Techno-Economic Optimization of Hybrid PV-BESS system in Day-Ahead and Ancillary Service Markets

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***Abstract*— The increasing deployment of renewable energy sources has created a growing need for flexible resources capable of supporting power system operation. Battery energy storage systems (BESS) are increasingly deployed together with photovoltaic (PV) plants to enhance system flexibility and improve project economics. Hybrid PV-BESS systems can generate revenues from multiple market streams, including electricity price arbitrage and participation in ancillary service markets. This paper investigates the optimal sizing of battery storage in hybrid PV-BESS systems considering participation in both energy markets and ancillary service markets. A techno-economic optimization model is developed to maximize the net present value (NPV) of the project while accounting for PV generation, battery operational constraints, ancillary service provision, and grid export limits. The model evaluates multiple combinations of PV and battery capacities using a grid-search approach. The results indicate that the economic value of battery storage in the analysed case study is primarily driven by ancillary service capacity payments, while revenues from energy arbitrage play a relatively minor role. The analysis further demonstrates that the optimal battery capacity is strongly influenced by the size of the ancillary service market. When the available ancillary service capacity increases, the economically optimal battery capacity increases accordingly. These findings highlight the importance of considering ancillary service market constraints when designing hybrid PV-BESS systems and provide useful insights for developers and investors evaluating storage deployment in renewable energy projects.**

Keywords*— *Ancillary services market, battery energy storage systems, day ahead market, PV-BESS hybrid systems, renewable energy integration, storage optimization

I. INTRODUCTION

The increasing penetration of renewable energy sources is significantly transforming modern power systems. In particular, photovoltaic (PV) generation has undergone rapid growth due to declining technology costs and strong policy support. However, the inherent variability and intermittency of PV generation introduce considerable operational challenges, including power fluctuations, voltage instability, and increased uncertainty in balancing supply and demand. These issues become more pronounced as the share of renewable energy in the grid increases, requiring additional flexibility and advanced control strategies to maintain reliable system operation [1]. Battery energy storage systems (BESS) have emerged as a key technology for addressing these challenges. Their ability to store energy and release it when required, supports the integration of renewable energy sources, enhanced grid stability, and increased operational flexibility. BESS can provide a wide range of services, including regulation up (reg-up), regulation down (reg-down), spinning reserve (spin), peak shaving, energy shifting, frequency regulation, as well as, making them a critical component of modern power systems [2]. Furthermore, their fast response capability allows them to effectively support real-time grid operations and ancillary services provision [3]. Early research on BESS primarily focused on specific operational applications, such as peak shaving and load levelling. In this context, Oudalov et al. developed a methodology for the optimal sizing and operation of BESS, aimed at reducing peak demand and associated electricity costs [4]. Similarly, Lu et al. proposed optimization models for both sizing and control of BESS, highlighting the importance of coordinated planning and operational strategies in achieving efficient system performance [5]. With the increasing complexity of power systems, more recent studies have extended the focus toward comprehensive techno-economic optimization of BESS under varying operational and market conditions. In particular, advanced optimization approaches have been developed to determine the optimal storage capacity while accounting for investment costs, operational constraints, and performance trade-offs [6]. Significant research efforts have been directed toward analysing BESS participation in electricity markets. Khalilisenobari and Wu proposed optimization frameworks for battery operation in both day-ahead (DAM) and ancillary service (ASM) markets, demonstrating the strong economic potential of regulation services [7]. Similarly, Alharbi investigated the optimal sizing and management of BESS providing multiple stacked services, highlighting the importance of market conditions, degradation costs, and operational constraints in maximizing economic performance [8].

While these aforementioned studies provide valuable insights into standalone BESS, the integration of storage with renewable generation, particularly PV systems, introduces additional operational and economic complexities that require dedicated analysis. In the context of hybrid photovoltaic and battery energy storage systems (PV-BESS), increasing attention has been devoted to the optimal integration of storage to enhance renewable energy utilization and system flexibility. Li et al. investigated optimal storage sizing in PV power plants with the objective of improving PV utilization and reducing energy curtailment, demonstrating the critical role of storage in enabling more efficient integration of PV generation [9]. A number of studies have addressed the optimal sizing and operation of PV-BESS systems using techno-economic optimization frameworks. Dufo-López et al. analysed grid-connected PV-battery

This research was funded by the project FLEXSYS—Implementation of Flexibility Sources and Advanced Control Algorithms for Supporting Modern Power Systems with a High Share of Renewable Energy Sources, IP-UNIST-05, funded by the European Union – NextGenerationEU.

979-8-3195-0122-6/26/$31.00 ©2026 IEEE

systems participating simultaneously in energy arbitrage and frequency containment reserve markets, showing that multi-market participation can significantly enhance system profitability [10]. Similarly, Gonçalves et al. investigated the optimal sizing of PV-BESS systems under contingency conditions, highlighting the trade-off between investment cost and system reliability [11]. Ren et al. further explored the joint sizing of PV and lithium battery systems, emphasizing the role of storage in reducing grid dependency and improving system autonomy [12]. Additionally, Monar et al. analysed community-scale PV-BESS systems, demonstrating that economic factors such as electricity prices and battery degradation play a key role in determining optimal system design [13].

Despite the considerable amount of research on BESS sizing and PV-BESS systems, several important gaps remain. Many existing studies rely on simplified assumptions regarding input data, generated synthetic electricity price profiles or limited time horizons, often considering only representative days or short-term periods instead of full-year analyses. In addition, PV generation is frequently modelled using idealized or generic production profiles, which may not accurately capture seasonal variability and real operating conditions. Furthermore, several studies investigate optimal sizing under fixed market conditions without fully accounting for the variability and constraints of real electricity markets. In particular, limitations related to market participation and available service capacity are often simplified or neglected, which may affect the accuracy of the obtained results. As a result, the combined impact of realistic input data, including full-year electricity price series, representative PV generation profiles, and market constraints, on the optimal sizing and economic performance of PV-BESS systems remains insufficiently explored. This indicates that more comprehensive analyses using realistic data and market conditions are required.

In this paper, a techno-economic analysis of hybrid PV-BESS systems is conducted based on detailed input data, including a full-year electricity price series, representative PV generation profiles, and explicitly considered market constraints. A techno-economic optimization framework is developed, considering participation in both DAM and ASM markets with limited capacity. The model evaluates the impact of market constraints on system sizing and economic performance using a net present value (NPV) analysis, with a particular focus on the interaction between system operator limits, optimal PV-BESS capacity, as well as the size of markets.

II. Case Study and Input Data

The analysis considers a hybrid PV-BESS system where the PV plant and the battery system are connected to the electricity grid as separate units. The hybrid PV-BESS system participates in both DAM and ASM markets, with PV generation traded only in the DAM, while the battery system operates in both markets. The considered ancillary services include reg-up, reg-down, and spin reserve, with incomes consisting of both, ancillary services capacity and energy components. The capacity limits for these services are predefined for each calculation, while the system is additionally constrained by the available hourly grid connection capacity. Several grid connection scenarios were considered, taking into account different grid export limits for participation in the DAM.

The PV plant capacity is assumed to vary between 10 MW and 100 MW, and the battery power capacity between 0 MW and 100 MW, both in steps of 10 MW, with a fixed battery energy duration of 4 hours. The battery round-trip efficiency is assumed to be 0.85 and its operation and maintenance (O&M) costs are also taken into account (fixed cost, time-dependent cost, energy-dependent cost and start-up cost). The available ASM market capacity is limited to 12 MW, consisting of 5 MW of reg-up, 4 MW of reg-down, and 3 MW of spin reserve. These constraints reflect typical market conditions under which the system operator may request services from the PV-BESS system.

The PV generation profiles used in the simulations are based on representative daily production curves for different seasons in 2025. Fig. 1 illustrates 50 MW PV one week output profiles for winter, spring, summer, and autumn days. These seasonal profiles capture the variability of solar generation throughout the year and provide realistic input data for the optimization model.

Electricity market prices are represented using an hourly price series for 2025. The DAM prices are based on data from the Croatian Power Exchange (CROPEX). To provide an overview of the electricity prices distribution used in the simulations, Fig. 2 presents the annual price duration curve, while Fig. 3 shows weekly price profiles (corresponding to the same days as in Fig. 1), highlighting seasonal variations in market conditions. The price profile reflects typical market behaviour with significant price variability, which creates opportunities for energy arbitrage and storage operation. The prices of ancillary service capacity components are assumed to be 40% higher than the corresponding hourly DAM prices, reflecting the higher value of flexibility and reliability services. Furthermore, the prices of ancillary service energy components are set to 8 €/MWh for reg-up, 6 €/MWh for reg-down, and 8 €/MWh for spin reserve, representing typical values observed in the Croatian power system [14].

Three grid export limit scenarios were analysed for the DAM: 30 MW, 60 MW, and 90 MW. These limits represent typical grid connection restrictions that can affect the PV-BESS system. They imply that the PV-BESS system is not allowed to export more than the specified values to the grid in every hour. The main parameters used in the techno-economic optimization model are summarized in Table 1.

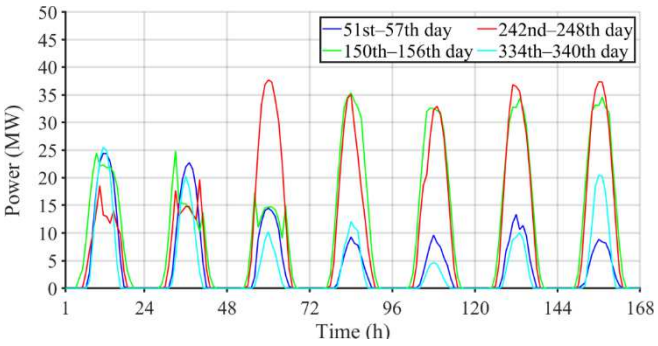


Fig. 1. One week 50 MW PV generation profiles

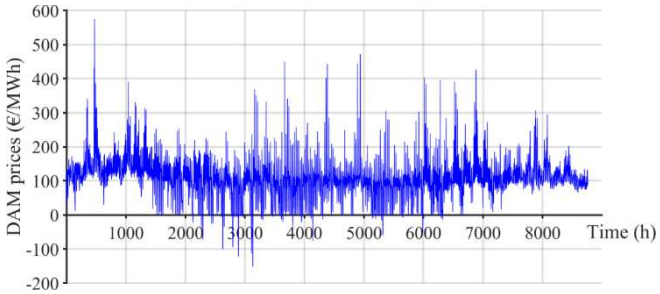


Fig. 2. Representative day-ahead electricity profile

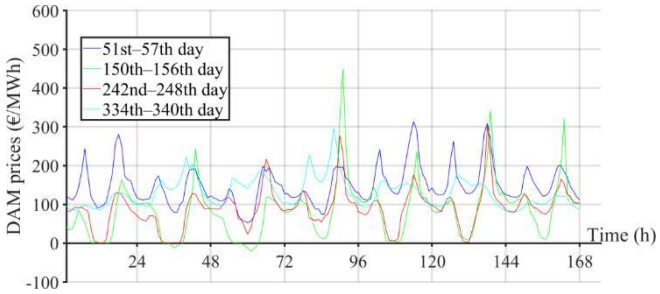


Fig. 3. One week electricity price profiles

TABLE I. MODEL ASSUMPTIONS USED IN THE OPTIMIZATION MODEL

	Parameter	Value	Unit
PV plant	Capacity range	10-100	MW
	Capacity step	10	MW
	Generation data	representative seasonal profiles	MW
	Lifetime	20	years
	Investment power capacity cost	850,000	€/MW
BESS system	Capacity range	0-100	MW
	Capacity step	10	MW
	Duration	4	h
	Energy capacity	Battery capacity range x 4	MWh
	Round-trip efficiency	85	%
	Reg-up capacity limit	5	MW
	Reg-down capacity limit	4	MW
	Spinning reserve capacity limit	3	MW
	Fixed cost	0-180	€
	Time dependent cost	0-10	€/h
	Energy dependent cost	0, 9	€/MWh
	Start-up cost	0-100	€/start-up
	Lifetime	20	years
	Investment power capacity cost	1,000,000	€/MW
	Investment energy capacity cost	308,700	€/MWh
	Grid export limits	30; 60; 90	MW
	Discount rate	7	%

III. OPTIMIZATION MODEL

A. Objective function and constraints

The optimization model, based on [15], maximizes the objective function (1), which represents the daily income of the hybrid PV-BESS system from participation in the DAM and ASM while considering system operation and maintenance (O&M) costs. By repeating the calculation for N=365 days, the total maximized income over one year can be obtained. In (1), the indexes N and n denote the number of days, t represents the hourly time index, while z denotes the ancillary service requested by the system operator. The variable $E_sys_{n,t}$ represents the hybrid system energy delivered to the DAM. The variables $c^e_{n,t}$, $c_{n,t,z}$ and $c^e_{n,t,z}$ denote the prices in the DAM as well as ASM capacity and energy components, respectively. The coefficient $sb_{n,t,z}$ represents the probability (0-1) that the system operator requests a specific ancillary service z. The hourly values are generated stochastically using a triangular distribution and scaled to preserve the predefined annual activation frequencies. The parameter η denotes the battery round-trip efficiency, while $h_{n,t,z}$ represents the battery energy activated for the ancillary service provision. The variables $t^r_{n,t}$ and $t^{su}_{n,t}$ represent indicators associated with operation-dependent and start-up costs, respectively, while $E_{n,t}$ denotes the BESS energy. The coefficient k_1 represents the fixed cost of the BESS, while k_2, k_3 and k_4, denote the unit prices of time-dependent, energy-dependent, and start-up costs, respectively. Based on the above definitions, in (1) the first term represents the income of the PV-BESS system from the DAM, the second term represents the income from ancillary services (including both, capacity and energy components), while the remaining five terms represent the O&M costs of the hybrid system. In (2), $h_{n,t}$ and $p_{n,t}$ represent the battery discharging and charging energy, respectively, while $pv_{n,t}$ represents the energy generated by the PV plant. Finally, in (3), $E_lim_{n,t}$ represents the hourly export limit, i.e., the maximum amount of energy that the PV-BESS system is allowed to inject into the grid due to system operator constraints.

$$\sum_{n=1}^{N}\sum_{t=1}^{24}\left\{E_sys_{n,t}\cdot c^e_{n,t}+\sum_{z=1}^{k}\left[\left(c_{n,t,z}\pm sb_{n,t,z}\cdot\eta\cdot c^e_{n,t,z}\right)\cdot h_{n,t,z}\right]\right. \quad (1)$$
$$\left.-k_1-k_2\cdot t^r_{n,t}-k_3\cdot E_{n,t}-k_4\cdot t^{su}_{n,t}\right\}$$

$$E_sys_{n,t}=h_{n,t}-p_{n,t}+pv_{n,t} \quad (2)$$

$$E_sys_{n,t}\le E_\mathrm{lim} \quad (3)$$

IV. RESULTS

This chapter presents the results of the techno-economic analysis of different PV-BESS configurations under the considered market and grid conditions. The PV capacity is varied between 10 MW and 100 MW, while the BESS capacity ranges from 0 MW to 100 MW. For each configuration, an operational dispatch optimization is first performed to determine the annual net cash flow, which is subsequently used to calculate the NPV together with the corresponding investment cost. Based on these results, the economically optimal PV-BESS configuration is identified for different grid and market scenarios.

A. Daily operation profile of PV-BESS system

To provide the understanding of the PV-BESS system operation, daily operation profiles are presented in this section (Figs. 4 and 5) for two grid export limit scenarios, 30 MW and 60 MW. The same system configuration, consisting of 80 MW of PV capacity and 50 MW of battery storage, is used in both cases to clearly demonstrate the impact of grid constraints on system operation. This configuration is selected for illustrative purposes and does not necessarily represent the optimal system design.

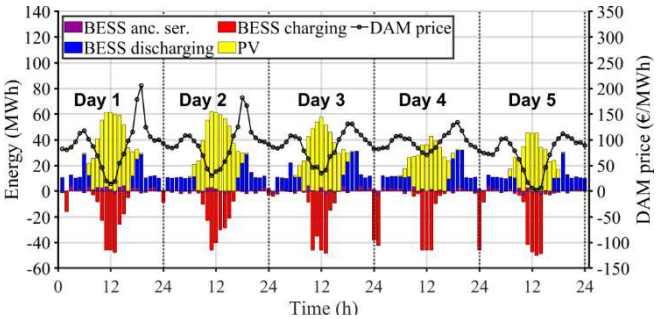


Fig. 4. Daily operation profile of the PV-BESS system for 30 MW grid export limit

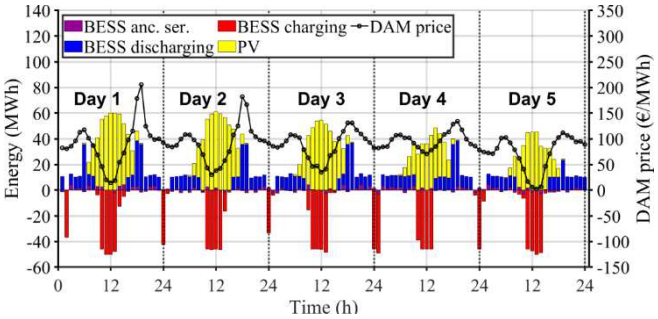


Fig. 5. Daily operation profile of the PV-BESS system for 60 MW grid export limit

Figure 4 shows the daily operation of the system for a 30 MW grid export limit. During periods of high PV generation, the export limit is frequently reached, resulting in battery charging to absorb surplus energy and mitigate PV curtailment.

In contrast, Fig. 5 illustrates the operation under a 60 MW grid export limit, where a larger share of PV generation can be exported directly to the grid. Consequently, battery charging is reduced during peak PV production, and battery operation is driven primarily by electricity market opportunities rather than grid constraints.

Overall, the comparison demonstrates that stricter grid limits increase the value of storage for absorbing excess PV generation, whereas higher export capacity enables greater direct PV injection and reduces reliance on battery storage.

B. *Optimal battery capacity*

In this section, the impact of battery capacity on the hybrid system NPV for grid export limits of 30 MW, 60 MW, and 90 MW was investigated (Fig. 6). For each battery size, the maximum NPV across all considered PV capacities is reported. The results indicate that the project NPV increases significantly when a battery is introduced. The highest NPV is achieved at a battery capacity of approximately 10 MW. Further increasing the battery capacity leads to diminishing economic benefits and eventually lower NPVs. This behaviour indicates that beyond a certain capacity, additional storage does not provide sufficient economic return to justify the increased investment costs. Overall, the results suggest that the optimal battery size is relatively small, and that increasing battery capacity beyond this point does not improve the overall project profitability.

To further investigate the interaction between PV and battery capacity, the techno-economic performance of the system is analysed in more detail in the following section.

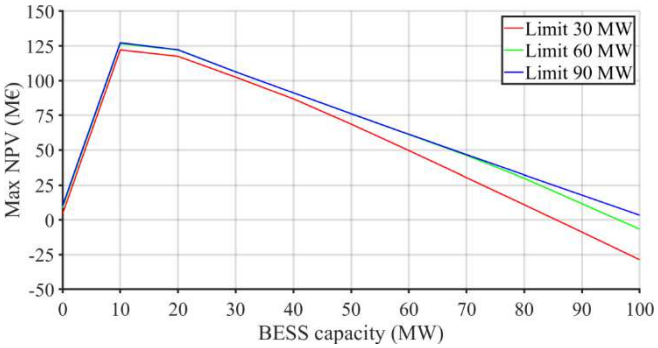


Fig. 6. NPV as a function od BESS capacity

C. *Maximun NPV of the hybrid system*

This section presents the NPV value of the PV-BESS system as a function of PV capacity and battery size for different grid export limit scenarios (Fig. 7). The heatmaps depict the techno-economic trade-off between PV capacity and BESS under varying grid limits. The results show that the optimal system configuration depends primarily on the grid export limit. When the grid constraint is relaxed, higher PV capacities become economically attractive because more generated energy can be exported to the DAM. However, as the grid export limit decreases, increasing PV capacity leads to higher curtailment levels, which reduces the economic performance of the system.

In contrast, the optimal battery capacity remains relatively stable across the considered scenarios. In most cases, the highest NPV is achieved with a battery capacity of approximately 10 MW. This observation suggests that the economic value of the battery is not strongly influenced by grid export constraints and indicates that other incomes streams may play a dominant role in determining the optimal battery size.

Overall, the results demonstrate that grid limits primarily influence the optimal PV capacity, while the optimal battery size appears to be driven by factors beyond grid constraints. To further investigate this behaviour, the impact of ancillary service market size on the optimal battery capacity and system performance is analysed in the following section.

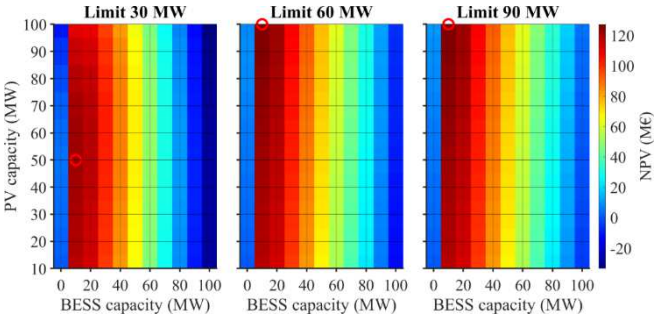


Fig. 7. Net present value of the hybrid system as a function of PV capacity and BESS size fir different grid export limit scenarios

D. *Impact of ASM size*

In this section, the income breakdown for different battery capacities (10 MW, 20 MW, 30 MW) under two ASM capacity scenarios (12 MW and 21 MW) was investigated. The results are presented for a system configuration of 30 MW grid export limit and 50 MW PV capacity.

TABLE II. ANNUAL INCOME SOURCES (M€/YEAR) AND NPV FOR DIFFERENT BESS CAPACITIES UNDER TWO ASM CAPACITY SCENARIOS

Scenarios	**ASM 12 MW**			**ASM 21 MW**		
BESS capacity (MW)	10	20	30	10	20	30
Reg-up capacity (M€)	5.5	6.5	6.5	3.9	9.6	10.3
Reg-down capacity (M€)	5.2	5.2	5.2	9.0	9.0	9.0
Spin capacity (M€)	2.7	3.0	3.0	4.9	5.7	6.0
ASM energy (M€)	0.1	0.7	0.1	-0.04	0.1	0.1
ASM Total (M€)	13.50	15.40	14.80	17.76	24.4	25.4
Energy selling (M€)	1.6	4.0	6.5	1.9	3.5	5.8
NPV (M€)	**122.1**	116.9	102.0	181.5	**216.4**	208.6

In 12 MW scenario, the considered ASM limits were set to 5 MW, 4 MW, and 3 MW for reg-up, reg-down and spin reserve respectively, while in 21 MW scenario these values were set to 8 MW, 7 MW, and 6 MW. The results present incomes from capacity and energy component of ancillary services as well as energy selling.

For the 12 MW ASM scenario, the optimal battery capacity is 10 MW, yielding an NPV of 122.10 M€. Increasing the battery capacity beyond this level does not significantly increase income from ancillary services due to the limited market capacity. As a result, larger batteries lead to lower project NPVs due to higher investment costs. When the ASM market capacity is increased to 21 MW, the optimal battery capacity increases to 20 MW, achieving an NPV of 216.39 M€. This result demonstrates that the optimal battery size strongly depends on the available ancillary service market capacity. In addition, most battery incomes originate from ancillary service capacity payments. In contrast, income from energy selling in the DAM represent a relatively small share of the total income.

Overall, the results indicate that the economic value of battery storage in the analysed PV-BESS system is primarily driven by participation in ASM rather than by energy arbitrage alone.

E. Sensitivity analysis

A sensitivity analysis was conducted to evaluate the impact of ancillary service capacity prices on the economic performance of the hybrid PV-BESS system. For this purpose, the ancillary service capacity prices were reduced by 20% compared to the base case, while all other input parameters remained the same.

The optimization was repeated for the 30 MW grid export limit scenario over the full range of PV and BESS capacities. The results show that the optimal configuration remains unchanged at 50 MW PV and 10 MW BESS, while the project NPV decreases from approximately 112.1 M€ in the base case to 93.86 M€ under the reduced-price scenario.

These results indicate that the economic performance of the system is sensitive to ancillary service market prices. However, the unchanged optimal configuration suggests that the identified system design is relatively robust under moderate reductions in ancillary service capacity payments.

V. CONCLUSION

This paper presented a techno-economic optimization of hybrid PV-BESS systems considering participation in both DAM and ASM. The developed optimization model maximizes the project NPV while accounting for PV generation profiles, BESS operational constraints, grid export limits, and incomes from electricity market participation.

The results indicate that the economic value of BESS in the analysed system is primarily driven by participation in ASM. Capacity payments associated with reg-up, reg-down and spin reserve services represent the dominant source of BESS incomes, while energy arbitrage in the DAM contributes only marginally.

The optimization results show that the optimal BESS size strongly depends on the available ASM capacity. For the base case scenario with an ASM market limit of 12 MW, the optimal BESS capacity is approximately 10 MW, while increasing the ASM market capacity to 21 MW results in an optimal BESS size of approximately 20 MW. This demonstrates the significant influence of market design on storage sizing decisions.

Furthermore, grid export constraints mainly influence the optimal PV capacity rather than the optimal battery size, as confirmed by the analysed scenarios. The presented dispatch examples additionally illustrate the operational interaction between PV generation, battery storage, and grid limitations.

A sensitivity analysis with reduced ancillary service capacity prices shows that the overall project profitability is affected by market conditions, while the optimal system configuration remains unchanged. This indicates that the identified PV-BESS design is relatively robust under moderate variations in ancillary service prices.

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