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Highlights

Marginal abatement cost curves of CO_2 for over 500 4-digit industries are measured

An industry rollout plan is suggested based on abatement cost savings through ETS

China's current ETS expansion plan does not minimize China's total abatement cost

Average abatement cost can be reduced by 39–78% in the revised included industries

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Optimizing the rolling out plan of China's carbon market

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SUMMARY

Although China has developed the world's largest carbon emissions trading scheme (ETS), there is no official documentation explaining how the current sectoral coverage plan was determined and what sectoral rollout plan is preferred. Here, we contribute to the policy development of the world's largest carbon market by suggesting a priority list of industries be covered in the ETS. We estimated marginal abatement cost curves using a database of more than two million firms covering over 500 four-digit industries that account for more than 97% of total industrial emissions, and simulating various carbon market scenarios including thermal power, 13 designated, and an additional 50 industries that have high emissions or are covered in other ETSs. Our analysis suggests that the cement industry should be the next sector to be included in China's ETS. In our revised list, the average abatement cost can be reduced by 39.5–78.3% compared with the business-as-usual scenario.

INTRODUCTION

Carbon emissions trading schemes (ETS) are a preferred instrument for achieving targeted CO_2 reductions.[1] In designing an ETS, sectoral coverage is a key decision which has to be balanced between broader coverage for higher effectiveness and reasonable administrative costs and data availability.[2,3] China is facing such a decision and provides a good example of how an ETS can perform and how it should be rolled out. Despite being the largest ETS in the world in terms of regulated emissions, China's ETS rollout plans are under-studied. China has announced its intention to expand the national ETS to eight energy-intensive sectors, including 14 four-digit industries,[4] hereafter designated industries. The power generation sector underpinned the first phase of the national ETS launched on 16 July 2021.[5] However, there was no official explanation of how China selected the designated sectors and industries and how the other sectors will be included in an expanded ETS. A case study of China's ETS can inform future ETS development in other countries.

Despite the increasing number of studies of the potential sectoral coverage in China's ETS,[6,7] there is a gap in the literature regarding the sectoral rollout plan. There are many studies that have calculated the effects and benefits of been covered sectors by China's ETS.[8,9] It seems that the selection of the sectors to be included in the ETS was based mainly on the size of emissions, whereas the cost-effectiveness of emissions reduction, i.e., abatement cost savings from the ETS, the central feature of carbon markets, was not considered. For example, the central government designated seven ETS pilots launched in the first stage based on total emissions or total energy consumption as a key criterion to determine whether a firm should be included in the ETS.[10] The abatement cost of each industry can be considered as its sacrificed total industrial output. Without ETS, each of the *n* industries to be covered by the ETS needs to reduce the same proportion of carbon emissions according to the principle of the grandfather method, and they will sacrifice different total industrial output and their marginal abatement costs (MACs) are different. Then, assuming that these *n* industries are included in the ETS, industries with low marginal abatement costs will reduce more, vice versa, until all industries have equal MAC. The abatement cost saving between the two scenarios is measured as the ratio to total industrial output. Compared to only making decisions based on the overall size of the industry's emissions, our indicator identifies the *n* industries that should be prioritized for inclusion in the ETS to minimize the total sacrificed industrial output and reduce China's total abatement costs. However, many of these sectors have not been identified and considered in the ETS plan.

Few studies have considered which sectors should be included in China's ETS and how to roll them out. Although the ETS and related issues have been widely studied, the choice of ETS coverage is unexpectedly

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under-examined, and emissions reduction characteristics of firms have seldom been considered.[11] The existing studies on sector coverage have focused primarily on the impact of sector coverage.[10,11] Some studies prioritized sectors based on a carbon revenue return index,[10] or suggested that the sectors having more emissions should be prioritized.[12] Others consider different sector coverage scenarios based on international experiences[11] and experience from China's ETS pilots,[13] or estimate the impacts of various sectoral coverage options for China's ETS using a computable general equilibrium model[6,14] which can design low-carbon development scenarios and generate economy-wide impacts,[15] but are highly aggregated and sensitive to parameters and model structure.[10]

Here, we prioritize the sectoral rollout among 63 four-digit industries including the current 13 designated industries based on their abatement cost savings. The marginal abatement cost (MAC), also known as the shadow price, reflects the possible sacrifice of industrial outputs or increase of inputs for reducing carbon emissions. The difference between the abatement cost with and without participation in the ETS is the abatement cost savings of the industries' inclusion in the ETS. We assess various sectoral rollout plans for China's national ETS based on firm-level emissions characteristics and abatement cost savings. Because the thermal power industry has been included in China's national ETS, we measure the abatement cost savings under various "thermal power +" scenarios. The industry that delivers the highest abatement cost savings in each of these different scopes of industrial coverage will be placed at the top of the priority list.

We add value to the literature by developing an abatement cost savings-oriented approach for determining industry coverage (ACSAIC) in the ETS policy decisions. In addition, by applying firm-level data to prioritize sector coverage, we can more precisely measure the impact of sector expansion in China's ETS and thus provide additional reference for planning China's future development of the carbon market.

RESULTS

The industries are prioritized by examining all possible expansion scenarios defined by different combinations of industries. We consider several cases based on the development plan of China's national ETS. In the business-as-usual (BAU) case, we first prioritize the 13 designated industries, and then further investigate 50 four-digit industries. The 50 additional industries are not only the top industrial carbon emitters in China, but also sectors that are proposed to be covered or are already covered by carbon markets in other parts of the world. These 63 industries plus the thermal power industry account for more than 97% of total industrial emissions and therefore provide a good representation of China's industrial total. In the alternative case, we prioritize 63 industries that have been identified in the BAU case without distinguishing the designated industries. In each of the different industry expansion cases, we compare all possible industry combinations and rank their abatement cost savings potentials to suggest a strategy of further rolling out China's national ETS. In quantifying the abatement cost savings, we estimated four different levels of CO_2 emissions reduction (5%, 10%, 15% and 20%) and three different levels of threshold for firm entry (5,000t, 10,000t and 26,000t per firm CO_2 emissions) to check the robustness of our findings. Threshold directly affects the number of firms included in ETS, and the number of firms controlling emissions will determine the total emission reduction amount.[16] Decisions of threshold selection are based on a balance of keeping a relatively controllable number of firms while maintaining a large share of emissions coverage.[17] Thus, different emission reduction possibilities can be discussed for different threshold level settings. The 26,000t is the threshold in China's current national ETS with 2,162 key emitters in the thermal power industry being the first to be included. The 5,000t and 10,000t are the thresholds for firm entry that have been set in China's pilot carbon markets, and are also important references for setting the thresholds for the next phase of China's national ETS. Based on the reduction potential of the industrial sectors as measured by the literature,[12] we set a conservative reduction target of 20% or less for the ETS. Our analysis suggests that if China adheres to its current plan of covering 14 designated industries in its ETS, the cement manufacturing industry should be the next step, followed by the steel smelting industry. The third industry to be included should be flat glass products. If we are not restricted to the current designation of industries and consider all 63 industries that have large emissions or are covered in the ETS elsewhere, only two designated industries (cement manufacturing and non-wood bamboo pulp manufacturing) may enter the top 13 list for abatement cost savings.

The BAU case: Put national designated industries first

Considering that the sectoral expansion in China's national ETS is likely to be gradual, we consider scenarios where additionally one, two, three, until 13 designated industries, respectively, will be introduced simultaneously to the existing "thermal power +" ETS designated plan. Because the estimated results will be different owing to different emissions reduction targets or entry thresholds of the covered firms, we estimate four different levels of reduction of CO_2 emissions (5%, 10%, 15% and 20%) and three different levels of threshold for firm entry (5,000t, 10,000t and 26,000t per firm CO_2 emissions). The literature shows that the current CO_2 emissions reduction potential of China's non-power sectors ranges from 18% to 50%.[18–21] According to China's Ministry of Ecology and Environment, enterprises with annual emissions of 26,000t of CO_2 should be listed as key emitters. We report the results based on the 20% emissions reduction target and 26,000t entry threshold per firm as the baseline scenario and conduct robustness tests with alternative emissions reduction targets and thresholds. See STAR Methods and supplemental information to the methods for detailed discussion of the estimation and calculating process. Considering the diversified practices in the various ETS pilots, we have considered three alternative emissions reduction targets for firms, namely, 5%, 10%, and 15%, and two alternative emissions thresholds for entry of firms: 5,000t and 10,000t for robustness checks.

We consider two stages in the BAU case: In the first stage, we limit our scope to the current 13 designated industries. In the second stage, we assume that the 13 designated industries have been included in the "thermal power +" ETS designated national plan and explore the priority list for the 50 additional industries that either have large emissions or are covered in carbon markets in other countries.

Stage 1: Sectoral priority list for the 13 designated industries

In the baseline scenario, we hold the emissions reduction target at 20% and the firm entry threshold at 26,000t while varying the number of industries to be simultaneously included in the next phase of China's national ETS expansion from 1 to 13 sectors.

Our results suggest that if only one designated industry were be introduced in the next phase of the national ETS, the top prioritized industry would be cement manufacturing (Figure 1A). Specifically, in the ETS composed of (BAU1-1) thermal power + cement manufacturing industries (hereafter BAU*n*-*i* is defined as the *i*th priority of the BAU case when inclusion of *n* industry), the emissions abatement cost savings would amount to 22.5% of the total industrial output of these two sectors, and the total emissions reduction would be 856.46 mt, both of which are higher than those in the ETS composed of (BAU1-2) thermal power + steel smelting industries (18.6% cost savings, 823.77 mt) (Figure 1B). In contrast, the benefits from (BAU1-3) thermal power + flat glass products (15.8%, 744.64 mt), (BAU1-4) thermal power + non-wood bamboo pulp manufacturing (15.7%, 743.70 mt), and (BAU1-5) thermal power + wood bamboo pulp manufacturing (15.7%, 744.00 mt) are similar and all lower than the benefits from (BAU1-1) industrial combinations.

Following the same estimation process for additionally introducing one designated industry at a time to the national ETS, we calculate cases in which an additional 2 to 13 designated industries would be included at the same time in the next phase of China's national ETS (Figures S1, S2, Tables S1 and S2). The estimation results show that in terms of abatement cost savings, the best way to expand the sectoral coverage of the ETS is to add the next prioritized industries to the previous ones (Tables S3–S5). In addition, the suggested sectoral coverage is consistent regardless of how many additional industries (1–13) are introduced at the same time. The optimal industrial combinations and the order of priority would still be robust under alternative emissions reduction targets (5%, 10%, 15%), and alternative firm entry thresholds of emissions (5,000t, 10,000t) (Tables S3–S5).

Through assessing all possible combinations, we conclude that the order of the currently designated industries, based on abatement cost savings, to be included in China's national ETS should be (1) cement manufacturing, (2) steel smelting, (3) flat glass products, (4) non-wood bamboo pulp manufacturing, (5) wood bamboo pulp manufacturing, (6) other basic chemical raw material manufacturing, (7) nitrogenous fertilizer manufacturing, (8) machine-made paper and paperboard manufacturing, (9) transmission and distribution of electric power, (10) aluminum smelting, (11) organic chemical material manufacturing, (12) copper smelting, and (13) crude oil processing and petroleum products (Figure 1C).

Stage 2: Priority list for sectors beyond the current 14 national designated industries

In the second stage of expansion, we identify additional industries that could be covered in the future assuming that the 14 designated industries in Stage 1 have all been successfully integrated. The sectors included in the carbon markets of other countries suggest that the sectoral coverage could be broader in China beyond thermal power and China's 13 designated industries, thus China could expand industries beyond the currently designated ones. Beyond the 14 four-digit industries in the nationally designated

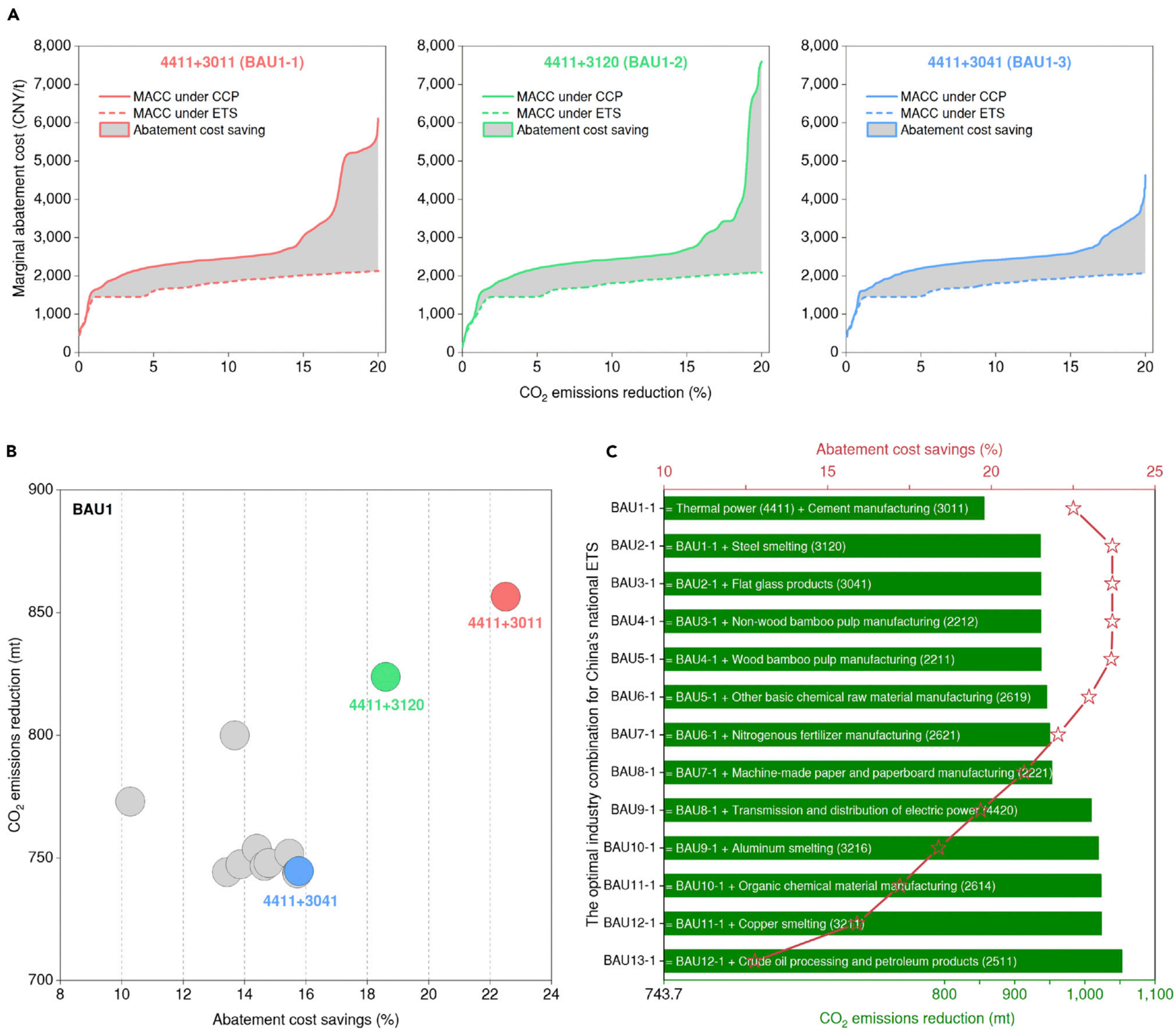

Figure 1. Prioritized industry inclusion order for the next stage of China's national ETS under the BAU case

In addition to the thermal power generation sector (4411), an additional 1 to 13 designated four-digit industries would be included in the national ETS. (A) and (B) show the marginal abatement cost curves (MACCs) and the abatement cost savings as a percentage of the total industrial output for different combinations of sectors when one industry is included in the ETS under the baseline scenario (i.e., 26,000t entry threshold and 20% emissions reduction target). Specifically, (A) shows the MACC for the relevant firms under the command-and-control policy (solid line), the MACC for these firms after inclusion in the ETS (dashed line), and the abatement cost savings (gray area) which are CNY 867.3, 765.2, and 515.9 billion for industry combinations 4411 + 3011, 4411 + 3120, and 4411 + 3041, respectively. See Figures S1 and S2 for results on the additional inclusion of 2–13 designated four-digit industries simultaneously. The combination when including *n* industries at the same time is to include the industries covered by BAU*n*-1 as shown in (C), which reports the CO_2 emissions reduction (bar) and CO_2 abatement cost savings as percentage of the total industrial output (star) for these *n* industries. The emissions reduction from the thermal power industry of 743.7 mt is set as the starting point of the x-axis.

plan, we also estimate other sectors that either have been currently covered by other major carbon markets in the world (such as the EU-ETS), or industrial CO_2 emissions ranked among the top 40 in China. Because 11 of the 14 designated four-digit industries are ranked among the top 40 CO_2 emitters in China, we included the remaining 29 four-digit industries from the top 40 emitters in the expanded list. We also considered another 23 four-digit industries that have been covered in major ETS systems in other countries. Of these 52 additional industries, two (other various household supplies and machine parts processing) were excluded because none of their firms in our database have emissions of more than 26,000t. Therefore,

Figure 2. Percentage of abatement cost savings to the total industrial output and emissions reduction of 50 additional industries in the expanded priority list

From top to bottom is the sequential rollout plan of 50 additional industries. The green bars and red stars represent the CO_2 emissions reduction (mt) and percentage of abatement cost savings to the total industrial output (%), respectively, when China's national ETS includes the corresponding industry and all preceding designated industries. The emissions reduction from the 14 designated four-digit industries would be 1,053.05 mt as indicated by the starting

Figure 2. *Continued*
point of the x-axis. The top star shows that if the heating power production and supply industry is additionally introduced in the ETS having 14 designated industries, the expanded ETS with these 15 industries would lead to abatement cost savings of 16.3% of the total industrial output, which will be higher than the cost saving of "14 designated industries + iron alloy making" combination, and all other "14 designated industries +" (15 industries) combinations. Similarly, the second top star shows that the combination of "14 designated industries + heating power production and supply + iron alloy making" would lead to abatement cost savings of 17.9% of the total industrial output, which is also higher than any other of the "14 designated industries + heating power production and supply +" (16 industries) combinations.

our expanded list for the next stage of the ETS expansion comprises 50 four-digit industries, in addition to the original 14 designated four-digit industries (Table S1). Overall, our expansion list accounts for more than 97% of total industrial emissions in our database: 72.6% of the 14 designated industries and another 25.1% of the additional 50 industries, which provide a good representation of China's industrial total because of our sample size of more than two million firms.

Our baseline estimation is that all 14 designated industries were introduced in Stage 1 of the national ETS. We then further determine the order of the rollout for 50 additional industries. Following the same estimation process as in Stage 1, we rank the additional 50 industries to determine a priority list for future ETS expansion. Because the calculation in Stage 1 demonstrates that the priority list will not change whether one or more industries are introduced in the ETS at once, and regardless of emissions targets and thresholds without loss of generality, we rank these additional 50 industries by introducing one additional industry at a time and use the 20% emissions reduction target and 26,000t threshold. A detailed discussion of the estimation and calculating processes are provided in the STAR Methods and supplemental information to the methods.

The estimates of the abatement cost savings and contribution to cumulative emissions reductions of additional industries are presented in Figure 2. The CO_2 emissions of the top 10 additional industries (i.e. sectors including 4430, 3150, 2669, 3130, 3021, 3110, 3029, 3022, 2661, 4500) plus the 14 designated industries account for 85% of the total industrial CO_2 emissions. Heating power production and supply is at the top of the priority list, and the inclusion of it in the ETS comprises 14 designated industries would contribute to accumulated abatement cost savings of 16.3% of the total industrial output of these 14 + 1 industries. The iron alloy making industry is ranked second on the expansion priority list and its introduction into the ETS comprises these 14 + 1 industries would lead to accumulated abatement cost savings of 17.9% of the total industrial output of these 14 + 2 industries. Furthermore, special chemical products manufacturing ranks third on the priority list whose introduction into the ETS would lead to accumulated abatement cost savings of 19.0% of total industrial output of these 14 + 3 industries.

The complete order of all of these 50 additional industries in various cases is reported in Figure 3. Our results show that the expanded priority list of the additional 50 industries, especially for the top ranked and bottom ranked industries, is also reliable under alternative scenarios of emissions reduction targets (15%, 10%, 5%) and entry thresholds (10,000t and 5,000t), indicating a good robustness of the prioritization of the 50 additional industries. See Datas S1, S2, S3, S4 and S5 for details of the rankings.

The alternative case: Without distinguishing designated industries

Although the Chinese government has planned to include eight major sectors in the above plan (specifically including 13 four-digit industries in addition to the thermal power industry), such selection has not been examined in the literature. To check whether the designated industries are the best choice, we do not distinguish the current 13 designated industries from the other 50 additional industries, and provide a more radical suggestion on what industries should be prioritized according to our estimated abatement cost savings. Specifically, we conduct our prioritization process among all the 63 industries that have been examined in the BAU case. However, unlike the previous estimation, we do not assume that the 13 designated industries would be introduced in the national ETS before the remaining 50 industries were considered. As argued in the previous case, without loss of accuracy, we only consider one industry to be added at a time.

Sectoral priority list for all 63 industries

We again report the estimation in the baseline scenario of a 20% emissions reduction target and 26,000t entry threshold. The calculations show that as the number of industries to be introduced in the national ETS increases, the cumulative emissions abatement cost savings start from 25.3% of the total industrial output (adding 1 industry, heating power production and supply, which ranks first), quickly rise and remain

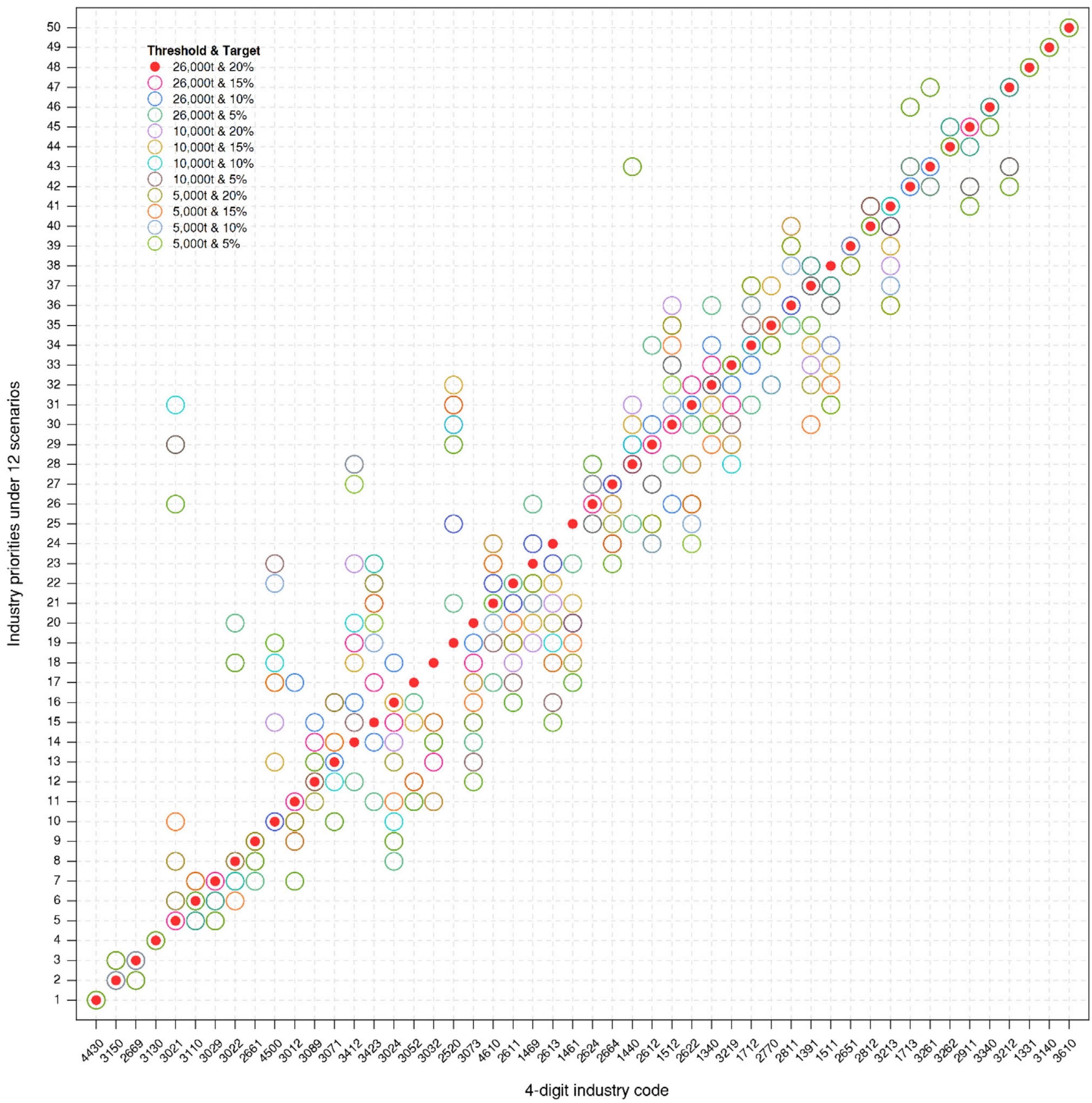

Figure 3. Prioritization of the inclusion of 50 additional industries under 12 scenarios

The red dots represent the inclusion priority of the 50 additional industries under the baseline scenario, and the other 11 colored hollow circles represent each of the other 11 scenarios. The more concentrated or even overlapping circles indicate that the priority of the industry is robust for a given scenario.

above 38% (from the 6th other cement product industry to the 25th inorganic acid manufacturing) and reach a maximum of 38.6% at the inclusion of the top 13 industries (from heating power production and supply to non-wood bamboo pulp manufacturing), and then decline significantly when the 26th-63rd industries are included (from 37.8% of the total industrial output in monosodium glutamate manufacturing to 14.2% of the total industrial output in automobile complete manufacturing) (Figure 4 and Table S2).

Detailed information on the priority list for the alternative case is reported in Table S2. We also test the robustness of the radical priority list with 63 industries under alternative scenarios of emissions reduction

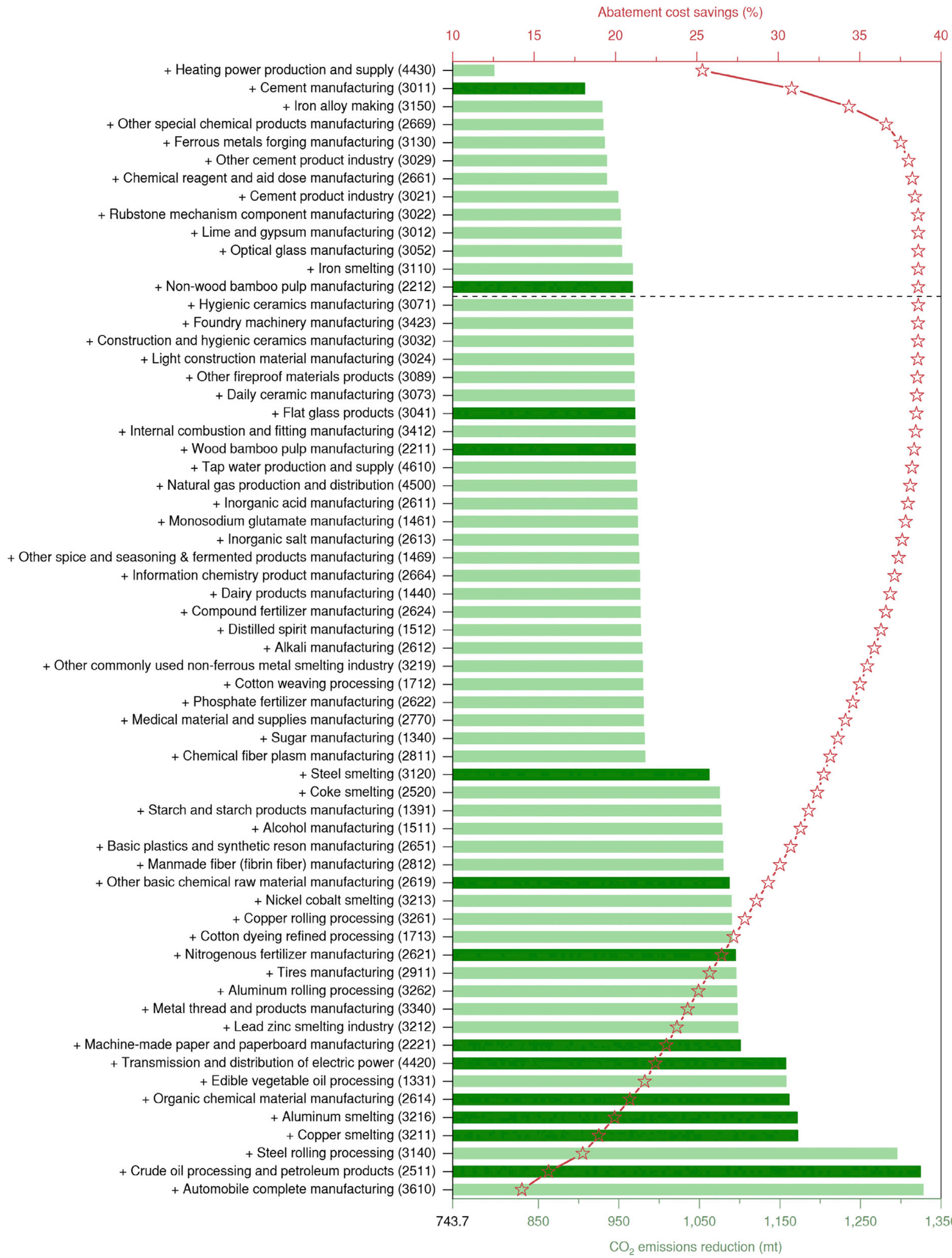
Abatement cost savings (%)
10
15
20
25
30
35
40
+ Heating power production and supply (4430)
+ Cement manufacturing (3011)
+ Iron alloy making (3150)
+ Other special chemical products manufacturing (2669)
+ Ferrous metals forging manufacturing (3130)
+ Other cement product industry (3029)
+ Chemical reagent and aid dose manufacturing (2661)
+ Cement product industry (3021)
+ Rubstone mechanism component manufacturing (3022)
+ Lime and gypsum manufacturing (3012)
+ Optical glass manufacturing (3052)
+ Iron smelting (3110)
+ Non-wood bamboo pulp manufacturing (2212)
+ Hygienic ceramics manufacturing (3071)
+ Foundry machinery manufacturing (3423)
+ Construction and hygienic ceramics manufacturing (3032)
+ Light construction material manufacturing (3024)
+ Other fireproof materials products (3089)
+ Daily ceramic manufacturing (3073)
+ Flat glass products (3041)
+ Internal combustion and fitting manufacturing (3412)
+ Wood bamboo pulp manufacturing (2211)
+ Tap water production and supply (4610)
+ Natural gas production and distribution (4500)
+ Inorganic acid manufacturing (2611)
+ Monosodium glutamate manufacturing (1461)
+ Inorganic salt manufacturing (2613)
+ Other spice and seasoning & fermented products manufacturing (1469)
+ Information chemistry product manufacturing (2664)
+ Dairy products manufacturing (1440)
+ Compound fertilizer manufacturing (2624)
+ Distilled spirit manufacturing (1512)
+ Alkali manufacturing (2612)
+ Other commonly used non-ferrous metal smelting industry (3219)
+ Cotton weaving processing (1712)
+ Phosphate fertilizer manufacturing (2622)
+ Medical material and supplies manufacturing (2770)
+ Sugar manufacturing (1340)
+ Chemical fiber plasm manufacturing (2811)
+ Steel smelting (3120)
+ Coke smelting (2520)
+ Starch and starch products manufacturing (1391)
+ Alcohol manufacturing (1511)
+ Basic plastics and synthetic reson manufacturing (2651)
+ Manmade fiber (fibrin fiber) manufacturing (2812)
+ Other basic chemical raw material manufacturing (2619)
+ Nickel cobalt smelting (3213)
+ Copper rolling processing (3261)
+ Cotton dyeing refined processing (1713)
+ Nitrogenous fertilizer manufacturing (2621)
+ Tires manufacturing (2911)
+ Aluminum rolling processing (3262)
+ Metal thread and products manufacturing (3340)
+ Lead zinc smelting industry (3212)
+ Machine-made paper and paperboard manufacturing (2221)
+ Transmission and distribution of electric power (4420)
+ Edible vegetable oil processing (1331)
+ Organic chemical material manufacturing (2614)
+ Aluminum smelting (3216)
+ Copper smelting (3211)
+ Steel rolling processing (3140)
+ Crude oil processing and petroleum products (2511)
+ Automobile complete manufacturing (3610)
743.7
850
950
1,050
1,150
1,250
1,350
CO_2 emissions reduction (mt)

Figure 4. The percentage of abatement cost savings and emissions reductions of 63 industries in the alternative case

From top to bottom is the sequential rollout for 63 industries (designated industries (dark) and additional industries (light)). The cumulative CO_2 emissions reduction (mt) increases with the number of industries included. The red star represents the percentage of abatement cost savings in terms of percentage of the total industrial output (%) when China's national ETS includes the corresponding industry and all preceding industries at the same time. The emissions reduction from the thermal power industry is 743.7 mt which is set as the starting point of the x-axis.

targets (5%, 10%, 15%) and entry thresholds (5,000t and 10,000t) in addition to the baseline estimation. The estimation results suggest that our alternative priority list is robust (Figure S3).

Our findings suggest that the designated industries may be far from the best choice in terms of abatement cost savings as many designated industries are not ranked highly in the priority list of our alternative case. The prioritized industries are presented in descending order in Figure 4 with the designated industries in dark green. Only two designated industries would be among the top 13 in this alternative case, i.e., cement manufacturing and non-wood bamboo pulp manufacturing. Two other designated industries, flat glass products, and wood bamboo pulp manufacturing, would be ranked 20th and 22nd. The remaining nine industries would be all ranked after the 40th in this alternative case. Furthermore, 6 of the 13 designated industries were among the bottom 10 of the priority list in the alternative case.

Cost advantage of the alternative rollout plan compared to the current plan

To quantify the cost advantage of our alternative case, we compare the cost savings of the alternative case with the BAU case assuming that the equivalent amount of emissions reduction between the designated industries and alternative industries will be achieved. We compare the results for 12 scenarios consisting of four different emissions reduction targets and three different entry thresholds.

With both cases including the thermal power industry in the ETS by default, we found that to achieve the same amount of emissions reduction as the BAU case (13 designated industries), the alternative case would need to include a total of 22–43 industries under 12 scenarios, because of the relatively larger emissions size of the designated industries (Table 1 and Table 2). The number of included industries is mainly influenced by the threshold. As the threshold increases, the number of included industries increases because the average firms in the additional 50 industries are smaller than those in the 14 designated industries and thus need more companies to produce the equivalent amount of emissions reduction. In contrast, the emissions reduction target has little impact on the number of included companies, and is basically stable for the same threshold scenario. This finding highlights the importance of setting reasonable thresholds. Under the equivalent emissions reduction assumption, the number of industries to be included in a low threshold case is significantly reduced. A smaller change in the number of included industries is conducive to the promotion of the alternative case. The increased number of industries and firms will somehow compromise the cost savings advantages because of the presentation of compliance costs and other transaction costs: smaller firms will likely face relatively higher compliance costs.

Specifically, among the 22 to 43 industry list, 4–5 are designated industries and 17–38 are additional industries. Six designated industries appear frequently in the 12 scenarios, whereas three industries appear in all 12 scenarios (Table 1).

Except for the transmission and distribution of electric power industry (4420), the remaining five of the six designated industries are the top five industries recommended for priority inclusion in the ETS in the BAU case. Whether it is the alternative case or the BAU case, these 5 industries have a very high priority, which is consistent with the first phase of the EU-ETS construction (2005–2007) that mainly incorporated the electricity, oil refineries, coke ovens, iron and steel, some building materials and paper industries.[22]

The average abatement cost under the ETS in the alternative case is much lower than that in the BAU case. The average abatement costs of the BAU case are in the range of CNY 1,070–1,727 per ton, whereas those of the alternative case are in a lower range of CNY 235–1,036 per ton (Figure 5). The wide range of abatement costs in both cases is the result of different emissions reduction targets: higher emissions targets are associated with higher average abatement costs.

Our average abatement cost distribution is consistent with that in other literature which uses a directional distance function to calculate the MAC for selected regions or industries. Most of the studies show that the

Table 1. The number of industries to be included in the alternative case and the specific distribution of designated industries in the 12 scenarios

Entry thresholds (kt)	Emissions reduction targets (%)	CO_2 emissions reduction under the BAU case (mt)	Number of industries included under the alternative case	Number of additional industries	Number of designated industries	Distribution of designated industries: Cement manufacturing (3011)	Non-wood bamboo pulp manufacturing (2212)	Wood bamboo pulp manufacturing (2211)	Flat glass products (3041)	Transmission and distribution of electric power (4420)	Steel smelting (3120)
5	5	273.67	23	18	5	✓	✓	✓	✓	✓	
	10	547.34	22	17	5	✓	✓	✓	✓	✓	
	15	821.01	23	19	4	✓	✓	✓		✓	
	20	1,094.68	33	28	5	✓	✓	✓	✓		✓
10	5	271.31	33	28	5	✓	✓	✓	✓	✓	
	10	542.62	33	28	5	✓	✓	✓	✓	✓	
	15	813.93	32	27	5	✓	✓	✓	✓	✓	
	20	1,085.25	36	31	5	✓	✓	✓	✓		✓
26	5	263.26	43	38	5	✓	✓	✓	✓	✓	
	10	526.52	43	38	5	✓	✓	✓	✓	✓	
	15	789.79	42	37	5	✓	✓	✓	✓		✓
	20	1,053.05	40	35	5	✓	✓	✓	✓		✓

Note: To ensure that the alternative case can achieve no lower emissions reduction than the BAU case, we try to make the emissions reduction of the alternative case slightly more than that in the BAU case when determining the number of included industries.

Table 2. Overview of the designated industrial sectors covered by China's national ETS

Sectors covered	Subsector industries covered	Four-digit code	Four-digit code industries
Petroleum processing	Crude oil processing	2511	Crude oil processing and petroleum products
	Ethylene manufacturing	2614	Organic chemical material manufacturing
Chemical materials	Calcium manufacturing	2619	Other basic chemical raw material manufacturing
	Synthesis manufacturing	2621	Nitrogenous fertilizer manufacturing
	Methanol manufacturing		
Nonmetal mineral	Cement clinker manufacturing	3011	Cement manufacturing
	Plate glass manufacturing	3041	Flat glass products
Steel smelting	Crude steel smelting	3120	Steel smelting
Nonferrous metals	Aluminum smelting	3216	Aluminum smelting
	Copper smelting	3211	Copper smelting
Paper making	Pulp manufacturing	2211/2212	Wood bamboo pulp manufacturing Non-wood bamboo pulp manufacturing
	Paper manufacturing	2221	Machine-made paper and paperboard manufacturing
Thermal power	Thermal power generation	4411	Thermal power generation
	Combined heat and power generation		
Electricity power	Electric power supply	4420	Transmission and distribution of electric power

national average MAC of CO_2 is between CNY 300–3,500 per ton in China,[23–25] whereas the average MAC of CO_2 for the power sector is between CNY 4,000–2,000 per ton.[26] The much higher costs, when compared to actual carbon prices (CNY 3–107 per ton in China's national and pilot carbon markets in 2021), is because of the immaturity of China's newly started carbon market in which the price discovery function is yet to be improved and the current carbon price deviates from the real abatement cost.[27–29] Another reason for the relatively higher abatement cost compared to the actual carbon prices is that the estimated abatement costs do not consider long-term technology progress, but instead, is considered as the opportunity cost of how much industrial output should be given up or how much input is needed to reduce one unit of carbon emissions.[30] The disparity between our estimated average abatement cost and carbon prices, however, would not undermine our results as the priority list is determined by the relative abatement cost, not the scale of the cost.

The average abatement cost can be effectively reduced by 39.5–78.3% by adopting the alternative case with an equivalent amount of total emissions reduction (Figure 5). By including the top 22–43 industries among the 63 examined ones, China's national ETS can achieve the same amount of emissions reduction as the 13 designated industries with an additional abatement cost savings of CNY 218.22–947.28 billion or USD 33.77–146.60 billion (i.e. 1.2–5.0% of China's total industrial output in 2011).

DISCUSSION

We contribute to the policy development of the world's largest carbon market by suggesting a priority list of industries to be covered in China's national ETS. Our priority list, among the 14 designated industries, suggests that cement manufacturing should be next step. This is different from the current plan which puts the steel smelting industry, ranked third in our analysis, as the next step.[31]

Our results further indicate that the current ETS expansion plan does not minimize China's total abatement cost. Without considering the differences between the designated industries and the other industries, only two of the designated industries will be among the top 13 industries on our priority list. Based on our estimation, if China's national ETS is limited to the 13 designated industries, the role of ETS in minimizing

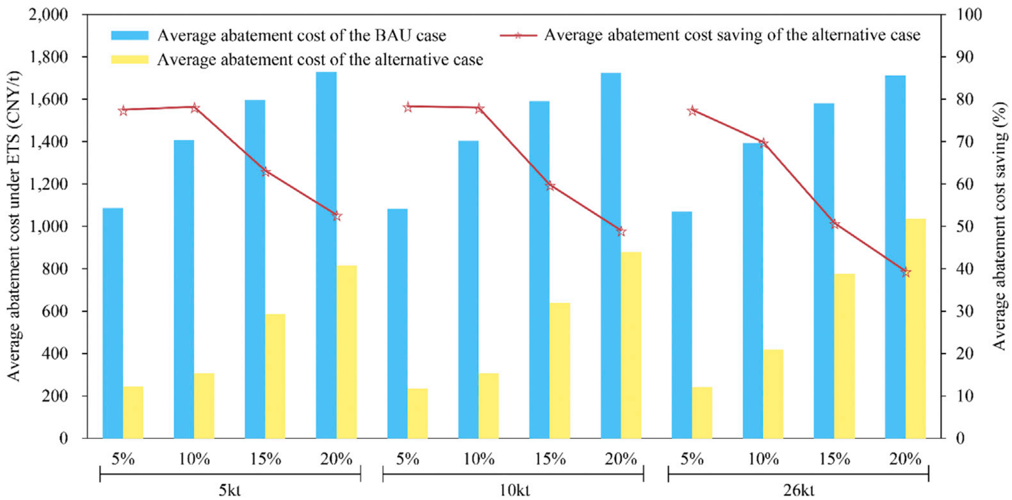

Figure 5. Change in average abatement costs after inclusion in China's national ETS for the BAU case and the alternative case

The blue bars indicate the average abatement cost when the ETS includes thermal power +13 designated industries of the BAU case under 12 scenarios. The yellow bars indicate that if the 13 designated industries are replaced with the 22–43 industries recommended for inclusion in the alternative case under 12 scenarios. The average abatement cost savings as a percentage of the average abatement cost of the BAU case are indicated by the red stars showing that there would be a significant cost advantage in the alternative rollout compared to the current plan of ETS.

abatement costs will be undermined. Achieving the equivalent amount of emissions reduction (236.26–1094.68 mt dependent on different scenarios) as the inclusion of 13 designated industries in the BAU case, the alternative case requires the inclusion of 22–43 industries under 12 scenarios, 4 to 5 of which are designated industries. In terms of cost-effectiveness, the average abatement cost of the alternative case is 39.5–78.3% lower than the BAU case, and the Chinese government may consider promoting the alternative case by lowering the entry threshold to cover a number of relatively small industries, which could save CNY 218.22–947.28 billion or USD 33.77–146.60 billion in abatement costs, equivalent to 1.2–5.0% of China's total industrial output.

Although we have proposed a sequence of sectoral rollout if China's national ETS is to be expanded, we are not able to pinpoint the best timing for each sector to be included. The fact is that there is no prior experience for a major and fast-growing developing country to achieve a carbon peak amid various uncertainties. Hence, China must gauge its carbon market roadmap very carefully.[32] In September 2020, when President Xi announced China's commitment to reach its carbon peak by 2030 and its carbon neutrality by 2060, there was no detailed experience to draw from. Under China's centralized governance system, many local governments, companies and other units proposed earlier peak targets and ambitious energy transition plans and took radical actions to please their superiors.[33] These radical climate actions were impeded by national power cuts and skyrocketing coal prices in the second half of 2021.[34] In February 2022 China's steelmakers were given five more years to reach peak carbon emissions, whereas the previous consensus was that the steel industry would reach peak emissions by 2025.[31] China's hesitation in its climate actions coincides with a worldwide momentum to redraw the energy transition roadmaps owing to the energy price surge that began at the end of 2021 and because of the ongoing Ukrainian War.[35] China's slow economic growth under its strict dynamic zero-Covid policy is further reducing the priority of addressing climate issues.

Intraregional coordination will have a significant impact on China's carbon market expansion. Regional efforts are expected to play a key role in delivering China's pledge to peak carbon dioxide emissions before 2030. As a large and centralized country, China's national policy goals are often decomposed to lower levels of government through the hierarchy of province, municipal city and county. However, peaking carbon locally as early as possible may not be the best scenario for China. Owing to the vast territory and large differences in socio-economic development and in the energy mix, some regions in China will not likely be able to keep pace in peaking carbon.[36] Although sectoral rollout seems to be fair, the impact on regions will vary given China's regional diversified economic and industrial structure. For example, China's steel production is concentrated in Hebei Province, which will pay higher carbon costs than any other province when the steel industry is put under the national ETS.

Inter-firm fairness also needs to be managed. Although our estimation suggests that the sector priority list is irrelevant to thresholds for the carbon markets, the threshold does matter for firms. Once a firm is subject to the carbon market, it will need to pay the carbon prices for its emissions, at least for those allowances purchased from the carbon market. Firms below and above the threshold will feel the most impact. The differential treatment may create significant competition distortion among firms.

Limitations of the study

It is important to note that our estimated abatement cost savings is an effort to measure the benefits of the ETS and subsequently prioritize sectoral rollout. It does not account for a potential timeline for industry inclusion or implementation costs of the ETS. A systematic analysis of these factors is critical to determine whether, and when, an industry should be included in the ETS. As the number of industries increases, the percentage of abatement cost savings of the total industrial output will first increase, then stagnate and decrease. If we further consider compliance cost and other transaction costs, we are able to identify the optimal number of industries to be covered by the carbon market. Another reason for not considering implementation costs is that the abatement cost measured in this study is based on the marginal abatement cost (shadow price) which may lack direct comparativeness with the real compliance or transaction costs in the ETS. Future extensions of this study could reveal the implementation costs by industries from China's national and pilot ETSs. It is possible that a lower ranked industry could be advanced in the priority list if its net benefits are higher than some of the industries ahead of it because of its relatively lower implementation costs.

STAR★METHODS

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SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2022.105823.

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AUTHOR CONTRIBUTIONS

K.W. and Z.W. designed the research. K.W. and X.S. conceptualized the research. K.H., K.F., and J.Y. helped organize the manuscript. Z.W. and Y.X. performed the analysis and prepared the manuscript with substantial input from K.W., X.S., K.H., and K.F. J.Y. provided SAT data. K.W. and Y.M.W. supervised the project.

DECLARATION OF INTERESTS

The authors declare no competing interests.

INCLUSION AND DIVERSITY

The author list of this paper includes contributors from the location where the research was conducted who participated in the data collection, design, analysis, and/or interpretation of the work.

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KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Firms' data	Chinese State Administration of Tax (SAT)	
CO_2 emissions	Carbon Emission Accounts & Datasets (CEADs)	https://www.ceads.net.cn/
Other data	National Bureau of Statistics	http://www.stats.gov.cn
Software and algorithms		
GAMS	https://www.gams.com/	35.2.0
Python	https://www.python.org/	3.8.1

RESOURCE AVAILABILITY

Lead contact

Further information and requests should be directed to the lead contact, Ke Wang (wangkebit@bit.edu.cn).

Materials availability

This study did not generate new unique materials.

Data and code availability

All data generated in this paper are available from the lead contact on reasonable request.

All original code has been deposited on our GitHub repository (https://github.com/WangKe-bit/MACC) and is publicly available as of the date of publication.

Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

METHOD DETAILS

Construction of the firm-level CO_2 emissions and marginal abatement cost database

The dataset we used is the firms surveyed by the Chinese State Administration of Tax (SAT).[29,36,37] We accessed the full SAT dataset from 2008 to 2015 and used the firm-level data to estimate the energy consumption-derived CO_2 emissions and to measure the marginal abatement cost (MAC) of each firm. The dataset contains firm-level information for more than 500 four-digit industrial sectors from code 1300 to 4600, covering a total of 2,116,400 firms across 30 provinces in China (Figures S4–S6, Tables S6, S8 and S9).

Data preparation

To measure the marginal abatement costs (MAC) of each firm and construct the marginal abatement cost curve (MACC) of each four-digit industrial sector, the major variables utilized from the raw dataset include firms' total industrial output, fixed assets, wages, intermediate inputs, coal consumption, oil consumption, and electricity consumption. We do not have high quality data on natural gas consumption for each year. But the existing data shows that the percentage of natural gas consumption as energy but not material input, over total energy consumption is on average less than 3%. Therefore, the missing natural gas consumption does not significantly affect our estimation of abatement cost savings. The measures of these variables are described as follows.

i) Uni-form industrial sector codes. Four-digit industrial sectors are collected for analyzing, and the corresponding sector codes are unified according to the Industrial Classification for National Economic Activities (GB/T 4754-2011) in China.

ii) Matching administrative areas. Based on the name of the firm and district where it is located, the latitude and longitude of each firm is obtained through the Baidu map's geocoding service (https://lbsyun.baidu.com/index.php?title=webapi/guide/webservice-geocoding).

iii) Cleaning missing data. At the provincial level, Tibet, Taiwan, Hong Kong, and Macao are not included in the sample due to incomplete data. At the variable level, if the value on total industrial output, fixed assets, wages, and intermediate input is zero, or all values on coal consumption, oil consumption, and electricity consumption are zero, the firm was deleted.

iv) Constant price conversion. The values on total industrial output, fixed assets, wages, and intermediate input are all converted into 2010 constant prices. The producer price index, producer purchase price index, fixed asset investment price index, and consumer price index are applied as the deflators for total industrial output, intermediate input, fixed assets, and wages, respectively.

v) Adjustment of firm-level energy consumption. To reduce the deviation of energy consumption between the sample and the whole industry, based on the energy consumption of j (j = coal, oil, electricity) reported by firm i ($EC_{i,j}^{reported}$), the adjustments to the consumption of energy j ($EC_{i,j}^{adjusted}$) are calculated using Equation 1. Where N_{AS}^{sample} represents the number of above-scale firms in the two-digit industry sample and $TEC_{AS,j}^{sample}$ is the total consumption of energy j by these firms. N_{AS}^{all} is the number of above-scale firms and $TEC_{AS,j}^{all}$ is the total consumption of energy j in the industry at the national level, both of which are obtained from the National Bureau of Statistics.

$$EC_i^{adjusted} = EC_i^{reported} \times \frac{TEC_{AS}^{all}}{TEC_{AS}^{sample}} \times \frac{N_{AS}^{sdd}}{N_{AS}^{all}} \quad \text{(Equation 1)}$$

vi) Calculation of firm-level CO_2 emissions from energy consumption. First, we calculate consumption of fuel coal and fuel oil based on their respective shares of coal and oil,[18] where the share of fuel coal was converted into four-digit subsectors in 2010 and the share of fuel oil was converted into two-digit subsectors in 2011. Production-based CO_2 emissions from energy consumption (ECO_{2i}) for firm i are calculated using Equation 2. We aggregate the CO_2 emissions from fuel coal consumption ($EC_{i,fuel\ coal}$), fuel oil consumption ($EC_{i,fuel\ oil}$) and electricity ($EC_{i,electricity}$) for firm i. The CO_2 emissions factors of fuel coal consumption and fuel oil consumption are taken from the Guidelines for Preparation of Provincial GHG,[38] whereas the factor of electricity consumption ρ_{hi} in area h (h = 1,2,…,6) is taken from China's regional power grid emission factors.[39]

$$ECO_{2i} = 1.9003 \times EC_{i,\text{fuel coal}} + 3.1705 \times EC_{i,\text{fuel oil}} + \rho_{\text{hi}} \times EC_{i,\text{electricity}} \quad \text{(Equation 2)}$$

vii) Calculation of firm-level CO_2 emissions from industrial processes. CO_2 emissions that are related to industrial processes (ICO_2) are considered for the nonmetal mineral products sector. The ICO_2 for firm i is calculated through the product of the industrial process emissions factor of province k and total industrial output (IO_i) of firm i (Equation 3).

$$ICO_{2i} = \xi_{\text{ki}} \times IO_i \quad \text{(Equation 3)}$$

where the industrial process emissions factor ξ_{ki} is the ratio of CO_2 emissions from industrial processes to the total industrial output of province k (Table S7).

viii) Correction of outliers of CO_2 emissions. An ordinary least-squares regression in Equation 4 is used to correct the outliers in CO_2 emissions for every four-digit industrial sector.

$$\ln(CO_{2\text{it}}) = \alpha_0 + \alpha_1 \ln(TP_{\text{it}}) + \varepsilon_{\text{it}} \quad \text{(Equation 4)}$$

where TP_{it} is the amount of total product value of firm *i* in year *t*. If a firm's CO_2 emissions are outside the 95% prediction interval, it would be considered an outlier and then replaced by the nearest predicted value.

Identification of industrial sectors

China's industrial CO_2 emissions come from several key sectors. Eight industrial sectors (involving 14 four-digit subsectors or industries), named as designated sectors or industries in this study, have been planned to be included in China's national ETS. Detailed information on the covered sectors and industries and the corresponding four-digit codes in GB/T 4754-2011 can be found in Table 2. Detailed industrial output, CO_2 emissions and location information on all industries covered in this study can be found in Tables S8 and S9.

Estimation of marginal abatement costs

The marginal abatement costs (MAC) or shadow price of undesirable outputs (i.e. CO_2 emissions) can be obtained through the duality relationship between the directional output distance function (DODF, $\vec{D}_T$) (supplemental information to the methods) and the revenue function (RF). Supposing $\boldsymbol{p_y} \in \Re^s_+$ represent desirable output (i.e. industrial products) prices and $\boldsymbol{q_b} \in \Re^l_+$ represent undesirable output shadow prices, the corresponding revenue function in terms of DODF is defined as:

$$\pi(\boldsymbol{x}, \boldsymbol{p}, \boldsymbol{q}) = \max\left\{\boldsymbol{p_y y} - \boldsymbol{q_b b} : (\boldsymbol{y}, \boldsymbol{b}) \in P(x)\right\} \quad \text{(Equation 5)}$$

In Equation 5, ***x***, ***y*** and ***b*** represent inputs, desirable outputs, and undesirable outputs of industrial production, respectively. The RF aims at maximizing the feasible revenue $\boldsymbol{\pi}$ within the production possibility set $\boldsymbol{P}(x)$, which is obtained from the positive revenue of desirable outputs $\boldsymbol{p_y y}$ and the negative revenue of undesirable outputs-$\boldsymbol{q_b b}$. Under the definition of DODF, if $(\boldsymbol{y}, \boldsymbol{b})$ is feasible, the elimination of inefficiency associated with it through moving along a given direction $\vec{g}_y, \vec{g}_b$ is also feasible. Thus, Equation 5 can be equivalently written as:

$$\pi(\boldsymbol{x}, \boldsymbol{p}, \boldsymbol{q}) \geq \left(p_y y - q_b b\right) + p_y \vec{D}_T \vec{g}_y + q_b \vec{D}_T \vec{g}_b \quad \text{(Equation 6)}$$

In Equation 6, the right-hand side equals the sum of revenue ($\boldsymbol{p_y y}$-$\boldsymbol{q_b b}$) and the gain of revenue from removing technical inefficiency, i.e., the gains due to both the increase in desirable outputs and the decrease in undesirable outputs. The DODF given in Equation 6 can be expressed from the revenue function as:

$$\vec{D}_T = \min_{p_y, q_b} \left\{ \frac{\pi(\boldsymbol{x}, \boldsymbol{p}, \boldsymbol{q}) - \left(p_y y - q_b b\right)}{p_y \vec{g}_y + q_b \vec{g}_b} \right\} \quad \text{(Equation 7)}$$

The direction $\vec{g} = (\vec{g}_y, \vec{g}_b)$ defines the distance function of DODF. $\vec{g} = (1, -1)$ that represents the production and emissions abatement strategy of increasing the total industrial output and decreasing CO_2 emissions, is chosen in this study.

Because the DODF and RF are both assumed to be differentiable, the envelope theorem to Equation 7 yields the MAC model can be applied. Therefore, given knowledge of the *r*th ($r = 1,2,\ldots,s$) desirable output price, the relative *f*th ($f = 1,2,\ldots,l$) undesirable output shadow price can be obtained as:

$$q_{b_f}^{y_r} = -p_{y_r} \times \left(\frac{\partial \vec{D}_T / \partial b_f}{\partial \vec{D}_T / \partial y_r} \right) \quad \text{(Equation 8)}$$

Analogously, given knowledge of the *i*th ($i = 1,2,\ldots,m$) input price, the relative *f*th ($f = 1,2,\ldots,l$) undesirable output shadow price can also be obtained as:

$$q_{b_f}^{x_i} = p_{x_i} \times \left(\frac{\partial \vec{D}_T / \partial b_f}{\partial \vec{D}_T / \partial x_i} \right) \quad \text{(Equation 9)}$$

There are two types of undesirable output shadow prices, i.e. MACs that simultaneously exist in the actual industrial production process. One is associated with the action of giving up desirable outputs (Equation 8) while the other relates to the action of expanding the use of inputs (Equation 9) for reducing the emission of undesirable output. According to the rational-economic assumption, the lower alternative MAC should be chosen by a firm.[40] Hence, the MAC of undesirable output f can be defined as:

$$q_{b_f} = \min_{i,r}\left\{q_{b_f}^{x_i}, q_{b_f}^{y_r}\right\} \qquad \text{(Equation 10)}$$

In order to additionally obtain the MACC based on the estimation of MAC, a hybrid method that combines a top-down economic approach and a bottom-up engineering approach[41,42] is employed for each firm in our database. The curve shows the MAC increase as the abatement level increases from 1 to 99% in 1% steps.

Specifically, first, the abatement potential on undesirable outputs for all production units is calculated. After obtaining the production frontier which is estimated by the data on the original input-output amount of firms, the abatement potential is measured by the adjustment of undesirable outputs along direction $\vec{g}_b$ to the production frontier, meaning the maximum abatement of undesirable outputs.

Secondly, the MACs of undesirable outputs under different abatement levels are estimated. Given the abatement level $\tau\%$ and assuming, without loss of generality, one desirable output and one undesirable output, there are two situations between the abatement potential and abatement level:

(i) The abatement level is lower than or equal to the abatement potential of undesirable output. The production unit would move by mitigating $\tau\%$ of its original emissions level of undesirable output, and reach a point on the frontier along direction $\vec{g}_b$. The MAC of this unit with the abatement level of $\tau\%$ is the slope of the point on the frontier, and the corresponding calculation formulation is:

$$q = \min\left\{\begin{array}{l} -p_y \times \left(\dfrac{\partial \vec{D}_T\left(x, y, b(1-\tau\%); g_y, g_b\right) \Big/ \partial b(1-\tau\%)}{\partial \vec{D}_T\left(x, y, b(1-\tau\%); g_y, g_b\right) \Big/ \partial y}\right), \\ p_x \times \left(\dfrac{\partial \vec{D}_T\left(x, y, b(1-\tau\%); g_y, g_b\right) \Big/ \partial b(1-\tau\%)}{\partial \vec{D}_T\left(x, y, b(1-\tau\%); g_y, g_b\right) \Big/ \partial x}\right) \end{array}\right\} \qquad \text{(Equation 11)}$$

(ii) The abatement level is higher than the abatement potential of undesirable output. In this case, the production unit would locate outside the production possibility set after moving by $\tau\%$ of its original emissions level of undesirable output. To satisfy the current production technology, this unit first mitigates emissions until reaching the boundary of the production possibility set, and then it moves on the boundary to meet the abatement level through contracting desirable output.

Since the point that achieves the abatement level is on the boundary of the production possibility set, it can be expressed as follows:

$$\vec{D}_T\left(x, y', b(1-\tau\%); g_y, g_b\right) = 0 \qquad \text{(Equation 12)}$$

where y' is the adjusted desirable output on the boundary when b decreases to $b(1-\tau\%)$ with the emissions abatement level $\tau\%$.

Consequently, the MAC of this unit with the abatement level of $\tau\%$ can be derived as:

$$q = \min\left\{\begin{array}{l} -p_y \times \left(\dfrac{\partial \vec{D}_T\left(x, y\prime, b(1-\tau\%); g_y, g_b\right) \Big/ \partial b(1-\tau\%)}{\partial \vec{D}_T\left(x, y\prime, b(1-\tau\%); g_y, g_b\right) \Big/ \partial y\prime}\right), \\ p_x \times \left(\dfrac{\partial \vec{D}_T\left(x, y\prime, b(1-\tau\%); g_y, g_b\right) \Big/ \partial b(1-\tau\%)}{\partial \vec{D}_T\left(x, y\prime, b(1-\tau\%); g_y, g_b\right) \Big/ \partial x}\right) \end{array}\right\} \qquad \text{(Equation 13)}$$

Thirdly, the abatement amount (or ratio) is further incorporated to generate a stepwise increasing curve.

Up to this point, we constructed the production frontier using firm-level input-output data from 2008 to 2015 and calculated the MACs for a total of 99,179 firms in 328 four-digit industries in 2011 to obtain the MACs corresponding to each percentage increase in each firm's emissions reduction target from 1% to 99%. The distribution of annual CO_2 emissions and MACs (20% emissions reduction target) of sample firms in the 14 designated industries and descriptive statistics for 64 industries at the firm level can be found in Tables S8 and S9. We assume that sample firms of different sizes are evenly sampled and representative within industries, and expand the industry output and CO_2 emissions of each sample firm proportionally based on the total output and total CO_2 emissions of each industry in Tables S8 and S9 for the China's national ETS scenario simulation.

Algorithm

Priority industry for ETS expansion

China's national ETS currently covers the thermal power industry (4411) and firms with annual CO_2 emissions exceeding 26,000t. The Chinese government plans to expand the ETS to include another seven industrial sectors, including 13 designated four-digit industries. Therefore, firstly, we consider all of the possible combinations of these 13 designated industries associated with the thermal power industry. Secondly, we assume that the 13 designated industries and thermal power industry have been included in the ETS and that another additional 50 industries would then be introduced. Thirdly, we consider that there is no priority difference between the 13 designated and 50 additional industries and assume all these 63 industries would be introduced. We try to find the most cost-efficient industry combination for the next phase of China's national ETS by including n ($n \geq 1$) industries simultaneously.

For each industry combination, there are two types of abatement cost measures for the same amount of CO_2 emissions reduction: the abatement cost under command-and-control policy (ACCCP), and the abatement cost under the emissions permit trading system (ACETS). Under the baseline scenario (26,000t entry threshold and 20% emissions reduction target), the former refers to the cost when each firm in the industry combination that meets the entry threshold (annual CO_2 emissions exceeding 26,000t) reduces its CO_2 emissions by the same percentage (20%) based on historical emissions. The latter refers to the cost when all included firms reduce their CO_2 emissions in increasing order of MAC until the total reduction task (20% of CO_2 emissions) of the industry combination is completed. Then, the effectiveness of introducing a specific industry combination into the ETS could be calculated as the percentage of abatement cost savings (P_{ACS}):

$$P_{ACS} = \frac{\text{ACCCP} - \text{ACETS}}{\text{total industrial output}} \qquad \text{(Equation 14)}$$

in which, the total industrial output refers to the industrial output of all covered firms within the industry combination that meets the entry threshold. An industry combination with higher P_{ACS} is suggested with higher priority to be introduced into China's national ETS. Furthermore, the emissions reduction for this industry combination is also an important indicator that we focus on in optimizing the rollout plan.

Optimize inclusion method

As the number of industries involved in the simulation grows, the computational effort of using the traversal of all industry combinations increases exponentially, and the optimal solution cannot be reached quickly. Based on the simulation results for the 13 designated industries, we have concluded that the optimal industry coverage when n - 1 industries are introduced into the ETS at the same time is a subset of the optimal industry coverage when n ($1 \leq n \leq 13$) industries are introduced simultaneously (Table S5). The optimal industry coverage is represented by the name of the *n*th newly introduced industry, as shown in the results of Section 2.1 and 2.2, and the suggested rollout plan indicating the first to the *n*th industries to be included. The percentage of abatement cost savings resulting from the inclusion of *n* industries at a time is expressed as the cumulative abatement cost savings percentage of the total industrial output corresponding to the *n*th industry, which is the ratio of the cumulative abatement cost over the cumulative total industrial output of the first to the *n*th industries.

Take the baseline scenario as an example, when three industries are included at the same time, there are 286 combinations, among which the best result is cement manufacturing + steel smelting + flat glass products. If we first determine an optimal industry (cement manufacturing) from the 13 industries to be included in the "thermal power +" ETS, and then determine an optimal industry (steel smelting) from the remaining 12 industries to be included, and finally determine an optimal industry (flat glass products) from the remaining 11 industries to be included, it will be found that each round of a single local optimal industry eventually forms a global optimal industry combination.

Based on the above robust rules, this study proposes a new simulation algorithm to solve the problem of a large number of industries without calculating all possible combinations of industries, and the optimal rollout plan can be derived faster by the following 3 steps:

Step 1. Only one industry is included in each round, and the remaining industries are respectively combined with all industries that have been determined to be included in the "thermal power +" ETS to calculate the P_{ACS} of this combination.

Step 2. The remaining industry in the industry combination with the highest P_{ACS} is identified in each round as the next included industry.

Step 3. Repeat steps 1 and 2 until all industries are identified for inclusion in the order.

To better visualize and understand the simulation process, Figure S7 provides more details with 50 additional industries as examples.

Simulation settings and cases

Following the schemes for China's pilot ETSs and national ETS, three types of entry threshold are set for firms in our simulations, namely, annual CO_2 emissions exceeding 5,000t, 10,000t, and 26,000t. Furthermore, for the firms to be included, it is assumed that the annual emissions reduction targets are 5%, 10%, 15%, or 20% of their annual CO_2 emissions. Although China's national ETS includes thermal power generation firms that emit more than 26,000t of CO_2 per year, we assume, for comparative convenience and without loss of accuracy, that the thermal power industry and other industries are subject to the same entry thresholds (5,000t, 10,000t, and 26,000t) and the same emissions reduction targets (5%, 10%, 15%, and 20%) under various scenarios, and the two abatement costs (ACCCP and ACETS) of the thermal power industry (4411) are calculated in the same way as for other industries.

One exception is the transmission and distribution of the electric power industry (4420), which is given a low and single emissions reduction target. The emissions abatement of this industry is mainly attributed to the reduction of line loss in distribution, and thus its emissions reduction potential is very limited. Therefore, the default emissions reduction potential of this industry is assumed to be no more than 5% in our estimation, and regardless of the emissions reduction targets applied, the ACCCP of this industry is calculated as the sum of industrial output values of the included firms. This guarantees that the calculation of emissions abatement cost savings of the transmission and distribution of electric power industry is rational.

According to the development plan of China's national ETS, this study simulates three possible cases for the industrial sectors to be included in the ETS and proposes the optimal rollout plan under each of these three cases, which are (1) the rollout plan of the 13 designated industries, (2) the rollout plan of the 50 expanding industries, and (3) the alternative case rollout plan of the 63 industries.

BAU case: Rollout plan of 13 designated and 50 expanding industries

This case has two stages. Stage one will cover the 13 designated industries, while stage two will further select 50 industries from the rest.

Stage 1: Rollout plan of 13 designated industries

In the next development phase, the Chinese government plans to introduce n ($1 \leq n \leq 13$) of the designated industries simultaneously into the current ETS of the thermal power industry. In this case, we simulate all C_{13}^{n} possible combinations of industries that would be introduced into the ETS, which is 8,191 combinations, and propose the optimal rollout plan of the 13 designated industries.

Stage 2: Rollout plan of 50 additional industries

Beyond the above 13 designated industries and thermal power industry, we assume in the second stage that another 50 major emitting industries are planned to be additionally introduced into the ETS. Through applying the previously optimized algorithm, the optimal rollout plan of the 50 expanding industries can be derived.

Alternative case: Rollout plan of 63 industries

In this case, we ignore the priority of the 13 designated industries and assume that 63 industries (13 designated and 50 additional ones) would be introduced into the ETS of the thermal power industry. Here, we assume n ($1 \leq n \leq 63$) industries would be included after the thermal power industry, and an alternative rollout plan of the 63 industries can be derived using the previously optimized algorithm as in stage 2.