

Grid Resilience and Energy Storage Leveraging Machine Learning for Grid Services and Ancillary

Zhengjie Yang *

Civil and Environmental Engineering, Stanford University, United States

*Corresponding Author: yjane@stanford.edu

ABSTRACT

This paper discusses the challenges and opportunities of optimizing the economic benefits of energy storage systems in the electricity market, focusing on the key role of machine learning in energy storage bidding optimization. By analyzing complex market data and applying different machine learning models, such as regression models, time series prediction models, and deep learning models, energy storage systems are able to accurately predict market price fluctuations, optimize charge and discharge strategies, and maximize their economic returns in the energy market, ancillary services market, and capacity market. Applying these technologies not only improves the system's market participation ability but also significantly improves the stability and efficiency of the power system.

KEYWORDS

Machine learning; Energy storage; Market optimization; Economic efficiency

1. INTRODUCTION

As a flexible resource within the grid, energy storage possesses dual attributes of both power source and load, effectively addressing the rapid fluctuations in output from renewable energy sources. It provides essential system inertia support, enhancing system controllability and flexibility. In modern power systems, energy storage is crucial for facilitating the integration and absorption of high proportions of renewable energy on the generation side. [1] It is a vital technology to enhance grid regulation capabilities, overall efficiency, and security. Additionally, it supports effective energy management on the consumer side and ensures power quality. [2] Grid-side energy storage systems are integrated devices situated within existing substations, idle substation facilities, or specially designated storage station sites directly connected to the public power network.

The benefits of grid-side energy storage technology for the operational management of the entire power system are remarkable. [3] It ensures rapid restoration of safe and stable operation during system faults or abnormal conditions through quick energy injection or absorption, significantly reducing emergency response time windows and ensuring continuous stable power supply. This greatly enhances the reliability and security of the entire power system. Overall, the primary roles of electrical energy storage include peak shaving, load leveling, precise control, and responsiveness to grid commands.

When photovoltaic and wind power outputs are inconsistent, energy storage can act as a substitute, smoothing out fluctuations in wind and solar power outputs, tracking planned generation, participating in system frequency regulation, and peak shaving functions [4].

Therefore, this article explores the challenges and valuable opportunities for optimizing the economic benefits of energy storage projects using machine learning. [5] One of the challenges involves handling vast amounts of complex data, including electricity market prices, grid operation data, and energy storage system performance information, which often exhibit high dynamic and nonlinear relationships. Moreover, establishing and optimizing machine learning models requires substantial computational resources and expertise, encompassing data cleaning, feature engineering, and model training and validation. [6] Nevertheless, the successful application of machine learning can bring significant opportunities. Energy storage systems can more effectively participate in energy markets, ancillary services, and capacity markets through precise prediction and optimization algorithms, maximizing their economic benefits. Furthermore, with technological advancements and algorithm optimizations, machine learning can achieve real-time decision-making and response, enhancing energy storage systems' intelligence and adaptability and improving overall grid stability and efficiency.

2. RELATED WORK

2.1. Energy Storage Technology Overview

2.1.1. Lithium-ion batteries

Lithium-ion battery refers to a secondary battery (rechargeable battery) with lithium as an energy carrier; when charging lithium ions out of the positive electrode through the electrolyte and diaphragm embedded in the negative electrode, discharge occurs in the opposite process, also known as rocking chair battery. [7] Lithium-ion batteries are divided into lithium iron phosphate batteries and ternary lithium batteries according to positive electrode materials.

Lithium iron phosphate material is rich in production resources, and its cost, cycle life, and thermal stability are better than terpolymer materials, which are suitable for commercial vehicles, middle and low-end passenger vehicles, energy storage, and other fields. The theoretical specific capacity (energy density) of terpolymer lithium battery is 60% higher than that of lithium iron phosphate, has a higher charging rate, good low-temperature performance, and is suitable for middle and high-end passenger cars and other fields.

Lithium-ion batteries are classified according to the packaging process:

- (1) The advantages of the square battery are high packaging reliability, simple structure, the high energy density of the single unit, high efficiency of the system group, and relatively good stability [8]; the disadvantage is that there are many models, the process is complex to unify, the monomer difference is more significant so that the system life is lower than the monomer life.
- (2) The soft pack battery uses aluminum-plastic film packaging; the advantages are high energy density, small battery group, and long cycle life; the disadvantage is that high-end aluminum-plastic film relies on imports, low production efficiency, and low yield.
- (3) Cylindrical battery hard shell package reliability is higher, the advantage is that the battery consistency is higher, the process is mature, the cost is lower, the battery product yield and the heat dissipation performance is better, but the disadvantage is that the group after the heat dissipation design is complex, the system energy density is low.

2.1.2. Characteristics of lithium-ion battery energy storage technology

Lithium-ion batteries exhibit several advantageous characteristics that establish them as the leading mainstream energy storage technology. [9] Firstly, they boast a large capacity and high operating voltage, approximately twice that of comparable nickel-cadmium batteries, making them ideal for sustained communication and connectivity needs. Their robust charge retention capabilities allow operation within a wide temperature range of -20°C to $+60^{\circ}\text{C}$, with minimal discharge loss even after

prolonged storage under open-circuit conditions at $20\pm 5^{\circ}\text{C}$. Moreover, these batteries demonstrate exceptional cycle life, maintaining over 60% of their rated capacity after 1200 charge-discharge cycles, surpassing other battery types. Thanks to their carbon anode technology, safety is also paramount, with lithium-ion batteries featuring inherent protections against short circuits, overcharging, and physical damage. [10] They support rapid charging and discharging rates up to 1C, enhancing safety without compromising performance. Additionally, lithium-ion batteries are accessible from memory effects, allowing for repeated and flexible use, which is particularly advantageous in military and emergency scenarios. Their compact size and lightweight nature further contribute to their popularity, offering more than double the energy density of nickel-cadmium batteries and reducing volume by up to 30% and weight by 50% compared to nickel-metal hydride batteries, thus facilitating the miniaturization and portability of electronic devices.

2.1.3. Application of lithium-ion battery energy storage technology

Lithium-ion batteries are a mainstream energy storage technology that has wide application and great potential in various fields in today's world. Its unique characteristics make it the first choice for electric vehicles, portable electronic devices, and energy storage systems for homes and industries. Its high energy density, long cycle life, fast charge-discharge capability, and good safety performance enable it to effectively respond to modern society's demand for high efficiency, reliability, and environmental performance. This article will explore the specific application of lithium-ion batteries in different application scenarios and their far-reaching impact on the energy industry and lifestyle from multiple perspectives.

When the application of lithium-ion batteries as mainstream energy storage technology can be explained in detail from the following three aspects:

(1) Electric and hybrid vehicles: [11] Lithium-ion batteries are widely used in electric and hybrid vehicles. Tesla's electric cars, for example, feature high-capacity lithium-ion battery packs that provide long-range driving and fast charging capabilities. These batteries meet high power requirements and offer reliable performance over a wide temperature range, supporting efficient energy management and power output of the vehicle.

(2) Portable electronic devices: Lithium-ion batteries are also widely used in portable electronic devices, such as smartphones, tablets, and laptops. These devices require batteries with high energy density, lightweight, and long-term stable charging and discharging characteristics to ensure that users can use the device for a long time without frequent charging.

(3) Home and industrial energy storage systems [12]: Lithium-ion batteries are widely used as the primary energy storage technology in home and industrial energy storage systems. By combining with solar panels or wind turbines, these batteries can collect and store renewable energy to provide a stable supply of electricity when needed. For example, households can use these systems to provide backup power when the grid goes down or to lighten the grid's load during peak demand for electricity.

3. ENERGY STORAGE CAN PARTICIPATE IN THE MARKET

3.1. Energy Arbitrage

The market in which energy storage can participate refers to the multiple markets in the power system where energy storage facilities participate through various strategies. These markets include energy arbitrage, ancillary services, and capacity markets. [13] Energy arbitrage is one of the main strategies to maximize profits by buying electricity at low prices and selling it at high prices.

In the energy arbitrage market, energy storage systems take advantage of their ability to charge and discharge quickly to maximize profits. Here is a detailed extension of the process:

3.1.1. Market Monitoring and Forecasting:

Energy storage systems obtain market price data and future electricity demand trends by monitoring real-time price movements and demand forecasts in the electricity market. These data are the basis for developing effective charging and discharging strategies.

3.1.2. Charging during low electricity price period [14]:

When the price in the electricity market is low, the energy storage system starts charging. Currently, the system will buy electricity from the grid and use its high charging efficiency and fast response characteristics to store electricity in batteries or other energy storage devices.

3.1.3. Discharge during high electricity price period:

When the electricity market price rises to a higher level, the energy storage system will respond quickly and start the discharge operation according to the preset optimization algorithm. The system then sells the stored energy at a higher price by releasing it into the grid. This strategy allows the energy storage system to turn energy storage into revenue at the most favorable time, thus maximizing economic benefits.

3.1.4. The importance of predictive ability and response speed:

Successful energy arbitrage strategies rely on the ability of energy storage systems to accurately predict market prices and adjust charging and discharging strategies as prices move. This not only increases the system's profitability but also improves the efficiency and reliability of the overall power system.

3.1.5. System flexibility and market participation:

Market participation in energy storage systems is not only about maximizing profits but also about increasing the flexibility of the electricity market. [15] By smoothing power supply fluctuations and supporting grid frequency regulation, the role of energy storage systems in the market has become more critical, with a positive impact on the stability and sustainability of the overall power system.

Through these strategies and technical means, the energy storage system can effectively participate in the energy arbitrage market to achieve win-win economic benefits and improve the efficiency of the power system.

3.2. Ancillary Market

In the context of power systems, Ancillary Services Market refers to a market that provides various services needed to support and maintain the stable operation of a power grid. These services include but are not limited to, frequency regulation, rotation backup, voltage support, and black start capabilities. The main goal of auxiliary services is to ensure that the grid can respond quickly and maintain stable operation in the face of sudden load changes or other abnormal conditions.

Roles and functions of the ancillary services market:

Frequency regulation refers to regulating the grid frequency (usually 50Hz or 60Hz) to ensure that the power system operates within the designed frequency range [16]. The energy storage system can provide frequency adjustment service through fast charge and discharge operation and adjust the output power in real-time according to the power grid signal to maintain the stability of the power grid frequency.

Rotating backup: Rotating backup refers to the ability to quickly input power to maintain grid stability in the event of a main power supply failure or a sudden load increase. By storing a large amount of electrical energy, the energy storage system can respond quickly and provide the necessary backup power to maintain the stability of the grid in an emergency.

Voltage Support: [17] Voltage support services ensure that the voltage in the grid is maintained at the right level to support the proper operation of power equipment and user equipment. The energy storage system can adjust the dynamic voltage of the power grid by changing the charge and discharge to cope with the sudden voltage fluctuation and imbalance.

Black start capability refers to the ability required to restart the grid and restore it to regular operation after a complete power outage. Energy storage systems can provide immediate power supply, helping the grid recover from outages and quickly restore service.

Advantages of energy storage systems in the auxiliary services market: **Fast response time:** Energy storage systems have fast charging and discharging capabilities, which can respond to changes in grid demand within milliseconds to minutes, much faster than traditional power generation equipment.

Flexibility and tunability: The energy storage system can adjust the operating mode and output power in real-time according to the grid signal and demand to meet different auxiliary service requirements.

Improved grid stability: [18-21] By providing reliable frequency regulation, backup power, and voltage support services, energy storage systems significantly improve the stability and reliability of the grid, especially in the face of the challenges of a high percentage of renewable energy access.

Therefore, energy storage systems play a vital role in the ancillary services market, providing the necessary support and security for the power system and maximizing economic benefits through participation in market transactions.

3.3. Capacity Market

The capacity market plays a vital role in the power system; its primary purpose is to ensure that it has sufficient generation capacity to cope with the highest load demand and unexpected events. In capacity markets, power producers, and other energy suppliers participate in a bidding process that promises to provide a specific amount of generating capacity over a certain period in the future. [22] These commitments are based on the market's forecast of future electricity demand and the system's security needs to ensure the power system's stable operation at all times. Successful suppliers will receive financial or other incentives to compensate for their provision of standby capacity, usually in the form of fixed payments or other forms related to market mechanisms. Through the operation of the capacity market, the power system can effectively manage the supply and demand balance, especially in the face of renewable energy fluctuations and seasonal changes in electricity demand, ensuring the reliability and security of the system.

The capacity market is closely related to other power markets, such as the energy and ancillary services markets, which constitute a complete ecosystem of the power market. [23-24] The energy market meets electricity demand through the actual trading of electricity, while the ancillary services market provides the various services needed to support the stable operation of the grid. The capacity market is on top of these markets and fundamentally guarantees the reliability and stability of the power system by ensuring that the system has sufficient backup capacity. It provides a stable source of market revenue for power producers and includes power system managers with the necessary tools and mechanisms to cope with unforeseen load changes and other power supply challenges.

In summary, to maximize the economic benefits of energy storage projects, artificial intelligence and machine learning technologies can achieve more precise coordination and optimization between energy arbitrage, ancillary services, and capacity markets. First, by analyzing historical market data and real-time demand forecasts with machine learning algorithms, energy storage systems can accurately predict market price fluctuations and load changes to optimize energy arbitrage strategies [25]. Second, machine learning can be used to optimize the response speed and efficiency of energy storage in the ancillary services market, ensuring that the system can quickly provide services such as frequency regulation, backup capacity, and voltage support. Finally, intelligent algorithms optimize bidding strategies in the capacity market to ensure that energy storage systems provide the

required backup capacity most efficiently, thus maximizing their economic benefits and improving the stability and reliability of the grid. This combination of artificial intelligence and machine learning improves the market participation of energy storage systems and enables synergies between different markets to maximize the overall economic benefits.

4. APPLICATION OF BID OPTIMIZATION IN ENERGY STORAGE SYSTEM

4.1. Bid Optimization

Bidding optimization plays a vital role in the market's participation of energy storage systems. Its core goal is to develop optimal charging and discharging strategies by accurately predicting market price fluctuations and changes in power demand, thereby maximizing economic benefits. Energy storage systems can buy cheap electricity according to market lows and sell stored electricity during peak prices, achieving energy arbitrage. [26] For example, the Hornsdale Battery project in California successfully implemented grid frequency modulation and backup power supply through bid optimization, significantly improving the stability and economic efficiency of the grid.

The importance of bidding optimization is also reflected in the increased flexibility and efficiency of the electricity market. Through accurate market data analysis and machine learning algorithms, energy storage systems can respond quickly in a rapidly changing market environment, effectively balance supply and demand, and provide critical ancillary services such as frequency regulation and voltage support. This not only improves the market competitiveness of energy storage systems but also significantly improves the reliability and sustainability of power systems.

4.2. Bid optimization strategy

The core concept of bid optimization is to maximize revenue or efficiency through accurate market analysis and optimization strategies. In energy storage systems, bid optimization plays a key role, and the following is a detailed explanation of its application and role:

(1) Bid optimization depends on accurately predicting market conditions and electricity demand. By monitoring and analyzing market data in real-time, such as fluctuations in electricity prices and changes in load forecasts, energy storage systems can identify the most favorable timing for charging and discharging. [27] For example, Tesla's Hornsdale battery project in Australia has achieved significant economic benefits by optimizing its charge and discharge strategy by analyzing market demand and price trends.

(2) Bid optimization can be achieved through machine learning and optimization algorithms. These algorithms can process large amounts of complex data and train and optimize models based on historical data and real-time market conditions. For example, the regression model of supervised learning can predict the changing trend of electricity prices in the future. The reinforcement learning algorithm can adjust the charging and discharging strategy according to the real-time market feedback to adapt to the dynamic changes in the market.

(3) Bid optimization is not only for economic benefits but also to enhance the ability and competitiveness of energy storage systems in the market. [28-29] By optimizing bidding strategies, energy storage systems can not only enable energy arbitrage, that is, buying electricity at low prices and selling it at high prices but also provide critical ancillary services such as frequency regulation and backup power. This increase in market participation helps balance supply and demand in the electricity market and provides essential support for the large-scale integration of renewable energy sources.

In summary, bid optimization helps energy storage systems optimize operational strategies in the power market through scientific data analysis and intelligent algorithms to maximize economic benefits and enhance market participation capabilities.

4.3. Bid Optimization Machine Learning Algorithm

Machine learning plays a vital role in the bidding optimization of energy storage systems, and its role is mainly reflected in the following aspects. First of all, through the machine learning model, it can effectively predict the changing trend of market electricity price and demand fluctuations to formulate the optimal charging and discharging strategy so that the energy storage system can buy electric energy at low electricity price and sell electric energy at high electricity price, realize energy arbitrage and maximize economic benefits. Secondly, the reinforcement learning model can dynamically adjust the charge and discharge strategy according to the real-time market feedback to respond to the dynamic changes of the market, provide efficient frequency regulation and backup power supply services, and further enhance the market competitiveness of the system. Finally, optimization algorithms and integrated learning models can maximize the efficiency and benefits of energy storage systems in the market through accurate market trading decisions and contribute to the sustainable development of the power market and the effective use of energy resources. Applying these machine learning techniques improves the economy of energy storage systems and enhances their importance and practicality in modern power systems.

4.3.1. Market forecasting and price optimization

Machine learning technology plays an important role in the power market for energy storage systems. Among them, regression models in supervised learning, time series prediction models (such as ARIMA and Prophet), and deep learning models (such as neural networks) have their characteristics, and they optimize bidding optimization and market participation strategies of energy storage systems through different methods.

1) Regression model in supervised learning

The regression model in supervised learning is used to predict the changing market price trend in the power storage market. By analyzing historical market data, these models can build a forecast model of future electricity prices. For example, the system can use linear regression models or support vector regression (SVR) to predict future price movements based on different market factors such as weather conditions, seasonal changes, and supply and demand balances.

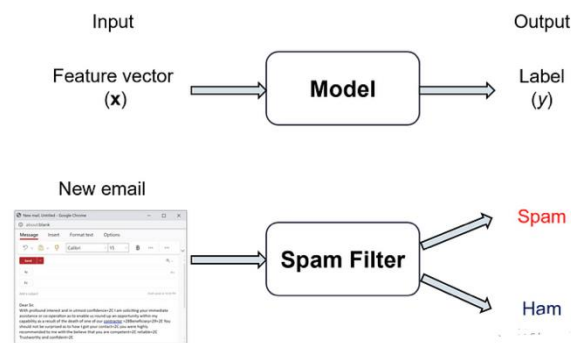


Figure 1. Supervised learning regression model-eigenvector architecture

This capability enables the energy storage system to sell electricity during expected high electricity prices and charge it during periods of low electricity prices, thus maximizing economic benefits.

2) Time series prediction models (e.g., ARIMA, Prophet)

Time series forecasting models also play an essential role in the power storage market, especially when trends and seasonal changes in historical data need to be considered. ARIMA (autoregressive

Integrated Moving Average Model) and Prophet (a time series forecasting tool developed by Facebook) can more accurately capture cyclical and trends in market electricity prices to help systems optimize charging and discharging strategies. These models not only consider the autocorrelation and seasonality of the data but can also integrate external factors such as policy changes and weather conditions to improve forecast accuracy, resulting in higher profits in market trading.

3) Deep Learning models (such as neural networks)

Deep learning models, especially neural networks, have significant advantages in handling large-scale complex data and nonlinear relationships. In the power storage market, neural networks can improve forecasting capabilities and decision-making accuracy by learning abstract and complex market patterns at multiple levels. For example, using a long-term memory network (LSTM) or a convolutional neural network (CNN), a system can learn and predict the market's long-term dependencies and nonlinear dynamics to more effectively plan charging and discharging timing and maximize market participation benefits.

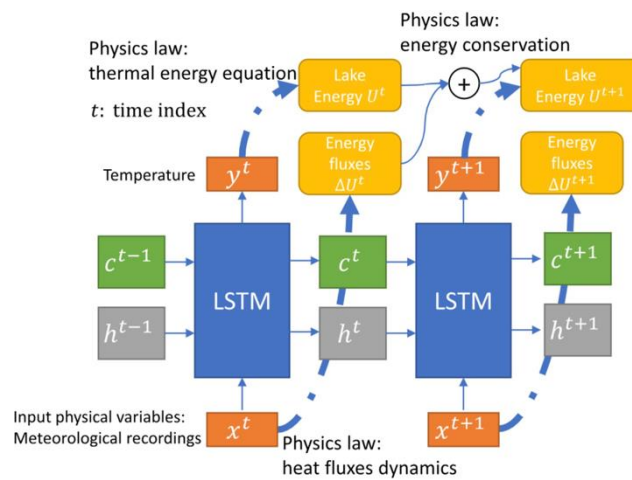


Figure 2. Physical information architecture design of neural network model

The idea behind physical information architecture design is to reshape the architecture of DNNs, inspired by the fields of physics and engineering. One way to use physical information to guide architecture is to impose some physical meaning on some outputs of hidden layer neurons and then impose specialized network layers and connections on those neurons, thus explicitly encoding some physical constraints. Domain knowledge can also be used to determine the node connections of deep neural networks and guide the flow of information. This idea is well illustrated in Figure 2, where the temporal evolution of lake temperature and energy flow is embedded in the RNN.

By applying these machine learning models, energy storage systems can make fast and precise decisions in the ever-changing power market, optimize resource allocation, improve economic benefits, and support the power system's stable operation and sustainable development.

4.4. Machine Learning Practical Application Examples

In practical applications, the bid optimization algorithm has shown significant economic benefit improvement in energy storage systems. For example, an energy company in the United States used machine learning algorithms to optimize market engagement strategies for its energy storage facilities. Using regression models and time series prediction models in supervised learning, they could accurately predict future price fluctuations in the electricity market and adjust charging and discharging strategies based on the expected results. These algorithms not only consider seasonal changes and market trends in historical data but also integrate weather data and load demand forecasts to improve the accuracy and comprehensiveness of projections. According to the report, their energy

storage system achieved more than 20% revenue growth in one year through effective market participation and optimization strategies and significantly reduced system operating costs.

Another example is a European power company that uses deep learning models, such as neural networks, to optimize charging and discharging strategies for its energy storage facilities. Through the learning ability of neural networks, the system can more accurately predict nonlinear changes in market electricity prices and adjust strategies based on real-time data to maximize profits. This optimization strategy not only improves the market participation ability of the energy storage system but also significantly increases the economic benefits of the system. For example, their system charges during predicted peak market times and releases stored electricity during high electricity prices, resulting in a higher market price. This kind of precise market transaction decision allows the energy storage system to obtain a remarkable competitive advantage and economic benefit from the fierce competition in the electricity market.

5. CONCLUSION

In conclusion, machine learning plays a vital role in the market optimization of energy storage systems, significantly improving the economics and market participation of energy storage projects by predicting market prices, optimizing charge and discharge strategies, and enhancing system flexibility and response speed. Whether it is regression models based on supervised learning, time series prediction models, or deep learning models, the application of these technologies in modern power systems demonstrates their significant potential to improve energy resource utilization efficiency and market competitiveness. With the continuous progress of technology and optimization of algorithms, the future application of machine learning in the field of energy storage has broad prospects, which are expected to further promote the development of clean energy and the sustainable development of power systems.

Through machine learning technology, energy storage systems can more effectively participate in the energy market, auxiliary service market, and capacity market, maximize market opportunities, and play an essential role in improving the stability and economic efficiency of the grid. Future research and development should focus on how to optimize algorithms further, improve prediction accuracy and system response speed, and achieve higher levels of market integration and resource utilization efficiency in different market environments, thus contributing to the energy transition and sustainable development of the power industry.

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