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Carbon capture utilization and storage promotes poverty alleviation and sustainable development in China

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Integrating of carbon capture, utilization, and storage with poverty alleviation strategies presents an innovative and sustainable development paradigm. Regional poverty, often exacerbated by challenging geographical conditions, can be transformed into opportunities for carbon storage development, promoting energy and economic rebalancing while avoiding poverty and resource traps. By introducing an evaluation index grounded in Sustainable Development Goals and technical requirements, we achieve a harmonious balance between potential and economic development. Techno-economic analysis in coal plant renovation and oil field projects demonstrates this project triggers a 7.70% growth in local gross domestic product per capita, and a decrease of 4.85% in local carbon dioxide emissions. Construction costs in impoverished regions can be over 20% lower than in more affluent areas for projects of the same scale because of cheaper labor and lower transportation and storage costs, highlighting the cost-effectiveness of pursuing poverty alleviation through carbon capture, utilization, and storage in China. This paper also emphasized the carbon storage demand in future's energy transition of China. The status of policy implementation underscored the significant potential of carbon capture, utilization, and storage in contributing to poverty alleviation in the world's largest carbon emitter and developing country, potentially serving as a critical testbed globally.

Main

In a landscape where the urgency of climate action, carbon capture, utilization, and storage (CCUS) attract research interest worldwide, which is an industrial process for reducing carbon emissions. The IPCC Special Report on 1.5 ˚C prominently underscores the indispensable role of CCS in three out of four envisioned pathways[1]. However, due to the slow process of energy transformation, even according to the most conservative inference, the advancement of CCUS technology is still inevitable[2]. Moreover, because of the special requirements of CCUS technology for geological conditions

selection, this technology may not only have the potential to create new job opportunities and green benefits, but also circumvent the potential pitfalls associated with direct welfare interventions[3].

Historically, balancing the sustainable development goals, poverty reduction, and carbon reduction has been a significant challenge[4]. Our findings suggest that promoting CCUS could serve as an important component—among other measures—in addressing these interlinked issues. The rationale is that certain regions, previously considered economically unfavorable due to their remote or undeveloped nature[5], may possess

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characteristics that are advantageous for the deployment of CCUS technologies, which motivates this study. For instance, areas that are not densely populated or those with geological formations suitable for CO_2 storage can be ideal for CCUS facilities[6]. CCUS in these poverty-stricken areas can contribute to SDG 1 (No Poverty) by creating employment opportunities, distributing subsidies, and lifting people out of poverty[7]. It also aligns with SDG 7 (Affordable and Clean Energy) by facilitating the transition to clean and sustainable energy sources[8,9]. More importantly, CCUS directly contributes to SDG 13 (Climate Action) by CO_2 sequestration[10]. By integrating CCUS with poverty alleviation strategies, these SDGs can be improved comprehensively, fostering a more inclusive and sustainable future[11].

Although the global call to address extreme poverty for 700 millions of people has captured the attention worldwide[12,13], efforts have usually been made by industry relocation[13,14] and financial assistance[15,16]. These two common categories can realize the promotion of local income[17]: one is industrial chain relocation, through new technologies[2,18] or traditional industries[19,20] to generate income[21,22], which may lead to environmental problems[23]. The implementation of sustainable development projects may also be challenged by less utilization of local geographical resources. The other is financial assistance, which usually requires great financial investment, and poses a risk of social security resources misuse and inequity caused by corruption[24], which is unsustainable and difficult to achieve stable results, sliding into double traps of poverty trap and resource trap[25,26]. Besides, the potential effect of integration of CCUS with poverty alleviation for SDGs promotion was first proposed, which has not been addressed in the existing literature[27].

As the world's largest emitter of CO_2, China's commitment to carbon neutrality and ongoing energy transition has a huge demonstration[28,29]. Besides, China has the largest poverty population group (over 1 billion) in the world and has achieved the largest number of people lifted out of extreme poverty[30]. China's experience provides valuable insights into how CCUS technology can be effectively integrated into regional poverty alleviation strategies, addressing both resource trap and poverty trap simultaneously[31,32]. In a landscape where the urgency of climate action meets the imperative of poverty eradication, our research takes a bold leap beyond traditional poverty alleviation strategies, unveiling CCUS as a transformative force in sustainable development. In this work, we proposed a comprehensive evaluation index of CCUS based on the SDGs and geographical conditions. The results showed that the most suitable sites were concentrated in the impoverished counties, and the geographical disadvantages of the past became the new advantages of energy equity. The techno-economic assessment and co-benefits analysis also show poverty countries can even earn more compared with before. One of the best ways for realizing source-link matching of top cities and poverty counties was also given through the scenarios comparison to accelerate the policy-making of China. By effectively navigating geographical obstacles, our study pioneers a pathway, challenging existing paradigms and offering fresh insights into the interconnected realms of climate change and poverty alleviation.

CCUS evaluation index and rebalance of energy equality

For policymakers and researchers, the first question that requires an urgent response is determining the locations that are most suitable for the deployment and development of CCUS. This requires screening and ranking candidate areas to determine the priority for CCUS, especially when time and money are limited. This paper proposed a CCUS index based on the SDGs, covering intensity of energy activities, economic development level, suitability index for construction, ecological conditions, and carbon emission, the results have been shown in Fig. 1a, more detailed screening criteria and related indicator rankings are given in supplementary information and attachment. Contrary to the usual impression, economic advantages have not brought potential advantages in the development of high technology of CCUS. Poverty counties have greater CCUS potential than other areas. Megacities like Shanghai (0.16), Beijing (0.17), and Shenzhen (0.23) have high carbon emissions but low carbon storage potential, making these cities much less suitable for CCUS projects than

impoverished areas like Pingjiang County (0.97) and Longshan County (0.96) (Fig. 1b). This is because these cities do not coincide with suitable underground formations, which happens to be an important condition for carbon dioxide (CO_2) storage. This counter-intuitive phenomenon brings the possibility of realizing energy equity through CCUS in poverty counties. In the marginal areas of traditional energy sources, the inequalities caused by geographical divisions can be compensated for by the promotion of CCUS.

Through the geographical structure-led CCUS index screening, policymakers can answer questions about CCUS construction project priorities in different regions, achieve new energy equality, and rebalance the economic development with sustainability. After this, next step is to conduct techno-economic assessment for CCUS projects and evaluate whether investment can realize break even or bring positive externality in future.

Techno-economic analysis and co-benefits of poverty counties with CCUS

In China, all 832 poverty-stricken counties have been lifted out of extreme poverty by 2020, but most areas are still below the average development level (6% annual economic growth rate) of China[33]. Based on the CCUS index, the most suitable 89 poverty counties have been screened in Fig. 2a. Although green parts occupy 9% of the entire land area and 5% population of China, these areas only own less than 3% GDP. These data further confirmed the need for development aimed at poverty alleviation in these areas, and where CCUS developments could offer a potential pathway. However, before measuring the co-benefits and spillover results of CCUS projects, the techno-economic analysis needs to be assessed first to ensure sustainability and refuse over-reliance on government subsidies or fall into the resource trap.

Compared to North America, where most large-scale carbon capture plants have already been built, China has the potential to reduce the cost of carbon capture retrofit projects. This expectation is based on China's generally lower labor and manufacturing costs, as well as the huge economies of scale. China has already significantly reduced costs in the mass production like solar photovoltaic power generation[7,34]. These advantages in low labor costs become more obvious in poverty counties, as shown in Fig. 2b, the first-year electricity costs can drop by more than 30% due to the reduction in investment and operating costs brought by cheap labor. Besides, other technologies progress used in the construction can reduce capital costs by 67%. This provided a unique opportunity for poor countries.

Despite the advantages mentioned above, the upfront investment of CCUS involves assessing all of the technical, social, environmental, and financial risks and uncertainties related to CO_2 capture, transport, and storage, which ultimately impact the net present value (NPV). This is also the basis for many countries to implement stimulus policies. Results show that the combined effects of tax subsidies, carbon price transactions, income from by-products, and exhibition tickets can effectively accelerate the process of CCUS investment to achieve a break-even. Figure 2c shows that the turning point always appears around the 10th year in all poverty counties, which will vary based on local conditions. Detailed results show that higher CO_2 prices (greater than $28/ton), combined with carbon tax subsidies for equipment modifications at $21/ton, can result in shorter payback periods. The distribution of NPV for CCS in poverty counties has been shown in Fig. 2d. The results indicated a substantial profit margin in Northwest and Northern China, in contrast to the narrower margins in the Northeast, which are usually traditionally developed areas in China. It is noteworthy that despite the Northwest having the largest NPV, its lagging industrial infrastructure and economy levels result in it not achieving the highest CCUS index for promotion in Fig. 1, this further demonstrates the robustness of the CCUS evaluation index.

The spillover effect of CCUS on economic growth with cities in impoverished counties also cannot be ignored. All different types of CCUS pilot projects in China (1990 ~ 2023) are processed into the same panel data for measuring spillover effects[35]. Specifically, the implementation of CCUS project leads to an increase of 7.70% in local GDP per capita. Moreover, CO_2 in counties having CCUS projects is mitigated by about 4.85%. The findings
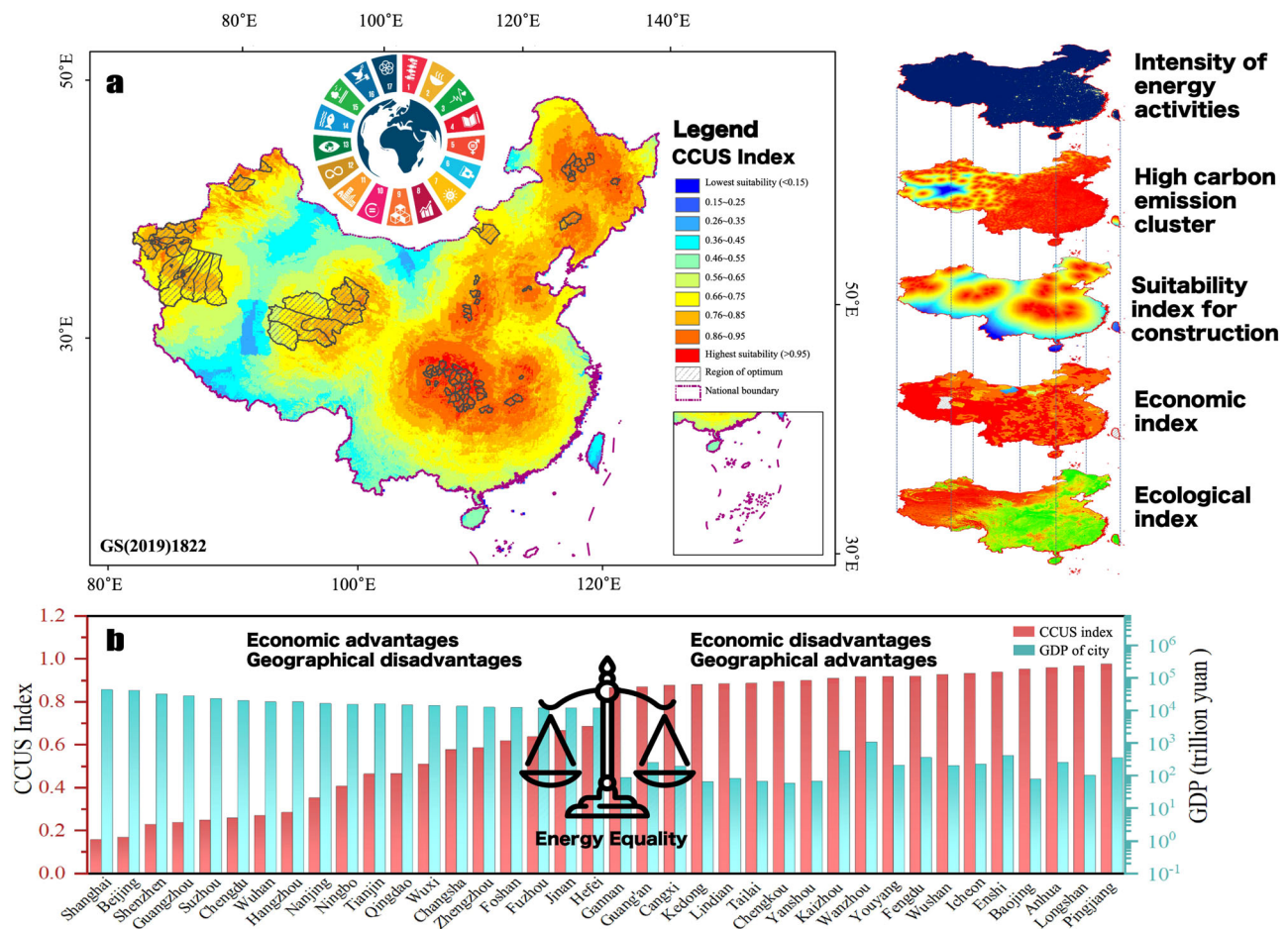
Fig. 1 | CCUS evaluation index and rebalance between energy equality and economy development. a Comprehensive evaluation of CCUS index based on SDGs; **b** Energy equality chance for developed cities and poverty counties (Annual income lower than $322 (¥2300) per capita/year). Areas are divided based on Chinese government reports, details of score see attachment and SI.).

suggest that CCUS is not only techno-economically feasible for poverty counties, but also conducive to accelerating economic growth and better environmental sustainability.

Robustness and superiority of application in poverty counties with high CCUS index

The NPV analysis shown CCUS projects in poverty counties have potential to achieve balance between income and expenditure. Under the same condition of initial investment, the low transportation costs brought by manpower and the storage advantages of geological structures in poverty counties will effectively increase the competitiveness of coal-fired power plants[36]. However, most subsidies in CCUS transformation projects still come from coal-fired power plants. Whether coal-fired power plants can ensure competitiveness in the electricity market during the transformation process is the key to whether this project can be sustained. Notwithstanding these expectations, there remains considerable uncertainty over the ability to develop and sustain billion tons/year CO_2 injection rates in 2060 and beyond. Figure 3a once again emphasizes the importance of transportation and storage costs in the cost competition of CCUS. When their highest expected cost is $20/ton, the levelized cost of electricity (LCOE) of coal-fired power plants has increased by 15% compared with the baseline. High weighted average capital cost (10%) of capture has the second largest impact. A 30% reduction in capital costs of transportation will only reduce LCOE by 5%. So if these coal-fired power plants want to be highly competitive after transformation, reducing transportation and storage costs will be undoubtedly the first step.

Considering different CCUS technology paths, key variables of techno-economic analysis have large uncertainties on project profitability. For all key variables, the largest impact is on carbon transportation and storage costs except initial investment, which are likely to vary within the range shown (10-20$/ton) compared to capital expenditures[37]. The 30% reduction in the lower bound on the carbon capture plant capital cost of Fig. 3b indicated the significant reductions in carbon capture plant costs after the early deployment of demonstration plants after 2020. Such cost reductions are not only dependent on technology advances, but rather on scale manufacturing[38].

To more effectively demonstrate the advantages of integrating CCUS with impoverished counties under the current conditions, a comparison was conducted between the top 30 cities in GDP and the top 30 cities in carbon emissions—representing the group with the greatest financial capability to implement CCUS and the most pressing need for it—and the top 30 impoverished counties ranked by CCUS index. The comparison will be based on the economic costs required to achieve the same scale of CCUS for the top 30 carbon-emitting cities. More detailed analysis in Fig. 3c shown that when building CCUS plant with the same scale of 100,000 tons CO_2, pipeline construction required by the top 30 carbon emissions cities and top 30 cities in GDP is far greater than impoverished areas (top 30 poverty counties in CCUS index ranking). For instance, Nantong (High-GDP city) needs to build pipelines more than 390 km to the nearest storage location, while Enshi (poverty county) only needs less than 10 km. The investment costs are approximately over 14 million ($) to build CCUS plant in the top 30 high-carbon emission cities, the cost in Wenzhou (High CO_2 emission city)
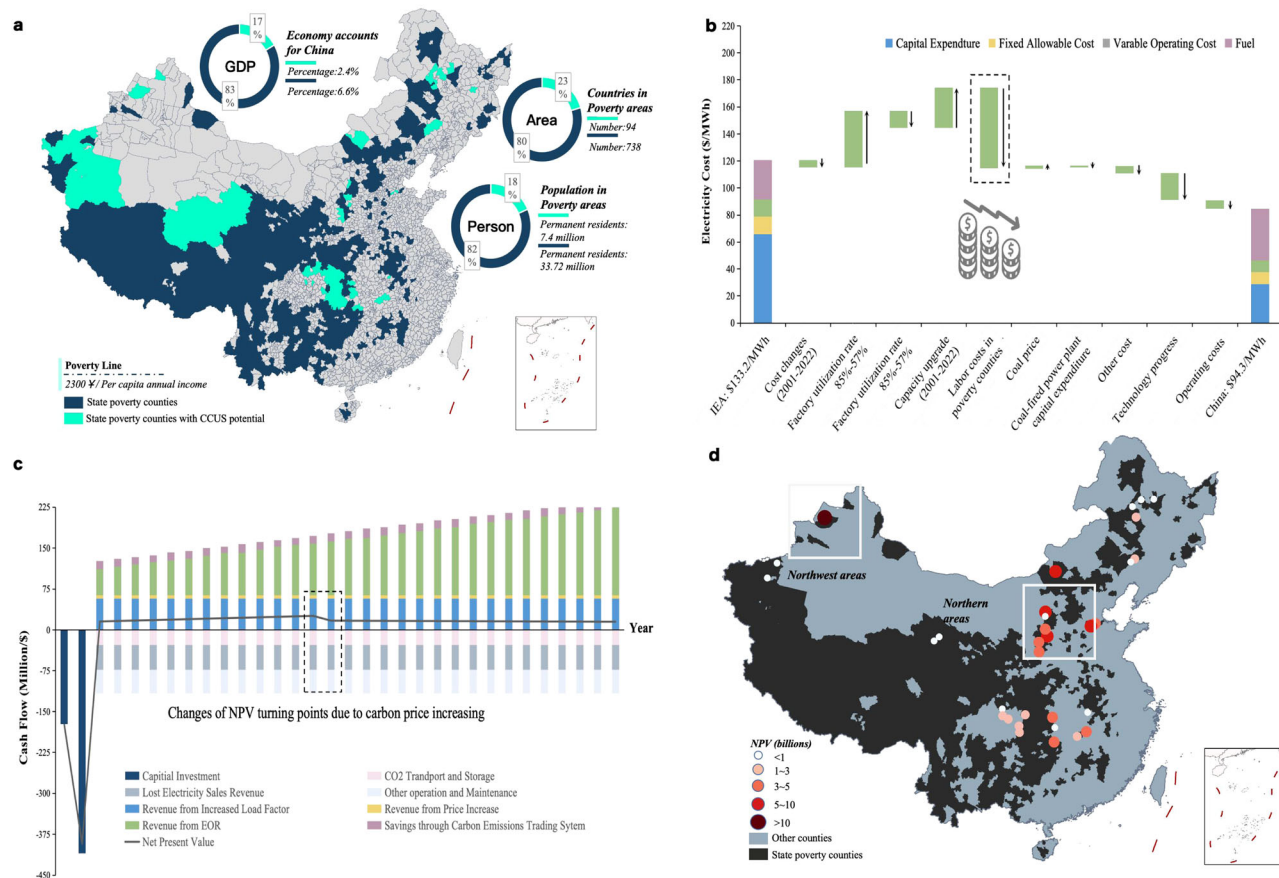
Fig. 2 | Positive externality and techno-economic analysis of Poverty alleviation with CCUS promotion. a Distribution of poverty counties with CCUS potential and their basic conditions; **b** Difference of first-year electricity costs for a supercritical coal-fired power plant with post-combustion carbon capture in China, considering impact factor of poverty counties; **c** Cash flows and present values of break-even CCUS retrofit projects with linearly increasing CO_2 prices; **d**: Distribution of NPV for CCS construction in poverty counties.

is even higher than $15.41 million. But in impoverished areas, the cost can be saved by more than 20%. In Wanzhou (poverty county), the cost is lower than $11.6 million. This phenomenon further proves the superiority and robustness in reducing transportation and storage cost of poor counties selected by CCUS index.

Despite these advantages, poverty counties with high CCUS index are usually not the main source of carbon emissions[19]. Large cities, as carbon emission-intensive areas, are spatially heterogeneous with poverty counties[39]. Especially under the long-term goal of energy transformation, carbon emissions are decreasing. Achieving spatiotemporal source-sink matching during the CCUS planning becomes the next important step for long-term policymaking.

Achieving poverty alleviation through CCUS in China

Before continuing to promote CCUS project transformation, the necessity of this demand must be clarified. Although China's energy transition is progressing rapidly, China's demand for new coal-fired power has also recovered. The pace of new coal-fired power construction has not accelerated, but the speed of retirement also slowed down[40]. Only in 2022, China's new coal-fired power plants announced, approved and under construction reached the highest level since 2015 (over 50 GW), with an increase of more than 50% over 2021, but only 0.1% of coal-fired power plants were retired. Corresponding to this is a sharp increase in carbon emissions, shown in Fig. 4a. In the next 20 years, they could continue to operate after CCUS conversion, thus avoiding the capital-intensive process of early retirement and the dispatchable capacity of power grid. This creates the continued existence of carbon sequestration demand in poverty counties even under energy transformation.

The demand for CCUS projects in different industries is also showing an increasing trend. Under the commitment target scenario[41], CCUS will contribute a total of 8% of China's cumulative CO_2 emission reduction from now to 2060, and the contribution will continue to increase over time. In terms of industries, shown in Fig. 4b, the coal power industry is still the focus of CCUS application, and it is expected that about 1 billion tons/year of CO_2 emission reduction can be achieved through CCUS in 2060; Industries such as steel, cement, and chemicals will still need to reduce some CO_2 emissions through CCUS; Although by the eve of carbon neutrality, other decarbonation technologies, such as BECCS and DAC are expected to contribute 500–800 million tons/year of CO_2 removal, as shown in Fig. 4c, These methods can reduce the net amount of CO_2 in the atmosphere, thus generating negative emissions, accounting for 25% of the total CO_2 capture[42]. Continued storage demand from other sectors can still meet the profitable demand of the poverty counties for next 40 years.

Under such a long-term and necessary demand, the next focus of analysis is to match the sources and sinks of poor counties with CO_2 emission areas. Source-sink matching between poverty counties with CO_2 storage potential and the top 30 high-carbon-emitting cities through pipelines are shown in Fig. 4d. The pipeline construction was guided by elevation data and constructed along the same horizontal height when possible[43,44]. Through economies of scale and shared infrastructure, centralized CO_2 storage locations were built with multiple large storage cluster centers (minimum Euclidean distance) to reduce transportation costs. The length of pipeline construction required by the Central areas is the smallest, and the total construction length is less than 20% of the Northern areas. Pipeline construction costs in the Northern areas are higher and might require policy subsidies. It is worth noting that in coastal areas, such as
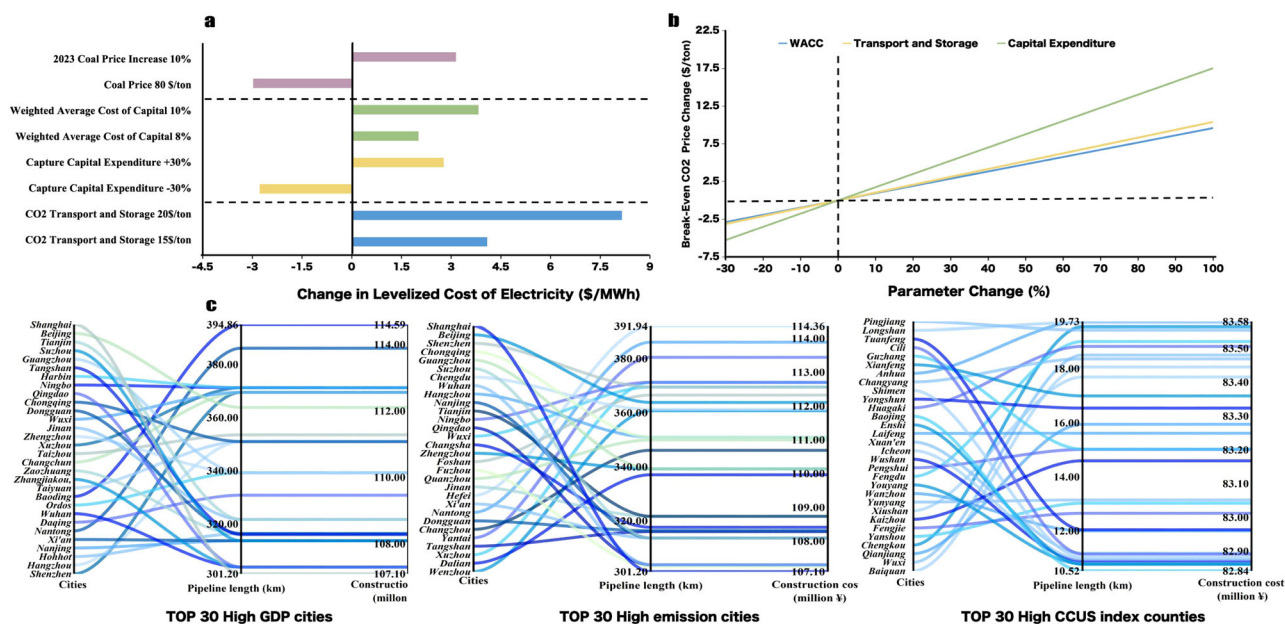
Fig. 3 | Robustness and superiority of poverty counties deploy CCUS in China.
a Impact of changes in coal prices, WACC, carbon capture plant capital, and transportation and storage costs on LCOE; **b** Effects of varying WACC, carbon capture plant capital expenditures, and transportation and storage costs on CO_2 price in achieving CCUS break-even; **c**: Comparison of different cities to realize the CCUS at same scale).

Shanghai and cities in the Greater Bay Area, which are far away from the inland sink, long-distance pipeline construction is not suitable. Choosing shallow sea areas for storage may be a better choice[45]. Although the above analysis shows implementing CCUS in poverty areas under the energy transformation can further promote energy equity and reduce China's emissions, the deployment of this infrastructure still requires government coordination and national level support to establish CO_2 transportation and storage network. As the largest developing country, there are still deficiencies of China in CCUS-related promotion policies, shown in Fig. 4e, which are directly related to SDG 7, 11, and 13[27]. Such mutual promotion of the integration of CCUS and poverty alleviation still requires further help from policies[46].

Discussion and conclusions

This paper mainly explores how the combination of CCUS with poverty-stricken countries can work as a sustainable development approach and create co-benefits. We proposed CCUS evaluation index based on the geological structure, economic development, energy activity levels and other parameters to evaluate the development potential of CCUS facilities. The results counterintuitively show that traditionally poor areas have greater priority, and the disadvantages of geological structure for city settlement in the past have become advantages for deployment of CCUS. This result not only helps to achieve energy equity, but also promotes the rebalancing of economic development and carbon reduction. Further technical and economic analysis shows that the low labor costs in poor areas (lower than 30%) can shorten the investment payback period faster (ten years). Further economic analysis shows that selected poverty-stricken countries by the CCUS index have higher superiority and can save more than 20% of investment at the same scale. The demand for infrastructure makes these areas not overlap with the most geologically suitability, verifying the CCUS index robustness. The difficulty in decommissioning coal-fired power plants (50 GW added in 2022) and the huge CCUS demand in various industries before 2060 mean that poverty counties do not need to face the unsustainability of energy transformation in the short term. By 2060, CCUS can help China reduce CO_2 emissions by 8% considering various decarbonation technologies. Based on this, CCUS source-sink matching pipeline planning

map based on poverty counties were also shown. However, the Chinese government's policy support is still insufficient so far, which is precisely crucial to fully integrate CCUS with poverty alleviation.

Previous research has shown that traditional poverty alleviation methods often increase environmental damage and may lead to a "double trap" of environmental degradation and carbon inequality[19,47]. However, implementing CCUS in poverty-stricken areas not only promotes sustainable development but also overcomes traditional geographical disadvantages, offering energy equity not achieved by past poverty alleviation efforts[44,48]. Surprisingly, carbon emissions might decrease with the integration of "CCUS + poverty alleviation," providing a compelling model for developing countries. This counterintuitive finding suggests the need to re-evaluate economic studies on CCUS projects and develop improved policies for poverty alleviation[36,41]. Importantly, the co-benefits of CCUS do not create new resource traps like those seen in South Africa and the Middle East, as the entire process and supply chain of CCUS effectively prevents dependence on single fossil resources[49]. Additionally, the rise of skilled labor and economic growth associated with local CCUS initiatives can help reduce birth rates and block population traps, fostering longer-term development[50]. China, as the world's largest developing country and carbon emitter, is also the country with the largest installed capacity of coal-fired power plants and renewable energy[40]. Should the proposals outlined in this study be implemented, they may provide a valuable demonstration effect for addressing challenges in impoverished areas worldwide.

This study offers important insights into the steps required to advance sustainable development and alleviate poverty, potentially contributing to broader efforts in addressing the global climate crisis. This article also has limitations. This paper mainly focuses on the project of coal-fired power plants[31], which are the main scenarios of CCUS applications in today's era. The interaction between technological progress and economic development has not been discussed. However, the qualitative analysis results of this paper remain unchanged; integrating CCUS with targeted poverty alleviation strategies could represent a promising pathway for sustainable development in the future. We also must emphasize that while our model provides valuable insights, the results should be interpreted with caution, given the uncertainties in technical, financial[51], and logistical aspects of rapid infrastructure development[52]. This requires decision-makers to formulate
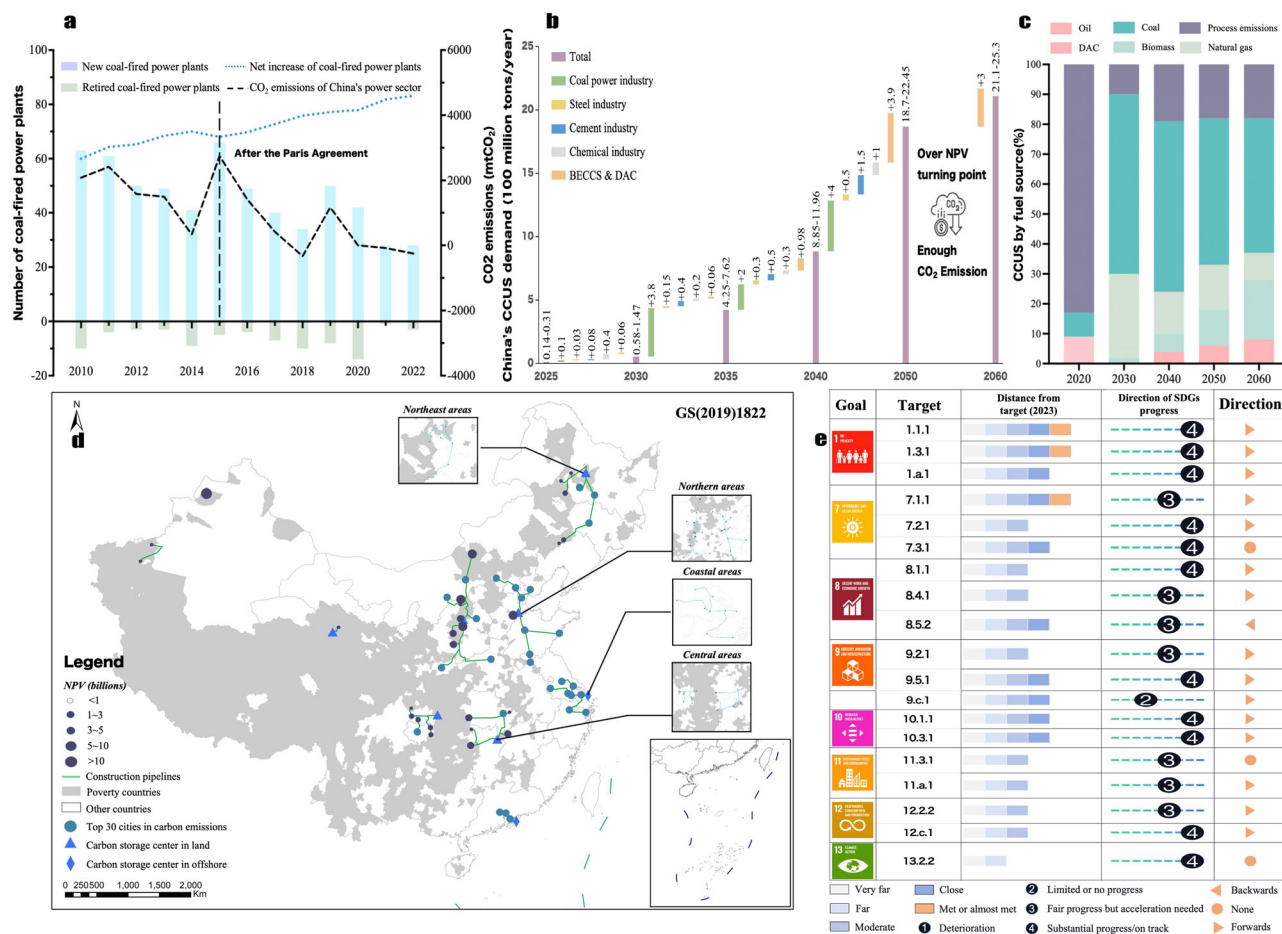
Fig. 4 | The way to realize poverty alleviation through CCUS in China. a China's coal-fired power plant additions and retirements slow in tandem with carbon emission increase; **b** CCUS emission reduction demand of various industries in China; **c** Various CCUS deployment for different fuel sector in China under the commitment target scenario; **d** Source-sink matching between top 30 cities of carbon emissions and poverty counties; b: Current status of China's CCUS policy implementation; **e** The deficiencies of China in CCUS-related promotion policies).

complete reasonable regulations and policies and pay more attention to the voices and human rights of poor communities, especially in today, when CCUS technology has become increasingly mature. From this point of view, China still has a long way to go in the future.

Methods
Comprehensive evaluation index for CCUS
The comprehensive evaluation index for CCUS includes the following components:

1. Economic index: CCUS projects require significant investments in infrastructure, technology, and operations.
2. High emission cluster: CCUS projects aim to capture and store carbon emissions from major sources. The index helps identify areas where CCUS implementation can substantially reduce greenhouse gas emissions. Targeting these clusters maximizes the effectiveness of CCUS efforts.
3. Energy activities intensity: CCUS projects are closely linked to energy production and consumption. This index helps determine the demand for CCUS technologies.
4. Ecological index: It assesses the potential environmental risks associated with carbon capture, transportation, and storage. This index helps identify potential environmental conditions and strategies.
5. Suitability index for CCUS: CCUS projects require suitable geological formations for carbon storage and well-connected transportation infrastructure. This index helps identify areas where CCUS projects can be effectively implemented.

After completing the calculation of the above parameters, a weighted average is taken for the five parameters, and the result is the CCUS index score of the region. Different parameters for CCUS evaluation have been shown in Supplementary Information Figs. S1–S4 and all related tables.

Economic index. Per capita GDP is a common index used internationally to measure the quality of regional economic development. Therefore, this paper chooses per capita GDP as an economic evaluation index. The population and GDP of China's county-level administrative regions from 2010 to 2020 were obtained through the China County Statistical Yearbook[53], and the per capita GDP was calculated. A spatial connection between per capita GDP and the map of China (GS (2019) 1822) is established. Due to the frequent changes in the administrative divisions of Chinese districts and counties in the past decade, a semantic recognition network including the province, missing value or not, and Chinese keywords has been established to realize the geographical spatial link of the per capita GDP of 2898 districts and counties in China (see Supplementary Information Fig. S2). The average per capita GDP of each district and county in China in recent 10 years is calculated, and the results are normalized into ten grades (score: 0 and 1) by using the Natural Breaks grading method, based on which the economic evaluation index atlas is established.

High emission cluster. High-emission cluster usually refers to the aggregation of a group with high emissions in a specific field. High-emission clusters are prioritized for CCUS projects because they represent regions with a significant concentration of CO_2 emissions.

Therefore, we collected the point of interest (POI) information of China's industrial, mining, metallurgical, chemical places through Google-map, with a total of 249,556 pieces of space vector data. In order to avoid too much computation, kernel density (KD) was calculated based on reasonable search radius. Ripley's K function can obtain an optimal search radius under the step size constraint through iterative clustering. The calculation formula is shown in Eq. (1):

$$L(d) = \sqrt{\frac{A \sum_{i=1}^{n} \sum_{j=1, j \neq i}^{n} k_{i,j}}{\pi n(n-1)}} \qquad (1)$$

where $L(d)$ is the value of Ripley's K function at distance d, n is the total number of POIs, A is the total area of the POI, and $k_{i,j}$ is the weight. The KD function was used as the basis for judging the specific function of construction land. The calculation formula is shown in Eq. (2):

$$f(x) = \sum_{i=1}^{n} \frac{1}{h^2} K\left(\frac{x - x_i}{h}\right) \qquad (2)$$

where $f(x)$ is the KD value of the POI_x, h is the search radius (i.e., the relative distance between point elements x and x_i), n is the number of elements contained within the search radius (h) of the POI_x, and K is the Kernel Function. Based on the calculation results, the density distribution map of the high energy consumption area is constructed. We divide the calculation results of KD function into ten categories (score: $0-1$) according to the Natural Breaks grading method to construct the cluster atlas of high energy consumption areas. Deploying CCUS projects within these clusters allows for shared facilities and infrastructure, reducing costs and technological complexities, which hold significant importance for CCUS projects[54].

Energy activities intensity. Assessing energy activities intensity helps determine the demand for CCUS technologies in a region, which will provide insights into the potential stored scale of CO_2. Generally, the more energy activity there is, the greater the intensity of the lights at night. Based on this, NPP-VIIRS, a satellite remote sensing instrument primarily, was used to monitor nighttime illumination on Earth's surface, including urban lighting and other radiance from energy usage. By utilizing NPP-VIIRS nighttime data, researchers can analyze the intensity and spatial distribution of energy use in different regions, aiding in understanding spatial patterns of energy utilization and influencing factors. This paper chooses China 2020 NPP-VIIRS nighttime data as the evaluation index of energy intensity[55]. A higher intensity of higher-energy activities indicates a greater potential for emissions reduction through CCUS implementation.

Ecological index. The ecological index refers to the assessment of potential environmental impacts and sustainability considerations associated with CCUS activities. Generally, a higher ecological index means less human activities, which makes it easier to construct CCUS. This index also important for the BECCS technology. normalized difference vegetation index (NDVI)[56] is often used to monitor vegetation growth and cover by remote sensing. The calculation method of NDVI shown in Eq. (3):

$$V_{NDVI} = \frac{N - R}{N + R} \qquad (3)$$

where V_{NDVI} denotes the value of NDVI; N is the near-infrared band of Landsat data; R is the red band. The NDVI of China in the summer of 2020 was obtained through Google Earth Engine (https://earthengine.google.com/), and its value was divided into ten levels (Score: 0–1) according to the Natural Breaks grading method, which was used as the measuring factor of ecological index.

Suitability index for CCUS. The geographical structure parameter takes into account the matching of porosity, permeability and formation thickness with storage requirements and is obtained by a weighted average of these factors, detailed scoring requirements can be gotten from ISO[57] and supplementary information. Most of above parameters and conventional data of the Chinese geological community (Data source: https://www.cgs.gov.cn/). Detailed high-definition map of China's CCUS geological suitability can be found in the attached file.

Difference-in-differences model
The implementation of CCUS projects in China is predominantly driven by government-led initiatives, characterized by a top-down administrative approach. Specifically, these projects are typically launched following the issuance of official policy documents after a specific "Plan" or "Notice" from China's government, and have the characteristics of pilot or demonstration. The locations selected for CCUS projects in China are primarily determined by geological suitability, such as the presence of depleted oil and gas fields or deep saline aquifers. Consequently, these CCUS projects can be regarded as external shocks. In addition, these regions are typically not the focus of other major economic policies or pilot programs. For instance, many of China's economic policies related to digital economy development or low-carbon transition are predominantly implemented in eastern regions, which are more economically developed and technologically advanced. In contrast, the areas selected for CCUS projects are often geographically distinct and less likely to overlap with regions targeted by other significant policy interventions.

At present, the difference-in-differences model is the most common and rational econometric model to evaluate the policy effect of exogenous shocks (Hausman and Kuersteiner, 2008; Romero and Strauch, 2008), which is widely used by scholars (Beck et al., 2010; Moser and Voena, 2012; Powell and Seabury, 2018). Also, the CCUS projects are not implemented at the same time in various counties; thus, this paper utilizes the multi-time DID model to estimate the impact of CCUS projects on local economy, society, and environment. We set $treat_i$, $post_t$, and their interaction term $treat_i \bullet post_t$ to represent the external shocks of CCUS projects implementation, all of which are dummy variables. Moreover, we take three dependent variables, namely economic development, inequality, and carbon emissions, and estimate the impact of the CCUS project implementation on these three dependent variables, respectively. Detailed model settings and variable descriptions can be found in the Supplementary Information.

Other technical paraments for CCUS
CCUS project's technical design include: CO_2 capture, compression (especially for coal-fired power plant, which is the main research target in this study), transportation, geographical utilization (like CO_2-EWR), and storage. Details had been given in supplementary information, this chapter show other key data.

CO_2 capture and compression. Predicted commercial costs of CO_2 capture still exhibit substantial range and uncertainty. The CO_2 capture cost estimation include different configurations of capture system designs, operational parameters, energy costs, and retrofit applications, most of them can be gotten from IOS standards[58]. This paper adopts the CO2 post-combustion capture model. The CO_2 must be cooled after being compressed because of its extreme temperature increase. Based on the McCollum and Ogden model of techno-economic CO_2 compression model, these capture steps can be represented as:

$$W_p = \left(\frac{1000 \times 10}{24 \times 36}\right) \times \left[\frac{m \times \left(P_{\text{final}} - P_{\text{cut}-off}\right)}{\rho \times \eta_p}\right] \qquad (4)$$

where power requirements (W_P) for increasing the final outlet pressure (P_{final}) from the cutoff pressure ($P_{\text{cut-off}}$). In this equation, ρ was set as 630 kg/m^3, η_p was assumed as 0.75 (efficiency factor), and the performance and costs of CO_2 compression were also evaluated based on this equation.

After simple purification (methanol removal) and dehydration, the pure CO_2 from the recti sol process can be transported to suitable geographical locations for CO_2 storage[3]. Typical low-purity post-combustion collection costs vary from 63 \$/t CO_2 to 126 \$/t CO_2[58]. Detailed cost of capture device can be gotten in Supplementary Information methods.

CO_2 pipeline transportation. For all parameters in pipeline transportation, the pipe diameter is one of the most important values since it directly affects the pipeline cost in current techno-economic models[59]. The larger the radius and length of the pipe, the greater the construction cost. Segment spacing, velocity, and pressure drop are used to determine the diameter of the pipe segment in construction, The specific iteration equation is as follows:

$$d = 1000 \left[\frac{64 Z_{ave}^2 R^2 T_{ave}^2 F_f m^2 F_f l}{\pi^2 \left[M Z_{ave} R T_{ave} \left(p_{in}^2 - p_{out}^2 \right) + 2 g p_{ave}^2 M^2 \left(h_{in} - h_{out} \right) \right]} \right]^{0.2} \quad (5)$$

where m is the design mass flow [kg/s]; p_{in} and p_{out} are the inlet and outlet pressures [Pa]; d is set as pipe inner diameter[mm]; Friction coefficient is F_f; M is the CO_2 molecular weight of [g/mol]; h_{in} and h_{out} are the pipeline outlet and inlet altitudes; the average CO_2 compression factor was Z_{ave}; R is the universal gas constant; the average temperature is T_{ave} [K]; p_{ave} is the average pressure [Pa]; and l is the length of a pipe segment. For more detailed information of well cost and CO_2 transportation cost, see Supplementary Information methods.

CO_2 utilization. Among all the utilization of CO_2, CO_2 enhanced oil recovery has been clearly proven to be an effective means of making profits. The underground water volume produced (OWIP) and overall recovery efficiency are used to express the enhanced water recovery. The specific description is as follows:

$$\begin{cases} EWR = OWIP \times E_r \\ OWIP = A_n h_n \varphi_e S_{wi} \\ E_r = E_m E_a E_v E_d \end{cases} \quad (6)$$

When CO_2 breakthrough occurs in the production wells, the amount of injected CO_2 would determine the storage site's maximum CO_2 capacity. *OWIP* stands for recoverable water, E_r means total sweep coefficient. There exist various physical barriers that prevent CO_2 from contacting the entire pore volume of a given region are reflected in the displacement efficiency components, which include mobilization efficiency (E_m), areal (horizontal) (E_a), vertical (E_v), and (linear) microscopic displacement efficiency (E_d). It is feasible to prevent potential leakage pathways and contamination of energy resources by maintaining enough well spacing d_{well} and distance between the injection well and sensitive objects, which can be calculated as follows:

$$d_{well} = \eta_{area} \sqrt{A / N_{inject}} \quad (7)$$

where A is the reservoir's predicted surface area and η_{area} is the coefficient—a number between 1.0 and 3.0—caused by reservoir heterogeneity and different injection techniques. The duration of the CCUS project is N. As the distance increases, the well length and diameter also gradually rise, bringing higher investment (Supplementary Information). When the distance exceeds 250 kilometers, it can be considered that it no longer has the value of transportation since the cost is too high[60].

Coal-fired power plant assumptions
Based on the average capacity factor of the National Grid in China, the base load factor of a coal-fired power plant should be set at around 60–90%. The benchmark load factor of coal-fired power plants that have completed the CCUS setting is set to 75%, a high load factor of 90% was set as the maximum operation extreme condition[61]. Coal-fired power plant location and capacity can be obtained from China Electricity Yearbook. Cost caused by pipeline construction and other load factor impact can be found in Supplementary Information.

Recursive dynamic GCAM model
This paper used the global change assessment model (GCAM), an integrated assessment model to simulate the interaction between human and Earth systems across a wide range of sectors including energy, economy, and environment[62]. This model was used for the analysis of future carbon emissions changes across various sectors and industries in China, aligning scenario settings with projections from the International Energy Agency and actual commitments made by the Chinese government. The carbon emission data employed in this analysis is sourced from the China Emissions Accounts and Datasets (CEADs) (CEADS: https://www.ceads.net.cn/), which provides detailed, sector-specific emissions data, enhancing the model's accuracy. Additionally, this paper included real data on reductions in labor costs and other expenses obtained from field surveys and contributions by Chinese enterprises, ensuring a realistic representation of economic factors within the model.

Policy quantification and economic models
The policy quantification mainly targets policies from the Chinese government, especially the State Council, and the collection range is from 2010 to 2023. After the statistics are completed, the data were divided according to different topics and then quantitatively analyzed. The economic model was divided into two parts: income and expenditure, which are described in detail in Supplementary information. The NPV model was used to measure the NPV of the CCUS project to see whether it can achieve a break-even and generate potential benefits in the future. The LCOE model was used to measure the market competitiveness of coal-fired power plants after the transformation is completed to see whether they can compete with renewable energy[63].

Data availability
All data generated or analyzed during this study are included in its Supplementary Information.

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Competing interests

The authors declare no competing interests.

Additional information

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