

Globally interconnected solar-wind system addresses future electricity demands

Received: 20 June 2024

Accepted: 2 May 2025

Published online: 15 May 2025



Hou Jiang^{1,8}, Ling Yao^{1,2}✉, Jun Qin^{1,3,8}, Yongqing Bai^{4,8},
Martin Brandt⁵, Xu Lian⁶, Steve J. Davis⁷, Ning Lu¹, Wenli Zhao⁶,
Tang Liu¹ & Chenghu Zhou¹✉

Accelerating energy transition towards renewables is central to net-zero emissions. However, building a global power system dominated by solar and wind energy presents immense challenges. Here, we demonstrate the potential of a globally interconnected solar-wind system to meet future electricity demands. We estimate that such a system could generate ~3.1 times the projected 2050 global electricity demand. By optimizing solar-wind deployment, storage capacity, and trans-regional transmission, the solar-wind penetration could be achieved using only 29.4% of the highest potential, with a 15.6% reduction in initial investment compared to a strategy without interconnection. Global interconnection improves energy efficiency, mitigates the variability of renewable energy, promotes energy availability, and eases the economic burden of decarbonization. Importantly, this interconnected system shows remarkable resilience to climate extremes, generation outages, transmission disruptions, and geopolitical conflicts. Our findings underscore the potential of global interconnection in enabling high renewable penetration and guiding sustainable energy transitions.

The 28th session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP28) agreement heralds the “beginning of the end” of the fossil fuel era¹, a pivotal milestone in limiting global warming to a ceiling of 1.5 °C² and achieving the Sustainable Development Goals (SDGs)³. Central to this shift towards a decarbonized future is the accelerated integration of renewable energy sources⁴ and the augmented use efficiency of their generation⁵, both of which are instrumental in facilitating deep carbon emissions cuts. Stakeholders have explored myriad avenues for a sustainable energy transition, relying primarily on the expansive deployment of PV and wind plants^{6–8}. While hydropower remains a key non-biomass renewable energy source, its large-scale expansion is constrained by

geographic and environmental factors. Consequently, it is often regarded as a flexible resource that complements the variability of wind and solar power⁶.

However, PV and wind generation are inherently intermittent, as their output is strongly influenced by fluctuating weather conditions⁹. This variability, coupled with diurnal and seasonal cycles⁷, poses a fundamental challenge in maintaining the balance between generation and demand¹⁰. Currently, regional power systems incorporating intermittent energy sources are heavily reliant on energy storage systems and flexible generation sources, such as hydropower, for peak shaving and load leveling amidst generation-demand mismatches¹¹. This strategy, however, faces unaffordable investments in establishing

¹State Key Laboratory of Resources and Environmental Information System, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China. ²College of Resources and Environment, University of Chinese Academy of Sciences, Beijing, China. ³Faculty of Geography, Yunnan Normal University, Kunming, China. ⁴Key Laboratory of Remote Sensing and Digital Earth, Aerospace Information Research Institute, Chinese Academy of Sciences, Beijing, China. ⁵Department of Geosciences and Natural Resource Management, University of Copenhagen, Copenhagen, Denmark. ⁶Department of Earth and Environmental Engineering, Columbia University, New York, USA. ⁷Department of Earth System Science, School of Sustainability, Stanford University, California, USA. ⁸These authors contributed equally: Hou Jiang, Jun Qin, Yongqing Bai.

✉ e-mail: yaoling@reis.ac.cn; zhouch@reis.ac.cn

and maintaining storage infrastructure^{12,13} and the risk of power supply disruptions, particularly during extreme weather¹⁴. For example, the extreme cold snap hitting Texas, USA, in February 2021 caused widespread blackouts across the state¹⁵. As we progressively shift towards power systems dominated by renewable sources, potentially reaching 100% penetration in a decarbonized future, the consequences of generation-demand imbalances could be more severe than those associated with fossil-fuel dependence^{11,12}.

Trans-regional interconnection of power systems is a promising solution for achieving high penetration of variable renewable energy (VRE) sources^{16,17}. Initially envisioned by Buckminster Fuller¹⁸ as a global energy grid to facilitate spatial integration of distributed generation^{9,19}, global interconnections has evolved from an idealistic vision to practical implementations at small scales. These include sub-regional, regional, and intercontinental interconnections^{16,20–22}. For example, Spain and Morocco are connected via three 400 kV 700 MW submarine power cables traversing the Mediterranean²², and the Central American Electrical Interconnection System exemplifies regional integration by interlinking six countries with a 300 MW backbone grid²¹. Building on these pioneering implementations, recent studies have further explored the potential benefits of global energy interconnection. Brinkerink et al.²³ developed a high-resolution model to simulate globally interconnected power systems, providing initial proof-of-concept results that showcase the viability and additional benefits of integrating European and North American power grids. Similarly, Guo et al.²⁴ examined the implications of renewable electricity trade facilitated by ultra-high-voltage direct-current (UHVDC) lines, finding that such interconnections could significantly reduce CO₂ emissions and air pollutant levels while offsetting investments in other generation options. While these studies underscore the importance of interconnection strategies, they also highlight gaps in addressing geographic and temporal specifics of resource allocation and utilization.

Policy initiatives have played a critical role in advancing the practical realization of global energy interconnections. During the 2015 United Nations Sustainable Development Summit, Chinese President Xi propelled China's initiative of establishing a "Global Energy Interconnection (GEI)" to meet worldwide power demand with clean and green alternatives²⁵. Subsequently, at COP24, GEI Development and Cooperation Organization promoted an action plan to scale up GEI to tackle fossil-fuel reliance²⁶. Following these pivotal events, the theoretical concept of GEI has evolved to tangible politics and practices²⁷, with several studies proposing various alternative pathways for its implementation^{28–30}. Yet, establishing a globally interconnected solar-wind system oriented towards net-zero emissions still needs to be clarified. Some scenarios proposed for this objective explored renewable energy potentials and national pathways to carbon neutrality, but they represent a macroscopic perspective that lacks essential geographic details^{6,8,14,31}. The practical implementation requires a holistic evaluation of various aspects, including the feasibility of delivering PV and wind generation to the grid, the dynamics of demand fluctuations, the balance between supply and demand, the strategic configuration of transmission and storage systems, and comprehensive assessments of costs and benefits^{4,13,16,32}.

To address the existing geographic and temporal gaps^{4,7,32,33}, this study investigates the feasibility and benefits of a globally interconnected solar-wind system in addressing future electricity demands. We integrate high-resolution spatial (500-meter) and temporal (hourly) data to comprehensively evaluate the global potential of solar and wind energy regarding their exploitability, accessibility, and interconnectability. We develop a multi-objective optimization framework to identify cost-effective and resource-efficient interconnection strategies that balance investment costs, renewable energy penetration, and power curtailment. Here, we outline an optimized,

phased pathway for integrating solar and wind energy into a globally interconnected and fully coordinated power system. This study provides valuable insights into the spatial distribution and deployment timeline of solar-wind power plants, the allocation of storage and transmission capacities, and potential benefits and risks of global interconnection. Our work advances a more nuanced understanding of global energy interconnection and offers a concrete pathway to realize this vision.

Results

Interconnectable solar-wind potential

Theoretically, the potential of solar and wind resources on Earth vastly surpasses human demand^{33,34}. In our pursuit of a globally interconnected solar-wind system, we have focused solely on the potentials that are exploitable, accessible, and interconnectable (see "Methods"). Through spatial filtering at a 500-meter resolution, we first mapped the suitability factors for deploying solar/wind power plants within each $0.25^\circ \times 0.25^\circ$ grid-box (Supplementary Fig. S1). Subsequently, the combination of suitability and simulated power generation efficiency (Supplementary Fig. S2) determines the spatial distribution of global potential for power generation (Fig. 1a).

In densely populated regions such as western Europe, India, eastern China, and western United States, most grid-boxes contain solar and wind resources apt for interconnection (Supplementary Fig. S1). Nevertheless, these regions exhibit modest power generation potential, typically not exceeding 1.0 TWh/year (Fig. 1a). The limited potential is primarily attributed to the intense competition for land use³⁵ and/or dense layout of electric power infrastructure³⁶. Conversely, grid-boxes in less populated regions like the midwestern United States, western and central Asia, southern Africa, and northern Africa near the Mediterranean manifest significantly increased productivity, often surpassing 10.0 TWh/year, due to a combination of expanded suitable lands and improved generation efficiencies (Supplementary Figs. S1 and S2). Notably, regional potential does not necessarily correlate positively with transmission line length (Supplementary Fig. S3) because centralized distribution of transmission lines considerably limits the actual interconnectable potential. The pronounced latitudinal (Fig. 1b) and longitudinal (Fig. 1c) variations in global potentials underscore that seasonal (with enhanced generation during the Northern Hemisphere's summer) and diurnal (with increased generation around noon at 100°W and 40°E) disparities⁹ in generation capabilities persist even with extensive global interconnections. This necessitates comprehensive energy storage solutions^{13,37}, forming the foundation of our vision for establishing a global solar-wind power system.

Our estimates suggest that the total electricity generation from global interconnectable solar-wind potential could reach a staggering level of $[237.33 \pm 1.95] \times 10^3$ TWh/year (mean $\pm$ standard deviation; the standard deviation is due to climatic fluctuations). This amount is 3.1 times the projected electricity demand for 2050 and 1.2 times that for 2100 (Fig. 1d), showcasing the immense potential of renewable resources in contributing to global carbon neutrality. Nevertheless, the spatial mismatch between generation capability and demand poses formidable challenges. Using the United Nations geoscheme, our analysis compares regional potentials with decadal electricity demands through the 21st Century (Fig. 1e). Regions like southeastern Asia, southern Europe, and Melanesia are likely to face shortfalls in meeting their 2030 electricity demands, while central Asia, southern Africa, and northern Africa have surplus potentials that exceed demands by over thirtyfold. The uneven distribution is expected to exacerbate regional power shortages as electricity consumption increases³⁴. By 2050, seven out of the twenty regions may have difficulty meeting their electricity demands solely relying on interconnectable solar-wind potentials. Additionally, temporal mismatches further compound these issues; for example, in eastern Asia, although

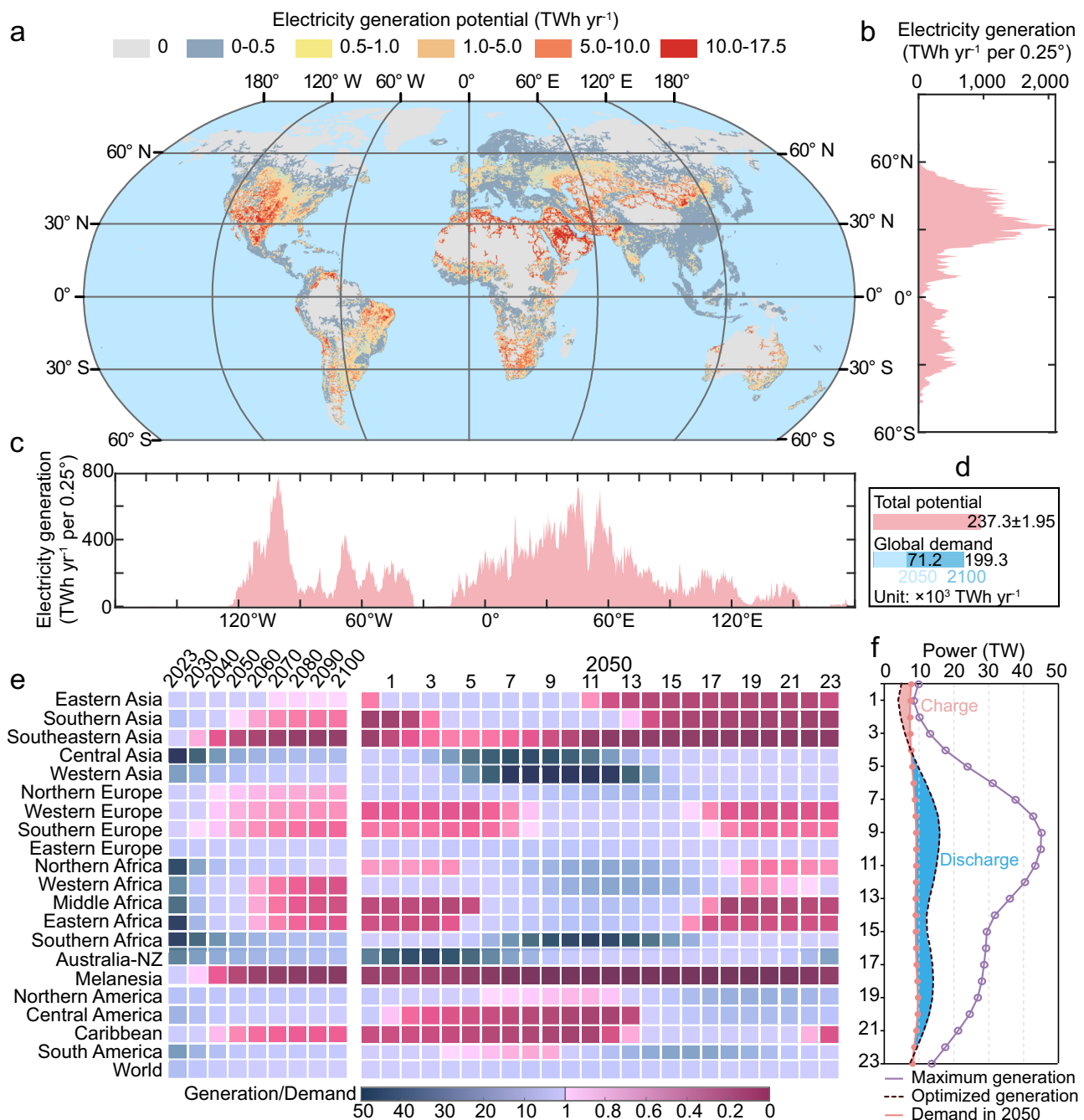


Fig. 1 | Exploitable, accessible, and interconnectable potential of global solar and wind energy. **a** Potential electricity generation within each 0.25° × 0.25° grid-box, accounting for land-use suitability, topographical and natural constraints, and proximity to existing transmission lines (up to 10 km distance) at a 500-m resolution. The base coastline layer was sourced from the Natural Earth database, which is in the public domain. **b**, **c** Latitudinal (**b**) and longitudinal (**c**) variations in electricity generation potential. **d** Comparison of total potential with global demand in 2050. **e** Discrepancies between regional potential and decadal demand during 2023–2100

(left), as well as the diurnal cycle of the discrepancy for 2050 (right). Global major regions are based on the United Nations geoscheme (Supplementary Fig. S4a), and Micronesia and Polynesia, primarily consisting of small island countries, are not discussed in this analysis. **f** Illustration of the necessity for optimization. An unoptimized scenario (solid line with hollow circles) necessitates full potential utilization for round-the-clock power supply, whereas combined storage and optimization strategies (black dashed line) markedly lower the required development size.

the total potential is comparable to the demand in 2050, average power generation during UTC 11:00–24:00 falls short of the electric load. Contrarily, western Europe, southern Europe, and middle Africa experience excess generation in these hours, suggesting trans-regional power exchange as a viable solution for addressing these temporal imbalances^{16,17}. These findings collectively accentuate the crucial role of regional interconnections in a globally synchronized energy transition centered around solar and wind energy.

It is also found that, without optimization, utilizing the full potential is necessary to ensure round-the-clock power supply since the global cumulative power generation at UTC 1:00 just manages to satisfy the demand at that moment (Fig. 1f). Yet, this rudimentary approach leads to substantial energy wastage, with over 75% of electricity generation being curtailed due to overproduction during UTC 3:00–24:00. Conversely, strategic optimization of spatial configurations, complemented by energy storage, can markedly reduce such

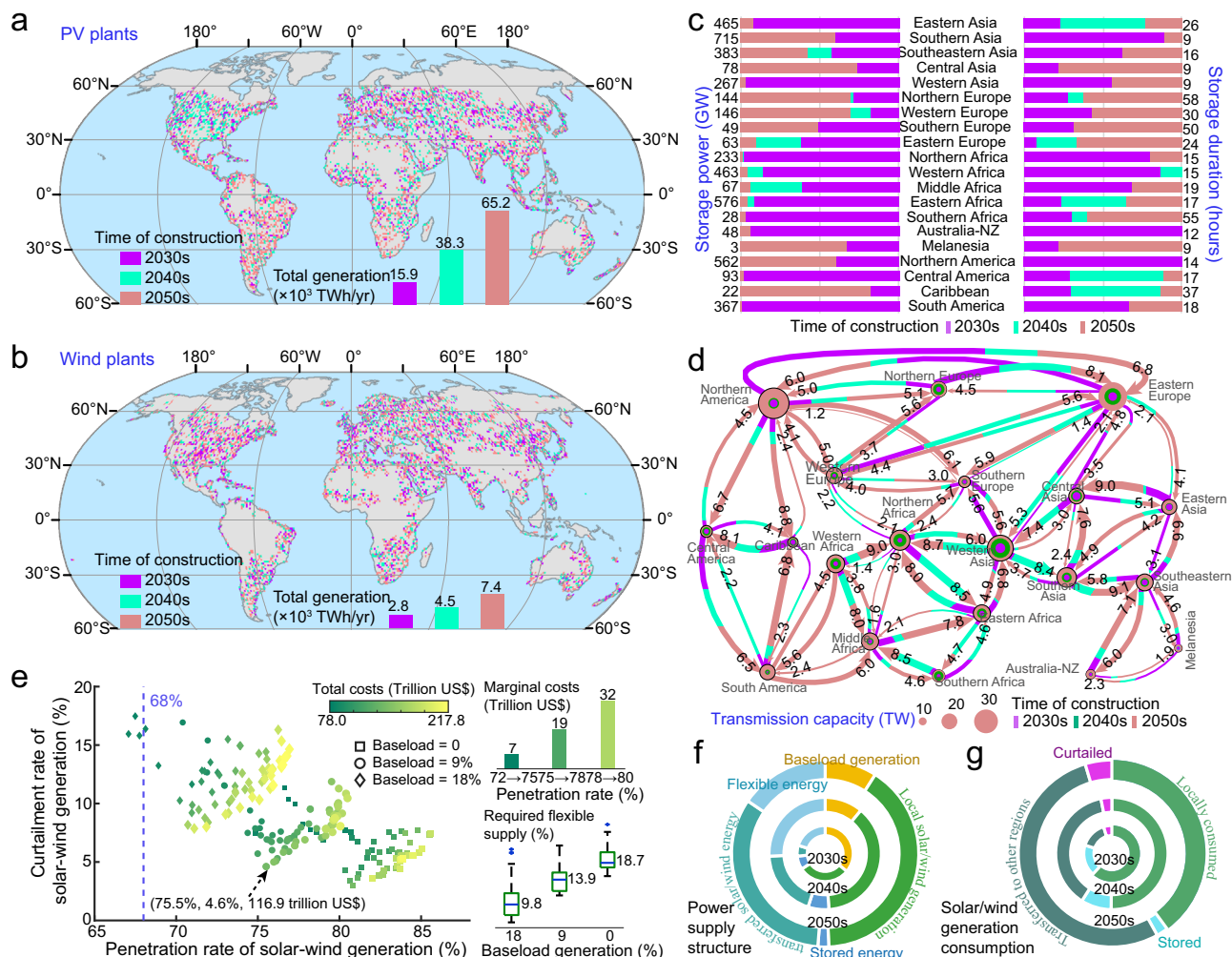


Fig. 2 | Optimal phased configuration of PV, wind, storage, and transmission capacities under progressive global interconnection scenario. a, b Placement and timeline for installations of solar PV (a) and wind (b) plants, with cumulative annual electricity generation shown in the bottom insets. The base coastline layers were sourced from the Natural Earth database, which is in the public domain. **c, d** Regional allocation of storage (c) and transmission (d) capacities for the 2030 s, 2040 s, and 2050 s. In (c), bars illustrate the proportional distribution of each phase and region, and labeled numbers denote total storage power and duration. In (d), line thickness and accompanying numbers indicate trans-regional transmission capacity, node size represents total outbound capacity, and color combinations

show the proportional allocation across the three phases. **e** Multi-objective optimization results highlight trade-offs among maximizing penetration, minimizing curtailment, and reducing overall costs. Different symbol shapes indicate the impact of varying baseload generation levels. Bars illustrate the marginal cost of increased penetration. Boxplots show the average flexible power requirements of all optimization results ($n = 70$) for different baseload scenarios. Boxplots represent the median (center line), the 25th and 75th percentiles (box bounds), and the minimum and maximum values (whiskers) (f, g), Evolution of power supply (f) and consumption (g) structures under the optimal spatial configuration and development pathway.

wastage, potentially preventing more than 80% of these curtailments. This emphasizes the need to optimize the development pathway towards a globally interconnected power system.

Optimal configuration and pathway

The optimization of developmental paths for a globally interconnected solar-wind power system necessitates balancing global power supply and demand, coordinating system-wide costs, ensuring efficient energy utilization, and guaranteeing uninterrupted power supply^{4,13,32}, as well as considering numerous geographic details, including the topology of interconnections, the spatiotemporal variations of generation and loads, and constraints in storage and transmission capacities pertinent to trans-regional dispatch. To address these complexities, we design a comprehensive multi-objective optimization framework to identify the optimal global interconnection pathway within the context of a full power system (see “Methods”). Central to this framework is a simplified trans-regional electricity dispatch model (Supplementary Fig. S5), which enables an hourly analysis

of electricity generation, transmission, storage, consumption, and curtailment while accounting for interactions with other generation sources, including baseload and flexible technologies. We optimized the placement and timeline for installing PVs and wind turbines (Fig. 2a, b), the phased configuration of storage capacities across regions (Fig. 2c), and the transmission power between interconnected grids during different phases (Fig. 2d), aiming at maximizing solar-wind penetration while minimizing power curtailment and overall costs. Our envisioned scenario evolves from adjacent interconnections in the 2030 s to continental interconnections in the 2040 s, culminating in a global interconnection by the 2050 s (Supplementary Fig. S4), in accordance with the low-emission scenario of the Shared Socioeconomic Pathway 1–2.6 (Supplementary Fig. S6). Employing the Non-dominated Sorting Genetic Algorithm-II³⁸ to solve the multi-objective optimization problem, we obtained a set of the Pareto-efficient solutions (Fig. 2e). The optimal one was selected based on meeting the minimum solar-wind penetration of 68%, as specified by the International Energy Agency (IEA)’s Net Zero Emissions (NZE)

scenario (Supplementary Table S1) while achieving a curtailment close to 5% and minimizing costs.

Our optimization results reveal a strong correlation between PV-wind deployment (Fig. 2a, b) and population distribution³⁹. In the early phase, the deployment strategy prioritizes proximity to demand centers to ensure adequate power supply in a relatively isolated power system. For instance, in the 2030 s, each region's share of power generation typically aligns with its share of power load (Supplementary Fig. S7a). As a compromise of the low interconnectivity, there is a need to increase energy storage reserves, encompassing both electrical power and capacity (Fig. 2c). As the degree of interconnectivity increases, solar-wind development gradually shifts towards regions with distinct resource advantages, such as the midwestern United States for superior solar resources, and coastal or high-altitude areas for high wind energy potential (Fig. 2a, b). By the 2040 s, the advent of intercontinental interconnections will boost resource development in regions such as western Asia and northern Africa (Supplementary Fig. S7b), and by the 2050 s, northern and southern America are anticipated to emerge as key development zones (Supplementary Fig. S7c). With improved interconnectivity, the urgency to expand storage capacity lessens (Fig. 2c). This tendency is especially pronounced in regions like eastern Asia, southern Asia, and Africa, which are projected to undergo rapid development in the 2030 s³⁴. By contrast, in regions reliant on shared electricity resources, like western Europe, northern Europe, and the Caribbean, the need for storage capacity will intensify in later stages due to diminished mutual support capabilities from adjacent regions.

Under a progressive global interconnection scenario, enhancing transmission infrastructure will be a focus in the later stages (Fig. 2d). Establishing transcontinental corridors across northern America–Eurasia and southern America–Africa will be paramount, followed by routes like western Asia–northern Africa, southern Asia–southeastern Asia, and central Asia–eastern Asia. The maximum transmission power along these key corridors varies markedly and exhibits directionality (Fig. 2d). The Northern America–Eastern Europe corridor should support up to 6.8 TW eastward and 6.0 TW westward, while the Southern America–Western and Middle Africa corridor should reach 10.5 TW eastward and 8.0 TW westward. These capacities are optimized to balance solar-wind generation and demand across interconnected regions and facilitate efficient transcontinental electricity exchange. Accordingly, the core nodes of northern America, eastern Europe, and western Asia will require enhanced outbound transmission capacities, aligning with the conception proposed in prior research^{28,30}. Future advancements in transmission technology, including the transition from high-voltage direct current (HVDC) to UHVDC as proposed by the Global Energy Interconnection Development and Cooperation Organization (GEIDCO), could reduce the capacity requirements for transregional transmission (Supplementary Fig. S8a). Nevertheless, under a globally interconnected system with equitable technology sharing, the general spatial distribution and interconnection patterns are expected to remain largely unchanged (Fig. 2d and Supplementary Fig. S8b).

Other feasible pathways (Fig. 2e) exhibit broadly similar patterns to the optimal one in terms of spatial layout and timeline, marked by a shift from centralized to decentralized configurations, an early emphasis on expanding energy storage, and a later focus on reinforcing transmission infrastructure. Evaluating these alternatives requires a careful examination of the trade-offs between penetration, curtailment, and cost within power systems that incorporate variable generation³⁷. High penetration of solar-wind generation is invariably associated with increased curtailments and system-wide costs, with pronounced marginal cost effects. For instance, the cost increase required to raise penetration from 78% to 80% is more than four times that of raising it from 72% to 75%. While our cost estimation does not account for potential reductions due to dynamic learning⁴⁰ and

technological advances⁴, it provides a practical basis for identifying cost-effective pathways. The initial investment for our preferred scenario is estimated at 116.9 trillion US\$, based on current pricing benchmarks (Supplementary Fig. S8), representing only 54% of the highest estimated cost of 217.8 trillion US\$. In grids with a lower proportion of baseload generation, a wider range of development pathways becomes feasible (Fig. 2e), enhancing flexibility and fault tolerance during system evolution. However, this enhancement necessitates a higher reliance on flexible power sources to maintain grid stability. Under an NZE scenario, where baseload generation is close to zero, the average proportion of flexible power required is ~18.7%. From the 2030 s to the 2050 s, a substantial transition in the electricity supply and consumption structures is anticipated (Fig. 2f, g), reducing reliance on flexible power reserves from 30% to 17% and increasing the share of trans-regional solar-wind power consumption from 15% to 53%.

Potential benefits of global interconnection

We find that global interconnection substantially enhances energy and infrastructure utilization efficiency, thereby reducing the overall costs of achieving NZE targets²⁸. This is evidenced by comparing the anticipated capacities, costs, and utilization rates for PV, wind, storage, and transmission facilities in the 2050 s under different interconnection scenarios (Table 1). Using the regionally independent (S-I) scenario as a reference, the global interconnection (S-G) scenario reduces the installed capacities (and corresponding power outputs) of wind and solar power plants by 22.1% (25.2%) and lowers the power (and capacity) requirements for storage systems by 41.6% (37.0%). Driven by a 33.6% reduction in curtailment, this streamlined solar-wind-storage configuration achieves a 5.1% increase in solar-wind penetration. The initial investment for constructing solar PVs, wind turbines, storage, and transmission facilities under the S-G scenario amounts to 84.2% of the cost required for the S-I scenario, translating to potential savings of around 22.47 trillion US\$. Notably, the decline in storage utilization rate under the S-G scenario represents an exception to the general efficiency improvements, indicating that global interconnection lessens the dependence of a solar- or wind-dominated power system on energy storage technologies¹¹.

Remaining at local interconnections is not conducive to fully capitalizing on the efficiency and cost benefits. Relative to the S-I scenario, the adjacent (S-A) and continental (S-C) interconnection scenarios yield only modest reductions in installed capacities and associated costs (Table 1). Achieving global interconnection markedly amplifies the benefits of these intermediate scenarios, underscoring the importance of prioritizing global interconnection as the ultimate goal in early planning of grid interconnection^{27,29}. Complementary analyses for the 2030 s support these findings (Supplementary Table S2). The positive amplifying effects of global interconnection become increasingly pronounced in later stages of development with higher solar-wind penetration. Compared to the baseline scenario, accelerating global interconnection by the 2030 s results in only a 4% increase in penetration (Fig. 3a). However, if development lags and only adjacent interconnections are achieved by the 2050 s, solar-wind penetration could decrease by 15.2%. Moreover, accelerating global interconnection offers advantages in investment allocation. In the baseline scenario, the investment burden is disproportionately concentrated in the early stages, whereas global interconnection by the 2030 s leads to a more balanced cost distribution across different phases.

Spatial aggregation is a key strategy for mitigating the challenges posed by the intermittent nature of solar and wind power generation¹⁹. By strategically deploying solar/wind power plants across geographically diverse locations, complementary systems can be developed to buffer stochastic fluctuations in power output arising from meteorological variability^{7,19}. Previous studies have shown that the

Table 1 | Anticipated capacities, costs, and utilization rates for PV, wind, storage, and transmission facilities by the 2050 s across different interconnection scenarios

Scenario	Installed solar capacity (TWp)	Installed wind capacity (TWp)	Energy storage power (TW)	Energy storage capacity (TWh)	Electricity transmission power (TW)	Annual solar generation ($\times 10^3$ TWh)
S-I	55.43	3.41	8.44	144.31	/	89.38
S-A	54.36	3.38	7.92	115.46	235.51	87.63
S-C	47.15	3.34	5.74	106.69	341.44	73.57
S-G	42.52	3.27	4.93	90.88	384.49	65.24
Scenario	Annual wind generation ($\times 10^3$ TWh)	Storage utilization rate (%)	Transmission utilization rate (%)	Total initial investment (trillion US\$)	Curtailment rate (%)	Penetration rate (%)
S-I	7.73	4.53	/	142.32	41.30	72.02
S-A	7.63	3.21	0.48	133.34	32.20	73.68
S-C	7.58	0.70	0.74	123.12	23.46	74.20
S-G	7.42	0.52	1.15	119.85	8.65	77.08

S-I Regionally independent, S-A Adjacent interconnections, S-C Continental interconnections, S-G Global interconnections. The values represent the average of all alternatives obtained through multi-objective optimization.

benefit of spatial aggregation increases with the scale of aggregation^{10,41}. Our analysis further confirms that transitioning from regional to global interconnections greatly enhances the stability of solar and wind power supplies (Fig. 3b). We observed a substantial decrease in the maximum volatility of the generation curve—from over 50% to below 8%—and a decline in the coefficient of variation from a range of 0.061–0.455 to 0.035.

Global interconnections potentially promote energy availability by facilitating extensive trans-regional power sharing²⁸. Our projections indicate a processive escalation in power exchange market, with trading volumes anticipated to reach 38.47×10^3 TWh/year by the 2050 s—2.4 and 13.9 times the volumes in the 2040 s and 2030 s, respectively (Fig. 3c and Supplementary Fig. S10). Northern and southern America ranks as the top two energy exporters, followed by central Asia and northern Africa, whereas densely populated regions like eastern, southern, and southeastern Asia dominate as major energy importers (Fig. 3c). This dynamic redistribution of solar-wind resources is expected to alleviate current imbalances between resource availability and power demand^{4,39}. Thus, a marked decrease in energy access inequality is expected, with the Gini index dropping from 0.327 in the S-I scenario to 0.173 in the S-G scenario (Fig. 3d). Furthermore, global interconnections could ease the burden of energy decarbonization and the inequalities it entails⁴². In the S-I scenario, less-developed regions would face the challenge of investing over 5% of cumulative GDP during 2030–2050 to achieve high solar-wind penetration. In contrast, the S-G scenario reduces the economic pressure on all regions and narrows the disparity in the ratio of initial investment to GDP across regions (Fig. 3e).

Resilience of a globally interconnected system

We conducted stress tests on the optimized globally interconnected grid (Fig. 2) to evaluate its resilience under extreme or unforeseen conditions and to identify potential risks. These tests targeted five critical scenarios: climate change, extreme weather events, incompatible regional policies, geopolitical tensions, and market competition (see “Methods”). Future climate change is projected to increase variability in solar and wind power generation^{9,19} and electricity demand³⁴, posing substantial challenges to power systems dominated by variable renewable energy⁴. Our simulations show that uncertainties in global power supply associated with changes in solar radiation ($\pm 5\%$)⁴³, wind speed ($\pm 2\%$)⁴, and electrical loads ($\pm 10\%$)³⁴ remain consistently below 0.1% within the interconnected grid (Fig. 4a). Notably, these uncertainties decrease as the degree of interconnection increases. Extreme weather events—exemplified by the 2021 Texas Winter Storm—pose considerable threats to power supply⁴⁴ by triggering frequent and severe regional generation failures. The globally interconnected grid exhibits exceptional robustness in addressing such disruptions. Under the S-G scenario, the decline in solar-wind electricity supply caused by the complete outage of a single regional grid averages only 2.6% (ranging from 0.7% to 11.7%), compared to declines of 5.8%, 15.1%, and 26.4% under the S-C, S-A, and S-I scenarios, respectively (Fig. 4b). Collectively, these results highlight the capability of global interconnection to buffer against climate-induced risks, rekindling the prospect of a global power system fully powered by variable generation resources^{6,12}.

However, the globally interconnected power system remains susceptible to disruptions from incompatible regional policies, geopolitical tensions, and aggressive market competition. For instance, economically advanced nations may prioritize energy self-sufficiency, particularly in response to geopolitical crises like the Russia-Ukraine conflict, which has heightened concerns over energy independence⁴⁵. Our analysis indicates that such self-sufficiency strategies—resembling the S-I scenario—drive overexploitation of solar and wind resources (Table 1), undermining the global electricity supply balance enabled by optimized interconnection. The resulting imbalance exerts

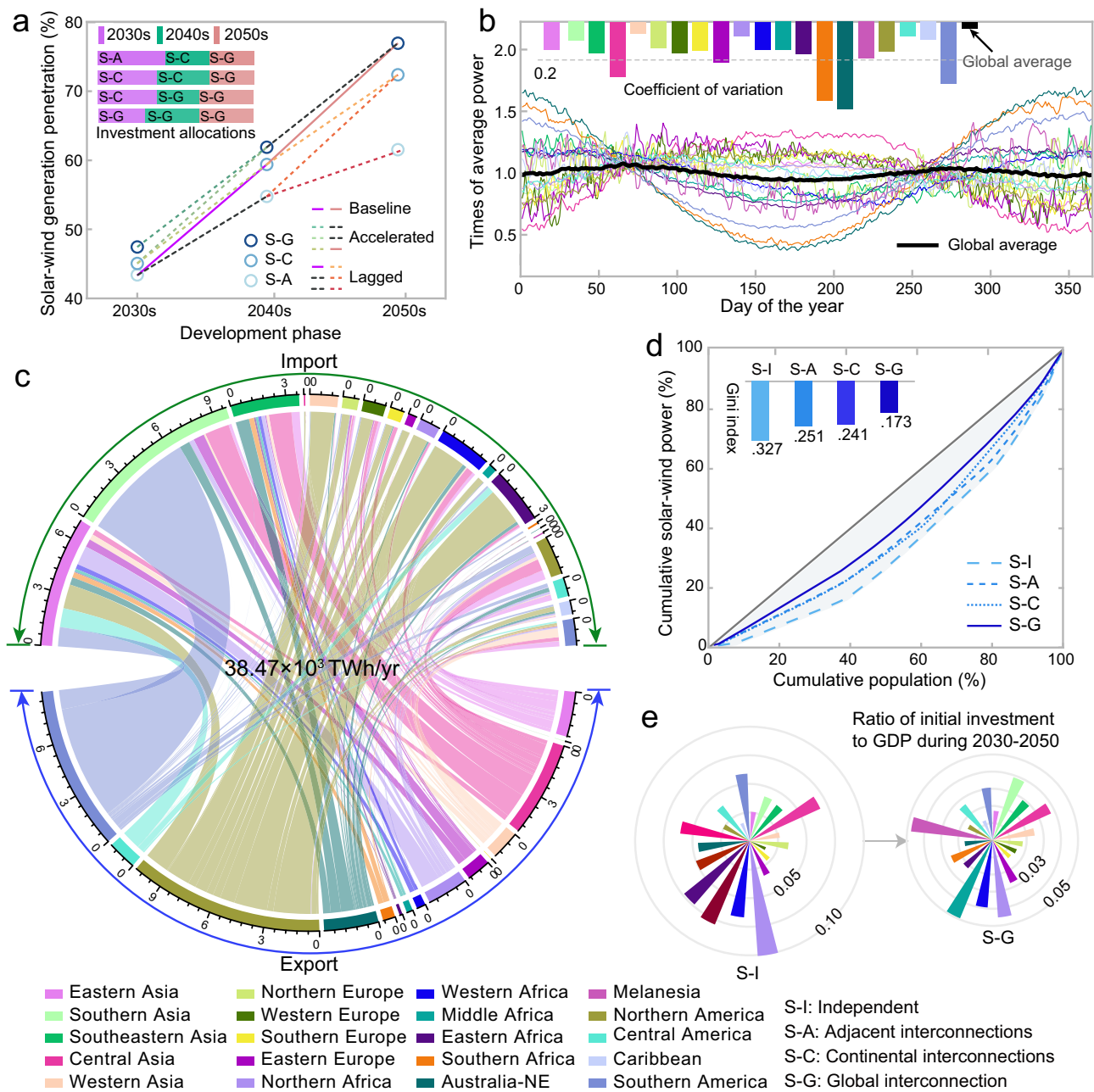


Fig. 3 | Potential benefits of global interconnection on electricity supply and access. **a** Impact of accelerated or delayed interconnection on phased solar-wind generation penetration. Solid lines represent the baseline scenario of progressive global interconnection. The inset compares phased investment allocations under baseline and accelerated scenarios. **b** Smoothing effect on solar-wind generation variability. The inset compares the coefficients of variation of generation curves.

c Trans-regional solar-wind power exchange in 2050 under the optima global interconnection. **d** Lorenz curves for renewable energy availability versus population in 2050 across different interconnection scenarios. The inset shows the Gini index for each scenario. **e** Comparison of initial investment as a percentage of GDP during 2030–2050 between the S-I and S-G scenarios. The correspondence between colors and regions in (b, c, e) is defined by the legend at the bottom.

widespread impacts. Specifically, policy incompatibilities in southern Asia, western Asia, northern Africa, and eastern Asia lead to the largest increases in solar-wind curtailment. In contrast, those in northern America, southern Asia, eastern Asia, and southern America cause pronounced decreases in demand for alternative energy sources (Fig. 4c). In an extreme scenario where all regional grids adopt self-sufficiency prioritization strategies, absolute increases in curtailment (reductions in demand) would reach 34.6% (13.5%).

Geopolitical tensions⁴⁶ further threaten the stability of transmission nodes and lines that underpin global interconnections. Failures at generation hubs like northern America, southern America, and Australia, or demand centers like eastern Asia, southern Asia, and

southeastern Asia would sharply increase global solar-wind curtailment and reduce penetration (Fig. 4d). By contrast, nodes like northern Africa and western Asia, which primarily serve as transregional transmission bridges exhibit relatively localized impacts when disrupted individually due to rerouting flexibility²⁷ in the interconnected grid. In an extreme scenario of a complete grid collapse, global solar-wind curtailment (penetration) would rise (drop) by an absolute 41.2% (22.9%). Although individual line failures generally have minimal global impacts, with changes in penetration or curtailment remaining below 1% (Supplementary Fig. S11), regions heavily reliant on external power supplies are particularly susceptible to such disruptions (Fig. 4e). For example, a disruption in the connection between eastern Asia and

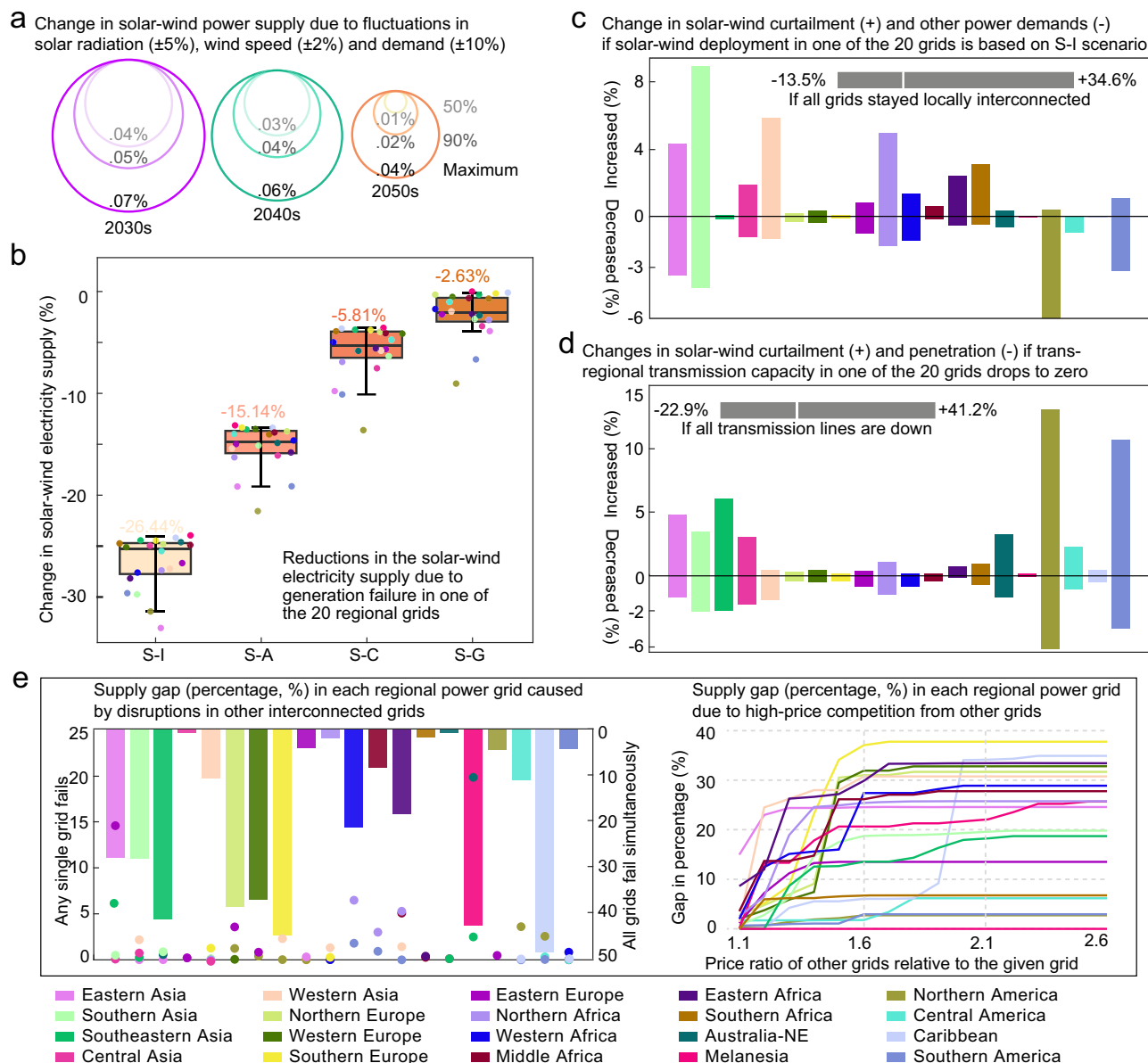


Fig. 4 | Resilience of a globally interconnected system to extreme or unforeseen conditions. **a** Impact of climate-induced variations in power generation and demand on solar-wind penetration at different stages. Maximum, 90th, and 50th percentiles of changes observed across 10,000 simulations are presented. **b** Reduction in global solar-wind penetration under S-I, S-A, S-C, and S-G scenarios when one of the 20 regional grids experiences a complete outage. Each circle represents a separate simulation in which a different regional grid experiences an outage, resulting in $n = 20$ simulations per scenario. Each simulation has identical modeling settings except for the grid where the outage occurs. Boxplots represent the median (center line), the 25th and 75th percentiles (box bounds), and the minimum and maximum values (whiskers) of outcomes across these 20 runs. **c** Changes in solar-wind curtailment and alternative energy supplies when one of

the 20 regional grids (denoted by bar colors) deploys solar-wind resources based on the S-I scenario. The horizontal gray inset illustrates the extreme case where all 20 grids remain locally interconnected. **d** Changes in global solar-wind curtailment and penetration when all transmission lines associated with a single regional grid (denoted by bar colors) are disrupted. The horizontal inset depicts the extreme scenario where all transmission lines fail simultaneously. **e**, Power supply gaps resulting from supply interruptions from interconnected grids (left panel) and aggressive market competition (right panel). Circles represent scenarios of a single grid disruption, while bars indicate simultaneous disruptions across all interconnected grids. The colors of circles in (b) and (e), bars in (c), (d), and (e), and lines in (e) correspond to the legend at the bottom.

eastern Europe would create a supply gap of nearly 15% for eastern Asia, and severing all transmission lines into eastern Asia would double this deficit. Furthermore, regions not directly connected to disruptions can still experience adverse effects through aggressive market competition (Fig. 4e). In Melanesia, for instance, if eastern Asia and southern Asia offered 1.6 times the baseline price to secure priority access to surplus power from Australia and southeastern Asia, Melanesia would face a supply gap exceeding 20%. These findings underscore the importance of coordinated global planning, stable

geopolitical environments, and equitable market conditions to ensure the long-term reliability and resilience of a globally interconnected power system^{27,28}.

Discussion

Achieving net-zero emissions by 2050 necessitates transformative strategies to scale up renewable energy penetration. Both the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA) advocate for solar-wind energy to constitute at least

68% of the global energy mix by mid-century^{40,47}. Global grid interconnection represents a compelling pathway to accelerate this transition, particularly given the uneven geographic distribution of solar-wind potential (Fig. 1a). By enabling regions with abundant solar-wind resources that are exploitable, accessible, and interconnectable to export surplus power generation (Fig. 3c), global interconnection facilitates the development of an international market for renewable electricity exchanges²⁸. Such exchange markedly enhances energy utilization efficiency and reduces the costs associated with achieving high penetration levels of variable generation, outperforming traditional decarbonization strategies^{6,31}. Our estimates indicate that exploiting only 29.4% of the interconnectable potential (Figs. 1d, 2a, b) could suffice to fulfill the projected electricity demand for the 2050s³⁴, at ~84.2% of the cost required under self-sufficiency prioritization strategies (Table 1). While regional policies may deviate from the optimal pathway, diverse, cost-effective alternatives ensure flexibility and resilience to such uncertainties (Fig. 2e).

Global interconnection addresses critical challenges in integrating solar and wind energy into traditional power grids. The diurnal and seasonal variability of solar-wind resources complicates their integration⁴, particularly amidst escalating electricity demand and increasing uncertainties in load distribution³⁴. Our findings demonstrate that global interconnection leverages the temporal complementarity of solar and wind energies across diverse geographic regions^{19,41}, markedly reducing generation variability over diurnal and seasonal cycles (Fig. 3b). Moreover, the growing frequency and severity of extreme climate events pose substantial risks to the security of renewable energy supplies^{9,43}. Unlike isolated regional grids^{12,31}, a globally interconnected power system exhibits enhanced stability and resilience under such conditions (Fig. 4b). Strategic optimization further reduces the capacity requirements for solar, wind, and storage infrastructures (Table 1), yielding environmental benefits by minimizing land resource occupation⁴ and alleviating PV/wind turbine decommissioning pressures⁴⁸. Additionally, the capital mobilized through trans-regional power flows can foster regional cooperation, revitalize economic activity, and promote sustainable development^{4,28}. These characteristics reinforce both the attractiveness and practical feasibility of global interconnection. In addition, we recognize the critical role of broader technological options in shaping its feasibility. Fossil generation with carbon capture, utilization, and storage (CCUS), Power-to-X (PtX) technologies, and demand-side solutions such as dynamic load management and energy efficiency improvements, provide essential flexibility to accommodate the intermittency of renewable energy. This increased flexibility broadens the range of pathways for achieving multi-objective optimization (Fig. 2e). The synergy between global interconnection and these complementary options has the potential to further reduce infrastructure requirements and investment costs, unlocking additional benefits in the transition to a renewable energy-dominated future.

Establishing a globally interconnected power system hinges on advancing trans-regional transmission capacities (Fig. 2d), which requires carefully balancing investments across various infrastructures through well-coordinated regional collaboration and targeted investment planning^{27,30}. Funding for new transmission lines can be derived from cost savings achieved through optimized solar, wind, and storage deployments (Table 1). These savings are expected to grow with future declines in the costs of long-distance, ultra-high-voltage transmission technology²⁰, and decreases in land acquisition⁴⁰ or other energy-related expenditures³¹. Moreover, prioritizing resources within a 10-kilometer distance of the existing transmission networks (Supplementary Fig. S12) minimizes the need for extensive expansion, potentially lowering actual infrastructure costs compared to current estimates. Investment allocation should also account for regional disparities in interconnection and grid development. For example, in

Europe, the primary focus is on resolving specific bottlenecks to optimize power sharing and reduce curtailments³⁰. Conversely, less connected regions, such as parts of Africa and Central Asia, face the dual challenge of enhancing cross-regional interconnections while simultaneously improving internal load balancing to stabilize their grids.

Accelerating the interconnection process is strongly recommended, as higher interconnection levels reduce the grid's reliance on energy storage (Fig. 2c) and maximize the advantages of prioritizing transmission infrastructure over large-scale storage solutions (Fig. 3a). Given the multifaceted advantages of global interconnection, we advocate for concerted global efforts to realize this vision. Pioneering projects such as the Asian Super Grid, the European Super Grid, and interconnection initiatives in the Middle East and North Africa are already underway^{28,30}. COP28's call to double global renewable energy capacity and efficiency¹ underscores the urgency of advancing interconnection efforts. These initial steps, together with future advancements, lay the foundation and act as catalysts for establishing a sustainable, globally interconnected power system.

We recognize that the implementation of global interconnections remains fraught with challenges. Transitioning from localized, self-sufficient modes to a broad, unified global paradigm necessitates robust international agreements and a supranational entity³⁰ to facilitate stakeholder communications, coordinate cross-regional investments, and ensure competitive and equitable transnational energy flows. Developing transcontinental and transoceanic infrastructure under diverse geographical and environmental conditions demands innovative engineering solutions alongside substantial investment in labor, materials, and financial resources^{21,22}. Geopolitical instability might be the greatest uncertainty for uninterrupted cross-border energy flows^{21,25}, particularly in the context of intense international competition. Furthermore, concerns over energy sovereignty, political pressures to safeguard domestic energy infrastructures, resistance from incumbent market participants toward new entrants, and local opposition to interconnection projects all pose potential barriers to the progress of global interconnection²⁸. Nevertheless, our stress tests demonstrate that a globally interconnected system exhibits substantial resilience to unforeseen disruptions (Fig. 4), with risks to generation, transmission, and consumption largely mitigated through diversified transmission routes and reinforced critical infrastructure. Even under extreme conditions, the likelihood of cascading failures remains exceptionally low.

These findings advance the understanding of global interconnection as a transformative approach to integrating solar and wind energy into the global energy mix. Unlike previous research^{6,31} that explored renewable energy potentials and pathways to carbon neutrality, this study offers a comprehensive and actionable roadmap for implementing a globally interconnected solar-wind power system. Moving beyond proof-of-concept^{23,27} or regional studies^{16,20,21}, we provide spatial estimates of interconnectable solar-wind potential, identifying critical regions of surplus and deficit while emphasizing the necessity of global-scale energy exchanges. Our analysis highlights the importance of delineating cost-effective configurations and development paths through multi-objective optimization, demonstrating its value in achieving balanced resource allocation, curtailment reduction, and efficiency improvements. Furthermore, we provide valuable insights into the potential benefits of enhancing energy availability and alleviating economic pressures on energy decarbonization while also examining potential risks under uncertainties. These thorough analyses enable a more nuanced perception of the feasibility of global interconnection, moving beyond the theoretical concepts of earlier research. By tackling practical challenges and offering alternative implementation plans, this study would contribute to the existing body of knowledge and provide valuable insights for policymakers and stakeholders in the renewable energy sector.

In summary, our findings underscore the substantial potential of a globally interconnected solar-wind system to enhance energy availability and grid stability on a global scale. By leveraging the spatio-temporal complementarity of renewable resources, such a system can bolster electricity supply resilience and reduce dependence on fossil fuels. Our results contribute to the ongoing discourse on large-scale renewable energy integration by quantifying the interconnectable potential of solar and wind resources and identifying optimal pathways for trans-regional power exchange. From a policy perspective, these findings highlight the critical role of international collaboration and strategic infrastructure investment in accelerating the transition toward a low-carbon, resilient energy future.

Methods

An overview of our workflow for global interconnected solar-wind system optimization and analysis is illustrated in Supplementary Fig. S13. The process begins by identifying suitable locations for solar PV and wind turbine deployment and assessing their theoretical generation potential. A multi-objective optimization model is then utilized to derive the optimal configuration of solar, wind, storage, and transmission capacities. This process involves trans-regional electricity dispatch to determine the objective function values for specific configurations. Subsequently, the optimization approach is applied to optimize phased configurations for the 2030s and 2040s, ensuring alignment with the 2050 configuration to establish a development path. Finally, comparative experiments are conducted to analyze the potential benefits and the resilience of a globally interconnected system.

Estimation of solar-wind electricity generation potentials

Suitability of solar-wind deployment. We evaluate the suitability of solar-wind deployment focusing on three aspects: solar/wind exploitability, accessibility, and interconnectability, as elaborated in Supplementary Table S3. ‘Exploitability’ pertains to the restrictions dictated by land use and terrain slope for installing PV systems and wind turbines. ‘Accessibility’ accounts for transportation obstacles encountered during physical deployment and operational constraints during power generation, determined by meteorological conditions like solar irradiance, air temperature, and wind speed. ‘Interconnectability’ refers to the requirement that any proposed power plant must be located no farther than 10 kilometers from the existing transmission lines. Notably, offshore wind energy exploitation is confined to the exclusive economic zone. Land use data are sourced from the European Space Agency (ESA) Climate Change Initiative (CCI) land cover products⁴⁹, featuring a spatial resolution of ~500 m. All land pixels are categorized into forest, shrubland, savannah, grassland, wetland, cropland, urban and built-up land, mosaics of natural vegetation, snow and ice, deserts, and water bodies. Terrain data are derived from the Shuttle Radar Topography Mission (SRTM) Global Enhanced Slope Database, possessing a spatial resolution of ~30 m. Constraints on solar PV and wind turbine deployment due to land use and slope are based on the study of Wang et al.⁴. Hourly data on surface solar radiation, surface air temperature, and wind speed at 100 m above the ground level are acquired from the ERA5 reanalysis⁵⁰, which has a spatial resolution of 0.25°. The 2000–2022 period averages are used to provide a representative estimate of solar and wind energy. Global road distribution is obtained from the Global Roads Inventory Project (GRIP) database⁵¹, which details freeways, primary roads, secondary roads, tertiary roads, and local roads at a 5' × 5' spatial resolution. Vectorized transmission lines are sourced from the work of Arderne et al.³⁶. All raster data are resampled to 500 m resolution by nearest neighbor interpolation. The suitability assessment is conducted by initially filtering pixels at a 500-m resolution based on the predefined criteria. The suitable pixels are aggregated to calculate the suitability factor for deploying solar or wind plants within each 0.25° × 0.25° grid-

box (Supplementary Fig. S1). Subsequently, we combine the suitability with simulated capacity factor (Supplementary Fig. S2) to determine the spatial distribution of global electricity generation potentials (Fig. 1a).

Capacity factor for solar PV output. We consider the installation of crystalline silicon PV panels, which are predominant in the market and exhibit relatively low sensitivity to variations in the radiation spectrum (Supplementary Fig. S14a). The panels, under standard test conditions (25 °C, 1000 W/m²), have a peak power of 395 W. Taking into account the necessary spacing between PV panels and maintenance access walkways, we adopt an average installation density of 74 W/m², as determined from our prior survey⁵². To calculate the power generation of PV panels, we employ the PVLIB toolkit⁵³ developed by Sandia National Laboratories to model the photovoltaic conversion process and system losses. First, the solar irradiance on the plane of the array (R_{poa}) is calculated as:

$$R_{poa} = 0.98 \times \left[\frac{R_{dir} \times \cos(AOI)}{\cos(90^\circ - \theta_Z)} + (R_s - R_{dir}) \right] \quad (1)$$

where the angle of incidence (AOI) is given by:

$$AOI = \cos^{-1} [\cos(\theta_Z) \cos(\theta_T) + \sin(\theta_Z) \sin(\theta_T) \cos(\theta_A - \theta_{A,a})] \quad (2)$$

Here, R_s and R_{dir} represent the total and direct solar radiation, respectively; θ_Z and θ_A the solar zenith and azimuth angles, respectively; and θ_T and $\theta_{A,a}$ the tilt and azimuth angles of the PV panels, respectively. All panels are oriented towards the equator and tilted at a latitude-dependent optimal angle⁵⁴ to maximize power generation. A factor of 0.98 accounts for losses due to shading, soiling, and reflection⁵³. Second, the module temperature (T_m) is estimated using the equation⁵⁵:

$$T_m = T_a + R_{poa} \times e^{-3.56 - 0.075 \times v_2} \quad (3)$$

where T_a denotes the ambient air temperature, and v_2 the wind speed at 2 m above ground level, derived from the speed at 10 m as $v_2 = v_{10} \times 0.2^{1/9}$. Finally, the PV electricity generation (E_s) is calculated from R_{poa} and T_m based on the model described by Huld et al.⁵⁶:

$$E_s = C_s \times \left[\frac{R_{poa}}{R_{STC}} \times \eta(R', T') \right] \quad (4)$$

where C_s is the installed capacity, and η the instantaneous relative efficiency, expressed as:

$$\eta(R', T') = 1 + k_1 \ln R' + k_2 [\ln R']^2 + T' \left(k_3 + k_4 \ln R' + k_5 [\ln R']^2 \right) + k_6 T'^2 \quad (5)$$

with normalized parameters $R' \equiv R_{poa}/R_{STC}$ and $T' \equiv T_m/T_{m,STC}$ in reference to standard test conditions (R_{STC} and $T_{m,STC}$). Coefficients k_1 – k_6 are empirically determined and their values for crystalline silicon are detailed in Huld et al.⁵⁶. A 10% loss in the conversion from direct current to alternating current is assumed, based on observations across 1,029 sites in Europe⁵⁷. Hourly solar radiation (R_s and R_{dir}), air temperature (T_a) and 10-m wind speed (v_{10}) data are sourced from ERA5 product⁵⁰, recognized for its high accuracy in various applications^{58,59}. We use the capacity factor (CF) to assess the efficiency of power generation, defined as the ratio of the actual output (kWh) of a PV module to its maximum output under standard test conditions (kWp) over a specified period, i.e., E_s/C_s . The CF for solar PV power generation is shown in Supplementary Fig. S2a.

Capacity factor for wind power generation. We consider two types of wind power plants: onshore (General Electric 2.5 MW) and offshore (Vestas 8.0 MW), both situated at a hub height of 100 meters above the ground. For each $0.25^\circ \times 0.25^\circ$ grid-box, turbines are arranged such that there is a spacing of seven rotor diameters between neighboring turbines⁶⁰. Consequently, the average installation density is ~ 2.7 MW/km² for onshore and 4.6 MW/km² for offshore wind farms. First, the wind power output (P_w) per turbine is calculated on an hourly basis using the respective power curves (Supplementary Figs. S14b, c). Subsequently, we incorporate the efficiency decay attributable to wake losses by referencing the mean wind efficiency curve (Supplementary Fig. S14d) derived from an analysis of 2000 wind farms in Germany⁶¹. Finally, the wind electricity generation (E_w) for each grid-box is calculated using the equation:

$$E_w = \frac{1}{C_0} [C_w \times P_w(v_{100}) \times f_w(v_{100})] \quad (6)$$

where C_0 signifies the rated power of a single wind turbine, C_w the total installed capacity within the grid-box, f_w the wind efficiency factor, and v_{100} the wind speeds at 100 m above the ground that are sourced from ERA5 product⁵⁰. The CF for wind power generation (i.e., E_e/C_w) is shown in Supplementary Fig. S2b.

Optimization of interconnected solar-wind system

Multi-objective problem definition. Our optimization strategy is designed to pinpoint the optimal deployment of solar-wind power stations (selecting among 13,296 solar and 8477 wind candidate grid-boxes), delineate the storage capacities (including maximum operational power and capacity) for each of the 20 regions (Supplementary Fig. 4a), and ascertain the requisite transmission capacity between interconnected regions. The overarching objectives of this optimization process are threefold: to minimize total investment costs, to maximize the overall penetration of solar-wind generation, and to reduce the curtailment rate as much as possible. This multi-objective optimization problem is formalized as follows:

$$\min_{\mathbf{I}_s, \mathbf{I}_w, \mathbf{P}_s, \mathbf{V}_s, \mathbf{P}_t} (T_{inv}, 1 - R_p, R_c) \quad (7)$$

Here, T_{inv} represents the total investment costs (see Eq. 8), R_p denotes the penetration rate (see Eq. 9), and R_c is the curtailment rate (see Eq. 9). The sets $\mathbf{I}_s = \{I_s^1, I_s^2, \dots, I_s^{13296}\}$ and $\mathbf{I}_w = \{I_w^1, I_w^2, \dots, I_w^{8477}\}$ indicate the selection status of candidate solar and wind grid-boxes, respectively. $\mathbf{P}_s = \{P_s^1, P_s^2, \dots, P_s^{20}\}$ signifies the maximum operational powers of regional storage systems, $\mathbf{V}_s = \{V_s^1, V_s^2, \dots, V_s^{20}\}$ their maximum storage capacities, and $\mathbf{P}_t = \{P_t^1, P_t^2, \dots, P_t^{n_t}\}$ the maximum transmission powers for direct connections (Supplementary Fig. S4), where n_t denotes the number of connections (e.g., 82 under global interconnection). Here, we optimize the bi-directional transmission capacity to capture the asymmetry in power flow needs between grids. The decision variables— $\mathbf{I}_s$, $\mathbf{I}_w$, $\mathbf{P}_s$, $\mathbf{V}_s$, and $\mathbf{P}_t$ —are subject to their current states (Supplementary Table S4) to ensure that the optimized future configuration keeps compatible with ongoing or planned efforts. Specifically, the designed capacities for solar, wind, or storage in each regional grid should exceed existing installed capacities, and the transmission power for each connection should surpass the current capacity.

In our analysis, we account for the construction costs of deploying solar, wind, storage, and transmission infrastructures. The total investment costs are encapsulated by the equation:

$$T_{inv} = \sum_{i=1}^{13296} \xi_{sol} I_s^i C_s^i + \xi_w \sum_{i=1}^{8477} \xi_w I_w^i C_w^i + \xi_{sto} \sum_{i=1}^{20} V_s^i + \xi_{tran} \sum_{i=1}^{42} P_t^i \quad (8)$$

Here, C_s and C_w correspond to the maximum installation capacities for solar and wind facilities within each grid-box. The terms ξ_{sol} , ξ_w , ξ_{sto} , and ξ_{tran} denote the unit costs of installing solar panels, wind turbines, storage facilities, and new transmission projects, respectively (see Supplementary Fig. S9). For onshore wind and solar PV, continental averages were calculated based on available country-level data from the IRENA to reflect regional cost differences. Due to data limitations, global averages of all available records were applied for offshore wind, energy storage, and transmission. Our cost optimization focuses on strategically allocating limited investments across solar, wind, storage, and transmission facilities to realize the most effective solution. A more refined estimation would further encompass a variety of complex factors^{4,13}, including variations in land and labor costs, discrepancies in transportation conditions, and the influence of proximity to the coast on offshore wind turbine installations. It is emphasized that our optimization framework assumes a high penetration of solar and wind energy as a central goal under the premise of a global commitment to decarbonization. While competition from fossil-fueled generation with CCUS, PtX technologies, and demand-side responses may influence the specific configuration of global interconnections, they do not change the overarching conclusion of a renewable energy-dominated NZE future. Therefore, simplifying these factors does not affect the main outputs of the optimization framework. Instead, this simplification allows us to focus on isolating and addressing the key issues associated with optimizing global interconnections.

Trans-regional electricity dispatch. We developed a trans-regional electricity dispatch model (illustrated in Supplementary Fig. S5) to simulate the consumption of solar-wind generation. The model accounts for the distinctive characteristics of regional generation and demand, as well as the capabilities of regional energy storage and trans-regional transmission. The modeling process can be formally represented as:

$$[R_p, R_c] = f(\mathbf{L}, \mathbf{G}, \mathbf{P}_s, \mathbf{V}_s, \mathbf{P}_t) \quad (9)$$

Here, R_p is defined as the ratio of the actual consumed solar-wind power generation (inclusive of real-time local consumption, non-local consumption through trans-regional transmission, and time-shifted consumption through storage) to the actual electricity demand, and R_c is defined as the fraction of the curtailed solar-wind power generation relative to the total power outputs. The term $\mathbf{L} = \{l^1, l^2, \dots, l^{20}\}$ denotes the load profiles of the 20 regional grids (see Eq. 12), and $\mathbf{G} = \{g^1, g^2, \dots, g^{20}\}$ denotes the solar-wind generation curves of these grids, which are obtained through spatial aggregation across the solar and wind power plants within each grid's spatial domain (Supplementary Fig. S4a). The function f symbolizes the trans-regional electricity dispatch model.

Electricity dispatch is conceptualized as a real-time analytical process that balances generation (supply) and load (demand) within the power grid, thereby determining the optimal deployment of generating units for subsequent intervals⁶². We categorize power generation units into four types: baseload generation, real-time solar-wind generation, stored solar-wind generation, and other flexible units. Baseload generation (including nuclear, geothermal, and unabated fossil fuels) and flexible units (including hydropower, hydrogen-based sources, and fossil fuels with CCUS) are treated as aggregate categories rather than individually modeled. During electricity dispatch, baseload generation is always prioritized, followed by solar and wind generation (to maximize their penetration), with any remaining gap filled by flexible units. When solar-wind generation within a grid exceeds its net power demand (i.e., total demand minus baseload), surplus power is first transferred to interconnected grids experiencing shortages, with the remaining surplus stored until

capacity is reached. Any surplus beyond storage capacity is curtailed. Conversely, when a grid's solar-wind generation is insufficient to meet demand, the shortage is first compensated by surplus from interconnected grids, then by stored solar-wind generation, and finally, if needed, by other flexible reserves. In our model, solar and wind generation are explicitly modeled with high-resolution temporal and spatial variations, whereas flexible units are collectively represented as a dispatchable reserve used to balance residual load fluctuations after solar and wind generation and trans-regional exchanges have been accounted for. Referring to the IEA's NZE scenario (Supplementary Table S1), we set the share of baseload generation to decline gradually from 36% in the 2030s to 11% in the 2040s and further to 9% by the 2050s. We assume that each regional grid can only access its own energy storage. Two key technical parameters of energy storage are considered: the maximum operational power and the average storage duration. The round-trip efficiency of energy storage is set to 90%, referencing commercial storage technologies⁶³.

According to the Energy Technology Systems Analysis Program (ETSAP) of the IEA, long-distance transmission losses on land are about 3% per 1000 kilometers for HVDC lines, and about 7% per 1000 kilometers for high-voltage alternating-current (HVAC) lines⁶⁴. For sea cables, HVDC losses are similar, but HVAC losses can reach 60% per 100 kilometers. Here, we assume a 50/50 split between HVDC and HVAC on land, while HVDC dominates for cross-sea transmission. As a result, transmission losses are calculated at 5% per 1000 kilometers on land and 3% per 1000 kilometers at sea. The centroid of each regional grid is used to calculate the average distances between grids, forming the transmission loss matrix shown in Supplementary Fig. S4c. When surplus power exists in any one grid, a path-finding algorithm identifies all potential transmission routes based on the network topology (Supplementary Fig. S4b), where each grid acts as a node. In the S-A scenario, transmission routes are limited to direct connections without intermediate nodes; in the S-C scenario, a single intermediate node is allowed; and in the S-G scenario, multiple intermediate nodes are permitted. Transmission losses for each route are calculated as the sum of losses from all sub-connections, and the least costly routes are prioritized for electricity transmission. Once a route is in operation, the remaining transmission capacity between nodes is updated. The usable capacity of a route is determined by the smallest remaining capacity among its sub-connections.

In this study, we adopt HVDC as the primary long-distance transmission technology on land due to its current feasibility and widespread global deployment. This approach differs from the GEI concept proposed by GEIDCO, which primarily relies on UHVDC technology. UHVDC offers lower transmission losses⁶⁵ but likely entails higher investment costs compared to HVDC. Future transition from HVDC to UHVDC is expected to reduce overall capacity requirements and improve transmission efficiency. Nevertheless, under the premise of fair technology sharing, the fundamental spatial layout and regional distribution patterns under global interconnection are unlikely to change substantially (Supplementary Fig. S8).

Projections of future generation and demand. We simulate the impact of climate change on solar-wind power generation under the low-emission Shared Socioeconomic Pathways (SSP) 1–2.6 scenario. To quantify these impacts, we utilize climate model projections of surface irradiance, air temperature, and wind speed from the Coupled Model Intercomparison Project Phase 6 (CMIP6). Recognizing that direct application of these uncalibrated projections would lead to substantial uncertainties^{66,67}, we have adopted a synthesis approach, proposed and validated by Lu et al.⁶⁸, to integrate projections from various CMIP6 models based on each model's performance in reproducing the historical changes. The synthesis is

mathematically represented as:

$$\theta_t^{syn} = \mathbf{\beta}^T \theta_t^{proj} \quad (10)$$

where $\theta_t^{proj} = [1, \theta_{t,1}^{proj}, \theta_{t,2}^{proj}, \dots, \theta_{t,N}^{proj}]^T$ denotes the CMIP6 projections from 2023 to 2100, $\mathbf{\beta}$ the vector of synthesis weights, θ_t^{syn} the synthesized projections, and N the number of CMIP6 model projections. We chose the projections of 30 models providing global data for synthesis. The ERA5 dataset⁵⁰, which has been proven to be high accuracy, is used as the synthesis benchmark. The synthesis weights are determined by minimizing the following cost function:

$$J = \sum_{t=1}^T \left(\theta_t^{ERAS} - \mathbf{\beta}^T \theta_t^{his} \right) \delta^{-2} \left(\theta_t^{ERAS} - \mathbf{\beta}^T \theta_t^{his} \right) + \alpha \mathbf{\beta}^T \mathbf{\beta} \quad (11)$$

where θ_t^{ERAS} denotes the historical ERA5 estimates from 1950 to 2022, $\theta_t^{his} = [1, \theta_{t,1}^{his}, \theta_{t,2}^{his}, \dots, \theta_{t,N}^{his}]^T$ the corresponding historical CMIP6 simulations, δ the standard deviation, α the regularization parameter to prevent overfitting, and T the length of synthesis window. Through re-simulation of solar and wind power generation using these calibrated meteorological projections, we quantify changes in solar-wind generation efficiencies over the coming three decades (Supplementary Fig. S6).

Real load profiles in power systems exhibit multi-level patterns⁶⁹, influenced not only by periodic astronomical events that affect temperature, lighting, and climate at specific locations but also shaped by regular cultural and economic practices. The sine function, adept at mathematically representing periodic events, aptly aligns well with the diverse factors affecting load patterns. The sum of sine functions has been extensively adopted to model the intricate relationships between power demand and its underlying influencing parameters⁷⁰. Here, we adopt a similar approach to predict the load profile³⁴:

$$load(t) = \sum_{i=1}^N y_i(t) = \sum_{i=1}^N (a_i \sin^{\eta_i}(b_i t + c_i) + d_i) \quad (12)$$

where t represents the hours since the start of the year (from 1 to 8760); a_i , b_i , c_i , and d_i the amplitude, frequency, phase shift, and additional vertical offset, respectively; η_i the power of the sine; and N the number of sine functions. Each sine function describes components of the entire load profile, including annual trends, annual and diurnal oscillations, summer day oscillations, weekly and weekend oscillations, afternoon and evening peaks, and contributions from variables such as air conditioning, travel, and tourism. Each component is (partially) related to factors like average temperatures in the coldest/warmest month, temperature difference between the warmest and coldest months, GDP, population, per capita electricity consumption, and peak load. In this study, future meteorological parameters are obtained through the synthesis approach (Eq. 10); GDP and population forecasts under the SSP1–2.6 scenario are sourced from the International Institute for Applied Systems Analysis (IIASA) SSP database⁷¹; and per capita electricity consumption (E_y) and peak load ($peak_y$) are estimated from per capita GDP (GDP_y) as follows:

$$E_y = a \cdot (e^{b \cdot GDP_y} - e^{c \cdot GDP_y}) \quad (13)$$

$$peak_y = a \cdot GDP_y + b \quad (14)$$

in which y denotes the forecasted year, with empirical parameters a , b , and c determined by fitting to historical data. We first fit the parameters in Eq. 12 using historical data from Toktarova et al.³⁴, and then incorporate future projections of influencing factors to derive future load profiles (Supplementary Fig. S15). To address the

inconsistency between our projections and the IEA's NZE scenario (Supplementary Table S1), we calibrate the forecasted hourly loads by applying a linear ratio based on their total generation forecasts.

Design of development pathways

Interconnection scenarios. We designed four interconnection scenarios, each reflecting different degrees of regional and global power grid integration (Supplementary Fig. S4). In the S-I (regionally independent) scenario, the world is divided into 20 regions, each operating as an independent energy system with no trans-regional power transmission. This scenario represents the current state of largely isolated country- or regional-level power markets. The S-A (adjacent interconnections) scenario allows power exchange between geographically adjacent regions, simulating practical cross-border electricity sharing, such as the European interconnected power grid system⁷². In the S-C (continental interconnections) scenario, full interconnection is established within each continent, enabling power exchange across larger geographic areas. In this scenario, two grids on different continents can connect through an intermediate grid that is spatially adjacent to both, facilitating the balancing of variable renewable resources¹⁰, such as solar and wind, across diverse climatic zones. Finally, the S-G (global interconnections) scenario envisions an idealized global load balancing framework, where all regions are interconnected without constraints on the number of intermediate nodes, and four transoceanic transmission lines are introduced to enable broader electricity exchange. This scenario aims to explore the theoretical limits of global solar and wind generation sharing. These progressively expansive scenarios allow us to assess the potential benefits and challenges of increasing grid interconnection levels on energy system resilience, efficiency, and costs.

Development scenarios. We designed one baseline and six (three accelerated and three delayed) alternative development scenarios (Supplementary Fig. S13) to explore how interconnection progressions affect global electricity supply. Factors such as technological and infrastructure maturity, policy and coordination complexities, economic feasibility, cost-effectiveness, and dynamic balance between energy demand and supply may hinder the development of grid interconnection. Successful cases, such as the European power market integration²², demonstrate that a stepwise approach—from local to regional, to continental, and ultimately to global interconnection—is a more robust and feasible pathway. This approach progressively addresses technical, policy, and economic challenges, optimizes grid stability and efficiency, and mitigates potential risks. Therefore, our baseline scenario assumes a phased approach to global energy interconnections, with interconnections initially designed to address regional bottlenecks and then gradually transitioning to a unified global load-balancing framework. Specifically, we envision a transition from S-A in the 2030 s to S-C in the 2040 s, culminating in S-G by the 2050 s. For each scenario, we optimized the configuration in line with the IEA's NZE scenario⁴⁷ and selected the most cost-effective solution that meets the minimum solar-wind penetration of 68% and a curtailment close to 5%, based on alternatives provided by the NSGA-II algorithm. In addition, we optimized configurations for the 2040 s and 2030 s to form a development pathway consistent with the 2050 configurations. The rationale behind optimizing these phased targets is to account for the gradual increase in global electricity demand from the 2030 s to the 2050 s. Designing the system solely for 2050 demand from the outset could result in unnecessary energy waste in previous years of lower demand. Therefore, setting phased goals provides a more strategic approach to guiding global grid interconnection effectively.

Analysis of globally interconnected system

Benefits of global interconnection. We first analyzed the impact of global interconnection on enhancing the penetration of solar and wind generations and reducing the costs of establishing a global power system dominated by these renewable sources. Optimization experiments were conducted under the S-I, S-A, S-C, and S-G scenarios. For each scenario, we calculated the average values of all feasible solutions provided by the NSGA-II to achieve a minimum solar-wind penetration of 68% by the 2050 s (Table 1). To assess the robustness of our findings, we performed a similar analysis for the 2030 s, targeting a minimum solar-wind penetration of 40% (Supplementary Table S2). Additionally, using the baseline development scenario as a reference, we investigated the effects of accelerating or delaying global interconnection on these benefits (Fig. 3a).

We further examined the potential benefits of global interconnection in reducing the variability of wind and solar power generation and improving equitable access to renewable power across regions. To assess variability, we compared the temporal fluctuations and coefficients of variation in aggregated power generation curves under different interconnection scenarios (Fig. 3b). For accessibility, we quantified the total solar-wind electricity accessible to other regions based on simulations of trans-regional electricity dispatch. Using population projections from the IIASA SSP database, we ranked 20 regions by their per capita accessible solar-wind power, enabling the construction of Lorenz curves (Fig. 3d) and the calculation of Gini indices. Finally, we compared the ratio of cumulative initial investments to the cumulative GDP for each region between the S-I and S-G scenarios (Fig. 3e), which provides a preliminary understanding of how global interconnection can reduce and balance the economic pressures faced by different regions in accessing renewable energy.

Stress tests. To evaluate the resilience and reliability of a globally interconnected power system, we conducted stress tests under extreme or unforeseen conditions, including climate change, extreme weather events, incompatible regional policies, geopolitical tensions, and market competition. Based on the optimal configurations identified for the S-G scenario, we introduced targeted stressors and assessed their impact by observing the resulting changes in regional or global electricity supply dynamics.

Climate change introduces variability in power generation and demand⁷³. We applied a $\pm 5\%$ variability in PV power generation to reflect changes in solar radiation and aerosol deposition on PV panels⁴³, a $\pm 2\%$ variability in wind power generation to account for shifts in wind resources⁴, and a $\pm 10\%$ fluctuation in global electricity demand across regional grids³⁴. These stochastic fluctuations were incorporated into 10,000 trans-regional electricity dispatch simulations to quantify uncertainties in solar-wind electricity supply (Fig. 4a). Extreme weather events⁴⁴, such as the 2008 South China Ice Storm and the 2021 Texas Winter Storm, can trigger large-scale regional generation failures. To assess their impacts, we simulated scenarios where any one of the 20 regional grids experiences a complete outage and analyzed the subsequent changes in global solar-wind electricity supplies. Comparisons were performed across the S-I, S-A, S-C, and S-G scenarios to investigate how higher degrees of interconnection mitigate the effects of such disruptions (Fig. 4b).

Incompatible regional energy policies lead to deviations from the optimal pathways toward global interconnection¹⁷. We designed scenarios where individual grids independently achieve 68% solar-wind penetration to analyze how regional overexploitation of solar and wind resources alters global electricity supply structures. In addition, an extreme scenario in which all regional grids adopt self-sufficiency prioritization strategies is modeled to uncover potential risks of power curtailment and the pressures exerted on alternative energy sources (Fig. 4c). Geopolitical tensions⁴⁶ could disrupt the transmission capacities of critical nodes and lines within the interconnected grid,

thereby impacting global power exchange. We simulated scenarios in which all transmission capacities associated with a specific node were reduced to zero and analyzed the resulting changes in global solar-wind curtailment and penetration. These simulations provide insights into the vulnerability of a globally interconnected grid to geopolitical disturbances (Fig. 4d). Lastly, we examined regional market competition, where economically dominant regions influence electricity flows by outbidding local grids. To simulate such dynamics, we introduced weighted adjustments to the transmission loss matrix (Supplementary Fig. S4c), creating scenarios where competitive regions gained a cost advantage. This allowed us to estimate the potential energy losses experienced by disadvantaged regions. Furthermore, we explored regional dependencies in the interconnected grid by quantifying power supply gaps in a specific grid when one or all of its interconnected grids ceased supply (Fig. 4e).

Limitations

We recognize that our analysis has certain limitations. First, the classification of roads and transmission lines was not considered in assessing the solar-wind potential. For instance, the inability of certain rural roads to accommodate large wind turbine transport and the inadequacy of low-voltage transmission lines for long-distance power transmission might lead to an overestimation of the interconnectable potential. Second, while we considered cost differences in deploying solar, wind, and storage facilities, our analysis did not account for regional cost variations and temporal cost reductions due to dynamic learning⁷⁴ and technological advancements⁴, which may undermine the reliability of our cost estimates in guiding investment decisions. Third, our optimization framework does not explicitly model the competition between global interconnections and fossil fuel generation, storage, or PtX technologies, nor does it incorporate demand-side responses. These aspects are critical for a holistic evaluation of global interconnection strategies, and their inclusion in future studies could provide deeper insights into the techno-economic trade-offs and feasibility of global interconnections. Fourth, our analysis primarily focused on the technical and socio-economic benefits without evaluating the potential environmental impacts of large-scale solar-wind deployment⁷⁵. Fifth, future research should integrate detailed grid requirements, including balancing mechanisms, frequency regulation, and regional coordination, to fully evaluate the operational feasibility of transitioning from regional bottleneck resolution to a unified global load-balancing system. Given these limitations, our analysis should be interpreted as providing foundational insights for conceptualizing and advancing a globally interconnected solar-wind power system. Future research should address these issues, striving to develop more nuanced, feasible, and actionable implementation strategies.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The European Space Agency (ESA) Climate Change Initiative (CCI) land cover products can be downloaded from the Copernicus Climate Change Service (C3S) Climate Data Store (CDS) at <https://doi.org/10.24381/cds.006f2c9a>; the Shuttle Radar Topography Mission (SRTM) data are available at <https://www.earthdata.nasa.gov/sensors/srtm>; the global road inventories are available at <https://www.globio.info/download-grip-dataset>; the hourly ERA5 data (including solar radiation, air temperature, and wind speed) can be downloaded from C3S CDS at <https://doi.org/10.24381/cds.adbb2d47>; the country-level projections of GDP and population are available from the IIASA SSP Database at <http://tntcat.iiasa.ac.at/SspDb>. The installed cost data for solar PV and wind turbine are extracted from IRENA reports at <https://www.irena.org/Publications/2023/Aug/Renewable-power-generation-costs-in-2022>. The cost of new transmission lines is based on the Energy Institute for the Electric Reliability Council of Texas, Inc. (ERCOT) transmission projects at https://energy.utexas.edu/sites/default/files/UTAustin_FCe_TransmissionCosts_2017.pdf. Energy storage cost data come from the U.S. Department of Energy at <https://www.pnnl.gov/ESGC-cost-performance>. Data on installed capacities for solar, wind, and storage are sourced from the Renewable Energy Statistics 2024 report at <https://www.irena.org/Publications/2024/Jul/Renewable-energy-statistics-2024>.

www.irena.org/Publications/2023/Aug/Renewable-power-generation-costs-in-2022. The cost of new transmission lines is based on the Energy Institute for the Electric Reliability Council of Texas, Inc. (ERCOT) transmission projects at https://energy.utexas.edu/sites/default/files/UTAustin_FCe_TransmissionCosts_2017.pdf. Energy storage cost data come from the U.S. Department of Energy at <https://www.pnnl.gov/ESGC-cost-performance>. Data on installed capacities for solar, wind, and storage are sourced from the Renewable Energy Statistics 2024 report at <https://www.irena.org/Publications/2024/Jul/Renewable-energy-statistics-2024>.

Code availability

The scripts used to generate all the results are written in MATLAB (R2023a) and are publicly available from the Zenodo repository at <https://zenodo.org/records/14491983>. All maps presented in the main text and Supplementary Information were generated by the authors using ArcMap (Version 10.2). The base layers, including coastlines and administrative boundaries, were sourced from the Natural Earth database (<https://www.naturalearthdata.com/>), which is in the public domain and freely available for academic and non-commercial use. The Exclusive Economic Zone layer was obtained from the Maritime Boundaries Geodatabase maintained by the Flanders Marine Institute (<https://www.marineregions.org>), provided under a CC BY 4.0 license.

References

1. UNFCCC. *COP28 Agreement Signals "Beginning of the End" of the Fossil Fuel Era*. (United Nations Framework Convention on Climate Change, 2023).
2. Matthews, H. D. & Wynes, S. Current global efforts are insufficient to limit warming to 1.5 °C. *Science* **376**, 1404–1409 (2022).
3. Schmidt-Traub, G., Kroll, C., Teksoz, K., Durand-Delacre, D. & Sachs, J. D. National baselines for the sustainable development goals assessed in the SDG index and dashboards. *Nat. Geosci.* **10**, 547–555 (2017).
4. Wang, Y. et al. Accelerating the energy transition towards photovoltaic and wind in China. *Nature* **619**, 761–767 (2023).
5. Davidson, D. J. Exnovating for a renewable energy transition. *Nat. Energy* **4**, 254–256 (2019).
6. Chen, X. et al. Pathway toward carbon-neutral electrical systems in China by mid-century with negative CO₂ abatement costs informed by high-resolution modeling. *Joule* **5**, 2715–2741 (2021).
7. Lu, T. et al. India's potential for integrating solar and on- and off-shore wind power into its energy system. *Nat. Commun.* **11**, 4750 (2020).
8. DeAngelo, J. et al. Energy systems in scenarios at net-zero CO₂ emissions. *Nat. Commun.* **12**, 6096 (2021).
9. Yin, J., Molini, A. & Porporato, A. Impacts of solar intermittency on future photovoltaic reliability. *Nat. Commun.* **11**, 4781 (2020).
10. Li, J. et al. How to make better use of intermittent and variable energy? a review of wind and photovoltaic power consumption in China. *Renew. Sust. Energ. Rev.* **137**, 110626 (2021).
11. Wang, S., Li, F., Zhang, G. & Yin, C. Analysis of energy storage demand for peak shaving and frequency regulation of power systems with high penetration of renewable energy. *Energy* **267**, 126586 (2023).
12. Jacobson, M. Z., Delucchi, M. A., Cameron, M. A. & Frew, B. A. Low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes. *Proc. Natl Acad. Sci. USA* **112**, 15060–15065 (2015).
13. Ziegler, M. S. et al. Storage requirements and costs of shaping renewable energy toward grid decarbonization. *Joule* **3**, 2134–2153 (2019).
14. Lu, X. et al. Combined solar power and storage as cost-competitive and grid-compatible supply for China's future carbon-neutral electricity system. *Proc. Natl Acad. Sci. USA* **118**, e2103471118 (2021).

15. Jiang, H., Yao, L. & Zhou, C. Assessment of offshore wind-solar energy potentials and spatial layout optimization in mainland China. *Ocean Eng.* **287**, 115914 (2023).
16. Brown, P. R. & Botterud, A. The value of inter-regional coordination and transmission in decarbonizing the US electricity system. *Joule* **5**, 115–134 (2021).
17. Deng, X., Lv, T., Xu, J., Hou, X. & Liu, F. Assessing the integration effect of inter-regional transmission on variable power generation under renewable energy consumption policy in China. *Energ. Policy* **170**, 113219 (2022).
18. Fuller, R. B. & Kuromiya, K. *Critical Path*. (Macmillan, 1981).
19. Tong, D. et al. Geophysical constraints on the reliability of solar and wind power worldwide. *Nat. Commun.* **12**, 6146 (2021).
20. Wang, H., Zhang, Y., Lin, W. & Wei, W. Transregional electricity transmission and carbon emissions: evidence from ultra-high voltage transmission projects in China. *Energ. Econ.* **123**, 106751 (2023).
21. Gomez, T., Enamorado, J. C. & Vela, A. Feasibility studies of a power interconnection system for Central American countries: SIEPAC Project. *IEEE Power Eng. Rev.* **14**, 11 (1994).
22. Valenza, D. & Cipollini, G. in *Proc. 1995 Int. Conf. on Energy Management and Power Delivery EMPD* **95**, 283–287 (IEEE, 1995).
23. Brinkerink, M., Deane, P., Collins, S. & Gallachóir, B. Ó. Developing a global interconnected power system model. *Glob. Energy Interconnect* **1**, 330–343 (2018).
24. Guo, F. et al. Implications of intercontinental renewable electricity trade for energy systems and emissions. *Nat. Energy* **7**, 1144–1156 (2022).
25. Quimbre, F. et al. *China's Global Energy Interconnection: Exploring the Security Implications of a Power Grid Developed and Governed by China*. (RAND Corporation, 2023).
26. UNFCCC. *UN Climate Change COP24 Partners Demonstrate Value of Collaborative Climate Action*. (United Nations Framework Convention on Climate Change, 2018).
27. Voropai, N., Podkovalnikov, S. & Osintsev, K. From interconnections of local electric power systems to Global Energy Interconnection. *Glob. Energy Interconnect* **1**, 4–10 (2018).
28. Brinkerink, M., Gallachóir, B. Ó. & Deane, P. A comprehensive review on the benefits and challenges of global power grids and inter-continental interconnectors. *Renew. Sust. Energ. Rev.* **107**, 274–287 (2019).
29. Rafique, S. F. et al. Global power grid interconnection for sustainable growth: concept, project and research direction. *IET Gener. Transm. Dis.* **12**, 3114–3123 (2018).
30. Li, J. et al. Research and outlook on global energy interconnection. *E3S Web Conf.* **209**, 01002 (2020).
31. Jacobson, M. Z. et al. 100% clean and renewable wind, water, and sunlight all-sector energy roadmaps for 139 countries of the world. *Joule* **1**, 108–121 (2017).
32. Jin, Y. et al. Energy production and water savings from floating solar photovoltaics on global reservoirs. *Nat. Sustain.* **6**, 865–874 (2023).
33. Chen, S. et al. The potential of photovoltaics to power the belt and road initiative. *Joule* **3**, 1895–1912 (2019).
34. Toktarova, A., Gruber, L., Hlusiak, M., Bogdanov, D. & Breyer, C. Long term load projection in high resolution for all countries globally. *Int. J. Elec. Power* **111**, 160–181 (2019).
35. Zheng, Q. et al. Future land-use competition constrains natural climate solutions. *Sci. Total Environ.* **838**, 156409 (2022).
36. Arderne, C., Zorn, C., Nicolas, C. & Koks, E. E. Predictive mapping of the global power system using open data. *Sci. Data* **7**, 19 (2020).
37. Solomon, A. A., Bogdanov, D. & Breyer, C. Curtailment-storage-penetration nexus in the energy transition. *Appl. Energy* **235**, 1351–1368 (2019).
38. Deb, K., Pratap, A., Agarwal, S. & Meyarivan, T. A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE T. Evolut. Comput.* **6**, 182–197 (2002).
39. Tatem, A. J. WorldPop, open data for spatial demography. *Sci. Data* **4**, 170004 (2017).
40. IRENA. *Renewable power generation costs in 2022*. (International Renewable Energy Agency, 2023).
41. Wu, C., Zhang, X.-P. & Sterling, M. Solar power generation intermittency and aggregation. *Sci. Rep.* **12**, 1363 (2022).
42. Wang, Q. et al. Examining energy inequality under the rapid residential energy transition in China through household surveys. *Nat. Energy* **8**, 251–263 (2023).
43. Li, X. Y., Mauzerall, D. L. & Bergin, M. H. Global reduction of solar power generation efficiency due to aerosols and panel soiling. *Nat. Sustain.* **3**, 720–727 (2020).
44. Zheng, D. et al. Climate change impacts on the extreme power shortage events of wind-solar supply systems worldwide during 1980–2022. *Nat. Commun.* **15**, 5225 (2024).
45. Xin, B. & Zhang, M. Evolutionary game on international energy trade under the Russia-Ukraine conflict. *Energ. Econ.* **125**, 106827 (2023).
46. Ge, Q. et al. Modelling armed conflict risk under climate change with machine learning and time-series data. *Nat. Commun.* **13**, 2839 (2022).
47. IRENA. *Net Zero by 2050: A Roadmap for the Global Energy Sector*. (International Renewable Energy Agency, 2021).
48. Jiang, H., Yao, L., Qin, J., Zhu, R. & Zhou, C. Unlocking multifaceted benefits of photovoltaic recycling via global collaborative efforts. *Innov. Energy* **1**, 100043 (2024).
49. European Space Agency. Land Cover CCI Product User Guide Version 2. http://maps.elie.ucl.ac.be/CCI/viewer/download/ESACCI-LC-Ph2-PUGv2_2.0.pdf (2017).
50. Hersbach, H. et al. The ERA5 global reanalysis. *Q. J. Roy. Meteor. Soc.* **146**, 1999–2049 (2020).
51. Meijer, J. R., Huijbregts, M. A. J., Schotten, K. C. G. J. & Schipper, A. M. Global patterns of current and future road infrastructure. *Environ. Res. Lett.* **13**, 064006 (2018).
52. Jiang, H. et al. Multi-resolution dataset for photovoltaic panel segmentation from satellite and aerial imagery. *Earth Syst. Sci. Data* **13**, 5389–5401 (2021).
53. Holmgren, W., Hansen, C. & Mikofski, M. pvlib python: a python package for modeling solar energy systems. *J. Open Source Softw.* **3**, 884 (2018).
54. Jacobson, M. Z. & Jadhav, V. World estimates of PV optimal tilt angles and ratios of sunlight incident upon tilted and tracked PV panels relative to horizontal panels. *Sol. Energy* **169**, 55–66 (2018).
55. Kratochvil, J. A., Boyson, W. E. & King, D. L. *Photovoltaic Array Performance Model*. (Sandia National Laboratories (SNL), 2004).
56. Huld, T., Gottschalg, R., Beyer, H. G. & Topic, M. Mapping the performance of PV modules, effects of module type and data averaging. *Sol. Energy* **84**, 324–338 (2010).
57. Pfenninger, S. & Staffell, I. Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. *Energy* **114**, 1251–1265 (2016).
58. Tang, W., Qin, J., Yang, K., Zhu, F. & Zhou, X. Does ERA5 outperform satellite products in estimating atmospheric downward longwave radiation at the surface? *Atmos. Res.* **252**, 105453 (2021).
59. Zhang, S.-Q., Ren, G.-Y., Ren, Y.-Y., Zhang, Y.-X. & Xue, X.-Y. Comprehensive evaluation of surface air temperature reanalysis over China against urbanization-bias-adjusted observations. *Adv. Clim. Chang. Res.* **12**, 783–794 (2021).
60. Musial, W., Heimiller, D., Beiter, P., Scott, G. & Draxl, C. *2016 Off-shore Wind Energy Resource Assessment For The United States*. (National Renewable Energy Lab.(NREL), 2016).
61. Knorr, K. et al. Modellierung von raum-zeitlichen Eigenschaften der Windenergieeinspeisung für wetterdatenbasierte Windleistungs-simulationen. <https://doi.org/10.24406/publica-fhg-282038> (2016).

62. Li, Y. et al. Two-stage real-time optimal electricity dispatch strategy for urban residential quarter with electric vehicles' charging load. *Energy* **268**, 126702 (2023).
63. Shan, R., Reagan, J., Castellanos, S., Kurtz, S. & Kittner, N. Evaluating emerging long-duration energy storage technologies. *Renew. Sust. Energ. Rev.* **159**, 112240 (2022).
64. IEA ETSAP. Electricity transmission and distribution. https://iea-etsap.org/E-TechDS/PDF/E12_el-t&d_KV_Apr2014_GSOK.pdf (2014).
65. Kasangala, F. M. & Atkinson-Hope, G. in *2013 Proceedings of the 10th Industrial and Commercial Use of Energy Conference*. (IEEE, 2013).
66. Shen, C. et al. Evaluation of global terrestrial near-surface wind speed simulated by CMIP6 models and their future projections. *Ann. NY Acad. Sci.* **1518**, 249–263 (2022).
67. Xu, J. et al. Assessment of surface downward longwave radiation in CMIP6 with comparison to observations and CMIP5. *Atmos. Res.* **270**, 106056 (2022).
68. Lu, N. et al. High emission scenario substantially damages China's photovoltaic potential. *Geophys. Res. Lett.* **49**, e2022GL100068 (2022).
69. Meriläinen, A., Puranen, P., Kosonen, A. & Ahola, J. Optimization of rooftop photovoltaic installations to maximize revenue in Finland based on customer class load profiles and simulated generation. *Sol. Energy* **240**, 422–434 (2022).
70. Anvari, M. et al. Data-driven load profiles and the dynamics of residential electricity consumption. *Nat. Commun.* **13**, 4593 (2022).
71. Riahi, K. et al. The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Glob. Environ. Chang.* **42**, 153–168 (2017).
72. Liu, Z., Zhang, Y., Wang, Y., Wei, N. & Gu, C. Development of the interconnected power grid in Europe and suggestions for the energy internet in China. *Glob. Energy Interconnect* **3**, 111–119 (2020).
73. Aldeman, M. R., Jo, J. H., Loomis, D. G. & Krull, B. Reduction of solar photovoltaic system output variability with geographical aggregation. *Renew. Sust. Energ. Trans.* **3**, 100052 (2023).
74. Victoria, M., Zhu, K., Brown, T., Andresen, G. B. & Greiner, M. Early decarbonisation of the European energy system pays off. *Nat. Commun.* **11**, 6223 (2020).
75. Rabaia, M. K. H. et al. Environmental impacts of solar energy systems: a review. *Sci. Total Environ.* **754**, 141989 (2021).

Acknowledgements

This study is jointly supported by the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant No. XDB0740200, LY), the National Natural Science Foundation of China (Grant Nos. 42201382, HJ; 42471386, LY), and the Young Elite Scientists Sponsorship Program by CAST (Grant 2023-2025QNRC001, HJ).

Author contributions

H.J. and J.Q. conceived and designed the experiments. H.J., L.Y., and J.Q. performed the experiments. H.J., L.Y., and T.L. analyzed the data. H.J., L.Y., J.Q., Y.B., and X.L. wrote the paper. L.Y., Y.B., M.B., S. J. D., N.L., W. Z. and C.Z. contributed materials/analysis tools. L.Y. and C.Z. provided funding acquisition.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s41467-025-59879-9>.

Correspondence and requests for materials should be addressed to Ling Yao or Chenghu Zhou.

Peer review information *Nature Communications* thanks Victor Hopo, Daniel Scholten, and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. A peer review file is available.

Reprints and permissions information is available at <http://www.nature.com/reprints>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© The Author(s) 2025