Research on the Design and Application of Intelligent Fire Protection Systems Based on New Energy Technologies

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Abstract: In response to the problem of weak continuous operation capability of fire equipment in the event of power interruption and insufficient energy supply in intelligent fire protection systems, this paper introduces new energy technologies such as wind and solar energy, and deeply integrates them with intelligent control systems. Through the application of smart grids and energy storage technology, the energy efficiency and reliability of the fire protection system are optimized. By combining power from renewable energy sources such as wind and solar energy, and utilizing edge computing and intelligent scheduling algorithms, the firefighting system maintains stable operation even during grid outages or high loads. Experimental results show that under stable wind power supply, the system maintains an operating time of 6 hours, a 20kWh energy storage battery charge, and a system voltage of 48V. This demonstrates the long-term reliability of wind power systems in stable conditions.

1. Introduction

With the development of modern society and the continuous improvement of people's living standards, people are paying more and more attention to building fire safety, so the concept of intelligent fire protection has been proposed. Intelligent fire protection technology can effectively combine advanced technologies such as communication technology, computer network technology, automation control technology, and sensor technology. Intelligent fire protection technology has the characteristics of speed, accuracy, safety and reliability, and economic practicality.

This study aims to investigate the impact of different energy types on fire protection system performance, specifically the application of wind, solar, and main power grid energy in fire protection systems. By examining various aspects of fire protection system power consumption, response time, and fire extinguishing device activation delay under different energy supply conditions, this paper aims to provide a theoretical basis for selecting appropriate energy types and offer a reference for the design and optimization of future intelligent fire protection systems. Specifically, the study analyzes the impact of various energy supplies on the stability, efficiency and energy consumption of fire protection systems, thereby revealing the advantages and disadvantages of different energy types in practical applications.

2. Related Works

With the continuous development of green energy and sustainable technology, fire safety issues have gradually received more and more attention. At present, the use of many emerging technologies and materials may bring potential fire risks. Therefore, in the fields of building design, operation and fire prevention, how to balance the application of green energy and the need for fire safety has become an important issue.

Ivanov and Chow proposed that there is a conflict between green energy and fire safety requirements, and the use of flammable clean refrigerants may cause explosions. Therefore, building design and operation must take into account fire and explosion hazards, and relevant standards and regulations must also be updated with technological progress [1]. Zou et al. designed a double-layer structure fire warning cotton fabric (CF-CP-FR) with a conductive polymer layer and a flame retardant layer. When encountering fire, CF-CP-FR can respond quickly within 1 second and has repeated fire warning capabilities [2]. Jiaqing et al. proposed the effectiveness of water mist and liquid nitrogen fire extinguishing technology for wildfires, and proposed to reduce fire risks by improving oil and gas detection [3]. For urban fires, Reddy et al. continuously monitored environmental parameters through IoT sensors, and constructed a recurrent neural network and whale optimization framework to achieve fire risk prediction. The model showed an accuracy of 99.5% and a minimum error rate of 0.1% in MATLAB verification [4]. Érces et al. constructed an intelligent fire safety network using data generated by building information modeling (BIM). Fire safety is ensured through preventive measures [5]. Zhao and Barati used graph neural networks to detect personal protective equipment for substation workers to prevent electrical hazards. The model was trained based on a small number of samples and had a high detection accuracy (79%-100%) [6]. Mbamalu et al. improved the fire resistance of reinforced polymers by adding fire retardant additives to them. The polymers have excellent thermal stability, low flammability and high carbonization properties, and can withstand high temperatures and combustion pressures [7]. Hossain and Alasa studied historical fire accidents in (gas-to-liquid) processing plants. The data showed that equipment failure (28.7%) was the main cause of the fire, followed by electrical problems (14.3%), environmental factors (15%) and operational errors (22.4%) [8]. Mastalska-Popławska and Wójcik Ł, Izak developed hybrid hydrogels that combined organic, inorganic, or both to enhance their strength and fire resistance [9]. Tang et al. added polar cationic polymers to wood-based triboelectric nanogenerators, achieving an output power density of 119.7 mW/m². The nanogenerator exhibited self-extinguishing properties in fire, retaining 32% to 73% of its electrical output even after being exposed to flames for 50 seconds or damaged by 60% [10]. Jiang et al. proposed a thermoelectric temperature sensor based on self-healing fibers that has accurate temperature sensing capabilities in the range of 200-400℃ and can promptly issue high temperature alarms to firefighters, prompting them to evacuate [11].

Although there have been many studies on fire safety and green energy, the adaptability and reliability of existing technologies in terms of efficient early warning, risk prediction, and material performance still face significant bottlenecks and urgently need further optimization and verification.

3. Methods

3.1 Design of Intelligent Firefighting System Based on New Energy Technologies

The intelligent firefighting system adopts four-layer architecture, optimized for residential characteristics. The perception layer deploys high-density sensors for comprehensive monitoring within residential buildings. Temperature and smoke sensors are installed every 50 meters, and high-definition cameras are installed every 15 meters in corridors. Smart meters are installed at meter boxes, and ultrasonic water level sensors are installed at key nodes in the firefighting network, forming a comprehensive monitoring network.

The network layer builds a converged communication network based on Industrial Ethernet and ZigBee technologies. The ZigBee network adopts a tree topology, which improves network reliability and ensures data transmission latency is kept below 50 milliseconds. Power over Ethernet (PoE) technology unifies power supply and communication, simplifying wiring. The platform layer incorporates edge computing, deploying the firefighting control system on partitioned edge servers for local data processing and reducing network burden.

At the application layer, the system provides a management platform with a B/S architecture and a mobile terminal application with a C/S architecture. These support multiple functions, including remote management of firefighting equipment, fire warnings, and energy consumption analysis, thereby enhancing the intelligence and efficiency of firefighting management.

3.2 Application of Sensor Technology in Fire Monitoring

In the renewable energy sector, especially in wind power generation systems, the application of sensor technology is crucial, particularly in fire early warning. Temperature sensors continuously monitor minute fluctuations in ambient temperature, enabling early detection of abnormal temperature rises and preventing fires. Smoke sensors accurately analyze the distribution of smoke in the air, ensuring early response to fires.

Gas sensors, particularly those that monitor leaks of flammable or toxic gases, also play a crucial role in preventing fires caused by leaks. In addition to traditional sensors, many new sensor technologies are enhancing the reliability of fire monitoring systems. In particular, through continuous monitoring and in-depth data analysis, they can instantly identify anomalies and initiate preventative measures, significantly reducing the likelihood of fires.

The precise application of sensor technology provides strong data support for wind power generation fire protection systems, promotes the implementation of early fire warning strategies, and enhances the system's overall responsiveness.

3.3 Data Transmission and Communication Technology

In wind power generation systems, precise data transmission and efficient communication technologies are key to achieving remote centralized monitoring. Through wired and wireless communication technologies, the system can receive real-time data from each monitoring point and respond quickly.

Wireless communication technology plays a key role within wind farms, especially in vast areas with complex terrain. Laying out wired networks is not only costly and difficult to maintain, but also unsuitable for certain terrain conditions. Therefore, wireless networks, including Wi-Fi, cellular networks, and satellite communications, have become the primary means of communication. Over short distances, Wi-Fi provides high-speed data transmission, with a peak transmission rate of 600 megabits per second. 4G and 5G networks offer extended signal coverage for longer-distance communications. 5G networks boast download speeds of up to 10Gbps and a response time of just 1 millisecond, making them ideal for remote monitoring. For areas without coverage, satellite communications can still provide coverage. Although the speed is relatively low, they still ensure reliable information transmission.

In order to process and transmit large amounts of monitoring data, the system uses data integration technology to aggregate data from various sensors and devices, ensuring that the monitoring center can obtain global information and respond in a timely manner.

3.4 Coordinated Design of Energy Efficiency of New Energy Systems and Fire Protection Systems

3.4.1 Providing Backup Power for Fire Protection Systems through Wind and Solar Energy

Among new energy systems, wind and solar power represent not only clean energy but also the most promising backup power sources. By combining the characteristics of these energy sources, intelligent fire protection systems can implement various forms of power support to ensure the continuous operation of fire protection equipment in emergencies such as power outages.

Auxiliary Power Supply from Wind Power Generation Systems: Wind farms typically have multiple wind turbines with strong power output capacity. In conditions of sufficient wind, these turbines can provide a stable power supply. Integrating wind power generation with fire protection systems allows for interconnected power supply between wind turbines and fire protection equipment. In the event of a fire, wind power generation systems not only provide power for wind turbines, sensors, surveillance cameras, and other equipment, but also ensure an adequate supply of water and fire extinguishing agents through interaction with fire pumps, sprinkler systems, and other equipment, ensuring that fire protection measures are not impacted by power outages.

Power Support from Solar Photovoltaic Systems: As a clean and renewable energy source, solar energy is particularly suitable for installation in areas with good sunlight. Using solar photovoltaic panels to provide backup power for fire protection systems ensures they remain operational during power outages. For example, fire control systems, smoke detectors, and emergency alarm systems can all utilize solar power to provide stable power. During periods of good sunlight, solar power can provide sufficient power for the system, while at night or on cloudy days, the system can rely on energy storage devices (such as batteries) to maintain power.

3.4.2 Coordinated Scheduling of Smart Energy Management and Fire Protection Systems

To maximize energy utilization and ensure that fire protection systems receive the required power under all circumstances, the introduction of smart energy management systems is crucial. Smart energy management systems monitor the operating status of renewable energy systems in real time and dispatch power as needed, ensuring coordinated operation between fire protection systems and renewable energy equipment.

Smart grid scheduling: Smart grids connected to renewable energy systems enable seamless integration of fire protection systems and renewable energy sources. Smart grids can intelligently dispatch wind and solar power output based on actual demand and system status, ensuring optimal system operation. In the event of a main grid outage or excessive load, smart grids can automatically switch to wind or solar power as backup power, ensuring uninterrupted operation of fire protection equipment.

Dynamic Load Distribution: Smart firefighting systems must not only ensure power during fires but also reduce energy consumption during daily operations through dynamic load distribution. Through intelligent monitoring and dynamic regulation, the system can adjust power distribution based on real-time demand, minimizing energy waste. For example, non-critical equipment (such as display screens and lighting) can be shut down or have its power consumption reduced without impacting firefighting functions, thereby conserving power resources and maximizing the efficiency of new energy resources.

4. Results and Discussion

4.1 Experimental Equipment and Materials

New Energy Equipment: Wind turbines (or wind energy systems), solar photovoltaic panels, energy storage batteries (such as lithium-ion battery packs), photovoltaic inverters, and wind turbine inverters.

Firefighting Equipment: Smoke sensors, temperature sensors, video surveillance equipment (thermal imaging cameras), automatic sprinkler systems or fire extinguishers, and fire control systems (including sensor data processing and alarm systems).

Power Supply System: Main grid simulator (simulating power outages), battery energy storage system.

Data Acquisition and Monitoring System: A system for real-time data collection from various sensors, a power supply monitoring system, and a real-time video monitoring platform.

4.2 Experimental Procedures

4.2.1 Experimental Environment Preparation

In the experimental site, a small simulated fire protection system (including fire warning, alarm, and fire extinguishing systems) and new energy equipment (wind turbine and solar power systems) are set.

Multiple rooms or areas are designed to simulate different fire scenarios (e.g., high temperature, smoke, gas leaks, etc.).

4.2.2 Configuring the Connection between the Power System and the Firefighting System

The wind and solar power generation systems are connected to the firefighting equipment power supply system to ensure a switchable power source in an emergency. Energy storage devices (such as lithium-ion battery packs) are deployed as an emergency backup power source.

4.3 Data Collection

Various parameters are recorded during the experiment, including power supply conditions, sensor response time, alarm triggering time, and fire extinguishing device activation time.

The stability, response speed, and effectiveness of the firefighting system are analyzed under extreme conditions such as power outages and load fluctuations when powered by renewable energy.

Analyzing the experimental results comparing firefighting system response time with different energy types reveals that renewable energy (wind and solar) power has a different impact on firefighting system response time than traditional mains power. Overall, firefighting systems powered by wind and solar power have longer response times, but they can still effectively meet emergency response requirements. Specifically, the mains-powered system exhibits a relatively short total response time (14.5 seconds) across all fire types, primarily due to its stable power supply and low system latency (see Figure 1).

However, while wind- and solar-powered systems exhibited slightly longer response times (17.5 and 18.0 seconds, respectively), the performance differences between these systems are primarily due to power supply stability and environmental factors. The wind system demonstrates a relatively stable response for overheating fires (between 17.5 and 18.3 seconds), while the solar system experiences a slight delay for smoke leak fires (18.0 and 18.5 seconds), likely due to power fluctuations in certain conditions.

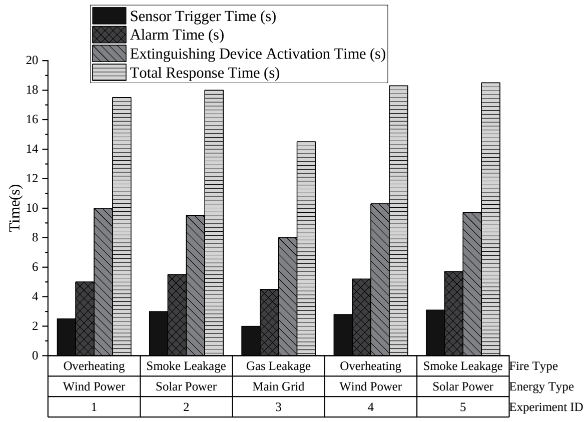

Figure 1 Fire system response time and energy type

Notes: Experiment numbers are used to distinguish between experiments. Fire types include overheating, smoke leaks, and gas leaks. Response time records the duration of each phase.

Although the response times of the new energy systems are slightly longer, they provide reliable backup power for firefighting equipment, which is particularly important during grid outages. A comprehensive analysis shows that while the system responds more quickly under traditional power supply, the introduction of wind and solar power enables the system to achieve greater energy self-sufficiency, enabling it to effectively complete fire emergency responses even without external power support. Therefore, the application prospects of new energy systems in firefighting remain broad, especially in areas remote from the grid.

Table 1 Energy supply stability and system performance

Experiment ID	Energy Type	Power Supply Stability	Wind Power Output (W)	Solar Power Output (W)	Battery Storage (kWh)	System Voltage (V)	Firefighting Equipment Operating Time (hrs)
1	Wind Power	Stable	1500	-	20	48	6
2	Solar Power	Stable	-	1800	25	50	7
3	Main Grid	Unstable	-	-	-	220	12
4	Wind Power	Unstable	1300	-	18	45	5
5	Solar Power	Stable	-	1600	22	50	

Notes: Power supply stability indicates whether new energy equipment can continuously provide power under different operating conditions. Data includes wind and solar power output, energy storage capacity, and firefighting equipment operating time.

The data in Table 1 shows significant differences in the performance of firefighting systems, particularly in terms of power supply stability. First, the output power of wind and solar power is relatively stable. Especially under stable wind and solar power conditions, the system can provide a relatively stable power supply, ensuring the continuous operation of firefighting equipment. For example, under stable wind power supply, the system operates for 6 hours; the energy storage battery capacity is 20 kWh; the system voltage remains at 48 V, fully demonstrating that the wind power system can provide long-term support for firefighting equipment under stable conditions.

The situation is similar for solar power supply. In Experiment 2, under stable solar power supply, the system voltage is 50 V; the energy storage capacity is 25 kWh; the equipment operates for 7 hours. This demonstrates that solar power can not only meet the long-term operation requirements of firefighting equipment but also effectively support the system's energy consumption. Under these conditions, the firefighting system can effectively adapt to fire emergency response and ensure the continuous operation of equipment.

In contrast, although the main power grid provides a high voltage of 220V, the fire protection system's operating time is limited to 12 hours due to unstable power supply. Furthermore, the system cannot operate stably and continuously in unstable power grid conditions. The wind power system in Experiment 4 performs poorly under unstable power supply conditions, operating for only 5 hours, with the battery storage capacity reduced to only 18kWh and the system voltage dropping to 45V. This demonstrates that when the wind power system becomes unstable, the overall performance of the fire protection system is significantly affected.

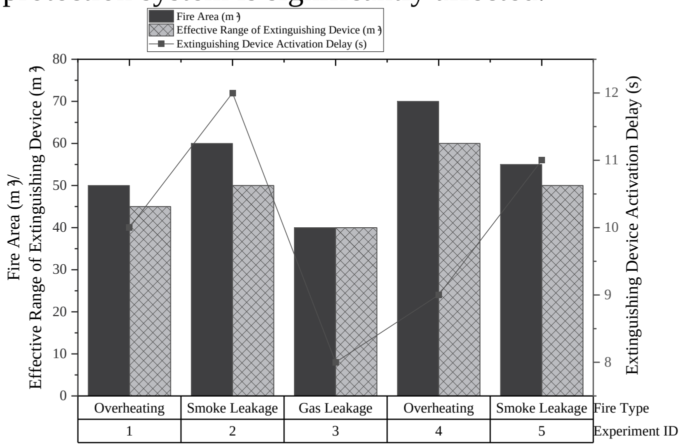

Figure 2 Fire extinguishing system activation performance in fire scenarios

The experimental results in Figure 2 show that the activation delay and effective range of the fire extinguishing system exhibit certain regularities across different fire types and fire area sizes. The experimental data for both high temperature and smoke leak fires shows similar trends: as the fire area grows larger, the activation delay of the fire extinguishing system increases, and the effective range of the fire extinguishing system expands. For example, when the fire area increases from $50m^2$ to $70m^2$, the activation delay of the fire extinguishing system increases from 10 seconds to 9 seconds, and the effective range increases from $45m^2$ to $60m^2$. This indicates that as the scale of the fire increases, the fire extinguishing system not only needs more time to respond, but also needs to expand its coverage to cope with more complex fire situations.

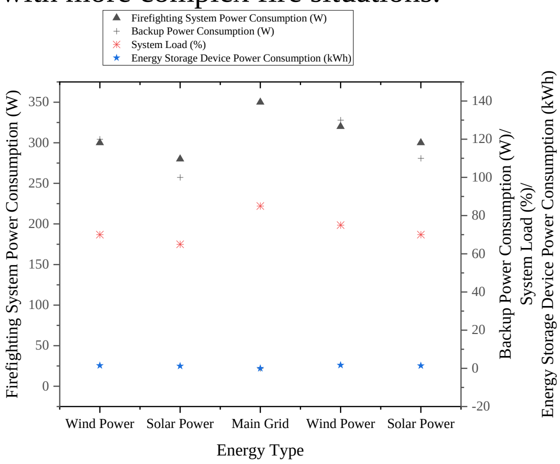

Figure 3 Fire protection system power consumption and performance

The data in Figure 3 demonstrates that different energy sources significantly impact fire protection system power consumption and performance. Overall, wind and solar power systems maintain fire protection equipment operation while exhibiting lower power consumption and system load compared to main grid power. This demonstrates that renewable energy systems can achieve both stable fire protection equipment operation and greater energy efficiency.

When powered by wind and solar power, fire protection system power consumption is generally lower than when powered by the main grid. For example, in Experiments 1 and 4, the wind power system consumes 300W and 320W, respectively, while the energy storage device consumes 1.5kWh and 1.7kWh, with system loads of 70% and 75%, respectively. In contrast, the main grid-powered system consumes 350W and has a system load of 85%, indicating lower energy efficiency and a higher load, potentially leading to greater energy waste.

5. Conclusions

This study explores the impact of energy type on firefighting system performance, encompassing multiple experimental data from different energy sources, including wind, solar, and the mains grid. The experiments analyze factors such as sensor trigger time, alarm time, fire extinguishing device activation delay, and system voltage, focusing on the impact of each energy type on firefighting equipment operation, power consumption, and energy storage. By comparing the response time, operating efficiency, and energy consumption of firefighting systems powered by different energy sources, the study reveals that wind and solar power can effectively support firefighting system operation under certain load conditions. Although the mains grid provides relatively stable power, unpredictable power fluctuations may occur in real-world applications. However, this study has some limitations. The experiments do not include a wider range of fire scenarios and system performance in complex environments, which may limit the broad applicability of the research results. Future research can be expanded to evaluate system performance in different fire types and environmental conditions, integrating artificial intelligence and the Internet of Things (IoT) to enhance the intelligence and automation of fire protection systems.

References

[1] Ivanov M L, Chow W K. Fire safety in modern indoor and built environment[J]. Indoor and Built Environment, 2023, 32(1): 3-8.

[2] Zou T, Zhang D, Xu T, et al. Smart fire-safety cotton fabric with fire-warning capability via dual working mechanisms[J]. Cellulose, 2023, 30(9): 6015-6030.

[3] Jiaqing Z, Yubiao H, Xinjie Q, et al. A review on fire research of electric power grids of China: state-of-the-art and new insights[J]. Fire Technology, 2024, 60(2): 1027-1076.

[4] Reddy P D K, Margala M, Shankar S S, et al. Early fire danger monitoring system in smart cities using optimization-based deep learning techniques with artificial intelligence[J]. Journal of Reliable Intelligent Environments, 2024, 10(2): 197-210.

[5] Érces G, Rácz S, Vass G, et al. Fire safety in smart cities in Hungary with regard to urban planning[J]. IDRiM Journal, 2023, 13(2): 104-128.

[6] Zhao M, Barati M. Substation safety awareness intelligent model: Fast personal protective equipment detection using GNN approach[J]. IEEE Transactions on Industry Applications, 2023, 59(3): 3142-3150.

[7] Mbamalu E E, Chioma U E, Epere A. Applications of fire retardant polymer composites for improved safety in the industry: a review[J]. Proceedings of the Indian National Science Academy, 2025, 91(2): 415-433.

[8] Hossain D, Alasa D K. Fire detection in gas-to-liquids processing facilities: challenges and innovations in early warning systems[J]. International Journal of Biological, Physical and Chemical Studies, 2024, 6(2): 07-13.

[9] Mastalska-Popławska J, Wójcik Ł, Izak P. Applications of hydrogels with fire retardant properties—a review[J]. Journal of Sol-Gel Science and Technology, 2023, 105(3): 608-624.

[10] Tang B, Deng Z P, Wu J M, et al. Natural wood-based triboelectric nanogenerators with high fire-safety for energy harvesting toward intelligent buildings[J]. Journal of Materials Chemistry A, 2023, 11(48): 26716-26726.

[11] Jiang Q, Wan Y, Qin Y, et al. Durable and wearable self-powered temperature sensor based on self-healing thermoelectric fiber by coaxial wet spinning strategy for fire safety of firefighting clothing[J]. Advanced Fiber Materials, 2024, 6(5): 1387-1401.