Proceedings of the 4th International Conference on Functional Materials and Civil Engineering
DOI: 10.54254/2755-2721/2026.35028

Advantages and Risks of Distributed Photovoltaic and Energy Storage Grid-Connection

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Abstract. Against the backdrop of dual carbon targets and the rapid development of new energy systems, large-scale grid integration of distributed photovoltaic (PV) generation and battery energy storage system (BESS) has emerged as a crucial pathway for the energy transition. This paper systematically investigates the advantages and risks associated with grid-connected PV-BESS integration. This paper reviews the structural configurations and key technologies of distributed PV-BESS systems, and analyzes representative engineering projects and control/optimization methods, including AC-coupled and DC-coupled demonstration cases, grid-forming control based on virtual synchronous generator technology, and two-stage coordinated optimization using second-order cone programming (SOCP) relaxation. Results indicate that properly coordinated PV-BESS integration can effectively improve voltage quality, mitigate power fluctuations, enhance PV hosting capacity, and provide ancillary services. Nevertheless, it may also introduce voltage violations, power quality degradation, relay protection coordination challenges, and elevated investment costs. Furthermore, this paper presents constructive recommendations from technical, planning, economic, and policy perspectives, providing a reference for the safe and stable planning and operation of distributed PV-storage integration.

Keywords: Distributed photovoltaics, energy storage systems, distribution network, grid connection

1. Introduction

In accordance with the Chinese dual carbon objectives, massive grid interconnection of distributed photovoltaics and energy storage is an important route in energy transition. The process of renewable energy integration needs to be reasonably enhanced to make sure that the system operates in a steady way [1]. Nevertheless, combined photovoltaic-storage grid connection may be an effective way to solve such contradictions because of the high intermittency of PV power generation and the limited ability of the distribution networks to handle this power.

The three underlying technologies that will be discussed in this paper are PV generation where solar radiation is converted into electrical energy; BESS which allows transferring energy in space and time using electrochemical methods; and PV-storage coordinated grid-connection which increases the renewable hosting capacity of the distribution network by means of unified control and complementary coordination.

The existing studies in optimizing power quality in grid-connected photovoltaic and energy storage systems have provided significant findings; nevertheless, such assessments of the benefits and typical risks, as well as respective countermeasures remain lacking [2]. This paper examines the benefits and risks of grid-connected distributed PV-BESS systems. With theoretical analysis, literature review, and case studies, it analyzes the system architecture and principles, common cases, benefits and risks in a systematic manner and finally proposes optimization strategies. As it is shown, photovoltaic-storage systems are able to solve the problem of daytime overvoltage and nighttime undervoltage coexistence by means of a two-stage coordinated optimization approach [3], which can serve as an important reference to analyze the risk management path of this study.

2. Basic theoretical analysis

2.1. Typical architecture of distributed photovoltaic and energy storage grid-connected system

The common structure of a distributed PV-storage grid-connected system is illustrated in Figure 1 which consists of photovoltaic arrays, storage units, grid-connected inverters, distribution transformers and monitoring systems. Operating modes involve self-consumption with excess energy exported to the grid, full grid interconnection and islanded microgrid working model. The AC coupling allows the PV and storage to have independent inverters, which can be expanded easily when retrofitted. With DC coupling, they use a common DC bus and central inverter, which can be more efficient when combined with new integrated projects. As shown in Table 1, the main features of these two models are outlined.

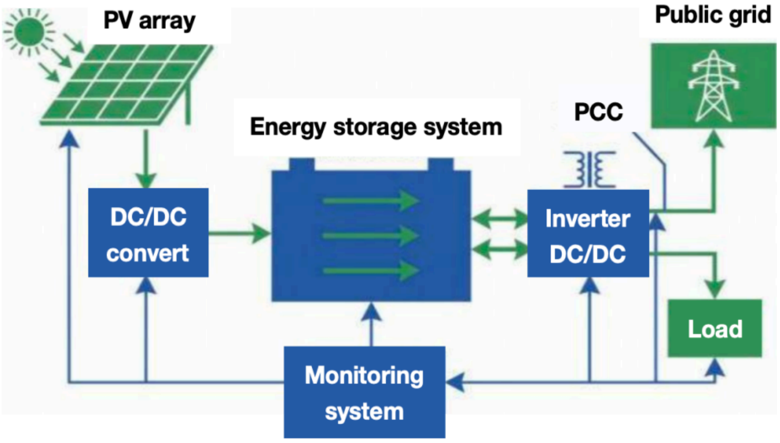

Figure 1. Typical architecture diagram of distributed photovoltaic storage grid-connected system(photo credit : original)

Table 1. Comparison of AC coupling and DC coupling photovoltaic storage systems

Comparison item	AC coupling type	DC coupling type
System structure	PV inverter and BESS PCS are independent	PV and BESS share a DC bus and inverter
Scalability	High; each module can be independently increased or decreased	Limited by the capacity of the DC bus
Conversion efficiency	Lower; multiple conversion losses exist	Higher; more direct energy path

Table 1. (continued)

Applicable scenario	Retrofitting energy storage to existing PV systems	New integrated PV-storage projects
Initial investment	Relatively high	Relatively low

2.2. Distributed photovoltaic power generation technology

The distributed photovoltaic power generation is a process of converting solar energy into electrical power through the semiconductor photovoltaic effect. Currently, the predominant technologies in the commercial market are single-crystal silicon PERC cells, TOPCon and heterojunction cells. Laboratory conversion efficiency can reach 25% to 26% [4]. Distributed PV systems generally feature short construction periods and can supply electricity close to the point of consumption. They are applicable to the installation of industrial and commercial rooftops and also to rural residential buildings.

2.3. Energy storage system technology

The energy storage system is important in coordinated PV-storage operation. Electrochemical storage is currently adopted in most PV-storage systems, which include lithium iron phosphate (LFP), NMC (ternary lithium), flow batteries, and sodium-ion batteries. In this group, LFP batteries are most popular as they account for over 90% of the new energy storage deployed in China because of their overall performance benefits [5]. Table 2 summarizes the performance parameters of the four main technologies.

Table 2. Performance comparison of main electrochemical energy storage technologies

Technology type	Energy density (Wh/kg)	Cycle life (times)	Response time	Efficiency (%)	Safety
Lithium iron phosphate	120-160	>6000	Millisecond level	90-95	Relatively good
NMC (ternary lithium)	150-260	3000-5000	Millisecond level	92-96	Moderate
Flow battery	15-75	>10000	Second level	70-85	Excellent
Sodium-ion battery	70-140	>3000	Millisecond level	85-92	Relatively good

2.4. Solar-storage integrated grid connection technology

PV-storage grid-connection technology coordinately regulates PV output and battery charging/discharging simultaneously. The main goals are leveling of PV variations, peak shaving/valley filling through time of use pricing, and ancillary services in the form of frequency regulation and reactive power support. Model Predictive Control (MPC) has been extensively applied in multi-constraint, multi-timescale optimization [6]. There are three layers of architecture: the bottom layer (real-time control), the middle layer (day-ahead/real-time dispatch), and the upper layer (economic-security decision-making).

2.5. Section summary

To summarize, distributed PV-storage systems use AC coupling when retrofitting and DC coupling in case of new integration. Storage is mostly dominated by lithium iron phosphate and MPC is gradually replacing empirical scheduling. The three levels relate to each other; the coupling describes the energy path, the battery type controls the response and safety and the control strategy facilitates multi-objective coordination. Case validation and analysis of advantages and risks are further discussed in the next paragraphs.

3. Literature and case study analysis

This section discusses four PV-storage cases related to the earlier technical paths. The examples of Quzhou and Tai'an provide practical application and economic aspects, illustrating real-world deployment benefits; the BESS as a grid-former and two-stage optimization emphasize the control and algorithmic advances. Each case has its own emphasis. Taken together, they underpin the analysis of the article from the engineering and academic perspectives.

3.1. Zhejiang Quzhou smart photovoltaic storage microgrid demonstration project

The microgrid demonstration project of smart PV-storage in an industrial park of Quzhou, Zhejiang, which was commissioned in 2025 is an example of AC-coupled PV-battery design in an industrial environment. The system consists of about 2 MWp distributed PV systems and 1 MW/2 MWh lithium-iron-phosphate batteries. An individual Energy Management Systems (EMS) offers hierarchical-controlled coordination on smoothing PV production, peak shaving/valley filling as well as economic dispatch. Since commissioning, the PV consumption rate has been more than 85%, resulting in annual electricity expenditure savings of roughly CNY 1.8 million. This proves that EMS-controlled PV-BESS microgrids can substantially enhance PV self-consumption rate and achieve peak shaving and valley filling [7], thus also confirming the financial viability of AC-coupled solutions in industrial parks.

3.2. Shandong Tai'an flexible smart park microgrid demonstration project

The green, flexible, smart, and low-carbon microgrid park in Tai'an, Shandong is an example of government-led energy savings. It has an integrated PV-storage-charging system with around 5MWp of distributed photovoltaics, 2MW/4MWh battery storage and charging stations. The components have a shared DC bus and are connected to the grid through a central inverter, which is more efficient in converting energy than AC-coupled designs (appropriate to be implemented on a large scale) [8]. The flexible DC interconnects and multi-port power routers provide cooperative control, power support, and peak shaving/valley filling between sub-microgrids. A control module that operates autonomously enables islanded operation with voltage stability during disturbances. Since its commissioning, the green electricity ratio in the park has been more than 60% and the reliability of supply has been at 99.99% thus ensuring seamless switching capability between grid-connected and islanded modes during severe weather. This proves that multi-port power routers DC-coupled PV-storage systems may provide smooth mode transition [9].

3.3. A study on the improvement of photovoltaic consumption capacity of distribution networks with grid-forming energy storage systems

Under high PV penetration in weak grids, the traditional grid-following control uses phase-locked loop (PLL) to follow the grid phase. Weak power grids have low PLL tracking accuracy and are susceptible to instability. But with the help of virtual synchronous generator (VSG) algorithm the energy storage converter is able to actively provide voltage and frequency references, introduce inertia support to the grid and transform the role of passive grid-following to active grid-forming [10]. Grid-forming energy storage configuration is an effective way to increase PV hosting capacity and reduce voltage deviation. In addition, grid-forming control can enhance fault support capability to some extent, partially compensating for the limited fault current contribution of power-electronic-interfaced BESSs [11].

3.4. Two-stage photovoltaic-storage collaborative optimization operation strategy

To resolve the voltage violations resulting from high PV penetration, a two-stage optimization strategy of PV-storage coordination is suggested. In stage I the candidates are chosen based on the storage locations and capacities using the node voltage sensitivity analysis. In stage II, the economic dispatch model is formed that minimizes the overall operation expenses, such as scheduling, interaction and network loss costs [3]. The SOCP algorithm replaces non-convex power flow constraints with second-order cones, increasing the computational efficiency and also guaranteeing the solution accuracy [12]. Incorporating the two-stage model with the SOCP relaxation makes the methodology balance between engineering rationality in siting and sizing with mathematical rigour in power flow optimization, thus showcasing the feasibility of the technical pathway of the optimization scheduling and convex relaxation.

3.5. Comprehensive comparison and analysis of the four cases

Table 3 compares the four representative cases from four perspectives: system structure, control architecture, optimization approach, and application focus. In terms of structure: Quzhou uses AC coupling (retrofit) and Tai'An DC coupling (new project). In terms of control architecture moves towards centralized EMS to grid-forming control architecture where VSG will provide an active voltage frequency support. In terms of optimization: the approach changes over a period of time between empirical scheduling and optimization/convex optimization and two-stage optimization transforms the constraints of the engineering into mathematical problems that can be solved. In terms of application: engineering focuses on economy and reliability, whereas academic solutions focus on technical limits. The four cases supplement each other. PV-storage technology is shifting to optimized, but systemization and intelligence are yet to improve.

Table 3. Summary and comparison of four typical cases/schemes

Case	Core technology	Innovation highlights	Main outcomes	Type
Quzhou, Zhejiang	Smart PV-storage integrated EMS platform	Global collaborative optimization dispatching	Self-consumption rate >85%; annual savings of CNY 1.8 million	Demonstration project
Tai'an, Shandong	Flexible DC + energy router	Multi-scenario flexible interconnection + island switching	Green electricity share >60%; reliability 99.99%	Demonstration project
Grid-forming BESS	Grid-Forming control	Active voltage/frequency support establishment	Improved PV hosting, mitigated voltage deviation, short-circuit current support	Academic research
Two-stage optimization	SOCP relaxation + SOC balancing	Balancing economics with equipment health	Resolved voltage violation, reduced network loss	Academic research

4. Analysis of advantages and risks

4.1. Advantages of PV-storage grid integration

Distributed PV-BESS integration can provide multiple technical and operational benefits to distribution networks when the system is properly configured and coordinated. These benefits are mainly reflected in power quality improvement, output smoothing, renewable hosting enhancement, and ancillary service support. The following subsections discuss the main advantages from the perspectives of electrical performance and system support capability.

4.1.1. Improving voltage quality and power smoothness

PV integration with high-penetration can lead to voltage violations and great variations in power. Millisecond response energy storage smoothes the output fluctuations and with coordinated volt-VAR control, it maintains the deviation within ±7% [10, 13]. Structurally, the AC coupling is compatible with distribution network retrofit, whereas the DC coupling is more efficient in new projects of large capacity. The grid-following type has lower costs and higher maturity, whereas the grid-forming type actively supplies voltage/frequency reference and inertia support to the weak grids [10].

4.1.2. Enhancing the capacity for absorbing and supporting multiple forms of renewable energy

The storage of energy can have an effect of increasing the PV hosting capacity by 30%-40% based on the transfer of energy both in space and time [10, 14]. The PV-storage systems also offer secondary benefits such as primary frequency regulation, reactive power compensation, and backup capacity [13, 14]. LFP batteries are appropriate for peak shaving and valley filling with high-frequency charge/discharge, whereas grid-forming storage is better at voltage and frequency support in weak grids.

4.2. Risks of PV-storage grid integration

PV-storage integration also poses a number of risks to distribution networks. These risks primarily concern structural, control, operational, and economic aspects. Each category presents different challenges that require careful assessment during system planning and operation. A comprehensive understanding of these risks is essential for safe and reliable grid integration. The following subsections discuss the most important risks from the four perspectives above.

4.2.1. Structural risk

PV-storage integration changes the unidirectional power flow nature of distribution networks. At high penetration, AC coupling may lead to bidirectional power flow, which impacts direction discrimination of overcurrent and distance protection [10]. Fault isolation is made complicated by the addition of DC coupling with a shared DC bus. Also, the inverter fault current is only 1.2-1.5 times the rated value which is significantly less than that of synchronous generators decreasing sensitivity of protection [9, 10].

4.2.2. Control risk

The grid-following control is based on PLL synchronization which may be unstable in weak grids [10]. The grid-forming control actively maintains both voltage and frequency but it has the risk of uneven power distribution and synchronization instability when operating in parallel. Multiple parallel inverters can generate harmonic superposition that can drive Total Harmonic Distortion (THD) beyond thresholds causing oscillations [13]. Incorrect management of SOC can lead to overcharging and over-discharging with consequences on the lifespan of the battery and the reliability of its schedule.

4.2.3. Operational risk

The prediction errors of PV and storage power output can be a cause of mismatches in dispatch plans. The midday charging, evening discharging arbitrage model has the ability to induce significant voltage fluctuations in the feeders [3]. Further, the distributed PV and storage systems do not have uniform online surveillance and O&M policies, which leads to uneven degrees of operation management.

4.2.4. Economic risk

The initial investment is quite significant. Depending on battery chemistry and operating conditions, major capacity degradation may occur over an 8- to 10-year period, which can significantly affect lifecycle costs [5], and therefore depreciation charges over the whole lifecycle are not negligible. The existing revenue depends on the time-of-use price arbitrage and subsidies, however, the change in policies puts investment gains into question.

4.3. Section summary

The section is a systematic analysis of PV-storage integration in terms of its advantages and risks. Benefits are enhanced voltage quality, 30%-40% growth in PV hosting capability, and ancillary services but performance is limited by the form of coupling and means of control. There are four risks namely structural (bidirectional power flow, lower protection sensitivity), control (PLL instability, harmonic superposition), operation (prediction errors, no O&M standards), and economic (high initial investment, non-guaranteed returns). Benefits and risks are two faces of the same technical path in varying conditions.

5. Grid connection risk optimization technology and countermeasures

5.1. Technical optimization measures

Control strategies include MPC, receding-horizon optimization, and reinforcement learning to achieve multi-time-scale coordination [6, 13]. Grid-forming storage can actively provide support in voltage/frequency of weak grids as an architecture of grid connection [10, 11]. The combination of Active Power Filter (APF) /Static Var Generator (SVG) and storage converters can be used to suppress harmonics and create a multi-level mitigation system, which is based on power quality [13]. Directional pilot protection, adaptive current protection, and Wide Area Measurement System (WAMS) are the solutions to address the weaknesses of the traditional protection in relay protection.

5.2. Countermeasures at the planning and operation management levels

The planning step should include such factors as the level of the distribution network voltage, source-load spatiotemporal matching and line power flow constraints with the optimum location and capacity of storage being determined by multi-objective optimization. During its operations, cluster control strategies and Virtual Power Plant (VPP) systems have the ability to centrally administer PV-storage units, eliminating the problem of disorderly operations [15]. On a regulatory front, voltage violations or equipment failure can be detected quickly with the Supervisory Control And Data Acquisition (SCADA) and online monitoring equipment with big data analysis.

5.3. Policy and market mechanism suggestions

The technical requirements of distributed PV-storage grid connection should be defined, and the power quality requirements should vary depending on the level of penetration. The capacity pricing mechanisms must be investigated as a way of ensuring steady income sources of PV-storage systems [14]. Ancillary service markets need to be created to widen PV-storage participation approaches and simplify administrative approval processes to reduce the cost of institutions on advancing projects.

5.4. Section summary

The present part is aimed at presenting the optimization countermeasures in PV-storage grid integration as a risk in terms of technology, management, and policy. It is these measures that cover structural/control, operational, and economic risks as outlined in Section 4. All three dimensions should be integrated in synergy to convert risk control into effective operation. Only through such coordinated efforts can distributed PV-BESS systems achieve both safety and economy in practical development.

6. Conclusion

The article analyzes the advantages and risks of coordinated grid connection of PV-storage systems. Photovoltaic energy storage systems could reduce power fluctuation, enhance the voltage quality, increase PV hosting capacity by approximately 30%-40%, and offer other ancillary services like frequency regulation and reactive power compensation. The Quzhou project and the Tai an project both demonstrated the technical viability and economic advantages of AC and DC coupling architectures respectively. Nevertheless, there are risks, including the reverse power flow, protection coordination difficulties, harmonic pollution, and grid-following instability in weak networks as well as economic uncertainty that grow with scale and should be addressed systematically via coupling structure, control architecture, and operational management. Overall, the net value of distributed PV-BESS integration depends not only on equipment deployment, but also on the coordinated design of coupling topology, control architecture, protection adaptation, and market mechanisms.

The future of grid-forming BESS, virtual power plants, and AI-based scheduling will make it possible to transform photovoltaic energy storage systems into active grid support resources rather than passive ones in the power generation process. This study provides a systematic framework for understanding the benefits and risks of distributed PV-BESS integration. These findings are expected to guide engineers, researchers, and policymakers working to build more reliable, efficient, and sustainable energy systems. As renewable energy becomes more widespread, the coordinated integration of PV-storage systems will play an increasingly important role in ensuring grid stability and maximizing the use of clean energy. Future research should focus on advanced control strategies, cost reduction pathways, and policy innovations to further accelerate the transition to a low-carbon energy future.

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