Integrating climate risk assessment into the Renewable-dominated Power System

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Renewable-dominated Power System (RDPS) is emerging as critical trend to achieve CO_2 emission reduction, and the COP28 climate summit has set a global goal to triple its capacity to at least 11,000 GW by 2030. However, this system is heavily reliant on weather and climate conditions. While the inclusion of the storage in the RDPS can alleviate the impact of the volatility and intermittency, the new source-grid-load-storage system creates more risks resulting from increasing complexity of interconnections. These include heightened variability in renewable energy generation under extreme weather, growing instability in transmission infrastructure due to climate-induced stress, performance degradation of storage systems under temperature extremes, and limited flexibility in demand response during climate-driven load surges. Critically, these risks are not isolated but often interdependent, as climate-triggered disruptions in one part of the system can cascade across interconnected components and amplify local failures into large-scale outages. In this perspective, we assess the risks for the system across source, grid, load, and storage from the dimensions of hazard, exposure and vulnerability, highlight the emerging cascading risks driven by climate variability and extremes, and call for an urgent expansion of climate risk assessment frameworks to ensure the resilience and reliability of future power systems.

INTRODUCTION

The global energy sector is undergoing a profound transformation toward deep decarbonization, with the renewable-dominated power systems (RDPS) becoming a central pillar in the pursuit of net-zero CO_2 emissions. In 2024, the global average surface temperature exceeded 1.5 °C above pre-industrial levels for the first time on the annual basis, while the carbon dioxide emissions reached a record high of 37.41 Gt, underscoring the urgency of accelerating the energy transition and the narrowing opportunity window for meaningful mitigation.[1,2] The growing mismatch between mitigation ambition and emission trajectories has made the large-scale deployment of renewable energy an imperative rather than an option. In response, the 28th session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP28) has set a global target to triple renewable energy capacity by 2030, reflecting an unprecedented commitment to the large-scale deployment of solar, wind, and other variable renewable energy sources.[3] This ambition has already begun to be translated into action, with 585 GW of renewable capacity added globally in 2024, accounting for 92.5% of new generation capacity. Total installed renewable capacity has surpassed 4,448 GW, providing more than 30% of global electricity.[4,5]

This large-scale shift in energy infrastructure, however, brings not only decarbonisation opportunities but also a new spectrum of operational, systemic, and climatic, challenges. Unlike conventional power systems dominated by dispatchable and controllable generation, the RDPS are inherently dependent on weather and climate conditions. Their output is subject to fluctuations in solar radiation, wind speed, precipitation and other meteorological factors, leading to temporal and spatial mismatches between electricity supply and demand. In addition, the frequency and severity of climate extremes (such as heatwaves, droughts, floods and storms) are projected to intensify under ongoing global warming, further increasing the risk of weather-induced disturbances. In China alone, the technical potential of wind power is projected to decline by approximately 10% due to long-term changes in wind patterns. Empirical evidence already indicates that nearly half of the 236 major power outages recorded globally in 1965-2025 were caused by weather- and climate-related events.[6] This trend is likely to become even more pronounced in the future. Consequently, the RDPS will have to withstand an increasingly hostile and less predictable climate change in the future.

As the RDPS continue to evolve by integrating renewable energy generation, advanced grids, flexible demand, and energy storage, the power system becomes more interconnected and complex. This shift introduces new risk patterns that are different in both nature and scale from those in traditional power systems. Climate risks to power-system security are intensifying, encompassing not only fluctuations in renewable generation but also deteriorating transmission stability, declining storage efficiency, and diminishing responsiveness of flexible demand. The impact of climate change on the power system has two main aspects. On the one hand, climate change can make the spatiotemporal distribution of renewable resources more uneven, such as wind energy may decrease at northern mid-latitudes as results of lower wind speed. On the other hand, the occurrence of extreme weather becomes more frequent with the intensification of global warming, imposing a greater risk on all links of the RDPS. Importantly, such risks are no longer discrete or localized. Instead, they interact across temporal and spatial boundaries. Climate-induced disruptions in one subsystem may propagate through the network, triggering a cascade of failures that amplify local disturbances into large-scale outages. The resulting cascading risks pose serious challenges to power system reliability and resilience.

Although awareness of climate risks to energy systems is growing, current risk assessment remains fragmented and often overlooks the complex interdependencies in the RDPS. As weather-driven generation, transmission, storage, and demand become increasingly linked, disruptions in one part can cascade across the system and trigger large-scale failures (Figure 1). Addressing these challenges requires a more integrated, climate-informed, approach that reflects the nonlinear dynamics of the RDPS. This perspective examines how the shift to RDPS creates a new class of risks and calls for rethinking risk governance to ensure resilience under intensifying climate stress.

CLIMATE HAZARDS ACROSS THE SOURCE-GRID-LOAD-STORAGE

Climate-related hazards that threaten the RDPS encompass both long-term climate shifts and acute extreme weather events, each posing distinct challenges across the source-grid-load-storage chain. Long-term changes in climate elements (such as wind speed, solar radiation, and precipitation) primarily affect the generation side by altering the spatial and temporal availability of renewable energy resources. For instance, declining wind speeds in the northern mid-latitudes can reduce wind energy production, while variations in radiation patterns impact the efficiency of photovoltaic (PV) genera-

Hazards	Source			Grid	Load	Storage
	Wind	Solar	Hydro			
Heatwave /Drought	/	Reduction of generation efficiency of crystalline silicon PV panels	Decrease of available water flow to reduce generation	Increase of electrical resistance to reduce transmission efficiency	Increase of cooling demand	High temperature reduces battery's performance and longevity
Cold wave /Snow and ice	Snow and ice accumulation on wind turbine blades reduces power output	Snow and ice cover reduce the efficiency of PV panels and the weight of snow may damage panels	Ice in rivers and reservoirs affects water flow and turbine operation	Wire icing, power lines sagged and broke	Increased heating demand	Low temperature can slow down the chemical reactions within the batteries
Flood	/	Flooding of electronic components, leading to short circuits	Extreme flood can damage infrastructure such as dams and turbines	Short circuits and physical damage to power lines and substations	/	Flooding of electronic components
Tropical cyclone	Damage of wind turbine and reduction of output	Physical damage to panels and supports, and potential electrical faults	Extreme flood caused by typhoons can damage infrastructure such as dams and turbines	Strong winds break lines and topple power poles, heavy rainfalls submerge transformers and substations	/	Strong wind and rain make water ingress in battery cabinets
Lightning	Lightning strikes on wind turbines can cause significant damage to blades and generators	Physical damage to panels, inverters, and cables	/	Insulation breakdown and line damage	/	/
Sandstorm	Sand particles cause erosion on wind turbine blades	Sand particles can abrasive protective glass of solar panels, reducing optical transmission	/	Sand accumulation on insulators can lead to insulation failure and short circuits	/	/

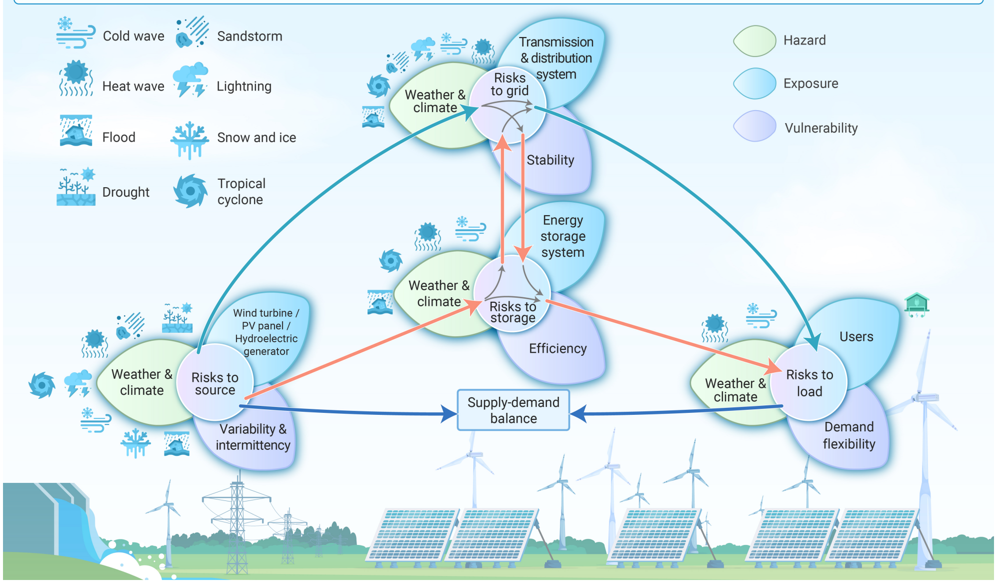

Figure 1. Framework of the climate risk assessment for the RDPS

tion. In China, from the 1970s to the early 21st century, near-surface wind speed exhibited a significant downward trend, with a decrease rate of approximately 2.1% per year. Similarly, solar radiation declined by 29.04 $MJ \cdot m^{-2}$ per decade, indicating a substantial long-term reduction in solar resource availability. These climatic trends not only suppress renewable output but also necessitate continuous adjustment of the spatial layout of wind farms and solar installations. They influence siting decisions, capacity factors, and even the economic viability of renewable projects over decadal time scales. Moreover, long-term hydrological shifts such as changes in precipitation patterns and snowmelt dynamics can influence hydropower generation and grid balancing. Unlike these gradual changes, extreme weather and climate events such as tropical cyclones, heatwaves with drought, cold waves, flooding, and sandstorms can disrupt every segment of the RDPS (Table in Figure 1). On the generation side, heatwaves reduce PV efficiency by approximately 0.66% per 1°C increase above 25°C,[7] while snow and ice can impair both solar panels and wind turbines. Transmission and distribution systems face physical damage and derating from lightning, icing, strong winds, and thermal stress. Storage systems are sensitive to temperature extremes. Cold conditions decrease electrochemical reaction rates and reduce capacity, while heat accelerates battery aging and safety risks. Load-side impacts include surging demand during climate extremes, such as increased air conditioning use during heatwaves or heating loads during cold waves, which can coincide with supply shortfalls. These hazards are not isolated, and events like snowstorms or tropical cyclones can simultaneously degrade generation, damage infrastructure, strain storage, and spike demand, making the RDPS particularly vulnerable to cascading failures triggered by compound climate extremes.

EXPOSURE OF POWER INFRASTRUCTURE TO CLIMATE EXTREMES

As the deployment of the RDPS expands rapidly, the spatial and structural exposure of critical power infrastructures to climate hazards has grown significantly. The increased frequency and severity of extreme weather events (such as snowstorms, high temperatures, strong winds, and sandstorms) now threaten a wider array of components across the source-grid-load-storage chain. The IPCC AR6 publications indicate that the frequency of heavy precipitation events, which currently occur once every 20 years, is likely to increase by 10%. Heatwaves that occur once every 10 years and 50 years are expected to increase to 4.1 and 8.6 times the pre-industrial levels, respectively. Drought frequencies that occur once every 10 years are projected to double.[8] These statistics underscore not only a global intensification of climate extremes but also a fundamental shift in baseline risk, as events that were once exceptional are becoming increasingly commonplace. Due to land and resource constraints, wind turbines and solar PV panels are often installed in climatically harsh and remote regions (such as deserts and plateaus), where meteorological hazards are more pronounced. While these areas offer favourable renewable resource conditions, they simultaneously heighten the physical exposure of energy assets to climate-induced damage. For instance, ice and snow can accumulate on turbine blades or solar modules, causing structural strain and reducing efficiency, while sandstorms and extreme heat accelerate material degradation and lower output. For the power grids, the densification and geographical expansion of modern transmission grids and distribution networks, especially with the widespread deployment of Ultra-High Voltage (UHV) lines and low voltage overhead lines, has increased the exposure of both long-distance transmission corridors and urban distribution feeders to lightning, wind loads and ice accretion. In China, 35 UHV projects had been completed by the end of 2020, and another 35 projects are planned under the 14th Five-Year Plan (2021-2025), collectively involving over 30,000 km of transmission lines.[9] These lines deliver unrivalled capacity and land-use efficiency, yet their very concentration of gigawatt-scale power also leaves the grid increasingly exposed to lightning, gales and icing. Moreover, to balance renewable variability and rising demand, the RDPS increasingly deploy distributed resources and small-scale energy storage systems, typically household or community units that are often sited on urban fringes or scattered rural locations with little weather protection, leaving them exposed to physical damage. At the same time, urban households and industrial users already constitute massive exposure vectors whose peak loads are rising with continued electrification and economic growth, are vulnerable to simultaneous cooling or heating demand during extreme heat or cold, potentially triggering demand-side curtailment or localized outages.

STRUCTURAL VULNERABILITIES OF THE RDPS

The vulnerability of the RDPS is structurally embedded in its source-grid-load-storage architecture, where each component exhibits specific susceptibilities under climate stress. On the generation side, the intermittency of renewable sources such as wind and solar is intrinsically tied to meteorological variability, with factors like wind speed fluctuations, cloud cover, dust, or heatwaves directly reducing power output and equipment efficiency. Moreover, physical hazards such as icing, snow accumulation, or sand abrasion can damage turbines and PV modules, causing prolonged outages. On the power grids side, the increasing reliance on long-distance UHV corridors and complex meshed networks has expanded the physical footprint of power lines, exposing them to high-impact events such as typhoons, rainstorms, and ice storms. Due to the linear and interconnected nature of grid infrastructure, local failures can rapidly escalate into widespread outages. On the load side, energy consumption patterns are now tightly coupled to weather extremes. Prolonged heatwaves push loads of air conditioning to record levels, especially in high-rise urban agglomerations where waste-heat entrapment further amplifies cooling demand, while severe cold snaps simultaneously drive electric-heating spikes across residential, commercial and increasingly electrified industrial sectors. These temperature-driven peaks are effectively rigid since users can neither postpone nor forgo them without jeopardising health or critical processes and the resulting synchronised stress peaks leave little redundancy for contingency events. On the storage side, while energy storage is critical for buffering supply-demand imbalances, current battery technologies are highly sensitive to temperature extremes. Cold weather reduces electrochemical reaction rates, while heat accelerates battery aging and raises safety risks such as thermal runaway. Additionally, short storage durations (typically 2–4 hours) limit system resilience during prolonged extreme events.[10]

CASCADING RISKS UNDER CLIMATE EXTREMES

The RDPS exhibits pronounced interdependencies across its source, grid, storage, and load components, making it inherently vulnerable to cascading risks under compound or sequential climate extremes, which often culminate in severe supply-demand imbalances. In the traditional power system, the meteorological risk chain followed a single, linear path: source-grid-load. With the integration of storage, this chain splits into three simultaneous and dynamically switchable configurations: (1) source-grid-storage-load, where renewable electricity is first fed into the grid and then buffered by centralized storage before delivery; (2) source-storage-grid-load, where generation is first absorbed by distributed or community-scale storage and subsequently released to the grid for end-users; (3) source-storage-load, a micro-grid configuration in which generation is stored locally and consumed on-site, with the grid acting only as a residual backup. When a climate hazard (such as snowstorm, heatwave, or typhoon) impacts one part of the system, its effects can rapidly propagate through other components. For instance, the 2025 Iberian Peninsula blackout demonstrated how a sudden grid disturbance led to the simultaneous disconnection of over 20 GW of renewable energy generation in Spain and Portugal. This caused a rapid collapse of the transmission network, emergency discharging of storage systems, and widespread load shedding. The outage affected more than 10 million people, disrupting transport, healthcare, and industrial operations. Although the event was initially triggered by voltage instability, it revealed how localized failures in generation can cascade into grid congestion, storage depletion, and massive load loss, amplifying the systemic impact. A similar example is the 2022 South Australia blackout. A series of thunderstorms and tornadoes damaged multiple transmission towers, forcing the automatic isolation of renewable energy generators. Although grid-scale storage responded quickly, the speed and scale of the disruption overwhelmed the system's capacity to maintain stability, resulting in power outages for approximately 500,000 customers, and the post-event analysis estimated that cascading losses totalled AUD 430 million. This event illustrates how extreme weather can simultaneously compromise multiple parts of the RDPS by damaging grid infrastructure, disrupting generation, draining storage, and creating sharp demand imbalances, ultimately leading to cascading failures across the entire system.

CONCLUDING REMARKS

As the global energy system transitions toward the RDPS, ensuring its resilience under intensifying climate stress has become an urgent priority. While the expansion of solar, wind, and storage technologies is central to achieving decarbonization goals, the RDPS introduces a new set of risks shaped by its deep reliance on weather-sensitive generation, complex interconnections, and distributed infrastructure. These risks span the entire source-grid-load-storage chain and are further amplified by climate hazards that are becoming more frequent, severe, and compound, often striking multiple regions concurrently and extending outage durations from hours to days. Our assessment highlights that these risks are not isolated, but deeply interdependent. Climate disruptions in one subsystem can rapidly propagate through others, triggering cascading failures with far-reaching social and economic consequences. Addressing these challenges requires moving from isolated, component-based, risk management to a more integrated approach that considers how different parts of the system interact and respond to changing climate conditions, and that embeds adaptive capacity at the planning, operation, and market levels.

REFERENCES

1. WMO (World Meteorological Organization). (2025). WMO confirms 2024 as warmest year on record at about 1.55°C above pre-industrial level. https://wmo.int/news/media-centre/wmo-confirms-2024-warmest-year-record-about-155degc-above-pre-industrial-level
2. GCB (Global Carbon Budget). (2024). https://globalcarbonbudget.org/gcb-2024/
3. IRENA (International Renewable Energy Agency). (2023). World energy transitions outlook 2023: 1.5°C pathway. https://www.irena.org/Publications/2023/Jun/World-Energy-Transitions-Outlook-2023
4. IEA (International Energy Agency) (2025). Global Energy Review 2025. https://www.iea.org/reports/global-energy-review-2025/co2-emissions
5. IRENA (International Renewable Energy Agency). (2025). Renewable capacity statistics 2025, International Renewable Energy Agency, Abu Dhabi. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2025/Mar/IRENA_DAT_RE_Capacity_Statistics_2025.pdf
6. GEIDCO (Global Energy Interconnection Development and Cooperation Organization). (2025). Global Energy Interconnection Report. China Electric Power Press. https://wikimili.com/en/List_of_major_power_outages
7. Radziemska E. (2003). The effect of temperature on the power drop in crystalline silicon solar cells. *Renew. Energy* **28**:1−12. DOI:10.1016/S0960-1481(02)00015-0
8. Intergovernmental Panel on Climate Change. (2021). Climate Change 2021: The Physical Science Basis. *IPCC* **2**:2391. https://www.ipcc.ch/report/ar6/wg1/
9. National Development and Reform Commission. (2022). The 14th Five-Year Plan for Renewable Energy Development. https://www.ndrc.gov.cn/xwdt/tzgg/202206/t20220601_1326720.html
10. National Renewable Energy Laboratory. (2023). Moving Beyond 4-Hour Li-Ion Batteries: Challenges and Opportunities for Long(er)-Duration Energy Storage. https://research-hub.nrel.gov/en/publications/moving-beyond-4-hour-li-ion-batteries-challenges-and-opportunitie

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AUTHOR CONTRIBUTIONS

All authors contributed the data collection and writing. The corresponding author conceived the project. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.