# Cross-sector energy system resilience and interdependence in a changing climate

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## eTOC blurb

Growing cross-sector interdependence during rapid electrification reshapes the resilience of energy systems under intensifying climate extremes by introducing both enhanced flexibility and heightened cascading risks. From the global energy transition to a regional case study in Texas, this study examines how evolving cross-sector interactions affect climate resilience and identifies system-level strategies to support a sustainable energy transition.

## SUMMARY

Rapid global electrification is deepening cross-sector interdependence, fundamentally reshaping the resilience of energy systems in the face of intensifying climate extremes. While increased integration across energy generation, transmission, and consumption sectors can significantly enhance operational flexibility, it can also amplify the risk of cross-sector cascading failures under extreme weather events, giving rise to an emerging resilience paradox that remains insufficiently understood. This study examines evolving cross-sector interactions and their implications for climate resilience by analyzing global electrification trends and regional cases in Texas, integrated with global and downscaled projections of climate extremes. By identifying critical vulnerabilities and flexibility associated with increasing sectoral interdependence, this study highlights the necessity of adopting resilience-oriented, system-level strategies for system operators and policymakers to mitigate cross-sector cascading risks and maximize the benefits of electrification in a changing climate.

## INTRODUCTION

The global energy system is the largest driver of climate change and a major victim. Energy accounts for over 75% of global greenhouse gas (GHG) emissions, with growing $CO_2$ emissions reaching a new record high of 37.4 billion tonnes (Gt) in 2023[1]. To achieve net-zero emissions goals and effectively mitigate climate change, a substantial reshaping of the existing fossil fuel-dominant energy sector is essential. This ambitious transformation is driven largely by two key factors: i) the availability of vast amounts of affordable, emission-free electricity by replacing fossil fuels in the energy supply with renewable energy sources such as wind and solar power, and ii) further expansion of the electricity sector to facilitate the decarbonization of transportation, building, and industrial sectors[2,3]. Limiting global warming to below 2°C above pre-industrial level necessitates a highly electrified future, with electricity supply increasing from the current 20% to 36–47% of final energy consumption by 2050 according to the latest Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6)[4].

However, reversing climate change is a gradual process during the ongoing decarbonization pathway. In the current changing climate, intensifying climate extremes, such as tropical cyclones, floods, and heatwaves, have already contributed to severe energy infrastructure damage and subsequent power outages. Over the past decade, there has been a 78% increase in weather-related power outages in the U.S. Climate projections under various emission scenarios, using global climate models (GCMs) from the Coupled Model Intercomparison Project Phase 6 (CMIP-6), consistently indicate intensifying and compounding extremes, potentially leading to escalating climatic damage through mid-century and beyond, absent large increases in resilience[5]. Meanwhile, rapid electrification is fostering deeper interdependence among energy supply, transmission, and consumption sectors, forming a cross-sector energy system with electricity as the core energy carrier, supplemented by "green" chemicals such as hydrogen, ammonia, and methanol produced through electrochemical processes using clean electricity. Under intensifying climate extremes, the cross-sector interconnections may enhance the operational flexibility of energy systems; paradoxically, it may also enlarge the potential for climatic damage to propagate across sectors due to network and functionality interdependence, triggering multi-sector cascading failures. This dual effect therefore raises a critical question during the rapid energy transition: whether this cross-sector interdependence enhances or impairs the overall system resilience.

Despite the advanced insights into challenges and solutions of decarbonizing energy systems[2,3,6] and building resilient renewable power grids[7], the emerging paradoxical resilience issues — arising from growing cross-sector interdependence, with potentially enlarged flexibility and heightened interdependent risks — are becoming more pronounced and remain insufficiently understood, particularly in the context of intensifying global climate extremes. Focusing solely on sector-specific risk mitigation and optimization is inadequate for addressing the complexities of an increasingly electrified and interconnected energy landscape. While decarbonization without cross-sector cascading risk management can still support climate change mitigation, it may pose additional challenges to climate change adaptation of energy systems in a changing climate. Therefore, a resilience-oriented cross-sectoral framework and analysis are essential for understanding the interdependent mechanisms, maximizing the benefits of cross-sector interdependence, and mitigating the propagation of risks across sectors. Here, we explore the evolving interactions within cross-sector energy systems, analyze the overlap of projected global electrification and climate change risks at a sub-national scale, and discuss the role of cross-sector interdependence as a key factor affecting climate resilience, exemplified by a Texas case. We also highlight the critical need and promising directions for resilience-oriented system-level optimization strategies and policies to strengthen cross-sector energy systems toward a net-zero emission future.

## FUTURE CROSS-SECTOR ENERGY SYSTEMS

Energy systems broadly encompass all the infrastructure and equipment used to produce, transform, transmit, and convert energy to provide energy services to a broad range of societal systems[4]. Energy systems connect primary energy sources to final energy consumption in end-user sectors through various energy carriers, such as electricity, natural and synthetic gas, heat, and biomass. Despite improvements in energy efficiency, global energy demand is still expected to increase markedly over this century[2]. As the largest global GHG emission sector, energy systems are transitioning toward electrification under progressive decarbonization roadmaps. In the pursuit of a net-zero emission future, the deepening cross-sector interdependence within energy systems — driven primarily by electricity and electricity-centric production of green chemicals — is a foreseeable outcome. Such a cross-sector energy system is an integrated framework centered around the bulk electric power system, enabling bidirectional interactions with other energy production and consumption sectors, including buildings, transportation, industry, water, agriculture, green chemicals, and distributed renewable sources (see Figure 1). Through these grid-connected, bidirectional interactions, each sector in future net-zero energy systems evolves into a broadly defined *prosumer* — not only consuming energy but also storing and producing energy or actively contributing to energy management.

### *The role of the bulk electric power system*

From the booming integration of renewable electricity on the supply side to the deep electrification of energy-intensive services on the demand side, the interconnected bulk electric power grid serves as the backbone of future cross-sector energy systems. The bulk power system primarily consists of utility-scale generation power plants and high-voltage network infrastructure for long-distance electricity transmission. In a net-zero emission energy system with large-scale integration of variable renewable energy (VRE) sources, the bulk power system can significantly enhance the energy system's flexibility and smooth renewable energy variation by connecting diverse energy sources across wide regions with varying environmental conditions. To deliver increasing amounts of electricity generated by distant wind and solar farms to increasingly electrified urban areas, there is a critical need to expand grid infrastructure. For example, the U.S. is projected to require a 2.1- to 2.6-fold expansion of its existing 600,000-plus-mile transmission grid, along with a 1.9- to 3.5-fold increase in interregional transmission capacity to meet future demand growth and reliability needs by 2050[8].

### *Evolving cross-sector interactions toward a net-zero emissions future*

The transition to a net-zero emissions future is fundamentally reshaping the relationship between the electric power grid and the energy supply and demand sectors, creating bidirectional cross-sector energy flows, as shown in Figure 1. The evolving bidirectional cross-sector flows strengthen the system's interdependence across sectoral operations and infrastructure.

Electrical cooling and heating demand in residential and commercial buildings is expected to increase, driven by rising summer temperatures and the shift to electrified heat pumps, including the rapid growth of ground-source heat pumps for geo-exchange systems. The electrification trend in the building sector also enhances demand response capability, where air conditioning or electric heating systems can be incentivized and dynamically controlled to smooth daily demand profiles. The electrification of the transportation system is accelerating with increasing demand on the grid through the higher penetration of electric vehicles (EVs) and the expansion of charging stations. EVs can also act as potential energy sources through vehicle-to-grid (V2G) technology, which allows them to inject stored energy back into energy systems. Electrification in industry is advancing, particularly in energy-intensive services such as data centers and steel manufacturing using electric arc furnaces[2]. On the other hand, in addition to demand response mechanisms similar to those in the building sector, industrial facilities with onsite co-generation plants can also act as energy producers within cross-sector energy systems. The ongoing urbanization trend deepens the power-water nexus, particularly in water treatment, pump, and distribution systems, which rely heavily on electricity. Water resources in turn play a crucial role in energy production, particularly in the direct power generation process of hydropower and green hydrogen and in water systems for firm power plants such as nuclear facilities, which support the reliability of future energy systems dominated by VRE. Electrification in agricultural processes, especially in automation, is driving increased electricity consumption in the agriculture sector. Although its life-cycle carbon savings are highly variable from system to system and contested, biomass produced by some agricultural activities can fuel electricity generation, acting as a firm renewable source that provides stable and controllable power.

Green chemicals and distributed renewable systems are considered separate from the bulk power system, as they are typically not directly controlled by the power grid independent system operator (ISO) yet are becoming more deeply interconnected with the electricity sector. In a net-zero electricity-centric energy system, green chemicals — including green hydrogen, ammonia, and methanol — are produced via electrochemical processes using emission-free electricity from the grid[2]. Despite existing challenges with energy conversion efficiency, green chemicals can decarbonize hard-to-electrify heavy industry sectors and offer significant life-cycle carbon reduction benefits due to their ability to store and transport clean energy, especially in a net-zero energy system with high curtailment of renewable generation where a large amount of surplus renewable energy is wasted. These chemicals as important alternative energy carriers can, in turn, supply electricity back to the grid through power generation systems such as fuel cells and gas turbines. Beyond the bulk transmission grid, the large-scale integration of distributed renewable sources, particularly rooftop photovoltaic (PV) systems paired with energy storage, is transforming traditional demand-side consumers into electricity prosumers within cross-sector energy systems.

## IN-DEPTH INTERDEPENDENCE RAISES A PARADOX FOR SYSTEM RESILIENCE

The in-depth cross-sector interdependence of energy systems highlights both the collaborative benefits and interdependent vulnerabilities in a changing climate. Ongoing global electrification, combined with various intensified climate extremes, may reshape the resilience pattern of existing energy systems. As shown in Figure 2, we present a global map illustrating the sub-national-scale overlap between country- and regional-level electrification, as projected by the Global Change Analysis Model (GCAM), and climate change risks, evaluated independently based on the projections by IPCC AR6, for all climatologically consistent land regions (see Figure S1 and Tables S1–S2).

The electrification projections are derived from the GCAM reference scenario by 2050, considering the interactions between energy, water, land, climate, and economic systems[9]. Although GCAM uses an integrated multisector modeling approach with lower spatial and temporal resolution compared to regional sector models that employ sector-specific approaches, it provides consistent global-scale electrification projections by incorporating cross-sector interactions, aligning with our need to explore the global electrification trend as shown in Figure 2. The GCAM model parameters were calibrated by using wide-range historical data, including IEA energy balances for supply and demand, ensuring consistency with global demand data and solving for market equilibrium across historical and future periods[9].

The climate change risks are characterized by composite confidence levels of the projected intensification of climate impact-drivers (CIDs) affecting energy infrastructure across all IPCC AR6 climatologically consistent land regions globally. For each climatologically consistent land region, the risk level is obtained by combining the confidence levels for the intensification of various CIDs in the IPCC AR6 mid-century projections, weighted by Gross Domestic Product (GDP)-adjusted damage losses attributable to each type of CID sourced from World Meteorological Organization (WMO) 1970-2019 climatic damage assessment (see *Supplemental Information* Note S1 and Figures S2-S3). For more granular analyses beyond the national or climatologically consistent zone level, we encourage the use of higher-resolution sectoral models and downscaled climate projections. It is important to note that a greater overlap between projected electrification and climate change risk in a specific sub-national region does not necessarily indicate increased vulnerability. Instead, it signals a more significant shift in the existing resilience patterns of future energy systems under climate change risks, emphasizing the need to evaluate how electrification and cross-sector interdependence reshape system stability and adaptation capability to climate extremes.

The United States, Central America, and the Caribbean stand out as regions undergoing some of the most significant shifts in resilience patterns, primarily driven by the projected net-zero energy transition and the intensification of tropical cyclones (Gulf of Mexico, the Caribbean, and the U.S. East Coast), wildfires (North Central America and Western North America), and flooding (North America). Eastern and Southern Australia also exhibit significant overlap between projected electrification and climate change risk, primarily due to projected nationwide increases in flooding and wildfires, with a marked intensification of droughts in the country’s most densely populated regions. Climate change risks in the East Southern Africa region are largely shaped by the intensification of tropical cyclones and drought. Western and central Europe emerge on the European continent due to the projected intensification of heatwaves, flooding, wildfires, and severe windstorms. Although tropical cyclones in the Indian Ocean are not expected to intensify according to IPCC, India is still projected to face escalating threats from river and coastal flooding risks. China, the world’s largest producer of hard-to-decarbonize energy services, commits to achieving net-zero emissions by 2060. However, as we focus on the 2050 scenario, the GCAM model projects a relatively low electrification level in its energy system. Nevertheless, eastern China, along with Southeast Asian countries, is expected to face more intense extreme natural hazards, especially from intensifying tropical cyclones, floodings, and droughts. The shift in their resilience pattern is likely to be more significant as decarbonization efforts progress or when considering more optimistic decarbonization policies.

### *Enhanced flexibility and system-wide optimality*

Intensifying climate extremes with more compound hazards can pose great challenges to energy security, particularly for electricity-centric net-zero energy systems that have stringent stability requirements for both short-term and long-term balances between energy supply and demand. However, enhanced sector coupling of energy systems provides greater cross-sector flexibility to mitigate energy imbalances during extreme events. Beyond contributing to cost-effective optimization under steady-state operation, demand response through resilience-oriented incentives can result in more flexible demand from highly electrified residential and commercial buildings, which is especially helpful for managing loads during extreme events. Cross-sector interdependence also enables a diverse portfolio of energy storage solutions, ranging from short-term storage, such as V2G-based EVs and household distributed energy storage, to long-term storage, such as pumped-storage hydropower and green chemicals. These complementary forms of energy resources and storage can support future net-zero systems, allowing them to ride through climate extremes that might otherwise cause significant energy shortages, for example, droughts that limit hydropower or tropical cyclones that affect wind and solar generation.

Moreover, cross-sector interdependence is beneficial for achieving a system-wide optimal resilient solution for energy systems and even broader social resilience. Coordinated optimization across sectors not only enhances the system-wide energy efficiency but also has the potential to facilitate cost-efficient, resilient, and equitable access to electrical services broadly. Such system-wide optimality is especially important during and in the aftermath of extreme events, for instance, demand response and on-site electricity generation within the industry sector can be incentivized to alleviate energy imbalances for prioritizing critical demands across sectors, including hospitals, public transportation, and municipal water supply.

In addition to leveraging the bulk interconnection system for large-scale energy complementarity and exchange, the cross-sector interconnections can enhance the flexibility for the resilient operation of localized energy hubs, particularly during climate extremes. As electrification progresses, the localized energy hubs move beyond traditional microgrid concepts that rely solely on electricity by integrating diverse forms of localized generation, distributed storage, and demand-side flexibility across sectors. From local communities to urban cities, distributed renewable sources, green chemicals, and other flexible resources from traditional demand-side sectors such as transportation and industry collectively enable energy autonomy, which reduces reliance on the bulk energy system and facilitates energy flexibility and mobility (see Figure S4).

### *Potential cross-sector cascading failures*

Cross-sector cascading failures in interconnected energy infrastructure are not merely a theoretical future risk; they are current realities with profound societal impacts. Recent events have illustrated how such interdependence can amplify the consequences of energy disruptions during extreme weather events. For example, the Texas power crisis during Winter Storm Uri in February 2021 exemplified the cross-sector cascading failure primarily caused by the gas-electric-heat interdependence[10]. Large-scale freezing and malfunctions in natural gas infrastructure significantly disabled the generation capacity in Texas, resulting in widespread rolling blackouts. These power outages, in turn, exacerbated the natural gas supply issues. At the same time, electricity demand continued to climb due to increasing heating needs, further enlarging the imbalance between electricity supply and demand. This extreme weather event affected not only gas facilities but also led to a total of 1,045 individual generation units experiencing over 4,000 outages, derates, or failures to start, including thermal power plants, solar and wind farms, and nuclear reactors[10]. Notably, malfunctions of water supply systems for power generation during the extreme event affected natural gas and nuclear power plants, further highlighting the cascading failure effect driven by the power-water interdependence.

Shenzhen, China — a highly modernized city with 100% electrified public transportation — exemplifies the deep interdependence between the electricity and transportation sectors. The prolonged outage caused by Super Typhoon Mangkhut in 2018 shut down all charging stations, forcing all taxis out of service across the megacity[11]. As light-duty vehicles become further electrified, a potentially large shift in charging demand to remaining unaffected areas during extreme events could also pose a risk to the regional energy supply-demand balance of an already vulnerable grid. Similarly, the catastrophic blackout in Puerto Rico caused by Hurricane Maria in 2017 severely impacted water distribution and supply, which heavily relied on electricity. As water infrastructure is also crucial for hydropower and green chemical production, such as electrolysis for hydrogen, this power-water interdependence exacerbated social impacts, affecting residential, commercial, and industrial sectors[12].

In a future climate, various extreme weather events closely linked to energy infrastructure are expected to intensify. When combined with the strong interdependence in cross-sector energy systems, such extreme events may exacerbate the risk of multi-sector cascading failures, damaging both physical infrastructure and societal systems. For example, a climate-induced prolonged power outage in a fully electrified city can paralyze its transportation system, while the significant amount of unmet EV charging demand would further challenge the energy supply-demand balance during the preparation, evacuation, and initial recovery phases. Moreover, as the compound hazards — such as tropical cyclones causing high winds and extreme rainfall, followed by heatwaves — are expected to increase in this changing climate, more energy infrastructure could be affected by different types of hazards than experienced historically[4], potentially triggering catastrophic cross-sector cascading failures.

## ENERGY TRANSITION IN CHANGING CLIMATES: THE TEXAS CASE

Here, we select Texas as an example to investigate the escalating challenges and opportunities for energy resilience in the face of intensifying climate extremes and increasing cross-sector interdependence of energy systems. Located along hurricane-prone US Gulf coast, Texas is a state with abundant renewable energy resources and is experiencing record-breaking electricity demand growth. The clean energy transition with deeper cross-sector interactions in Texas, the largest renewable energy-producing state in the US, driven not only by policy but also by economic and efficiency forces, directly reshapes transformation in energy systems. Meanwhile, the increasing cross-sector coupling in Texas that makes the integrated system more exposed to the environment, can be coupled with intensifying climate risks such as tropical cyclones and heatwaves. However, as we highlighted in the paradox of cross-sector energy system resilience, such cross-sector interconnections can also enhance the system's flexibility and capacity to withstand climate risks. As illustrated in Figure 2, Texas is in a critical region that may face the most significant shift in energy resilience patterns under these evolving conditions, which underscores the urgent need to address the resilience paradox by maximizing the benefits of cross-sector interdependence while mitigating its associated risks under climate risks.

To project future climate trends under uncertain patterns of socioeconomic development and policy trajectories, the IPCC AR6 adopted Shared Socioeconomic Pathways (SSPs), with SSP2-4.5 and SSP5-8.5 representing moderate and high emissions scenarios, respectively. We illustrate the increasing climate risk that Texas faces, drawing on downscaled tropical cyclone projection datasets[13] based on an ensemble of six Coupled Model Intercomparison Project Phase 6 (CMIP6) general circulation models (GCMs) under both scenarios (see Figure 3a and *Supplemental Information* Note S3). Future changes in tropical cyclone frequency remain uncertain and are subject to ongoing scientific debate[14], with divergent predictions from climate models using saturation deficit and convective relative humidity as indicators for tropical cyclone genesis. Nevertheless, there is a broad consensus on the intensification of severe tropical cyclones. Given the uncertainty in frequency projections, we incorporate the 5th–95th percentile range of projected frequency changes from an ensemble of state-of-the-art studies for the North Atlantic basin[14] into the wind intensity return period calculations with the baseline frequency derived from ERA5 reanalysis datasets (see Figure 3A and Supplementary Information). Accounting for this large uncertainty of frequency change, tropical cyclones associated with return periods shorter than five years may become less intense in Texas. However, since return periods depend not only on tropical cyclone frequency but also on intensity, future projections indicate a significant intensification of severe events even under moderate emission scenario (SSP2-4.5), consistent with previous general findings[13,14]. For example, a 100-year return period storm, currently classified as a Category 3 hurricane (50–58 m/s), is expected to strengthen to Category 4 (58–70 m/s) under future scenarios by the late 21st century. The return period of Category 3 hurricanes could shorten to approximately 20~50 years under future scenarios, indicating an elevated risk of extreme events to the region's energy infrastructure.

Increasing climate risk intersects with the clean energy transition, as the future of cross-sector energy systems depends heavily on emission-free and low-cost electricity from renewable sources. Climate extremes, especially tropical cyclones associated with cumulonimbus clouds and strong winds, have substantial impacts on environment-sensitive renewable generation like solar and wind. For example, even a Category 1 hurricane (Hurricane Beryl) that made landfall in Texas on July 8, 2024, reduced the maximum wind and solar generation potential within the Electric Reliability Council of Texas (ERCOT)[15] interconnection by nearly 40% compared to normal conditions, with losses of about 10,000 MW generation at the highest point and 8,000 MW at the lowest point (see Figure 3b). The reduction in solar and wind generation from this event was approximately 15% of ERCOT's daily average electricity demand. As the penetration of such renewables increases, intensified tropical cyclones are likely to disable larger shares of the energy supply, posing a greater threat to energy resilience. It is noteworthy that, as shown in Figure 3b, although the heat index on the day of Hurricane Beryl's landfall was within normal ranges, a compound heatwave hazard was observed on the day prior to and following landfall, with heat index values exceeding 100°F (37.8°C, the threshold for a heat advisory). The heatwave exacerbated electricity demand for cooling, particularly in the aftermath of grid disruptions, further intensifying the energy imbalance between supply and demand and amplifying the societal impacts of power outages. Climate change is projected to significantly increase the tropical cyclone-heat compound hazards, with their frequency expected to rise nearly 4-fold from the current rate under a scenario of 2°C global mean temperature increases above the pre-industrial level[16]. In addition to the escalation of heatwave and tropical cyclone hazards under climate change, the IPCC AR6 mid-century climate projections also indicate an intensification of various climate extremes affecting energy infrastructure, including river and coastal floods, severe wind storms, and wildfires in the climatologically consistent land region where Texas is located (see Figure S1 and Table S2).

The infrastructure damage caused by Hurricane Beryl, which made landfall as a Category 1 storm, was primarily limited to distribution networks due to relatively low wind speeds, yet it still caused outages for 2.6 million customers. Although the future frequency of such relatively low-intensity hurricanes remains uncertain, the rapid growth in local electricity demand driven by urbanization and electrification can amplify the potential impacts. Disruptions to growing electricity demand, combined with delayed restoration caused by compound hazards such as the hurricane-heatwave compound hazard observed during this event, may cascade into other critical sectors, including transportation and industry, in a highly electrified and cross-sector coupled energy system. Moreover, as less frequent hurricanes, such as current Category 3 storms, are projected to intensify under future climate scenarios, the resulting infrastructure damage may extend to transmission networks, potentially inducing system-level stability issues and even triggering cross-sector cascading failures due to deeper interdependence within multiplex infrastructure networks. System-level risks originating in one region may also affect interconnected energy systems elsewhere, even in areas not directly impacted by climate extremes. Beyond mitigating system-level risks, the potential cascading risk demonstrates the necessity of developing localized resilient energy hubs, including robust distribution network infrastructure with aggregated distributed energy resources for energy hub formation, as well as mechanisms and optimizations to incentivize cross-sector demand response during extreme events.

As we noted, deeper sectoral coupling and interdependence on the demand side are driving demand growth. Using the EV charging demand profile projections for Texas based on the Transportation Energy

& Mobility Pathway Options (TEMPO) model[17] under its defined high electrification scenario (about 75% of transportation energy consumption from EVs by 2050), we observe that electrification of the transportation sector in Texas can not only add an average of nearly 7,000 MW of daily electricity demand by 2050, representing an increase of over 10% from the current demand level, but also introduce greater demand variability (see Figure 3c). The increasing demand variability requires more fast-response flexible resources like energy storage to maintain real-time energy balance within the system. During extreme weather events, the risk of system imbalances could be further amplified due to significantly impacted generation capacity. However, EVs can also serve as potential flexible resources to the energy system, as they store substantial amounts of electricity in a highly electrified transportation sector. By simply assuming that 10% of off-charging battery EVs in Texas can be incentivized to support the system, their distributed battery storage through V2G technology could supply over 9,000 MW of power even during peak charging times, helping to mitigate energy imbalances (see details in *Supplemental Information* Note S4 and Figure S5). This demonstrates the vast potential of sectoral coupling to improve energy system resilience during extreme events, yet this potential remains largely unexplored in practice.

## PROSPECTS

In this rapid energy transition, focusing on climate mitigation while overlooking climate adaption could undermine energy system resilience in the face of intensifying climate extremes. This paper aims to highlight the emerging paradoxical resilience challenges arising from the growing cross-sector interdependence of energy systems in the pursuit of a net-zero future, offering a global perspective that is then downscaled to a regional energy system example. However, rather than opposing sector coupling, which is crucial to decarbonize hard-to-abate sectors via electrification and ensure affordable energy supply, we note that to maximize the benefits of cross-sector interdependence and mitigate associated cascading risks during extreme events, resilience-oriented system-level cooperative optimization strategies and policies are essential.

First, policies and market mechanisms should be designed for better incentivizing cross-sectoral demand response and flexible resources. Existing electricity market mechanisms, such as Energy-Only Market[15] used by ERCOT in Texas — where power plants are paid only for the electricity they generate — lack incentives for maintaining sufficient reserve capacity to handle extreme weather events. Beyond the concept of virtual power plants, cross-sector energy systems offer greater aggregated energy capacity through distributed renewable generation, green chemicals, transportation, buildings, and other sectors. Meanwhile, they also introduce more complex responses from multi-stakeholders. Microgrid-level research suggests that while self-optimized individual energy storage systems enhance self-sufficiency, they can undermine overall system stability[18]. This phenomenon will likely become more pronounced in future energy systems with evolving participants from multiple sectors if appropriate regulations and incentivization mechanisms are not implemented. To fully harness the potential of cross-sector flexibility and maximize overall social welfare, climate-resilient market and policy mechanisms should further support the aggregation of virtual energy hubs with complementary multi-energy forms, enabling system operators to coordinate energy flow and ensure system stability. Additionally, policy and market designs also need to address the associated challenges of data privacy and security arising from the aggregation of diverse stakeholders in cross-sector energy systems.

Second, in the context of cross-sector energy system planning, establishing robust rapid-response capabilities through cross-sector energy storage is crucial for enhancing system resilience. Relying on fossil fuel power plants as backup generation in capacity expansion planning is a conservative and cost-intensive approach[6], as it may result in extremely low capacity factors for these conventional plants, which are maintained solely for emergency supply. Cross-sector energy storage ranges from short-term solutions such as EV batteries to long-term solutions such as chemical and geothermal storage hold substantial potential not only in terms of energy capacity but also mobility, which remains to be further explored. To fully utilize these rapid-response resources, capacity expansion planning should account for cross-sector complementarities and incorporate high-resolution climate-energy risk assessments to better capture the spatiotemporal impacts of extreme events.

Third, achieving system-wide optimality of cross-sector energy system resilience requires developing advanced multi-agent optimization strategies for real-time collaborative operation. The role of current grid operators, such as ERCOT for Texas and California Independent System Operators (CAISO) for California, needs to be expanded to encompass interdependent systems with multiplex energy infrastructure. Existing energy management systems (EMS) developed for monitoring, controlling and optimizing electric power grids, are expected to evolve into integrated energy management systems (IEMS) to accommodate cross-sector operations. The various dynamic characteristics of multiple sectors, such as the electromechanical transients in electric power grids (on the millisecond-to-second scale) and the thermal dynamics of heating systems (on the second-to-minute scale) create discrepancies in the definition of steady-state and energy balance within existing optimization methods. Therefore, the optimization frameworks within advanced IEMS should account for heterogeneous dynamic characteristics and balance competing objectives to reach a consensus that ensures system-wide resilience and efficiency.

Lastly, building decentralized or localized resilient energy hubs can help prevent cascading failure propagations in the bulk interconnected energy system during extreme events and facilitate the rapid recovery of local communities afterward[7,12]. Compared to traditional electricity-based microgrids, decentralized cross-sector energy hubs offer greater flexibility and synergies but also impose higher requirements on localized energy infrastructure to support these prosumer interactions. These requirements include bidirectional-capable charging stations, distributed green chemical storage, transportation, and generation facilities, along with a resilient, multiplex infrastructure network designed for self-healing and standardized plug-and-play interfaces for distributed resources. Additionally, within such energy hubs, enhanced information and communication technologies, combined with efficient multi-agent distributed algorithms, are essential for ensuring reliable coordination and management across multiple stakeholders.

### *Data and code availability*

Data and code are publicly available on a GitHub repository (https://github.com/LuoXu-THU/Cross-sector-energy-system-resilience-and-interdependence-in-a-changing-climate).

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## AUTHOR CONTRIBUTIONS

Conceptualization, L.X. and N.L.; methodology, L.X., and A.T.D.P.; investigation, L.X., H.V.P., Q. G., and H. S.; writing—original draft, L.X. and N.L.; writing—review & editing, A.T.D.P., H.V.P., Q.G., H.S., and M.O.; funding acquisition, N.L. and H.V.P.; resources, L.X., N.L. and A.T.D.P.; supervision, N.L., H.V.P., and M.O.

## DECLARATION OF INTERESTS

The authors declare no competing interests.

## SUPPLEMENTAL INFORMATION

**Document S1. Notes S1–S4, Figures S1–S5, and Table S1–S2**

## FIGURE TITLES AND LEGENDS

### Figure 1. Cross-sector interdependence in a highly electrified energy system

The bulk electric power grid (center) is the backbone of future net-zero energy systems, facilitating bidirectional energy exchanges with other sectors. Arrows extending from the electricity grid to other sectors illustrate the flow of energy from the grid as an input to these sectors, and vice versa. The accompanying text specifies the mechanisms of these cross-sector energy interactions.

### Figure 2. Global electrification and intensifying climate change risks at the sub-national scale

A bivariate map illustrating the intersection between future electrification trends and climate change impacts across sub-national regions. These color-code regions are defined by the electrification levels for 2050 in various countries projected by GCAM v7.1[9], as well as the IPCC AR6 composite confidence levels of intensification of energy infrastructure-related climate extremes, weighted by GDP-adjusted damage losses linked to the specific climate extremes.

### Figure 3. Escalating challenges to energy resilience in Texas

(A) Projections for tropical cyclone intensity in Texas under the current climate scenario (green), moderate emission scenario (SSP2-4.5, blue), and high emission scenario (SSP5-8.5, red) by the late 21st century. Wind intensity is calculated at Galveston, Texas. Colored scatter points represent individual samples of the wind intensity (m/s) for each synthetic tropical cyclone that makes landfall in Texas under each scenario, corresponding to the median projected frequency change of tropical cyclones in the North Atlantic basin[14]. The solid curves show the statistical fitting using the Generalized Pareto Distribution (GPD) for extreme wind intensities (90th percentile) in each scenario. Shaded areas for future scenarios indicate uncertainty ranges of projected storm intensity levels, accounting for variations associated with the 5th-95th percentile range (approximately -34.5% to +29%, with a median of -14%) of projected tropical cyclone frequency changes in the North Atlantic basin[14]. The shaded area for the current climate indicates the uncertainty range derived from GPD fitting under the current tropical cyclone frequency. Each climate scenario presents synthetic tropical cyclones[13] projected by downscaling the ensemble of six Coupled Model Intercomparison Project Phase 6 (CMIP6) general circulation models (GCMs), including CanESM5, CNRM-CM6-1, EC-Earth3, IPSL-CM6A-LR, MIROC6, and UKESM1-0-LL.

(B) Maximum potential of wind and solar generation and the associated heat index in Texas during Hurricane Beryl from July 7th to July 17th, 2024. The maximum generation potential for renewables is recorded hourly by the Electric Reliability Council of Texas[15]. The heat index is calculated using air temperature and dew point temperature data recorded by the Houston Ellington AFB station, sourced from NOAA's Global Hourly Integrated Surface Database (https://www.ncei.noaa.gov/products/land-based-station/integrated-surface-database).

(C) EV charging demand projections from 2024 to 2050 in Texas. Each boxplot represents the projections of hourly light-duty passenger electric vehicle charging profiles in Texas during hurricane season (June to November) for the corresponding year, derived from the Transportation Energy & Mobility Pathway Options (TEMPO) model[17] under a high electrification scenario. The median is represented by the line within the box, the box edges show the interquartile range (25th to 75th percentiles), the whiskers extend to the 5th and 95th percentiles, and the white dot inside the box represents the mean value.

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