Increased wildfire exposure of energy infrastructure amid declining global wildfire activity

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CLIMATE-DRIVEN WILDFIRE SURGE POSES NEW THREATS TO ENERGY INFRASTRUCTURE

The accelerating interplay between climate change and wildfires is reshaping ecosystems and socio-economic structures worldwide. Historically, wildfires functioned as ecological regulators. However, driven by anthropogenic climate change, their intensity and destructiveness have been continuously amplified.[1] Unprecedented fire events over the past decade—from Australia's "Black Summer" to record-breaking blazes in California—have altered global atmospheric circulation while inflicting economic losses exceeding USD 100 billion annually.[2] Yet, an overlooked vulnerability remains: the escalating threat wildfires pose to global energy infrastructure, a challenge compounded by geopolitical instability and systemic preparedness gaps.

Critical energy assets, including high-voltage transmission lines, substations, and fossil fuel facilities, often occupy fire-prone landscapes, simultaneously serving as wildfire casualties and ignition catalysts. From 2014 to 2023, equipment failures from California's three largest utilities ignited over 3,000 fires; notably, the 2018 Camp Fire obliterated 18,000 structures and bankrupted Pacific Gas & Electric. Renewable infrastructure proves equally vulnerable: during Australia's 2019–2020 megafires, $PM_{2.5}$ deposition reduced photovoltaic efficiency by 15%–45%,[3] concurrently forcing wind farm shutdowns amid peak demand. Climate projections indicate a 50% increase in extreme fire weather days by 2100 under current emissions trajectories, raising concerns that synchronized wildfire outbreaks and cooling-driven electricity demand surges could establish a dangerous feedback loop. Geopolitical conflicts further exacerbate these threats, as evidenced by targeted attacks on energy infrastructure in Ukraine and the Middle East,[4] where wildfires could amplify wartime destruction.

ENERGY INFRASTRUCTURE IS FACING WORSENING AND PERSISTENT EXPOSURE TO WILDFIRES

Overall, between 2012 and 2022, global wildfire occurrences decreased by 4.5% from 9.1×10^5 to 8.7×10^5. Concurrently, the total burned area declined by 16.8% from 4.4×10^8 to 3.6×10^8 hectares (Figure 1A). Despite this downward trend, the wildfire exposure risk for global energy infrastructure is continuously rising. Spatial overlay analysis reveals that 30.4% of global power plants (approximately 11×10^4) and 43.6% of energy facilities (approximately 24×10^4) were located in moderate-to-high wildfire exposure zones (10×10^4 to 30×10^4 cumulative fires) during the study period. Furthermore, 2.7% of power plants (about 10,000) and 2.2% of energy facilities (about 12,000) fell within extreme exposure zones exceeding 60×10^4 cumulative fires (Figure 1C). This situation is particularly pronounced in countries such as Australia, Brazil, the United States, Germany, and China, which represent hotspot regions where energy facilities face heightened wildfire threats.

This escalating risk profile is strongly associated with the absolute expansion of energy infrastructure over the same period. Specifically, global power plants increased by 6.7%, while energy facilities surged by 213.2% (Figure 1B). Compared to 2012, the number of power plants located in areas experiencing over 1,000 and 10,000 wildfires increased by 455 and 86, respectively. In the same high-fire regions, energy facilities grew sharply from 13,417 and 7,523 in 2012 to 42,833 and 19,198 in 2022, representing increases of 219.2% and 155.2%, respectively. However, it should be noted that in the spatial overlay analysis, wildfire data were aggregated at the national level and cumulative fire counts were used over relatively large spatial units. This may imply that the spatial exposure of energy facilities does not necessarily equate to actual losses incurred. Nevertheless, these data still clearly demonstrate that rapid energy infrastructure expansion significantly increases exposure to wildfire risks and potential damage (Figure 1D & E).

MULTILEVEL STRATEGIES AND POLICY PATHWAYS FOR REDUCING WILDFIRE EXPOSURE OF ENERGY FACILITIES

Mitigating wildfire threats to energy systems requires integrated, multilevel, and cross-disciplinary interventions. At the facility level, measures such as enforcing the use of fire-resistant materials in accordance with the International Wildland-Urban Interface Code (https://www.iccsafe.org/), burying key transmission corridors underground, and establishing buffer zones around substations can be implemented. Concurrently, deploying artificial intelligence monitoring systems, for example, the global in-orbit AI platform "Wildfire Guardian" developed by the German company OroraTech (https://ororatech.com/), which can significantly enhance real-time wildfire detection and early-warning capabilities. At the system design level, priority should be given to developing distributed micro-grids in conflict prone areas, while incorporating wildfire risks into multilateral energy-security frameworks such as the International Energy Charter. On the technological front, merging satellite remote sensing with Internet of Things (IoT) data streams is essential to build intelligent prediction models and enable adaptive grid control. Concurrently, fostering inherently resilient energy infrastructures, such as geothermal systems, remains a strategic imperative.

At the institutional and financial levels, system operators can leverage mechanisms such as the United Nations Environment Programme (UNEP) Principles for Sustainable Insurance, the EU Critical Raw Materials Act, and the US Inflation Reduction Act to establish risk-sharing insurance systems and link wildfire resilience of energy facilities to permitting processes. At the same time, it is essential to strengthen energy siting and planning, improve cross-sectoral coordination between energy and wilderness management,[5] promote community-based adaptive governance, and enhance technical and financial support for developing countries through channels such as the Green Climate Fund. In summary, in an era of climate extremes, the multidimensional integration of technological reinforcement, system redesign, policy innovation, and international cooperation can effectively enhance the overall resilience of energy systems (Figure 1F).

SUMMARY AND OUTLOOK

This commentary reveals a striking paradox: global wildfire incidents have declined, yet expanding energy infrastructure faces sharply increased fire exposure. Currently, over 30% of power plants and 40% of energy facilities

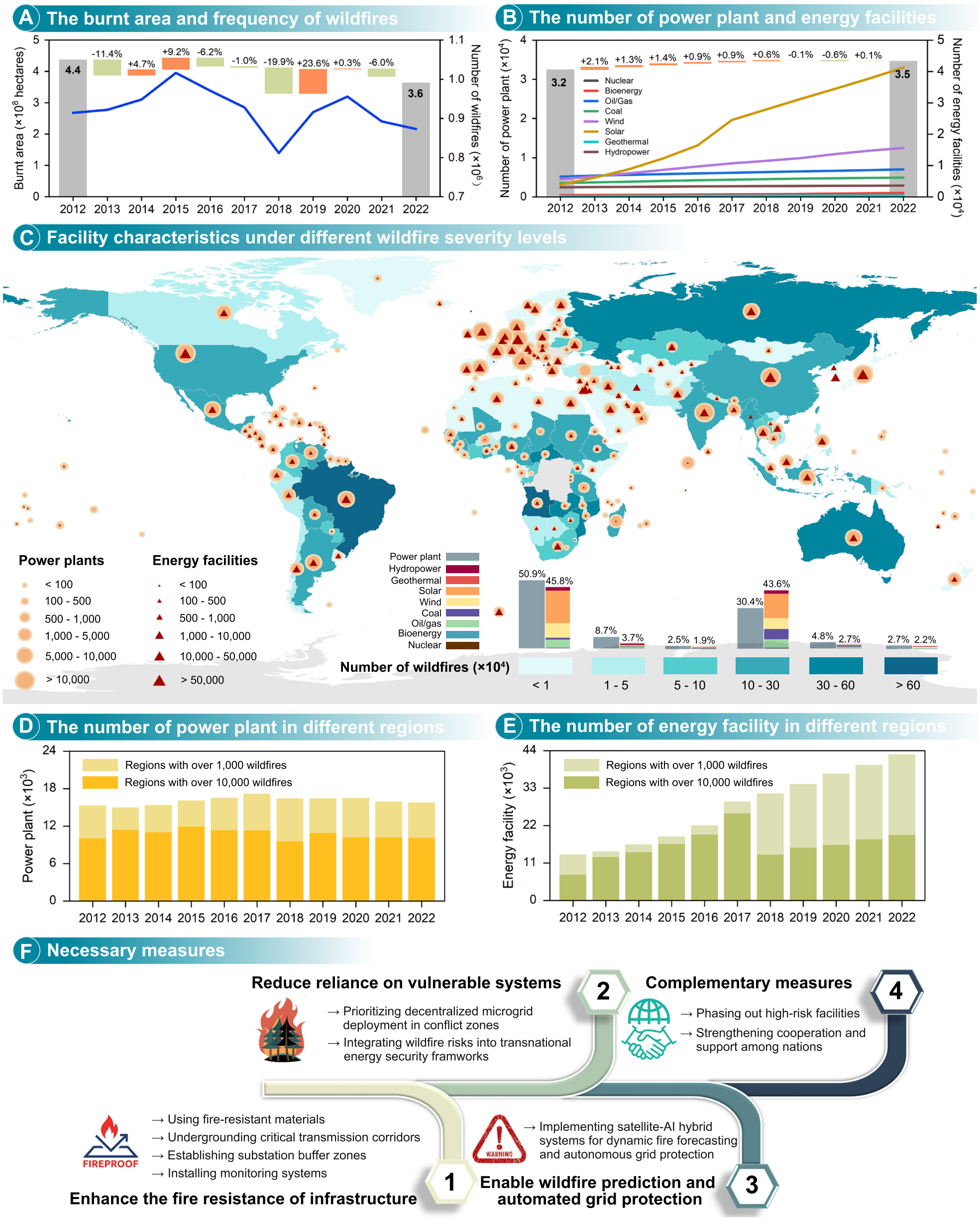

Figure 1. The multidimensional spatio-temporal patterns of energy infrastructure exposure to wildfires. Herein, (A) illustrates the trends in global wildfire burned area and the number of wildfire occurrences from 2012 to 2022, where the bridge chart depicts changes in burned area, the line graph represents the count of wildfires; (B) presents the trends in the number of power plants and energy facilities worldwide during the same period, with the bridge chart indicating changes in the quantity of power plants, the line graph reflecting variations in the number of different energy facilities; (C) illustrates the spatial distribution of energy facility exposure across different wildfire intensity categories, where yellow circles represent the number of power plants per country (larger circles indicate higher counts), triangles denote the quantity of energy facilities per country (larger symbols correspond to greater numbers), and the histogram in the legend associated with different quantity categories illustrates the proportional distribution of power plants and energy facilities; (D),and (E) show the temporal variations in exposure levels for power plants and energy facilities, respectively, in areas where the annual cumulative wildfire occurrences exceed 1,000 and 10,000 events during the study period. (F) outlines a policy recommendation process for reducing the exposure of energy assets to wildfires.

occupy areas experiencing 10,000–30,000 wildfires during the study period, revealing critical systemic vulnerabilities. In response, system operators and planners should not only enhance grid resilience through measures such as fire-resistant design and distributed microgrids, but also integrate energy wildfire exposure layers into siting and repowering decisions for energy infrastructure. Priority should be given to hardening or implementing managed retreat for the small fraction of energy assets located in extreme risk zones. Furthermore, wildfire risk scenarios that energy facilities may face should be incorporated into their reliability standards and stress tests. On the other hand, this commentary has certain methodological and data limitations. For example, aggregating wildfire data at the national scale may obscure regional hotspots of energy facility exposure, and the lack of asset level vulnerability modeling prevents quantitative estimation of wildfire-induced losses to energy facilities. In future research, we will develop asset level exposure and vulnerability models for energy infrastructure using AI techniques to quantitatively estimate the specific losses caused by wildfires to energy facilities.

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DECLARATION OF INTERESTS

The authors declare no competing interests.