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Perspective

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Resilience of renewable power systems under climate risks

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Abstract

Climate change is expected to intensify the effects of extreme weather events on power systems and increase the frequency of severe power outages. The large-scale integration of environment-dependent renewables during energy decarbonization could induce increased uncertainty in the supply–demand balance and climate vulnerability of power grids. This Perspective discusses the superimposed risks of climate change, extreme weather events and renewable energy integration, which collectively affect power system resilience. Insights drawn from large-scale spatiotemporal data on historical US power outages induced by tropical cyclones illustrate the vital role of grid inertia and system flexibility in maintaining the balance between supply and demand, thereby preventing catastrophic cascading failures. Alarmingly, the future projections under diverse emission pathways signal that climate hazards – especially tropical cyclones and heatwaves – are intensifying and can cause even greater impacts on the power grids. High-penetration renewable power systems under climate change may face escalating challenges, including more severe infrastructure damage, lower grid inertia and flexibility, and longer post-event recovery. Towards a net-zero future, this Perspective then explores approaches for harnessing the inherent potential of distributed renewables for climate resilience through forming microgrids, aligned with holistic technical solutions such as grid-forming inverters, distributed energy storage, cross-sector interoperability, distributed optimization and climate–energy integrated modelling.

Sections

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Key points

- Large-scale integration of environment-dependent renewables coupled with intensifying climate extremes introduces superimposed risks on future net-zero power systems, expected to increase the frequency of severe power outages.

- High-penetration renewable power systems under climate change may face escalating challenges, including more severe infrastructure damage, lower grid inertia and flexibility, and longer post-event recovery.

- Achieving a climate-resilient power system in a net-zero future requires approaches for harnessing the inherent potential of distributed renewables through forming microgrids.

Introduction

Electric power systems serve as critical lifelines that underpin modern societies and enable the functioning of nearly every aspect of contemporary existence. The electricity sector holds a prominent role in the energy transition towards decarbonization and climate change mitigation[1]. As outlined in the Sixth Assessment Report (AR6) of the United Nations Intergovernmental Panel on Climate Change (IPCC)[2], the imperative to limit global warming to 2 °C necessitates a shift towards over 90% of the world's electricity being generated from low-carbon sources, and mandates that proactive measures start immediately.

Decarbonizing the electricity sector is in full swing globally. The US Inflation Reduction Act of 2022, the most prominent piece of climate legislation from the US government so far, has strongly promoted renewable energy development, committing nearly US$400 billion to mitigate climate change[3]. The European Green Deal of the European Union sets an ambitious action plan to ensure that at least 32% of the EU's total energy consumption comes from renewable sources by 2030[4]. The 14th Five-Year Plan of China anticipates that by 2030, non-fossil sources will account for approximately 25% of the total energy consumption, with over 1,200 GW combined installed capacity of wind and solar energy[5]. Although the goal of the energy transition is to mitigate climate change, its effects on reversing the warming trend are expected to be gradual and slow[6]. On the long-term pathway towards climate mitigation, power system resilience – the ability of a power system to withstand and recover from high-impact low-probability hazards[7] – is undergoing escalating challenges due to climate change and the intensified extreme weather events. From 2000 to 2021, over 80% of US power outages were associated with extreme events such as hurricanes, wildfires, heatwaves and flooding, with 2011–2021 witnessing a 78% increase in weather-associated power outages compared with 2000–2010[8,9]. Hurricane Maria in 2017 and Hurricane Fiona in 2022 both wreaked havoc on the Puerto Rico power grid, plunging the entire island into darkness and resulting in an estimated total damage cost of US$113.3 billion[10].

Climate change is intensifying climate extremes such as heatwaves[11] and tropical cyclones (a generic term including hurricanes and typhoons)[12–14] that have caused considerable effects on energy systems. In anticipation of economic development and climate mitigation policies, the Shared Socioeconomic Pathways (SSPs)[15] have been developed in association with the IPCC AR6. The SSPs outline five global socioeconomic pathways (SSP1–5: from sustainable to conventional economic growth) that correspond to different radiative forcing levels (2.6–8.5 W m^{-2}) by 2100[16]. For example, SSP2-4.5 and SSP5-8.5 exemplify moderate and high greenhouse gas emission scenarios. Future projections under all emission scenarios suggest an increase in global average temperature of 0.8–1.3 °C from the present to the 2050s, accompanied by more-intense heatwaves, tropical cyclones and floods[17–19]. Additionally, the likelihood of experiencing multiple hazards simultaneously or sequentially – that is, compound hazards – is also expected to increase[20–22].

Despite the intensifying climate risks, modern power system infrastructures become more exposed to the environment, owing to the large-scale integration of renewable energy such as solar photovoltaic systems and onshore and offshore wind farms[23–25]. Currently, most bulk power systems operate with relatively low renewable penetration (the proportion of total energy consumption supplied by renewables), such as 21.5% in the US mainland[26]. However, in view of net-zero emission targets, traditional power systems are expected to be reshaped to renewable-dominated formats with, for example, over 80% penetration[27]. Leading renewable generation infrastructures, including solar panels and wind turbines, are sensitive to the environment and vulnerable to climate extremes[28,29]. As a result, large-scale integration of these variable renewable energy resources is associated with increased operational uncertainty in maintaining stringent real-time electricity supply–demand balance during extreme weather events[30].

The risks posed by climate change and integration of renewable energy (Fig. 1a) are not independent but rather interconnected. Globally, large-scale integration of renewable energy will eventually mitigate the effect of climate change. However, throughout this prolonged global energy transition, an individual power system might still face compound risks from climate change and renewable integration. For example, under a severe climate change scenario for 2050 (SSP5-8.5), a high-penetration renewable power system might face much higher risks than systems either with lower penetration or under less-severe climate scenarios (Fig. 1b). Moreover, electricity demand is expected to increase in the future because of more-frequent and more-intense heatwaves[31,32]. This spike in demand contrasts with the projected decline in renewable generation due to disruptions caused by extreme climate events (Fig. 1c). The gap between electricity supply and demand could be further enlarged during compound hazards – such as a tropical cyclone followed by a heatwave, causing tropical-cyclone–blackout–heatwave hazards[33]. Consequently, the intensification of climate extremes coupled with an increased penetration of renewable energy resources introduces superimposed risks to future net-zero power systems.

Informed by observations of climate change and ongoing energy decarbonization, the research community has increasingly emphasized the need to bridge the fields of climate and energy. Such integration has been examined and discussed from multiple angles, including energy sustainability and policies[34], decarbonization for climate change mitigation[35,36], system design and operation[37,38], and socioeconomic costs[39]. However, the interdependence of the risks from escalating climate extremes and large-scale renewable integration – that is, the climate-renewable superimposed risk – requires further investigation. Specifically, there is a lack of comprehensive understanding of the effects of climate extremes on renewable-dominated power systems.

In this Perspective, we outline current understanding of the climate-related risks to renewable energy and describe potential solutions aimed at reducing these risks and achieving climate resilience of future power systems. We discuss the lessons learned from historical blackouts in the United States caused by tropical cyclones and analyse

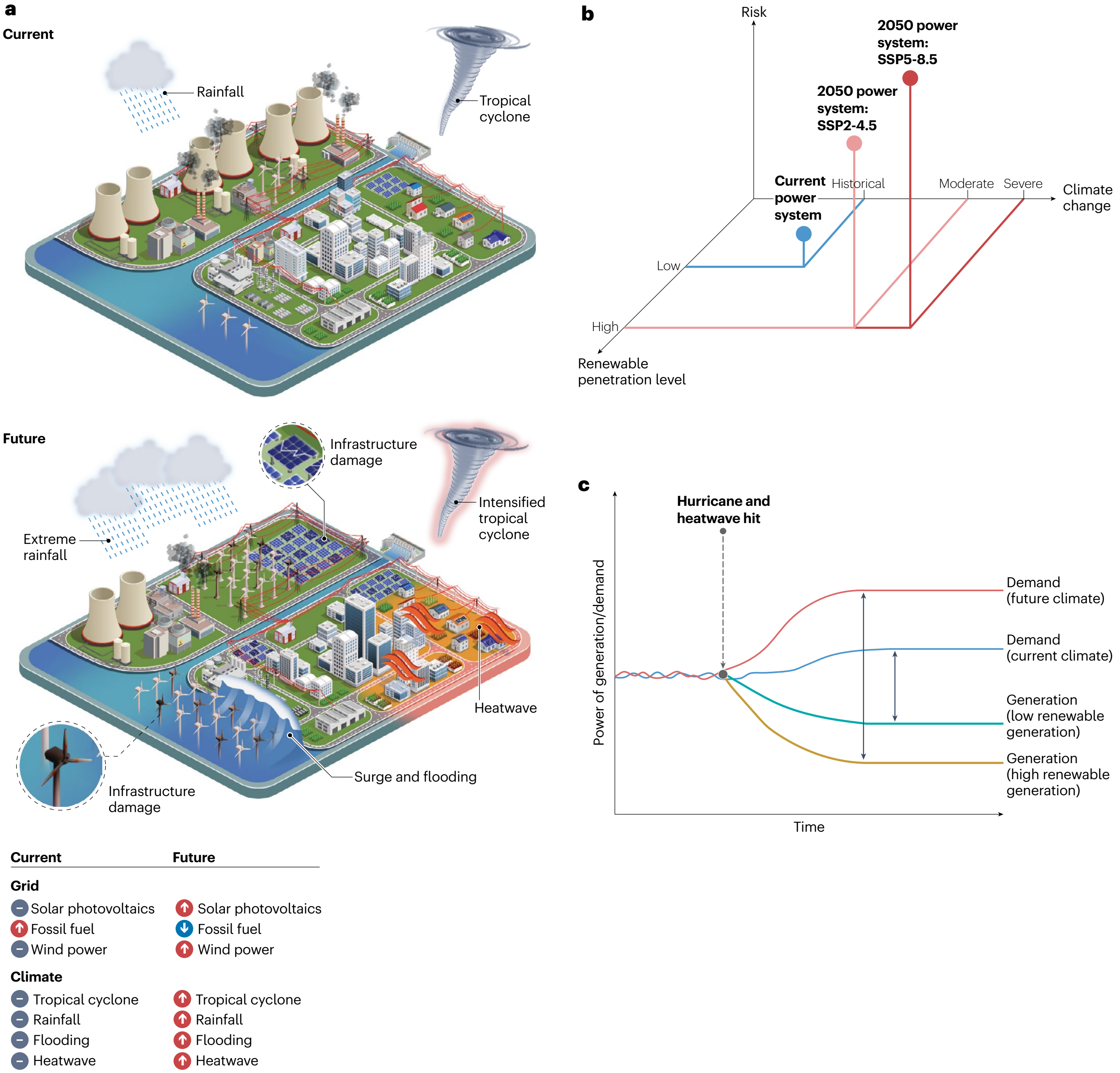
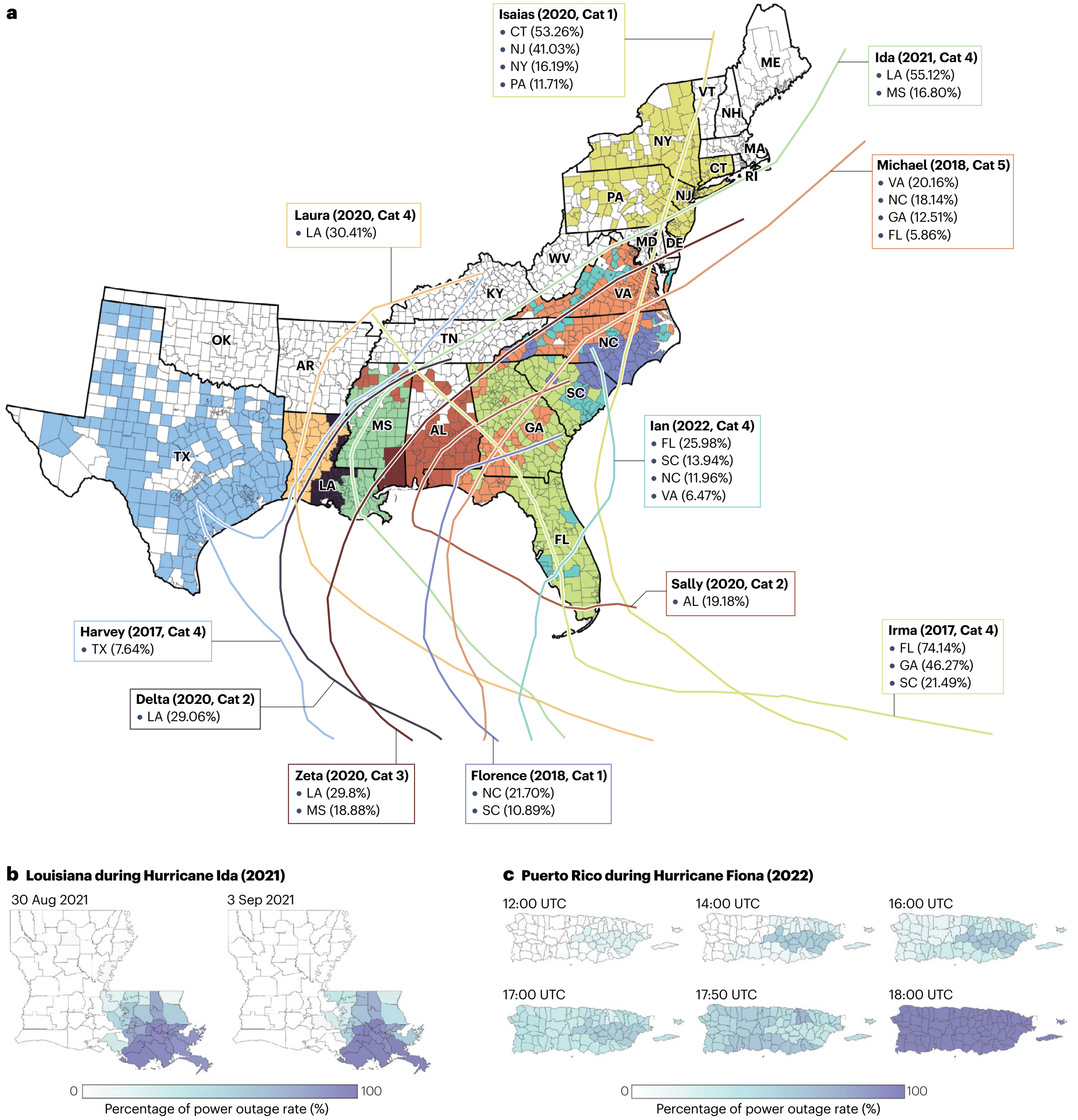


Fig. 1 | Superimposed risks for future high-penetration renewable power systems. a, Traditional power systems under current climate conditions differ considerably from future renewable-dominated power systems operating under intensifying climate risks. In the bottom panel, red increase symbols denote dominant power generation methods or intensifying climate extremes, blue decrease symbols indicate power generation methods with decreasing proportions, and grey neutral symbols indicate non-dominant power generation methods or climate extremes without intensification. **b**, Superimposed risks for current and future power systems under different climate scenarios. Current power systems in the historical climate present a low-risk scenario (blue). High-penetration renewable power systems under future moderate (SSP2-4.5, pink) and high (SSP5-8.5, red) emission scenarios present increasing levels of risk. SSP, shared socioeconomic pathway. **c**, Current and future imbalances between energy demand and generation due to intensifying compound climate extremes and renewable energy penetration. During a compound hazard (a hurricane followed by a heatwave), a future power grid with high renewable penetration is expected to face a larger generation loss than one with low renewable penetration, owing to the climate vulnerability of environment-dependent renewables. Moreover, electricity demand is expected to increase owing to more-intense heatwaves in the future climate than in the current climate.



the key factors that influence power system resilience. Taking into account projections of future climates under different emission pathways, we evaluate future tropical-cyclone and heatwave hazards along with their compound risks along the US East and Gulf coasts and discuss the escalating challenges they pose for future power systems with high penetration of renewables. However, we emphasize that large-scale integration of distributed renewable energy resources brings more than just the challenges posed by these superimposed risks: it also offers an opportunity to achieve climate resilience through forming microgrids, supported by interdisciplinary cutting-edge solutions. With a focus on intensifying climate risks on renewable power systems in the United States for specific analysis, this Perspective points to the broader importance and urgency of incorporating climate resilience into the global renewable energy transition.

Fig. 2 | Tropical-cyclone-induced power outages in the United States during 2017–2022. a, Regions in the USA affected by tropical-cyclone events. Each event is assigned a unique colour. Each county is shaded with the colour associated with the tropical cyclone responsible for the largest peak power outage in that county. Each tropical-cyclone track has an associated label denoting the hurricane name, its occurrence year and the intensity category at landfall (Cat 1, 119–153 km h^{-1}; Cat 2, 154–177 km h^{-1}; Cat 3, 178–208 km h^{-1}; Cat 4, 209–251 km h^{-1}; Cat 5, 252 km h^{-1} or higher[138]), followed by the state abbreviation and its maximum power outage percentage (only those with over 5% power outages are noted). The US state abbreviations refer to: AL (Alabama), AR (Arkansas), CT (Connecticut), DE (Delaware), FL (Florida), GA (Georgia), KY (Kentucky), LA (Louisiana), MD (Maryland), MA (Massachusetts), ME (Maine), MS (Mississippi), NC (North Carolina), NH (New Hampshire), NJ (New Jersey), NY (New York), OK (Oklahoma), PA (Pennsylvania), RI (Rhode Island), SC (South Carolina), TN (Tennessee), TX (Texas), VA (Virginia), VT (Vermont) and WV (West Virginia). **b**, Spatiotemporal maps of persistent power outages in Louisiana, USA, during Hurricane Ida (illustrated by a comparison of data from 30 August and 3 September 2021[42]; landfall occurred on 29 August 2021). **c**, Spatiotemporal maps of power outages in Puerto Rico during Hurricane Fiona (timeseries are from 18 September 2022[42]; landfall occurred at 19:20 UTC on 18 September).

Lessons from past blackouts

In the past decade, hurricanes have threatened the power grids serving nearly 60 million people along the US East and Gulf coasts, as well as US territories such as Puerto Rico[40,41]. Power outages resulting in catastrophic blackouts have become increasingly common during such extreme weather events[9]. This trend, marked by a nationwide increase in annual power outage durations, has magnified societal concerns regarding power system resilience. Large-scale spatiotemporal datasets on US power outages[42] sparked by severe hurricanes from 2017 to 2022 (Fig. 2) provide important information on the resilience characteristics of US power grids. The lessons learned from these historical events not only lay the foundation for understanding the superimposed risks on future high-penetration renewable power systems under intensifying climate change but also pave the way for developing future climate-resilient net-zero power systems.

Events overview

Widespread power outages caused by hurricanes over the past 6 years (Fig. 2a) remind us that our current power systems are not fully prepared to cope with intensifying climate risks. In 2017, the US East and Gulf coasts experienced two substantial disruptions: Hurricane Irma left over 70% of residents in Florida without electricity, and Hurricane Harvey disabled over 10,000 MW of electricity generation capacity in Texas, which took over a week to restore. During 2018–2020, Hurricanes Florence, Michael, Laura, Isaias, Sally, Delta and Zeta collectively caused severe outages that affected 0.6–4.3 million customers at their peak. Hurricane Ida in 2021 led to the most extensive power outage in the history of Louisiana, with the loss of 200 million customer hours, which surpassed both Hurricane Katrina in 2005 (140 million customer hours) and Hurricane Laura in 2020 (110 million customer hours). Recovery from the power outage was notably slow over the initial 5 days following Hurricane Ida (Fig. 2b) owing to long-lasting flooding in New Orleans. In 2022, the devastating Hurricane Ian made landfall twice on the US East Coast and resulted in power outages comprising over 3.5 million customer hours across four states. Other remarkable catastrophic blackouts happened in Puerto Rico during Hurricane Maria in 2017 and Hurricane Fiona in 2022. The high-resolution spatiotemporal dataset[42] shows a sharp rise in the power outage percentage during Hurricane Fiona, which soared from over 50% to 100% within 10 minutes at around 18:00 UTC on 18 September 2022 (Fig. 2c) over an hour before storm landfall, which indicates that a cascading failure happened.

An analysis of power outage data reveals a 20–80 scaling law pattern, where the most impactful 20% of failures, ranked by the number of affected customers, are responsible for 80–90% of all customer outages[43]. This suggests that outages caused by top-severe damages can have widespread effects, affecting customers across a broad area. It highlights the risks of failure propagation within grids during extreme events, due to the connected network topology and network dynamics. In terms of recovery from these outages, data analysis also exhibits a similar 10–90 scaling law pattern, where about 10% of disrupted customers account for nearly 90% of total customer interruption hours due to delayed restoration[44,45]. Moreover, as the severity of weather-induced events escalates from moderate to extreme levels, the effectiveness of rapid recovery degrades by nearly 30%, with more customers suffering from prolonged disruptions[45]. These scaling law patterns with strong nonlinearity consistently indicate that extreme weather events significantly exacerbate the vulnerability of power systems and underscore the urgent need to focus more on the effects of these less-frequent but extreme events on system resilience.

During-event operation

Small island power systems such as the Puerto Rico power grid seem to be more vulnerable to climate risks than bulk power systems. Whereas small power grids are generally expected to exhibit increased susceptibility to disturbances, it is less recognized that this vulnerability fundamentally arises from their deficiency in two different aspects of resilience: grid inertia[46] and system flexibility[47], which act at different timescales.

Grid inertia, represented by the kinetic energy stored in the rotating masses of conventional synchronous generators such as fossil-fuel steam or gas turbines, is a crucial short-term resilience metric. Grid inertia indicates the system-wide capability to immediately respond to transient power imbalances between energy supply and demand[46]. During the initial disturbance phase, for instance, within the first few hundred milliseconds, transient power imbalances and grid inertia jointly determine the rate of change of frequency – the time derivative of the power system frequency, prior to the response of system-wide automatic generation control for eliminating frequency deviations[48]. A high rate of change of frequency, above a preassigned threshold value such as 2 Hz s^{-1}, signals an extreme frequency zenith or nadir and can activate off-grid service-protection mechanisms for generators[49]. The tripping of generators can exacerbate the existing imbalance, potentially leading to a widespread blackout. By contrast, bulk power systems such as the Texas power grid[50] have an increased capability to handle the same level of imbalance, owing to sufficient grid inertia to maintain frequency stability.

A perfect, sustained balance cannot exist in a power system owing to the inherent fluctuations in demand and generation. System flexibility is characterized by its capacity to manage this variability and uncertainty through the effective deployment of flexible resources, such as spinning reserves (online generators with available and unused capacity) and energy storage systems that can provide rapid responses to unexpected imbalances[51]. Compared with grid inertia (which mitigates short-term, transient disturbances), system flexibility plays a crucial role in maintaining the relative long-term balance between supply and demand, ranging from second-level frequency control to intra-hourly generation dispatch, and even extending to day-ahead unit commitment[52]. Any shortfall in system flexibility exacerbates long-term imbalances in supply and demand, and can result in additional losses of service. During extreme events, these unexpected losses are even more pronounced, especially in small island power systems like Puerto Rico that lack spatial flexibility.

During Hurricane Fiona in Puerto Rico, the shortage of flexibility and grid inertia for dealing with multiple timescale imbalances amplified the effect of damage from the extreme event and contributed to the catastrophic blackout (Fig. 2c). This scenario aligns with the US Department of Energy's Hurricane Fiona situation report, which stated that damage to energy distribution and transmission infrastructure led to a system imbalance that resulted in the tripping of generation units and caused an island-wide blackout[53].

Post-event recovery

Post-event recovery is crucial for mitigating the influence of prolonged disruptions on societal and economic well-being. The restoration process is primarily carried out by power utility crews and therefore is constrained by post-event environmental conditions. Flooding from tropical cyclones is an important factor that impedes the initial recovery of electricity grids[54,55]. For example, the prolonged (over 3 days) inland flooding caused by Hurricane Ida in New Orleans[56] led directly to a power outage affecting more than 50% of customers and lasting over 5 days in the city (Fig. 2b). Flooding also dominated the initial recovery after Hurricanes Laura, Harvey, Michael and Sally, and prevented service restoration in the coastal region for 3 days, 5 days, 3 days and 2 days, respectively[57].

Heatwaves are another critical factor in the process of recovery[33,58]. Extended heatwaves can greatly affect residents, especially those who have lost power, and impair recovery efficiency while heightening the health risks of outdoor repair crews. In the absence of air conditioning, heatwave-related fatality risk increases by threefold owing to thermal stress[59]. The tropical-cyclone-induced blackout plus heatwave is an emerging compound hazard[33,60]. In 2021, a prolonged heatwave (with a heat index surpassing 37.8 °C or 100 °F) occurred in the aftermath of Hurricane Ida, which particularly affected households that lost power and consequently had no air conditioning[61]. During the post-event grid restoration, utility contractors had to work 16 hours per day in intense heat and humidity, which constrained the recovery efficiency. As a result, Louisiana residents experienced a total of 35 million hours of blackout–heatwave compound hazard over 10 days after the landfall of Hurricane Ida.

Climate-renewable challenges

In the summer of 2023, record-breaking peak electricity demand was repeatedly reported in Texas under sustained heatwave conditions[62]. Intensification and prolongation of heatwaves stress the steady-state (hourly to daily) balance between supply and demand of power grids. Along with heatwaves, tropical cyclones are a primary climate-related cause of widespread catastrophic blackouts and pose a direct threat to the dynamic stability of power systems[63]. Moreover, the challenges of maintaining both steady-state balance and dynamic stability of power systems are exacerbated in the context of high penetration of renewables.

Intensifying climate extremes

General circulation models (GCMs) are widely used to project the climate change conditions corresponding to specific SSPs[64]. To foster consensus among climatologists, the Coupled Model Intercomparison Project (CMIP)[65] was initiated to aid GCM comparisons, sensitivity tests and refinements. CMIP6, the sixth and newest phase of CMIP, contributes to the comprehensive evaluation and reporting of IPCC AR6 findings[11]. Surface temperature and relative humidity data from six CMIP6 GCMs reveal the anticipated changes in annual heatwave days (those with a daily maximum heat index over 37.8 °C) along the US East and Gulf coasts under both moderate (SSP2-4.5) and high (SSP5-8.5) emission scenarios (Fig. 3a,b). The model projections indicate a consistent rise in heatwave frequency. Moreover, high-latitude regions are expected to experience increased heatwave frequency compared with low-latitude areas.

Across diverse emission scenarios and GCM projections, a prevailing consensus also suggests a global increase in the intensity of tropical cyclones[66–69]. This projection is verified across an array of physically driven[66–68] and statistically driven methods[69]. Among these, the statistical-deterministic method[70,71] offers an advanced simulation framework for generating synthetic tropical cyclones based on climate environmental conditions that capture their physical processes[72]. The projection based on this approach, averaged over six CMIP6 GCMs, shows that in most regions along the US East and Gulf coasts, the frequency of major (category 3–5) tropical cyclones will increase by at least 30% under the SSP2-4.5 scenario (Fig. 3c) and by at least 50% under the SSP5-8.5 scenario (Fig. 3d). Although some climate studies suggest a decrease in the annual frequency of tropical cyclones[73,74], climatologists broadly acknowledge that the intensity of tropical cyclones is increasing and a greater proportion are evolving into major tropical cyclones in a changing climate[14,67–69,73,74]. In addition to these findings, research suggests that to eliminate the increase of hazards due to tropical-cyclone intensification, there needs to be a substantial decrease in tropical-cyclone frequency (~70%)[75] that is far larger than the maximum decrease (~30%) projected by the climate studies[14,67–69,73,74]. Also, mirroring the trends observed with heatwaves, high-latitude regions also show a greater increase than is seen in low-latitude regions in the frequency of major tropical cyclones. This correlation highlights the challenges posed to power grids by compound hazards.

Intensifying compound hazards

Climate-related extreme weather events can also become more correlated in space and time. Coastal flooding in the context of rising sea levels and compound flooding from storm surge, heavy rainfall and rising sea levels can cause direct damage to power systems and present substantial challenges to system restoration. For the US East and Gulf coasts in the high-emissions (SSP5-8.5) scenario, historical 100-year floods could occur annually or every 1–30 years by the end of the twenty-first century, because of the combined effects of rising sea levels and changes in tropical-cyclone climatology[76]. The frequency of joint hazard events driven by tropical-cyclone rainfall, storm surge and sea level rises could increase 7- to 195-fold along the US East and Gulf coasts under SSP5-8.5 by 2100[20]. As a result, the extension of compound flooding is projected to increase by 27% and inundation volumes by 62% in North Carolina under SSP5-8.5[77]. Even under the moderate climate change scenario (SSP2-4.5), we can expect locally meaningful changes in the land area at risk from compound flooding by 2050, with defences protecting 2,200 km^2 of land along the US East and Gulf coasts potentially compromised[78].

Moreover, the frequency of lengthy heatwaves following intense tropical cyclones could increase sharply. For example, the expected percentage of residents in Harris County, Texas experiencing at least one tropical-cyclone-related blackout plus heatwave lasting more than 5 days in a 20-year period could increase by a factor of 23 over the twenty-first century[33]. Tropical-cyclone-induced blackout and

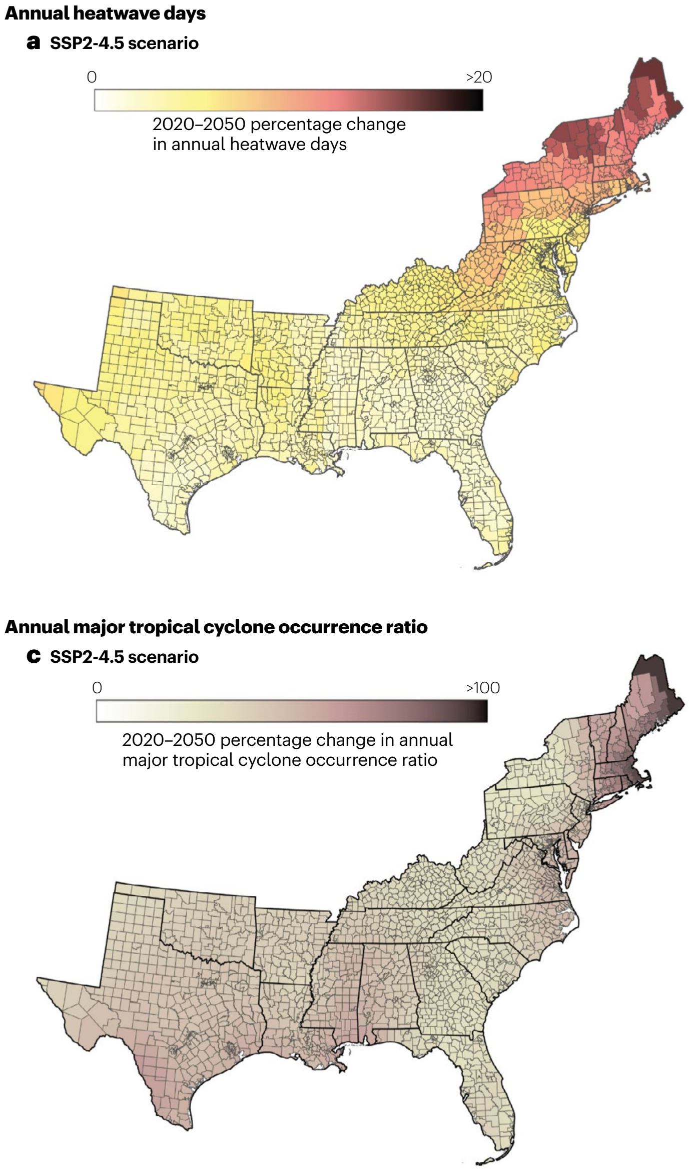


Fig. 3 | Expected increases in heatwaves and major tropical cyclones from 2020 to 2050 along the US East and Gulf coasts. a, Heatwave increase under shared socioeconomic pathway (SSP) 2-4.5. **b**, Heatwave increase under SSP5-8.5. **c**, Major tropical-cyclone (category 3–5) increase under SSP2-4.5. **d**, Major tropical-cyclone increase under SSP5-8.5. SSP2-4.5 and SSP5-8.5 represent future moderate and high emission scenarios. Colour bars in **a** and **b** denote the expected change (percentage) in annual heatwave days. Colour bars in **c** and **d** denote the expected change (percentage) in the annual occurrence rate of major tropical cyclones. Projections of heatwave and tropical-cyclone occurrence rates are averaged over six Coupled Model Intercomparison Project Phase 6 (CMIP6) general circulation models: Canadian Earth System Model version 5 (CanESM5); the National Center for Meteorological Research (CNRM) and Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique (CERFACS) model (CNRM-CM6-1); UK Earth System Model (UKESM1-0-LL); European Community (EC-Earth3); Institut Pierre Simon Laplace (IPSL-CM6A-LR); and Model for Interdisciplinary Research on Climate 6 (MIROC6). For each county, the heat index is determined from the daily maximum temperature and relative humidity (given data availability) at the county's centre. The calculated heat index is bias-corrected by eliminating the monthly differences between estimates from general circulation models (GCM) simulations during the historical period and those from historical observations based on North American Land Data Assimilation System (NLDAS) reanalysis[139], which includes hourly temperature and relative humidity. Annual heatwave days are quantified by the number of days for which the county's heat index exceeds 37.8 °C following the heat advisory in the United States. Annual major tropical-cyclone occurrence rates are computed by tallying major tropical cyclones that pass within 300 km of the county's border. Tropical-cyclone projections for the beginning and end of the twenty-first century[79] are linearly interpolated to the year 2050.

heatwave compound hazards have been rare until recently (for example, Hurricanes Laura in 2020 and Ida in 2021, both affecting Louisiana). As climate change is expected to intensify both heatwaves and tropical cyclones, possibly in correlation, tropical-cyclone-induced blackout and heatwave compound hazards may emerge in many coastal areas.

In addition to the superimposition of multiple hazards during extreme events, the increases in event frequency can lead to temporal compounding of events, which can also greatly challenge power system resilience. Two sequential tropical cyclones[79] that make landfall close together in space and within the timeframe of power system recovery can induce more severe damage to the power system than each storm individually. For example, Hurricane Irma and Hurricane Maria made landfall successively in Puerto Rico in 2017 within 2 weeks, leading to a prolonged disruption in the island's power grid[80]. Under the high (SSP5-8.5) and moderate (SSP2-4.5) emission pathways, the chance of two tropical cyclones affecting the same location within 15 days of each other could substantially increase along the US East and Gulf coasts (with the return period decreasing from 10–92 years to 1–3 years over the course of the current century) owing to rising sea levels and changes in storm climatology[79].

Superimposed risks

The power outage dataset in the US from 2017 to 2022 indicates that major tropical cyclones affected an average of 3.32 million customers annually[42], leading to average socioeconomic losses of US\$94.4 billion per year (consumer price index adjusted)[10]. Based on the historical damage data[10,42] and the intensifying trends of major tropical cyclones (Fig. 3c,d) weighted by county-level population[81], linear estimations suggest, under SSP5-8.5 (SSP2-4.5), an annual increase of 1.83 million (1.39 million) affected customers in the United States with an additional US\$53.6 billion (US\$40.7 billion) in losses. Notably, this linear estimation only provides a lower bound, as it does not consider compound hazards and the increasing renewable penetration level in US power grids. Additionally, there is an increase in cooling demand in almost all regions of the world, including the United States, China and Europe, due to climate change, with Europe experiencing a notable annual rise of up to 5%[82]. This increasing cooling demand can further stress the electricity supply–demand balance during extreme heatwaves[83].

Adopting a holistic climate and energy perspective, the escalating challenges of integrating environment-sensitive renewable power systems into future net-zero power systems under climate change conditions can be considered in terms of three aspects: infrastructure safety, grid operation and system recovery.

Vulnerability of infrastructure. Solar panels and wind turbines are directly exposed to the environment, and these leading renewable generation methods are therefore much more vulnerable to wind hazards than conventional power plants[84,85]. Historical data from the US East Coast and the Caribbean region highlight that current solar panels broadly perform below the designed reliability requirement during hurricane events[86]. During Hurricane Maria in 2017, one-third of solar farms in Puerto Rico reported over 50% damaged panels. This vulnerability is not limited to just wind hazards; ground-mounted utility-scale solar photovoltaic systems are particularly susceptible to the combined effects of intensifying wind, rainfall and storm surge from tropical cyclones. Wind turbines also face intensifying challenges. The Inflation Reduction Act of 2022 has spurred a boom in offshore wind farm development along the US coasts. However, approximately two-thirds of the US offshore wind energy potential in deep water zones requires floating platforms, as the current fixed-bottom technique is limited to water depths of about 50 m (ref. 87). With further rising sea levels and intensifying tropical cyclones, changes in wind and wave patterns could lead to more severe structural damage to wind turbines[88].

Reduced grid inertia and flexibility. Grid inertia and flexibility (the two essential features that provide resilience against operational imbalances) are further constrained by high penetration of renewables. Renewable energy resources, such as solar photovoltaic systems, are integrated into the grid via power inverters. Increasing inverter-based renewable penetration with proportionately fewer conventional synchronous generators reduces the grid inertia associated with rotational kinetic energy from grid-connected rotating turbines[89]. The low-inertia issue compromises the capacity of power grids to respond to transient imbalances caused by climate extremes, resulting in escalating risks of frequency oscillations or even catastrophic blackouts. This problem is amplified by intensifying climate risks.

In terms of the flexibility, the variability of renewable energy introduces additional uncertainty to system balance between supply and demand, necessitating greater flexibility to mitigate the uncertainty. The 'duck curve', the shape of daily electricity demand considering solar generation[90], is becoming more pronounced in view of the increasing disparity between peak and nadir demand. Environment-dependent renewables introduce the uncertainty from weather systems into both minute-level and hour-level scheduling. For example, unpredictable cloud cover and low-wind periods can result in shortfalls in solar and wind generation that enlarge existing power imbalances.

During extreme weather events, solar generation experiences a steep drop as a result of the substantial drop in solar irradiance caused by thick cloud structures such as large cumulonimbi[91]. California, which rarely experiences tropical-cyclone events, experienced a strong system-wide reduction in solar generation (the daily peak declined from over 15,000 MW to 4,703 MW, nearly one-third of California's total demand) during Hurricane Hillary in August 2023[92]. Moreover, wind turbines are designed to automatically shut down once wind speeds reach a specific threshold, typically set at around 55 mph (ref. 93). Even a Category 1 hurricane, which has 74–95 mph sustained wind speed, exceeds this limit. Such realities underscore the prominent risks of future power systems that are heavily reliant on renewable energy generation.

Delayed system recovery. Severe storms and other extreme climate events have a pronounced effect on the post-event recovery of renewable-dominated power systems. In addition to damaging energy infrastructure, tropical cyclones can cause an up to 80% reduction in solar radiation for several days post-landfall[91]. Moreover, environment-sensitive renewable energy generation systems are more susceptible to severe damage and face longer, more challenging recovery. For instance, Punta Lima, a 23 MW wind farm in Puerto Rico, lost almost half its turbine blades during Hurricane Maria in 2017. As of 2023, the facility remains non-operational because of an extensive rebuilding process[94]. The expected increase in post-tropical-cyclone heatwaves is likely to make power system restoration, primarily an outdoor activity, even more challenging. Additionally, wildfires resulting from heatwaves can induce post-event damage to environment-exposed infrastructure and further impede recovery[95]. The prolonged recovery periods associated with increasing renewable energy penetration could lead to substantial shortfalls in electricity generation capacity required to initially restart power grids from a blackout (black starts[96]).

Opportunities from renewables

Although, in the context of a changing climate, renewable integration poses serious challenges to power system resilience, it is critical to look beyond these challenges. The ongoing energy transition, marked by increasing penetration of renewable energy, brings new opportunities to achieve climate resilience through the shift from centralized to distributed architectures. Despite the limited flexibility of renewable electricity supply, large-scale distributed renewable energy resources can offer improved topological flexibility owing to the formation of microgrids (Fig. 4). Distributed renewable integration is reshaping the traditional transmission-focused architecture of power systems[97]. Under steady-state conditions, distributed renewables foster flexible bidirectional power flow in active distribution networks[98], thereby providing localized clusters with energy autonomy in microgrids. These microgrids improve both renewable energy integration and resilience. Under climate extremes, proactively configured microgrids can prevent failure propagation and mitigate the risk of cascading failure, which improves the continuity of electricity supply in less-affected areas. For example, microgrid formation is recognized as an effective and economical way to improve power system resilience in response to increasing wildfires in California, compared with the controversial public safety power shutoffs used in recent years to prevent outage propagation[99,100]. Puerto Rico Electric Power Authority is also pursuing a transformation to a more flexible power grid with the capability to form independent microgrids in response to the challenges posed by hurricanes and other climate extremes[101].

However, to achieve climate-resilient net-zero power systems, a substantial effort towards reshaping the traditional grid architecture is required along with innovative solutions and cutting-edge techniques, detailed in the following few sections.

Grid-forming inverters

Current grid-connected renewables mainly adopt grid-following inverters, which rely on phase-locked loops (feedback control loops that track the phase and frequency of input signals) to follow the grid voltage and frequency[102]. Grid-following inverters act as current sources that passively respond to voltage and frequency fluctuations, but rely on the grid being formed by its traditional inertial source: synchronous generators. An emerging solution to the low inertia of renewable-dominated power grids under intensifying climate risks is grid-forming inverters[103,104]. These devices function as controllable voltage sources supported by power synchronization loops (feedback control loops to emulate the rotor characteristics of synchronous generators) without relying on phase-locked loops; they actively support and stabilize grid frequency and voltage, thereby providing virtual inertia (electronic-control-based emulation of traditional mechanical inertia) and have a fast frequency response, particularly for islanded microgrids[104]. In addition, grid-forming inverters can also serve as black-start resources by offering voltage and/or frequency reference values for the recovery of power systems during climate extremes[105].

However, even though grid-forming inverters can theoretically operate in 100% renewable power systems, empirical observations of their efficacy in high-penetration renewable power systems are still lacking. For example, reliance on control-driven virtual inertia instead of physical grid inertia could introduce latency in responses to disturbances that lead to potential grid instability[106]. In addition, the applications of grid-forming inverters in bulk power systems are limited by their insufficient ability to withstand high short-circuit current during outages (a capability known as fault ride-through) because of current-carrying limitations of power electronics[107]. Therefore, grid-forming inverters are more suitable for establishing climate-resilient microgrids than bulk power systems.

Distributed energy storage

Energy storage systems are considered one of the most efficient solutions for maintaining the balance between electricity supply and demand, especially for power systems with high penetration of variable renewable sources[108,109]. The spectrum of energy storage encompasses a variety of methods, including electrical, electromagnetic, mechanical, thermal, hydrological and electrochemical systems. Moreover, the scope of energy storage systems can be expanded by incorporating power-to-X technologies[110–112] such as power-to-gas (hydrogen) and power-to-heat solutions. The standout attribute of energy storage systems in terms of climate resilience is their inherent potential to be distributed[113]. A distributed energy storage system, characterized by high spatiotemporal flexibility and rapid response capability, serves as an indispensable component of renewable-dominated power systems, particularly microgrids. During climate extremes, distributed energy storage systems provide fast response services that maintain the short-term and long-term power balance. For post-event recovery following widespread blackouts, distributed energy storage systems become vital in addressing power shortages in fragmented grids that have experienced sectionalization (intentional or unintentional grid separations) caused by climate extremes.

Incorporation of portable energy storage[114] into the electricity market as a prominent concept has emerged to mitigate grid congestion. However, its potential role in response to climate extremes remains to be explored. The mobility of portable energy storage systems further enhances their spatiotemporal flexibility and might be a promising solution for future renewable power systems. Additionally, the widespread implementation of distributed energy storage systems is hindered by technological difficulties. Optimization of capacity planning and the configuration of distributed energy storage systems, along with efficient aggregation strategies in response to power imbalances, remains a challenge. In multi-stakeholder power systems, the market participation mechanism is still in the exploratory phase.

Cross-sector interoperability

Interactions between closely connected sectors (such as transportation, electricity and industry) will be instrumental in increasing the energy autonomy of microgrids, which is expected to improve the flexibility of future net-zero power systems during climate extremes[115–117]. For instance, decarbonization of the transportation sector through electrification is highly dependent on the electricity sector. The ongoing expansion of the electricity sector aids the formation of an energy ecosystem[36,118]. In the face of climate challenges, the electricity sector can mitigate stress on power supply and demand through increased cross-sector flexibility, for example by using the energy storage capabilities of electric vehicles and promoting active demand responses in industry and other sectors[119]. Such cross-sector interoperability requires reliable sensing, communication and integrated business models. However, promising attempts are ongoing to improve the interoperability of isolated system frameworks by exploring more integrated system-of-system architectures[120].

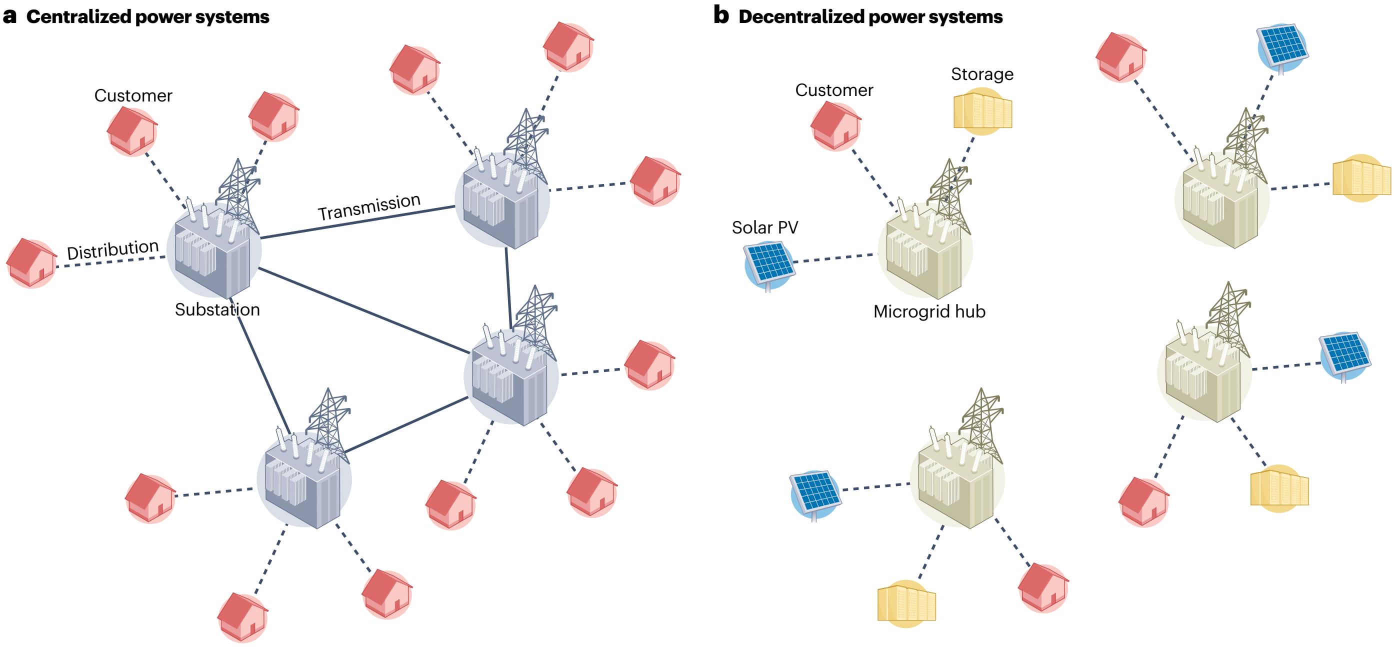


Fig. 4 | Topological flexibility of power systems. a, In traditional centralized power systems, a local power outage can propagate to the whole grid and can result in a catastrophic cascading failure of the bulk power system. **b**, In decentralized power systems that consist of multiple microgrids supported by distributed large-scale renewable energy resources, such as solar photovoltaic (PV) systems and energy storage facilities, outages within a microgrid are constrained locally and do not affect other microgrids.

Distributed optimization

Distributed optimization offers a way for power systems to transition from centralized to distributed operation[121]. Systems with distributed operation have inherent resilience without relying on a centralized control centre. This characteristic enables microgrids to adapt to climate risks by allowing them to coordinate autonomously and ride through or recover from extreme events[122].

Distributed optimization algorithms decompose a centralized problem into subproblems and coordinate the available agents to achieve a system-wide solution[121]. They present better scalability for a large-scale problem, by parallelly solving the subproblems, and offer a more resilient communication architecture than centralized methods[97]. A unique challenge in designing distributed optimizations for power systems is the nonlinearity of power flow equations, which makes it difficult to guarantee the provable convergence of the designed algorithms[123,124]. Moreover, the speed of convergence and communication requirements as critical algorithm performance metrics make the deployment of the algorithms challenging[125]. Theoretical advances in understanding algorithm complexity, designing new distributed optimization algorithms, and efficient implementations are further needed.

Distributed control is a dynamic version of distributed optimization that aims to maintain the stability of a power grid in response to disturbances around a stable operating point set by distributed operation[126]. One promising line of research is the development of simple, distributed control strategies for ensuring the stability of power grids. Many fundamental questions remain to be addressed in the application of distributed control to microgrids. For example, the Braess paradox shows that increased network connectivity can lead to instability[126]. Increased damping coefficients (parameters that reflect the capability of power systems to reduce oscillations) can also lead to instability in the context of the nonlinear dynamics of power grids[127]. Additionally, large-scale network delays in multiagent systems have a strong effect on stability[106,128]. Further research is required to improve fundamental understanding and develop innovative designs for future low-inertia microgrids under distributed control.

Climate–energy integrated model

Renewable-dominated power systems require the integration of climate, weather and energy system models. Such interdisciplinary analyses offer insights into the superimposed risks, which support the improvement of steady-state operation and dynamic stability of future power systems. In particular, standards for planning and operation of climate-resilient microgrids would be dependent on a climate–energy integrated perspective.

Although well-developed individual models exist for climate, weather and energy systems, these models were not originally conceived as an interconnected whole. As each model has unique specifications and requirements, coupling them requires substantial research to ensure their compatibility and applicability. Mismatches between climate, weather and power system models can result in considerable overestimation or underestimation. For instance, a preliminary study for mid-twenty-first-century planning of the Texas power system shows a disparity in estimated resource adequacy amounting to nearly a 1,500 MW difference between high-resolution and low-resolution climate models[129].

Moreover, extreme weather events are not well resolved in global climate models, and various compound hazards[130] – such as tropical cyclones, rising sea levels, flooding and heatwaves – that can affect the power system have not been modelled consistently in the risk analysis of power systems. Several research directions might help to bridge the gaps between climate, weather and power system models and aid the assessment of power system risk and resilience.

Compatible spatiotemporal climate–energy integrated modelling and risk analysis. Towards a resilient future under intensifying climate risks, the adaptive coordination of climate extreme models and power system models in both spatial and temporal dimensions becomes increasingly important. Specifically, research on extreme-event-induced cascading power outages requires the incorporation of high-resolution models of power system dynamics along with compatible spatiotemporal projections of climate hazards. These compatible hazard projections can be generated by consistent downscaling of advanced climate models[131] and simulation of the specific hazards[33,79]. To effectively optimize the planning and operation of renewable-dominated power systems, especially microgrids under climate extremes, future resilience-oriented research should focus on developing such compatible climate–energy integrated models.

In risk analysis, existing conservative-driven risk analysis and adaptation methods, such as stress testing[132] (risk magnification) and robust optimization[133] (worst-scenario approach), have demonstrated their effectiveness in enhancing the resilience of engineering decisions in the context of extreme events. However, given the extensive scale, complexity and economic considerations of modern power systems, it is essential to incorporate compatible high-resolution climate extreme scenarios into risk analysis. This offers a promising direction to better understand the intensifying superimposed risks and develop appropriate risk adaptation techniques towards a climate-resilient future.

Climate-coupled system planning. Climate-coupled system planning is essential for the design of future power systems that require increased resilience and reliability. Research should focus on the development of metrics to support the planning of power systems under diverse architectures adapting to climate change, taking into account factors such as power reserve needs, climate data integration, market behaviour and investment incentives. For instance, when planning the expansion of renewable energy such as solar and wind energy resources, comprehensive climate–energy metrics need to be applied for conducting cost–benefit analysis[134]. Moreover, the transition from a centralized network architecture to multiple microgrids requires a climate-coupled planning model to ensure both economic efficiency and climate resilience requirements.

Weather-coupled system operation. Operation of future net-zero power systems is increasingly weather-dependent and vulnerable to weather extremes. High-resolution and compatible models for forecasting spatiotemporal weather extremes and hazards[135] should be further developed and incorporated into real-time operation and emergency control of future power systems. For instance, pre-event scheduling and during-event dispatch of flexible resources, informed by high-resolution weather forecasting, are beneficial to mitigate power imbalances caused by extreme weather events. Although numerous approaches account for meteorological uncertainties for both solar and wind power in day-ahead unit commitment[136] and real-time economic dispatch[137], there is an urgent need for developing operation strategies of future power systems, particularly in coordination of multi-microgrids, to incorporate these high-resolution hazard models during extreme events.

Outlook

The large-scale integration of environment-dependent renewable energy, coupled with intensifying climate extremes, brings superimposed risks to power systems. Climate extremes affect power system resilience and necessitate climate-resilient solutions based on the examination of historical events and future projections.

In this Perspective, we highlight large-scale historical datasets of spatiotemporal power outages caused by tropical cyclones in the United States over the past 6 years, focusing on the key features that affect power system resilience in both during-event operation and post-event recovery scenarios. The 12 tropical cyclones that made landfall in the United States between 2017 and 2022 caused extensive power outages and substantial damage to energy infrastructure, and led to prolonged recovery efforts. Two catastrophic power grid blackouts occurring in 2017 and 2022 in Puerto Rico reveal that island power grids are far more vulnerable to climate extremes than bulk power systems. These climate vulnerabilities stem from low grid inertia, which affects short-term (transient) energy balance, and decreased system flexibility, which affects the long-term balance. In the post-event recovery phase, the initial progress of recovery is profoundly influenced by persistent climate hazards such as flooding induced by extreme rainfall and storm surges. Subsequent heatwaves can further limit the efficiency of power restoration.

Taking the US East and Gulf coasts as an example, climate projections from both moderate (SSP2-4.5) and high (SSP5-8.5) emission pathways indicate a considerable rise in the frequency of heatwaves and major tropical cyclones from 2020 to 2050. Moreover, these projections predict the exacerbation of compound hazards such as combinations of tropical cyclones, extreme rainfall and heatwaves. Under conditions of intensifying climate extremes, the large-scale integration of renewable energy imposes escalating challenges on future power system resilience, from aspects of infrastructure and operation to recovery.

Nevertheless, the inherently distributed character of renewable energy presents unique opportunities to establish climate-resilient power systems. The transition from a centralized power system to distributed microgrids can improve system resilience during climate extremes by offering additional topological flexibility. In particular, we highlight several state-of-the-art technologies and strategies that might contribute to a net-zero future in a changing climate. Important advances include grid-forming inverters, distributed energy storage, cross-sector interoperability, distributed optimization and climate–energy integrated models. These advances could play a pivotal role in reshaping the traditional power grid into a climate-resilient distributed system with large-scale integration of renewable energy. However, achieving climate resilience requires intense efforts to integrate climate, weather and energy system models and to apply such integrated models to support infrastructure planning as well as real-time operation and recovery.

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L.Xu and N.L conceived the article. L.Xu, K.F. and N.L. wrote the initial draft. A.T.D.P., H.V.P., L.Xie, C.J., X.A.S., Q.G. and M.O. participated in initial discussions and contributed to the writing or reviewing of the article.

Competing interests

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