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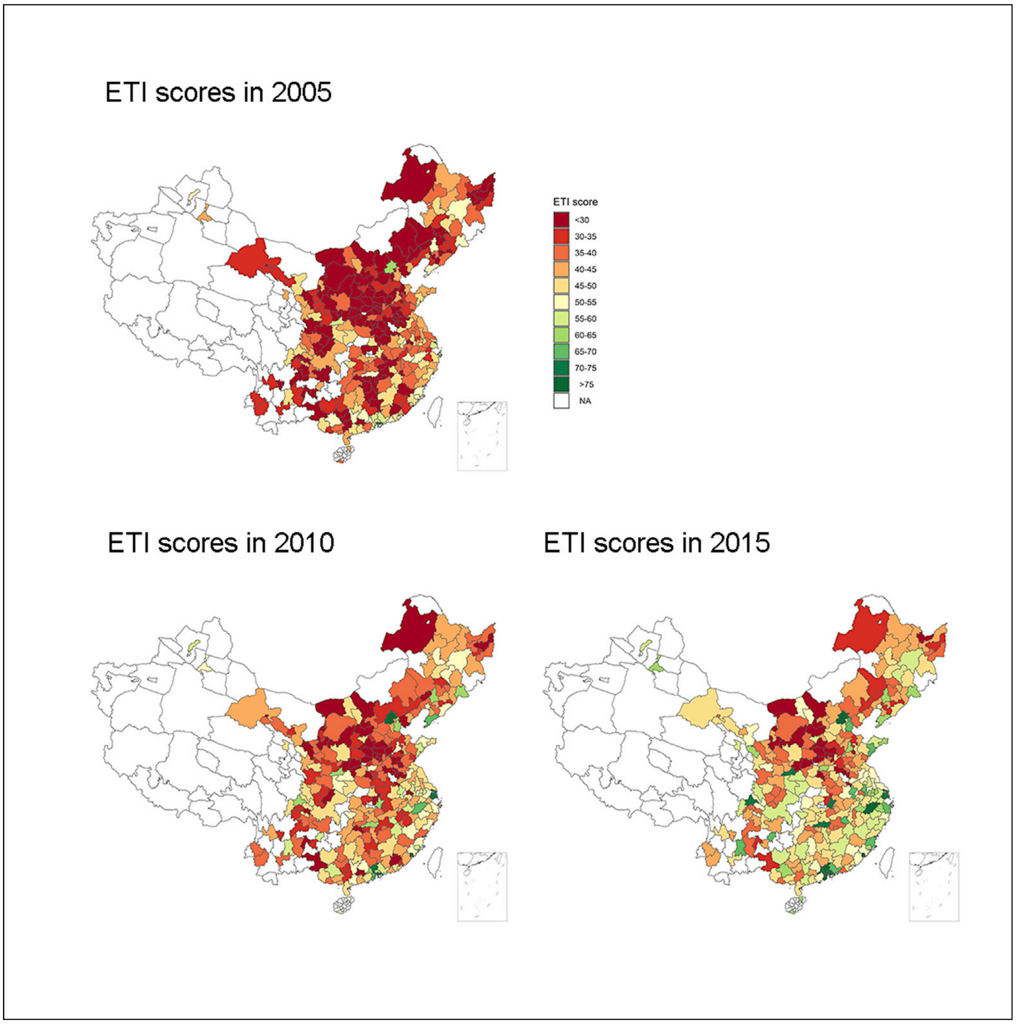

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Highlights

Developed an Energy Transition Index (ETI) to characterize cities' energy transitions

ETI scores revealed a significant heterogeneity across Chinese cities and over time

The gap between the cities in the top and bottom quartiles was persistent

Within-group catch-up produces a 30+% reduction in China's energy and carbon intensity

Shen et al., iScience *26*, 105803
January 20, 2023 © 2022 The Author(s).
https://doi.org/10.1016/j.isci.2022.105803

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Measuring the low-carbon energy transition in Chinese cities

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SUMMARY

Cities' transition from fossil-based systems of energy production and consumption to renewable energy sources—the energy transition—is critical to mitigating climate change impact as cities' energy consumption and CO_2 emissions account for two-thirds and over 70% of the world's total, respectively. Given cities' heterogeneity, they need specific low-carbon roadmaps instead of one-size-fits-all approaches. Here, we used an Energy Transition Index (ETI) to characterize the city-level energy transitions from energy system performance and transition readiness dimensions. The ETI scores for 282 cities in China revealed a significant heterogeneity across cities and over time, and the gap between the cities in the top and bottom quartiles was persistent. We estimated that China's energy and carbon intensity could decrease by 34% and 32%, respectively, and that carbon per capita could fall by 17% if each city modestly follows the sustainable development path forged by the best performing cities with similar economic structures.

INTRODUCTION

Governments around the world need to set ambitious and unprecedented climate change targets, and the key focus must necessarily be the energy sector that accounts for two-thirds of global greenhouse gas emissions.[1] However, implementing the energy transition from fossil-based systems of energy production and consumption to renewable energy sources is complex, involving not only radical technological changes but also deep socioeconomic and political structural changes. It also requires investment in related infrastructure, as well as market incentives, public education, and other policy and governance support measures.[2–4] The readiness of these supporting measures determines the progress of the energy transition and is likely to be different over time and across regions. Analyzing the energy system transition performance and the ability of cities to provide the necessary support is essential to achieving fast and just transitions that will not leave anyone behind.[5]

Cities must urgently begin monitoring their energy transition progress as they play an important role in addressing two global challenges: climate change and Sustainable Development Goals (SDGs). Cities are key players in climate change mitigation because they account for two-thirds of global energy consumption and over 70% of global CO_2 emissions.[6] Furthermore, meeting SDG 11, which aims to make cities inclusive, safe, resilient, and sustainable,[7] is contingent on cities' successful transition to low-carbon energy systems. City systems are prioritized by the World Bank as one of five key systems that are major emissions contributors that face significant adaptation challenges.[8] Understanding the differences in energy transitions among cities and over time is required for national and city policymakers to make efficient energy transition plans that not only lead to faster transitions but also to just transitions that will not leave vulnerable cities behind.[9]

Energy transitions in cities have been seen as an important channel to achieve the mitigation of climate change and sustainable development. More and more studies focused on the cities' energy transitions recently.[10,11] For example, Hoppe and van Bueren[12] highlighted the importance and challenges of managing climate change and energy transition in cities from a throughout review of seven articles. They also discussed the possible solutions to achieve energy transitions in cities. Villamor et al.[13] examined the energy transitions in 27 EU cities based on a Horizon 2020 project mPower. The results found that these cities are still highly relying on fossil fuels, even though their renewable energies have a significant presence. Fraser[14] used Japanese cities as examples to discuss the drivers of socioeconomics and local policies on energy transition. As a large country, China's policymakers must understand the differences in the energy

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https://doi.org/10.1016/j.isci.2022.105803

transition at subnational levels. China's pledge to achieve carbon neutrality by 2060 is "the most" encouraging climate policy for years.[15,16] The final destination of China's energy future must be in line with the "Dual Carbon" or so called 30/60 goals, namely, to achieve a carbon peaking by 2030 and carbon neutrality by 2060. Owing to the vast differences among China's regions, the progress toward these 30/60 goals will have to be gradual and region specific.[17] Improper timing could lead to unjust or unsustainable energy transitions that undermine the efforts toward the 30/60 goals. For example, the widespread power rationing in some of China's provinces in the second half of 2021 was due to unrealistic energy caps and skyrocketing coal prices. Therefore, China's policymakers must monitor progress at various governmental levels and be able to adjust their policies and align the diversified regional efforts toward the 30/60 goals.

The existing energy transition assessments focus primarily on partial aspects of the energy transition, such as sustainability,[18] energy security,[19] and energy poverty.[20] However, the energy transition includes all of these aspects, and thus assessing it will need multi-level and multi-dimensional metrics. Although the World Economic Forum[21] and World Energy Council[22] proposed various comprehensive measurements of the energy transition among countries, comprehensively quantifying the energy transition progress at the sub-national level—in particular the city level—is still absent. Other transition-related studies at the subregional level focus only on some parts of the energy transition, such as transitional vulnerability,[9] not the full energy transition.

Using China as an example, this study aims to develop a comprehensive sub-national energy transition measurement by examining cities' energy transition indexes (ETIs) from both energy system transition performance and transition readiness dimensions. Following the World Economic Forum,[21] the ETI includes two sub-indexes: the system performance index that measures the maturity of the current energy system to improve system structure and environmental sustainability and the transition readiness index that evaluates the presence of an enabling ecosystem, namely, economic development, capital, technology, and human resources, for effective energy transitions (detailed framework and justifications are presented in STAR Methods). By quantifying the ETI scores of 282 Chinese cities between 2005 and 2015, we provide assessments of China's progress and socioeconomic capability toward feasible energy transitions at the city level. These cities covered 98% of the country's entire population, 99% of its gross domestic product (GDP), and 97% of its CO_2 emissions in 2015.[23] The key methodological novelty is adapting the most comprehensive ETI measure proposed by the World Economic Forum[21] to the city level, making it applicable to the sub-national analysis. Apart from this methodological innovation, our study is of policy significance. First, given that Chinese cities are in a wide range of industrialization and urbanization phases, their experience is informative to other developing economies as they likewise try to reduce their emissions. Second, as China is the world's largest energy consumer and CO_2 emitter, its success (or not) in its energy transition has global implications. Specifically, it is very much a determining factor in the global efforts to meet the 1.5°C target listed in the Paris Agreement.[24]

Our study provides baselines for and quantitative evidence of the spatiotemporal progress in the energy transitions of 282 Chinese cities, and the potential impacts of different future paths. We elucidate how energy system transition progressed and socioeconomic readiness evolved at the national and sub-national levels. We shed light on China's energy transition and decarbonization roadmap by presenting the status quo of energy system performance and transition readiness for different types of cities, and identify four transition statuses: emerging, potential challenges, leapfrog, and leading. We also used the framework to explore the possible improvements if more cities could follow the growth paths of frontier cities within their groups, showing that learning from frontier cities could significantly reduce energy and carbon intensity, and concomitantly CO_2 emissions, in China.

RESULTS

Energy transition patterns in China and 282 cities

Our results indicate that China has improved its national average ETI score over time by approximately 38.1%, from 34.7 in 2003 to 47.9 in 2016 (Figure 1). This corresponds with the findings of the World Economic Forum for China at the national level.[21]

Notably, the scores for the sub-index of *transition readiness* consistently improved over time, reflecting the rapid socioeconomic development in China over the sample period (Figure 1B). However, the scores in the sub-index of *energy system performance* remained stagnant in the 2000s (Figure 1B), shifting to a fast-improving track only after 2011. After China's accession to the World Trade Organization in 2001, its

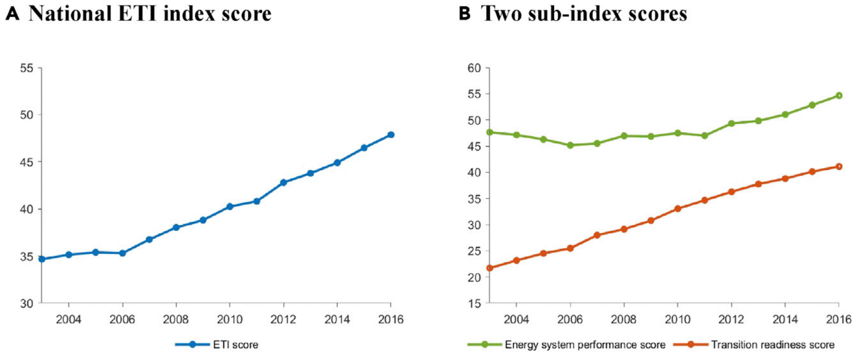


Figure 1. Change in China's national ETI and its sub-index scores from 2003 to 2016

(A) ETI score.

(B) ETI sub-index scores. For more details on generating the national ETI scores, see STAR Methods.

economy experienced rapid growth for more than a decade, inducing rapid energy consumption and CO_2 emissions growth. China's coal consumption dramatically increased from 31.1 EJ in 2003 to a historic high level of 79.7 EJ in 2011. Meanwhile, its CO_2 emissions increased dramatically from 3.5 Bt in 2003 to 8.8 Bt in 2011.[25] The steady improvement in the energy system performance score after 2011 was due to a shift toward a new and more sustainable development model that was initiated by the leadership group.

At the city level, the most recent and representative ETI scores in 2015 show a substantial regional disparity. In particular, Eastern China had a significantly higher ETI score than Western China, whereas Southern China had a higher ETI score than Northern China, suggesting that substantial disparity in progress and socioeconomic capability toward feasible energy transition occurred across different regions (Figure 2 and Table S2). In particular, the Southeast Coastal Area scored higher not only in *transition readiness*, which mainly reflects its socioeconomic development potential for energy transition, but also in *system performance,* which captures the development in the energy systems (Figures S2 and S3). In general, Southern China performed better than Northern China.

The dynamic patterns of the city-level energy transitions since 2005 reveal that although most cities have been steadily transforming their energy systems, the improvements are not consistent across regions (Figure 3). Of the 282 cities, 279 improved their composite ETI score over the 10 years. All 282 cities improved their performances in *transition readiness*. However, 54 cities (19%) experienced a decline in energy system performance, mainly due to their increased reliance on coal or the increased carbon emission during their ongoing socioeconomic developments.[23]

Maintaining steady progress on the energy transition is a challenge for cities. From 2005 to 2010, 19 cities (6.7%) documented a decline in their ETI scores, with 93 cities (32.9%) having worse energy system performance and none of the cities having worse transition readiness. From 2010 to 2015, 17 cities (6.0%) documented a decline in their ETI scores, with 45 cities (16.0%) having worse energy system performance and 16 cities (5.6%) having worse transition readiness. Notably, some cities recorded a decline in the transition readiness score during the 2010–2015 period. In contrast, no city reduced their transition readiness score during the previous five-year period. This is a warning sign indicating that some cities' future energy transition progress will be more difficult than in the past due to the slowdown of the Chinese economy.

Over the decade, the gap between the ETI scores for cities in the top and bottom quartiles remained, if not enlarged (Figure 4). Although most of the cities in the bottom quartile gradually improved, the pace at which they did so was significantly slower than that of their counterparts in the top quartile. The average ETI score for the top 10 cities increased by 18.0, but only 7.9 for the bottom 10 cities. The average ETI score increased by 13.1 for the top 100 cities, but only 11.0 for the bottom 100 cities. The results reflect the fact that there was no convergence in the current energy transition path across cities. This implies that cities that lag behind in the energy transition need extra boosts to their energy transition to not only make progress but also narrow their gaps with frontier cities.

Shenzhen (81.6 in 2015, +9.3 from 2005 to 2015) leads the rankings table for 2005, 2010, and 2015, followed by Hangzhou (79.1, +25.5), and Xiamen (78.8, +20.6) (Table S2). The list of top 10 cities remained roughly the

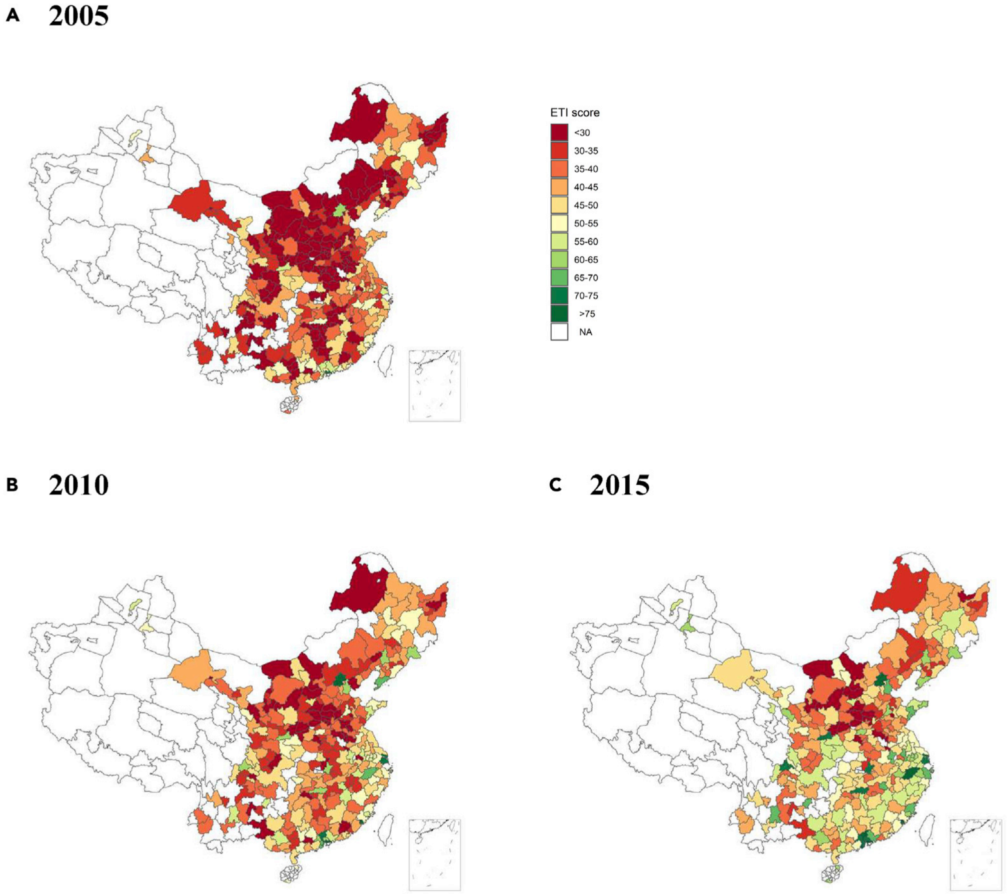


Figure 2. Spatial pattern of ETI scores in 2005, 2010, and 2015 for 282 Chinese cities

(A) 2005.

(B) 2010.

(C) 2015. For more details on generating the city-level ETI scores, see STAR Methods. NA, data not available.

same over the sample period, highlighting the robustness of their energy transition processes. The cities in the bottom quartile are mainly energy production cities located in Central or Western China, such as Huaibei (19.9, +6.2), Jincheng (22.0, +4.6), and Huainan (23.7, +2.3) (Table S2). The results raise the urgency for a proper policy design for these cities. The bottom cities not only have a low level of energy transition performance but also have difficulty keeping pace with the national average energy transition performance. Therefore, special attention should be given to the bottom cities to ensure that they will not become further disadvantaged during the transition process, which is a basic requirement of just transitions.[5,26]

Energy transition roadmap for different city groups

The huge differences in the geographic, economic, and resource (including energy) endowment circumstances of China's regions suggest that the energy transition plans need to be region specific and also take into account the cities' varying industrial structures and economic development situations.[4,17] Recognizing these differences, we combined the official documents (for the energy production cities[27]) with formal cluster analysis as suggested in Shan et al.[28,29] to classify the 282 Chinese cities into five city functional groups according to their industrial output structure, GDP per capita, and innovation and entrepreneurship performance (more details, see STAR Methods): energy production cities (n = 52), manufacturing cities (n = 93), service cities (n = 44), high-tech cities (n = 16), and other less developed cities (n = 77) (Table S2). Our classification results are consistent with those of Shan et al.[28,29] The ETI scores and spatial patterns for these five city groups are presented in Figure 5.

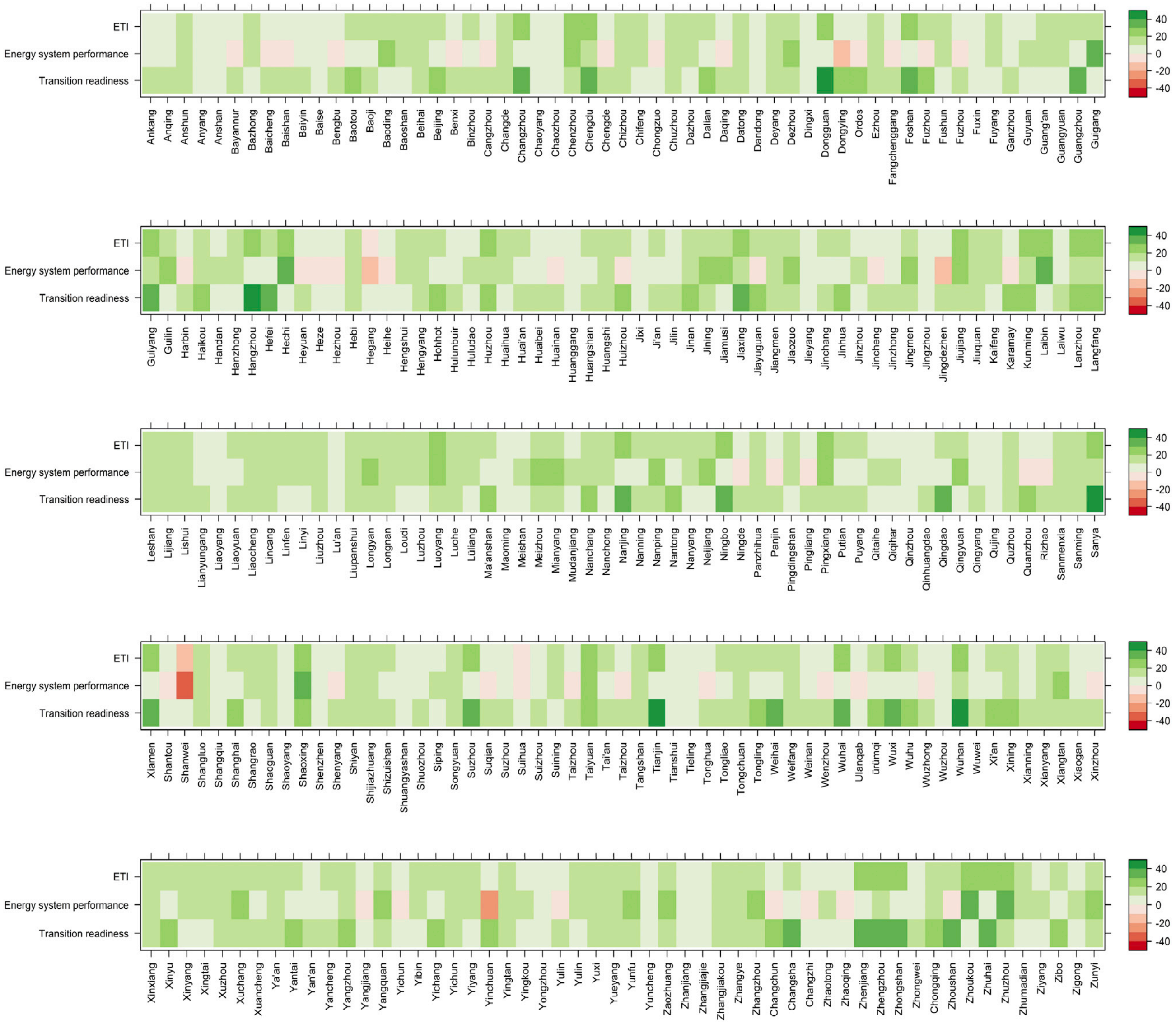


Figure 3. Changes in ETI and its sub-index scores between 2015 and 2005 for 282 cities in China

The color scale shows the change in the ETI scores and ETI sub-index scores. A positive value (green) indicates an increase in the score from 2005 to 2015, whereas a negative value (red) indicates a decrease in the score from 2005 to 2015. For more details on generating the city-level ETI scores, see STAR Methods.

Figure 5A shows the ETI mean values and SDs of the five city groups. The high-tech cities had the highest average ETI scores (71.9), whereas the energy production cities recorded the lowest average ETI scores (36.3) due to their lowest energy system performance and underperforming transition readiness. The service (58.4), manufacturing (45.7), and other cities (44.5) lay between them. Although the energy production cities recorded a significantly lower energy system performance compared with the others, it is the difference in transition readiness that drives the group heterogeneity. The service cities and high-tech cities had significantly higher transition readiness scores than the other three types of cities. Although there is a distinct mean value across the group, a similar variation was documented within each group. The SDs of the ETI scores were 8.6 (energy production), 8.0 (others), 8.1 (manufacturing), 8.5 (service), and 6.5 (high-tech), suggesting that there are potential opportunities to improve the cities' energy transition status by having underperforming cities strive to catch up within each group.

Figure 5B shows the geographical distribution of the cities in each group, and the amounts of CO_2 emissions. The energy production cities are clustered in Northeast and Central China, particularly Shanxi and

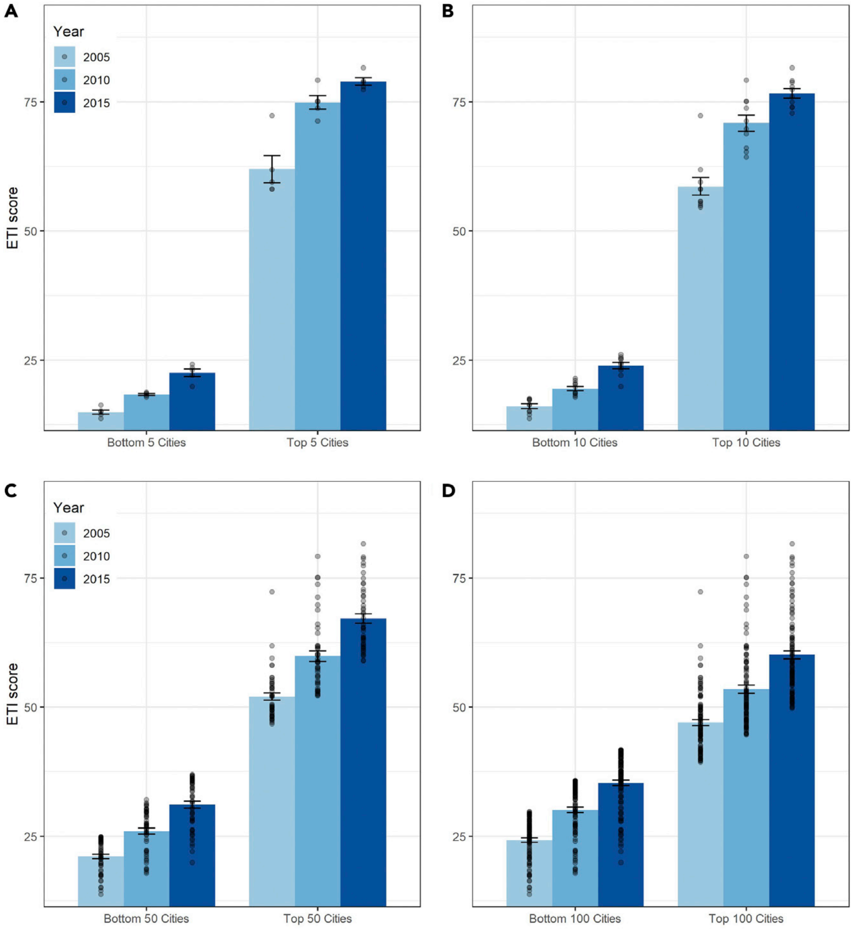


Figure 4. Comparison of average ETI scores for top and bottom cities

(A) The top five (best ETI scores) cities and the bottom five (poorest ETI scores) cities in China in 2005; same cities with 2010 and 2015 data are compared.

(B) The top ten developed (best ETI scores) cities and the bottom five developing (poorest ETI scores) cities in China in 2005, the same cities with 2010 and 2015 data are compared.

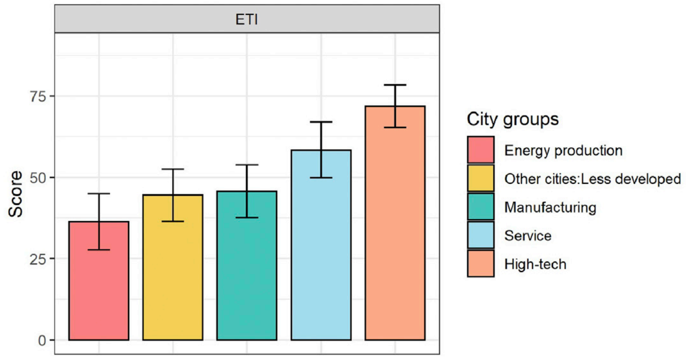
(C) Top and bottom 50.

(D) Top and bottom 100. The vertical lines within the bar indicate the SE for average ETI scores.

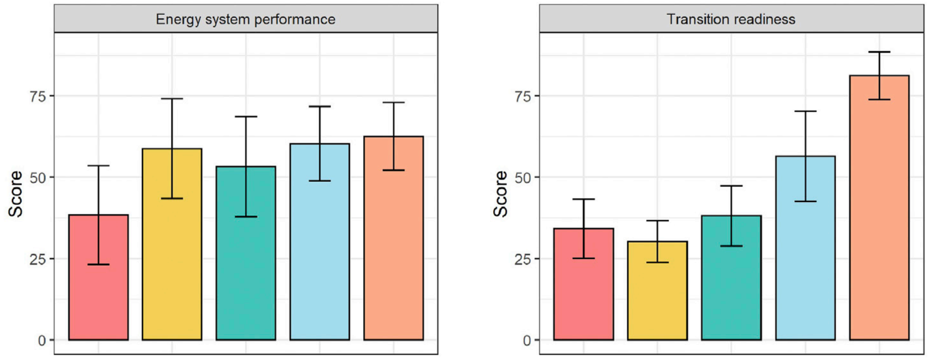
Inner Mongolia. These regions have the highest average emissions per capita (25 t), but the lowest average ETI scores, which suggests that their energy transition is urgent and challenging. In contrast, the high-tech cities are located mainly in economically developed regions, such as Jing-Jin-Ji, Yangtze River Delta, and Pearl River Delta. Given their relatively high emissions per capita (15 t), and the highest ETI scores, these regions should be the leaders in the energy transition. Similarly, the manufacturing cities (12 t CO_2 emissions per capita) that are mainly in the coastal regions should also be prioritized in the energy transition due to their significance of emissions accounts and relatively advanced transition status. The service cities (10 t CO_2 emissions per capita) are quite diverse, and most provincial capital cities fall into this category. The less developed cities (8 t CO_2 emissions per capita) are mainly in Central and Western China. The low emission accounts combined with the low transition readiness scores show that the energy transition policies should not be too radical for these regions.

To further understand the implied status of each city and to design the national transition roadmap, we developed a bivariate analysis framework from the WEF practice.[21] We divided the cities into four quadrants (emerging, leapfrog, potential challenges, leading), based on their relative energy system performance and transition readiness in 2015. The location of the five city types within the four quadrants is presented in Figure 6.

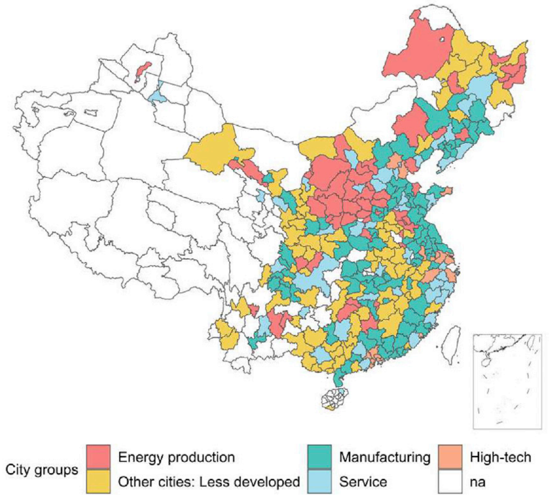
A **ETI scores for different city groups**



B **Two sub-index scores**



C **Spatial patterns for different city groups**



Total Emissions (% of total):

Energy: 3239 *mt* (28%)

Others: 1674 *mt* (15%)

Manufacturing: 3257 *mt* (28%)

Service: 1900 *mt* (17%)

High-tech: 1403 *mt* (12%)

Emissions per capita:

Energy: 25 *t*

Others: 8 *t*

Manufacturing: 12 *t*

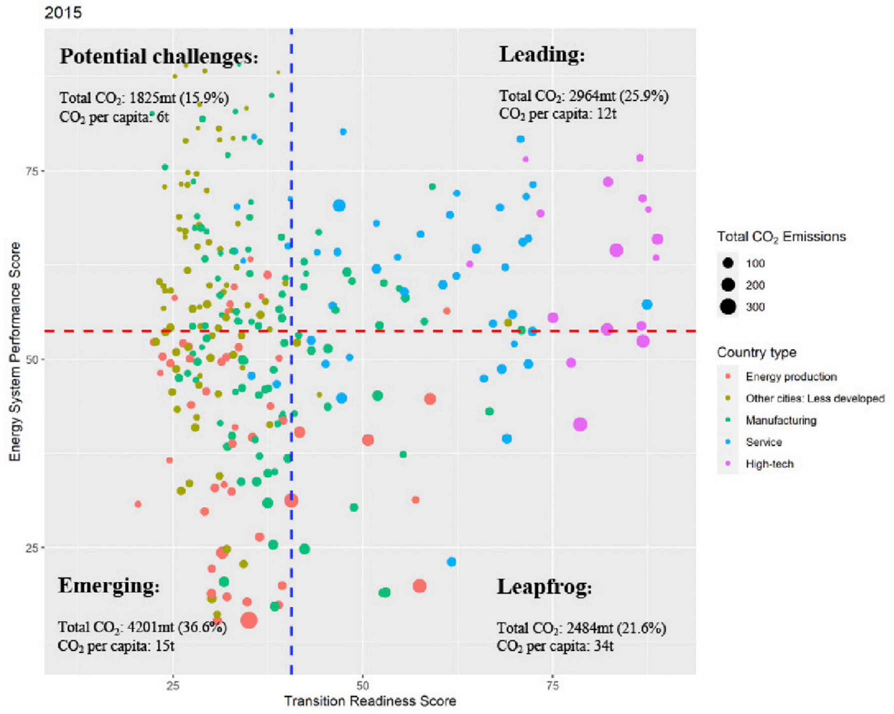
Service: 10 *t*

High-tech: 15 *t*

Figure 5. Energy transition index and spatial patterns for different city groups

(A) Energy transition index for different city groups. The bars present the mean value of the variables; vertical lines within the bar show the +1 SD of the variables. (B) Two sub-index for different city groups. (C) Spatial distribution of five city groups, together with their CO_2 emission accounts.

A Transition status in 2015 for different types of cities



B Data in 2005 **C Change in transition status**

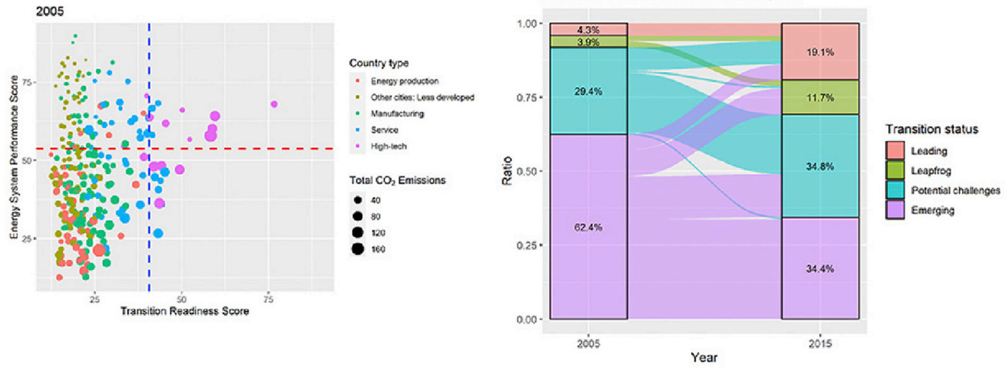


Figure 6. Energy transition roadmap for Chinese cities

(A) Transition status in 2015. The red horizontal line is the mean value of energy system performance score across 282 cities in 2015, whereas the blue vertical line is the mean value of transition readiness score.

(B) Transition status in 2005 with same classification criterion as in (A).

(C) Historical transition path of 282 cities.

Most service cities and high-tech cities, like Beijing, Shenzhen, Guangzhou, and Shanghai, are in the leading status. They have performed well and are ready to further advance their energy transitions. However, despite their leading position in the energy transition, these cities face urgent energy transition needs as their CO_2 emissions are high (25.9% of the national total, 12 t per capita). Fortunately, they have the capacity to further advance their energy transitions, and their emissions are more likely to have peaked or are close to peaking. Thus, they can serve as leaders in China's carbon peaking and carbon neutrality goals.

Most of the energy production cities, such as Hegang, Huaibei, Jincheng, and Tangshan, belong to the emerging country group, which not only has poor energy system performance but also lacks the capacity to further advance energy transitions. This is consistent with the findings in the literature that communities that depend on fossil fuel production are vulnerable in the energy transition.[30] However, these emerging cities have the largest share of national CO_2 emissions (36.6%) and relatively high CO_2 emissions per capita (15 t).

The manufacturing cities and less developed cities are located mainly on the left side of the vertical line, suggesting that low transition readiness is a prevailing characteristic of these two groups. However, about half of the cities in each of these two groups have relatively good energy system performance (potential challenges groups), whereas the other half is in a dire situation similar to that of the energy production cities (emerging group). The differences in the manufacturing cities are due to differences in their pillar industries; those with poor performance in energy system performance have high-polluting or energy-intensive industries (e.g., steel production in Anyang). Those in the emerging and potential challenges groups need to further improve their energy transition readiness. As the potential challenges cities have the lowest share of total CO_2 emissions (15.9%) and lowest CO_2 emissions per capita (6 t), their decarbonization policies need not be extremely stiff.

The few cities in the leapfrog group, such as Suzhou (the one in Jiangsu province), Wuxi, Ordos, and Shijiazhuang, should be incentivized for faster energy transition as they have the capacity to do so while their system performance is relatively poor. For them, the energy transition is feasible and urgently needed due to their largest CO_2 emissions per capita (34 t) and large share of total CO_2 emissions (21.6%) with few numbers of the cities.

Figures 6B and 6C demonstrate the changes in cities' transition status that occurred between 2005 and 2015. Overall, the improvement in city status occurred in all categories, including the energy production cities that were generally considered as facing the most challenges during the energy transition (Figure S5). However, the development paths are quite different for cities with the same initial transition status (Figure 6C). For example, among 176 emerging cities in 2005 (62.4% of all the cities), 79 cities (45% of the emerging cities) have migrated to other categories in 2015, including 17 (10% of the emerging cities) best-performing cities that were even able to migrate to the leading status. Meanwhile, half of the underperforming cities remain as emerging status. Analysis of growth path for each city suggests that decarbonizing the energy system while maintaining socioeconomic developments is practical but has not taken place in all the cities.

Cities' sustainable growth paths and CO_2 reduction capacities

We explored the impacts of lesser performing cities learning from the higher achieving cities (referring to following sustainable development paths) on the energy transition status, and estimated CO_2 reduction capacities in China. We formulated the following three scenarios. The national frontier scenario (S1) is the most desirable scenario in which each city follows the paths of the national top 20% cities (the top 20% of cities are selected by changes in ETI scores over the sample period; for more details and explanations, see STAR Methods). In the group frontier scenario (S2), each city follows the growth paths of the top 20% cities within its group (e.g., top cities within the energy production group). The group catch-up scenario (S3) focuses on the catch-up of those below their group average and assumes that they follow the average paths of their group. The lists of the selected top cities are given in Table S3.

Figure 7A shows that China's transition level could be enhanced by 6.9 p.p. and 5.5 p.p. (percentage points, equal to 14.8% and 11.8%) if each city could follow the path of the country or city group frontiers in achieving inclusive development paths, despite the fact that the scale and drivers of mitigation vary across cities and city groups. The difference in ETI score improvements (6.9 vs. 5.5) is caused mainly by the difference in transition readiness between the group frontiers and national frontiers, suggesting that extra socioeconomic development is possible alongside decarbonizing the energy system. The extra socioeconomic development is carried out mainly by the service and high-tech cities (e.g., Shaoxin, Wuhan, Hangzhou, Table S3), whose development paths we capture as national frontiers.

Notably, the energy transition that accounts for group characteristics (S2) can deliver significant decarbonization benefits without forcing all cities to follow national frontiers (S1), which may have significantly different characteristics. This is due to the large dispersions in energy system performance and the heterogeneous development models that cities within each group have adopted (Figures 5 and S5). In particular, in the S1 and S2 scenarios, China could achieve significant decarbonization while the share of coal in the energy mix could fall by 8% and 6%, energy intensity could drop by 35% and 34%, carbon

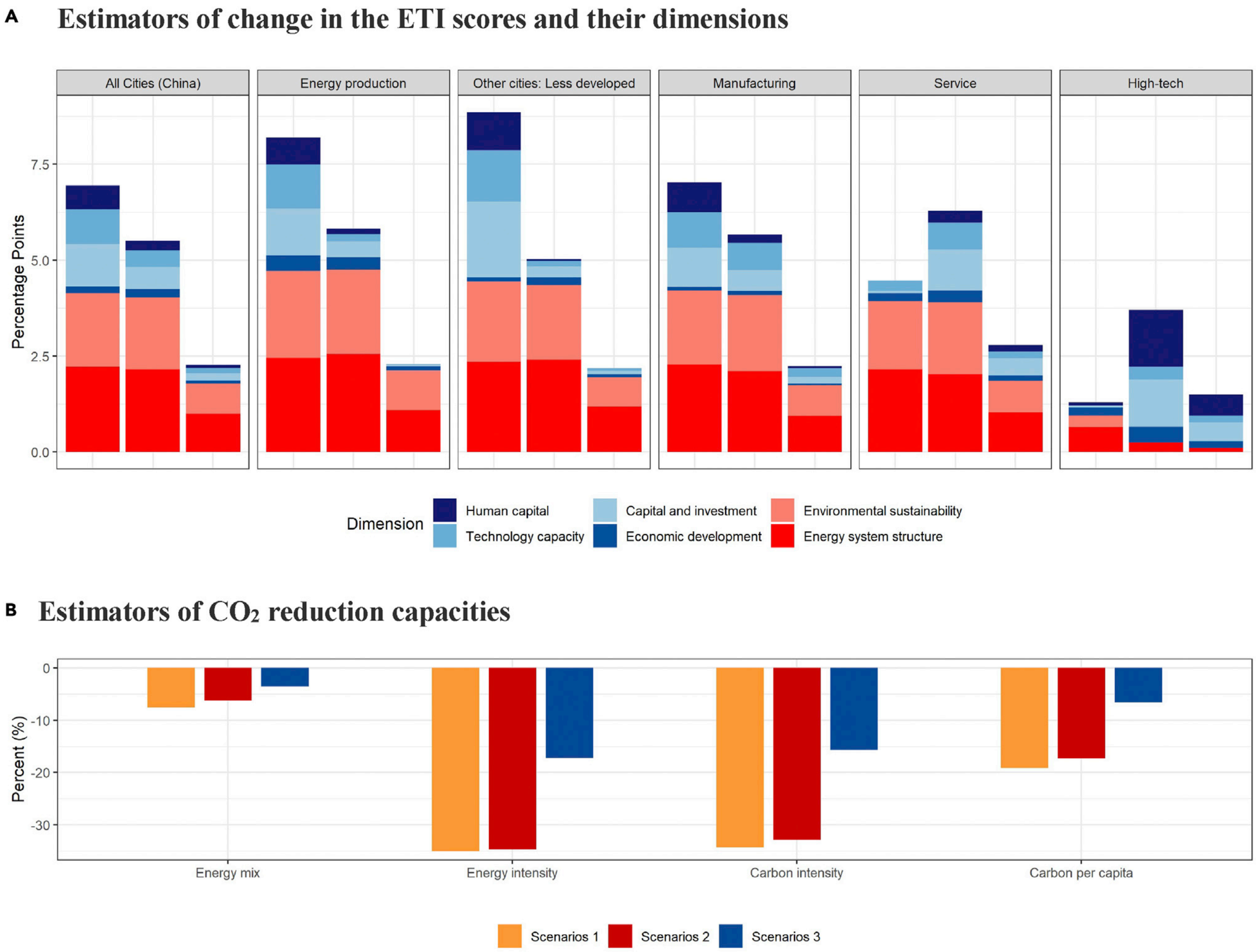


Figure 7. Estimators of changes in the ETI score and key variables when adopting different sustainable development paths

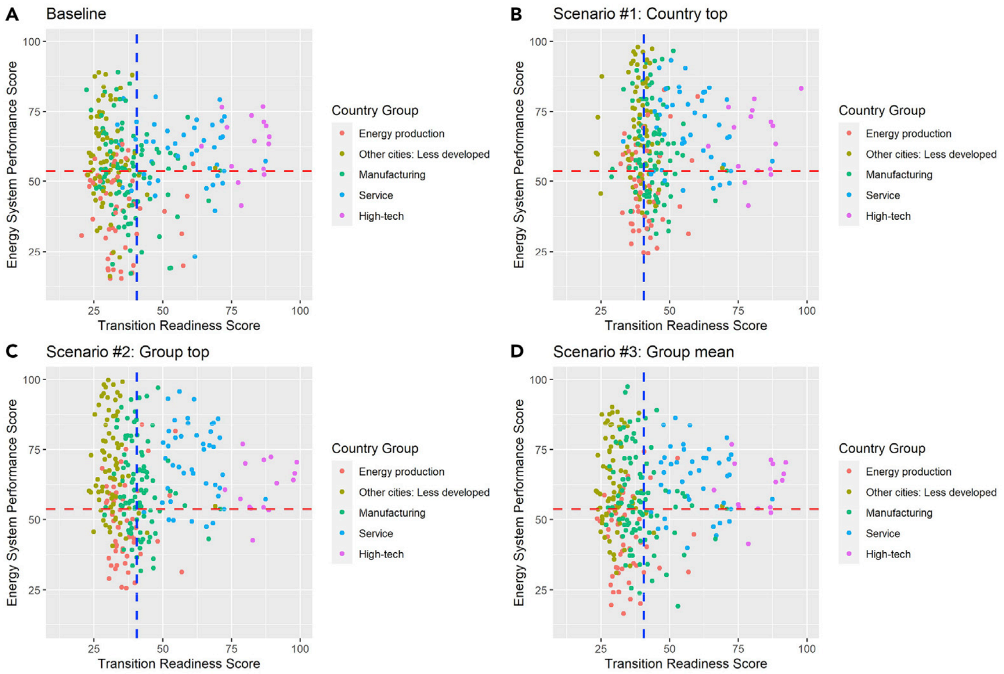
(A) Changes in the ETI scores and their dimensions. The red color refers to the dimensions that belong to the sub-index of energy system performance, whereas the blue color refers to the dimensions that belong to the sub-index of transition readiness.

(B) CO_2 reduction capacities when adopting different sustainable development paths.

intensity could decrease by 34% and 32%, and carbon per capita could decline by 19% and 17%, respectively (Figure 7B).

In the group catch-up scenario (S3) where cities below average are catching up with the group average, although the improvement was the smallest among the three scenarios, it could still lead to measurable progress in China's decarbonization. More specifically, with the ETI score increasing by 2.3 p.p., the share of coal in energy mix, energy intensity, emission intensity, and per capita emissions in S3 will decline by 3.5%, 17.3%, 15.6%, and 6.6%, respectively. Note that this is the least challenging scenario as only the bottom cities need to catch up with their group average.

The changes in cities' energy transition status under the three scenarios are reported in Figure 8. The cities that are struggling the most with their energy transitions, namely, the emerging cities, the ratio could reduce from 34.4% in 2015 to 11.3% (S1) and 19.1% (S2), respectively. Meanwhile, the ratio of leading cities could increase from 19.1% in 2015 to 42.6% (S1) and 30.1% (S2). In the less ambitious scenario where those below the group average catch up to the group average (S3), the share of the emerging group declines by 5.0%, and share of leading group increases by 3.6%. Our estimators imply that learning from frontier counterparts leads to progress in decarbonization in China's cities, therefore contributing to global climate actions.



E **Changes in transition status**

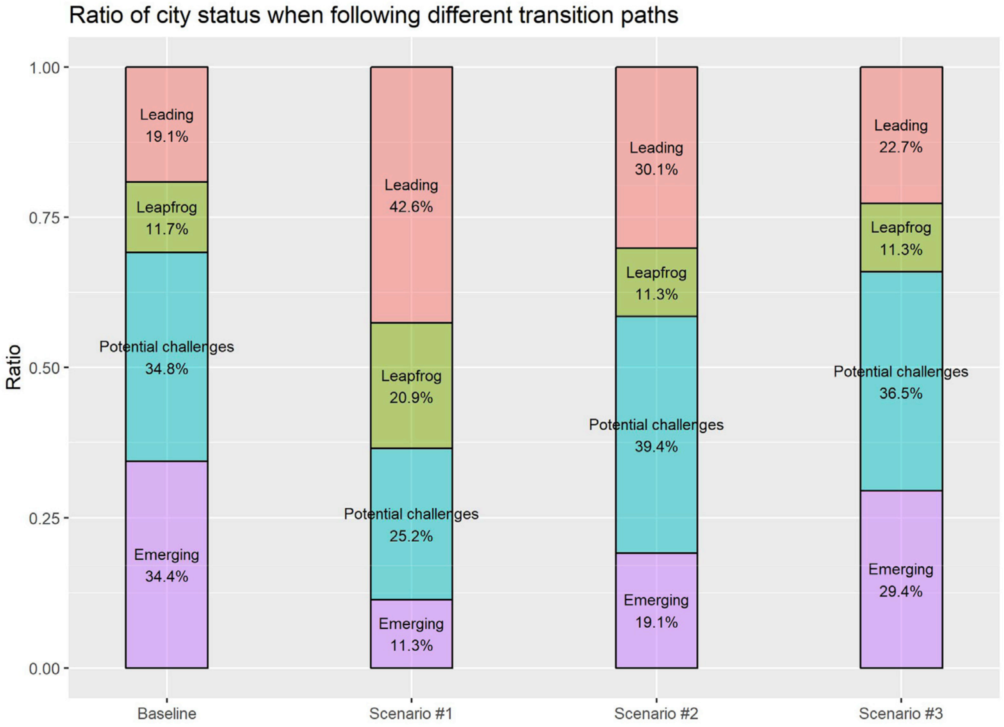


Figure 8. Changes in transition status when adopting different sustainable development paths

(A) Data in 2015.

(B–D) Changes of transition status for 282 cities in three scenarios.

(E) Changes of ratios of different transition groups, compared with the data in 2015.

DISCUSSION

In this article, we present measures of transition toward low carbon energy systems for 282 Chinese cities by merging the most detailed and up-to-date city-level accounts of CO_2 emissions and energy data with comprehensive official socioeconomic indicators. Our results indicate that China has improved its national average ETI score by approximately 38.1%, from 34.7 in 2003 to 47.9 in 2016. The achievement is due to the consistent advancements in transition readiness over the sample period combined with the improvements in energy system performance after 2011. At the city level, our results show that large heterogeneity exists across space and city types. The underperforming cities are mainly energy production cities clustered in Central or Western China (e.g., Huaibei, Jincheng, and Yulin), whereas the top performing cities are mainly in Eastern China and are pillared with high-tech or service sector (e.g., Shenzhen, Xiamen, and Hangzhou). The gap between the cities in the top and bottom quartiles is persistent over the decade.

Analysis of the development paths shows that city energy systems can be decarbonized without hindering or discouraging socioeconomic development, but that this has not taken place in all the cities. Take two energy production cities as examples; Pingdingshan in Henan province achieved decoupling of economic growth and CO_2 emissions in its development (its emissions decreased by 24.6%, whereas its GDP per capita increased by 27.2% from 2010 to 2015). In contrast, Shuozhou in Shanxi province exhibited the coupling of economic growth and emissions (its emissions increased by 142.3%, whereas its GDP per capita increased by 24.7% from 2010 to 2015). Overall, we estimate the CO_2 reduction capacities and show that China's energy and carbon intensity could decrease by 34% and 32%, respectively, whereas per capita carbon emissions could fall by 17% if each city could follow the sustainable development path of frontier cities with similar economic structures. From the decarbonization perspective, group-specific policies that encourage cities to follow their group leaders, such as the "Top Runner" program initially implemented in Japan,[31] are desirable to promote green development in cities. Specifically, China's current New Development Philosophy should uphold green growth requirements for industrial cities that are still growing, and for the less developed cities.

Given cities' heterogeneity, specific low-carbon roadmaps are needed instead of one-size-fits-all approaches to achieve China's carbon peaking and carbon neutrality goals. Cities should be mandated with different emissions reduction and energy transition targets depending on their current energy system performance and transition readiness. The common and differential responsibility principle that is well established in international climate negotiations should be applied when setting targets for cities. Cities that are advanced in their energy transition (such as Shenzhen, Suzhou, Wuxi) can play a leading role in China's progress toward carbon peaking and carbon neutrality because they may have already reached their emission peaks or are close to doing so while having the highest capability to reduce their emissions.

Energy transition policies should prioritize cities that have lagged in their energy transition in terms of either energy system performance or transition readiness. Our identification of cities that fall into the lagging groups (such as Hegang, Jincheng, Huaibei, and Yulin) is the first step to help them. For example, as energy production cities face the most difficult challenges in their energy transitions, they should be discussing ways to improve their energy system performance and transition readiness. On the performance side, energy producing cities should promote economic restructure to achieve lower carbon energy mix and reduce energy and emission intensities. On the transition readiness perspective, resource cities could attract investment, human resources, and technology to boost their economic development level and future growth potential.

As cities are at the core of successful implementation of the SDGs, and face multiple, often competing dimensions,[32] to achieving their energy transitions, a holistic approach is needed. Currently, local governments often separate policy and implementation[33] and suffer from a lack of integrated, cross-sectorial views.[34] To advance cities' energy transitions, a holistic approach will improve energy system performance and transition readiness, and turn high readiness into good system performance from at least six dimensions including energy, environmental performance, economic development, investment, technology, and human capital. These approaches include supply-side strategies, such as renewable power generation and resilient transmission and distribution networks, and demand-side strategies, such as building energy-efficiency technologies and applications, low-carbon urban designs and infrastructure, and behavioral changes.[35] To advance their energy transitions, cities must also overcome the widespread inertia, or "carbon lock-in effect," which currently pervades cities' physical and institutional systems.[36] Operationally, this transition justice can be better delivered by community-led, bottom-up responses than government-led, top-down approaches.[12]

As countries act to control the economic and social consequences of COVID-19, the situation today could provide an opportunity for cities to leapfrog into their energy transitions. Applying economic stimulus to energy infrastructure modernization, research and development, and human capital development could deliver long-term sustainable economic growth and also cause step changes in the energy transition. Such recovery packages could be aimed at cities that are lagging in the energy transition. Green economic stimulus will not only deliver the joint benefits of economic growth and emissions reduction, but could also facilitate more just transitions by assisting vulnerable cities in their transition process.[23,37,38]

Limitations of the study

Admittedly, this study also has the following limitations; therefore, improvements on these aspects in future research may provide more accurate assessments of the city-level energy transition. First, due to the data limitation, this study did not include explicit measures on the renewable energy industry or its development potential in each city. Appropriately incorporating these dimensions and indicators (e.g., cumulative solar photovoltaic and wind capacity, renewable power generation, and jobs created in the renewable energy industry) into our index system can possibly improve the results. Second, our study primarily aims to build a valid index system that captures the key aspects of the energy transition for each city while considering the country-specific features in China (e.g., the high reliance on coal in China's energy system). The index system proposed in this article may need careful adaptation before being applied to assess the city-level energy transition in other countries.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2022.105803.

ACKNOWLEDGMENTS

This study was supported by National Natural Science Foundation of China (72104184, 72174056, 72074069), and Interdisciplinary Joint Research Fund of Tongji University (2022-4-YB-14). We especially thank the editor and the anonymous referees for their careful review and insightful comments. We also thank Z. L. Liao for helpful discussions and Y. N. Chen for excellent research assistance.

AUTHOR CONTRIBUTIONS

Conceptualization, Y. Shen and X.S.; methodology, Y. Shen and X.S.; formal analysis, Y. Shen, and Z.Z.; investigation, Y. Shen, X.S., and Z.Z.; data curation, Z.Z., Y. Shan, and Y. Shen.; writing – original draft, Y. Shen and X.S.; writing – review & editing, Y. Shen, X.S., Z.Z., Y. Sun, and Y. Shan; funding acquisition, Y. Shen, X.S., and Y. Sun; supervision, X.S. and Y. Shan.

DECLARATION OF INTERESTS

The authors have no conflicts of interest to declare.

Received: August 3, 2022
Revised: November 8, 2022
Accepted: December 9, 2022
Published: January 20, 2023

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Note: The sources the complete data set can be found in Supplemental information (Table S1)		
Software and algorithms		
R 4.2.1	R Core Team, 2022	https://www.r-project.org/

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Xunpeng Shi (Xunpeng.Shi@uts.edu.au).

Material availability

This study did not generate new unique materials.

Data and code availability

This paper analyzes existing, publicly available data which are listed in the key resources table. Code and ETI scores generated by our analysis are available from the lead contact upon request. Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

METHOD DETAILS

City-level ETI framework

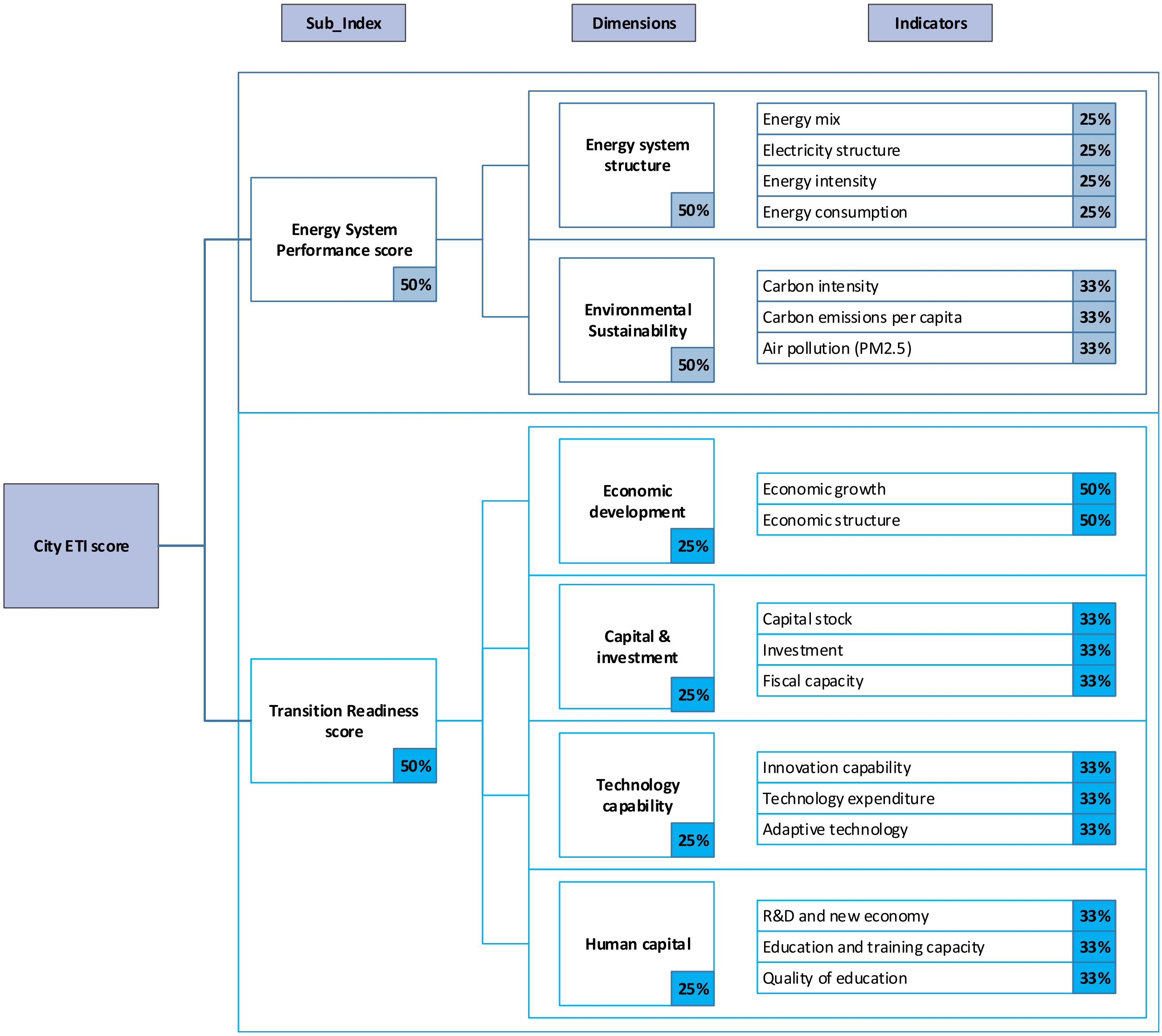
Our city-level energy transition index (ETI) framework was developed from the national ETI proposed by the World Economic Forum (World Economic Forum, 2022). We modified the conceptual framework to fit the city context. The World Economic Forum's ETI is a composite score aggregating 40 variables that benchmark energy transitions among countries from two *sub-indexes* — current energy "system performance", and their readiness for further energy transition ("transition readiness") — with variables carrying equal weights applied hierarchically. Its "system performance" part measures three *dimensions*: economic development and growth, environmental sustainability, and energy access and security; while its "transition readiness" part measures enabling factors from six dimensions including regulation and political commitment; institutions and governance; capital and investment; infrastructure, innovation, and business environment; human capital and consumer participation; and energy system structure. Each of these dimensions is measured by at least two to five indicators.

We adopted the two sub-indexes from the WEF-ETI framework—energy system performance and transition readiness. However, we initiated several variations at the dimensional levels. First, we did not consider three dimensions that are not applicable at China's subnational level. Two dimensions in the "system performance" part of the WEF-ETI –regulation and political commitment and institutions and governance are homogenous in a centralized country like China and are thus not applicable at China's subnational levels. Additionally, the "energy access and security dimension" in the "system performance score" part was not selected because China has achieved universal electricity access.[39]

Second, among the remaining six dimensions, we swapped the economic development and growth with the energy system structure for better alignment with the name. In the WEF-EFI,[21,40] "economic development and growth" measures the energy sector's role in national economic growth. The indicators that measure the "economic development and growth" dimension, including GDP contribution, industrial competitiveness, household affordability, subsidies, and externalities are not different at the city level in

China. The available economic indicators at China's city level — economic growth and economic structure — indicate the macro-economic capacity for future transition. Thus we included them in the energy transition readiness sub-index. In contrast, we regard the energy system structure as being more a measure of energy system performance than transition readiness.

In sum, our conceptual framework of city-level ETI measures have two sub-indexes, six dimensions and 18 components. Each component is described by one or several indicators. In all, we collected 29 indicators. For each of the sub-index and dimensions, we adopted those in the WEF-ETI framework or close proxies or equivalents in China's prefectural regions. For each of the sub-index and dimensions, we adopted those in the WEF-ETI framework or their close proxies or equivalents in China's prefectural regions. The indicators that measure each dimension may be modified to reflect the energy transition at the Chinese city level, or data availability. (See Table S1 for detailed definition of each indicator). Our ETI framework is summarized in the following chart.



The energy system performance measures the status of cities' energy systems in terms of energy transition, and the transition readiness measures the preparedness of cities for future energy transition. The system performance sub-index consists of two dimensions: energy system structure and environmental sustainability. The environmental sustainability is defined the same way as for the WEF-ETI framework. The energy system structure in our cities' ETI framework is also similar to that in the WEF-ETI except for the growth of energy demand which is not a snapshot of the energy transition status. Each dimension is evaluated by critical components related to the energy transition according to the existing literature. In particular, the energy structure is measured by the energy mix and power generation mix from the production side, and energy consumption and energy intensity from the consumption side. Meanwhile, environmental sustainability is measured by air pollution, a key negative consequence of fossil fuel consumption, and two comparable emission indicators, emissions per unit of GDP and emissions per capita. See International Energy Agency[41] for similar measurement of energy transitions.

The transition readiness sub-index is quantified by four dimensions, three of which are typical factors in production functions, and can be adapted to measure the socioeconomic capability for transition: capital and investment, technology capacity, and human capital.[42] Again, each dimension is evaluated by critical components related to the energy transition according to the existing literature. In particular, the capital and investment dimension measures the monetary resources that can be mobilized to support the energy transition in the financial market (capital stock), the energy sector (investment) and government (fiscal capacity) (e.g., Polzin and Sanders[43]; Fadly[44]; Tian et al.[45]). The technology capacity dimension measures both specific ready-to-use technology (adaptive technology), and economic resources (technology expenditure) and technology potential (innovation capacity) to develop new technologies (e.g., Babayomi et al.[46]; Hoggett[47]; Kittner et al.[48]). The human capital dimension includes both human resources in R&D as well as new economy, education and training capacity that facilitates human capital transition, and quality of education that determines the productivity of human resources (e.g., Jin et al.[49]; Hao et al.[50]; Shahbaz et al.[51]; Yao et al.[52]). The economic development dimension broadly measures the macroeconomic condition that adapts to the challenges from the energy transition, including whether the economy is fast changing (economic growth) and whether the economy is relying heavily on the extractive and mining sectors (e.g., Carley et al.[9]; Carley and Konisky[5]; Davidson[53]; Markard[54]). A city with high level of GDP will have more resources and higher capacity to adapt to unfavorable changes from the energy transition. Furthermore, a city on the fast track of economic growth would have faster growing adaptive capacity to copy with the possible shocks from the energy transition, which results in a higher level of transition readiness. Our broad definition of transition readiness could be an advantage over the WEF-ETI framework at the city level as the literature finds that while decarbonization is the core part, the energy transition also requires the support of infrastructure and investment; technologies and innovations; policy, institutions, and governance; and market incentives and public education.[2,3]

Calculation of city-level ETI scores

In this paper, 282 prefecture-level cities in China were selected as the research sample. The city-level energy and carbon emissions data from 2003 to 2016 were retrieved from Shan et al.[23,55–57] and CEADs (www.ceads.net). Specifically, the calculation of territorial carbon emissions in this paper was based on 17 types of fossil fuels and seven industrial processes. Moreover, the cities' carbon emissions inventories were constructed with 46 socioeconomic sectors. The socioeconomic and environmental data came mainly from the *China City Statistical Yearbook* and Atmospheric Composition Analysis Group (http://fizz.phys.dal.ca/~atmos/martin/?page_id=140). The data about innovation capability were taken mainly from the Peking University Open Research Data Platform (https://opendata.pku.edu.cn/file.xhtml?fileId=10543&version=4.1) and the Chinese Research Data Services (CNRDS) Platform (https://www.cnrds.com/Home/Index#/). More details of data extraction can be provided by the corresponding authors upon request.

We adopt standard composite index analysis to construct the city-level ETI scores. Composite index analysis has been adopted by many international organizations to generate the cross-entity comparable index, e.g. Human Development Index (HDI), Sustainable Development Goals (SDG) index published by the United Nations (UN), and national ETI scores published by the World Economic Forum (WEF). In particular, we adopt three interrelated steps for calculating city-level ETI scores.

Step 1: Indicator collection and data sources. Following the developed conceptual framework, we collected indicators for each ETI component from authoritative energy, environmental, and socioeconomic data sources. Each component is described by one or several indicators with equal weight. The indicators were selected on the basis of relevance to our conceptual framework and of data availability across cities and time. Our final list of indicators included a total of 29 energy transition indicators from 2003 to 2016 (for more details, see Table S1). Our dataset provides the emissions inventories and socioeconomic accounts of 282 Chinese cities; these cities covered 98% of the population, and their GDP and CO_2 emissions accounted for 99% and 97% of the national values in 2015, respectively. Most of the studied cities are located east of the Heihe-Tengchong line, where 96% of China's population lives on 43% of the land.[58] The 282 cities were selected on the basis of data availability.

Data for the selected indicators in this study were obtained from the following authoritative sources: The National Bureau of Statistics of the People's Republic of China, China Statistical Yearbook, Finance 'Yearbook of China, China Statistical Yearbook on the Environment, Educational Statistics Yearbook of China, China Health Statistics Yearbook, China Energy Statistical Yearbook and China Population Statistics Yearbook. See Table S1 for a list of ETIs and their corresponding indicators, and the data sources used in this paper.

Step 2: Normalization of indicator values. To ensure comparability across different ETI dimensions, the indicator values for each ETI dimension were normalized to a standard scale ranging from 0 (the worst performance) to 100 (the best performance). Following the general practice as for the HDI and SDG index, we adopted the min-max method to transform the data. In particular, we used the following two formulas to normalize ETI indicator values on a common scale of 0-100:

$$x' = \frac{x - min(x)}{max(x) - min(x)} \times 100, \qquad \text{(Equation 1)}$$

$$x' = \frac{max(x) - x}{max(x) - min(x)} \times 100, \qquad \text{(Equation 2)}$$

where x is the original data value of each ETI indicator, max/min represents the upper/lower bounds for the best/worst performance, and x' is the normalized individual score for a given ETI indicator. Equation 1 is valid for indicators with higher values representing better performance (e.g. GDP per capita); Equation 2 is valid for indicators with lower values representing better performance (e.g., energy intensity). We adopted common top and bottom 2.5th-percentile performers as the upper and lower bounds for all the indicators when presenting baseline results. The 2.5th-percentile has been used in previous studies[59,60] to minimize the potential effects of skewed data distributions on the standardized values during normalization. We also experimented with the alternative upper and lower bounds such as the 1st and 99th percentile, and 5th and 95th percentile in robust analysis (Figure S1).

All normalized values greater than the upper bound received a score of 100, and all normalized values less than the lower bound received a score of 0. Values between the upper and lower bounds were distributed along the spectrum from the worst performance (score 0) to the best performance (score 100). An indicator with a score of 50 is halfway towards achieving the best performance. The normalized scores can be used to evaluate relative performance over time and space towards achieving the energy transition. For example, if for a particular ETI indicator a city lagged behind all the other cities in both 2005 and 2015, but improved over time, its score for that ETI indicator in 2015 would be greater than its score in 2005, but in both years, its score would be lower than that of the other cities.

Step 3: Calculation of ETI scores in China and 282 cities. We calculated ETI scores using arithmetic means, following the approach used in the World Economic Forum Report.[21] In particular, we calculated ETI Index scores by combining two sub-indexes using arithmetic means with equal weight. Within each sub-index, all ETI dimensions were weighted equally to convey the importance of integrated solutions that address all six ETI dimensions. Consistent with previous research,[9,40,59] within each sub-index, there is no a priori reason to give one dimension greater weight than another. Within each ETI dimension, each indicator is equally weighted. This means that every indicator is weighted inversely to the number of indicators available for that ETI. We experimented with the geometric mean instead of the arithmetic mean when generating the ETI in robust analysis (Figure S1).

At the city level, we aggregated each city's two ETI sub-index scores for 2005, 2010, and 2015, separately, yielding three ETI scores per city (Figure 2). At the national level, we averaged China's 282 cities' ETI scores into one national ETI score for each year from 2003 to 2016, yielding 14 national ETI scores (Figure 1). We reported each city's ETI score for 2005, 2010, and 2015 – three periods instead of 14 continuous years – to avoid the abnormal jumps for indicators in a particular year with the city-level data. The median value for the corresponding period was used to eliminate the outliers. For example, we used the median value between 2003 and 2007 to represent the indicator value in 2005. In addition, we calculated the scores of two sub-indexes and six dimensions with the same method for China as a whole and 282 cities.

Sensitivity analysis for ETI scores

The robustness of the ETI scores can be tested by taking uncertainty factors into consideration and conducting a sensitivity analysis. We tested the composite index's level of sensitivity to various changes in parameters – different upper and lower bounds, weighting schemes, aggregation methods and a successive exclusion of indicators. In particular, we experimented with the alternative upper and lower bounds of 0.01 and 0.99, 0.05 and 0.95. We also experimented with the geometric mean instead of arithmetic mean when generating the ETI. In addition, we experimented with a successive exclusion of six dimensions in the ETI framework to check if the results were sensitive to one particular dimension. The resulting variation of countries' scores and rankings are depicted in Figure S1. Overall, our results are generally robust to reasonable changes in the way we constructed the index.

Extracting the sustainable development paths from the frontier cities

Changes in the ETI score over time provide a proxy of the development pathway that a city chooses, which is summarized from two dimensions of improvements in the energy system and socioeconomic conditions. In scenario analysis, we assessed the impact of the different development pathways that cities adopt on the transition status and national energy and environmental variables. For example, for Scenario #2 (S2, cities group frontier scenario), we experimented to see if each city follows the pathway of the top 20% cities in their city group. First, we extracted the top 20% cities for each city group based on the changes in ETI score (Table S3). Second, we averaged the changes in all of their indicators, and generated the top growth pathway for each group. Third, we applied the group's top growth pathway for the rest of the cities in the group and calculated the changes in the results of interest, e.g. the ratio of emerging countries and new level of national emissions.

Although the magnitude of change in the ETI score serves as a good rule of thumb proxy for a sustainable development path, it may suffer abnormal movement in one of the two sub-indexes due to the nature of the arithmetic mean. Here we also experimented with the geometric mean of the changes in two sub-indexes instead of the arithmetic mean to choose the top cities (Supplementary S.6.2). Overall, the two methods led to robust results.

Cluster analysis for city classification

Cities are commonly clustered into different functional groups in order to reveal the spatial patterns and simplify the policy design. The advantage of cluster analysis is that it groups samples with a set of indicators rather than a single one. The basic rationale of cluster analysis is to group samples with similar attributes. The samples within the groups will be close together geometrically, while the statistical distance between groups will be farther. The statistical distance is measured by distance metrics, such as Euclidean distance, Manhattan distance, and Minkowski distance. A *K*-means algorithm is one of the cluster algorithms in which the desired number of clusters could be specified in advance before choosing the "best" solution. Cluster analysis has been widely used in econometrics and other interdisciplinary studies. For example, in the carbon emission studies, Ramaswami et al.[61] used GDP share to classify 285 Chinese cities into 38 industrial cities, 44 commercial cities, and 203 mixed-economy cities to discuss city-level emissions. Shan et al.[28] used cluster analysis with a *K*-means algorithm to divide 182 case cities into five city groups with different pillar industries and development pathways.

Here, we combined the official documents with the formal cluster analysis as suggested in Shan et al.[28] to classify the 282 Chinese cities into different functional groups: energy production, manufacturing, service, high-tech and other less developed cities. First, the energy production cities were defined by the official documents.[27] Second, we applied the formal cluster analysis with a *K*-means algorithm according to five dimensions: ratio of value-added in the manufacturing sector, ratio of value-added in the service sector, GDP per capita, regional innovation and entrepreneurship index, and ratio of R&D employments. We used a *K*-means algorithm implemented using the Euclidean distance metric to group cities in this study. According to a previous study on the comparison of different distance metrics used in *K*-means algorithms,[62] the Euclidian distance metric's performance is better than others. The package ClusterR in R software was used to generate the results.

Table S2 presents the classification results. Overall, we documented energy production cities (n=52), manufacturing cities (n=93), service cities (n=44), high-tech cities (n=16), and other less developed cities (n=77). Our classification results are consistent with those of Shan et al. (2018). Meanwhile, the results are able to capture the key stylized factors. For example, the four first-tier cities (Beijing, Shanghai, Guangzhou, Shenzhen) were all identified as high-tech cities. The service cities are mainly provincial capital cities. The service and manufacturing cities are mostly along the eastern coast or in Southern China.