Mitigating PV curtailment through energy storage in south Germany: A PyPSA-based analysis

Summary

The present study utilises energy data from southern Germany to examine the potential for reducing photovoltaic (PV) curtailment through the use of energy storage systems. Two scenarios featuring fluctuating and constant demand profiles are analysed to assess the influence of different energy storage systems, utilising the Python for Power System Analysis (PyPSA) simulation framework. Using sensitivity analysis, various system topologies based on battery and hydrogen technologies are optimised by means of mixed-integer linear programming. The modelling indicates that depending on the scenario and the energy system, the optimal PV orientation and the storage capacity varies. Furthermore, buffering PV and electrolysis by batteries creates a unique symbiosis that increases the full-load hours and efficiency of the energy system. The findings indicate that a combination of optimal PV orientation, batteries and electrolysers capable of trading on electricity exchanges maximises PV utilisation.

Keywords: PV curtailment, microgrid, energy storage system, PyPSA, hydrogen, batteries

Field of application for the findings: decentralised energy systems, hybrid energy storage

Addressed audience: grid operators, PV system owners, researchers in the field of energy, Techno-economic analysts, energy system modelers

1. Introduction

The rapid expansion of photovoltaic installations has made solar power a significant contributor to renewable electricity generation in Germany. By 2025, installed PV capacity reached around 119 GW_p and generated more than 91 TWh of electricity, while system costs have fallen by nearly 90 % since 2010 (Wirth 2026, p. 6-9). However, the growing share of PV also creates operational challenges. High solar irradiation frequently leads to grid congestion, causing substantial curtailment of PV systems. In 2024, curtailment amounted in Germany to approximately 1.4 TWh, representing a 97 % increase compared to 2023 (Diermann 2024). These interventions restrict the effective use of renewable resources and pose a risk to PV system investments. Consequently, local energy storage solutions are becoming increasingly important for enhancing grid stability and improving the integration of distributed PV.

Microgrids provide a suitable framework for coordinating distributed generation, flexible loads, and storage, while counteracting the increase in PV curtailment. This study is conducted in southern Germany, where average wind speed is lower and solar irradiation higher than in the north (Energydata.info, 2026), and where a substantial share of the country's energy-intensive industry is concentrated (Hladik et al., 2020). These prerequisites render the location particularly well-suited for PV capacity expansion and the analysis of curtailment mitigation.

Therapontos et al. (2025) have demonstrated that battery systems alone can reduce curtailments in Cyprus to 10 %. In hybrid storage concepts, batteries mitigate short-term fluctuations in PV output, while hydrogen-based storage enables long-term and seasonal energy balancing (Bondar 2025). This work presents the conception, modelling, and techno-economic optimisation of a microgrid integrating PV, battery storage, and hydrogen technologies with the objective of reliably meeting a fluctuating and a constant electricity demand. These topologies are analysed regarding self-consumption, curtailments and full-load hours, with the aim of identifying an optimised hybrid storage strategy that maximises PV utilisation while minimising feed-in peaks and curtailment.

2. Methods

The analysis begins with evaluating existing PV systems, including PV generation and curtailment data recorded in 2024. Two real load profiles with identical annual electricity consumption, one featuring fluctuating demand and the other constant demand, are analysed. Furthermore, technological and economic datasets from local grid operators, encompassing information on existing infrastructure, component characteristics, electricity prices and operational profiles are incorporated. These datasets form the basis for the subsequent modelling and optimisation steps. To ensure an accurate representation of the microgrid and its future expansion scenarios, the model employs 15-minute intervals of load profiles, combined with meteorological datasets. Based on these data, the system is modelled using PyPSA and subsequently extended by integrating battery storage as well as a hybrid hydrogen system comprising an electrolyser, hydrogen tank, and fuel cell. A mixed-integer linear programming (MILP) algorithm is used for the optimisation of technological parameters, including capacity and performance. Fig 1 shows the topology of the microgrid.

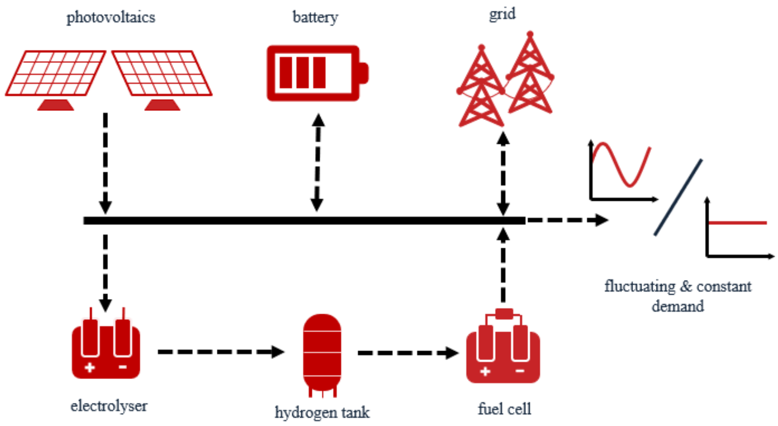

Fig 1: Network topology of the analysed microgrid

The simulation evaluates the complementary roles of both storage technologies in combined operation, depending on self-consumption and real electricity prices. Systematic parameter sensitivity analyses regarding storage capacity and performance are conducted to identify the potential of reducing curtailments and techno-economic break-even regions based and full-load hours and full load cycles. Grid feed-in limitations and curtailment through grid congestion are incorporated to reflect real operational constraints.

3. Results and discussion

The results presented herein are relevant to both scenarios. The analysis reveals several key insights into the performance and economic viability of PV systems and the energy system configuration. The east–west orientation of the PV system allows a higher installed capacity per unit area than a south-facing layout. Installing east–west oriented PV modules enhance energy production during the morning and evening hours while lowering the midday peak, thereby reducing the risk of curtailment.

When photovoltaic systems are coupled with battery storage, the economic operation strategy strongly determines the number of full load cycles. If the battery is used exclusively for self-consumption optimisation, the cycle count remains low because it is seldom utilised on days with limited solar irradiation, while its capacity must be oversized to buffer the surplus energy generated during summer periods. In contrast, participation in the day-ahead electricity market through arbitrage significantly increases full load cycles and improves profitability. Larger storage capacities generally enhance economic returns under market-based operation. Systems with longer discharge durations tend to outperform short-duration storage under comparable cycling conditions. Although PV expansion supports demand coverage and batteries reduce curtailment, grid power remains indispensable.

The integration of PV with hydrogen production shows that exclusive reliance on PV for hydrogen generation remains challenging. Achieving a positive net present value requires either the combination of PV with wind power or the procurement of very low-cost grid electricity. Smaller electrolyser units benefit from higher full-load hours, improving technical efficiency and reducing fixed costs per unit of hydrogen produced. The economic viability of electrolysers is strongly dependent on the number of full-load hours, which tend to be limited under highly variable PV-only operation. Utilising the waste heat from electrolysis increases overall system efficiency.

The combination of PV, hydrogen production, and battery storage creates synergistic benefits. The battery acts as a buffer that smooths power fluctuations and supplies the electrolyser during periods of low solar irradiation, thereby increasing its full-load hours. An optimal balance between PV capacity, battery size, and electrolyser rating enables high levels of energy autonomy while mitigating PV curtailment. Adding a fuel cell for reconversion of stored hydrogen enhances winter-season self-sufficiency and moves the system closer to complete energy independence. This integrated configuration provides the greatest benefit by supplying electrical demand as well as portions of the thermal and fuel requirements through renewable energy sources. Fig 2 reveals the possibilities of curtailment reduction in PV-microgrids using a hybrid storage system to utilise excess power on the example day July 1st, 2025.

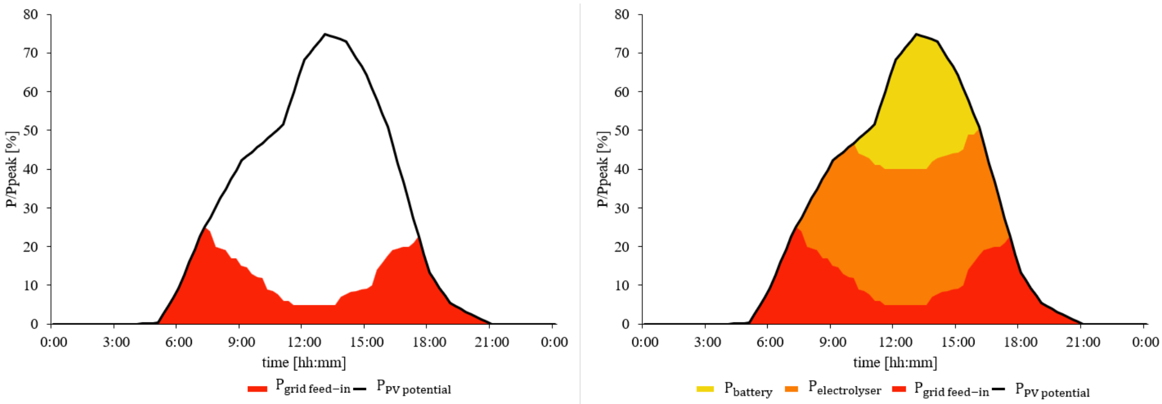

Fig 2: Stacked area chart showing the proportional power output of the installed PV peak power on July 1st, 2025, without energy storage (left) and with combined battery and hydrogen storage (right).

4. Conclusion

This data-driven, simulation-based approach enables a systematic integration of energy storage systems with innovative operational strategies, as well as the targeted resolution of grid-related issues such as the curtailment of PV systems caused by overload. Optimised PV layouts and tracking strategies expand usable generation windows, while batteries mitigate short-term power peaks that typically trigger grid-side limitations. Hydrogen production further contributes by absorbing prolonged surplus generation and shifting it seasonally, enabling high utilisation of the available PV potential. Across all investigated configurations, PV–battery–hydrogen microgrids consistently increase self-consumption, stabilise operation, and reduce grid feed-in peaks. Thus, the study confirms that integrated hybrid storage is a robust strategy to minimise PV curtailment and enhance the reliability and economic performance of PV-dominated microgrids.

References

Bondar, Petro. Analysis of the Impact of Integrated Hydrogen and Battery Energy Storage Systems on the Dynamic Stability and Reliability of Local Power Grids with High Renewable Energy Penetration. World Journal of Advanced Research and Reviews, 2025, 27(02), 2192–2198

Diermann, Ralph. 2024. Abregelung von Photovoltaik-Anlagen stieg 2024 um 97 Prozent. pv magazine. https://www.pv-magazine.de/2025/04/03/abregelung-von-photovoltaik-anlagen-stieg-2024-um-97-prozent/. (Accessed: 3 March 2026)

Energydata.info. 2026. https://energydata.info/. (Accessed: 10 March 2026)

Hladik, D., Fraunholz, C., Kühnbach, M., Manz, P., Kunze, R., Insights on Germany's Future Congestion Management from a Multi-Model Approach. Energies, 13(16), 2020.

Therapontos, P., Tapakis, R., Aristidou, P., Charalambides, A.G.. RES curtailments in Cyprus: A review of technical constraints and solutions. Solar Energy Advances, 5, 2025.

Wirth, Harry. Aktuelle Fakten zur Photovoltaik in Deutschland. Fraunhofer ISE. 2026