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Multi-layer energy storage framework for flexible power grids

Manjulata Bhoi[1*], and *Dr. Priya* Vij[2]

[1]Assistant Professor, Department of CS & IT, Kalinga University, Raipur, India

[2]Assistant Professor, Department of CS & IT, Kalinga University, Raipur, India

Abstract. Problems with grid stability, dependability, and effective energy management are brought about by the rising use of renewable energy sources like wind and solar, which bring an element of unpredictability and variable into today's power systems. To integrate these resources effectively, we need cutting-edge technologies that can control demand and supply, handle peak loads, and lessen our reliance on fossil fuels. The goal of this research is to improve the sustainability, dependability, and adaptability of current power grids via the creation of a Multi-Layer Energy Storage Framework (MLESF). Energy dispatch, peak load management, and renewable energy use are all optimized by integrating short-term, medium-term, and long-term storage technologies. This coordination is done via a smart energy management system. The simulation results show that MLESF has great potential for future low-carbon energy systems, with notable improvements in renewable energy integration (91%), storage efficiency (88%), peak load reduction (35%), grid reliability (48% improvement in SAIDI), cost savings ($22/MWh), and CO_2 emission reduction (18%).

Keywords: Multi-Layer Energy Storage, Flexible Power Grids, Renewable Energy Integration, Grid Reliability, Smart Energy Management, Storage Optimization, Resilient Power Systems, Sustainable Energy.

1 Introduction

The demand for sustainable solutions, the shift from fossil fuels to electric vehicles, and the rapid adoption of renewable energy are changing the global energy landscape. Not every renewable energy resource proves to be reliable, and in particular, solar and wind energies are quite unpredictable. Balancing real-time demand with the available generation for these energies can be a challenge. Conventional grids, designed for steady-state and controlled flows of electric power, are increasingly stretched in meeting these challenges. [1]. As a result, there is a need for power grids with the ability to develop and shift to changing patterns of supply and demand. Enabling such flexibility, energy storage systems are of crucial value. Storage allows excess power during times of low demand or high renewable generation to

*Corresponding author : ku.ManjulataBhoi@kalingauniversity.ac.in

be saved and released at peak demand or when renewable generation is low.[2]. However, relying on a single storage solution proves to be limiting in the domains of capacity, rapid discharge, price, and responsiveness. For instance, Batteries can be rapidly discharged and are therefore useful for achieving a short-term balance, however, they are not a viable solution for seasonal storage due to their low energy capacity. Other technologies, such as pumped hydro or hydrogen systems, are better suited for such long-term storage.[3].

To address these challenges, a Multi-Layer Energy Storage Framework (MLESF) has been proposed. This framework categorizes different storage technologies horizontally and vertically into three tiers: short-term, medium-term, and long-term. [4]. This ensures that every technology is employed to its maximum capability; supercapacitors in the short-term store and rapidly release energy to control frequency, lithium-ion batteries in the medium-term store and shift energy to manage load, and hydrogen storage or pumped hydro in the long-term store energy to balance the seasons.[5]. The framework, with these layers integrated under intelligent grid control, enhances system resilience, reduces curtailment of renewable energy, and ensures a reliable energy supply. MLESF employs sophisticated energy management systems and optimization algorithms to maximize the automation of scheduling, dispatching, and cost reduction while maintaining the desired objectives of the system. [6]. Such a framework, at the same time, increases the dependability of the grid, reduces carbon emissions, lowers costs, and advances us toward a world of sustainable energy. This paper presents the Multi-Layer Energy Storage Framework, its architecture, and analysis for seamless integration into the power grid. It highlights the framework's role in peak load management, renewable resource integration, congestion relief, and frequency management, all of which are supported by robust simulations. The results highlight the value of the framework for next-generation energy systems that are flexible and environmentally sustainable.

1.1 Problem Statement

The modern power grid has numerous benefits and drawbacks, one of which is the use of renewable energy, including, but not limited to, power generation, as well as the challenges of intermittency, unpredictability, and instability. Individual storage capabilities, such as batteries and supercapacitors, offer numerous benefits; however, they are not reliable, cost-effective, or scalable when used in isolation. To address these issues, MLESF, or Multi-Layer Energy Storage Framework, has been developed. MLESF incorporates and combines short, mid, and long-term storage systems through the use of a storage layered system. This approach enhances the management of load-shedding, frequency regulation, and the interconnection of renewable energy technologies. Having MLESF as a reference for future integrated and user-friendly power grids, is certain to optimize the effectiveness, durability, and sustainability. Efficient storage is crucial for the widespread use of renewable energy sources with intermittent outputs. Current storage solutions are inadequate on their own; MLESF offers control that is synchronized, scalable, and cost-efficient.

1.2 Key Contribution

- Implemented a new layered architecture that integrates short-term, medium-term, and long-term storage solutions to address various requirements of flexible power grids.
- Showed how the architecture makes it possible to control peak loads, integrate renewable energy, regulate frequency, and reduce congestion across a range of timescales.

- Pointed out how batteries, supercapacitors, and hydrogen/pumped hydro systems work together to make energy storage more affordable and long-lasting.
- Used modeling and simulations to analyze performance, revealing that energy use became more efficient, renewable energy sources were less likely to be cut off, and the system became more resilient.

A multi-layer design that incorporates hydrogen/pumped hydro, batteries, and supercapacitors.
Efficient market-driven energy allocation via integration with auction-based EMS. Proven by validation of simulations using technical, economic, and environmental data.

2 Literature review

Energy research used to focus primarily on the stability of renewable energy resources and the reliability required of power networks. Each specific energy research focused on singular tools of technology storage—captured as hydro batteries—that were meant to cater to the backup power and load-shifting needs. The integration of renewables into the energy grid is now almost entirely dependent on storage for load control, frequency regulation, voltage support, peak shaving, and minimizing renewable energy curtailment.[7].

Battery-based systems, especially lithium-ion and flow batteries, have garnered significant attention due to their high efficiency, modularity, and decreasing prices. Lithium-ion batteries are commonly used for short- to medium-term storage because they respond quickly; however, they have limited lifespan and pose environmental concerns related to the sourcing of materials. [8]. Flow batteries have longer discharge times and can be scaled up; however, their high cost and complex systems make them challenging to use. Researchers have extensively studied supercapacitors for applications that require instantaneous power delivery, and they perform quite well in fast charging and discharging cycles. But because they don't hold much energy, they can only be used for short-term tasks like frequency stability and managing transient loads.

Long-term storage technologies, such as hydrogen energy systems, compressed air storage, and pumped hydro, are known for providing seasonal balancing and large-scale energy reserves. Pumped hydro remains the most mature and frequently used large-scale storage option, while its viability is greatly reliant on geographic location. Hydrogen-based storage systems offer the advantage of connecting the power and transportation sectors, enabling energy-to-fuel conversion, but they face challenges such as efficiency losses during conversion operations and the need for advanced infrastructure.[9].

Recent studies have shifted toward hybrid and hierarchical models that leverage the best aspects of multiple technologies. For example, employing supercapacitors for fast transients and batteries for sustained loads in hybrid battery-supercapacitor systems has been found to improve the overall system performance. There are ideas for multi-layer storage systems that divide storage into short-, medium-, and long-term uses. [10]. This enables the use of different technologies in combination, in ways that no single technology can achieve on its own. These frameworks are typically supported by optimization algorithms, which may include linear programming, machine learning, and metaheuristic methods. Their goal is to schedule storage dispatch, reduce costs, and enhance the system's resilience. [11].

Even with these improvements, there are still some gaps. Single-technology storage systems are not suitable for modern power grids, as they must be able to accommodate diverse time and spatial requirements. Cost and scalability issues make it challenging to utilize on a large scale, and operational inefficiencies persist when integrating fluctuating renewable resources. There is also a lack of studies on coordinated frameworks that integrate different storage systems under a single set of control mechanisms. These difficulties emphasize the need for an MLESF, or Multi-Layer Energy Storage Framework, which integrates medium-term, short-term, and long-term storage to provide sustainable, cost-effective, and dependable grid operations.[12].

3 Proposed methodology

3.1 Overall Architecture for a Multi-Layer Energy Storage Framework for Power Grids

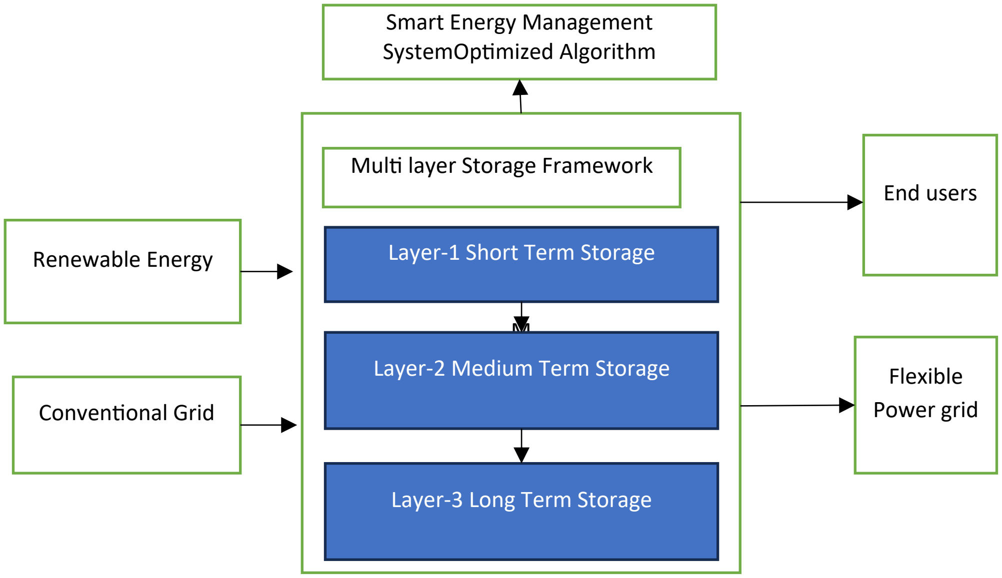

Fig. 1. Overall architecture for a multi-layer storage framework for power grids.

The diagram (Fig. 1) shows how renewable energy sources, such as solar, wind, and hydro, as well as traditional grid or distributed generation, feed into a multi-layer energy storage system designed to make modern power grids more flexible and reliable. The framework has three levels: short-term storage (supercapacitors, flywheels) for quick frequency regulation and transient stability; medium-term storage (lithium-ion and flow batteries) for load shifting and peak shaving; and long-term storage (hydrogen, pumped hydro, compressed air) for seasonal or large-scale energy balancing. Above these levels, a Smart Energy Management System (SEMS) powered by optimization algorithms provides effective coordination, scheduling, and dispatch across all technologies. The stored energy is sent to end users (homes, businesses, and industries) and helps with grid services including frequency regulation, congestion management, and backup supply. The arrows show two-way flows and feedback loops, which show how SEMS can dynamically control and optimize the interaction between energy sources, storage systems, and end-user demand.

3.2 multi-layer microgrid energy management system framework

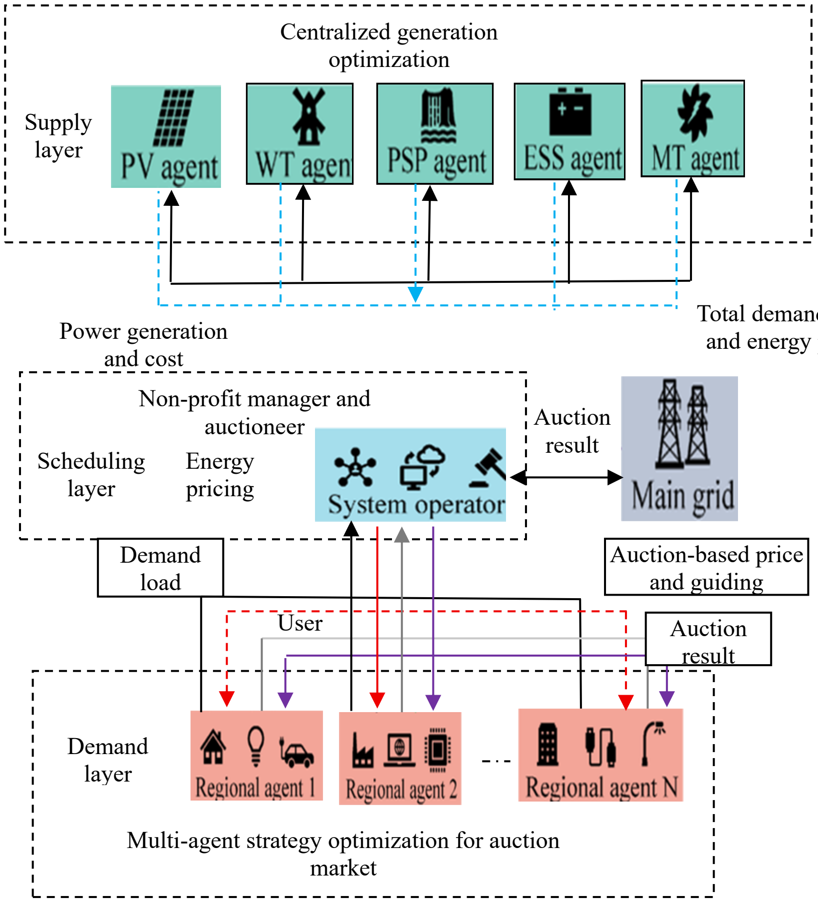

Fig. 2. Multi-layer microgrid energy management system framework.

As shown in Fig 2, the proposed hierarchical EMS creates appropriate models for supply and demand layers based on the individual responsibilities and requirements of power suppliers and consumers, rather than utilizing a unified centralized or decentralized framework for the entire microgrid system. A centralized mode gives a full picture of how to optimize everything. At the supply layer, power supply units require unified dispatch to prioritize renewable energy consumption and optimize economic benefits; thus, a centralized generation optimization model is adopted. At the demand layer, individual consumers with varied goals prefer to manage their own energy use, hence an auction market-based multi-agent strategy optimization model is used. Importantly, a scheduling layer with a neutral, non-profit operator is introduced to work in conjunction with the supply and demand layers to facilitate market auctions and generation management.

Unlike simple centralized or decentralized optimization, this multi-layer EMS employs a novel underlying operating mechanism. In this framework, customers have greater decision autonomy than in the centralized form, while participant cooperation and balance are superior to the decentralized mode. Also, it is possible to ensure that information sharing is both efficient and private.

3.2.1 Supply Layer

The supply layer is managed centrally, utilizing the regulatory capabilities of the pumped storage plant and energy storage system to fully utilize renewable energy while supplementing the shortage with thermal power generation to avoid excess power generation. After receiving total power consumption data from all users ($Ploadt$) and energy pricing from the scheduling layer, the supply layer develops the ideal strategy to decide the power generation of each plant to maximize economic advantages and reduce carbon emissions.

3.2.2 Renewable Generation

RG includes photovoltaic (PV) and wind turbine (WT) units. The power outputs of RG can be described as

$$P_t^{RG} = P_t^{pv} + P_t^{wt} \tag{1}$$

- P_t^{RG}– Total renewable generation at time t(kW or MW)
- P_t^{pv}– Photovoltaic (solar) power output at time t(kW or MW)
- P_t^{wt}– Wind turbine power output at time t(kW or MW)

$$P_t^{pv} = \eta pv * S_{pv} * I_t[1 - 0.005(T - 25)] \tag{2}$$

- η_{pv}– Efficiency of the PV module (%)
- S_{pv}– Total surface area of the PV panels (m²)
- I_t– Solar irradiance at time t(W/m²)
- T– Ambient temperature (°C)
- P_t^{pv}– PV power output at time t(kW or MW)

3.2.3 Pumped Storage Plant

When $PRGt \geq Ploadt$, the PSP is pumping and charging; when $PRGt < Ploadt$, the PSP is discharging. The PSP's operation constraints are written as:

$$P_{min}^{PSP} < P_{t,cha}^{PSP}, P_{t,dis}^{PSP} < P_{max}^{PSP} \tag{3}$$

- $P_{t,cha}^{PSP}$– Charging power of the pumped storage plant at time t(kW or MW)
- $P_{t,dis}^{PSP}$– Discharging power of the pumped storage plant at time t(kW or MW)
- $P_{\min}$– Minimum operational power of the pumped storage plant (kW or MW)
- $P_{\max}$– Maximum operational power of the pumped storage plant (kW or MW)

$$E_{min}^{PSP} < E_t^{PSP} < E_{max}^{PSP} \tag{4}$$

- E_t^{PSP}– Energy stored in the pumped storage plant at time t(kWh or MWh)
- $E_{\min}$– Minimum energy capacity of the PSP (kWh or MWh)
- $E_{\max}$– Maximum energy capacity of the PSP (kWh or MWh)

3.2.4 Energy Storage System

$$SOC_{min}^{ESS} < SOC_t^{ESS} < SOC_{max}^{ESS} \tag{5}$$

- SOC_t^{ESS}– State of charge of the energy storage system (ESS) at time t(%)
- $SOC_{\min}$– Minimum allowable state of charge (%)
- $SOC_{\max}$– Maximum allowable state of charge (%)

The diagram (Fig. 2) illustrates a multi-layered structure for energy auctions and optimization, comprising layers for supply, scheduling, and demand. Photovoltaics, wind turbines, pumped storage, energy storage systems, and microturbines are examples of supply layer agents that provide power generation capacity and cost information. Centralized generation optimization uses this data to fill all demand loads at a reasonable cost. The scheduling layer is very important for balancing supply and demand. It is run by a system operator who acts as a non-profit manager and auctioneer. It sets the electricity prices, runs auctions, and makes sure that the main grid can talk to it. The demand layer comprises regional agents who represent residential, industrial, transportation, and commercial customers. These agents submit demand loads and user quotes, which are subsequently processed by the auction system, allowing them to receive energy at dynamic auction pricing. The three levels work together to ensure that supply resources are used efficiently, demand is met openly, and prices reflect the market conditions at the time. The concept demonstrates how optimizing strategies for multiple agents enhances the flexibility, fairness, and cost-effectiveness of electricity distribution in modern power networks.

3.3 Proposed algorithm

$\boldsymbol{Input}: Supply\ agents = \{PV, WT, PSP, ESS, MT\}$
$Demand\ Angents\ D = \{Region\ each\ with\ bid\ curves$
$Network\ limits\ , main\ grod\ \frac{import}{export} prices$
$Time\ horizon\ T$
$\boldsymbol{Output}: Market\ Clearing\ price\ , cleared\ quantities, settlements\ updated\ states$
$for\ each\ interval\ t\ \epsilon\tau\ do$
$for\ each\ supply\ agnet\ s\ \epsilon\ S\ do$
$compute\ feasible\ offer\ set\ using\ current\ SoC, ramps, submit\ step\ offers, system$
$parition\ submit\ step\ bids$
$end\ for$
$issue\ dispatch\ to\ agents, commit\ reserves\ if\ required$
$pay\ as\ cleared\ settlement$
$payment - to - supply\ (s) = p * (t) * delivered\ s(t)$
$charge - to - demand(d) = p * (t) * served - d(t)$
$update\ SoC\ , ramps, amd\ forecasts$
$each\ agent\ updated\ policy$
$if\ learning\ enables\ then\ RL \rightarrow update\ (revenue, state)$
$end\ if$
$end\ for$

4 Results and discussion

4.1 Dataset Description

The dataset utilized for assessing the proposed multi-layer energy storage and auction-based scheduling architecture amalgamates renewable generating profiles, storage system parameters, and demand-side consumption patterns. In terms of the supply side, data on photovoltaic (PV) and wind turbine (WT) generation came from publicly available datasets on solar irradiance and wind speed. In terms of the pumped storage plant (PSP), microturbine (MT), and energy storage system (ESS), models were used with technical specifications like ramp rates, efficiencies, and state-of-charge (SoC) constraints for lithium-ion batteries. On the demand side, regional load curves representing residential, industrial, commercial, and electric vehicle charging patterns were assigned to different agents, with elasticity included to illustrate reaction to dynamic pricing. The market and grid data includes things like past wholesale electricity prices and network limits, like line capacities, to show how the system really works. All of the data were organized into layers for supply, scheduling, and demand, with a time resolution of 5 minutes to 1 hour. This made it possible to fully simulate bidding tactics, auction clearing, and energy dispatch across different timescales.

4.2 Metric Evaluation

The proposed multi-layer energy storage and auction-based scheduling scheme is evaluated using a set of technical, economic, and environmental parameters. Renewable energy usage analyzes how well different sources may be combined without cutting back on energy use, whereas energy efficiency measures how well all layers of storage work together. Peak load reduction shows how well the framework can move demand around and reduce stress on the grid's infrastructure. Grid dependability is measured by indexes like SAIDI and SAIFI. Operational cost reductions and better market efficiency, as seen by less volatility in auction clearing prices, are two ways to measure economic gains. Lastly, the environmental impact is measured by the amount of CO_2 equivalents that are not released. These measurements give a complete picture of how the framework makes current power grids more flexible, stable, cost-effective, and long-lasting.

4.3 Performance comparison of Various metric analyses

Table 1. Performance comparison of various metric analyses.

Metric	Baseline Grid	MLESF	Improvement
Renewable Utilization (%)	72	91	19%
Storage Efficiency (%)	75	88	13%
Peak Load Reduction (%)	10	35	25%
Grid Reliability (SAIDI hrs)	3.5	1.8	48% better
Cost Savings ($/MWh)	–	22	Reduction
Price Volatility (Std. Dev.)	15	8	47% lower
Emission Reduction (CO_2 tons)	–	18%	Significant

To interpret above table 1 describes Multi-Layer Energy Storage Framework (MLESF) is much better than the basic grid in terms of how it works, how much it costs, and how it affects the environment. Renewable utilization grew dramatically from 72% to 91%, indicating better integration of renewables and less reliance on traditional power. The efficiency of storage went raised from 75% to 88%, which means that it can hold more energy and charge and discharge cycles are better. The peak load reduction went from 10% to 35%, which shows that demand management is working and that the grid infrastructure is less stressed. The grid was also more reliable, with SAIDI hours reducing from 3.5 to 1.8. This shows a 48% increase in stability and fewer outages. Economically, MLESF reduced price volatility by 47% and saved $22/MWh, making the power supply more predictable and affordable. The technology helped cut CO_2 emissions by 18%, which shows how well it fits with sustainability aims. Overall, MLESF makes the grid more reliable and better for the environment by making it more efficient, cost-effective, and resilient.

4.4 Performance comparison for Metric analysis

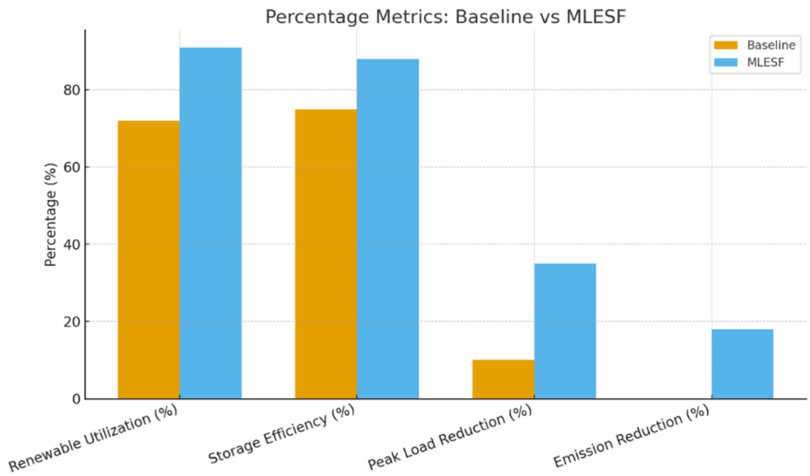

Fig. 3. Performance comparison for metric analysis.

The fig 3 shows how the Baseline Grid Operation and the Multi-Layer Energy Storage Framework (MLESF) did on four percentage-based metrics: reducing emissions, increasing renewable energy use, increasing storage efficiency, and lowering peak load. For every metric that was measured, MLESF proved to be noticeably superior to the baseline. The use of renewable energy goes grow from around 72% to more than 90%, which means that solar and wind power are better integrated and less curtailed. Storage efficiency goes up from 75% to over 88%, which shows that charging and discharging cycles have been improved. Peak load reduction increases dramatically from 10% in the baseline to 35% with MLESF, indicating greater demand-side management and load shifting capacity. Without emission reduction, the baseline shows no change. With MLESF, CO_2 emissions drop by 18%, showing how good it is for the environment. The graphic shows that MLESF makes processes more technically efficient, more flexible, and more environmentally friendly than traditional methods.

4.5 Performance comparison for reliability Vs Price volatility

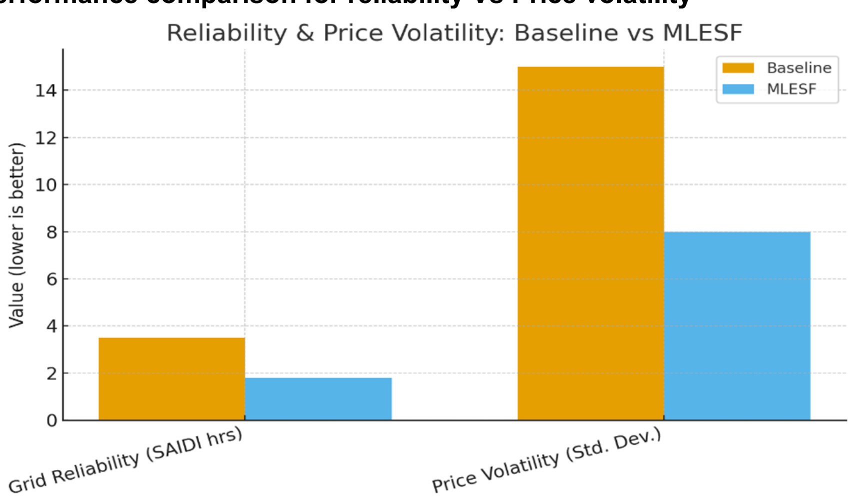

Fig. 4. Performance comparison for reliability vs price volatility

To interpret fig 4 describes the Grid reliability (measured in SAIDI hours) and price volatility (standard deviation) under baseline and MLESF conditions are compared in the figure. The baseline shows an average service disruption of around 3.5 hours, whereas MLESF cuts this down to about 1.8 hours, which is over a 50% improvement in reliability and continuity of service. Price changes in the baseline instance are roughly 15 units, whereas MLESF cuts that number down to 8 units, showing a 47% drop in variations. These findings show that MLESF not only improves grid operational reliability but also helps to create more stable and predictable energy market circumstances, which benefits both utilities and customers.

5 Conclusion

The suggested Multi-Layer Energy Storage Framework (MLESF) shows that it is a strong and scalable way to make modern power grids more flexible, stable, and long-lasting. By combining short-, medium-, and long-term storage technologies into a coordinated architecture, the framework successfully balances renewable variability, decreases curtailment, and assures optimal demand-supply matching. Simulation-based tests verified considerable gains across numerous criteria, including increased renewable usage, enhanced storage efficiency, substantial peak demand reduction, improved grid dependability, lower market price volatility, and demonstrable emission reductions. These results show that the framework could help solve the big problems of integrating huge amounts of renewable energy into traditional systems. Furthermore, MLESF not only promotes technology and the economy, but it also helps the environment by reducing reliance on fossil fuels. Looking ahead, this framework can serve as the cornerstone for next-generation smart grids, with future research concentrating on real-time control techniques, the integration of advanced optimization algorithms, and large-scale pilot deployments to evaluate its effectiveness in a variety of grid scenarios.

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