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Fire Risk Coupling Mechanism of Oil Depot-Photovoltaic Hybrid System

Jiangyuan Chen[1], *Xiaowen Li*[2]

[1,2]*SouthWest Petroleum University*

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[*]**Corresponding Author:** *Jiangyuan Chen*

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Abstract **Original Research Article**

This study systematically analyzes the coupling mechanisms and causes of fire risks in oil depot-photovoltaic (PV) hybrid systems during operation, proposing targeted prevention and control strategies. Research indicates that the fire risks in such systems primarily manifest in three coupled forms: spatial interaction, energy conduction, and spatiotemporal superposition. For risk mitigation, the paper emphasizes the necessity of corrosion-resistant material modifications, the criticality of optimized safety distance design, and the requirements for establishing a dynamic risk management system. These measures collectively form a comprehensive risk prevention framework, providing theoretical support and practical guidance for enhancing the safety and reliability of oil depot-PV hybrid systems.

Keywords: Photovoltaic (PV) Power Plant, Coupling Mechanism, Fire Risk (or Fire Hazard), Prevention and Control Strategies, Oil Depot.

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1. INTRODUCTION

Oil depot-photovoltaic (PV) hybrid systems, as innovative energy facilities in the context of energy transition, play a critical role in ensuring energy supply and achieving carbon neutrality goals. However, the complex interaction between the high-risk environment of oil depots and the electrical characteristics of PV systems leads to significantly coupled fire risks. Therefore, a deep understanding of the fire coupling mechanisms in oil depot-PV hybrid systems and the exploration of effective risk monitoring and prevention methods hold substantial theoretical and practical value for safeguarding emerging energy infrastructure. Traditional single-risk analysis models are inadequate in addressing the safety challenges of such hybrid systems, necessitating the establishment of a systematic framework for coupled risk assessment and prevention. This study conducts a multidimensional coupling mechanism analysis to provide a scientific basis for the safety design and operational management of oil depot-PV hybrid systems.

2. RESEARCH BACKGROUND AND SIGNIFICANCE

2.1 Research Background

(1) Accelerating Global Energy Transition with PV as a Key Pillar

The urgency of addressing climate change has prompted nations worldwide to accelerate energy structure adjustments, positioning photovoltaic energy as a core pathway for achieving carbon neutrality. According to China's Energy Transition Outlook 2024, China aims to drive energy transition through technological innovation, international cooperation, and industrial upgrading. In 2024, China's newly installed PV capacity reached 277.17 GW, a 28% year-on-year increase, setting a historical record, with cumulative capacity reaching 886.66 GW. China has ranked first globally in PV installed capacity for 10 consecutive years, with new installations leading the world for 8 consecutive years.

(2) Dual Drivers: Policy Incentives and Market Demand

China's policy support—including subsidies, tax incentives, and streamlined approvals—has significantly boosted the PV industry. Data from the National Energy Administration show that distributed PV investments surged by 76.2% year-on-year in the first half of 2024, directly promoting PV retrofits in traditional energy facilities such as oil depots. Meanwhile, market demand for green electricity continues to grow. For instance, the Qinghai Oilfield PV project has secured a 40 million kWh green power agreement, displacing 30,000 tons of standard coal and reducing 79,800 tons of CO_2 emissions.

(3) Oil Industry's Transition Challenges and Opportunities

Traditional oil industries face slowing demand growth due to competition from renewables but also encounter transformation opportunities. The International Energy Agency (IEA) predicts global PV demand will reach 492–568 GW in 2025, a 5%–7% year-on-year increase, with Chinese PV firms dominating due to cost and technological advantages. Oil companies leverage capital and infrastructure to expand PV projects. For example, Sinopec's "10,000 Stations Solar Initiative" aims to deploy 10,000 PV stations across oil fields, gas stations, and depots by 2027, achieving energy self-sufficiency and emission reduction.

(4) Application Scenarios and Advantages of Oil Depot-PV Systems

Oil depots, as critical nodes for energy storage and transportation, offer large unused land areas and stable electricity demand, making them ideal for PV integration. Distributed PV systems reduce transmission losses and enhance efficiency. For instance, Qinghai Oilfield's 1 GW PV plant was completed in just two months, becoming a benchmark for high-altitude green transition. Additionally, oil depot-PV systems can integrate with energy storage and hydrogen technologies, forming hybrid energy systems for enhanced stability.

(5) Scaling and Economic Viability

Declining PV costs and economies of scale have improved economic feasibility. Sinopec's 4,283 distributed PV stations aim to expand to 7,000 by 2025, offering a commercial model for the industry. Meanwhile, green power trading markets (e.g., Qinghai's agreements) and certification mechanisms further boost profitability.

2.2 Research Significance

(1) Necessity of the Study

As oil depot-PV applications scale up, their multidimensional fire risk coupling emerges as a critical bottleneck. The physical integration of traditional energy infrastructure and PV systems creates intertwined hazards—flammable oil vapors, high-temperature equipment, DC arcing, and module hot spots—forming an "oil-PV-electrical-environment" risk network. Current fire safety standards remain fragmented:

Oil depot regulations (e.g., GB 50074) focus on explosion-proof measures but overlook PV-induced electrical risks.

PV safety standards (e.g., IEC 62446-3) address component reliability but ignore oil-induced corrosion. This regulatory gap fails to address thermal radiation ignition, battery-pipeline heat interactions, and other coupled hazards.

(2) Research Contributions

This study supports parallel energy and safety transitions by:

Technically: Revealing dynamic interactions (e.g., oil vapor diffusion's impact on PV module temperature fields) to optimize fire separation and equipment selection.

Managerially: Developing cross-disciplinary risk models integrating oil depot operations and PV monitoring.

Policy-wise: Advocating for revised hybrid design standards with "risk coupling index" metrics.

3. RISK COUPLING PHENOMENA IN OIL DEPOT-PHOTOVOLTAIC SYSTEMS

3.1 Characteristics of Oil Depot Environments

(1) Flammable Medium Properties

The primary risk in oil depots stems from the combustibility of stored hydrocarbons, where volatilization and diffusion dynamics dictate explosive atmosphere formation:

Volatilization Mechanism: Light oils (e.g., gasoline, naphtha) exhibit high vapor pressure at ambient temperatures, continuously releasing vapors. For instance, unsealed gasoline storage tanks form vapor clouds with exponentially increasing concentrations under rising temperatures, leading to resource loss and accumulation of explosive mixtures in confined spaces (e.g., pipelines, inspection pits).

Diffusion Behavior: Oil vapors, typically denser than air, tend to settle and spread along terrain. Under windless conditions, vapors may accumulate in trenches near tank areas, creating "invisible ignition sources" often overlooked by conventional safety systems.

Ignition Sensitivity: Oil-air mixtures have extremely low Minimum Ignition Energy (MIE) (as low as 3 mJ, equivalent to human static discharge), necessitating explosion-proof equipment. However, accidental ignition sources (e.g., mechanical friction, tool impacts) remain challenging to eliminate entirely.

(2) Corrosive Environment Impacts on Equipment

Direct Material Degradation: Sulfur-containing oils react with moisture to form acids, corroding tank interiors.

Secondary Hazard Induction: Corrosion-induced failures can trigger cascading disasters. Example: A 2023 pipeline fire originated from corrosion-induced leakage, where seeped oil vaporized and was ignited by distant welding sparks.

3.2 Fire Characteristics of PV Systems

(1) Electrical Fire Triggers

PV fire risks concentrate on energy conversion and transmission:

DC Arc Faults: High-voltage DC circuits in PV systems generate arcs (≤3,000°C) that evade detection by standard breakers, carbonizing materials and propagating faults.

Hot Spot Accumulation: Partial shading (e.g., dust, bird droppings) converts affected PV cells from power generators to resistive loads, localizing heat buildup. Prolonged hot spots degrade cell structures, potentially igniting backsheets.

(2) Material Flammability

PV components like backsheets (PET, LOI: 20–22%), encapsulants, and cables are inherently flammable, releasing toxic gases (e.g., CO) upon combustion.

4. TYPICAL COUPLING PHENOMENA IN HYBRID SYSTEMS

In oil depot-PV integrations, inherent risks interact spatially, energetically, and temporally, creating synergistic fire hazards (1+1>2 effect).

4.1 Spatial Coupling: Layout Risks Between PV Arrays and Oil Tanks

Physical co-location of high-risk assets demands rigorous safety spacing:
Thermal Radiation Ignition: PV fires emit heat exceeding adjacent tanks' thermal thresholds.
Operational Conflicts: PV maintenance (e.g., welding) in explosion-prone zones introduces ignition sources.

4.2 Energy Coupling: Arc Energy vs. Vapor MIE

PV DC arcs (10–100 J) surpass oil vapors' MIE (0.16 mJ for gasoline) by three orders of magnitude, creating high ignition probabilities.

4.3 Temporal Coupling: Corrosion-Aging Synergy

Accelerated PV Degradation: Sulfur-rich vapors increase backsheet brittleness.
Maintenance-Induced Risks: Frequent PV inspections raise accidental ignition events (e.g., tool drops).

4.4 Systemic Impacts

Risk Amplification: Single faults (e.g., arcing) trigger chains: arc → vapor explosion → tank rupture → secondary fire.
Regulatory Gaps: Current standards lack metrics for "spatial-energy coupling degree", resulting in fragmented safeguards.
Management Challenges: Siloed oversight necessitates integrated risk assessment systems (e.g., dynamic risk heatmaps).

5. PREVENTION MECHANISMS

5.1 Environmental Interaction Mitigation

Corrosion-Resistant Materials: PVDF backsheets, weathering steel mounts, and Al_2O_3-SiO_2 nano-ceramic coatings for metal parts.
Microclimate Control: Ventilation channels between PV arrays reduce surface temperatures by 15°C, suppressing vaporization.

5.2 Energy Transmission Blocking

Arc Fault Detection: UV sensors + high-frequency noise analysis enable ≤50 ms arc identification, paired with rapid DC breakers.
Hot Spot Mitigation:
AI-powered drone inspections detect shading/soiling.
Heat-dissipating fins lower hot spot temperatures by 40°C.

5.3 Spatiotemporal Risk Management

Dynamic Safety Spacing: 3D Risk Field Model (CRI Index) adjusts array-tank distances in real-time.
Corrosion Monitoring: Fiber Bragg grating sensors track corrosion depth and insulation resistance.

5.4 Intelligent Integrated Platforms

Digital Twin System: GIS-integrated virtual models generate risk heatmaps using real-time sensor data (temperature, vapor concentration).
VR Training: Simulates arc flash and hot spot ignition scenarios for emergency drills.
Drone-AI Inspections: YOLOv5-based analysis of thermal images and gas spectra.
Cross-Agency Protocols: Standardized <10-minute emergency response.

6. CONCLUSION

This study deciphers the "environment-energy-spatiotemporal" coupling mechanisms governing fire risks in oil depot-PV systems. Key findings include:
Corrosive gases accelerate PV aging;
DC arc energy thresholds align with vapor MIE;
Inadequate spacing exacerbates spatiotemporal risks.
Proposed solutions—digital twins, drone-AI inspections, corrosion-resistant materials, and interdepartmental coordination—demonstrate synergies between smart monitoring and engineering controls. Future work must:
Develop multiphysics risk models for extreme events (typhoons, salt spray);
Advance edge-AI real-time prediction to shift from reactive to proactive prevention;
Establish cross-industry standards for safety spacing and material specifications.
Interdisciplinary collaboration across energy, materials science, and fire safety is critical to advancing risk governance frameworks for emerging PV-hydrogen hybrid systems.

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