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Near-Zero Carbon Demonstration Zone "Source-Grid-Load-Storage-Use" Collaborative Technologies and Applications—A Case Study of Shunde Kawasaki Industrial Park

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Abstract: *Under the guidance of the "dual carbon" strategy, the construction of near-zero carbon industrial parks has become a key pathway for promoting the green transformation of industries. This paper takes Shunde Kawasaki Industrial Park as a case study, focusing on the "Source-Grid-Load-Storage-Use" collaborative system. It explores the integration of distributed photovoltaic systems, energy storage systems, energy-carbon management platforms, and intelligent energy systems to create an integrated energy management system that is perceptible, controllable, and operable, aiming to improve the utilization of clean energy and energy management efficiency. The goal is to provide technical references for the construction of near-zero carbon parks.*

Keywords: *Near-zero carbon demonstration zones; Source-Grid-Load-Storage-Use collaboration; Smart parks; Energy management; Virtual power plants*

1. Introduction

Under the guidance of the "dual carbon" goals, energy transformation has become a core global development issue. Industrial parks, as important areas for economic activity, are not only major energy consumers but also key areas for achieving low-carbon development. The emergence of "Source-Grid-Load-Storage-Use" collaborative technologies provides strong support for industrial parks to solve energy problems and move toward near-zero carbon development. The Shunde Kawasaki Industrial Park is a pioneer in this wave. With enormous industrial energy demand, the park faces the dual challenges of carbon reduction and energy efficiency. This paper takes it as a typical case to analyze in-depth the application of "Source-Grid-Load-Storage-Use" collaborative technologies, aiming to explore key points, outcomes, and challenges in technology application, and to provide a reference model for other parks, assisting the overall green and low-carbon transformation of industrial parks in China.

2. Design of the "Source-Grid-Load-Storage-Use" Collaborative System Architecture

2.1 Overall System Architecture Design

The overall architecture of the "Source-Grid-Load-Storage-Use" collaborative system is an organic integration that combines multiple technologies and links to achieve efficient energy allocation and low-carbon development. The architecture adopts a design concept of layering, zoning, and collaborative interaction, aimed at addressing the volatility and randomness of new energy generation, and providing stable, reliable, and clean energy supply for the park, as shown in Figure 1.

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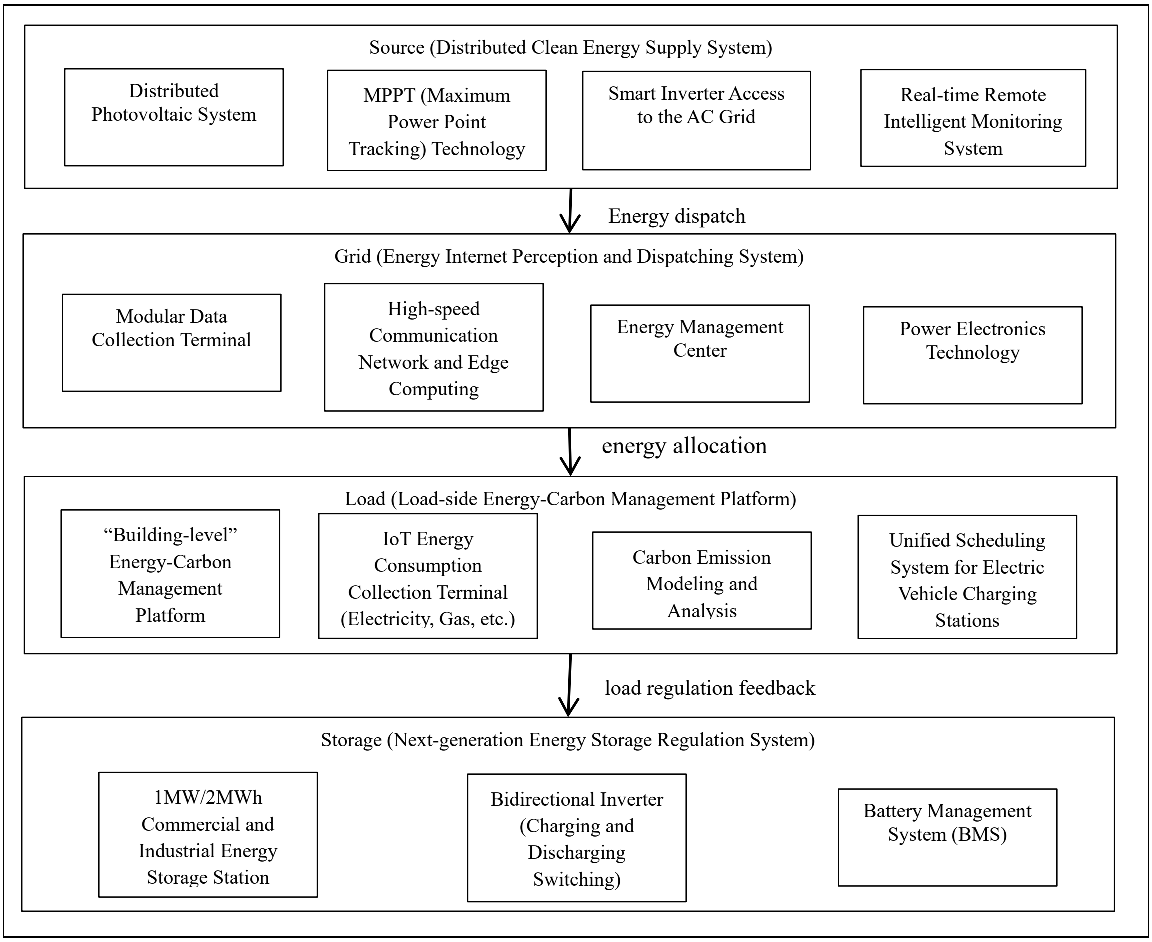

Figure 1: Overall Architecture of the "Source-Grid-Load-Storage-Use" Collaborative System

The "Source" side fully exploits the rooftop resources of the park to build a 1.91MWp distributed photovoltaic + management system. The system includes photovoltaic panel arrays, with MPPT technology installed to efficiently generate electricity under different light conditions. The DC electricity is converted into AC electricity by inverters and fed into the park's power grid. Intelligent monitoring technology is applied to monitor the photovoltaic system's generation efficiency, equipment operation status, and other parameters in real time to ensure power generation stability and reliability.

The "Grid" architecture uses modular collection and computing terminals as nodes to comprehensively perceive and collect data from the park's energy facilities. These modular collection and computing terminals are deployed at key points such as power supply lines and substations, collecting data on voltage, current, power, etc. The data is uploaded through a high-speed communication network to the integrated energy management center, thereby building the park's energy internet. The energy management center coordinates and dispatches the source, load, and storage to achieve intelligent energy-carbon management[1]. The energy internet integrates advanced power electronics and communication technologies to optimize power transmission paths, reduce line losses, and ensure stable and efficient power supply.

On the "Load" side, a smart energy management system is built to create a "building-level" energy-carbon management monitoring platform for precise monitoring and classification of carbon emission sources from each building in the park. IoT technology is used to collect energy consumption data such as electricity and gas usage from each building in the park. Big data analysis models are applied to build the park's carbon emission model, providing precise data support for carbon emission management. A charging management system is used to uniformly schedule the electric vehicle charging stations in the park, realizing refined load control based on the grid load and vehicle charging demand, thus improving the efficiency of the grid operation.

On the "Storage" side, a 1MW/2MWh next-generation commercial and industrial energy storage station is built, using advanced battery storage technologies such as lithium-ion batteries. The energy storage station is connected to the grid through a bidirectional inverter, charging during low electricity

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price periods and discharging during high electricity price periods to take advantage of the price differences and reduce energy costs for businesses. When there is an excess of new energy generation or sudden changes in the grid load, the energy storage station can respond quickly to store or release electrical energy, providing flexible adjustment capability for the park's power supply and enhancing grid stability.

The "Use" phase emphasizes energy efficiency and user behavior guidance, promoting energy-saving devices and technologies such as efficient lighting and smart air conditioning control within the park to encourage the use of green energy by users. The energy management system presents energy consumption data and energy-saving suggestions to users, guiding them towards energy-saving behaviors and helping users form energy-efficient habits. Through tight collaboration and data interaction across all stages of the park's system architecture, the efficient use of energy is realized, achieving the near-zero carbon goal.

2.2 Functional Module Division and Technical Coordination Mechanism

The "Source-Grid-Load-Storage-Use" collaborative system has a clear hierarchical structure and well-defined division of labor in its functional modules. The "Source" module is centered around distributed photovoltaics, using Maximum Power Point Tracking (MPPT) technology. The DC electricity generated by the system is converted into AC and fed into the grid to supply power to the park, ensuring the photovoltaic panels operate efficiently. The "Grid" module uses modular collection and computing terminals to sense the status of energy facilities and collect data, forming the industrial park's energy internet, responsible for power transmission and data communication, bridging all modules. The "Load" module utilizes a charging management system to centrally schedule charging stations for load management, while also employing a smart energy management system and "building-level" energy-carbon management monitoring platform to accurately monitor building energy consumption and carbon emissions. The "Storage" module includes next-generation commercial and industrial energy storage stations that charge during off-peak hours and discharge during peak hours, adjusting the supply and demand of electricity. The "Use" module focuses on promoting energy-saving devices and guiding user behavior to reduce energy consumption.

In terms of technical coordination, the photovoltaic system in the "Source" module works in conjunction with the bidirectional inverter technology in the "Storage" module. When excess photovoltaic power is available, the energy storage station quickly responds by charging; conversely, it discharges to supplement the power, ensuring the balance of power supply and demand. The energy internet technology in the "Grid" module collaborates with load monitoring and forecasting technology in the "Load" module. Based on real-time load data, it intelligently allocates power, optimizes transmission paths, and reduces losses. The carbon emission monitoring technology in the "Load" module collaborates with energy-saving technologies in the "Use" module to promote targeted energy-saving measures based on carbon emission levels and guide users to use green energy[2]. Each module interacts with the integrated energy management center through a high-speed communication network. The center utilizes big data analysis and intelligent control technologies to integrate the operation status of each module, formulating a collaborative scheduling strategy to ensure efficient coordination across all stages: Source, Grid, Load, Storage, and Use, guaranteeing stable energy supply, efficient utilization, and low carbon emissions in the park.

2.3 Technical Route and Implementation Strategy

The "Source-Grid-Load-Storage-Use" collaborative system uses efficient photovoltaic panels and MPPT technology at the source end to convert solar energy into electrical energy, feeding it into the grid. The high-speed communication network and smart grid technology at the grid end ensure stable transmission of power and data. IoT and big data analysis technologies at the load end enable real-time monitoring and control of the load, while advanced lithium-ion battery storage technologies and intelligent charging and discharging control strategies are used at the storage end.

First, a comprehensive assessment of the park's energy status is conducted to determine the scale of photovoltaic and energy storage systems. The energy internet infrastructure is built first, integrating distributed photovoltaic and smart electric rooms, while simultaneously advancing the construction of energy storage stations. Later, the load-side management system is gradually perfected, with charging stations integrated, and a "building-level" energy-carbon management platform is constructed. After completion, the integrated energy management center will dynamically optimize the energy sources,

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energy network, load, storage, and use components, using real-time energy data and intelligent algorithms to achieve efficient energy allocation and the near-zero carbon goal[3].

3. Key Subsystems and Core Technology Analysis

3.1 Photovoltaic Power Generation System (Source) Design and Intelligent Operation & Maintenance

When designing the photovoltaic power generation system, sufficient consideration should be given to the rooftop resources of the park. Polycrystalline silicon photovoltaic panels are selected to enhance photoelectric conversion efficiency. String inverters are used to convert the DC power generated by the photovoltaic panels into AC power with MPPT functionality, tracking the maximum power output point of the photovoltaic array in real time, adapting to different lighting and temperature conditions, and improving power generation efficiency.

In terms of intelligent operation and maintenance, an intelligent monitoring system is introduced, using data analysis techniques to deeply mine the collected data, predict changes in the photovoltaic panel's power generation performance, and detect potential faults when abnormalities are found. The system automatically sends alarms, and maintenance personnel can use a remote monitoring platform to locate fault points, develop maintenance plans, and install sensors to collect real-time data on temperature, light intensity, current, and voltage of the photovoltaic panels. Regular drone inspections are conducted to check the appearance of the panels, reducing manual inspection workload and ensuring stable and efficient operation of the photovoltaic power generation system, continuously supplying green energy.

3.2 Commercial and Industrial Energy Storage System (Storage) Optimization and Operation Mechanism

The commercial and industrial energy storage system is designed based on the park's electricity load characteristics and the peak-valley electricity price difference. After precise calculations, the scale of the 1MW/2MWh energy storage station is determined, using lithium-ion batteries with high energy density and long cycle life to ensure the efficient and stable operation of the storage system. At the same time, the intelligent control system is combined with photovoltaic power generation forecasts and load prediction data to optimize the charge and discharge strategy of the storage system, achieving efficient utilization of power resources.

The energy storage system charges during peak hours and discharges during peak hours, reducing electricity costs for businesses. This is achieved through the peak electricity price arbitrage model. When there is excess photovoltaic power, surplus energy is stored to avoid wasted power; when the grid power supply is insufficient or photovoltaic power generation is low, the energy storage system quickly discharges to fill the power gap, maintaining a stable power supply for the park[4]. The energy storage system can quickly respond to grid frequency fluctuations and voltage instability, adjusting power output and participating in grid frequency and voltage regulation, enhancing the grid's stability and reliability, laying a solid foundation for the stable operation of the park's energy.

3.3 Energy Management System (Grid + Load) Construction and Data Integration

The energy management system integrates the key elements of "Grid" and "Load", relying on advanced technologies to achieve efficient construction and deep data integration. In terms of construction, modular collection and computing terminals are deployed to comprehensively cover the park's transmission lines, transformers, and other grid facilities, as well as various electrical devices, collecting real-time data on voltage, current, power, and the electrical load data from buildings and production equipment.

At the data integration level, the collected grid and load data are integrated through big data processing and analysis technologies. Using data mining algorithms, relevant information is extracted from vast amounts of data to construct energy supply-demand models, thus enabling data integration for the grid.

3.4 Smart Energy Use and User Behavior Guidance Mechanism (Use)

In terms of smart energy, the park has introduced IoT devices such as smart meters and smart sockets to monitor users' electricity consumption in real time. By installing an intelligent control system, the operating time and power of non-critical electrical devices are automatically adjusted based on real-time electricity price information, photovoltaic power generation, and storage status, enabling smart management of electrical devices and improving energy utilization efficiency.

Regarding user behavior guidance, a visualized energy management platform is built to present real-time energy consumption, carbon emission data, and energy-saving suggestions directly to users. By analyzing users' electricity consumption habits, personalized energy-saving plans are developed for different users, encouraging active participation in energy-saving actions through incentive methods such as point rewards and energy-saving rankings[5]. At the same time, the park organizes energy management knowledge training and publicity activities to enhance users' awareness of energy conservation and energy management capabilities, guiding them to develop green energy habits. Through smart energy utilization and user behavior guidance mechanisms, the park helps achieve the near-zero carbon goal and promotes the development of energy use toward efficient and low-carbon directions.

4. System Integration and Empirical Application: A Case Study of the Shunde Kawasaki Industrial Park

4.1 Basic Overview of the Park and Energy Status

The Shunde Kawasaki Industrial Park is a manufacturing hub with a large scale, covering industries such as automotive manufacturing. It has diverse electrical equipment and complex operations, requiring high stability in energy supply. In terms of energy status, the park has traditionally relied on the power grid for electricity, with a single energy structure. The energy consumption of industrial production is high, and the total carbon emissions are significant. As the park develops, energy demand continues to rise. Under the drive of the "dual carbon" goals, the traditional energy supply model can no longer meet the demands. There is an urgent need to optimize the energy structure and improve energy efficiency, laying the foundation for the construction of the "Source-Grid-Load-Storage-Use" collaborative system.

4.2 Construction Process and Key Nodes of the "Source-Grid-Load-Storage-Use" System

When building the "Source-Grid-Load-Storage-Use" system in Shunde Kawasaki Industrial Park, the rooftop resources were thoroughly surveyed, and 1.91MWp of distributed photovoltaic panels were installed. These were connected to maximum power point tracking devices and inverters to achieve efficient power generation and grid connection. The key was to precisely plan the layout of the photovoltaic system to maximize light utilization. At the grid side, modular collection and computing terminals were deployed to build a communication network covering the park, consolidating data from all energy facilities into the energy management center. The key node was ensuring high-speed and stable data transmission to support subsequent energy scheduling decisions. On the load side, a smart energy management system and "building-level" energy-carbon management monitoring platform were developed. These systems integrate monitoring modules for various electrical devices to enable real-time load data collection. A charging management system was set up to centrally schedule the charging stations. The key here was the accurate collection and integration of load data. On the storage side, a 1MW/2MWh next-generation commercial and industrial energy storage station was built, connecting bidirectional inverters to the grid with intelligent charging and discharging strategies. The key here was determining the optimal storage capacity and charging/discharging control logic. After the completion of all the components, the integrated energy management center uses intelligent algorithms to coordinate the subsystems, achieving optimized energy allocation and efficient utilization.

4.3 Operational Data and Performance Analysis

The "Source-Grid-Load-Storage-Use" system in Shunde Kawasaki Industrial Park has shown significant operational results, as shown in Table 1.

From the perspective of power generation, the daily average is about 5345kWh, and the park can supply approximately 1.9517 million kWh of green electricity annually, significantly increasing the proportion of clean energy. In terms of cost control, the park's electricity cost per unit has decreased by 28%, effectively reducing the financial burden on businesses. In terms of environmental protection, 240 tons of standard coal are saved annually, reducing CO2 emissions by approximately 920 tons and SO2 emissions by around 4.9 tons, demonstrating significant environmental benefits. The energy storage station provides 955,500 kWh of peak-shaving power annually, ensuring stable power supply. This highlights the system's outstanding performance in energy supply, cost optimization, and environmental protection across multiple aspects.

Table 1: System Performance Results

Specific Data	Specific Data
Daily Average Power Generation	Approximately 5345kWh
Annual Green Power Supply	Approximately 1.9517 million kWh
Park's Electricity Cost Reduction Percentage	28%
Annual Standard Coal Savings	240 tons
Annual CO2 Emission Reduction	Approximately 920 tons
Annual SO2 Emission Reduction	Approximately 4.9 tons
Annual Peak-shaving Power Provided by Energy Storage Station	955,500 kWh

5. Key Technical Challenges and Solutions

5.1 Communication and Control Challenges in Multi-energy Collaborative Regulation

In the "Source-Grid-Load-Storage-Use" system's multi-energy collaborative regulation, communication and control face significant challenges. In terms of communication, there are numerous devices in the park, each with different communication protocols, leading to barriers in data exchange, making efficient interconnection difficult. Moreover, the large volume of real-time data transmission requires high network bandwidth and stability, and the delivery of energy scheduling commands can be severely impacted by network delays or interruptions, causing regulatory delays.

On the control side, the dynamic characteristics of each link in the source, grid, load, and storage are complex, requiring precise coordinated control. However, current control algorithms struggle to balance fast response with global optimization of each link. Traditional control strategies fail to quickly balance energy supply and demand in cases where photovoltaic output fluctuates sharply due to sudden weather changes or when there is an instantaneous surge in load, leading to potential power imbalances. Therefore, developing unified communication protocols, optimizing network architecture, and designing advanced multi-objective coordinated control algorithms are key to overcoming communication and control bottlenecks in multi-energy collaborative regulation.

5.2 Load-side Prediction Uncertainty and Machine Learning Optimization

In the "Source-Grid-Load-Storage-Use" system, uncertainty in load-side prediction presents a significant barrier to energy collaborative regulation. The park has a wide range of industries, and the operation patterns of electrical equipment are complex. Factors such as production plan adjustments, seasonal changes, and unforeseen events cause highly uncertain load fluctuations. Traditional forecasting methods rely on historical data to build simple models, making it difficult to accurately capture these complex dynamic changes, resulting in significant forecasting errors that impact the precision and reliability of energy scheduling.

Machine learning technology offers an effective solution to this problem by building deep neural networks and using automatic data feature extraction and underlying pattern recognition. These machine learning models deeply mine and analyze massive historical load data, environmental factor data, production plan data, etc.[6]. The model can adaptively learn load change patterns, and even in the face of complex and changing operating conditions, it can leverage powerful learning capabilities to improve prediction accuracy, providing more reliable load forecasting results for energy scheduling, aiding in the precise matching and efficient coordination of source, load, and storage.

5.3 Energy Information Security and Park Data Silos

In the "Source-Grid-Load-Storage-Use" system, energy information security and the problem of data silos in the park are prominent. In terms of energy information security, the system involves large amounts of sensitive energy data such as power dispatch commands and equipment operation parameters, facing risks of cyberattacks. Hackers could steal or tamper with data, interfering with normal energy supply and even causing safety incidents. Meanwhile, data between different departments and systems in the park are isolated, forming data silos. Data from different energy facilities cannot be shared or integrated, leading to the inability to manage and make decisions on energy from a holistic perspective. For example, photovoltaic generation data and electricity load data belong to different systems, making it difficult to perform correlation analysis. To solve these issues, it is necessary to establish unified data standards and a shared platform, break down data barriers, achieve data interconnection and interoperability, and lay the foundation for efficient energy collaborative regulation, while also building a comprehensive cybersecurity defense system to ensure information security.

5.4 Virtual Power Plant Integration Compatibility and Standardization Challenges

In the “Source-Grid-Load-Storage-Use” system, the integration compatibility and standardization of virtual power plants face significant challenges. These plants have diverse equipment and technology sources, and there are difficulties in ensuring compatibility with the park’s existing energy system in terms of interfaces, communication protocols, and control logic. The virtual power plant integrates distributed energy, energy storage, and controllable load resources, making its equipment and technology sources highly compatible and standardized. Different virtual power plant operators have varying equipment parameters and operational methods, making seamless integration and collaborative operation difficult when connecting to the park’s energy management system. At the same time, from equipment specifications and data exchange formats to operational management processes, the industry lacks unified standards for virtual power plant integration. This inconsistency leads to increased difficulty in system commissioning, operation, and maintenance when integrating virtual power plants, making it impossible for the park to establish standardized operational procedures, resulting in inconsistencies during operational management. Therefore, establishing unified integration standards and developing compatible technical interfaces are necessary measures to ensure the smooth integration of virtual power plants into the park’s energy system, achieving efficient and collaborative operation.

6. Conclusion

The “Source-Grid-Load-Storage-Use” collaborative system in Shunde Kawasaki Industrial Park has been successfully established, creating a low-carbon development path through multi-energy integration, intelligent scheduling, and efficient utilization. The system optimizes the energy structure and significantly reduces carbon emissions through the integration of key technologies and system collaborative optimization, offering valuable demonstration and promotion potential. In the future, further smart construction will be promoted, and new applications such as virtual power plants will be implemented, aiming to create a near-zero carbon park.

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