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Application of Energy Storage Technologies in Power Grid Frequency Regulation and Peak Shaving

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Abstract. Wind and photovoltaic power have made grid operation less predictable. The problem is not only that renewable output fluctuates; it is that these fluctuations now appear at a scale large enough to affect peak regulation, reserve scheduling, and frequency control. This review looks at energy storage from that practical angle. It asks where storage is genuinely helpful, where its role is often overstated, and what must be considered before a project is sized. Pumped hydro, compressed air, flywheels, lithium-ion batteries, flow batteries, supercapacitors, thermal storage, and hydrogen are compared according to response speed, storage duration, siting limits, safety requirements, and cost behavior. For peak shaving, storage shifts energy from low-value or curtailed periods to stressed hours, but the benefit depends on the local net-load shape and tariff rules. For frequency regulation, fast converter-based response is valuable in low-inertia systems, yet batteries must still manage state of charge and aging. A point that deserves more attention is the conflict between services: a battery kept ready for evening discharge cannot always sell the same capacity into regulation markets. The paper therefore argues for service-specific sizing, hybrid storage where time scales differ, and economic models that include degradation, auxiliary equipment, safety systems, and market saturation. Storage is becoming a necessary flexibility resource, but it is not a simple cure for every renewable-integration problem. The main conclusion is deliberately cautious: storage should be planned as part of a portfolio of flexibility resources, not treated as a stand-alone answer to variability.

Keywords: energy storage, frequency regulation, peak shaving, renewable energy integration

1. Introduction

Wind and photovoltaic generation have grown from supplementary resources into daily operating variables. That change is uncomfortable for grid operators. Solar output may be high at noon and fall quickly before the evening peak. Wind can move in the opposite direction, or simply miss the forecast. When these errors are small, conventional units absorb them. When they accumulate across a region, the gap between scheduled generation and real-time load becomes much harder to cover [1]. The older operating model, built around dispatchable synchronous machines, still matters; it just has less slack than before.

Storage is attractive because it works on the time mismatch directly. It can charge when the system has too much energy and discharge when the system is short. That sounds simple, but the

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value comes from speed and controllability. A battery station or flywheel does not wait for a fuel ramp. Pumped hydro and compressed air move more slowly, but they can carry much more energy. In this sense, storage is not one technology. It is a family of tools for moving electricity across seconds, minutes, hours, or sometimes seasons.

Policy has made this family of tools more visible. China's new power system agenda treats storage as part of renewable integration, and many renewable projects now face storage-allocation requirements. Markets in the United States, Europe, and Australia have also opened products for fast frequency response, regulation mileage, and reserve. Still, one should be careful with the word 'storage'. A two-hour lithium-ion battery, a pumped-hydro plant, and a flow-battery project do not solve the same problem. The wrong match between duration, location, and payment rule can turn a technically sound project into a weak investment.

This paper follows that concern. It first reviews the main storage technologies and their present maturity. It then separates two common applications, peak shaving and frequency regulation, because their time scales and revenue logic are different. The final technical section discusses sizing, hybrid configurations, degradation, and safety. The central question is deliberately modest: under which conditions does storage provide useful flexibility without hiding costs elsewhere in the system?

2. Classification and current status of energy storage technologies

Storage is often classified by the way energy is held. The classification is useful, but it can also hide important details. Mechanical options include pumped hydro storage (PHS), compressed air energy storage (CAES), and flywheel energy storage (FES). They store height, pressure, or rotation. Electrochemical systems include lithium-ion, sodium-ion, lead-acid, and redox flow batteries. Supercapacitors and superconducting magnetic energy storage (SMES) sit closer to the power-quality end of the spectrum [2]. Thermal storage and hydrogen extend the list into heat and chemical carriers. The practical differences are large: response speed, round-trip efficiency, usable duration, land requirement, cycle life, and levelized cost do not move together [3].

PHS is still the most mature option for large energy shifting. Its long service life and gigawatt-hour scale are difficult for batteries to match. The limitation is familiar: reservoirs need suitable geography, environmental approval, and long construction periods. Many of the best sites in industrialized regions have already been used. Closed-loop and underground concepts may ease this constraint, but they are not yet a quick substitute for conventional pumped hydro.

Lithium-ion batteries sit at the other end of the deployment story. Manufacturing scale from electric vehicles and consumer electronics has made them the default choice for many short-duration grid projects. They are efficient and fast. They are also sensitive to heat, high-rate cycling, and cumulative throughput. LFP chemistry has reduced some fire and supply-chain concerns compared with NMC, which helps explain its strong use in Chinese utility projects. Even then, the battery container is only part of the asset. Cooling, monitoring, fire suppression, augmentation, and eventual recycling all shape the real cost.

Flow batteries are interesting because power and energy can be sized more separately: the stack determines power, while the electrolyte tank determines duration. That makes them attractive once the target duration moves beyond several hours. The drawback is still cost and system complexity. Lead-acid batteries survive in smaller or niche photovoltaic systems where low upfront cost matters more than deep cycling. Sodium-ion batteries have drawn attention because sodium is abundant and less exposed to lithium supply pressure, although large-scale grid economics are still being proven.

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Flywheels and supercapacitors are good at very short bursts. They can absorb or release power quickly, but they do not carry enough energy for long peak-shaving periods [4]. SMES has similar speed advantages but remains limited by cryogenic cost. Hydrogen is almost the opposite: it can store large amounts of energy for long periods, yet the full electricity-hydrogen-electricity chain is inefficient. For now, it is better viewed as a seasonal or long-duration option than as a daily regulation resource.

The overall pattern is clear enough. Storage is moving from backup use toward stacked grid services. But stacking is not magic. A project that earns arbitrage revenue in the evening may not have the same capacity free for regulation earlier in the day. A project that cycles heavily for frequency response may lose capacity faster than expected [5]. This is why technology comparison should not stop at efficiency or capital cost. The dispatch task and the local market rule matter just as much. I would also separate maturity from popularity. Lithium-ion systems are popular because their supply chain is ready and their response is fast, not because they are always the cheapest long-duration option. Pumped hydro is mature, but it cannot be copied into every province or every market. Flow batteries and compressed air look more attractive when the required duration grows, yet they need stronger project-level evidence before investors treat them as routine choices. This uneven maturity is exactly why planners should begin with the grid problem and only then choose the storage medium.

3. Application of energy storage in power grid frequency regulation and peak shaving

3.1. Application of energy storage in peak shaving

Peak shaving can be described without starting from the storage device. Look at the net-load curve. When renewable output is high and demand is low, the system may have surplus energy. Later, usually in the evening, demand rises while solar output falls. Storage tries to move part of the midday surplus into that later interval [6]. If it works, thermal units ramp less deeply, renewable curtailment falls, and grid upgrades can sometimes be delayed. The result is not automatic. It depends on how long the peak lasts and whether the storage duration matches it. A two-hour battery can be useful when the evening peak is sharp. It is much less convincing when the stress lasts across a cold evening or a cloudy week. This is a common source of over-optimistic project assessment: the model captures the highest-price hour but misses the hours around it.

On the generation side, storage is usually placed near wind or solar plants. The aim is not to make renewable output perfectly flat. That would be unrealistic and often too expensive. A more reasonable target is to reduce short-term deviations, improve dispatch compliance, and capture energy that would otherwise be curtailed [7]. In western Chinese renewable bases, for example, storage paired with wind farms has been used to ease curtailment during congestion periods. The reported benefit varies because the bottleneck is local: a strong battery cannot fix every transmission constraint. If the line is congested for many hours, a small battery fills quickly and then faces the same curtailment problem as the renewable plant. If congestion is brief, the same battery may perform well. This simple difference is sometimes lost when storage ratios are discussed only as a percentage of installed renewable capacity.

Grid-side storage is more like a shared system resource. It may follow area-control-error signals, reduce congestion on a key corridor, support emergency supply, or help with black start. Some of these functions are paid through markets; others are valuable but harder to price. Customer-side storage has a simpler motive. A factory or commercial building charges when the tariff is low and discharges during the expensive window. If demand charges apply, the system may also cut the

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monthly peak based on the highest 15-minute draw [8]. The catch is that the customer must cycle the battery enough to save money but not so aggressively that degradation erases the saving. In practice, the operator often has to choose between a conservative strategy that protects the battery and an aggressive strategy that chases every price spread. The best answer depends on warranty terms, tariff stability, and the customer's tolerance for operational complexity.

3.2. Application of energy storage in frequency regulation

Frequency regulation is a faster and less forgiving service. Frequency changes whenever active power is out of balance. A unit trips. A load jumps. A forecast error arrives at the wrong moment. In the old system, the kinetic energy of synchronous machines slowed the rate of change, and governors responded before AGC restored the setpoint [9]. With more inverter-based generation, this natural cushion becomes thinner. The grid then needs resources that can respond before a slow thermal ramp has time to matter. This does not mean conventional plants become useless. They still provide energy, reserve, voltage support, and fault-current behavior that batteries do not fully replace. The better question is how much fast response is needed before slower resources can take over.

Batteries, flywheels, and supercapacitors fit this need because converter control is fast [10]. In primary regulation, the device measures local frequency and changes active power according to a droop setting. No central instruction is needed for that first movement. The delay is mainly in measurement, filtering, and control [11]. Tests in low-inertia systems have shown battery response in hundreds of milliseconds, while gas turbines are normally discussed in seconds. That gap explains why storage is often treated as a frequency tool, not only as an energy-shifting tool.

Secondary regulation works differently. The operator sends an AGC signal, and the storage unit tracks it. Batteries can follow sign-changing signals with high accuracy, so they have performed well in pay-for-performance markets such as PJM. High regulation scores are attractive, but there is a trap in the story. If too many batteries chase the same product, the price can fall. Good technical performance does not guarantee a durable business model.

SOC management is the awkward part. Regulation signals are not always energy-neutral. A battery may drift upward or downward until it reaches a protective limit. Then the operator has a choice: reduce the regulation offer, force a recovery cycle, or accept higher risk of saturation during the next event. None of these choices is free. Recovery reduces revenue; saturation reduces reliability; extra cycling speeds aging. In practice, the dispatch rule has to balance all three. Market rules also matter: response duration, dead-band, telemetry, and settlement formulas can change the result. A small detail, such as whether the market pays for capacity, mileage, or accuracy, can change how the same battery is operated. This is why frequency regulation should be studied as an engineering and market problem at the same time.

Grid-forming inverters make the discussion more interesting. A grid-following inverter listens to an existing voltage waveform. A grid-forming inverter can help establish voltage magnitude and phase. When storage is attached behind it, the plant may provide fast power and synthetic inertia in weak grids. This is promising, but it is not a solved problem. Protection settings, fault current, controller interaction, and stability under disturbances still need careful engineering. The technology expands what storage can do, but it also raises the standard for modeling.

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4. Optimal configuration of energy storage systems

Sizing storage is less about choosing a large number than choosing the right constraint. The planner decides rated power, usable energy, connection point, SOC limits, and dispatch rules. A peak-shaving project may be judged by curtailment reduction or tariff savings. A regulation project may be judged by mileage revenue after degradation and auxiliary losses [10]. Network limits, voltage constraints, and feeder capacity can rule out an otherwise attractive site. Because renewable output and load are uncertain, robust or scenario-based models are more credible than a single perfect daily curve [12]. A useful planning model should include ordinary days, stressed days, and near-failure cases. Otherwise, the selected size may work well in an average simulation but fail during the few hours that actually justify the investment.

Under-sizing and over-sizing fail in different ways. Too little storage leaves the peak almost unchanged. Too much storage creates a large asset that waits for rare events and earns a poor return [13]. The right duration depends on the local curve. A sharp evening spike may need only two hours. A broad winter peak, or a congestion event lasting half a day, needs something else. For frequency regulation, the question shifts again. Ramp speed and tracking accuracy may matter more than stored energy. This is why using the same four-hour template everywhere is risky. It may satisfy a procurement rule, but it does not prove that the asset is well matched to the local grid.

Multi-service operation sounds efficient, but it creates conflict. Capacity promised for evening peak shaving is not fully available for regulation at noon. Capacity held for regulation may leave the battery short when the peak arrives. A dispatch model has to price that opportunity cost. MILP methods remain common because the constraints are explicit and auditable. Reinforcement-learning controllers are being studied for changing prices and signals, but they bring a new concern: operators must understand why a controller made a risky choice before they trust it in the control room. For a planning study, this means the optimization result should not be presented as a black box. The assumed price path, degradation cost, SOC reserve, and penalty for missed service should be visible to the reviewer.

Hybrid storage is a practical answer to mismatched time scales. Lithium-ion batteries can handle hourly shifting. Supercapacitors or flywheels can take fast pulses that would otherwise age the battery. For longer discharge, flow batteries, iron-air systems, or compressed-air storage may be cheaper per stored kilowatt-hour, though they bring lower efficiency or stronger site limits [14]. The design question is not simply which pair to buy. It is how to divide current, how to reserve capacity, and how to switch roles when the grid event lasts longer than expected. A poor controller can make a hybrid system behave like two disconnected assets. A good one lets the high-power device handle sharp transients while the high-energy device follows the slower trend.

The economics should include costs that are easy to ignore. Battery replacement may be needed once usable capacity falls below 70-80 percent of nameplate. Cooling, fire suppression, inverter replacement, monitoring, insurance, land, and end-of-life treatment all add cost [15]. A spreadsheet that counts only cell price will usually look better than the real project. This gap explains why some procurement processes now ask for life-cycle cost assumptions rather than a single installed-cost number.

Safety deserves the same treatment. Thermal-runaway events in lithium-ion installations have shown that failures can involve more than one bad cell. Ventilation, monitoring, spacing, propagation barriers, emergency response access, and fire-suppression design all matter. Standards such as NFPA 855 reduce risk, but they also add land and capital requirements. From a planning viewpoint, these are not optional extras. They are part of the feasible solution. The social cost of a

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serious battery incident is also larger than the direct equipment loss. It can delay permitting, raise insurance costs, and reduce public acceptance of later projects. A realistic optimization model should therefore treat safety investment as a condition for deployment, not as a cosmetic addition after sizing is finished.

5. Conclusion

Energy storage is now a central part of the flexibility discussion, but the conclusion is not that every grid problem should be handed to batteries. For peak shaving, storage is useful when the surplus period and the peak period are separated by a manageable number of hours. For frequency regulation, storage is useful because converter response is fast and accurate. These are different services. Treating them as the same problem leads to poor sizing and weak economics. The paper also suggests a more cautious way to read current deployment enthusiasm. Fast growth in installed capacity proves that storage is needed, but it does not prove that every project has been optimally designed. Some projects will earn stable revenue; others may depend on temporary subsidies, wide tariff spreads, or early-market scarcity.

Several lessons stand out from the review. Storage projects need revenue models that survive market saturation, not just a first-year arbitrage calculation. Dispatch should treat SOC and degradation as operating variables. Safety and auxiliary systems must be counted before the project is called economical. Long-duration storage and grid-forming control also deserve more work, especially for weak or renewable-heavy networks. In short, storage can become a foundation of the clean-energy grid, but only when technology choice, control strategy, market design, and safety engineering are planned together. The less glamorous details will decide the outcome. For future research, the most useful work may not be another broad list of storage types. It may be careful case studies that show how one storage plant performs under real tariffs, real degradation, real grid constraints, and real maintenance costs. That kind of evidence is harder to produce, but it is exactly what planners need.

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