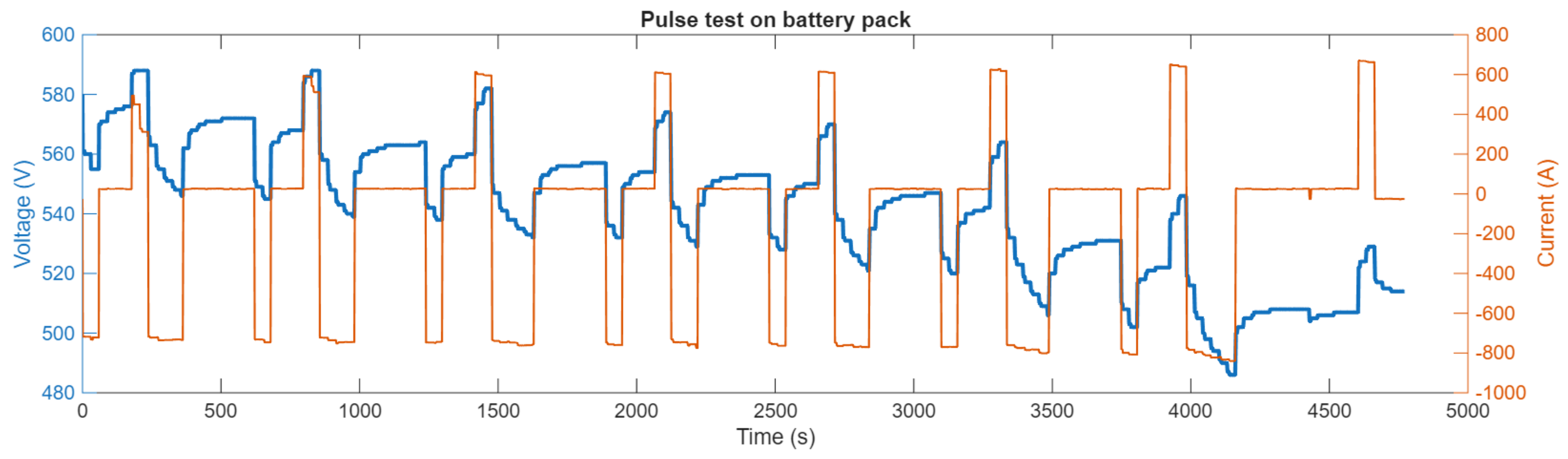
Introduction

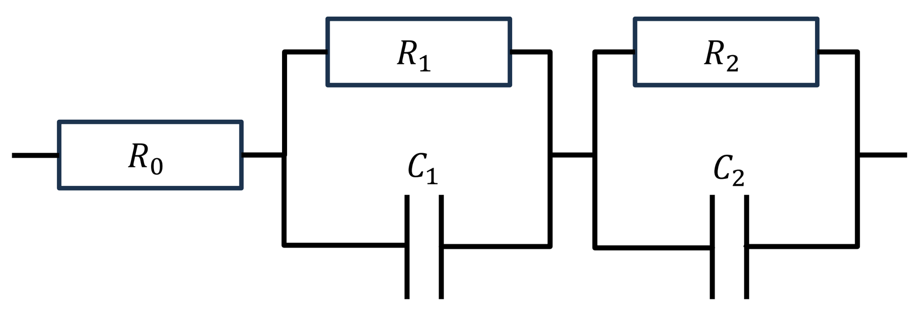
- **Motivation:** Reliable, flexible battery energy storage systems are essential to ensure power supply security and grid stability in increasingly renewable-dominated energy systems
- A high-power battery storage system with $LiMn_2O_4$ chemistry has been installed and commissioned at the Forschungszentrum Jülich GmbH
- The system is one of many energy demonstrators within the Living Lab Energy Campus (LLEC) Project [1]
- The system has two functionalities: Peak-shaving on the 10kV grid and uninterruptable power supply (UPS) for a building
- System rating: 525 kWh / 1.500 MW
- **Objective (analysis):** Use the digital twin to analyze losses, efficiency, and energy management strategies under realistic operating scenarios
- **Objective (operation, 2nd-stage):** Ensure reliable system functionality while enabling predictive, degradation-aware control

Methods and measurements

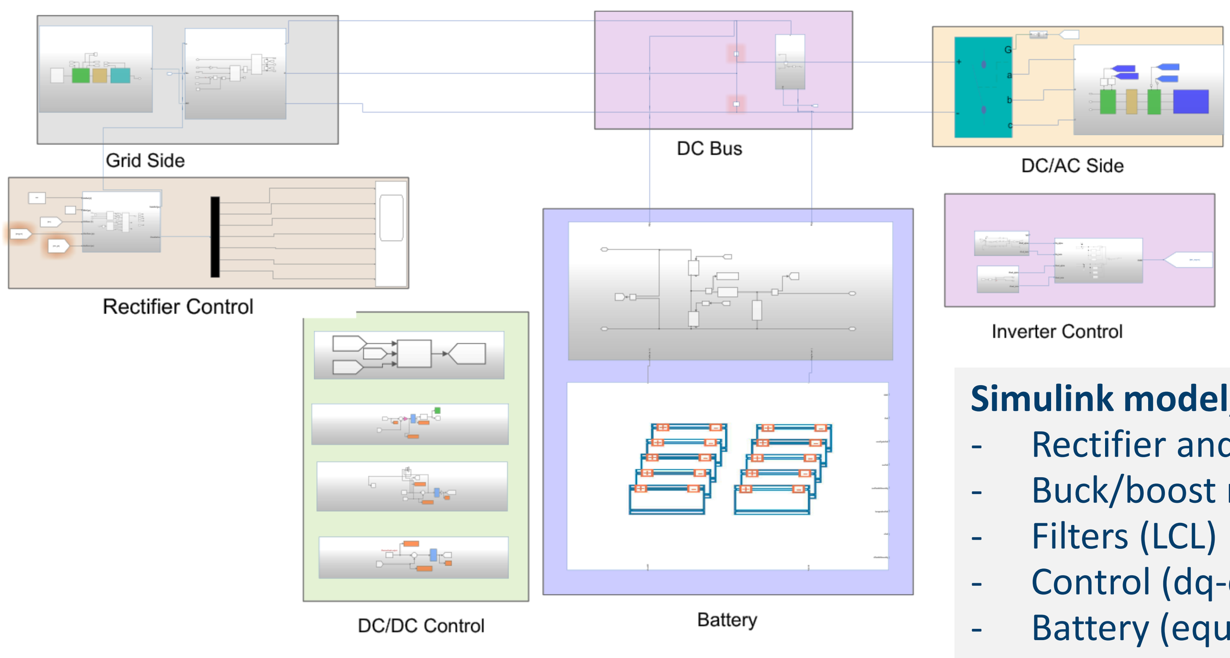


Battery system :
- 3x 500 kW inverters (parallel)
- 12 cells per module
- 12 modules in series
- 7 modules in parallel (1 rack)
- Total: 252 modules, 3024 cells

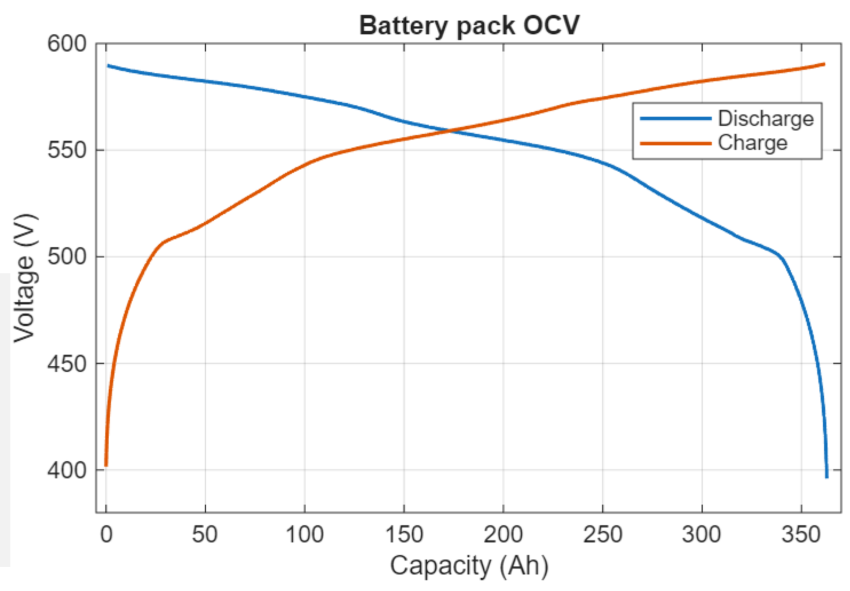


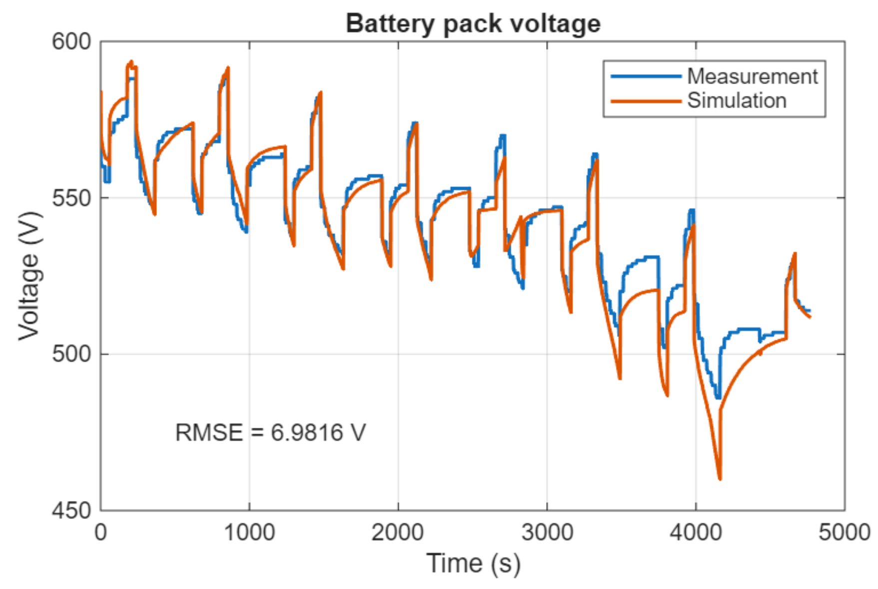


- Battery represented by a second-order equivalent circuit model (R_0 + 2×RC)
- Model parameterization based on pack-level pulse tests and measured open-circuit voltage (OCV)
- Parameters identified from time-domain fitting, and pulse response verified to measurements



Simulink model, with:
- Rectifier and inverter model
- Buck/boost model
- Filters (LCL)
- Control (dq-control + quasi-PR control)
- Battery (equivalent circuit model)





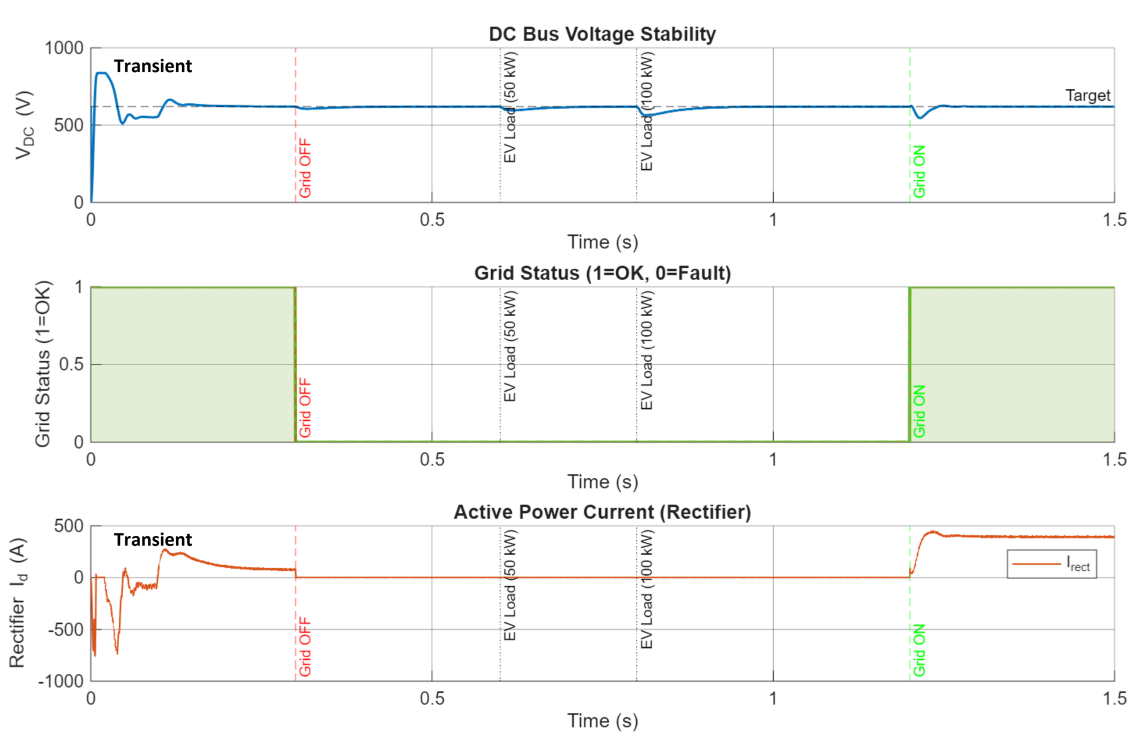
Results and discussion

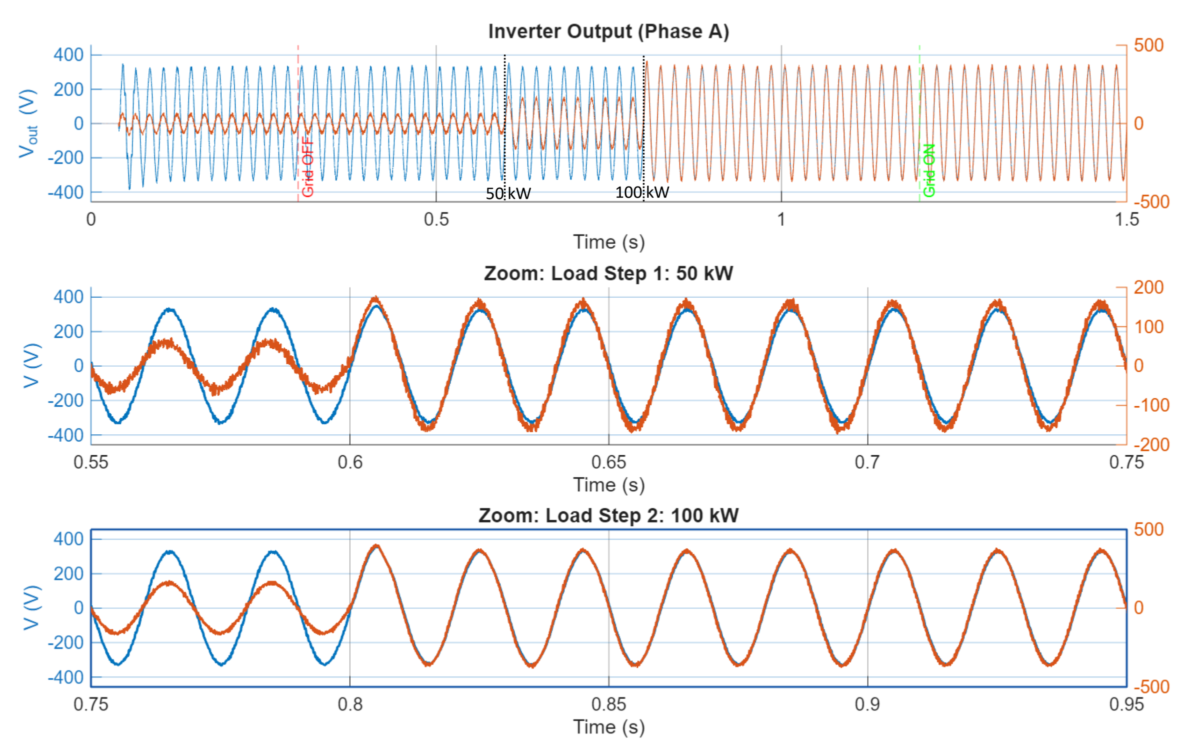
System-level stability and control:
- Robust system stability achieved through cascaded control with clear bandwidth separation
- Stable operation maintained during grid loss, load steps, and grid reconnection
- DC bus voltage remains tightly regulated around 620 V throughout all events
- Confirms suitability of the digital twin for dynamic UPS and grid-support scenarios

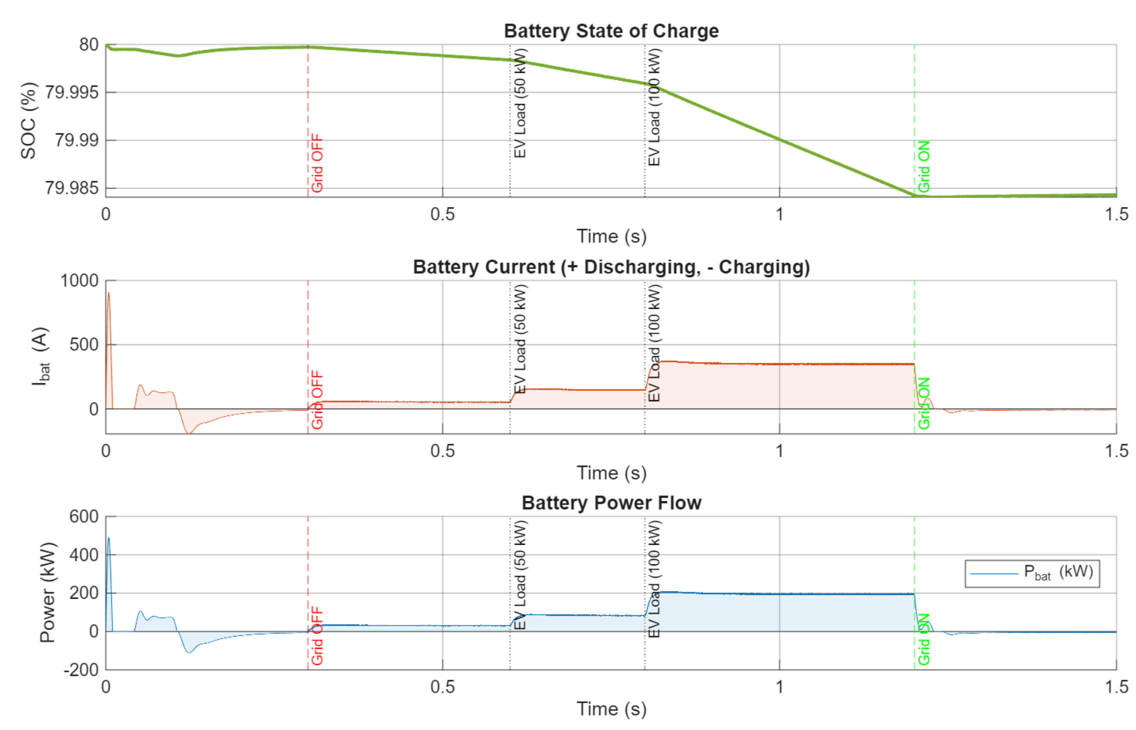
Rectifier (AC/DC) and grid interaction:
- Seamless transition from grid-connected to islanded operation during grid outage
- DC bus voltage deviation during grid loss remains < 10 V (<1.6%)
- Immediate battery takeover prevents voltage interruption at the DC link
- Unity power factor operation during grid-connected phases (PF > 0.99)
- Smooth, overshoot-free current ramp during grid restoration (soft-start behavior)

Inverter (DC/AC) output behavior:
- Stable AC output voltage maintained during all UPS load transitions.
- Load steps of +50 kW and +100 kW result in proportional current increase
- No visible voltage drop or oscillations during transient events
- Low harmonic distortion, compliant or close to IEEE power quality requirements

Battery dynamics and model behavior:
- Battery supplies UPS load immediately upon grid disconnection, i.e., no power interruption at the load side
- Discharge current and power scale consistently with applied UPS load
- Peak battery current (~370 A at 200 kW) is larger than a 1C rating
- Battery current/power converges to zero when grid is back on
- Note: Only minor state of charge decrease due to short grid interruption







Conclusions and outlook

The developed digital twin successfully reproduces the dynamic interaction between battery, power electronics, and control systems in a UPS configuration. The results demonstrate stable operation during grid outages, UPS load transients, and reconnection events, providing a reliable basis for system-level analysis. Ongoing work focuses on extended validation using detailed DC-bus and load-side measurements, including active and reactive power, voltage quality, and system efficiency. Building on this foundation, the digital twin will be used to investigate predictive control strategies, such as model predictive or data-driven approaches, and later enable condition-based maintenance concepts targeting long-term system reliability and degradation-aware operation.

Acknowledgements and funding

The authors would like to thank their colleagues at Forschungszentrum Jülich GmbH for their great support and the Helmholtz Society, the German Federal Ministry of Research, Technology and Space as well as the Ministry of Culture and Science of the Federal State of North Rhine-Westphalia for financing these activities as part of the Living Lab Energy Campus. The authors also would like to thank the Interreg project Multi Agent Systems For Trading Energy on the Blockchain (MAS4TE), which is co-financed by the Interreg Euregio Meuse-Rhine program with additional co-funding from the region of Wallonia (BE), the province of Limburg (NL) and the state of North Rhie-Westphalia (DE)

References

[1] Living Lab Energy Campus (LLEC) Project - www.fz-juelich.de/de/llec
[2] Gururaj, H. C., et al. (2021). Advances in Renewable Energy and Electric Vehicles: Select Proceedings of AREEV 2020, 139-147
[3] Adeyinka, A. M., et al. (2024). Sustainable Energy Research, 11(1), 26.

Corresponding author

L.H.J. Raijmakers

l.raijmakers@fz-juelich.de

With funding from the: Federal Ministry of Research, Technology and Space