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Abstract

Climate mitigation efforts aim to electrify end uses of energy and rapidly expand the share of zero-carbon electricity, and especially electricity from renewable sources such as solar and wind. Yet recent growth in renewable generation worldwide (541.7 TWh per year 2020–2024) has not kept up with rising electricity demand (999.6 TWh per year over the same period), and thus substantial decreases in fossil-derived electricity have not occurred. Here, we assess these recent trends in the context of climate mitigation scenarios, using up-to-date, power plant specific data and a stock turnover model to assess how different trajectories of renewable deployment and electricity demand may impact both decarbonization pathways and the feasibility of climate targets. We find it plausible that growth in fossil generation could turn negative by 2030, if the fraction of renewable generation growth over electricity demand growth can accelerate from 54.2% over the half a decade to ~130% between 2025 and 2030. An even faster shift to clean electricity, stronger efficiency improvements to temper total demand, and carbon management at scale will be required to decrease committed emissions in line with international climate goals. ***[186 words]***

Introduction

The Paris Agreement Global Stocktake calls for a transition to zero-carbon electricity, the concomitant phase-down of fossil fuel-based generation, and the widespread electrification of energy end uses[1–4]. Although the economic inertia of long-lived fossil infrastructure restrains the pace of this transition[5–7], ever-lower costs of renewable electricity sources such as solar and wind have made them the fastest-growing source of electricity worldwide since the 2010s[8–10]. But as additional renewable generation is used to meet rising electricity demand, less is available to displace fossil generation that continues to drive cumulative CO_2 emissions and global warming[5,8,11,12].

A critical hinge point will be when additional zero-carbon electricity generation persistently exceeds electricity demand growth: additions of fossil generation will then become redundant and its decline will be a matter of time. Encouragingly, the world seems on the verge of this threshold: solar and wind outpaced demand growth in the first half of 2025[13,14]. Yet increases in electricity demand driven by ongoing industrialization, vehicle and building electrification, and expanding data centers may outpace renewables deployment once again[15–17]. This moment therefore represents a critical window in which faster renewable expansion could decisively shape the timing and pace of the phase-out of fossil generation.

Unfortunately, the energy and emissions scenarios developed for the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6)[18] are of limited use as benchmarks for the balance between renewable generation and electricity demand growth because most are based on dated technology costs and economic assumptions, and their first projection year is usually 2020 or earlier. Substantial recent decreases in the costs of solar and wind generation, electric vehicles, and heat pumps[19,20], as well as the artificial intelligence boom might therefore be missing from these scenarios. Although the International Energy Agency (IEA) World Energy Outlook (WEO)[21], provides more up-to-date projections, it covers a limited set of scenarios. Moreover, as global warming approaches 1.5°C, greater emphasis is placed on actionable transition goals (e.g., clean-energy shift) rather than relying solely on a limited scenarios defined by temperature targets or policy implementation[22]. These together highlight the need for a flexible framework that can simulate transition outcomes under varying trajectories of electricity demand growth and renewable deployment.

Here, then, we develop a data-driven complement to energy-emissions models based on unit-level datasets of electricity generating infrastructure and projected turnover of capital stocks to quantify how different growth of renewable generation and electricity demand can inform decarbonization pathways (Extended Data Fig. 1). Details of our analytic approach and data are provided in the Methods and Supplementary Information. In summary, we use IEA World Energy Balance (WEB)[23] data and the Global Power plant Emissions Database (GPED)[24,25] to analyze trends in renewable generation, electricity demand, and the fleet of fossil generators across regions and end-use sectors between 2020 and 2024. These recent trends are then compared with projections over 2024–2050 from the IEA WEO scenarios[21] and the AR6 1.5°C+2°C mitigation scenarios[18] (C1–C4 categories; see Methods for definitions). We project future changes in capacity changes, defined committed emissions, and carbon management—defined as carbon capture, utilization, and storage (CCUS) deployment in fossil power, across a broad range of scenarios to identify how specific trajectories of renewable generation and electricity demand shape the fate of fossil electricity, emissions, and climate. Our findings underscore the importance of accelerating the transition to clean electricity to enable the phase-out of fossil generation in line with international climate goals.

Recent trends in renewable generation and electricity demand

Figure 1 compares recent trends and drivers of renewable generation and total demand between 2020 and 2024, a period marked by rapid expansion in renewable deployment. Renewable generation grew faster during 2020–2024 than in the previous decade, despite disruptions from the pandemic, and this trend is likely to persist in the near term (Fig. 1; Extended Data Fig. 2). However, the absolute growth in renewable generation has not kept up with the growth in global electricity demand (Fig. 1a,c; Extended Data Fig. 3). Since 2020,

electricity generation from renewables has increased at an average annual rate of 7.0%—nearly twice the growth rate of global electricity demand (i.e., 3.8%)—adding 2,167 TWh in total (Fig. 1a,b). Yet this increase met only 54.2% of the 3,998 TWh rise in electricity demand (Fig. 1a), leaving the remainder to be supplied by expanding fossil generation and continued fossil capacity additions of 209.8 GW since 2020[26].

Regionally, the balance between renewable generation growth and electricity demand growth varies considerably (Fig. 1b,c). In the OECD+EU, the increase in renewable generation outpaced demand growth during 2020–2024, with electricity demand in the EU27 even occasionally decreasing, mainly due to weak economic performance[27,28] (Fig. 1b,c). In contrast, demand growth has outpaced renewable generation growth in developing regions of Asia, the Mideast+Africa, and Eastern Europe+Russia (Fig. 1a,b; regional definitions in Supplementary Table 1). Nevertheless, these regions also drove most global renewable expansion, accounting for 66% of the increase in renewable electricity generation (1,440 TWh), led by rapid growth in Asia where renewable generation grew at 10.8% annually.

Sectoral trends reveal the drivers of electricity demand growth (Fig. 1a): industry accounted for 39.6% of demand growth over 2020–2024, with nearly 85% of this increase occurring in Asia (Fig. 1a; Extended Data Figs. 3 and 4). Buildings accounted for a similar 41.5% of demand growth over the period, with strong growth in the Middle East+Africa, Latin America, and Eastern Europe+Russia driven by rising incomes and cooling demand (Fig. 1a; Extended Data Figs. 3 and 4). Transportation accounted for a comparatively small share of global electricity demand growth (6%), but the US, the EU27, and Asia saw rapid growth, signaling an emerging source of demand (Extended Data Fig. 4).

Where electricity demand growth exceeds renewable generation growth, the remainder is supplied by a mix of fossil fuels and other sources. Globally, fossil generation met 42.3% of demand growth over 2020–2024, with coal-based generation accounting for roughly 70% of fossil-based increases (purple and pink bars in Fig. 1a), largely reflecting coal-dominated power plant expansion in Asia (Extended Data Fig. 3). Elsewhere, 75.3% of generation growth in the USA was from natural gas, only 13.1% of generation growth in Latin America was fossil-based, and fossil generation decreased on net across the OECD+EU region (Extended Data Fig. 3).

How does this reality compare to scenarios?

Figure 2 compares recent trends in electricity generation and demand with projections from IPCC AR6 and IEA WEO scenarios. Recent growth rates of renewable generation (7.0%/yr) are lower than what is projected for 2024–2030 in the WEO Current Policies Scenario (8.8%/yr), but these growth rates are well within the range of AR6 1.5°C+2°C scenarios—particularly the C2–C3 categories, which include scenarios returning warming to 1.5°C after a high overshoot

or limiting warming to below 2°C with >67% likelihood—over the same period (Fig. 2a; results by category in Extended Data Fig. 5a,d). Absolute annual growth in renewable generation in these scenarios continues through midcentury (2030–2050), though the projected growth rates moderate as the renewable generation base expands (Fig. 2d).

Similar to renewables, recent growth in global electricity demand is within the range projected in WEO and AR6 1.5°C+2°C scenarios for 2024–2030, although it lies toward the upper end (e.g., 0.5%/yr higher than in the WEO Current Policies Scenario; Fig. 2b,e). Annual absolute increases in electricity demand are larger over the longer term under scenarios with stringent climate mitigation, with recent demand increases (999.6 TWh/yr) falling at the lower end of the C2–C3 scenarios during 2030–2050 (Extended Data Fig. 5b,e). Large long-term uncertainties across mitigation scenarios reflect diverging expectations for electrolysis-based hydrogen production and electric vehicle adoption[29] (Extended Data Figs. 6 and 7).

Even so, the fraction of renewable generation growth over electricity demand growth—representing the share of demand growth met by renewables—in the scenarios is consistently much higher during 2024–2030 than has been the case recently. For example, even in the WEO Current Policies Scenario and at the lower end of AR6 1.5°C+2°C scenarios (e.g., the 25th percentile), renewable generation accounts for >100% of annual increases in electricity demand, compared with 54.2% between 2020 and 2024 (blue bars in Fig. 2g). In the more ambitious WEO Net Zero Emissions by 2050 scenario and the AR6 C1 scenarios that limit warming to 1.5°C with no or limited overshoot, the corresponding fraction during 2024–2030 rises to 175.1% and ~190.6%, respectively (Extended Data Fig. 5g). In turn, these numbers reflect a projected dwindling of demand for fossil generation, which declines in both relative and absolute terms in most of the WEO and AR6 1.5°C+2°C scenarios in the near and longer term (pink bars in Extended Data Fig. 5c,f).

Thresholds for phasing out fossil fuel power

Figure 3 illustrates how growth in electricity demand and renewable generation will shape the future of fossil electricity, emissions, and the need for carbon management. The black squares in each panel show the implication if recent trends (2020–2024) persist for the next 25 years, compared with a range of mitigation scenarios (circles and dots). Although recent demand growth is not drastically more than the average level in mitigation scenarios, the fraction of demand growth over renewable generation growth (i.e., the share of demand growth met by renewables) is substantially lower than in most mitigation scenarios—and too low to allow decreases in fossil generating capacity (Fig. 3a; Extended Data Figs. 8 and 9; Supplementary Fig. 1). Indeed, renewable generation is not yet growing fast enough to avoid increases in fossil capacity, risking carbon lock-in and jeopardizing the goal of the 2023 Global

Stocktake to triple worldwide renewable capacity by 2030 (Supplementary Figs. 2 and 3).

This imbalance defines a transition threshold for reversing fossil capacity expansion (Fig. 3a; Extended Data Figs. 8). Crossing this threshold creates a key opportunity: raising the share of demand growth met by renewables to 112.5% over 2024–2050 would reverse fossil capacity expansion and initiate sustained declines. Faster transitions would further accelerate the phase-down of fossil capacity and bring forward its peak, particularly in developing regions (Extended Data Fig. 9). For example, under the current electricity demand trajectory (i.e., 3.8%/yr), increasing this share to 125% (i.e., average renewable generation growth of 12%/yr over 2024–2030) would bring Asia's peak in fossil capacity to ~2030.

Similarly, recent trends in electricity demand and renewable generation imply increases in committed emissions (i.e., total future emissions expected if existing fossil electricity generators are not prematurely retired or further retrofitted with CCUS after 2050; Fig. 3b). For example, whereas we estimate committed emissions in the WEO Net Zero Emissions by 2050 scenario are 149.6 Gt as of 2024—equivalent to 187% of the remaining carbon budget for 1.5°C[30] (80 Gt at 67% likelihood; Fig. 3b and Extended Data Fig. 10), in reality current committed emissions are over 300 Gt.

Avoiding this level of carbon lock-in requires a more stringent threshold: renewable generation must grow at ~265% of electricity demand growth (i.e., 21%/yr and 8%/yr renewable growth over 2024–2030 and 2030–2050) under the current electricity demand trajectory (i.e., 3.8%/yr), a substantially higher bar than that required to reverse fossil capacity expansion. Given underlying uncertainties of electricity demand (Fig. 2), higher demand growth will require even faster renewable deployment to unlock emissions reductions and avoid additional carbon lock-in. For example, at ~4.5% annual electricity demand growth, keeping fossil committed emissions within the 1.5°C carbon budget would require renewable growth to reach ~240% of demand growth (i.e., 22%/yr and 8%/yr renewable growth over 2024–2030 and 2030–2050).

Further, the magnitude of carbon management that would be needed to compensate for recent demand-renewables trends is large, and adds to the already substantial quantities entailed by mitigation scenarios. For example, 78.9% of AR6 1.5°C+2°C scenarios include cumulative >50 Gt CO_2 of CCUS between 2024 and 2050, an average of ~1.9 Gt/yr (Fig. 3c; Extended Data Fig. 8b), and this requirement could increase by roughly a factor of 6 if current trends persist. Avoiding lock-in to CCUS-reliant power systems therefore requires increasing the share of demand growth met by renewables to 200% (i.e., 17%/yr and 8%/yr renewable growth over 2024–2030 and 2030–2050) could substantially reduce cumulative CCUS deployment in fossil power (to 11.5 Gt CO_2) under 3.8%/yr electricity demand growth, substantially reducing reliance on large-scale carbon management. This is particularly critical given that CCUS has

yet to reach commercial scale[31] and near-term power-sector decarbonization faces substantial pressure[21].

Discussion

Our results show that the decarbonization of electricity systems and phase-out of unabated fossil fuel-based electricity are largely determined by uncertain growth of electricity demand and zero-carbon electricity generation. When additional renewable generation persistently exceeds electricity demand growth, fossil generating capacity and emissions from the electricity sector will peak and decline. In scenarios that meet Paris Agreement goals, renewable generation grows roughly 1.4 times as fast as electricity demand between 2024 and 2050—or even faster failing deployment of ~2 $GtCO_2$/yr of carbon management (Extended Data Fig. 8). Such growth is well-aligned with the COP28 pledge to triple global renewable capacity by 2030, which would mean renewable generation growing 1.75 times as fast as electricity demand 2024–2030 under 3.8%/yr electricity demand growth (i.e., 16%/yr renewable growth; Supplementary Fig. 3).

But as of 2024, annual increases in electricity demand still outpace annual increases in renewable generation, fossil generation continued to grow, and CCUS-equipped electricity generators captured <0.04 Gt CO_2/yr in total[29]. Still-falling costs are a powerful accelerant of renewable electricity deployment if practical barriers of siting, grid integration, transmission, and energy storage can be overcome[13,30], but climate goals may also depend on maximizing the efficiency of electricity use, for example by improving the insulation of electrified buildings, moderating the size and range of electric vehicles, and reducing electrical intensity of electronics and computing systems[31].

Our results are subject to several limitations and caveats that may warrant further analysis in future studies. First, the projections and sensitivity analyses shown in Figure 3 isolate the effects of different renewable generation and demand trajectories by assuming values derived from AR6 1.5°C+2°C and WEO scenarios for fuel shares within fossil generation, nuclear generation trajectories, emission reductions in fossil generation, changes in fossil capacity factors, and the regional allocation of future electricity demand. We systematically tested the sensitivity of fossil capacity, committed emissions, and carbon management to these assumptions (Supplementary Fig. 4; Supplementary Text 1; Supplementary Table 2), and our main conclusions remain robust. For example, committed emissions from fossil power in the WEO Stated Policies Scenario range from 161.6 to 192.2 Gt CO_2 across most sensitivity tests. The only notable deviation arises in the test group assuming substantially different rates of fossil emission reductions (Tests 8–9). Second, we evaluate the effects of different renewable generation and demand trajectories at the regional level rather than the grid level. Although

grid-level analyses would likely improve accuracy, the details of future regional interconnection and power-exchange infrastructure remain highly uncertain. Finally, our framework focuses on annual trajectories of electricity generation and demand, as well as the turnover of fossil plants, but does not resolve intra-annual variations (e.g., hourly variability or operational constraints) due to uncertainties in future conditions and computational limitations.

Despite these methodological caveats, our findings carry important implications for monitoring progress in electricity decarbonization with respect to global climate goals. As overshooting 1.5°C becomes increasingly unavoidable, the rate at which clean energy displaces fossil fuels should become a key metric of decarbonization progress, rather than chasing intangible temperature targets[22]. We reframe decarbonization not as incremental progress toward a long-term target, but as a decisive sufficiency criterion: the fraction of renewable generation growth over electricity demand growth. Recognizing the dynamic nature of global electricity, this provides a dynamic framework to track whether growth in renewable electricity is sufficient to enable the phase-out of fossil power generation. The degree to which this fraction needs to exceed 100% depends on climate ambition, the growth of other zero-carbon electricity sources, and the scale of carbon management, but there is little doubt that decarbonization of the electricity sector and phase-out of fossil generation is predicated on renewables substantially outstripping demand in the near-term and through mid-century.

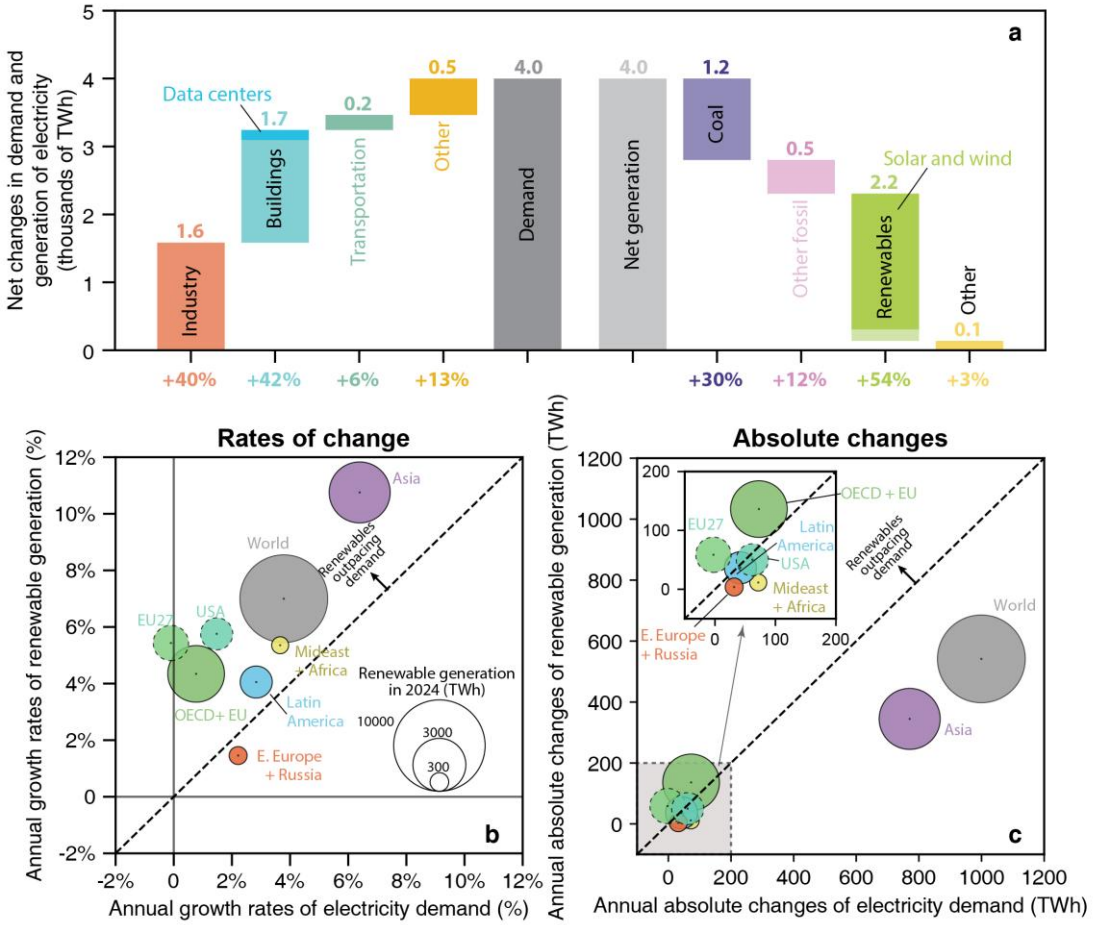


Figure 1 | Trends in electricity demand and electricity generation 2020–2024. Bars in panel (a) show changes in sectoral electricity demand as well as electricity generation by technology over 2020–2024. Annual growth rates (b) and absolute changes (c) in renewable generation and electricity demand globally and regionally over 2020–2024. The size of bubbles in panels (b) and (c) indicate each regions' renewable generation in 2024. Net generation excludes transmission and distribution losses as well as statistical discrepancies to ensure consistency with electricity demand. Electricity demand from energy transformation is included in the "Other" sector.

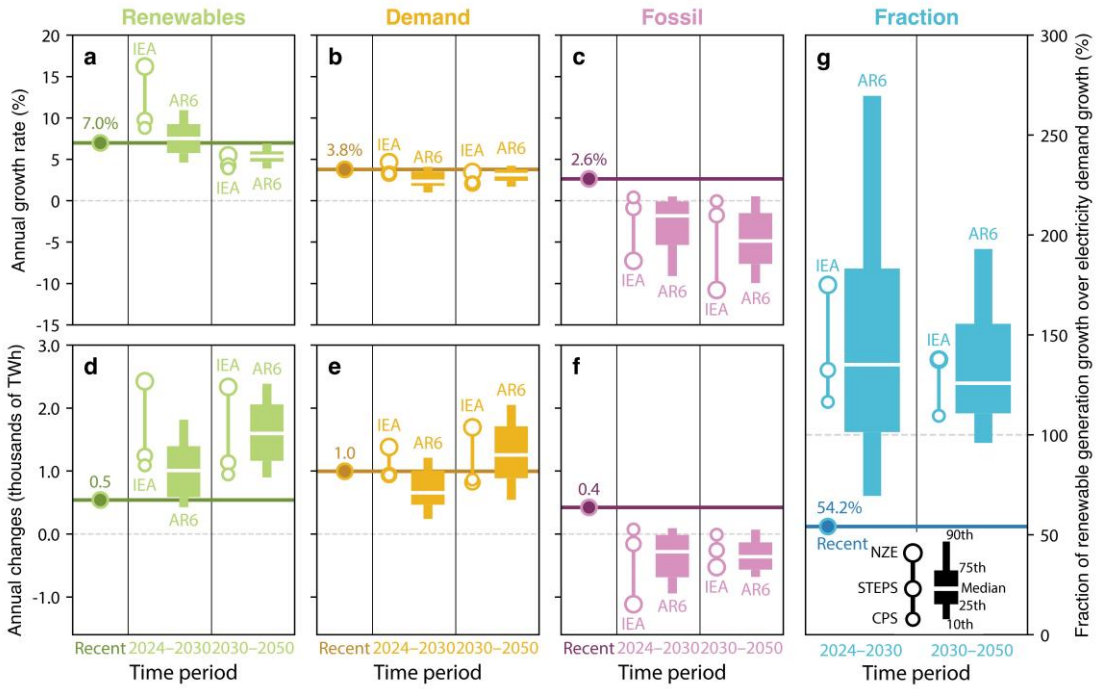


Figure 2 | Trends in renewable generation, electricity demand, and fossil fuel generation across the recent period (2020–2024), 2024–2030, and 2030–2050. Annual growth rates (a–c) and absolute changes (d–f) in renewable generation (in green), electricity demand (in yellow) and fossil generation (in pink). Panel (g) shows the fraction of renewable generation growth over electricity demand growth (in blue). In each panel, the solid circle and horizontal line denote recent trends and reference projections, assuming recent trends persist. The smaller, medium, and larger hollow circles the WEO-projection of the Current Policies Scenario (CPS), the Stated Policies Scenario (STEPS) and the Net Zero Emissions by 2050 Scenario (NZE). The boxes show the range from the 25th to 75th percentiles during 2024–2030 and 2030–2050 projected by 1.5°C+2°C scenarios from AR6 Scenarios Database; the whiskers show the 10th and 90th percentiles; the lines show the median values.

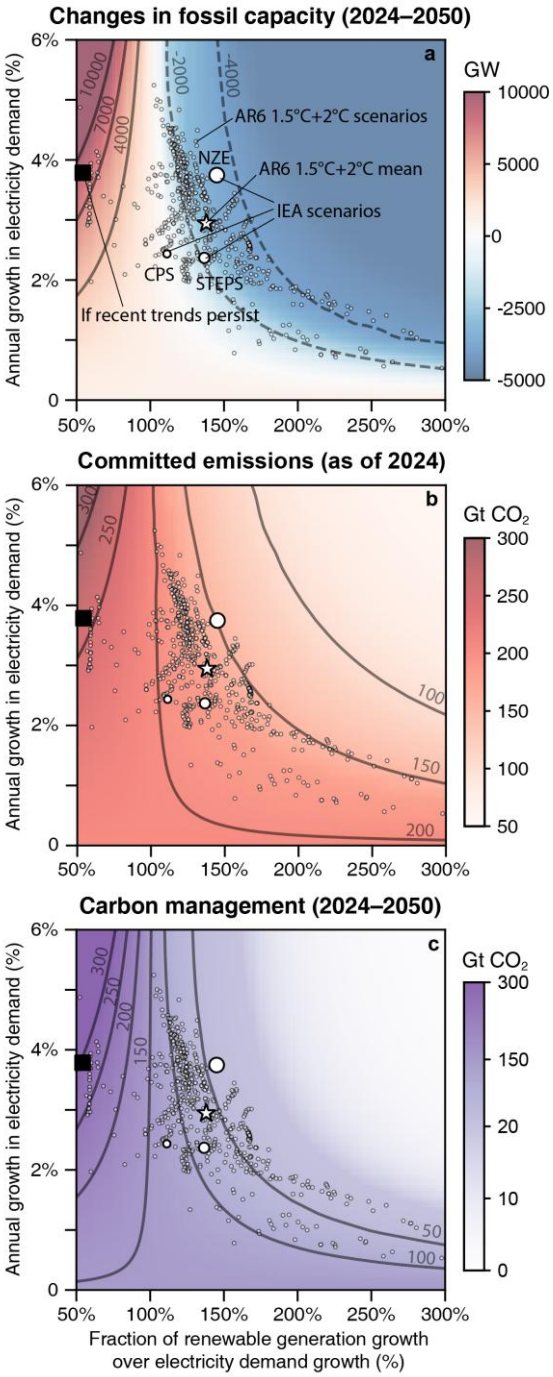


Figure 3 | How electricity demand growth and fraction of renewable generation growth over electricity demand growth shape fossil power fleets by 2050. Changes in total capacity by 2050 (a), committed emissions as of 2024 (b) and total CCUS deployment by 2050 (c) across different rates of electricity demand growth and fraction of new demand met by renewables. In each panel, circles denote the WEO-projected electricity demand and renewable growth of the Current Policies Scenario (CPS), the Stated Policies Scenario (STEPS) and the Net Zero Emissions by 2050 Scenario (NZE) over 2024–2050. Squares denote the recent demand and renewable growth during 2020–2024, assuming recent trends persist. Stars and dots represent the ensemble mean and individual projections of electricity demand and renewable growth across the AR6 1.5°C+2°C mitigation scenarios over 2024–2050, respectively.

Method

In this study, we develop a data-driven complement to energy–emissions models that integrates recent trends with future projections, and conduct sensitivity analyses to assess how electricity demand and renewable generation dynamics are forestalling phase-out of fossil generation (Extended Data Fig. 1).

Specifically, recent trends are derived from the fusion of IEA World Energy Balances (WEB; https://www.iea.org/data-and-statistics/data-product/world-energy-balances)[23], the Ember global energy think tank (Ember; https://ember-energy.org/data/#datasets)[34] and the latest IEA World Energy Outlook (WEO; https://www.iea.org/reports/world-energy-outlook-2025)[21] to compare renewable generation expansion with electricity demand growth in the post-COVID period (i.e., 2020–2024), providing a consistent basis for assessing their evolving balance. Scenario-based projections of future power-sector trajectories are drawn from the IPCC AR6 Scenarios Database (https://data.ece.iiasa.ac.at/ar6/)[18] and the WEO to benchmark recent power-sector trajectories against climate mitigation requirements over the short term (2024–2030) and the long term (2030–2050). This comparison enables us to identify the hinge point at which renewable generation fully meets incremental electricity demand and subsequently reshapes the overall supply structure of the power system.

Given the uncertainty and governing role of renewable generation and electricity demand growth in shaping the future of fossil power, we conduct sensitivity analyses using a unit-by-unit transition algorithm based on the Global Power plant Emissions Database (GPED)[24,25] updated in this study. This unit-level framework simulates the turnover of fossil generation capacity through unit-level construction and retirement dynamics, and tracks the resulting implications for emissions trajectories and CCUS deployment. By varying combinations of future electricity demand growth and renewable generation expansion, we assess how these interacting dynamics shape decarbonization pathways for fossil power.

Recent trends

Region- and sector-specific electricity demand and technology-specific electricity generation for the period 2020–2024 are derived from the WEB 2025 edition[23], Ember[34] and WEO 2025[21]. The WEB provides a standardized database of energy balance tables covering 156 countries and 35 regional aggregates worldwide from 1960 to 2023, which is widely recognized as an essential tool for emission inventories and energy system management[35–37]. To generate recent trends for the period 2020–2023, we aggregate detailed fuel categories of electricity generation into technology types (Supplementary Table 3), extract sectoral electricity demand from specific energy flows (Supplementary Table 4), and aggregate country-level results to the regional level using a country-to-region mapping (Supplementary Table 1). For 2024,

electricity generation and demand are scaled from 2023 values using growth rates calculated from WEO 2025 and Ember, respectively. Electricity demand for data centers during 2020–2024 is obtained from the IEA Energy and AI report[38] to account for emerging demand that is not explicitly separated in the building sector. Electricity generation is adjusted to net generation at the regional level to ensure consistency with electricity demand.

Scenario-based projections

Scenario-based projections of electricity demand and generation growth over the short term (2024–2030) and the long term (2030–2050) are derived from the AR6 Scenarios Database[18] and the WEO 2025[21]. The AR6 Scenarios Database is widely used to characterize the diversity and uncertainty in future electricity decarbonization pathways, as it compiles scenarios from multiple integrated assessment models (IAMs) with different methodologies, technology options, and parameterizations[3,39–41]. Scenarios consistent with the 1.5°C and 2°C climate targets (categories C1–C4) are extracted from the AR6 Scenarios Database. These categories represent mitigation pathways limiting warming to 1.5°C with little or no overshoot (C1), returning warming to 1.5°C after a high overshoot (C2), limiting warming to 2°C with >67% likelihood (C3), and limiting warming to 2°C with >50% likelihood (C4). To characterize uncertainty in future trajectories, we group these scenarios into three sets (i.e., C1, C2+C3 and C4), because C2 and C3 exhibit similar mitigation characteristics before mid-century. Additionally, we incorporate projections from WEO 2025, which utilizes the Global Energy and Climate Model based on updated data to better capture emerging trends. We select the Current Policies Scenario (CPS), Stated Policies Scenario (STEPS), and Net Zero Emissions by 2050 Scenario (NZE), representing different opportunities and challenges in the future. As WEO 2025 reports projections for 2024, 2035, 2040, and 2050, values for 2030 are obtained by linear interpolation for near-term analysis.

Electricity generation by technology and sectoral electricity demand for industry, transport, and buildings are directly obtained from the above databases. Beyond end-use sectors, hydrogen production is projected to emerge as a growing electricity load[42,43]. Electricity demand for hydrogen production is estimated based on the hydrogen output from different technologies (Supplementary Text 2).

Sensitivity analyses of power-sector transition dynamics

Sensitivity analyses are designed to explore power-sector transition dynamics across a wide range of plausible growth trajectories for renewable generation and electricity demand. Building on these assumptions, we construct a unit-level turnover model for fossil-fired power plants that integrates unit-level technical attributes, and emissions information. This framework enables a systematic assessment of potential capacity evolution, future emissions, and CCUS

deployment in fossil generation.

Sensitivity test design. To comprehensively capture how future renewable generation and electricity demand growth govern the pace of fossil power transition, we design a structured grid of sensitivity tests across a broad range of renewable generation and electricity demand growth rates. According to the WEO and AR6 1.5°C+2°C scenarios, plausible annual growth rates of electricity demand during 2024–2050 span 2.7–8.9%, and the fraction of renewable generation growth over electricity demand growth spans 52.4–338.7%. In light of these uncertainty ranges and the potential for unforeseen growth drivers, we conduct a series of sensitivity tests across electricity demand growth rates and the fraction of renewable generation growth over electricity demand growth of 0–6%/yr and 50–300% during 2024–2050, using step sizes of 0.5%/yr and 12.5%, respectively.

The AR6 Scenarios Database is used to characterize regional shares of electricity demand across the five major regions[18] (Supplementary Table 1). For each region, we construct projections of electricity demand by taking the median values across the AR6 1.5°C+2°C scenario ensemble (categories C1–C4; hereafter referred to as the AR6 median projections). These projections, originally provided at 5-year intervals, are interpolated to an annual resolution using linear interpolation, after which they are harmonized to the 2024 values based on recent trends. For each assumed demand growth rate in the sensitivity tests, we first compute the global electricity demand trajectories by applying a constant growth rate, and then reconstruct annual regional demand trajectories by scaling global demand using the regional demand shares in the AR6 median projections.

Absolute renewable generation is projected based on the annual increase in electricity demand and the assumed fraction of renewable generation growth over electricity demand growth in the sensitivity tests. Regional renewable generation trajectories are then estimated using a similar method to that used for demand to preserve region-specific growth patterns. To exclude the impact of future nuclear deployment, we fix regional nuclear-generation trajectories using the AR6 median projections, harmonized to the 2024 values based on recent trends (Supplementary Table 5). When projected renewable generation in a given region exceeds residual electricity demand after accounting for nuclear generation, renewable output is capped at the level of electricity demand minus nuclear generation. To further disaggregate regional renewable generation into individual technologies, we allocate the region-level renewable trajectories to each technology using the annual technology-specific generation shares in the AR6 median projections (Supplementary Table 6), as follows:

$$RE_{r,t,y,sens} = RE_{r,y,sens} * S_{r,t,y,RE,AR6} \quad (1)$$

where $RE_{r,t,y,sens}$ represents the generation of renewable technology t (solar, wind, hydro, geothermal, or biomass) in region r, year y, under a specific sensitivity test; $RE_{r,y,sens}$ represents total renewable electricity generation in region r and year y under the same sensitivity test; $S_{r,t,y,RE,AR6}$ is the share of technology t in total renewable generation in region r, year y derived from the interpolated AR6 median projections.

For each region, fossil generation is obtained as the residual between total electricity demand and the sum of renewable and nuclear generation, which is then allocated to individual technologies using their annual generation shares from the AR6 median projections (Supplementary Table 7).

Unit-level information collection. To simulate the turnover of fossil power plants over 2024–2050, we update our previously developed unit-level emissions database of global fossil power plants from 2019 to 2024 and compile technical and emission attributes for generating units. Specifically, we update GPED v1.1[25] by integrating multiple versions of the World Electric Power Plants (WEPP) database[44] and data from Global Energy Monitor (GEM)[45,46]. This integration incorporates information on plant location, fuel type, installed capacity, operational status, commissioning year, and retirement year for global power-generating units commissioned after 2019. For China, the United States, and India, localized databases with more comprehensive and reliable data are combined and harmonized to enhance data quality[47–51].

For units without emissions records, emissions are estimated as the product of unit-level fuel consumption and fuel-specific emission factors, following the methodology of our previous study[25]. Unit-level electricity generation and fuel consumption are inferred by downscaling country-level generation and fuel consumption based on installed capacity, operational status, operating hours, and technology-specific efficiencies. Fuel-specific CO_2 emission factors are derived from IPCC guidelines using fuel carbon content, oxidation factors, and heating values.

Using the updated GPED, we extract unit-level technical attributes (i.e., installed capacity, fuel consumption, electricity generation, and age) and emissions for over 4,000 GW of global fossil-fuel power plants (coal, gas, and oil) in 2024 to drive the turnover simulations. We then harmonize these plant-level data with the WEB database to reconcile discrepancies between the two data sources. An overview of the dataset is provided in Supplementary Fig. 5.

Unit-level turnover model. To quantify the influence of renewable deployment and electricity demand growth on fossil power capacity, future emissions, and CCUS deployment, we develop a unit-level turnover model for fossil-fired power units. The model is driven by region- and fuel-specific trajectories of fossil power demand aligned with sensitivity tests based

on assumed global electricity demand growth rates and fraction of renewable generation growth over electricity demand growth.

The model begins by simulating fossil power capacity dynamics. For each region, facility type, and year, the algorithm evaluates the generation capability of the existing fleet based on the technical attributes (e.g., installed capacity and capacity factors) of in-fleet units. Capacity factors are assumed to change over time, following the change rates implied by the AR6 median projections, to reflect the increasing flexibility requirements associated with expanding variable renewable energy. If existing units are insufficient to meet the regional electricity demand, new units with advanced efficiency are commissioned to bridge the generation gap. Conversely, if generation capability exceeds demand, the oldest units are prioritized for retirement to maintain the generation–demand balance. Therefore, capacity changes in fossil technologies are taken directly from outputs of the model, whereas those in renewable technologies are estimated following the procedures described in Supplementary Text 3.

We then model unabated CO_2 emissions (i.e., emissions before CO_2 capture) from both existing and new units. For existing units, energy efficiency (i.e., energy consumption per unit of electricity generation) and CO_2 emission factors are assumed to remain constant. Unabated emissions are therefore determined directly by changes in their capacity factors, as follows:

$$UE_{i,y,sens} = UE_{i,y-1,sens} \times \frac{CF_{i,y,sens}}{CF_{i,y-1,sens}} \quad (2)$$

where $UE_{i,y,sens}$ denotes unabated CO_2 emissions of existing unit i in year y under a given sensitivity test; $CF_{i,y,\mathrm{sens}}$ represents the corresponding capacity factor; and $UE_{i,y-1,sens}$ and $CF_{i,y-1,sens}$ are the unabated emissions and capacity factor of the same unit in the previous year, respectively.

For new units, we use regional average CO_2 emission factors from the GPED dataset and assume advanced energy consumption intensity, defined as the 25th percentile of energy consumption per unit of electricity generation for each fuel type. Unabated CO_2 emissions are then estimated based on electricity generation, energy consumption intensity, and emission factors, as follows:

$$UE_{i,y,sens} = Generation_{i,y,sens} \times Eff_{f,r} \times EF_{f,r} \quad (3)$$

where f denotes fossil fuel types (coal, gas, or oil); $UE_{i,y,sens}$ represents unabated CO_2 emissions of new unit i in year y under a given sensitivity test; $Generation_{i,y,\mathrm{sens}}$ is its electricity generation; $Eff_{f,r}$ denotes the assumed advanced energy consumption intensity for fuel type f in region r; and $EF_{f,r}$ is the corresponding regional CO_2 emission factor derived from the GPED dataset.

A CCUS retrofitting module is developed to simulate carbon management in fossil-fired

power units. Projected emission-reduction rates for each fossil fuel type are first derived from the average emission trajectories of the WEO Net Zero Emissions by 2050 Scenario and Announced Pledges Scenario[52], and used as external emission constraints within the module. For each fuel type and region, when reductions in unabated emissions cannot meet the prescribed emission-reduction rates, CCUS deployment is triggered to bring emissions back in line with these constraints. CCUS installations are prioritized for newer units, given their substantial capital and O&M costs. Following prior studies, we set the maximum CO_2 capture rate of CCUS-equipped units at 90%[53,54]. Retrofitted units are further assumed to incur a 15% increase in energy consumption and consequently higher CO_2 emissions.

The committed emissions for each sensitivity test are used to characterize the tension between shrinking carbon budgets and future CO_2 emissions from global fossil power units. This metric is defined as the sum of (i) projected emissions from fossil power units over 2024–2050 and (ii) future emissions from power units still operating in 2050, assuming that their emissions in 2050 remain constant over their expected remaining operating lifetimes. The metric is calculated as follows:

$$CE_{sens} = \sum_{i} \left(\sum_{y=y_0}^{2050} (E_{i,y,sens}) \right) + \sum_{i \in I_{2050}} \left(E_{i,2050,sens} * (LT - Age_{i,2050,sens}) \right) \quad (4)$$

where CE_{sens} represents the committed emissions under a given sensitivity test. $E_{i,y}$ represents the annual emissions of a specific unit i in year y. I_{2050} represents the set of power units still operating in 2050. $Age_{i,2050}$ represents the operating age of an individual unit in 2050, and LT is the assumed economic lifetime of 40 years.

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Data availability

The historical electricity generation and demand are from IEA WEB (https://www.iea.org/data-and-statistics/data-product/world-energy-balances) and Ember global energy think tank (https://ember-energy.org/data/#datasets). Scenario-based projections of future power-sector trajectories are from the IPCC AR6 Scenarios Database (https://data.ece.iiasa.ac.at/ar6/) and IEA WEO (https://www.iea.org/reports/world-energy-outlook-2025). The technology-specific unit cost data are compiled from the NREL 2024 ATB (https://atb.nrel.gov/electricity/2024/references). The facility-level data on technical attributes and emissions for global fossil-fuel power plants are from GPED of Global Infrastructure emission Detector (GID, http://gidmodel.org.cn/).

Code availability

The code for the data-driven complement to energy-emissions model developed in this study is available at https://github.com/yanxzh/Unit-level-Turnover-Model/.

Acknowledgments

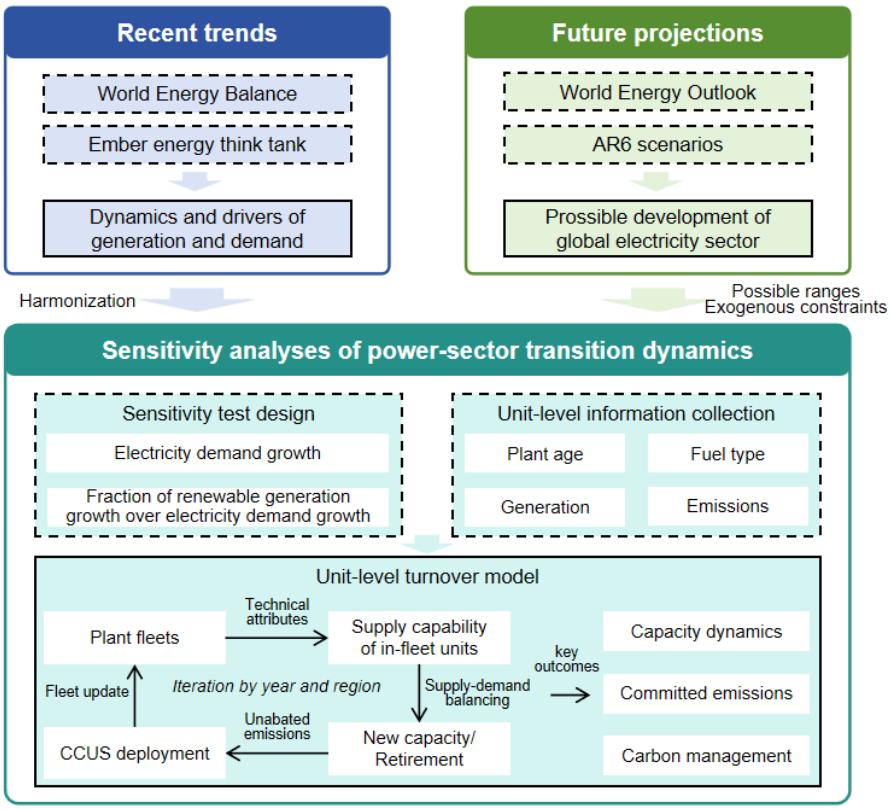
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Author contributions

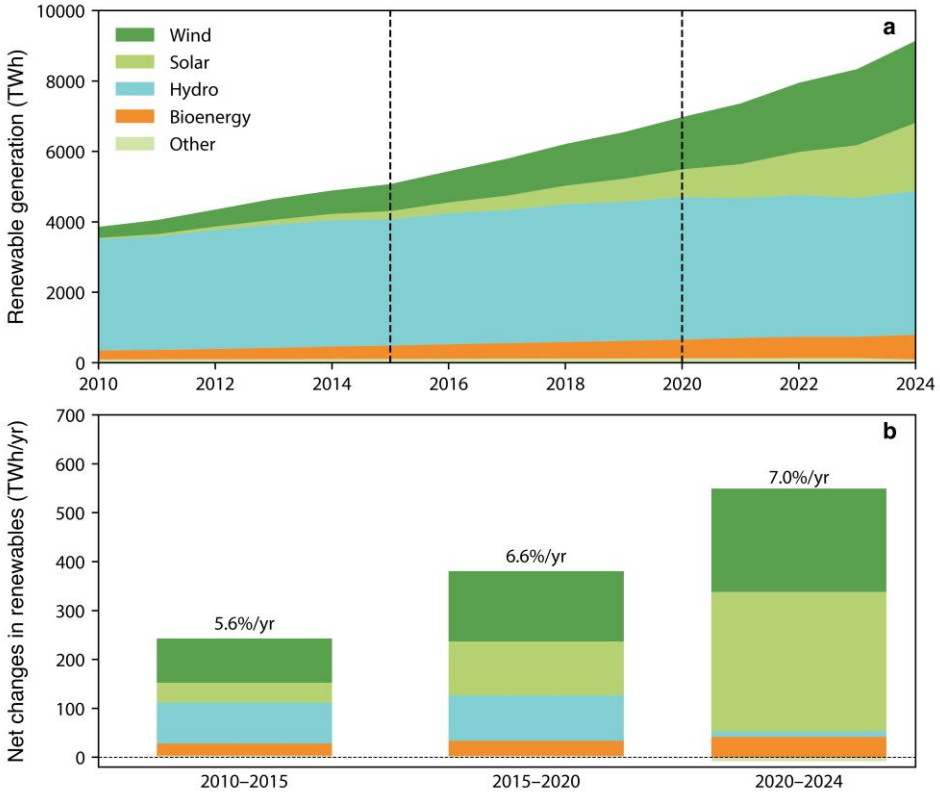
D.T., S.J.D. and Q.Z. designed the study. X.Y. and X.X. performed the simulations, D.T., X.Y. and X.X. performed the analyses, with support from Q.Z., S.J.D., J.R., J.C., D.G. and K.H. on analytical approaches. D.T., S.J.D. and X.Y. interpreted the results. X.Y. and X.X. prepared the figures. D.T., S.J.D. and X.Y. led the writing with inputs from all coauthors.

Competing interests

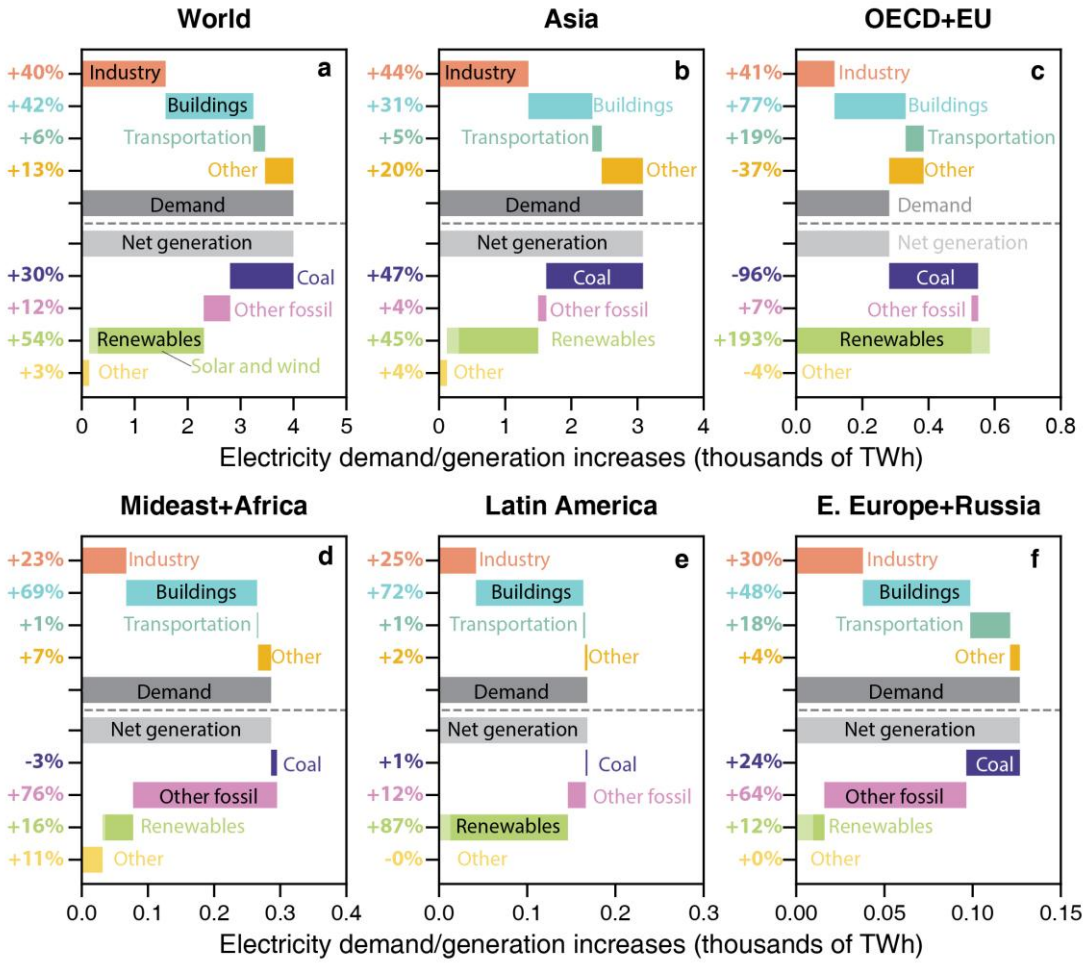
The authors declare no competing interests.



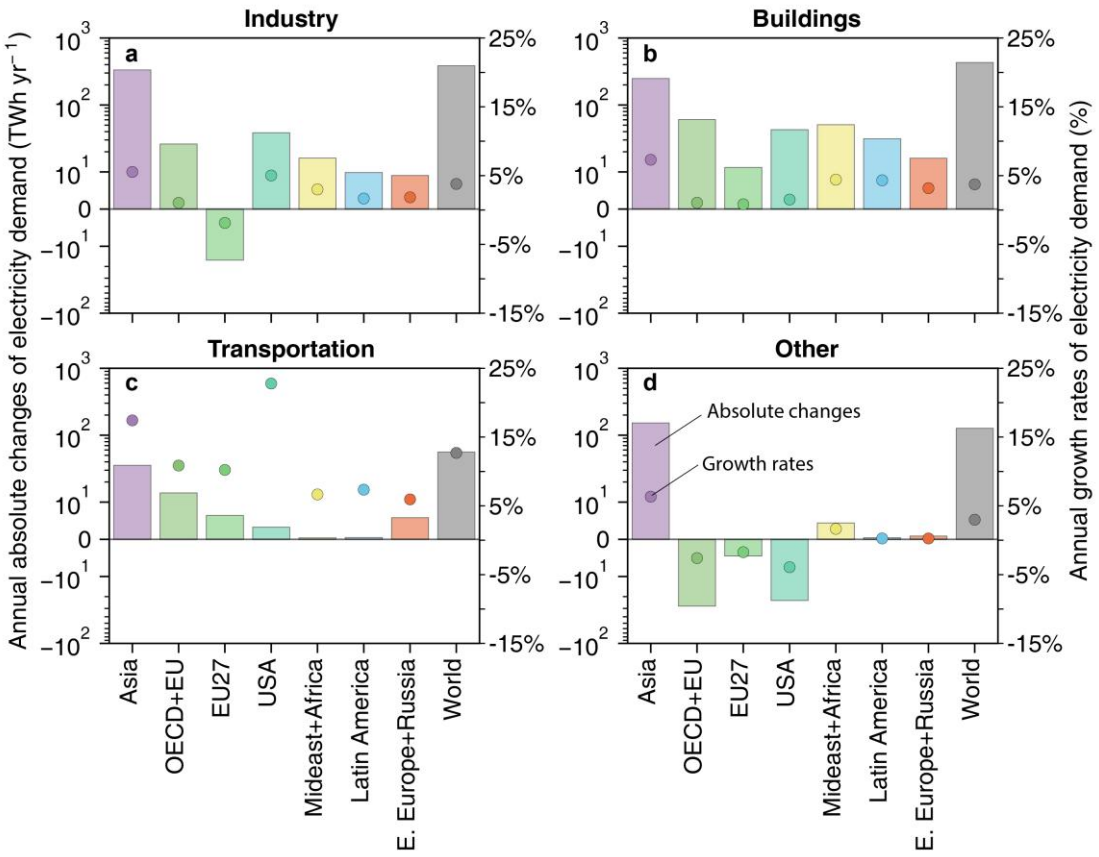
Extended Data Fig. 1 | Framework for analyzing how growth in electricity demand and renewable generation is forestalling phase-out of fossil generation.



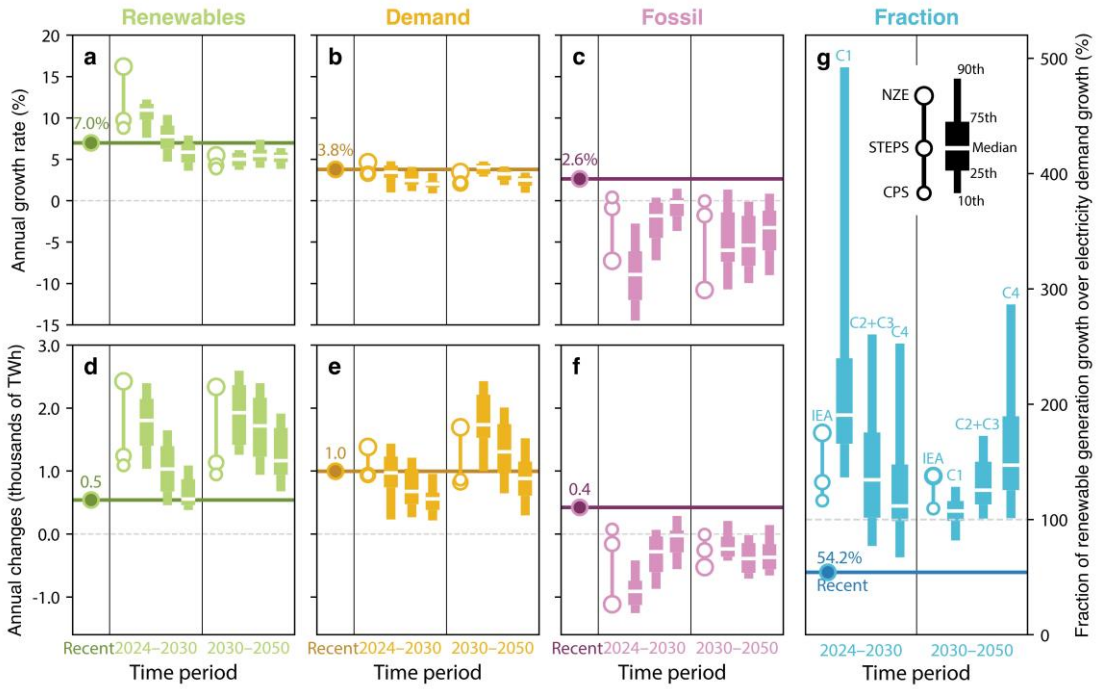
Extended Data Fig. 2 | Comparison of renewable electricity generation trends across periods of 2010–2015, 2015–2020, and 2020–2024. Stacked plot (a) shows changes in renewable electricity generation by technology over 2010–2024. Bars (b) show the growth of renewable generation during across the three periods.



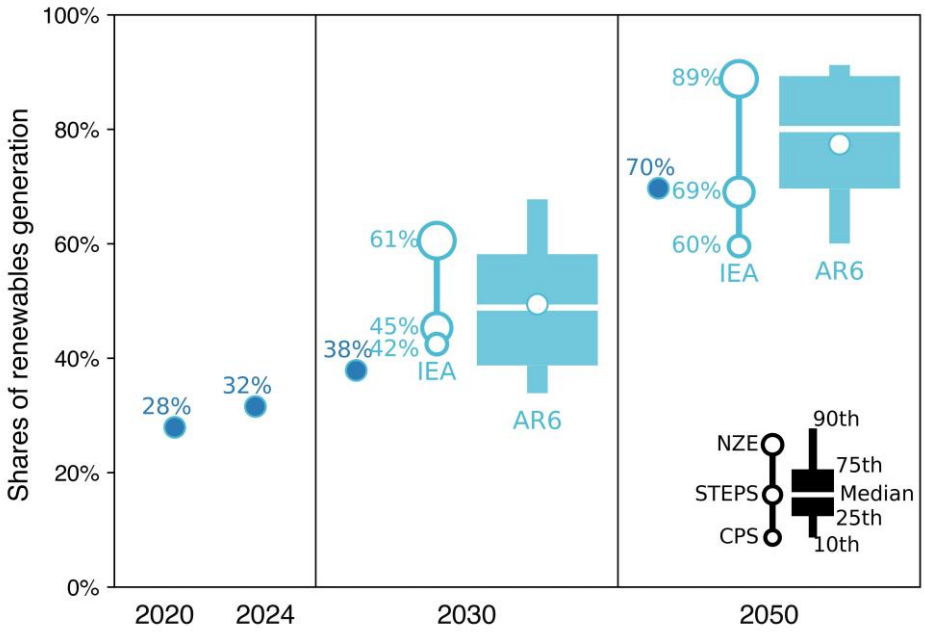
Extended Data Fig. 3 | Trends in electricity demand and electricity generation 2020–2024. Bars in each panel show changes in sectoral electricity demand as well as electricity generation by technology over 2020–2024. Net generation excludes transmission and distribution losses as well as statistical discrepancies to ensure consistency with electricity demand. Electricity demand from energy transformation is included in the "Other" sector.



Extended Data Fig. 4 | Trends in electricity demand by sectors during 2020–2024. Panels (a–d) correspond to industry (a), buildings (b), transportation (c) and other (d), respectively. In each panel, bars show annual absolute changes in sectoral electricity demand, while dots show the annual growth rates.



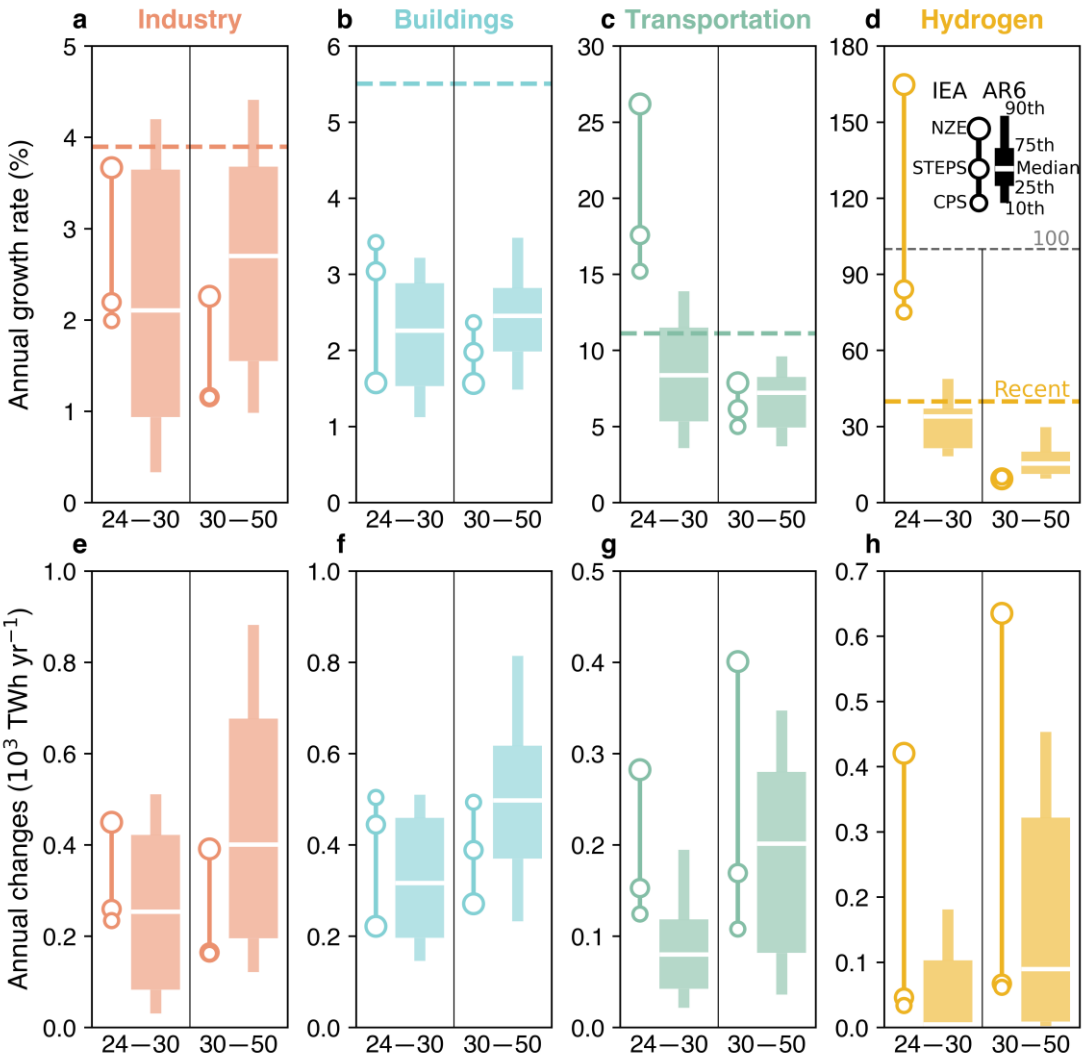
Extended Data Fig. 5 | Trends in renewable generation, electricity demand, and fossil fuel generation across the recent historical period (2020–2024), 2024–2030, and 2030–2050. Annual growth rates (a–c) and absolute changes (d–f) in renewable generation (in green), electricity demand (in yellow) and fossil generation (in pink). Panel (g) shows the fraction of renewable generation growth over electricity demand growth (in blue). In each panel, the solid circle and horizontal line denote recent trends and reference projections, assuming recent trends persist. The smaller, medium, and larger hollow circles the WEO-projection of the Current Policies Scenario (CPS), the Stated Policies Scenario (STEPS) and the Net Zero Emissions by 2050 Scenario (NZE). The boxes show the range from the 25th to 75th percentiles during 2024–2030 and 2030–2050 projected by C1, C2+C2 and C4 categories from AR6 Scenarios Database; the whiskers show the 10th and 90th percentiles; the lines show the median values.



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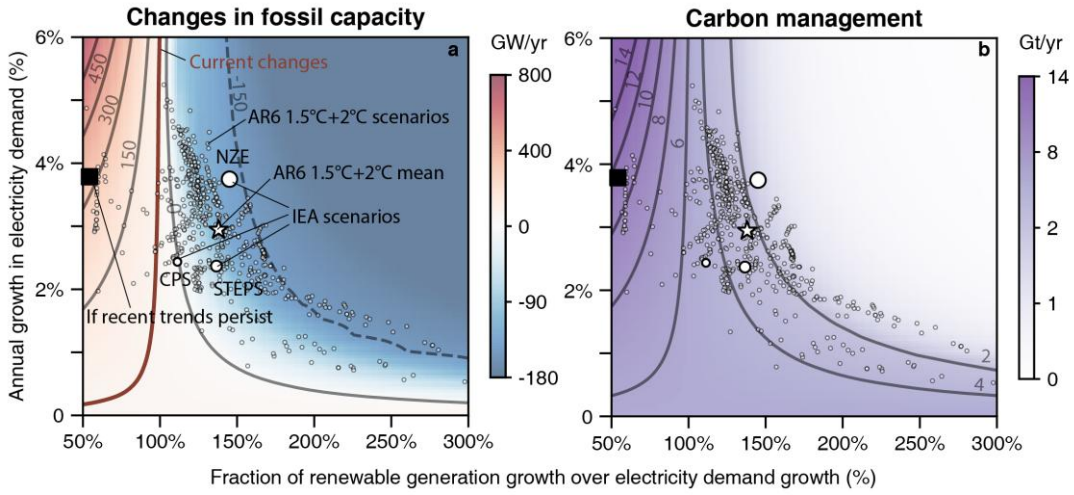
632 **Extended Data Fig. 6 | The shares of renewable generation in total electricity generation.**
633 The solid circles denote the current data and reference projections assuming recent trends
634 persist, based on recent growth rates in renewable energy and total electricity generation over
635 2024–2030. The smaller, medium and larger hollow circles the WEO-projections under the
636 Current Policies Scenario (CPS), the Stated Policies Scenario (STEPS) and the Net Zero
637 Emissions by 2050 Scenario (NZE), respectively. Boxes show the range from the 25th to 75th
638 percentiles in 2030 and 2050 projected by 1.5°C+2°C scenarios from AR6 Scenarios Database;
639 whiskers show the 10th and 90th percentiles; lines and scatters show the median and average
640 values, respectively.

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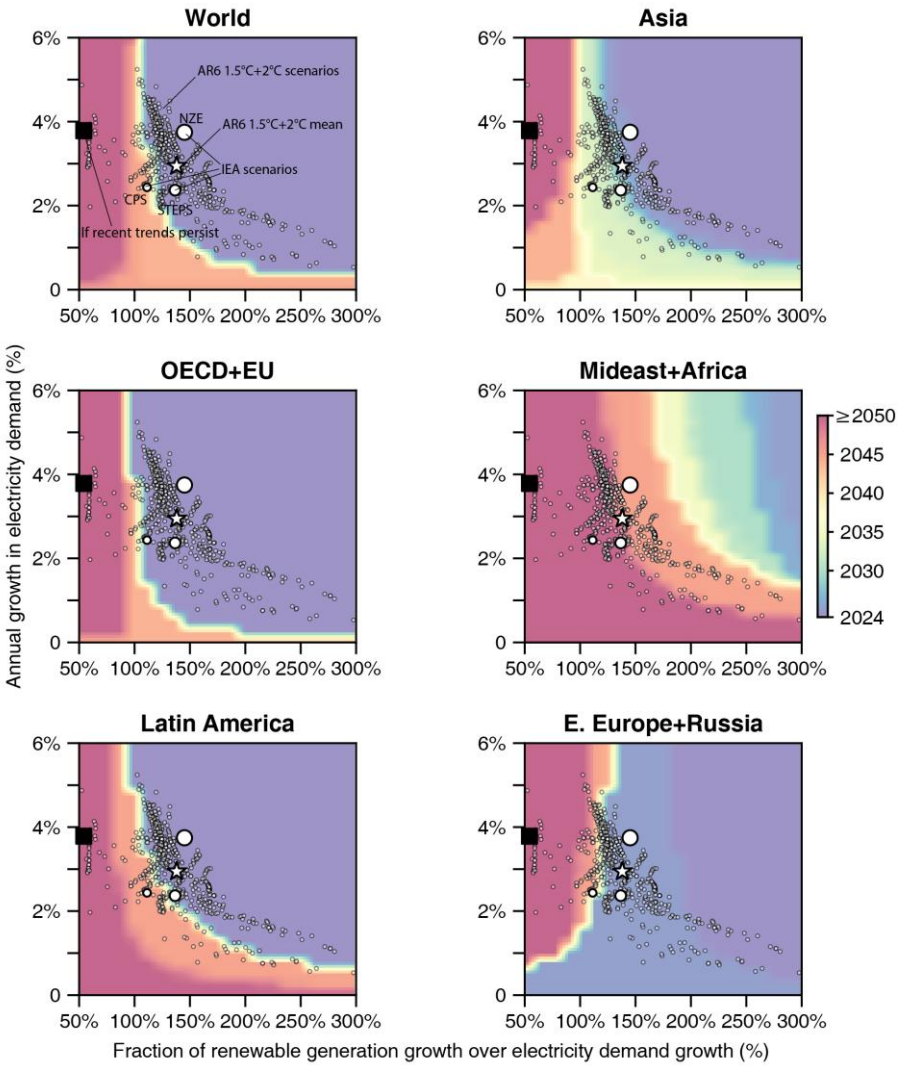


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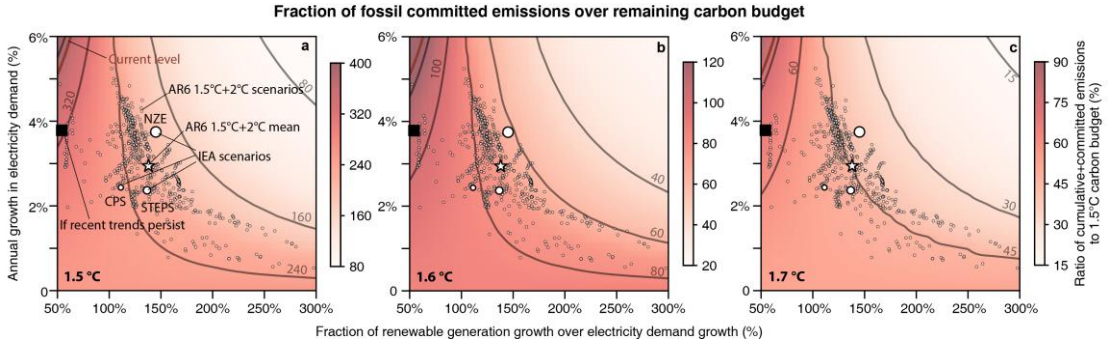
643 **Extended Data Fig. 7 | Electricity demand trends across different sectors during 2024–**
644 **2030 (left) and 2030–2050 (right), including industry, buildings, transportation, and**
645 **hydrogen production.** (a–d) demonstrate the average annual growth rate, while (e–h) show the
646 annual absolute changes. In each panel, the horizontal dashed lines denote recent trends. The
647 smaller, medium, and larger hollow circles the WEO-projection of the Current Policies
648 Scenario (CPS), the Stated Policies Scenario (STEPS) and the Net Zero Emissions by 2050
649 Scenario (NZE). The boxes show the range from the 25th to 75th percentiles during 2024–2030
650 and 2030–2050 projected by 1.5°C+2°C scenarios from AR6 datasets; the whiskers show the
651 10th and 90th percentiles; the lines show the media values.



Extended Data Fig. 8 | How electricity demand growth and fraction of renewable generation growth over electricity demand growth shape fossil power fleets by 2050. Annual average changes in fossil capacity (a) and CCUS deployment (b) by 2050 across different rates of electricity demand growth and fraction of renewable generation growth over electricity demand growth. In each panel, circles denote the WEO-projected electricity demand and renewable growth of the Current Policies Scenario (CPS), the Stated Policies Scenario (STEPS) and the Net Zero Emissions by 2050 Scenario (NZE) over 2024–2050. Squares denote the recent demand and renewable growth during 2020–2024, assuming recent trends persist. Stars and dots represent the ensemble mean and individual projections of electricity demand and renewable growth across the AR6 1.5°C+2°C mitigation scenarios over 2024–2050, respectively. Red line in (a) represents the recent changes of global fossil capacity.



Extended Data Fig. 9 | How electricity demand growth and fraction of renewable generation growth over electricity demand growth shape the timing of the peak in global fossil power capacity over 2024–2050. In each panel, circles denote the WEO-projected electricity demand and renewable growth of the Current Policies Scenario (CPS), the Stated Policies Scenario (STEPS) and the Net Zero Emissions by 2050 Scenario (NZE) over 2024–2050. Squares denote the recent demand and renewable growth during 2020–2024, assuming recent trends persist. Stars and dots represent the ensemble mean and individual projections of electricity demand and renewable growth across the AR6 1.5°C+2°C mitigation scenarios over 2024–2050, respectively.



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676 **Extended Data Fig. 10 | How electricity demand growth and fraction of renewable**
677 **generation growth over electricity demand growth shape the climate risks of fossil power**
678 **fleets by 2050.** Colors represent the fraction of fossil committed emissions over remaining
679 carbon budget[30] for 1.5°C (a), 1.6°C (b), and 1.7°C (c), respectively. Circles denote the WEO-
680 projected electricity demand and renewable growth of the Current Policies Scenario (CPS), the
681 Stated Policies Scenario (STEPS), and the Net Zero Emissions by 2050 Scenario (NZE) over
682 2024–2050. Squares denote the recent demand and renewable growth during 2020–2024,
683 assuming recent trends persist. Stars and dots represent the ensemble mean and individual
684 projections of electricity demand and renewable growth across the AR6 1.5°C+2°C mitigation
685 scenarios over 2024–2050, respectively. Red lines represent the ratio of committed emissions
686 from existing fossil power plants in 2024 to the 1.5°C carbon budget.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- 2.SIElectricityImbalance0322.pdf