Transforming China's Power Systems To Facilitate Carbon Reductions

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Article

Keywords:

Posted Date: February 21st, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1278252/v1

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In order to fulfill China's commitment to reaching the carbon peak by 2030 and carbon neutrality by 2060, it is crucial to reduce carbon emissions from its power systems, especially from coal-fired power generation. Here we examine how China's electricity generation mix, i.e., the share of electricity generated by different types of power sources, can be reformed to maximize carbon reductions. We use China's national development in the SSP5 scenario (a specific scenario of Shared Socio-Economic Pathways) from the Global Change Analysis Model (GCAM) as the base scenario and recalculate SSP5's electricity sector. We calculate the generation mix of six regional power grids, under the constraint of frequency stability, to find out the national minimum share of coal-fired power and corresponding carbon emissions, and then develop a carbon reduction pathway. We observe that under the base scenario, China could achieve carbon neutrality by 2060 with the contribution of adjusting the generation mix and significantly reducing the share of coal-fired generation. If other appropriate strategies are adopted, such as optimizing the structure of transmission networks and promoting energy storage, China's power systems are well positioned to completely drop coal by 2100 and China can achieve carbon peak and neutrality more quickly.

Electricity production is a major source of carbon emissions from energy production and consumption system, and is also one of the root causes of the global carbon crisis[1]. The full electrification of industry, construction, transportation, and other sectors in the future, for example, the rapid development of electric vehicles, will considerably boost electricity consumption[2]. The development strategy of the power sector is therefore central to addressing the carbon issue. Coal-fired power generation not only depletes fossil fuel supplies, but also produces harmful pollutants including SO_2 and NO_x along with enormous CO_2, leading to acid rain and climate warming[3-5]. As a result, it is necessary and urgent to reduce the share of coal-fired power generation in the electricity generation mix.

Carbon capture, utilization and storage (CCUS) technologies can convert CO_2 generated by coal-fired power into useable resources[6], for example by producing synthetic biodegradable plastics and mineralization[7]. In addition, carbon sinks can absorb CO_2 from the atmosphere through measures such as afforestation and revegetation[8]. But as industrialization continues and urban land becomes scarce, the planning of large-scale green space is challenging for urban construction[9]. In the power sector, the vigorous development of fluctuating renewable energy generation (wind and solar power) has become one of the quickest and most effective ways to reduce carbon emissions. Solar panels on building roofs, for example, can make full use of construction land to promote local renewables.

China is a key country to investigate when it comes to development strategies of power system and carbon concerns. On the one hand, it is currently the greatest producer and consumer of electricity, as well as the top carbon emitter in the world, and its electricity production accounts for roughly half of China's overall carbon emissions[10-12]. On the other hand, China has recently proposed a series of policies to overhaul its energy mix[13-15], demonstrating unprecedented determination to reduce carbon emissions. China's President Xi Jinping announced in the 75th Session of the UN General Assembly in 2020 that China will aim to have CO_2 emissions peak before 2030 and strive for carbon neutrality before 2060[16]. Thus, managing the share of coal-fired power and adjusting the generation mix have become the key challenge for China to realize the decarbonisation ambition.

It should also be noted, however, that coal-fired power, as a continuous and stable power source, can provide "inertia" to the power grid apart from power. It means, when grid frequency fluctuates, coal-fired generating units can automatically release the rotational kinetic energy of the generator to stabilize the frequency[17]. By contrast, wind and solar power cannot offer such inertia due to their intermittency. Virtual synchronous generator (VSG) technologies, through power electronic equipment, enables the use of wind and solar power to achieve frequency regulation, but the control effect is hardly comparable to that of coal-fired units because of little regulation range[18,19]. If coal-fired power generation is significantly reduced (even completely decommissioned), fluctuating renewable energy generation will have to be largely expanded to satisfy the growing electricity demand, and the power grid will inevitably be short of inertia. Furthermore, wind and solar power are generally volatile, and their fluctuations might result in severe power shortage problems under certain operating conditions, where stability problems, such as frequency collapse, are more likely to occur. The recent large-scale power cuts in northeast China due to coal scarcity and abrupt output cutbacks of wind power have illustrated the seriousness of this problem[20].

We focus on the following fundamental questions in this study: how should China adjust its coal-dominated electricity generation mix so that the power systems can contribute the greatest to carbon emission reductions? More specifically, to what extent can the share of coal-fired generation be lowered to minimize carbon emissions from electricity production while maintaining the stability and safety of the power gird? And what steps should be taken if China wants to completely drop coal from its electricity generation?

Although changes to the generation mix and carbon emissions are a national issue, implementation plans should be designed according to the specific conditions of the power grid. In the case of China, the national continental grid is constituted by six regional grids - Northeast Gird (NE), North Grid (N), Central Grid (C), East Grid (E), Northwest Grid (NW), and South Gird (S) - with asynchronous interconnections between regions mainly via High Voltage Direct Current (HVDC) transmissions. The potential for emission reductions varies within each regional grid due to differences in load, amount of each type of power source, and grid architecture and resilience (Fig. 1a), and the distribution of quite a bit of generation resources also exhibits significant geographical diversity. Therefore, we will study the generation mix of the six regional grids separately, and then aggregate them to obtain that of the whole country.

In this study, we first select the SSP5 scenario from GCAM as the base scenario to simulate China's future development. We reformulate the development scheme for all types of power sources in the scenario. We change the proportion of coal-fired generation in the six regional grids and then check whether secure operating requirements are met through a stability analysis method based on primary frequency regulation (PFR) to find the minimum share of coal-fired power at each time point. We develop carbon reduction plans for each regional grid based on the national policy[15] and frequency stability assessment, on which basis we obtain national results and examine the response of these plans to the carbon peak and neutrality targets. Afterwards, we investigate the impact of the national transmission structure and the penetration of energy storage. Finally, we analyze the future trend of China's power systems and propose plausible approaches for coal removal.

Results

Carbon reduction pathway for electric power under the base scenario. We find out that China's future electricity generation mix will progress in a more logical and cleaner path. The share of coal-fired power generation steadily decreases, from 62.15% in 2019 to 29.19% in 2060, and a further 6.67% in 2100, and it will no longer be the principal power source. The share of gas-fired power gradually declines as well, and natural gas will not be used for electricity generation in 2100, as cleaner hydrogen-fired generation is in large scale. Between 2020 and 2045, the rapid growth of electricity demand, as well as the minor increase in hydroelectric generation due to the protracted construction cycle of hydropower units[21], causes the share of hydropower to fall before rising. Nuclear power production continues to increase and will be the second biggest source after fluctuating renewables in 2100 (Fig. 2a), thanks to the considerable sites for building nuclear power plants, notably the untapped inland nuclear power in China[22](Fig. 2b). Fluctuating renewable energy generation develops most rapidly, expanding from 8.59% in 2019 to 30.60% in 2060, dominating China's generation mix from 2060 onwards. Other forms of generation are in a stable state of development, with little change in their share. Fluctuating renewable power, coal-fired power, nuclear power and hydropower are the major sources in 2060's generation mix, accounting for 89.87% of total electricity generation. Specifically, the proportion of clean energy generation will reach 63.76%, renewable energy generation will be 51.45%, and non-fossil energy generation will be 68.95%. By 2100, fluctuating renewable power, nuclear power and hydropower will dominate the primary sources, constituting 82.70% of total electricity generation. It clearly indicates that China's power systems will be highly clean by the end of the 21st century.

Under the base scenario, electricity generation maintains a high rate of growth from 2020 to 2045, but gas, hydro, hydrogen, nuclear and other forms of power generation cannot fully meet the growth due to constraints in natural gas extraction, hydropower potential, construction cycles, etc. As a consequence, despite of declining share, the total capacity of coal-fired generation still goes up during this period, peaking in 2040 (Fig. 2a). We also discover that hydrogen, nuclear and fluctuating renewable energy generation multiply between 2020 and 2035, making these years a critical phase for restructuring China's power systems.

In addition, the six regional power grids show various degrees of capability to cut coal power generation. Although China would not be able to completely phase out coal in its power systems by the end of the century under this scenario, Northeast, East, Central and South Grid could completely decommission coal power generation to zero by 2080, 2090, 2080 and 2075 respectively, while North and Northwest Grid still retain some by 2100 (Fig. 2c). Disparities in the distribution of regional demand and resources (mainly hydropower and nuclear power) play a major role in these differences. The South Grid enjoys the biggest coal power reduction because of its geographical advantages to have the most abundant hydroelectric and nuclear supplies. The Central Grid is also well endowed with hydropower resources and has huge potential for inland nuclear power, allowing it to completely remove coal generation earlier. The Northeast Grid has low demand, and its own hydroelectric and nuclear resources, though small, can fulfill its needs and thus can realize coal removal. The East Grid is rich in coastal nuclear power resources, but due to that it is in the middle and lower reaches of the river basin, it has inadequate hydropower resources. In addition, because of high electricity demand, it is the last grid to completely drop coal power compared to the above three grids. The Northwest Grid has low electricity consumption and good hydropower resources, but due to the harsh geographical conditions, nuclear power cannot be developed. Also because of its essential role in the "West-East electricity transmission project" in China's existing power system configuration, its coal power is difficult to completely eliminate (11.06% in 2100). The North Grid is not only in the greatest demand for electricity, but also has an extreme lack of hydropower and nuclear power capabilities. With more than half of the fluctuating renewable generation in 2100, it will also have 19.56% of coal power, making it the hardest grid to phase out coal.

Under this scenario, even the maximum CO_2 emission reductions from the power sector are insufficient for China to fully realize its declared carbon emission objectives. Total national net carbon emissions are expected to peak around 2035 at 1503.62 MTC, illustrating that with rapid electricity demand growth, emission reductions from restructuring power systems alone will not be enough to meet the 2030 carbon peak target, necessitating concrete efforts from other energy sectors and industries (Fig. 2d). National net carbon emissions decline to -303.58 MTC in 2060 and remain negative from 2060 to 2100, achieving the 2060 carbon neutrality target with sustainable development. Carbon neutrality, of course, cannot be realized without contributions from other sectors in the reductions and construction of carbon sinks. Carbon emissions from other sectors start to drop in 2045, while terrestrial carbon uptake continues to increase steadily until 2070. Compared to the original GCAM-SSP5 results, the ratio of carbon reduction from electricity production is prominent at 33.36% in 2060 and 68.99% in 2100 (Supplementary Table 23). Furthermore, from 2030 to 2100, the share of carbon emissions from electricity production decreases gradually (34.31% in 2060 and 2.81% in 2100), indicating that electricity production will no longer be the major source of carbon emissions in China by the end of this century.

Impact of the structure of power transmission networks. We conclude that by modestly changing the current transmission network structure, China can phase out coal from its generation mix in 2095 or 2100. The current transmission system consists mostly of four corridors: "NW-N-NE", "NW-E", "NW-C-E", and "S-E", which shows an overall architecture of "West to East". The Northwest Grid takes on the heavy obligation of exporting electric power and the East Grid becomes the main power recipient as a load center. The optimized transmission structure for coal removal mainly contains three corridors: "NE-N", "S-C-N" and "S-E" (the 2095 findings include an additional corridor - "C-NW" corridor) (Fig. 3a,b), displaying a "South to North" architecture. Electric power is primarily supplied by the Central and South Grid, with surpluses sent to the North and East Grid. The new transmission structure accurately reflects the regional distribution of generation resources. The Central and South Grid are rich in hydroelectric and nuclear resources, and their systems still have enough inertia to accommodate fluctuating renewables and export electric power when coal power is removed. If the Northwest Grid is to eliminate coal power by 2095, it will need to import electricity from other areas due to lack of nuclear resources, and it can no longer support power to eastern regions. The North Grid, which has the heaviest load and is severely short of hydroelectric and nuclear supplies, is the region in the most need of power support, as fluctuating renewables generation is limited due to lack of inertia.

Taking into account factors including economy, stability and the difficulty of constructing transmission lines, we believe that the power transmission structure in 2100 is better than that in 2095. Compared to 2100, in addition to the construction of two new lines, "C-N" and "S-C", and the expansion of the "S-E" line, the 2095 plan also needs to enlarge the "C-NW" line. The 2095 plan has more capacity of transmission lines, greater total amount of electricity transmitted across regions, and worse stability in regions without coal power, with the maximum frequency fluctuations in the Central, East and South Grid already approaching 0.2 Hz (Fig. 3b).

The new transmission network also optimizes the regional electricity generation mix. Fluctuating renewable energy resources are better utilized in the Northeast, Central and South Grid. In 2100, for example, under the original transmission structure, the share of fluctuating renewables generation in the above three grids is only 8.01%, 8.15% and 6.80% to ensure the priority of nuclear power and to avoid hydropower abandonment (Supplementary Fig. 6,8,10), implying that wind and solar power curtailment is serious in these regions. After modifying the structure, the share of fluctuating renewable energy generation in these three grids reaches 21.44%, 30.83% and 31.48% respectively, which is a good improvement.

Impact of energy storage. The optimistic development of energy storage will bring a bright prospect for carbon reduction in China's power systems. If the PFR utilization of energy storage increases from 10% in the base scenario to 20%, or if the total installed capacity doubles, China will have CO_2 emissions peak around 2035, achieve carbon neutrality ahead of schedule around 2055, and drop coal from its power system in 2090 (Fig. 4a). After 2090, the share of carbon emissions from electricity production will be below 7%. Regionally, the North and Northwest Grid, which would otherwise have to retain coal power, are both able to completely remove coal by 2090, and the other four grids are 10-15 years ahead of the original coal removal plan respectively. If energy storage further develops (the PFR utilization rate rises to 30% or the total installed capacity triples), China's CO_2 emissions will peak around 2030, carbon neutrality will be achieved around 2055, and coal power will be completely phased out by 2080 (Fig. 4b). The South Grid could even reduce coal power to zero as early as 2055. This outcome is undoubtedly more appealing than that in the base scenario. Not only does it contribute significantly to China's energy transition and environmental sustainability, but also it provides a bigger contribution to the global temperature rising targets and net-zero greenhouse gas emissions in the COP 26 in Glasgow[23].

Ideally, of course, the entire fluctuations of load and wind and solar power could be smoothed out by configuring sufficient energy storage at various positions in the power grid. However, due to the highly volatile fluctuations, electrochemical energy storage would need frequent switches between charging and discharging, leading to a dramatic decrease in lifespan. Therefore, using large-scale energy storage for PFR is not economical enough.

Discussion and conclusions

Our analysis indicates that China's power systems have tremendous potential to reduce carbon emissions. In the base scenario, China could realize its stated goal of carbon neutrality in 2060 by reducing emissions from electricity production. The national share of coal-fired power generation could be lowered to a minimum of 6.67% of the total electricity generation mix, and all coal-fired power plants in the Northeast, East, Central, and South Grid could be shut down by the end of the 21st century. In addition, with existing structure of power transmission networks and penetration of energy storage, regional hydroelectric and nuclear generation resources, as well as electricity demand significantly determine whether the regional grid has the capacity to drop coal. It is still difficult to completely remove coal-fired power from China's power systems due to a mismatch between generation resources and demand. We suggest two approaches to tackle this problem.

One solution is to change the existing transmission structure and strengthen the power support between regional power grids. Transmission lines in China's power systems are currently built based on the inverse distribution of power supply and demand, i.e., transporting surplus electric power from regions with sufficient resources to load centers. In the future, driven by carbon reduction, we propose to construct transmission systems based on the stability of regional grids, transport electric power from areas with high inertia to areas with low inertia, gradually shift from "West to East" layout to "South to North" layout, and strengthen the role of the Central Gird as a power transmission hub. HVDC transmission lines, which have long distances and high efficiency[24,25], will still be the most common. This will not only speed up the phase-out of coal power, but also optimize the utilization of fluctuating renewable energy generation resources.

The other solution is to increase the scale of installed energy storage applied to primary frequency regulation. This is not a simple task. On the one hand, the low-cost performance for PFR place certain requirements on energy storage technology and the national economy for investment. There will be an urgent demand for mainstream energy storage technologies with high energy density, long life cycle, low operating requirements, and excellent reliability. On the other hand, if customer-side energy storage is to participate in PFR, a reasonable market mechanism for auxiliary services has to be established to ensure the profits of users to motivate them.

The above two options are not mutually exclusive and can be deployed together to meet specific requirements. For example, in the case of breakthroughs in energy storage technologies, changes to the transmission network structure can further accelerate carbon reductions (Supplementary Note 7).

Although our study focuses on China, the developed generation restructuring tactics and coal removal plans of power systems are also valuable for other countries to incorporate environmental objectives into their power sector strategies. India, for example, also has a coal-dominated power system with grid structure similar to that of China[11,26], and its power grid is relatively weak, which has experienced several serious blackouts[27]. Moreover, in terms of energy transition[28], India's environmental goal of achieving carbon neutrality by 2070 is no less pressing than that of China, which must be supported by appropriate carbon reduction pathways for power systems. Our methodology is generic and applicable to different scenarios and other nations and areas with different backgrounds, and can offer reference to them (Supplementary Note 8).

Our study provides a new perspective of power grid stability for carbon reduction in power systems. To obtain more rigorous and reliable results, we suggest three directions for future research. First, a finer time scale could be adopted. Though our analysis is based on the time step of five years, a year-by-year study would offer a more detailed picture of national policies for power system development, and make it possible to precisely extrapolate the year when China will reach its carbon peak and neutrality targets. Secondly, attention might be paid to a broader range of operating conditions of the power systems. Our analysis uses average power to represent the output of generating units and demand of load, while future studies can build on this to discuss special cases and extreme events. For example, there might be abolut tens of hours of peak load per year (8760 hours in a calendar year), where the change rate of load power surpasses 1%; the output of hydropower units varies with the availability of water; the actual output of wind and solar power is closely related to meteorological conditions, and thus their volatility is more complicated[29,30]. Finally, it would be beneficial to develop a comprehensive decision model that takes multiple factors into consideration. In addition to the dimension of grid stability, the economy of the construction and operation and the responsiveness of electrical consumers to national policies are equally, if not more, important in the discussion of carbon reduction in power systems[31,32]. These three dimensions together will help generate a quality carbon reduction pathway of power systems that underpins sustainable national development.

Methods

Base scenario based on GCAM. The time period for this study is from 2020 to 2100, with a five-year time step, as it covers the three key time points: i) China's carbon emissions peak in 2030; ii) China achieves carbon neutrality in 2060; and iii) the climate targets of the Paris Agreement[23] in the second half of this century. The electric power data in 2019 (including the amount of electricity generated by each type of power source in each region, the electricity consumed, line loss rate, etc.) is taken from China Electric Power Yearbook 2020[33] and China Electric Power Statistical Yearbook 2020[34]. The data of population, environment, economy, society, energy, etc., from 2025 to 2100 are calculated by the GCAM model.

The Global Change Analysis Model (GCAM) is an integrated assessment model based on global climate change, designed to explore the interactions between complex systems and provide insight into long-term development trends in the world as a whole and across regions. GCAM has been widely used in producing assessment scenarios and multi-model multi-scale analysis, such as the Intergovernmental Panel on Climate Change (IPCC) reports[35], the Shared Socioeconomic Pathways (SSP)[36], and the Integrated Earth System Model (IESM)[37].

We select the SSP5 scenario from the GCAM database as the base scenario for this study. The SSP5 scenario is characterized by rapid and fossil-fueled development with high socio-economic challenges to mitigation and low socio-economic challenges to adaptation[38], so it is consistent with China's development. On this basis, we recalculate SSP5's electricity sector. We use the same total amount of electricity generation but redistribute the share of electricity generated by each type of power source.

Firstly, we use the current power transmission structure of the six regional grids as the base, then use the total electricity generation forecasting from GCAM to calculate the electricity transported across regions proportionally from 2025 to 2100, and check the above results according to the present transmission lines in China.

Secondly, we estimate the electricity consumed by each region based on the development level of population and economy on a proportional basis in 2019, and determine the generation capacity of each regional grid by combining the line loss ratio predicted using the ARIMA algorithm.

Thereafter, we calculate the generation capacity of each type in each region based on the geographical characteristics of different power source types. We classify generating units in China into seven types: coal-fired, gas-fired (natural gas), hydrogen-fired (hydrogen fuel cell), hydroelectric, nuclear, fluctuating renewables (wind and solar), and others (biomass, geothermal, etc.). Oil-fired generation accounts for a very small proportion (less than 0.02%)[33] and thus is neglected in this study. Of all generation types, gas, hydrogen, hydroelectric, nuclear and others are estimated based on existing national policies and corresponding generation resources, coal power generation is calculated according to the minimum ratio derived from the PFR model of the multi-unit system, and the remaining capacity to be generated is compensated by fluctuating renewable energy generation, which is checked by wind and solar power potential. In addition, we use the regression model to predict the installed capacity of energy storage and set the utilization rate of PFR at 10%.

The above calculations will produce a preliminary carbon reduction plan for each regional grid. Finally, we revise the aforementioned plans aligned with the economic development and stability assessment results and obtain the final carbon reduction pathway for China's power systems. (See Supplementary Note 3 and 4 for more detailed calculations)

$$E_{gen,total,t} = \sum_i E_{gen,i,t} = \sum_i \left(\frac{E_{cons,i,t}}{1-\eta_{loss,i,t}} + E_{trans,i,t} \right) = \sum_i \frac{\lambda_{i,t}}{1-\eta_{loss,i,t}} \cdot E_{cons,total,t}$$
$$i = N, NE, E, C, NW, S$$

where, at time t, $E_{gen,total,t}$ is the total national generation, $E_{cons,total,t}$ is the total national demand, $E_{gen,i,t}$ is the generation of region i, $E_{cons,i,t}$ is the demand of region i, $E_{trans,i,t}$ is the electricity transmitted by region i (taking positive values for outgoing and negative values for incoming), $\eta_{loss,i,t}$ is the line loss ratio of region i, and $\lambda_{i,t}$ is the share of electricity consumed by region i.

$$\lambda_{i,t} = \frac{\lambda_{i,t-1} \cdot (1+\alpha_{pop,t}) \cdot (1+\alpha_{eco,t})}{\sum_i \lambda_{i,t-1} \cdot (1+\alpha_{pop,t}) \cdot (1+\alpha_{eco,t})}$$

where, $\alpha_{pop,t}$ is the demographic impact factor and $\alpha_{eco,t}$ is the economic impact factor.

Carbon emissions from electricity generation, including coal-fired power, gas-fired power, and other forms of power, are obtained by scaling the values from the original GCAM-SSP5 scenario and the proportion of carbon reduction from electricity production is estimated based on this. The results in GCAM are used to assess carbon emissions from other sectors and terrestrial carbon sink (net terrestrial carbon uptake). Net CO_2 emissions are the difference between the total CO_2 emissions and terrestrial carbon sinks. We assume that carbon neutrality is achieved when net CO_2 emissions are less than or equal to zero.

$$\mathrm{CO_2}\ emissions_{act,j} = \frac{E_{act,j}}{E_{orig,j}} \times \mathrm{CO_2}\ emissions_{orig,j} \quad j = coal, oil, gas, others$$

where, $E_{orig,j}$ and $E_{act,j}$ are the electricity capacity generated by type j, CO_2 $emissions_{orig,j}$ and CO_2 $emissions_{act,j}$ are the carbon emissions of power generation type j. The subscript *orig* denotes the original GCAM-SSP5 scenario and *act* denotes the actual scenario.

$$net\ \mathrm{CO_2}\ emissions = total\ \mathrm{CO_2}\ emissions - net\ terrestrial\ \mathrm{C}\ uptake$$

where, all values are in units of Megatonne of carbon (MTC).

Stability analysis of power systems based on frequency regulation. For large regional grids, we focus on the frequency stability problem caused by the imbalance between load and generation, and calculate the frequency response of the power grid when load and the output of wind and solar power fluctuate, i.e. the primary frequency regulation of power systems. The grid has the characteristic of power balance under normal operating conditions, which means that the total electricity generation equals the sum of the total consumption and losses.

$$\sum_i P_{Gi} = P_{load} + P_{loss} + P_{storage} + P_{trans}$$

$$P_{Gi} = \frac{E_{Gi}}{T} \quad i = coal, gas, hydrogen, hydro, nuclear, wind, solar, others$$

where, P_{Gi} is the power output by unit i, P_{load} is the load, P_{loss} is the power loss, $P_{storage}$ is the output power of energy storage (taking positive values for charging and negative values for discharging), P_{trans} is the power transmitted across regions (taking positive values for outgoing and negatives values for incoming), E_{Gi} is the annual electricity generated by unit i, and T is the total hours in a calendar year.

When the load suddenly increases or the output of renewables suddenly decreases, due to the lagging time of mechanical inertia of the prime motor, generating units can only convert part of the kinetic energy of the rotor into electric power to maintain power balance, resulting in a decrease in the system frequency. Assume a sudden load change with a value of ΔP_{Li} (considering the output change of fluctuating renewables as load change) in regional grid i. As a result of the speed governor, the frequency in this region changes by Δf_i, and the input power of the generating unit changes by ΔP_{Ti} accordingly. ΔP_{Ti} and ΔP_{Li} are not equal here and the difference can be compensated by the following four solutions: (1) power change provided by the kinetic energy of the generating unit; (2) power change due to the frequency regulation effect of load; (3) power change on transmission lines; (4) power change provided by energy storage. We assume that the power on transmission lines between regional grids does not change.

$$\Delta P_{Ti} - \Delta P_{Li} = \frac{\mathrm{d}W_{ki}}{\mathrm{d}t} + D_{Li}\Delta f_i + \Delta P_{Bi}$$

where, in region i, W_{ki} is the total kinetic energy of generating units, K_{Li} is the load-damping constant, and ΔP_{Bi} is the power change of the energy storage.

Time domain simulation is used to analyze the frequency response characteristics of the power grid and to construct the PFR model of the multi-unit system (see detailed model in Supplementary Note 2). Laplace transform is used on the power-frequency equation to build a block diagram of the closed-loop frequency regulation of the regional grid. The time-domain simulation model is constructed in MATLAB 2020b/Simulink 10.0 environment to obtain the frequency response curves. With reference to Kunder's *"Power System Stability and Control"*[17], we consider that when the maximum change in frequency during the dynamic process exceeds 0.2Hz, the power system enters the alert/emergency operation state, no longer able to meet stability requirements.

$$-\sum_j \frac{\alpha_{i,j}}{R_{i,j*}} G_{nTj}(s)\Delta F_{i*}(s) - \Delta P_{Li*}(s) = \left(sT_{Gi} + D_{Li*} + \frac{K_{B*}}{1+sT_B} \right)\Delta F_{i*}(s)$$

where, in region i, $\alpha_{i,j}$ is the electricity generation share of unit type j, $R_{i,j}$ is the droop of unit type j, G_{nTj} is the equivalent transfer function of unit type j, ΔF_i is the frequency deviation, T_{Gi} is the equivalent inertia time constant, K_B is the response rate of energy storage, T_B is the time constant of energy storage, s is the Laplace operator, and * denotes the per unit value. In addition, the dead zone and limiting link are added to energy storage.

Sensitivity analysis. We select the power transmission structure and the penetration of energy storage as key influences on the result of the base scenario from a number of variables, and study them independently.

Changes in power transmission structure can help eliminate coal from China's power systems by enhancing inter-regional power support. Based on the results of the base scenario, we increase the capacity of fluctuating renewable energy generation in regions that have no coal power and transport this electricity to regions that still have coal power through transmission lines. It might result in a variety of structures. We produce feasible structure by i) first, altering the current construction of transmission lines as little as possible, ii) then, minimizing the maximum frequency fluctuations in the main transmission regions, and iii) finally, reducing the total electricity transmitted across regions as much as possible.

$$\min \quad F = \left[\Delta f_{\max}, N_L, E_T\right]$$
$$s.t. \begin{cases} P_{Ti} = \sum_{j \neq i} P_{ij} & i, j \in \{N, NE, E, C, NW, S\} \\ P_{ij} \leq P_{ij\max} & i \to j \in \Omega \end{cases}$$

where, $\Delta f_{\max}$ is the maximum frequency fluctuation of the main transmission regions, N_L is the number of new and expanded transmission lines, E_T is the total electricity transmitted across regions, P_{Ti} is the power transmitted by region i, P_{ij} is the power transmitted from region i to region j, $P_{ij\max}$ is the maximum power transmitted between region i and j, and Ω is the set of transmission lines. It is stipulated that new lines can only be bulit between adjacent regions.

The penetration of energy storage in power systmes is influenced by the PFR utilization rate, i.e. the proportion of capacity used for PFR to total capacity, and the total installed capacity under carbon reductions. Among all types of energy storage, pumped-storage units can be integrated with conventional hydropower generating units, while technologies such as flywheel energy storage and compressed air energy storage, are difficult to obtain large scale applications due to the limitations of operating requirements[39]. Thus, we focus on electrochemical energy storage, i.e. battery energy storage in this study. We increase the maximum charging/discharging power of the energy storage in the base scenario by 100% and 200% respectively to simulate more applications for PFR encouraged by electricity market, or China investing more in energy storage. The methodology remains the same as in the base scenario, while the optimal response rate of energy storage is calculated for each region.

Code availability

The Global Change Analysis Model is an open-source integrated assessment model, available at: https://github.com/JGCRI/gcam-doc. Frequency stability analysis is conducted using MATLAB 2020b/Simulink 10.0 version. Figures are created using OriginPro 2022 (Learning Edition), Apache Echarts (an open source visual charting library, available at: https://echarts.apache.org/zh/index.html) and Visio 2016.

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Author contributions

M.P. designed the scenario, conducted the analysis and created the figures. D.X. coordinated the research, conceived the idea and led the writing of the paper. M.P., D.X. and C.G. contributed to paper writing. G.L. collected the data. X.W. and C.Z. performed the data analysis. All authors discussed the results and commented on the manuscript.

Competing interests

The authors declare no competing interests.

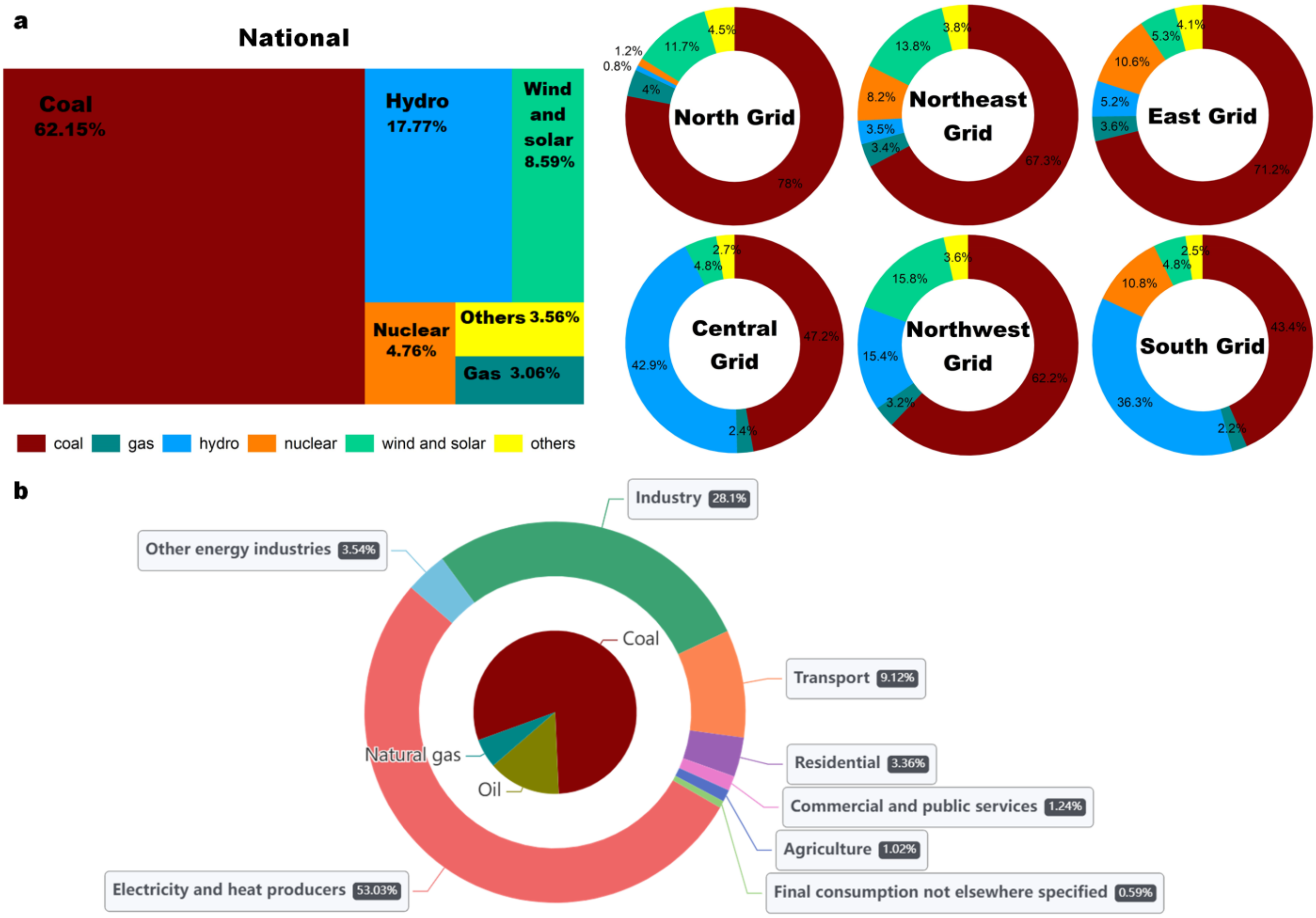

Fig.1 | China's electricity generation mix and carbon emissions in 2019. a, China's national and regional electricity generation mix in 2019 (data from ref.[33,34]). Regional power grids include the North Grid, Northeast Grid, East Grid, Central Grid, Northwest Grid, and South Grid. National results are calculated by adding the data of the six regional grids. **b**, China's carbon emissions in 2019 (data from ref.[12]). The inner pie denotes the carbon emissions classified by energy source. The outer ring denotes the carbon emissions classified by sectors.

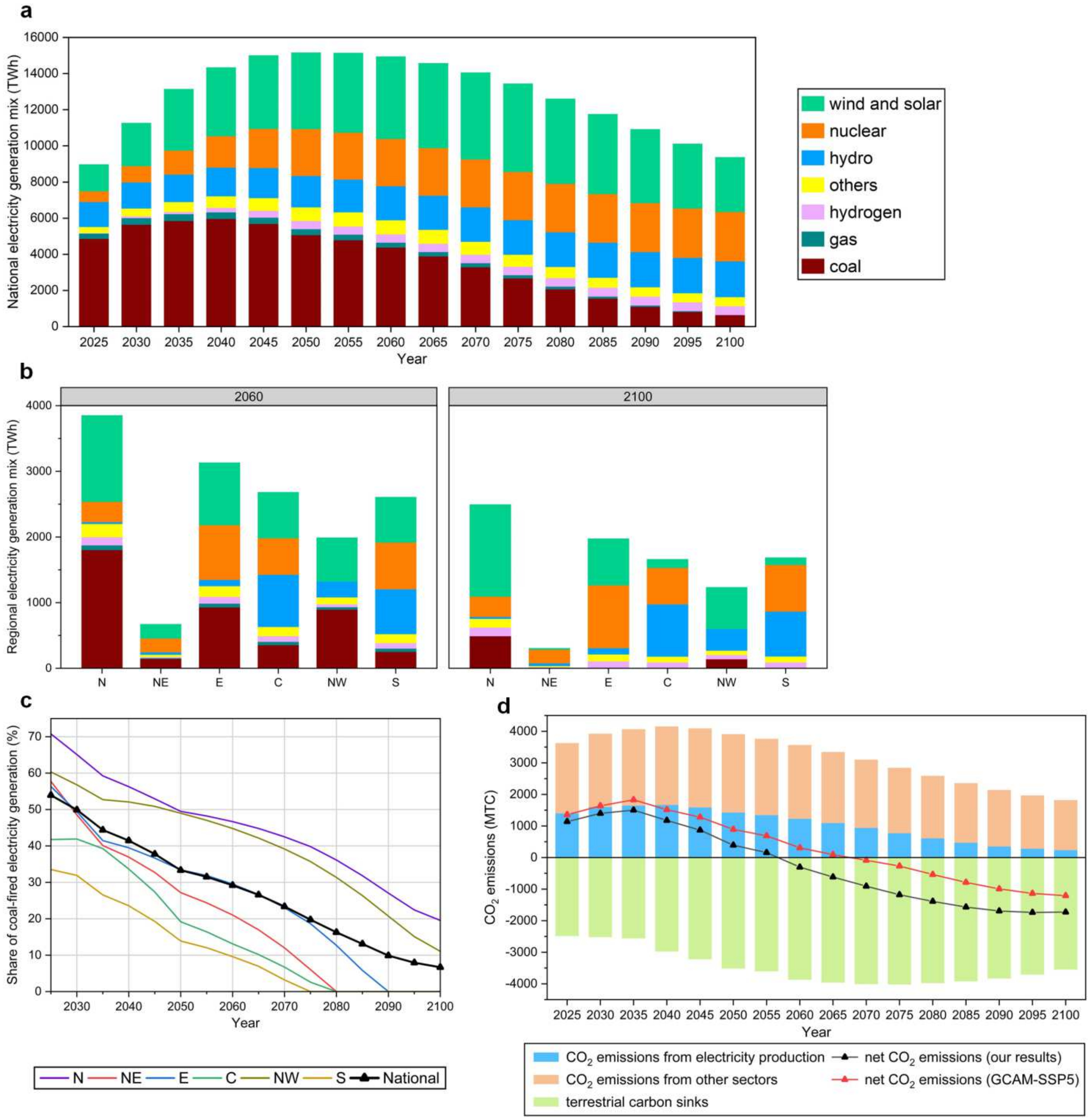

Fig.2 | Carbon reduction pathway of China's power systems under the base scenario. a, National electricity generation mix in 2025-2100. **b**, Regional electricity generation mix in 2060 and 2100. **c**, National and regional share of coal-fired electricity generation (i.e. the proportion of coal-fired electricity generation to total electricity generation). **d**, National carbon emissions in 2025-2100. The data includes carbon emissions from electricity production and other sectors, terrestrial carbon sink, and net carbon emissions in GCAM-SSP5 and our results.

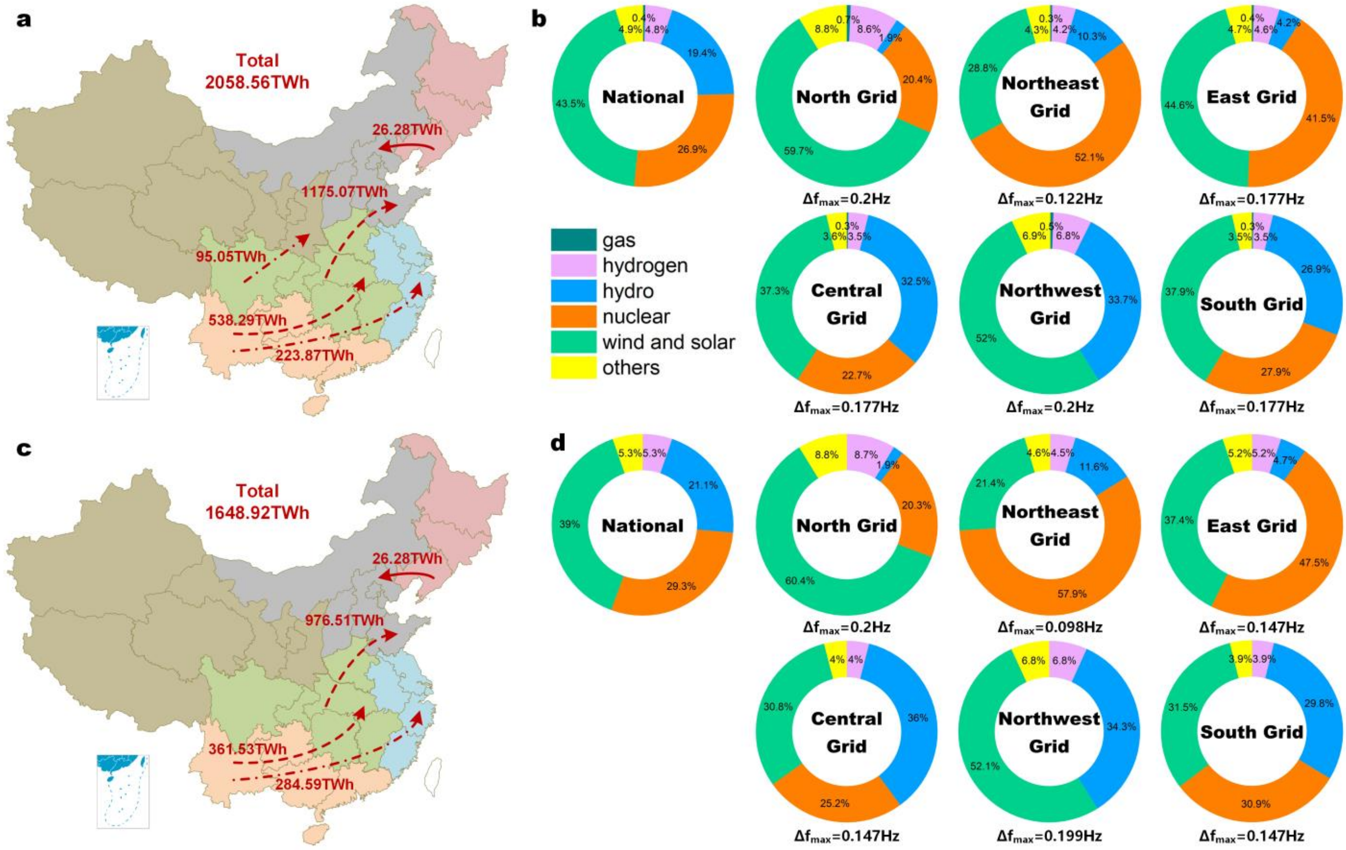

Fig.3 | Different results of coal-fired power removal in 2095 and 2100 after adjusting the power transmission structure. a, Optimized power transmission structure for coal-fired power removal in 2095. **b**, National and regional electricity generation mix and maximum frequency fluctuations of regional power grids in 2095. **c**, Optimized power transmission structure for coal-fired power removal in 2100. **d**, National and regional electricity generation mix and maximum frequency fluctuations of regional power grids in 2100. In the diagram of power transmission structure, arrows with solid lines denote the currently existing power transmission lines, arrows with dotted lines denote the power transmission lines that need to be constructed, and arrows with dot dash lines denote the power transmission lines that need to be expanded. Regional power grids are shown through different colors, i.e. provinces and municipalities with the same color belong to the same regional power grid.

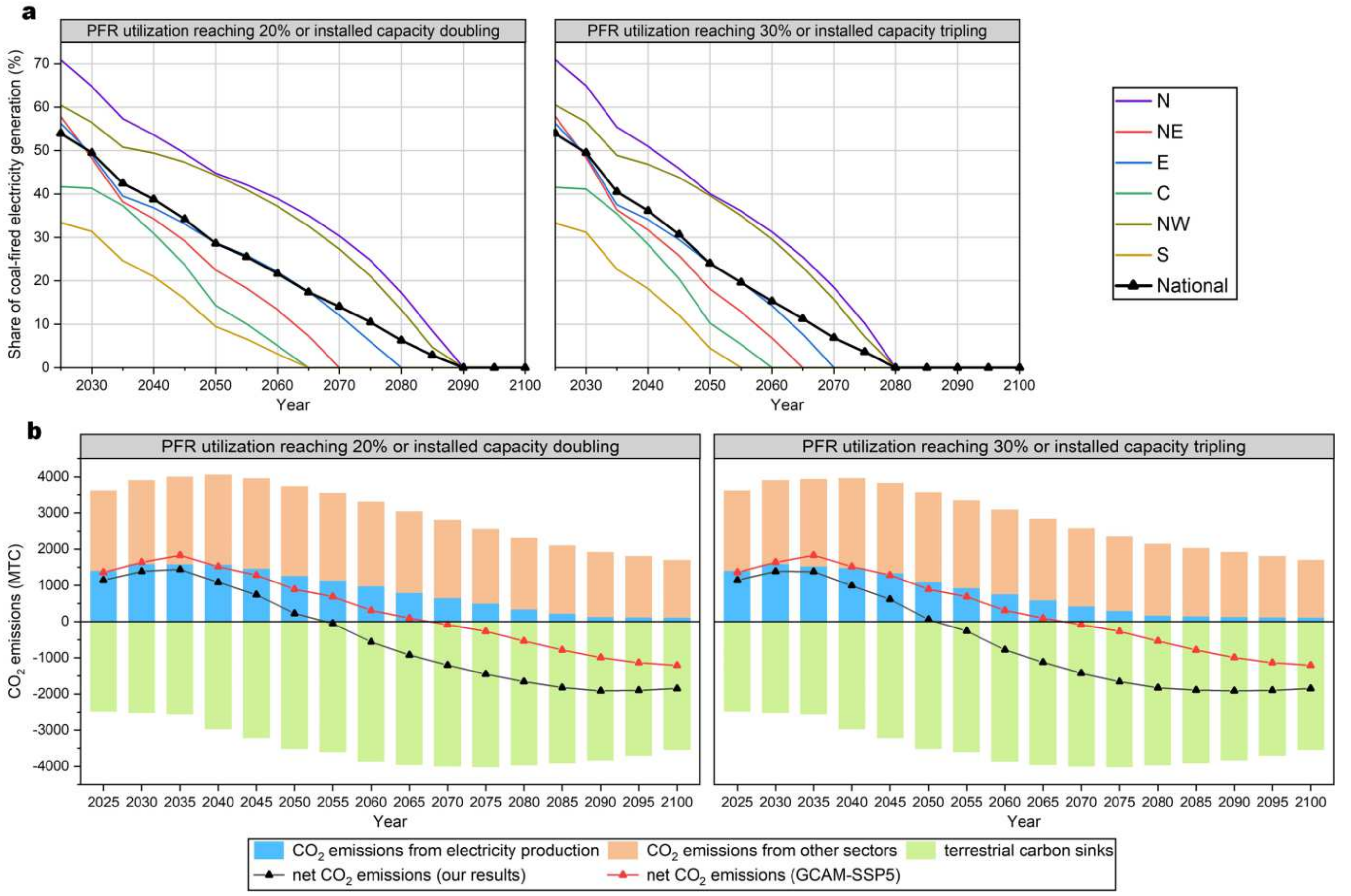

Fig.4 | Impact of energy storage on carbon reduction pathway under the original power transmission structure. **a**, National and regional share of coal-fired electricity generation when the PFR utilization of energy storage reaches 20% (30%) or the total installed capacity of energy storage doubles (triples). **b**, National carbon emissions in 2025-2100 when the PFR utilization of energy storage reaches 20% (30%) or the total installed capacity of energy storage doubles (triples).

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