In collaboration with
China Huaneng Group

WORLD ECONOMIC FORUM

Building Climate-Resilient Utilities: Lessons from China and Future Pathways

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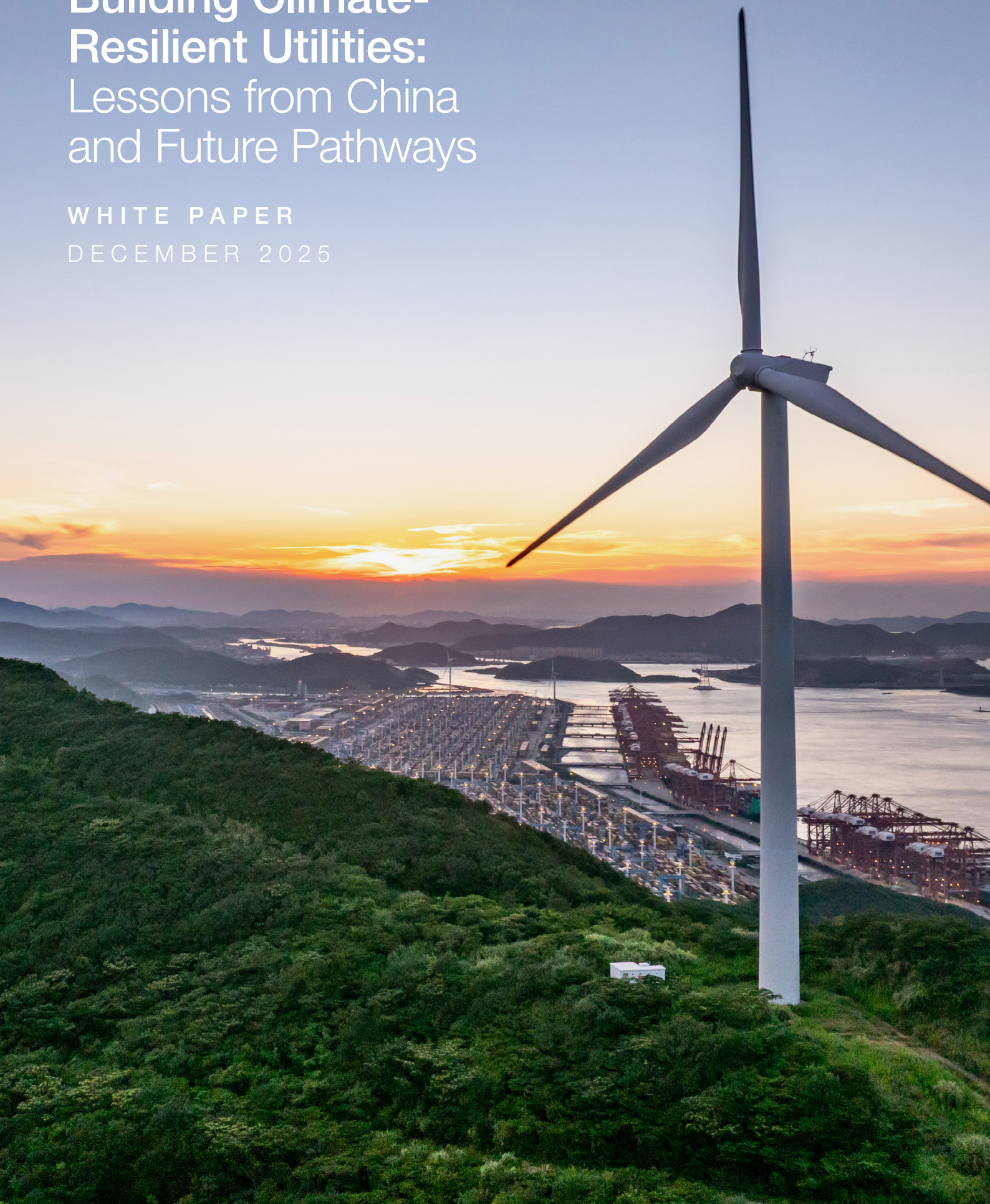

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Developing climate resilient infrastructure requires a dual-pronged strategy of cutting emissions while adapting to fast-changing climatic conditions, characterized by the increased frequency and intensity of extreme weather events. This ensures that we avoid the worst outcomes of climate change and environmental degradation, while enabling industries and communities to deal with the ecological changes that are already happening.

Ensuring the security and stability of critical infrastructure – especially power and water utilities, transport and communication networks and essential services – is a strategic imperative for both businesses and governments. Prolonged disruptions or destruction due to extreme weather conditions, such as heatwaves, floods and drought, could severely undermine public health and safety, economic stability and national security.

This report examines how policy, technology and finance can work in concert to safeguard the vital arteries of our economies and societies in a structured and systemic approach. It draws on case studies to illustrate how China – one of the world's largest players in the construction and operation of power assets – is responding to climate-related risks. As defined by the concept of "Resilience 2.0", the report proposes a forward-looking model in which adaptation can be institutionalized, digitally driven and anchored in innovative financial design.

This report offers lessons learned for global leaders in the utilities sector and beyond to build a more climate-resilient future. Through anticipatory governance, cross-sector integration and data-driven innovation, governments and businesses can move away from a static defence model towards a more dynamic, agile approach to resilience that will better safeguard lives and livelihoods.

Executive summary

China's approach to climate-proofing its critical infrastructure integrates strategic coordination with AI-powered technology and innovative finance.

As global average temperatures mount and climate volatility becomes the new normal, the utilities sector – backbone of the global economy – faces escalating challenges. For the global utilities sector, climate-driven impacts represent a fundamental challenge to its operational continuity, financial stability and capacity to serve society. The World Economic Forum's insight report, *Business on the Edge: Building Industry Resilience to Climate Hazards*, identifies the utilities sector as one of the most exposed to future fixed asset losses from climate hazards.[1]

China's approach to climate-proofing its critical infrastructure reveals a resilience framework that integrates state-led strategic coordination with AI-powered technology and innovative finance. This triangular model, combined with proposed evolutionary pathways, offers a clear blueprint for safeguarding utility infrastructure worldwide against the intensifying impacts of a rapidly changing climate.

Chapter 1 of this report establishes the unprecedented threat facing essential utilities. Building the sector's resilience is a particularly acute challenge in China. With its vast geography, densely populated urban centres and status as a global manufacturing hub, China's critical infrastructure for power, water and gas is on the frontline of climate change. The increasing frequency of record-breaking typhoons, devastating floods and prolonged heatwaves poses a systemic risk, where a failure in one utility can trigger cascading disruptions across entire supply chains and economic regions. The urgency to build climate-resilient utilities in China is therefore both a national imperative and a global concern, given the country's central role in the world economy and its leadership in infrastructure development.

In response to these escalating risks, China has adopted a comprehensive, multi-dimensional approach to enhancing the climate resilience of its utilities sector. This strategy is anchored in three core pillars: **policy and governance**, which orchestrate a hybrid government-business response; **technology**, which empowers resilience through innovation; and **finance** to fund the resilience transition. This resilience-building framework combines top-down policy direction with bottom-up innovation, and is termed "Resilience 1.0" for the utilities sector. Chapter 2 explores this methodology in greater detail and demonstrates its principles through case studies.

While this foundational framework for resilience has proven effective, the evolving climate challenge necessitates a more advanced approach. Chapter 3 therefore introduces "Resilience 2.0" – a future pathway that fosters proactive, intelligent and integrated adaptation across the utilities sector through in-depth, public-private collaboration and broad, society-wide support. This evolution will enhance existing pillars as follows:

- **Policy and governance**: Embedding resilience into governance through standardized metrics and market-driven approaches.
- **Technology**: Advancing technology into an integrated AI-powered ecosystem for predictive maintenance and cross-sector collaboration.
- **Finance**: Innovating financially by anchoring risk pricing to verified resilience performance, while promoting public-private partnerships through blended finance mechanisms.

This set of models for building resilience for the utilities sector exhibits distinct characteristics: state-led strategic coordination, a commitment to rapid and large-scale technology deployment, a multi-faceted financing mechanism, an iterative and pragmatic approach to piloting and scaling-up, and a deep alignment between policy and industry. While not a one-size-fits-all model, it provides invaluable insights for other nations grappling with similar climate pressures.

As the world confronts a shared climate future, the lessons from China's journey underscore a universal truth: building resilience is a collaborative effort. Fostering global partnerships to share best practices, co-develop standards and accelerate technology innovation and transfer is no longer optional – it is essential for securing a sustainable and resilient global commons.

1 Utilities on the frontline of climate change

The rise of compound disasters, with record-breaking heat and floods, has undermined the foundational assumptions on which China's infrastructure was built.

1.1 New risk landscape: growing frequency and intensity of extreme weather events

> The nation is confronting a new risk landscape of climate variability, where historical data is no longer a reliable guide to future risk.

The foundational assumption of a stable, predictable climate, upon which much of the world's infrastructure was designed, has been undermined by a series of ever more frequent and intense extreme weather events, such as heatwave, floods and windstorms.

According to the *Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (IPCC) released in 2023[2] and the recently published *Blue Book on Climate Change in China 2025,*[3] the warming trend of the planet's climate system has continued to climb since the 1990s, with global ocean warming, sea-level rise and glacier melting all accelerating significantly.

Consolidated analysis from the World Meteorological Organization (WMO) confirms two milestones: 2015-2024 stands as the warmest decade on record, while 2024 is likely to be the first calendar year with a global mean temperature exceeding 1.5°C above the pre-industrial average.[4] These findings provide further evidence that the era of stable climate predictability is over. In its place, a new reality of ever-greater volatility is emerging, where extreme weather events are no longer outliers but commonplace.

For China, this is not a distant risk but a present-day reality. The country's geography is both extremely sensitive to and significantly affected by global climate change, with a warming rate higher than the global average. Extreme weather and climate events are becoming more frequent and intense. In 2024, key indicators – including China's annual average temperature, ice loss from Glacier No. 1 at the source of the Urumqi River in the Tianshan Mountains and rising sea-levels along China's coastline (see Figure 1) – all hit new highs.

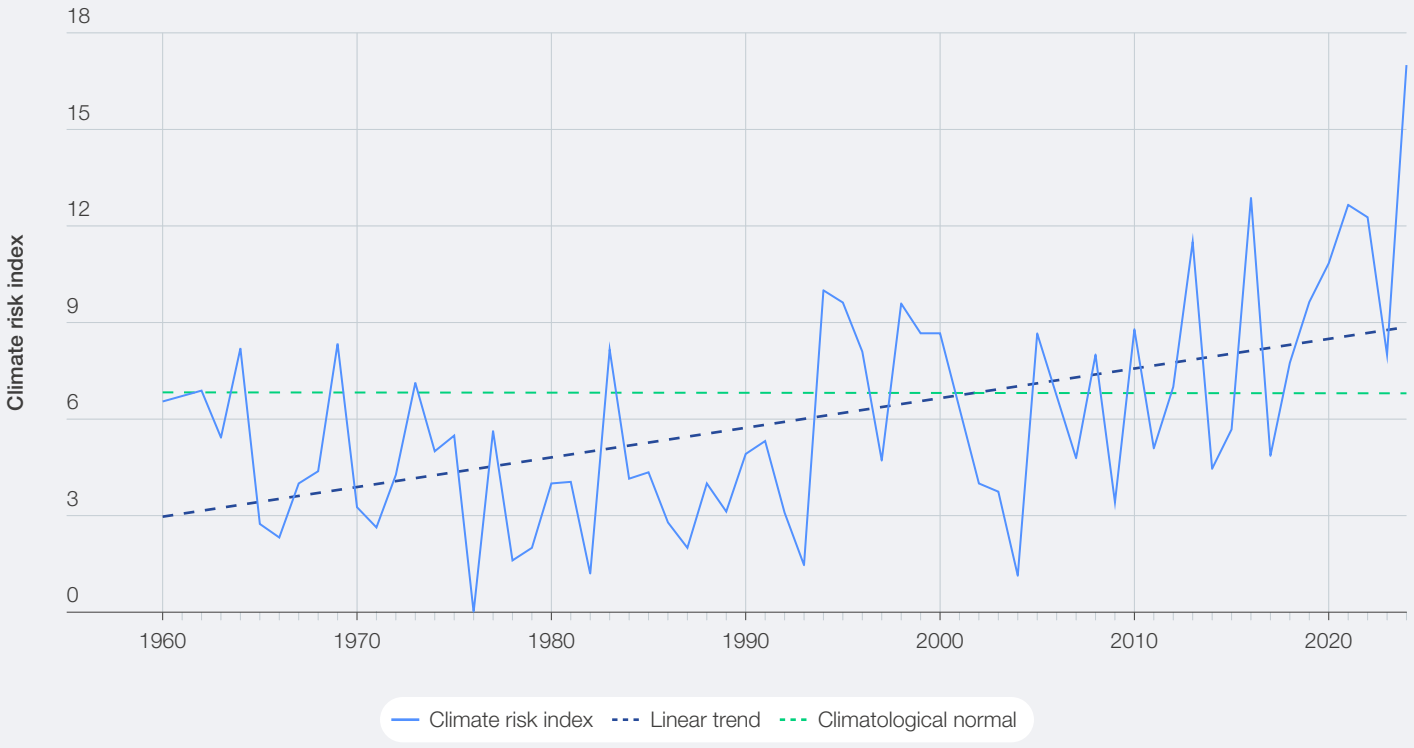
From 1961 to 2024, extreme high-temperature and heavy precipitation events in China increased. Since the late 1990s, the average intensity of typhoons making landfall in China has fluctuated and increased. In 2024, China's climate risk index reached the highest level since 1961 (see Figure 2), with flood risk and high temperatures being particularly prominent.

FIGURE 1 | **Sea-level anomalies along China's coastline (1980-2024)**

Note: Anomalies measured against horizontal baseline representing 1993-2011 average sea-level.

Source: Reproduced with kind permission of China Meteorology Administration, Climate Change Centre (2025).[5]

FIGURE 2 | **China's climate risk index (1961-2024)**



Source: Reproduced with kind permission of China Meteorology Administration, Climate Change Centre (2025).[6]

In addition, compound extreme events – such as sequential heatwaves and precipitation (SHP) and concurrent droughts and heatwaves (CDH) across China – have increased substantially in frequency, duration and magnitude. Nationwide, their duration is projected to double, with more significant rises under higher emission scenarios (e.g. SSP5-8.5).[7] By the 2050s, about half of China will be affected by SHPs with CDHs affecting three-quarters of the country.[8]

The nation is now confronting a new risk landscape characterized by a documented increase in the frequency, intensity and unpredictability of extreme weather events. This is the new normal of climate variability, where historical data is no longer a reliable guide to future risk.

1.2 Systemic vulnerabilities: cascading impacts on critical utility infrastructure

The power sector is on the frontline, under attack by a pincer movement of record-breaking demand and crippled supply.

The new climate landscape does not merely threaten isolated assets; rather, the systemic vulnerabilities of interconnected utility infrastructure are becoming increasingly exposed and exploited. A single extreme weather event can now trigger a cascade of failures across the power, water and gas sectors, leading to operational paralysis, severe economic disruption and societal distress. The infrastructure designed for a stable 20th-century climate is proving dangerously fragile against the dynamic forces of the 21st.

The power sector is on the frontline, under attack by a pincer movement of record-breaking demand and crippled supply.[9] Extreme heatwaves – such as the one in summer 2022 that saw Sichuan's peak electricity load surge by 25% and an increase in daily residential consumption of more than 200% – simultaneously drive unprecedented demand for cooling while undermining generation capacity.[10] Wind power output drops sharply – or even ceases entirely – in stagnant, hot conditions, while photovoltaic (PV) efficiency declines by 0.3-0.5% for every 1°C temperature rise, with risks of component damage with mounting temperatures.[11] Extreme drought and flood disasters, particularly the increasingly frequent and intense alternations between drought and flood, are posing severe threats to the stable output and reliability of hydropower generation.[12]

At the other extreme, sudden cold snaps can cause widespread icing on wind turbine blades. One such event in late 2023 forced the shutdown of over 2 GW of capacity at a single company and threatened grid stability during peak winter demand. Under the compound effects of extreme drought, low wind and weak solar radiation, the annual utilization hours of China's hydro-wind-solar power system are projected to decline by nearly 12% between now and 2060.[13]

While climate extremes can clearly affect the supply capability of power generation facilities, they can also put the physical infrastructure at risk. Coal-fired power plants, for example, are vulnerable to multiple climate hazards. Extreme heat degrades cooling performance and lowers thermal efficiency, forcing units to operate at elevated temperatures that accelerate wear and increase the likelihood of equipment damage. Coastal power plants face significant risk from flooding, where seawater intrusion can inundate facilities, submerging critical equipment such as generators and turbines, causing short circuits and widespread component failure.

Intense typhoons now exceed the design thresholds of coastal wind turbines. In 2024, Typhoon Yagi caused catastrophic tower collapses and blade fractures, leading to a power outage affecting more than 1.6 million people.[14] Inland, river floods driven by torrential rain not only inundate power plants and substations but also unleash secondary disasters. Severe convective storms, especially freezing rain and hail, can shatter PV panels and damage grid assets. In March 2024, hailstorms in Jiangxi destroyed large sections of a local solar farm.

These impacts cascade directly onto other essential services. The urban gas supply network, a web of linear infrastructure, is highly susceptible. Flooding and typhoons can damage or rupture pipelines, creating significant public safety risks from gas leaks and potential explosions. Extreme cold strains the system by causing demand for heating to spike, while simultaneously risking freeze-ups in critical equipment. Urban water supply faces similar destructive extremes of "feast or famine": floods can contaminate water sources with sediment – increasing turbidity by orders of magnitude and overwhelming treatment plants – while prolonged droughts deplete reservoirs, forcing cities into disruptive water rationing.

For all utilities, these events translate into a daunting financial reality of soaring repair costs, lost revenues and an urgent need for massive capital investment in resilient upgrades. In this new climate of extreme weather impacts, the lesson is clear: the resilience of a single utility is inseparable from the resilience of the entire system.

2 Climate-resilient utilities: China's multi-faceted approach

China's power reliability is rooted in coordination of government, business and communities, effective early warning and growing investments in resilience.

2.1 Resilience 1.0: a framework to strengthen the utilities sector

Resilience 1.0 is a comprehensive framework for strengthening the utilities sector's ability to withstand and adapt to climate extremes, distilled from China's practical experience in climate adaptation. It emphasizes building resilience not only in technical systems, but also across institutional and financial dimensions, ensuring that utilities can maintain critical services under increasingly volatile conditions.

For some definitions of "resilience", including one specific to infrastructure and utilities, please refer to the Appendix.

The Resilience 1.0 model is structured around three mutually reinforcing pillars:

- **Governance and policy** provide the strategic direction, with climate adaptation integrated into top-level policy design. This creates a powerful synergy between government mandates and corporate action, orchestrated through robust government-enterprise partnerships that ensure a coordinated, society-wide response.
- **Technology and innovation** are leveraged as primary enablers. China is deploying advanced early-warning systems powered by AI and big data, hardening physical assets and developing intelligent operational systems to enhance situational awareness and enable rapid, data-driven decision-making during extreme events. Concurrently, it is pioneering ecosystem-integrated solutions, such as the "PV-sand control" model and smart hydropower infrastructure, to augment traditional engineering.
- **Innovative finance** is being mobilized to fund this transition. This includes significant public sector investment and subsidies, complemented by market-based mechanisms such as green bonds and the nascent development of climate-risk insurance schemes to de-risk critical investments.

In essence, Resilience 1.0 is about strategically orchestrating governance, technology and finance to proactively prepare utilities for climate extremes, rather than only reacting to crises after they occur.

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FIGURE 3 | **Resilience 1.0: a triangular model for the utilities sector**

2.2 Policy and governance: orchestrating a hybrid government-business response

China's National Climate Adaptation Strategy

As the clock ticks on the global climate crisis, China has responded with a robust, multi-layered governance framework that places climate resilience at the top of national security and sustainable development priorities. The country's approach is characterized by a "government-led, enterprise-participating, society-wide co-governance" model, which integrates policy, technology, public awareness and international cooperation to build a comprehensive approach to climate adaptation.

China's climate adaptation strategy is guided by the principles of proactive adaptation, systematic coordination and scientific precision.

China's utility infrastructure is distinctive in its uneven spatiotemporal distribution of natural resources and significant disparities in regional socioeconomic development. To address this, top-down design is required to strengthen regional coordination and integration. Initiatives such as transmitting electricity from west to east, diverting water from south to north, and constructing large-scale renewable energy bases in arid, desert and wasteland areas – combined with long-distance, cross-regional power transmission in the new power system – exemplify this mutual support strategy. Such measures are effective for enhancing climate resilience at the macro-regional level.

A landmark in China's climate governance was reached in 2022 with the release of the *National Climate Change Adaptation Strategy 2035*, jointly issued by the Ministry of Ecology and Environment and 16 other ministries.[15] This strategy is guided by the principles of "proactive adaptation, systematic coordination and scientific precision", and it explicitly incorporates climate risk into the national security framework. The strategy sets out clear objectives for enhancing climate resilience across all sectors, emphasizing the need for integrated risk management, technological innovation and cross-sectoral collaboration.

> At the industry and enterprise level, China's approach to climate resilience is rapidly evolving from passive defence to proactive, systematic strengthening.

To ensure effective execution, China has continued to strengthen its institutional architecture. In 2024, the National Disaster Prevention, Reduction and Relief Committee was officially consolidated and activated. This body is tasked with unifying and coordinating disaster response across different government agencies and industries, breaking down bureaucratic silos to ensure a more coherent and rapid response to major climate-related events.

This strategic framework is underpinned by a robust technological backbone for monitoring and early warning. Recognizing the inherent uncertainty in weather forecasting and the need for decisive disaster response, China has pioneered a "progressive" meteorological service model. This approach delivers increasingly precise, targeted and timely forecasts as a disaster evolves – akin to peeling an onion layer by layer. At each stage, information becomes more specific and emergency actions more focused, enabling local governments to make informed, science-based decisions.[16]

For instance, Fujian and Yunnan provinces have developed a "1262" model tailored to local climate and geography, which ensures context-specific responses:

- **12** hours ahead: identify key risk areas.
- **6** hours ahead: deploy rescue resources.
- **2** hours before disaster impact: evacuate at-risk populations.

The "31631" model in Hubei and Guangdong provinces is similar:

- **3** days ahead: major weather forecasts and special reports.
- **1** day ahead: county-level warnings and emergency preparations.
- **6-3** hours before disaster impact: precise township-level alerts.
- **1** hour before impact: immediate village-level warnings and evacuation orders.

These progressive, multi-tiered warning systems have proved highly effective in narrowing the "defence circle" around disasters, supporting rapid, coordinated action and minimizing losses.

Implementation is both top-down and locally tailored. As of 2024, 30 provinces had issued provincial-level adaptation action plans and 39 pilot cities were actively exploring best practices for climate-adaptive urban development.[17] In Shanghai's Chongming District, for example, a system blending "ecological protection red lines" with climate adaptation indicators has been established. By including metrics such as the accuracy of severe weather warnings in official performance evaluations, it creates a closed-loop management cycle comprising "monitor-assess-act-feedback", ensuring that national resilience goals are not just declared, but actively pursued and measured at every level of governance.[18]

Proactive protocols at the enterprise level

At the industry and enterprise level, China's approach to climate resilience is rapidly evolving from passive defence to proactive, systematic strengthening. The China *Climate Change Adaptation Progress Report (2024)* notes the significant enhancement of the power grid's capacity to withstand extreme weather events as a result of national directives such as the Guidance on High-Quality Development of Distribution Grids. According to the report, in 2024, the national average power outage time per household decreased by 1.12 hours and the average supply reliability rate reached 99.924%. Behind these statistics lies a disciplined system of pre-disaster risk warning and post-disaster recovery, demonstrated by the successful management of 95 major natural disaster emergencies, restoring power to over 29 million households.[19]

The sophisticated management systems being deployed by leading utility companies such as China Resources Gas and China Huaneng Group are a good illustration of this more proactive approach. China Resources Gas, a major urban gas operator, illustrates a governance-led model which mitigates risk through a multi-layered framework that establishes clear accountability, a tiered risk-management system and collaborative mutual aid agreements with government and industry peers (see Case Study 1). China Huaneng Group, a key power and heat supplier, demonstrates an operationally integrated model with its "monitor-warn-act-recover" life-cycle framework to ensure critical service reliability. Its proactive approach includes hazard-specific protocols such as redundant heat sources and typhoon reinforcements, validated by dedicated rescue teams and regular emergency drills (see Case Study 2).

CASE STUDY 1

"Dual responsibility" risk mitigation framework of China Resources Gas

As one of China's largest urban gas operators, China Resources Gas plays a critical role in the nation's utilities sector. Its 2024 sales volume of 39.9 billion cubic metres represents nearly 10% of total urban consumption. To safeguard its vast network and systemic importance, the company has built a robust management architecture designed to anticipate and mitigate climate risks systematically, which features:

- **Institutionalized accountability**: An enterprise-wide EHS (environment, health and safety) committee provides centralized oversight. Critically, it implements a "dual responsibility" system, making both the party committee leadership and the operational leadership directly accountable for climate safety, with performance tied to official evaluations.
- **Differentiated risk management**: The company conducts specialized risk assessments for climate hazards, categorizing threats into a four-tiered system (blue, yellow, orange, red). This allows for differentiated and proportionate control measures, focusing resources on the most critical vulnerabilities.
- **Resource and emergency preparedness**: A dedicated safety production fund is allocated specifically for the construction and maintenance of climate protection facilities. The company has established a network of emergency response bases, fully stocked with essential equipment such as mobile power generators and flood control sandbags. This physical readiness is matched by human readiness, with regular, comprehensive training drills extending to all employees to cultivate a universal culture of risk awareness and response capability.
- **Collaborative ecosystem**: Recognizing that resilience is a shared responsibility, the company has forged formal mutual aid agreements with local governments and peer enterprises. This synergy between government and business enables the sharing of emergency resources and expertise, enhancing the collective response capacity of an entire region.
- **Closed-loop learning system**: After any climate-related incident, a mandatory debriefing is conducted to identify root causes and formulate corrective actions. These findings and case studies are then integrated into training materials, ensuring that lessons learned are institutionalized and shared across the organization to improve future responses.

Source: China Resources Gas.[20]

CASE STUDY 2

China Huaneng Group's "monitor-warn-act-recover" risk mitigation framework

China Huaneng Group, a major power and heat supplier nationwide, demonstrates how strategic governance translates into highly specific, technology-driven operational protocols across its "monitor-warn-act-recover" framework. This system is designed not just to withstand high-frequency climate risks such as heavy rainfall, typhoons and ice storms, but to maintain critical service delivery throughout them.

The company's approach is built on a foundation of proactive protocols and targeted hazard defence:

- **Integrated meteorology-energy mechanism**: Huaneng has developed a dynamic mechanism that links meteorological disaster monitoring with real-time energy supply and demand management. By tracking data from over 2,000 meteorological stations nationwide, the company can dynamically adjust the operation modes of its power generation units. This ensures that essential electricity loads for public welfare are covered at a rate of 99.95% or higher, even during extreme weather events.
- **Redundant heat source assurance in cold regions**: For regions prone to severe cold, Huaneng has implemented a "redundant heat source assurance plan". In areas with a single heat source, an emergency heat source is deployed to ensure that any interruption in heating supply can be restored within four hours, minimizing the impact on residents and critical facilities.
- **Flood and typhoon preparedness**: In high-risk areas such as the Yangtze River basin and the southeast coastal regions, Huaneng is developing early warning and response mechanisms for extreme precipitation. This includes pre-emptive reservoir discharge to maintain at least 15% flood control capacity and a strict "wind resistance reinforcement checklist" for coastal power plants. Before typhoons of grade 10 or above, 21 mandatory tasks are completed, such as reinforcing steel roofing and conducting stress tests on wind turbine towers, to ensure plant safety and operational continuity.

- **Emergency response force development**: Huaneng has strengthened its emergency response capabilities by enhancing the maintenance centres for thermal and hydropower plants and building specialized coal emergency rescue teams. The company has established five dedicated rescue teams with a total of 451 personnel. During Typhoon Yagi in 2024, Huaneng's Hainan branch, with 25% of the island's installed capacity, supplied 40% of the island's electricity by remaining operational when other plants shut down due to extreme weather conditions.
- **Emergency drills and continuous improvement**: Huaneng regularly conducts large-scale emergency drills to test and refine its disaster response protocols. In 2024, the company organized four group-level emergency exercises, including flood control at Dezhou Power Plant in Shandong and an earthquake emergency drill at Nuozhadu Hydropower Plant in Yunnan.

Through these comprehensive and proactive measures, China Huaneng Group has set a benchmark for climate risk management in the utilities sector, demonstrating how a technology-driven and operationally integrated approach can significantly enhance the resilience of critical energy infrastructure in the face of escalating climate threats.

Source: China Huaneng Group.[21]

2.3 Technology: empowering resilience through innovation

If policy and governance provide the strategic blueprint for resilience, technology serves as the powerful engine driving its implementation. China's approach moves beyond incremental, one-off upgrades to leverage a technological transformation that future-proofs its critical utility infrastructure, through a multi-layered strategy that fuses early warning, reinforcement and nature-inspired design. This integration of advanced technologies is transforming how utilities anticipate, withstand and recover from extreme weather events.

Advanced early warning – using meteorological data and AI for predictive risk assessment

China has established the world's largest integrated meteorological observation system, comprising nine in-orbit satellites, 546 weather radars and over 70,000 ground-based stations.[22] The country has developed advanced numerical weather prediction models and AI-based forecasting systems with several performance indicators reaching international standards.

> **China's innovative practices have not only enhanced its own disaster prevention and mitigation capabilities, but also provided valuable experience for the construction of the global early warning system.**
>
> Ko Barrett, Deputy Secretary-General, World Meteorological Organization.[23]

While this public infrastructure provides a vital macro-level shield, leading utility enterprises recognize that a one-size-fits-all forecast is insufficient for managing asset-specific risks. They are actively bridging this last-mile gap by developing and implementing their own advanced, in-house early warning systems.

These enterprise systems – exemplified by China Energy Investment Corporation (see Case Study 3) and Beijing Drainage Group (see Case Study 4) – integrate meteorological and hydrological data with real-time monitoring of utility infrastructure, enabling predictive risk assessment at much higher spatial and temporal resolution. By leveraging big data analytics and AI, utilities can anticipate and respond to climate-related threats with unprecedented precision and speed.

CASE STUDY 3

China Energy Investment Corporation

China Energy has pioneered the use of digital and intelligent early warning systems to create a closed-loop process that links monitoring, forecasting, operational management and planning. By integrating advanced meteorological monitoring equipment, big data analytics and AI algorithms, the company has built a collaborative, intelligent and highly efficient meteorological support capability. This system enables comprehensive situational awareness of weather changes across all operational regions, significantly enhancing both operational efficiency and risk resilience.

- **Precision decision-making**: Real-time, high-accuracy meteorological data and risk warnings provide a scientific basis for management decisions across production, logistics and sales. For example, before the onset of heavy rainfall, precise precipitation forecasts allow the company to adjust coal mining schedules in advance, preventing equipment flooding and reducing the risk of personnel injury.
- **Proactive contingency planning**: Based on early warnings, China Energy formulates forward-looking emergency plans for production, transportation and sales, optimizing resource allocation and improving the foresight and scientific basis of decision-making. This proactive approach enables business units and subsidiaries to prepare thoroughly for adverse weather, minimizing operational disruptions and economic losses, while maximizing resource utilization and cost control.

Source: China Energy Investment Corporation.[24]

CASE STUDY 4

Beijing Drainage Group

Beijing Drainage Group is a state-owned enterprise responsible for wastewater treatment, drainage management and flood control in the centre urban area of Beijing. The company has harnessed digitalization and AI to transform urban flood risk management, for example by establishing a "smart flood control" command and dispatch system that integrates over 300 video monitoring points at pump stations, underpasses and known waterlogging hotspots. Proprietary AI algorithms analyse video feeds in real time to identify water accumulation, replacing manual inspection with a more efficient, automated process.

- **Digital twin and risk simulation**: The company has developed a digital twin model for urban flood risk simulation, enabling precise prediction of waterlogging based on real-time rainfall forecasts and hydrological modelling. This supports intelligent scheduling and rapid emergency response.
- **Automated meteorological monitoring and alerts**: All high-risk locations are equipped with automated weather monitoring and alert systems. Leveraging the BeiDou satellite system, the company can pinpoint stormwater inlets to within 50 centimetres, enabling field teams to quickly locate and clear blockages. Mobile applications ensure that early warnings and dispatch instructions are instantly communicated to all relevant personnel, streamlining the emergency response.
- **Upgraded infrastructure for rapid response**: To support early warning with rapid action, Beijing Drainage Group has upgraded 76 underpass pump stations in the city centre, expanded rainwater pipelines and increased pumping and storage capacity. The total pumping capacity has nearly doubled and storage capacity now exceeds 200,000 cubic metres, providing a robust hardware foundation for fast drainage following early warnings.

Source: Beijing Drainage Group.[25]

By integrating national meteorological resources with enterprise-level digital innovation, China's utilities sector is setting new standards in predictive risk assessment and early warning. These advanced systems not only enable more precise and timely responses to extreme weather but also support smarter, more resilient operations across the entire utilities value chain. As climate risks continue to evolve, the ongoing development and deployment of such technologies will be critical to safeguarding infrastructure, ensuring service continuity and protecting communities.

Infrastructure hardening and intelligent operations systems

Effective early warnings are only valuable if the infrastructure can withstand the initial shock and operations can be intelligently managed during a crisis. Recognizing this, Chinese utilities are pursuing a dual strategy of physical fortification and operational digitalization. This involves deploying more resilient materials and hardware, while wrapping this hardened infrastructure in a layer of intelligent software, creating a "sentient" grid capable of self-assessment and rapid, semi-autonomous response.

For example, advanced sensors (IoT devices) on transformers, switches and power lines constantly measure voltage, current and temperature. This data is fed into a central system, providing a live "health check" of the entire grid, far beyond a simple on/off status. Real-time data from monitoring terminals feeds into AI-driven models that can predict conditions such as icing up to three days in advance, enabling precise, proactive de-icing. The key to a semi-autonomous response is that the system intelligently takes pre-approved actions on its own but keeps a human operator in the loop for confirmation or high-level direction.

China Southern Power Grid (CSG), one of China's two power transmission giants, supplies electricity to more than 250 million people across five southern provinces. Managing a vast and climate-vulnerable service area, CSG has become a national leader in grid modernization and disaster resilience, fusing digital intelligence with robust physical infrastructure. Its systems have transformed disaster management – delivering faster recovery, higher accuracy and minimal damage even under extreme icing and typhoon events (see Case Study 5).

CASE STUDY 5

China Southern Power Grid

China Southern Power Grid (CSG) has pioneered a comprehensive defence system – spanning perception, prediction, response and recovery – by tightly integrating hardware upgrades with intelligent operations software.

Icing disaster response: hardware-software synergy

In regions prone to cold waves and freezing rain, such as Guizhou, CSG has established a multi-layered anti-icing system. The grid has deployed 108 sets of DC ice-melting devices and 620 online icing monitoring terminals, forming a "three-tier, four-protection" system: 1) DC ice-melting for main grids; 2) flexible ice-melting for county-level grids; 3) AC ice-melting for township grids; and 4) manual de-icing for village lines.

This system can melt 10 centimetres of ice on 350 kilometres of 500kV lines within one hour, achieving "zero tripping, zero damage" for main grid equipment. Real-time data from monitoring terminals feeds into AI-driven models that predict icing conditions up to three days in advance, enabling precise, proactive de-icing. Digital twin technology simulates the de-icing process, optimizing strategies and ensuring near-100% success rates.[26]

Typhoon response: air-ground integrated operations

During typhoons, CSG uses unmanned aerial vehicles (UAVs) and intelligent systems for rapid reconnaissance and restoration. For example, during Typhoon Wipha, "Wing Loong" drones penetrated cloud walls to relay real-time imagery to the emergency command centre and deployed airborne base stations to restore communications. Ground-based smart repair systems, informed by UAV data, automatically generate optimal repair routes, enabling a fully digitalized "reconnaissance-location-repair" workflow.

The Guangdong grid's "one map for emergency" system integrates wind, rain and disaster data, supporting rapid restoration: during Typhoon Butterfly, 60% of the 15,000 affected users had power restored within two hours. This swift response was enabled by AI-powered dispatchers such as the "Mingyue" system, whose rapid analysis and forecasting enabled crews to be dispatched almost immediately to the exact fault locations, streamlining the entire repair. Without such a system, simply diagnosing issues and coordinating a response could take hours. AI's second-level risk analysis has reduced this process to just five minutes, with load forecasting accuracy reaching 98.3%.

Meanwhile, CSG's digital repair platforms, such as the "elink" system in Zhanjiang, enable real-time sharing of damage information and boost work order dispatch efficiency by 70%. In Xuwen, the integration of UAVs and manual teams enabled the restoration of power to 1,758 households within 45 minutes during a typhoon event.

Source: China Southern Grid.[27]

“ By integrating under-panel vegetation, grazing and soil rehabilitation, the Kubuqi Desert PV project restores over 6,700 hectares of desert and abates 3.19 Mt of CO_2 annually.

By integrating resilient equipment, AI-driven operations and smart grid technologies, the utilities sector is achieving new levels of infrastructure resilience and operational intelligence. These innovations not only protect physical assets but also enable rapid, data-driven decision-making, ensuring that utility services remain robust and adaptive in the face of escalating climate risks.

Integrating green infrastructure to supplement traditional engineering

As China's utilities sector advances towards climate resilience, ecosystem-integrated solutions are emerging as a vital complement to traditional engineering approaches. By harnessing the power of ecosystems, utilities are not only mitigating climate risks but also delivering co-benefits for biodiversity, land restoration and community well-being. These green infrastructure strategies are increasingly integrated into utility planning and operations.

The China Three Gorges Corporation's 2 GW Kubuqi Desert PV project in Inner Mongolia demonstrates how large-scale solar installations in arid regions can deliver environmental and socio-economic benefits (see Case Study 6). By integrating solar energy generation with sand control measures – including under-panel vegetation, grazing and soil rehabilitation – the project reduces wind erosion, conserves moisture, restores over 6,700 hectares of desert land and abates 3.19 million tonnes of CO_2 annually. It also boosts local livelihoods through eco-agriculture, offering a scalable model for climate adaptation and rural development.

China Huaneng Group's hydropower operations in the Lancang River basin showcase how digitally integrated, cascade reservoir systems can serve as powerful tools for climate adaptation – balancing clean energy production with flood control and drought relief (see Case Study 7). During China's severe 2024 floods, these stations cut flood peaks by ~70%, storing 147.1 billion cubic metres of water to protect downstream communities. Beyond borders, emergency water releases during Mekong droughts (notably 12.65 billion m^3 in 2016) aided neighbouring countries, fostering regional cooperation. This model demonstrates how smart hydropower infrastructure enhances resilience at home and abroad, setting a global benchmark for adaptive, multi-functional water-energy systems.

Together, these case studies illustrate how China's utilities are pioneering ecosystem-integrated solutions that go beyond conventional engineering to build holistic climate resilience. By blending renewable energy infrastructure with ecological restoration and smart water management, they deliver cascading benefits – from carbon reduction and biodiversity recovery to transboundary cooperation and rural livelihoods.

CASE STUDY 6

China Three Gorges Corporation – desert-based photovoltaic (PV) project

In the Gobi Desert and Loess Plateau, large-scale photovoltaic (PV) arrays are demonstrating significant ecological and climate adaptation benefits. Beyond generating clean energy, these installations act as physical barriers that suppress wind erosion and retain soil moisture, creating favourable microclimates for the growth of native grasses and shrubs. This, in turn, stabilizes soils and supports the recovery of local biodiversity.

A prime example of this synergy is the China Three Gorges Corporation (CTG) Kubuqi Desert-based 2 GW PV Project. Located in the heart of the Kubuqi Desert in Inner Mongolia, it is the country's largest single-site desert-based PV project.

The project employs a comprehensive “PV + sand control” model, combining solar panel foundations for sand stabilization, under-panel planting and grazing and the use of crops to rehabilitate and improve soil quality. This integrated approach has yielded multiple benefits:

- **Wind and water control**: PV arrays reduce desert wind speeds and surface water evaporation, while enhancing soil fertility.
- **Vegetation recovery**: The project has significantly increased vegetation cover, restoring 100,000 mu (about 6,700 hectares) of desert land.
- **Carbon and energy benefits**: Annually, the site generates approximately 4.1 billion kWh of clean electricity, reducing CO_2 emissions by 3.19 million tonnes.
- **Socio-economic impact**: The project supports local livelihoods through eco-agriculture and animal husbandry, demonstrating a scalable model for climate adaptation and rural revitalization.

Source: China Three Gorges Corporation.[28]

CASE STUDY 7

China Huaneng Group – hydropower for flood control and water security[29]

Hydropower infrastructure, when managed with advanced data and digital technologies, serves as a multifunctional resilience tool – producing clean energy, storing water resources and regulating flood and drought risks. In 2024, China's major river basins experienced 26 significant flood events, the highest since 1998. The Ministry of Water Resources initiated 43 emergency responses and issued over 4,300 flood warnings. During this period, hydropower reservoirs collectively retained 147.1 billion cubic metres of floodwater, playing a critical role in disaster mitigation and safeguarding lives and property.

The Lancang River basin, managed by China Huaneng Group, exemplifies the climate adaptation value of coordinated hydropower systems. Twelve cascade hydropower stations, equipped with digital monitoring and basin-wide centralized dispatch,[30] have optimized power generation and joint reservoir operations across wet and dry seasons. During the 2024 flood season, this system reduced the natural flood peak by approximately 70%, significantly lowering downstream flood risks.

The benefits of this approach extend beyond national borders. During severe droughts in the Mekong River basin in 2016 and 2019, upstream Huaneng hydropower stations provided emergency water releases, alleviating shortages for downstream countries. In 2016 alone, emergency releases totalled 12.65 billion cubic metres – an 85% increase over natural inflows at Jinghong Station – earning recognition from riparian nations and strengthening cross-border cooperation and trust.

China Huaneng's Lancang River Hydropower Base has put two multi-year regulated reservoirs[31] into operation, which will play a critical role in maintaining water and power supply capabilities amid prolonged droughts and changes in spatial-temporal patterns of precipitation. Additionally, an integrated hydro-wind-solar energy system is being developed basin-wide. By leveraging the complementary effects of wind, solar and hydropower, this system will enable a high-quality emergency response capacity to combat extreme weather events such as droughts, heatwaves and cold spells.

Sources: World Economic Forum, China Huaneng Group.[32]

2.4 Finance: funding the resilience transition

Building climate-resilient utilities in China requires not only technological and governance innovation but also robust and diversified financial support. The financial dimension of China's resilience transition is characterized by strong public sector mobilization, the development of risk transfer mechanisms and the rapid growth of green and blue finance as a strategic tool for both mitigation and adaptation.

Public sector mobilization: strategic investment and financial support

China's central and local governments have made significant, sustained investments in climate monitoring, disaster preparedness and emergency response. From 2019 to 2023, national funding for disaster prevention, mitigation and emergency management grew at an average annual rate of 8.85%. In 2024, the central government allocated ~RMB 334 billion (~$46 billion) for disaster and emergency response, providing a critical financial backbone for effective disaster management across regions and sectors.[33]

Targeted fiscal support has been further strengthened, with RMB 2.51 billion in central natural disaster relief funds allocated to support local flood control, drought mitigation and responses to low-temperature, snow and ice disasters.[34] These funds have enabled the construction and equipping of grassroots emergency rescue teams, the enhancement of emergency management bases and the deployment of specialized water engineering rescue units.

Urban resilience has also benefited from dedicated funding. In 2024, city renewal initiatives included comprehensive "health checks" for all prefecture-level cities and above, the construction or renovation of 163,000 kilometres of utility pipelines, 201 kilometres of new integrated utility corridors and the remediation of over 900 flood-prone sites. These investments have significantly improved urban capacity to withstand and recover from flood disasters.[35]

Risk transfer mechanisms: climate insurance and financial risk management

To address the growing financial risks posed by climate change, China is rapidly developing climate insurance and public-private risk transfer mechanisms. The government has issued guidance to strengthen the integration of meteorological and financial services, establishing a climate-related financial risk monitoring and control system. This includes the exploration of climate risk stress testing for financial institutions, enabling systematic assessment of potential exposures under different climate scenarios and transition policies.

The insurance sector is playing an increasingly important role. Catastrophe models for flood and typhoon risks have been developed and commercialized, providing a foundation for innovative insurance products that can be tailored to local needs. The ongoing upgrade of these models is enhancing the industry's ability to price and transfer climate risks effectively. Additionally, new insurance products have been introduced to support marine ecosystem restoration and wetland biodiversity protection, further aligning financial incentives with climate adaptation and environmental goals.

Green and blue finance: sustainable financing for resilience

China is a global leader in green finance, with rapid growth in both green loans and green bonds. By the end of 2024, the outstanding balance of green loans reached RMB 36.6 trillion (~$5.09 trillion), up 21.7% year-on-year – outpacing overall loan growth by 14.5 percentage points. The outstanding balance of green bonds stood at RMB 2.09 trillion (~$290.6 billion), with cumulative issuance exceeding RMB 4.1 trillion (~$570 billion).[36]

Financial institutions are encouraged to innovate and tailor products to the specific needs of resilience-focused projects, under the principles of risk control and commercial sustainability. This includes the creation of specialized insurance for marine vegetation restoration and wetland biodiversity, as well as the development of differentiated financial services for climate adaptation projects.

To enhance transparency and accountability, China has introduced new standards for corporate sustainability disclosure, including the trial *Basic Standards for Corporate Sustainable Disclosure* and the *General Guidelines for Corporate Greenhouse Gas Information Disclosure*. These frameworks encourage companies to disclose their climate mitigation and adaptation targets and measures, supporting informed investment and risk management decisions.[37]

While China is directing significant resources towards safeguarding infrastructure and promoting a resilience transition in utilities, achieving the necessary scale, consistency and geographic coverage will require stronger policy coordination and the establishment of a multi-faceted financing mechanism.

From 2019 to 2023, China's national funding for disaster prevention, mitigation and emergency management grew at an average annual rate of 8.85%.

3 The next frontier: upgrading to Resilience 2.0

To adapt to escalating climate risks requires evolving governance, AI-powered technology and innovative financing.

While China's current framework for utilities resilience has established a robust foundation, the escalating and compounding nature of climate risk demands a forward-looking evolution. The next frontier is an upgrade to Resilience 2.0, a paradigm shift that moves towards a state of proactive, intelligent and systemically integrated adaptation. This is not just an incremental improvement of existing measures but a fundamental reimagining of how utilities are operated, governed and financed in an era of climatic uncertainty. Resilience 2.0 is defined by a holistic ecosystem where governance, technology and finance are seamlessly interwoven to create a self-learning and self-healing infrastructural backbone for the nation.

3.1 Evolving governance: institutionalizing climate resilience

> Resilience 2.0 governance involves embedding climate resilience so deeply into institutional DNA that it becomes an automatic, non-negotiable component of all strategic and operational decision-making.

The governance model of Resilience 1.0 was characterized by strong, top-down directives and the creation of effective emergency response plans. While crucial, this approach often remains event-driven. The evolution to Resilience 2.0 governance involves embedding climate resilience so deeply into institutional DNA that it becomes an automatic, non-negotiable component of all strategic and operational decision-making.

The first major shift is moving from hazard-driven plans to proactive capital planning and asset management. In a Resilience 2.0 framework, every capital allocation decision – whether for a new power plant, a pipeline extension, or a grid upgrade – will be filtered through a critical climate resilience lens. This means moving beyond traditional ROI calculations to incorporate a "resilience-adjusted return on investment" (R-ROI). Projects will be evaluated not just on their economic output but on their ability to withstand a range of future climate scenarios, their potential for cascading failures and their contribution to overall system stability. Asset management will similarly transform from a schedule-based or "fix-it-when-it-breaks" model to a condition-based, predictive model where maintenance and reinforcement are prioritized based on forward-looking climate risk exposure.

The second and perhaps most critical evolution is the development of standardized resilience metrics, certification and disclosure frameworks. To effectively manage and invest in resilience, it must be quantifiable. The next frontier will focus on the government regulators, industry associations and academic institutions collaborating to create a common language for resilience. This could manifest in the following ways:

- **Standardized resilience metrics**: a suite of key performance indicators (KPIs) to measure the resilience of a specific utility asset or system. These might include metrics such as "time to full recovery" after a simulated category 4 typhoon, "grid stability index" under a 15-day heatwave, or "water supply security level" during a 1-in-100-year drought.
- **Climate-ready certification**: a formal certification system, akin to LEED for green buildings,[38] that awards a "climate-ready" or "resilience-certified" rating to infrastructure projects that meet stringent design, material and operational standards. This would provide a clear signal to investors and insurers about the quality and durability of the asset.
- **Mandatory resilience disclosure**: building on existing sustainability reporting, listed utilities companies are required to disclose their physical climate risk exposure and the results of their resilience stress tests in their financial reports. This transparency will enable markets to accurately price risk and reward companies that demonstrate superior resilience management.

In addition, it is critical to strengthen market-orientated values and development. For example, the recent implementation of Policy No. 136[39] on deepening the market-orientated reform of new energy on-grid electricity prices outlines a pathway for China's utilities sector – particularly the power industry – towards greater marketization and enhanced resilience. By adopting an approach that "deregulates pricing while regulating mechanisms", these policies shift the new energy industry from subsidy dependency to competition-driven efficiency, using market mechanisms to explicitly value system flexibility and reliability. This incentivizes all stakeholders – such as in generation, grid, load and storage – to collectively participate in building resilience.

This evolving governance architecture will create a powerful feedback loop, turning resilience from an abstract priority into a measurable, reportable and auditable mandatory function that directly influences strategy, operations and market valuation.

3.2 Technological leapfrogging: AI-powered integration

The technology of Resilience 1.0 focused on establishing critical capabilities such as early warning and infrastructure hardening. Resilience 2.0 represents a technological leapfrog into a future defined by AI, autonomy and hyper-integration, creating a truly intelligent and adaptive utility network.

The core of this leap is leveraging predictive analytics for pre-emptive maintenance and dynamic infrastructure reconfiguration. The AI of Resilience 2.0 will go beyond just forecasting a storm; it will predict the specific consequences of that storm at a component level. An AI model could analyse real-time sensor data from a transformer, combine it with a hyper-local heatwave forecast and flag a 90% probability of failure within 48 hours, automatically dispatching a maintenance crew before the failure occurs.

In the event of an unavoidable outage, the system will move towards a "self-healing" state. An AI-powered grid controller will autonomously reroute electricity or water flows around the damaged section in milliseconds, isolating the fault and minimizing the scope and duration of the service disruption for customers.

This will be complemented by the large-scale deployment of autonomous systems for rapid damage assessment and maintenance support, especially in remote and inaccessible areas. While drones are already used for reconnaissance and data collection, the next generation will feature swarms of automated drones and ground-based robotics capable of delivering lightweight components and, in time, performing initial repairs. This will drastically reduce restoration times and improve safety for human crews who would follow up to complete the work.

The carbon emissions associated with AI applications are drawing significant attention, particularly the environmental impact of large language models (LLMs). According to recent analysis by Google, the median Gemini Apps text prompt uses less energy than watching nine seconds of television (0.24 Wh) and consumes roughly the equivalent of five drops of water (0.26 mL) – impacts that are small relative to many everyday activities.[40] While such per-use metrics illustrate efficiency gains, it is equally important to address the broader, systemic challenge: the carbon footprint of the global data centres that power these AI applications. The total energy consumption of these facilities represents a significant environmental concern that requires a different scale of solutions.

Addressing this macro-level challenge relies on broad, multi-faceted commitments. On one front,

> Resilience 2.0 represents a technological leapfrog into a future defined by AI, autonomy and hyper-integration, creating a truly intelligent and adaptive utility network.

> The ultimate technological frontier is the creation of cross-sector data platforms for integrated risk management.

global power systems are progressing towards decarbonization. For instance, by mid-2023, renewable sources in China had overtaken thermal power, accounting for more than half the country's total installed electricity generation capacity.[41] On another front, technology companies are pursuing ambitious clean energy goals. Google, for example, aims to operate its data centres on 24/7 carbon-free energy by 2030, a goal supported by direct investments in grid decarbonization and in both nature-based and technological carbon removal solutions.[42]

Over the longer term, technological advances combined with a greener electricity supply are likely to mitigate AI's carbon footprint; nevertheless, sustained monitoring, transparency and rigorous assessment remain essential.

At the regional scale, it is essential to further strengthen coordination and backup capacity to improve resilience. Feasible solutions must be comprehensively evaluated from technical, economic and security perspectives. For instance, within the new power system, one of the key challenges remains optimizing the understanding, utilization and dispatch of wind, solar and hydropower to maximize both profitability and reliability. This is precisely where AI can play a transformative role.

Finally, the ultimate technological frontier is the creation of cross-sector data platforms for integrated risk management. Siloed approaches where the power utility, water utility and transport authority operate on separate data systems will become obsolete. Resilience 2.0 envisions a central "city resilience operating system" or a regional "integrated utility data hub".

Such platforms would ingest real-time data from all critical infrastructure sectors. An AI monitoring platform could see that a power substation outage will knock out the pumps for a specific water district in 30 minutes and cripple traffic signals along a key evacuation route. It could then autonomously trigger contingency plans across all three sectors simultaneously: alerting the water utility to switch to backup reservoirs, rerouting traffic around the affected area and prioritizing power restoration to the most critical assets. This level of integrated intelligence transforms risk management from a sector responsibility into a coordinated, system-wide capability.

3.3 Financial innovation: risk pricing as the architect of resilience

In the Resilience 2.0 framework, the role of finance must evolve from being a passive provider of post-disaster capital to an active architect of pre-disaster risk reduction. This transformation of finance is illustrated by the growing use of weather derivatives in China's power sector.

For example, faced with severe financial volatility from heatwave-driven electricity demand, a power company, Guorui New Energy, secured a parametric insurance contract tied to the official CMA-DCE Temperature Index. Jointly compiled by the China Meteorological Administration (CMA) and the Dalian Commodity Exchange (DCE), this index reflects temperature changes in major cities across China and provides intuitive and comprehensive information for temperature-sensitive industries.[43] The insurance serves as a pre-disaster hedge: if temperatures exceed a predefined threshold, the company automatically receives a payout to offset the high cost of procuring emergency power on the spot market. By converting an unpredictable climate risk into a manageable financial variable, this approach moves beyond passive post-event compensation, allowing the company to build economic resilience against climate extremes before they inflict financial damage.

By moving beyond traditional indemnity models, innovative financial mechanisms can create powerful market-based incentives that reward proactive resilience measures and unlock private capital. Three key innovations can lead this change, described below.

Dynamic parametric insurance

This product links premiums and payouts directly to real-time, verified risk data. Instead of a static annual premium, a utility's rate would be dynamically adjusted based on its resilience posture. For instance, a power distribution company that installs smart lightning arresters and demonstrably reduces its fault rate by 20% could receive an automatic 15% reduction in its premium for the following year. Crucially, payouts are triggered by objective data points (e.g. temperature or wind speed exceeding a threshold), not by slow loss adjustment. This ensures that upon a triggering event, capital is disbursed within a guaranteed timeframe, such as 48 hours, injecting vital liquidity when it is needed most.

Resilience-building bonds (R-bonds)

This hybrid instrument fuses risk transfer with capital formation. A utility or municipality could issue an R-Bond to finance resilience upgrades. The bond's coupon payments would be contingent on climate outcomes. In a year without a major disaster

event, investors receive their full coupon. However, if a pre-defined catastrophe (such as a 1-in-50-year flood) occurs, a portion of the coupon payment is automatically diverted to a pre-established insurance and recovery fund. This innovative structure lowers the net cost of risk capital for the issuer while systematically building a financial buffer to absorb future shocks, effectively spreading risk to the broader capital markets.

Public-private resilience pools

To cover critical but often underinsured assets such as smaller municipal water systems, government can act as a convener to establish regional co-insurance pools. These public-private partnerships would bring together insurers, industry associations and the utilities themselves to underwrite risks collectively. The premium structure would be designed to drive behaviour, consisting of a base premium plus a "risk adjustment levy". A member utility that completes a certified resilience upgrade – such as retrofitting its water pipes for frost protection – would earn a significant discount on its levy, creating a powerful and self-sustaining cycle of "investment for discount".

It is essential to engage the private sector. In Europe, according to a recent study, although the scale of private-sector investment in climate change adaptation is relatively small, it has grown significantly. In 2018, the annual adaptation investment of the private sector in the European Union and the United Kingdom was €15.4 billion EUR; by 2022, it had increased to €52.9 billion, representing 243% growth over five years.[44] In 2023, the global blended climate finance market overcame macroeconomic challenges to achieve historic growth, with total financing reaching $18.3 billion (a 120% year-on-year increase), including a near-200% surge in private sector investment to $6 billion.[45]

The reliability of energy, water and other infrastructure – once a given for global commerce – has become a direct and material risk to corporate profitability, operational stability and long-term growth. Investing in resilience not only mitigates these risks but also unlocks new opportunities: it drives market expansion for emerging technologies and services, creates channels for innovative financing and enhances the competitiveness of firms that deliver climate-adaptive solutions. In short, climate resilience represents both a strategic safeguard and a new frontier for private sector growth.

Private sector participation can be achieved through multiple pathways, including strategic co-investment via public private partnerships (PPPs), targeted capital allocation towards digital and resilience-enhancing technologies, and collaborative ventures with financial institutions to develop new risk-sharing and financing instruments.

Together, these innovations transform finance from a simple compensatory tool into a dynamic engine that accurately prices risk, powerfully incentivizes mitigation and mobilizes private capital at scale for a more resilient future.

3.4 Science and education: essential foundation for resilience

Science and education form the indispensable foundation of the resilient utilities triangle. Future-proofing critical infrastructure requires not only physical defences but the cultivation of a deep-seated culture of knowledge, innovation and preparedness. Strengthening these twin pillars requires a concerted effort to translate cutting-edge research into actionable strategies and to empower every level of society with the understanding to navigate a new climate reality.

> Future-proofing critical infrastructure requires not only physical defences but the cultivation of a deep-seated culture of knowledge, innovation and preparedness.

Strengthening the science pillar: from global risks to local solutions

The first priority is to evolve scientific capabilities to match the complexity of modern climate threats. This begins with moving beyond traditional, isolated risk models to understand the emerging systemic risks posed by Earth system tipping points and crossing of planetary boundaries.

Societies must invest in research that reveals how a cascade of hazards – for instance, a compound event of extreme heat, drought and wildfire – can cripple energy, water and transport systems simultaneously.

Furthermore, science needs to downscale global climate projections to conduct impact studies at a finer, city-level or even asset-level scale. This granularity is crucial for utility planners to determine which substations are most vulnerable to flooding or which transmission lines are at greatest risk from wildfires.

Finally, harnessing the power of artificial intelligence is key. AI can process vast datasets to predict equipment failure, optimize grid load during stress and model disaster scenarios. However, its outputs must be "explainable" to earn the trust of engineers and policy-makers, ensuring that AI-driven insights lead to confident, pre-emptive action.

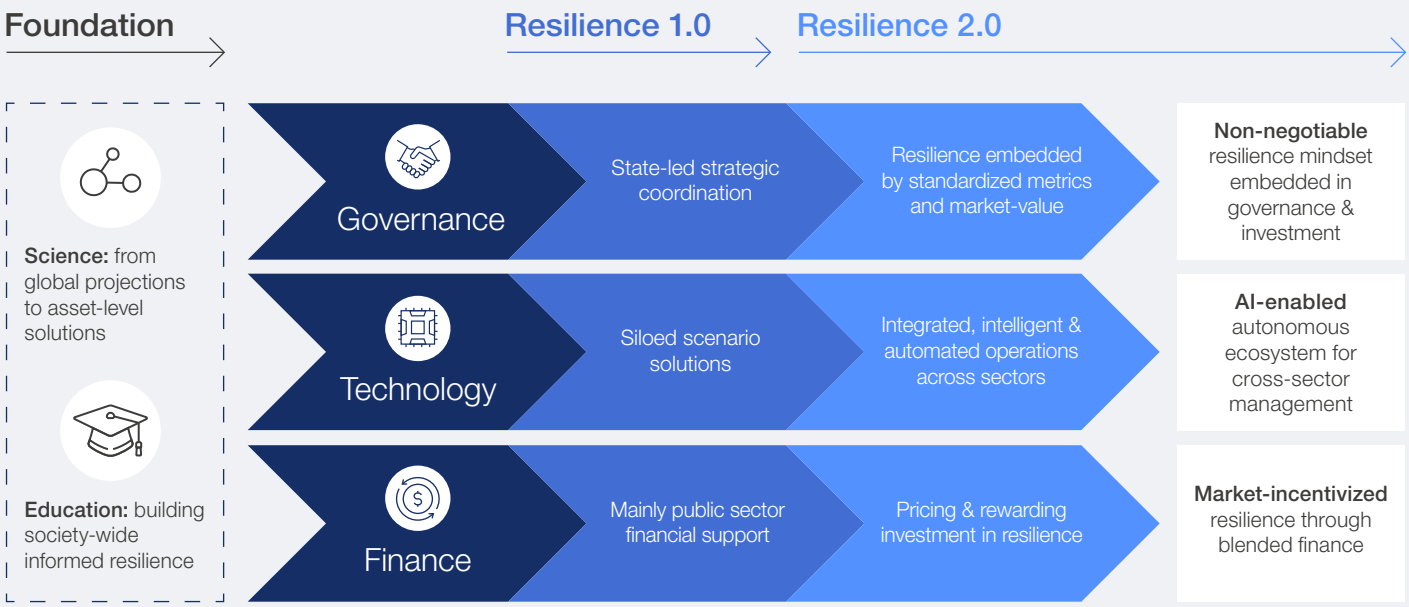
Strengthening the education pillar: building society-wide informed resilience

Scientific knowledge is only as strong as society's capacity to absorb and act upon it. Therefore, the education pillar must focus on creating a resilient population. This extends far beyond formal academia to encompass comprehensive public training, disaster education and community workshops. The goal is to enhance public awareness of climate risks and emergency response capabilities, making it a critical foundation for adaptation.

For the general public, this means clear, accessible information on how to prepare for and respond to escalating threats such as floods, heatwaves and storms. For utility customers, it involves educating them on demand-side management, such as how reducing consumption during peak periods can prevent blackouts. Most importantly, for utility professionals and local government officials, it requires continuous, advanced training on implementing new science and strategies – from interpreting AI-driven risk maps to executing emergency protocols. An informed public is a resilient public; they are the first responders in a disaster and the most crucial partners in sustaining community-wide operations when systems are under stress.

A resilient utility sector cannot be built on concrete and cables alone. It must be built on the bedrock of sophisticated science that anticipates the unforeseen and on an educational ecosystem that ensures every citizen, from engineer to homeowner, is equipped with the knowledge to act. By systematically strengthening these two pillars, the utilities triangle is transformed from a static structure into a dynamic, learning and resilient system.

FIGURE 4 **Resilience 2.0 – a dynamic, intelligent, proactive system**



Conclusion

China's approach to designing climate-resilient critical infrastructure is grounded in proactive planning, strategic coordination and technological agility.

As nations across the globe grapple with the escalating reality of climate change, the imperative to build resilient infrastructure has become a defining challenge of the 21st century. The journey of China's utilities sector – from confronting its acute vulnerabilities to systematically designing a multi-faceted defence – offers an instructive case study. Distilling this experience reveals a comprehensive resilience-building framework for climate adaptation of the utilities sector at national scale. China's approach is characterized by a unique blend of cultural philosophy, state-led strategic coordination and rapid technological deployment – each contributing to the country's ability to address climate risks at scale and speed.

Cultural imperative for proactive planning

China's long-standing cultural tradition of "planning for a rainy day" is deeply embedded in its approach to risk management. This cultural gene manifests in a proactive attitude towards disaster prevention, preparedness, long-term planning and the integration of resilience into every aspect of infrastructure development. Rather than reacting to crises after they occur, Chinese society and institutions emphasize anticipation, early warning and continuous improvement. This mindset has enabled China to mobilize resources and public support for large-scale adaptation initiatives, ensuring that resilience is not just a technical goal but a shared societal value.

State-led strategic coordination

A pivotal feature of China's approach to resilience is its unified national vision, underpinned by the strong synergy forged through a "government-led, enterprise-participating, society-wide co-governance" mechanism. The central government plays a crucial role in setting strategic priorities, coordinating across ministries and sectors, and mobilizing both public and private resources. This state-led approach enables rapid policy alignment, efficient allocation of funding and scaling-up of best practices nationwide. The ability to integrate climate adaptation into national security, economic planning and urban development ensures that resilience is embedded in the country's long-term growth trajectory. Moreover, close collaboration between government, enterprises and local communities creates a robust ecosystem for innovation and implementation.

Rapid, large-scale technology deployment

China's commitment to leveraging technology as a primary driver of solutions is evident in its world-leading investments in regional coordinated development, such as west-to-east electricity transmission and south-to-north water diversion, as well as in digital infrastructure, smart grids and smart water networks, AI-powered early warning systems and ecosystem-integrated solutions.

The country's ability to pilot, scale up and mainstream new technologies at speed and scale has transformed the resilience landscape. From the deployment of digital twins and autonomous systems in utility operations to the integration of green infrastructure in arid and flood-prone regions, China demonstrates how technological innovation can be harnessed to address complex, systemic risks. This technological agility is supported by a strong policy framework, robust public-private partnerships and a culture of continuous learning and adaptation.

While born of China's specific context, the core principles that underpin its approach – the value of a national strategy, the power of public-private alignment and the transformative potential of technology – offer universal lessons for the global pursuit of a climate-resilient future.

Call for global collaboration

The climate crisis is a shared global threat that respects no borders. China's vast territory, diverse geography and complex climate conditions magnify this challenge. While China is committed to its own development efforts, global partnerships are needed

> Building resilience is no longer a purely domestic concern – it requires a new era of international partnership.

to effectively overcome these immense challenges. The failure of a critical utility in one major economy can send shockwaves through international supply chains, financial markets and humanitarian systems.

Therefore, building resilience is no longer a purely domestic concern; it is a collective global responsibility. The path forward requires moving from isolated national efforts to a new era of international partnership.

The challenge of building climate-resilient utilities is a global imperative; to ensure success requires:

- **Sharing best practices**: Create formal platforms and networks for utility operators, regulators and engineers from different nations to share practical knowledge on what works, from technical standards for infrastructure hardening to governance models for risk management.
- **Co-developing standards**: Collaborate on developing international standards for resilience metrics, certification and disclosure. A common language for defining and measuring resilience will unlock global capital flows and enable more effective cross-border investment in climate-adaptive infrastructure.
- **Fostering technology collaboration and transfer**: Establish clear frameworks for technology transfer, capacity building and intellectual property-sharing that bridge the gap between developed and developing nations and make critical innovations accessible and affordable for all. In line with COP30 priorities and Article 10 of the Paris Agreement,[46] advance joint R&D, demonstration and deployment of next-generation resilience solutions – from AI-enabled grid management and predictive maintenance to advanced heat- and flood-resistant materials and nature-based protective infrastructure – aligned with the Global Goal on Adaptation.

A mission-orientated global innovation ecosystem will speed diffusion, lower costs and scale up resilience benefits for all. Ultimately, the challenge of building a climate-resilient future is too great for any single nation to solve alone. By learning from each other's experiences and working together to forge common solutions, the world can build a more secure, sustainable and resilient global commons for generations to come.

Appendix: Definitions

Definition of utilities sector

In accordance with the industry classification of the World Economic Forum[47] and China's National Standard (GB/T 4754 – 2017), *Industrial Classification for National Economic Activities,*[48] Table 1 provides a detailed definition of the utilities sector as discussed in this report.

TABLE 1 **Definition of utilities sector**

Utilities sector	Definition
Production and supply of electric power and thermal energy	Biomass energy production
	Electric/nuclear power transmission and distribution
	Nuclear and thermal power stations
	Solar energy provision
	Wind energy provision
	Hydropower production
	Geothermal energy production
Production and supply of gas	Gas distribution
	Oil and gas transportation
	Integrated oil and gas
	Oil and gas storage
	Gas retail
Production and supply of water	Water services (e.g. waste water, treatment and distribution)

Definition of resilience – in general and for the utilities sector

Intergovernmental Panel on Climate Change (IPCC)

"The capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure. Resilience is a positive attribute when it maintains capacity for adaptation, learning and/or transformation."[49]

United Nations Office for Disaster Risk Reduction (UNDRR)

"The ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management."[50]

International Bank for Reconstruction and Development / The World Bank

Definition of resilience specific to infrastructure and utilities, in its 2019 publication: *Lifelines: The Resilient Infrastructure Opportunity.* [51]

"The ability of infrastructure to provide the services users need during and after a natural shock. While natural hazards are only one of the causes of infrastructure disruptions, resilience is still an essential dimension of the overall reliability of infrastructure systems.

'Resilience' here is used in a broader sense than the traditional definition in ecology, which refers to the ability of systems to recover and bounce back. Boosting resilience, using this broad definition, can be achieved in many ways, including:

- Reducing the exposure of infrastructure assets to natural hazards, such as by building energy assets outside floodplains
- Reducing the vulnerability of assets, such as by making roads able to cope with heavy precipitation or bridges able to resist strong wind
- Designing infrastructure systems so they are able to deliver services, even if some of their components have been damaged or destroyed
- Ensuring that infrastructure systems do not fail catastrophically, can recover quickly, and be repaired efficiently if damaged
- Making the users of infrastructure services better able to cope with service disruptions, such as by installing batteries or generators in hospitals or ensuring that firms rely on multiple suppliers."

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Endnotes

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