General Equilibrium Analysis of Cost-Effectiveness and Distributional Impacts of China's Nationwide CO_2 Emissions Trading System

Final Report

March 2023

Authors: Xianling Long[1], Da Zhang[2], Lawrence Goulder[3], and Chenfei Qu[2]

The authors are grateful to Asia Society Policy Institute Director of Asia-Pacific Sustainability Alistair Ritchie for helpful advice throughout this project. We thank Bing Liu for excellent research assistance and gratefully acknowledge financial support from the Asia Society Policy Institute, China's Natural Science Foundation, and the Environmental Defense Fund.

[1] National School of Development, Peking University
[2] Institute of Energy, Environment and Economy, Tsinghua University
[3] Department of Economics, Stanford University

Table of Contents

I. Introduction

This report indicates potential impacts of China's recently introduced tradable performance standard (TPS), a rate-based system for reducing CO_2 emissions. The potential impacts are results from the application of a multiperiod general equilibrium model developed for this study.

Under any TPS, compliance requires that a covered facility's ratio of authorized emissions[1] to output not exceed the benchmark ratio assigned to the facility by the government. The number of allowances allocated to each facility in a compliance period is the product of the assigned benchmark and the facility's level of output during that period. The connection under the TPS between the level of output and the allowance allocation is a major difference from cap and trade (C&T), in which each covered facility must keep its emissions within an absolute cap that is exogenous from the perspective of the facility.[2,3] As several studies have noted,[4] the endogeneity of the allowance allocation under the TPS gives rise to an implicit output subsidy, which tends to compromise the cost-effectiveness of the TPS relative to C&T.

China's TPS is being implemented in phases. The first phase was launched in 2021 and covered only the electricity sector. The second phase is assumed to expand TPS's coverage to include the cement, aluminum, and iron&steel sectors. It is expected to start within the next two years. The third phase is expected to begin a few years after the second phase. It is expected to add five sectors: pulp&paper, other non-metal mineral products, other non-ferrous metals, raw chemicals, and petroleum refining.[5]

This report is the second in a series of two. The first report (Long *et al.,* 2022) described in detail the model and its structure, data, and parameters, and presented results from a range of potential emissions-reduction policies. In this second report, we focus on recent extensions to the model's capabilities and consider new types of potential TPS policies. The extensions to the model include the expansion of the time-interval of the model to 2035 and further disaggregation of the model's production sectors. The extensions also include giving the model the capability to assess two policy changes that the Chinese planners are contemplating: the introduction of an auction as a potential source of supply of emissions allowances, and the possible future transition from the TPS to C&T. We apply the extended model to evaluate these potential policy changes.

We also explore more closely the various phases of China's TPS, exploiting the greater disaggregation and longer time-interval to include a focus on the third TPS phase and the

---

1 Authorized emissions are the facility's own emissions allowances net of the emissions credited via the facility's purchases of emissions allowances on the emissions market.

2 A few C&T systems include provisions for output-based allocation, in which case a facility's allowance allocation is tied to its level of output. In this case, the incentives and outcomes under C&T approach those of a TPS. Our earlier report (Long *et al.*2022) discussed this issue in detail.

3 The word "benchmark" can be used to refer to two different things. First, it can refer to an emissions-output ratio that forms the ceiling for compliance; this the function of benchmarks referred to in this study. It is also possible to let "benchmark" refer to the ratio used to determine an initial allowance allocation. The latter interpretation applies under the TPS and can also apply under C&T when ratios are used to determine the initial allocation of emissions allowances under that system. In this report, to avoid confusion we use the term "benchmark" only in the former sense, that is, as an emissions-output ratio that determines TPS compliance.

4 See, for example, Fischer (2003), Fischer & Newell (2008), and Goulder *et al.* (2022).

5 The other non-metal products include but are not limited to ceramics, bricks, and glasses; other non-ferrous metals includes copper and tin; raw chemicals include ethylene, methanol, synthetic ammonia, caustic soda, soda ash, synthetic fiber, and plastic; refined petroleum refining includes gasoline and diesel fuels.

longer-term impacts of the TPS. The applications in this report make use of updated production data as well as the updated benchmarks recently announced by the Ministry of Ecology and Environment (MEE).

As in the first report, this report considers a range of policy scenarios differing in stringency and the number of benchmarks. The analysis also contrasts the impacts of the TPS with those of a C&T system of similar scope and yielding the same economy-wide emission reductions.

Key insights and policy implications from this analysis include:

- **Emissions reduction.** Our central estimate is that Phase 1 (2020-2022) of China's TPS reduces the electricity sector's CO_2 emissions relative to the baseline by about 4 percent, which is a reduction in economy-wide emissions of slightly over 2 percent. The broader coverage, as well as more stringent benchmarks under Phase 2 (2023-2025) more than doubles the percentage reduction in economy-wide emissions. Our central estimate is that during Phase 2 these emissions are reduced by about 5 percent. In Phase 3 (2026-2035), the percentage of emissions reduction increases to about 16 percent, again reflecting the broader coverage and more stringent benchmarks. Over the entire 2020-2035 interval, emissions are reduced by about 12 percent relative to the baseline.
- **Economic costs.** The costs per ton of reduced emissions are 45 RMB, 46 RMB, and 76 RMB in the first years of Phases 1, 2, and 3, respectively. These costs correspond to 0.008 percent, 0.014 percent, and 0.05 percent of baseline GDP in each of the respective years. We find that the TPS's costs are quite similar to those under C&T in the first several years of the policy, but that the TPS's abatement costs per ton become higher than those of C&T in the longer term. This reflects the increasing stringency of the benchmarks and the higher distortions associated with the TPS's implicit subsidy to output.
- **Benefit-cost ratio.** The TPS's climate-related benefits are estimated to be well above its economic costs. Under the assumption of a social cost of carbon of 353 RMB/tCO_2 in 2020,[6] the climate-related benefits from CO_2 reductions over the 2020-2035 interval exceed the economic costs by a factor of five.
- **Impacts on renewable-based electricity.** The TPS and C&T add costs to the use of carbon-intensive fuel inputs. In the electricity sector, they promote the transition away from fossil-generated to renewables-based electricity. China's TPS increases wind and solar generation by 0.5, 1.1, and 6.0 percent over the intervals spanned by phases 1, 2, and 3, respectively. C&T would bring about larger shifts to renewables: increases of 3.9, 7.3, and 19.2 percent during the three phases. The smaller shifts under the TPS reflect the TPS's implicit output subsidy, which mitigates the increase in the price of fossil-based energy and thus lessens the increase in demand for renewable electricity.
- **Impacts of benchmark variation.** The economic costs depend on the variation of benchmarks. The central case, which reflects the actual TPS design, includes four benchmarks for the electricity sector in 2021. Reducing the number of benchmarks to two (while maintaining the same average policy stringency) reduces costs by about 1 percent in 2020-2035. Reducing the number to one reduces costs by 29 percent. Greater variation in benchmarks implies higher costs because the TPS's implicit subsidy is proportional to the magnitude of the applicable benchmark. Thus, greater variation of benchmarks implies greater variation in the subsidy and greater disparities in the marginal costs of abatement,

[6] The social cost of carbon at time *t* is the cost to the economy, from time *t* into the indefinite future, from the change in climate stemming from an incremental increase in the CO_2 emissions. This estimation is adopted from the estimate of social cost of carbon (SCC) by the Biden Administration (2021)– 353 RMB/ton in 2020 that increases by 3% per year.

which entail a sacrifice of efficiency and higher costs. Thus, an attraction of greater uniformity of benchmarks is the lower associated cost of meeting given overall abatement targets. Nevertheless, policymakers may wish to have some variation of benchmarks: specifically, to customize the benchmarks in a way that avoids undesirable distributional impacts.

- **Impacts of auctioning.** Introducing allowance auctioning into the emissions trading system can lower the economic costs of achieving given emissions reduction targets under the TPS. This is the case to the extent that the revenues from the auction are used to reduce pre-existing distortionary taxes and thereby counter the distortionary impact of the TPS's output subsidy. We find that using the revenues to offset pre-existing capital and labor taxes yields the largest cost reductions, lowering economic costs by 34 percent relative to the case with no auctioning over the period 2020-2035. An alternative is to use the revenues to finance output subsidies for wind and solar-generated electricity. This option reduces the economy-wide costs by 25 percent relative to the no-auctioning case – slightly less than when revenues are used to cut pre-existing taxes. But this approach has the attraction of increasing renewables-based electricity generation by more over the 2020-2035 interval (by 38 percent, as compared with 5 percent in the no-auctioning case and 29 percent in the case when auction revenues are used to cut pre-existing taxes).
- **Transition to C&T.** Our previous research has shown that when the TPS is maintained over the entire simulation interval, the costs are higher than under a pure C&T policy maintained over that interval.[7] China is considering transitioning to C&T. Perhaps surprisingly, a policy in which a transition to C&T begins after eight years of the TPS has lower costs than in the case where C&T is introduced from the beginning. This reflects the beneficial impacts of the TPS on aggregate capital accumulation.[8] The TPS's higher levels of capital accumulation in the years preceding the transition lower the costs of C&T after the transition by yielding a higher post-transition capital stock than what would be the case in later years if C&T had been implemented from the start. Such TPS-induced higher capital stock lowers the post-transition costs of substituting away from high-carbon fuels under C&T.

The remainder of this report is organized as follows. Section II describes the model and its data. Section III describes the scenarios examined in this study. Section IV presents and interprets the results from the model under a range of specific policy designs. Section V concludes.

---

[7] To yield useful comparisons, The C&T allowance allocations were scaled so that the economy-wide emissions reductions in each year were the same as under the TPS.

[8] The TPS's implicit subsidy to output leads to lower prices of new capital to be used in production than under C&T. These lower prices give rise to higher investment than under C&T.

II. Model and Data

A detailed description of the model's structure and its data is given in Appendixes A and B.

A. Sectors

The general equilibrium model includes 31 production sectors, as shown in Table 1. The model is updated from the version in the first report. Disaggregation identifies new sectors. What was the paper sector now divides into the pulp & paper and printing & stationery sectors, and the original chemicals sector now divides into the daily chemical products and raw chemicals sectors.

Table 1. Sectors

Name	Description
Agriculture	Crop cultivation, forestry, livestock and livestock products and fishery
Mining	Metal minerals mining and non-metal minerals and other mining
Food	Food and tobacco
Textile	Textile
Clothing	Clothing
Log furniture	Log and furniture
Pulp & paper	Pulp and paper
Printing & stationery	Printing and stationery
Raw chemicals	Raw chemical materials, chemical products
Daily chemical products	Chemical fibers, medicines, rubber & plastics products
Cement	Cement
Other non-metal	Non-metal processing other than cement
Iron & steel	Iron and steel
Metal products	Metal products
General equipment	General equipment manufacturing
Transport equipment	Transport equipment manufacturing
Electronic equipment	Electronic equipment manufacturing
Other manufacturing	Other manufacturing
Aluminum	Aluminum products
Other non-ferrous	Non-ferrous metals other than aluminum
Water	Water
Construction	Construction
Transport	Transport and post
Services	Services
Coal	Coal mining and processing
Crude oil	Extraction of crude oil
Natural gas	Extraction of natural gas
Petroleum refining	Petroleum refining
Heat distribution	Heat distribution
Gas distribution	Gas distribution
Electricity	Electricity

B. The Allowance Market

The extension to the model includes the ability to consider policies in which some or all allowances are distributed through auction. The model can consider a range of scenarios regarding the share of allowances that are supplied via the auction. The auction is assumed to be a uniform-price sealed bid auction, so it would yield the same price as the allowance price in the secondary market. The model allows for a range of recycling methods for the auction revenue, including lump-sum recycling, cuts in capital and labor taxes, and output subsidies.

Details of the auction policy and the revenue use have not yet been decided. Some general information is offered in Interim Regulations for the Management of Carbon Emissions Trading (Draft) (MEE, 2021), which mentions that the revenue will be used to "support the construction of the national carbon emissions trading market, and key greenhouse gas emissions reduction projects." Consistent with this general description, we consider four recycling methods and their combinations: output subsidies to wind and solar electricity production, lumpsum transfer to households, lumpsum transfer to the sectors that are hit most by carbon pricing, and subsidies to capital and labor inputs in most-hit sectors. Details are offered in Appendix C.

The modeling of other features of the allowance market, such as allowance trading and allowance banking, remains the same as in the previous report. Appendix B provides the details.

C. Dynamics

The model solves at one-year intervals from 2020 through 2035, which is longer than the timespan 2021-2030 in the first report. The dynamics of the stocks of production factors (capital, labor, natural resources), technological progress, and industrial structure are detailed in Appendix B.

D. Data

Please refer to Appendix A for details on data sources and preprocessing. The data are based on China's 2017 input-output table. We use three scalars to translate these input and output data to 2020 (the first simulation year): one for the service sector, one for the agriculture sector, and one for other sectors, so that the GDP, the value-added share of the service sector and agriculture sectors match the published statistics in 2020 (National Bureau of Statistics, 2021).

We have updated the data on emissions from the newly added sectors in Phase 3 of China's TPS. For these sectors – namely, pulp & paper, raw chemicals, petroleum refining, other non-metal products, and other non-ferrous metals – we use the emissions data from the energy balance table of 2017, which are more precise than the GTAP 10 emissions data we had used in the first report.

We have also updated the import and export data. The input-output table does not provide the import and export data for the cement and the aluminum sector. We thus used the import and export data from the industry organizations for the aluminum and cement sector in this report.[9]

[9] The data on cement imports and exports are collected from the China Concrete & Cement Products Association. The data on aluminum imports and exports are collected from the China Nonferrous Metals Industry Association, Aluminum Branch.

III. Scenarios

A. The Baseline

The baseline simulation projects outcomes for the Chinese economy in the absence of the TPS or C&T.[10] Economic growth in the baseline reflects the growth of two primary factors of production: labor and capital. The stocks of renewable resources are assumed to remain constant over time.

The growth of capital is determined by net public and private savings in each period. The time profile of effective labor is exogenously specified and calibrated so that the model's GDP growth rate in the baseline matches government projections.[11] We calibrate the model to yield a growth rate of 5.5% in 2020-2025, 4.5% in 2026-2030, and 3.5% in 2031-2035, consistent with government projections. The average growth rate over 2020-2035 is 4.7%.

B. Policy Cases

The policy cases follow closely the key discussions by decision-makers in the MEE and other administrative bodies concerning China's current TPS policy and its future evolution. In the model's simulations, the time-intervals for the TPS's three phases are as follows. The first year of each interval represents the year of the first compliance period for the phase in question. The first phase of the TPS began in 2020 and covered only the electricity sector. The second phase is assumed to begin in 2023, when the TPS expands to cover the iron&steel, aluminum, and cement sectors. In the third phase, which is assumed to begin in 2026, coverage is expected to expand to include pulp&paper, other non-metal products (including facilities that produce ceramics, bricks, and glasses), other non-ferrous metals (including facilities that produce copper and tin), raw chemicals (including facilities that produce ethylene, methanol, synthetic ammonia, caustic soda, soda ash, synthetic fiber, and plastic), and petroleum refining (including facilities that produce gasoline and diesel fuels).

The policy cases considered are as follows. Table 2 displays the benchmarks employed in each case. These benchmarks are updated according to the information from the recently issued document *Draft Plan for the Allocation of the National Carbon Emission Quotas in 2021 and 2022 (Power Generation Industry)*.[12]

[10] We abstract from any new policy interventions that might occur between 2020 and 2035.
[11] The government projections are in Outline of the 14th Five-Year Plan (2021-2025) for National Economic and Social Development and Vision 2035 of the People's Republic of China, 2021).
[12] The plan specifies the new benchmarks for 2021-2022. The large difference between the benchmarks in 2020 (the benchmarks we use in the first report) and the benchmarks in 2021 is due to the change in the emission accounting method. Starting in 2021, a new accounting method is implemented. For consistency, we use the new accounting method for all years in the 2020-2035 interval, because the new accounting method is more consistent with the accounting method applied to the emission data we use. We align the accounting method by adjusting the benchmarks in 2020 to the levels as if the new accounting method applied to them. Case 1 benchmarks for the electricity sector in Table 2 show the adjusted 2020 benchmark.

Table 2. Benchmarks under Case 1 and Case 2

Sector	Subsectors	Initial benchmarks[1]		
		Case 1	*Case 2a*	*Case 2b*
Electricity (tCO_2/MWh)	Coal-fired generators with capacity ⩽ 300 MW (Small SC, Small SUB, and Other coal)[2]	0.882	0.859	0.843
	Coal-fired generators with capacity > 300 MW (Large USC, Small USC, Large SC, and Large SUB)[2]	0.824	0.859	0.843
	Circulating fluidized bed generators (Large CFB, Small CFB)	0.940	0.859	0.843
	Gas-fired generators (High-Pressure Gas, Low-Pressure Gas)	0.394	0.394	0.843
Cement (tCO_2/ton)	Low (L), medium (M) and high (H) efficiency	0.848	0.848	0.846
Iron & steel (tCO_2/ton)	Basic oxygen furnace – L, M, H	0.017	0.017	0.016
	Electric arc furnace – L, M, H	0.004	0.004	0.004
Aluminum (tCO_2/ton)	L, M, H	7.941	7.936	7.914
Other non-metal products (tCO_2/*k*RMB)	All facilities	0.055	0.055	0.055
Other non-ferrous metal (tCO_2/*k*RMB)	All facilities	0.049	0.049	0.048
Pulp&paper (tCO_2/*k*RMB)	All facilities	0.048	0.048	0.047
Petroleum refining (tCO_2/*k*RMB)	All facilities	0.042	0.042	0.041
Raw chemicals (tCO_2/*k*RMB)	All facilities	0.087	0.087	0.086

[1] Initial benchmarks are the benchmark values for a given sector when they are first introduced to that sector under the TPS. Thus, in a given column of the table, the values are for different years, depending on when the sector's coverage begins. For a given sector, the benchmark values differ across cases (or columns) in keeping with differences in the number of benchmarks and the requirement that aggregate emissions reductions be the same across these cases.

[2] Large USC: Ultra-supercritical coal-fired generators with capacity > 600MW; Small USC: Ultra-supercritical coal-fired generators with capacity ⩽ 600MW and > 300MW; Large SC -Supercritical coal-fired generators with capacity ≤ 600MW and > 300MW; Small SC: Supercritical coal-fired generators with capacity ≤ 300MW; Large SUB: Subcritical coal-fired generators with capacity ≤ 600MW and > 300MW; Small SUB: Subcritical coal-fired generators with capacity ≤ 300MW; OTHC: other coal-fired generators with capacity ≤ 300MW.

Case 1 (central case):

In the electricity sector, four benchmarks apply in each phase: three for coal-fired generators and one for natural-gas-fired units.

Starting in Phase 2, one benchmark applies to the aluminum sector, one to the cement sector, and two to the iron&steel sector (consisting of one for the basic oxygen process and one for the electric arc furnace process). Starting in Phase 3, there is one benchmark for each of the newly added sectors (pulp&paper, other non-metal products, other non-ferrous metals, raw chemicals, and petroleum refining).

The rates of tightening of the benchmarks are 0.5%/year for the electricity sectors during 2020-2022, as announced by the MEE.[13] Starting in 2023, the rates of tightening of the benchmarks are 1.5%/year for the electricity sectors, and 2.5%/year for the non-electricity sectors.[14] The initial benchmarks for Phase 2- and Phase 3- newly added sectors are set to be 2.5% lower than their emission intensities of the previous year.

It is likely that at some point China's TPS will include provisions that allow covered facilities to bank some of their current allowances for use in future compliance periods. However, the specifics of such provisions have not yet been announced, leaving uncertainties about the initial introduction of banking provisions, the restrictions on banking, and the length of time over which allowances can be banked. It is also uncertain how much the covered facilities would choose to engage in banking, were it allowed.[15] In light of these uncertainties, we have not incorporated banking in this central case and most other cases. However, Case 4 considers outcomes in the presence of allowance banking.

Case 2 (Fewer benchmarks for the electricity sector):

Case 2a: 2 electricity sector benchmarks – 1 for coal-fired and 1 for gas-fired

This case involves fewer power-sector benchmarks than in Case 1. The number of benchmarks for coal-fired generators is reduced from three to one, and there remains one benchmark for natural-gas-fired generators. The single benchmark for the coal-fired generators in this case is the weighted average benchmark of the three coal-fired generators in Case 1. In addition, all benchmarks are scaled by a common factor to achieve the same economy-wide reductions in each period as those under Case 1.

Case 2b: 1 electricity sector benchmark – 1 for all generators

In all phases, a single benchmark applies to all of the coal-fired and natural-gas-fired generators. Again the single benchmark is the weighted average benchmark under Case 1, and

---

[13] See the *Draft Plan for the Allocation of the National Carbon Emission Quotas in 2021 and 2022 (Power Generation Industry)* issued by the MEE.

[14] This assumption is made according to our latest communications with the MEE: it is expected that MEE will set a lower benchmark tightening rate for the electricity sector than for the non-electricity sectors because the room for energy efficiency improvement in the electricity sector is considered relatively low. This assumption is made according to our latest communications with the MEE. From the ministry's perspective, there is relatively little room for energy efficiency improvement in the electricity sector. The ministry holds the view that most of the opportunities for low-cost abatement in the electricity sector have already been exploited over the past decade or so. The slower planned tightening of electricity-sector benchmarks reflects this perspective.

[15] According to the experience of the pilots in China, the lack of opportunities for hedging and speculation from future allowance price movements undermines the incentives to bank allowances (Cong & Lo, 2017; Zhao et al., 2016).

then all benchmarks are scaled to achieve the same economy-wide reductions in each period as those under Case 1. Other settings are the same as in Case 1.

Case 3 (Faster increase in benchmark stringency):

This case has a faster increase in benchmark stringency than in Case 1.

Case 3a: Faster tightening rates

Starting from 2023, the tightening rates of benchmarks are 1.7%/year for the electricity sectors and 2.7% for the non-electricity sectors, so that the emissions *from the TPS-covered* sectors in 2035 (the end of the modeling period) match the predicted emissions from these sectors on the path to achieving the carbon neutrality goal by 2060.[16] Other settings are the same as in Case 1. We do not consider any additional policies in the uncovered sectors.

Case 3b: Carbon neutrality

Starting from 2023, the tightening rates of benchmarks are 2.8%/year for the electricity sectors and 3.8% for the non-electricity sectors, so that the *economy-wide* emissions in 2035 match the predicted economy-wide emissions on the path to achieving the carbon neutrality goal by 2060. Other settings are the same as in Case 3a.[17]

Case 4 (Provisions for allowance banking included):

We assume the detailed rules for allowance banking will be announced in 2024, so firms are allowed to bank allowances starting in 2024. Other settings are the same as in Case 1.

Case 5 (Allowance auction):

We consider policies that differ in the trajectories of the share of auctioned allowances and in the forms of recycling auction revenues. The five cases are presented in Table 3. In all the cases, the auction starts in the year 2025, and the auction share increases yearly over the interval 2025-2035. With auctioning, the benchmarks that determine the supply of free allowances are adjusted to achieve the same economy-wide reductions in each period as those under Case 1.

[16] We adopted the emission path suggested by He et al.(2020), a much-cited and comprehensive study. He et al.(2020) indicates that emissions from the TPS-covered to be around 6 Gt in 2035.
[17] The emission path in He et al.(2020) leads to an economy-wide CO_2 emissions of around 9 Gt in 2035.

Table 3. Auction Cases

<table>
<tr><th>Case</th><th>First auction year</th><th>Share of auctioned allowances in 2025</th><th>Share of auctioned allowances in 2035</th><th>Recycling method</th></tr>
<tr><td>5a</td><td rowspan="5">2025</td><td rowspan="4">Electricity: 10%
Others: 0%</td><td rowspan="4">Electricity: 100%
Others: 30%</td><td>100% recycled as output subsidies for wind and solar electricity production.</td></tr>
<tr><td>5b</td><td>50% recycled as output subsidies for wind and solar electricity production.
50% recycled as lumpsum transfer to households.</td></tr>
<tr><td>5c</td><td>50% recycled as output subsidies for wind and solar electricity production.
50% recycled as lumpsum transfer to coal and mining sectors.</td></tr>
<tr><td>5d</td><td>50% recycled as output subsidies for wind and solar electricity production.
50% recycled as subsidies to capital and labor inputs in coal and mining sectors.</td></tr>
<tr><td>5e</td><td>Electricity: 10%
Others: 0%</td><td>Electricity: 50%
Others: 0%</td><td>100% recycled as output subsidies for wind and solar electricity production.</td></tr>
</table>

Case 5a:

In 2025, the auction accounts for 10% of total allowances for the electricity sector, and 0% for the other sectors. This auction share increases annually, reaching 100% for the electricity sector and 30% for the other sectors in 2035.

100% of the auction revenue is recycled as output subsidies for wind and solar electricity production.

Case 5b:

The auction trajectory is the same as in Case 5a. This case differs from Case 5a in the nature of the recycling of the auction revenues. Here 50% of auction revenue is recycled as output subsidies for wind and solar electricity production, and the other 50% is recycled as lumpsum transfer to households.

Case 5c:

The auction trajectory is the same as in Case 5a. Recycling in this case is the same as that in Case 5b, except that the 50% of auction revenue recycled as a lump sum transfer to households is now transferred to the coal and mining sectors, which are the sectors that otherwise would experience the largest impacts on profits.

Case 5d:

The auction trajectory is the same as in Case 5a. As with cases 5b and 5c, 50% of the auction revenue is recycled as output subsidies for wind and solar electricity production. The other 50% is recycled as subsidies to capital and labor inputs in the coal and mining sectors.

Case 5e:

This case differs from Case 5a in the share of emissions allowances supplied by the auction. In 2025, the auction accounts for 10% of total allowances for the electricity sectors, and 0% for the other sectors, same as Case 5a. However, the auction share for the electricity sector increases annually, reaching only 50% for the electricity sector in 2035. The auction share for the other sectors remains 0% throughout. The auction revenue recycling is the same as in Case 5a.

Case 6: C&T and Transition to C&T

These cases compare the TPS's impacts in Case 1 with those of a C&T policy that leads to the same economy-wide emissions as the TPS. The cases differ in terms of the length of the transition. During the transition, it is a mixture of TPS and C&T, under which the proportion involving TPS-based allocation decreases linearly to zero during the transition stage. Additional free allowances are issued during the transition, scaled to ensure that in each year of the transition economy-wide emissions match the levels under the central case TPS.

This case subdivides into two transition scenarios:

Case 6a: Instant transition to C&T

The TPS operates until the end of 2027 and is then replaced by a pure C&T system in 2028. The benchmarks of 2021-2027 are the same as in the Case 1 TPS, while the total allowances under C&T in 2028 and beyond are set so that the economy-wide emissions in each period match those in the Case 1 TPS.

Case 6b: Gradual transition to C&T

The transition from the TPS to C&T begins in 2028 but is gradual. There is a two-year transition period during which both the TPS and C&T are in place. During the transition, the proportion of allocation with TPS's benchmarking method decreases linearly to zero in 2030. That is, the benchmarks in 2028 and 2029 are 2/3 and 1/3 of the benchmarks in 2027, respectively. During and after the transition, covered facilities receive exogenously supplied "C&T allowances." The allocation of C&T allowances is proportional to the allocations of Case 1. The supply of these allowances is scaled so that the economy-wide emissions are the same in each period as in Case 1 TPS. The distribution of these allowances across sectors matches the distribution under the TPS.

IV. Policy Results

A. Central Case Results

Phase 1 Outcomes

Phase 1 spans the interval 2020-2022.[18,19] The phase includes three one-year compliance periods. We focus on the model's predictions for the year 2021. Table 4 presents the key results of the TPS in 2021. The results differ from those of the first report because the data and benchmarks have been updated, as detailed in sections IID and IIIB.

TPS outcomes. Our central estimate is that in 2021, the TPS reduces economy-wide emissions by 1.7 percent. The emissions reductions all come from the electricity sector, in which emissions decline by 182 million tons, or 4.1 percent from the baseline. Emissions from the uncovered (i.e., non-electricity) sectors increase slightly -- by 2 million tons. This increase reflects the slightly increased use of coal in the uncovered sectors because of the lower coal price due to lowered coal demand. The equilibrium price of allowances is 52 RMB/tCO_2.[20] The trading volume is 140 million tons.

The TPS causes the aggregate electricity supply to decline by 23 billion kWh, about 0.3% from the baseline. The TPS induces a shift in electricity production from the units with baseline emissions-output ratios above the applicable benchmark to other units with baseline ratios below the benchmark. The former units reduce output by 294 billion kWh and the latter units expand output by 268 billion kWh. Overall, the generation from the fossil-fuel-based units decreases by 26 billion kWh, or 0.5%, a reflection of the fact that the TPS imposes benchmarks that are tighter than the average emissions intensities of the covered units. The TPS increases the costs of power generation by 0.4 percent. The higher costs are reflected in higher prices of electricity. Renewables-based generators are not covered under the TPS, and since their costs are relatively unaffected, renewable electricity generators capture more of the electricity market. Wind- and solar-powered generators increase their production by 0.5%.[21]

By putting a price on emissions, the TPS generally introduces costs to both the electricity sector and the overall economy. The overall cost to the economy in 2021, measured as the

---

[18] The official allowance trading began in 2021, and the compliance in 2021 is assessed based on emissions of 2019 and 2020. In other words, in the current system, the output and emission decisions are made in a different year (2019 and 2020) from the allowance trading decision (2021). In the model, we assume for simplicity that these decisions are made in the same year. With this simplification, the results are the same as what would occur if the benchmarks were "revealed" after a one-year lag while covered facilities correctly anticipated the next year's benchmarks.

[19] We choose the year 2020 as the first period of our modeling analysis, because draft provisions of the policy circulated in 2020, so firms do not have incentives to alter their decisions until 2020.

[20] This is comparable to the allowance price observed in China's TPS in the previous compliance period, which has a weighted average price of about 43.85 RMB ($6.89) per ton with a range of 40-60 RMB/ton.

[21] The model incorporates important elements of China's regulation of electricity markets. For a given generating unit, electricity output up to a government-assigned quantity (the "guaranteed-hour" level) must be sold at a price set by the government, which is usually higher than the market price. Therefore, generating units gain additional rents with the guaranteed hour production. Production in excess of the guaranteed-hour level will be sold at market prices. In this way, the regulation of electricity markets does not affect the decision on generation, as long as the generation is above the guaranteed-hour level. In the model, this is done by adding a lower bound to the electricity production level for each electricity subsectors, and using a lump-sum tax transfer to represent the excessive rent associated with the guaranteed-hour production. The shares of the guaranteed-hour production in the base year are from China Electricity Council, and decrease linearly to zero before the year 2025 to reflect the ongoing electricity market reform.

economy-wide changes in GDP, is about 8.0 billion RMB, or 0.008 percent of baseline GDP for the entire economy. The cost per ton of reduced emissions is 45 RMB. Labor income (in real terms, with the price of the composite produced good as the price index) falls by 8.9 billion RMB (or 0.016%), while capital income increases by 5.3 billion RMB (or 0.013%) because of the substitution from fuel inputs to capital inputs and the value of free allowances granted to capital owners. The overall lower output level implies lower tax payments, which leads to a decline in total tax revenue by 4.5 billion (0.05 %).

When a social cost of carbon of 353 RMB/tCO_2 is applied, the climate benefits generated from the emissions reductions in 2021 are about eight times the economic cost of 8.0 billion RMB in that year.

Comparison with C&T. Table 4 includes results from a C&T system scaled to achieve the same emissions reductions in each year.

Under both the TPS and C&T, the aggregate reductions in emissions are achieved through the following three channels: 1) reductions in emissions intensity, 2) reductions in the level of output, and 3) changes in sector composition. The pie charts in Figure 1 display the relative contributions of these three channels. The TPS relies less on the output-reduction channel (10% under TPS, 46% under C&T), because of its implicit subsidy to output. Thus, electricity prices rise less under the TPS than under C&T. Correspondingly, the TPS has to rely more on reduced emissions intensity (35% under TPS, 11% under C&T). The relative contribution of changes in sector composition is also larger under the TPS (55% under TPS, 43% under C&T).

Since C&T leads to greater output reductions, the demand for allowances under C&T is lower than under the TPS. Consequently, the C&T allowance price (13 RMB/tCO_2) is lower than the price under the TPS (52 RMB/tCO_2).[22]

Compared with the TPS, C&T accomplishes a larger shift of production toward renewables-based electricity. The TPS's implicit output subsidy mitigates the cost-increase to fossil-based generators, which reduces the extent to which renewables enjoy a cost-advantage. Under C&T, the production of wind- and solar-power electricity increases by 3.9% relative to the baseline, as compared to 0.5% under the TPS.

[22] As shown in Figure 1, emissions intensities decline by less under C&T than under the TPS. This works toward a higher demand for allowances under C&T than under the TPS. However, this intensity effect is more than offset by the increase in demand for allowances associated with C&T's higher output relative to output under the TPS.

Table 4. Aggregate Impacts of the TPS and C&T in the Second Compliance Period of Phase 1 (Year 2021)

Figures in italics are percentage changes from the baseline

	Baseline	TPS	C&T
Allowances Traded (million tCO_2)		140	96
Allowance Price (RMB/tCO_2)		52	13
Policy Impacts			
Emissions (million tCO_2)			
Economy-wide emissions	10,725	*-1.7*	*-1.7*
Power Sector emissions	4,395	*-4.1*	*-4.1*
from units that increase supply	1,714	*9.4*	*-0.4*
from units that reduce supply	2,681	*-12.8*	*-6.5*
Electricity Supply (billion kWh)			
Aggregate Electricity Supply	7,622	*-0.3*	*-1.3*
Coal-fired electricity	4,481	*1.3*	*-2.1*
CFB electricity	424	*-27.0*	*-16.2*
Gas-fired electricity	140	*20.5*	*27.1*
Wind and solar electricity	778	*0.5*	*3.9*
Electricity Price (RMB/kWh)	0.6	*0.4*	*2.2*
Income (trillion RMB)			
GDP [1]	106	*-0.008*	*-0.008*
Capital income [2]	42	*0.013*	*0.108*
Labor income	56	*-0.016*	*-0.084*
Government income	9	*-0.050*	*-0.074*
Costs per ton of reduced emissions (RMB/tCO_2)[3]		45	46

[1] The GDP and income are expressed in real terms. The price index is the price of the composite produced good.
[2] Capital income here is the return to capital, including any economic rent generated by the free allocation of allowances.
[3] In our first report, the cost-disadvantage of the TPS emerged even in the first years of implementation. The new results differ from the earlier results in the first report because of the updated benchmarks. The present report employs less stringent benchmarks in early periods. The lower stringency reduces the relative strength of the adverse efficiency impact of the TPS's implicit output subsidy. This underlies the small differences in cost-effectiveness in the early years. We have performed a counterfactual simulation with the current model and the old stringency level. This simulation yields a pattern of relative costs very close to the pattern in the first report.

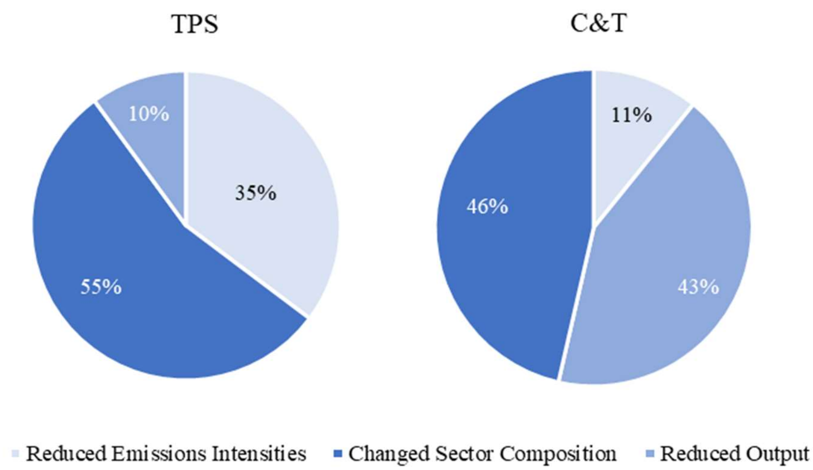


Figure 1. Sources of Emissions Reductions under the TPS and C&T, 2021

Economic theory indicates that the TPS's implicit output subsidy compromises its cost-effectiveness. However, as shown in Table 4, in Phase 1 the differences in costs per ton between the TPS and C&T are slight.[23] This partly reflects the fact that during this phase the power sector benchmarks are not very stringent, so the distortionary impact of the TPS's implicit output subsidy is not very great.

There is a second reason for the very small differences in cost-effectiveness in the first years of the TPS. Indeed, this second reason explains why, in the first years, the TPS is incrementally more cost-effective. As in other economies, there are significant pre-existing taxes on the labor, capital, and intermediate inputs used in production in most sectors in China. Although the TPS's implicit output subsidy leads to inefficiently high output relative to C&T, it also has the beneficial effect (in terms of efficiency) of reducing the distortionary effect of taxes on labor, capital, and intermediate inputs. It achieves this because this distortionary effect is an increasing function of the prices of inputs and outputs. This "tax-interaction effect" has been examined theoretically and numerically in the environmental economics literature.[24] Because of its implicit output subsidy, the TPS leads to smaller increases in prices, which implies a smaller tax-interaction effect than under C&T. This mitigates the main disadvantage of the TPS emphasized above – the disadvantage related to its less efficient use of output-reduction as a channel for reducing emissions.[25]

---

[23] The differences between the TPS and C&T in terms of GDP is slight, while the difference in allowance prices between the two policies is much larger. There are two main reasons:
a.) Coverage: the allowance price reflects the cost of covered sectors only, while the economy-wide cost per ton is an economy-wide cost. The allowance price does not take into account the loss in other sectors, such as the coal sector and the downstream sectors of the electricity sector.
b.) The allowance price is a marginal concept: it is the cost for the last unit of abatement in the covered sectors. In contrast, private cost per ton is an average concept: it is the total economy-wide (or GDP) cost, divided by the total tons of abatement. Because marginal costs tend to be an increasing function of abatement, marginal costs exceed average costs.

[24] See, for example, Goulder et al. (1999), and Parry and Bento (2000), and Parry and Williams (2010).

[25] In the simulations for our first report, the cost-disadvantage of the TPS emerged in the first years of implementation. In the current report, the disadvantage begins to appear only after 2027. As was noted in Section II.D and Section III.B, this reflects the current report's use of the associated lower stringencies of the benchmarks.

To confirm the significance of pre-existing taxes for the relative costs of the TPS and C&T, we have performed counterfactual simulations in which the magnitudes of pre-existing taxes on capital, labor, and intermediate inputs to production are different. As indicated in Table 5, the ratio of the TPS's costs to the costs under C&T is lower, the higher the level of pre-existing taxes.

In the subsection below, "TPS and C&T emissions and relative costs over time", we show that in later years, the TPS's costs per ton become significantly higher than those under C&T. This is because the distortionary impact of the TPS's implicit subsidy becomes more important over time, since the subsidy is a function of the continued tightening of the benchmarks.

Table 5. Ratios of TPS Economic Costs to C&T Economic Costs with Different Assumptions of the Extent of Pre-Existing Taxes in 2021.

Pre-existing taxes	Ratios of TPS economic costs to C&T economic costs
200% of the central case	0.89
180% of the central case	0.90
160% of the central case	0.92
140% of the central case	0.94
120% of the central case	0.95
Central case	0.98
80% of the central case	1.00
60% of the central case	1.03
40% of the central case	1.06
20% of the central case	1.10
Zero	1.15

Phase 2 Outcomes

Table 6 presents key results for the TPS and C&T in 2023, the first compliance period of Phase 2, when the TPS is expanded to cover the electricity, cement, aluminum, and iron&steel sectors.

TPS outcomes. As a result of the expansion of coverage, the CO_2 emissions reductions in 2023 are about twice the 2021 amount. The emission reductions are 364 million tons in 2023, and increase to 746 million tons by the end of Phase 2 (2025).[26]

[26] Under the TPS, the emissions associated with electricity production are priced twice: the electricity sector faces the price of emissions from its generation of elctricity, and non-electricity sectors are also charged for the emissions from the generation of the electricity that they use as an input in production. This deliberate double-counting is intended to encourage high-electricity consuming industries to further reduce emissions, to offset the reduced incentives to reduce electricity-sector emissions because of free allocation and the presence of administered prices for some electricity. This report recognizes the double-counting and displays the actual economy-wide emissions reductions.

The allowance price is 51 RMB/t CO_2. The increase in the allowance price reflects the higher overall stringency of the benchmarks, as indicated by the higher output-weighted average percentage reduction in emissions-intensities under the Phase 2 benchmarks.

The TPS's economy-wide economic cost is 17 billion RMB, 0.014% of the baseline GDP and 46 RMB/tCO_2. Phase 2 costs are higher than that in Phase 1, reflecting broader sectoral coverage of the TPS as well as the higher stringency of the electricity sector.

Comparison with C&T. In this phase, C&T again relies more than the TPS on reduced output to achieve emissions reductions: In 2023, C&T achieves 40% of the reductions through reduced output, as compared with 11% under the TPS. TPS must rely more on reduced emissions intensity for compliance -- the weighted average emissions intensity of the covered sectors (using output levels as weights) decreases by 4% under the TPS, compared to 3% under C&T.

Again the allowance price is lower under C&T than under the TPS. As indicated in Table 6, this price is 19 RMB/t CO_2 under C&T, as compared to 51 RMB/tCO_2 under the TPS. This reflects the lower costs of reducing emissions under C&T and the associated reduced demand for purchasing allowances for compliance.

The economic cost of C&T is again very close to that of the TPS. As discussed above in connection with Phase 1, this reflects the fact that the TPS has two implications for efficiency that work in opposite directions. The implicit subsidy distorts output decisions, but it also reduces the distortionary cost of pre-existing taxes on inputs. In later years, when the benchmarks are more stringent, the former (adverse) effect dominates, and the TPS's costs per ton surpass those of C&T. [27]

[27] The TPS becomes increasingly cost-effective relative to C&T in the time-interval from Phase 1 to Phase 2, although this trend is reversed in the years that follow. The temporary improvement in the TPS's relative cost-effectiveness reflects the slightly higher rate of investment under the TPS, which stems from the lower prices of new capital goods under the TPS. The faster capital accumulation contributes to the TPS's early cost-advantage because it reduces the cost of switching from high-carbon fuels to other inputs. This influence of faster capital formation is relatively small, although it is enough to explain the time-pattern of the slight differences in cost-effectiveness of the two policies in the early years, when stringency is relatively low. As indicated, in later years the time-pattern of differences in cost-effectiveness is largely determined by changes in stringency.

Table 6. Aggregate Impacts of the TPS and C&T In the First Compliance Period of Phase 2 (Year 2023)

Figures in italics are percentage changes from the baseline

	Baseline	TPS	C&T
Allowances Traded (million tCO_2)		293	207
Allowance Price (RMB/tCO_2)		51	19
Policy Impacts			
Emissions (million tCO_2)			
Economy-wide emissions	11,597	*-3.1*	*-3.1*
Covered sectors' emissions [1]	7,559	*-4.9*	*-4.9*
Electricity	4,745	*-4.4*	*-6.0*
Cement	1,546	*-3.4*	*-1.6*
Aluminum	349	*-1.1*	*-2.8*
Iron&steel	1,518	*-7.3*	*-4.1*
Output			
Economy-wide [2]		*-0.3*	*-1.0*
Electricity (billion kWh)	8,203	*-0.5*	*-1.9*
Wind and solar electricity	959	*0.6*	*5.0*
Cement (million t)	1,781	*-0.1*	*-0.3*
Aluminum (million t)	43	*-0.3*	*-2.1*
Iron&steel (billion t)	108	*-0.2*	*-0.2*
Prices			
Electricity (RMB/kWh)	0.6	*0.5*	*3.1*
Cement (RMB/t)	450	*0.3*	*3.9*
Aluminum (RMB/t)	18,654	*0.3*	*2.2*
Iron&steel (RMB/t)	61	*0.1*	*0.6*
Income [3] (trillion RMB)			
GDP	119	*-0.014*	*-0.015*
Capital income	47	*0.022*	*0.215*
Labor income	62	*-0.030*	*-0.169*
Government income	10	*-0.085*	*-0.124*
Costs per ton of reduced emissions (RMB/tCO_2)		46	49

[1] We deduct the double-counted emissions of electricity use in the cement, aluminum, and iron&steel.
[2] Calculated as the average of the output supply change, weighted by the output value of the baseline.
[3] The economic costs and changes in different sources of income are measured in real terms.

Phase 3 Outcomes

Table 7 presents key results for the TPS and C&T in the first compliance period of Phase 3, 2026, when the TPS is eventually expanded to cover five new sectors: pulp&paper, other non-metal products, other non-ferrous metals, raw chemicals, and petroleum refining.

TPS outcomes. In the first year of Phase 3 (2026) the TPS reduces emissions by 974 million tons or 8 percent of the baseline emissions, which is more than twice that of 2023 and four times that of 2021. The largest reductions are from the electricity sectors and the sectors that were added in Phase 2, with the former accounting for 51% and the latter accounting for 37% of the total emission reductions. The new sectors in Phase 3 only contribute to 12% of the total emission reductions. Uncovered sectors increase their emissions slightly, by 16 million tons. The increase reflects an increase in demand for coal by these sectors: the coal price falls as a consequence of reduced demand for coal by the covered sectors.

Similar to the outcomes in phases 1 and 2, the reduction in emissions comes from both reduced emissions intensities and reduced outputs of the covered sectors.

As Table 7 indicates, the Phase 3 allowance price in 2026 is higher than in the earlier phases, reflecting the higher overall benchmark stringency in this phase. The TPS's economy-wide economic cost is 74 billion RMB, 0.05 % of the baseline GDP and 76 RMB/tCO_2, compared to 45 RMB/tCO_2, and 46 RMB/tCO_2 in Phases 1 and 2, due to the broader coverage and the higher stringency.

Comparison with C&T.

The 2026 allowance price is 44 RMB/t CO_2 under C&T, as compared with 116 RMB/tCO_2 under the TPS. This again reflects the fact that C&T leads to larger reductions in output and associated demands for allowances.

In the same year, the TPS costs per ton are again quite similar to those of C&T, for the same reasons as discussed in connection with the earlier phases. However, in later years, the TPS's costs per ton become larger than those under C&T. We examine this closely in the next subsection.

Table 7. Aggregate Impacts of the TPS and C&T in the First Compliance Period of Phase 3 (Year 2026)

Figures in italics are percentage changes from the baseline

	Baseline	TPS	C&T
Allowances Traded (million tCO_2)		355	380
Allowance Price (RMB/tCO_2)		116	44
Policy Impacts			
Emissions (million tCO_2)			
Economy-wide emissions	12,868	*-7.6*	*-7.6*
Covered sectors' emissions [1]	9,130	*-10.8*	*-10.8*
Electricity	5,232	*-13.3*	*-14.8*
Phase 2 newly-added sectors	3,747	*-13.4*	*-11.5*
Petroleum refining	274	*-8.3*	*-4.9*
Chemical	946	*-4.2*	*-4.6*
Pulp&paper	112	*-11.2*	*-6.7*
Other non-metal material	411	*-11.4*	*-7.2*
Other non-ferrous metal	254	*-12.4*	*-9.0*
Output			
Economy-wide [2]		*-0.3*	*-1.2*
Electricity (billion kWh)	9,042	*-0.5*	*-1.9*
Wind and solar electricity	1,201	*1.7*	*10.4*
Phase 2 newly-added sectors (weighted average)		*-0.5*	*-0.9*
Petroleum refining (billion RMB)	929	*0.0*	*-0.1*
Chemical (billion RMB)	1,547	*-0.3*	*-1.6*
Pulp&paper (billion RMB)	335	*-0.1*	*-0.4*
Other non-metal products (billion RMB)	1,063	*-0.2*	*-0.7*
Other non-ferrous metals (billion RMB)	746	*-0.5*	*-2.3*
Income (trillion RMB)			
GDP	139	*-0.05*	*-0.05*
Capital income	54	*0.04*	*0.49*
Labor income	73	*-0.09*	*-0.43*
Government income	12	*-0.21*	*-0.24*
Cost per ton of reduced emissions (RMB/tCO_2)		76	76

[1] We deduct the double-counted emissions of electricity use in Phase 2 newly-added sectors (cement, aluminum, and iron&steel) and Phase 3 newly-added sectors (petroleum refining, chemical, pulp&paper, other non-metal material, and other non-ferrous metal).

[2] Total value of output in real terms, using the price of composite consumption good as the price index.

TPS and C&T emissions and relative costs over time

Figure 2 offers the model's projected time profiles for emissions from the TPS-covered sectors as well as from the economy as a whole. The simulations indicate an emission profile that peaks around 2028-2030. Our assumed values for the Phase 3 benchmarks indicate that over the longer term the TPS would cover around 60%-70% of the economy's emissions.

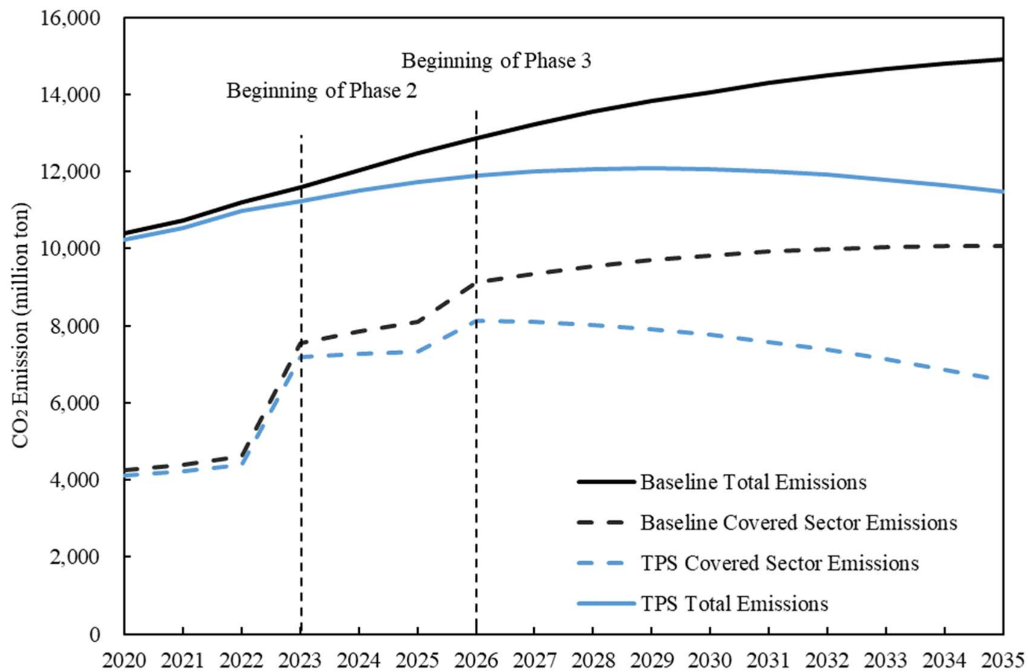


Figure 2. Emissions Over Time, Baseline and Case 1

Over the 2026-2035 interval, 25% of the cumulative emissions reductions from C&T are attributable to reductions in emissions intensity, as compared with 49% under the TPS. Over the entire 2020-2035 simulation interval, 37% of the cumulative emissions reductions from C&T are attributable to reduced output, as compared with 20% under the TPS.

Figure 3 shows the economic costs as a percentage of the baseline GDP of the same year. In the first year (2020), the TPS has an economic cost of about 0.006% of GDP. This cost increases to 0.039% in 2025, 0.168% in 2030 and 0.408% in 2035. With a 5% discount rate, the present value of the economic costs over the period of 2020-2035 is 2.1 trillion RMB. With a social cost of carbon of 353 RMB/t in 2020, the cumulative emissions reduction can bring an environmental benefit of 11.7 trillion RMB. The benefit exceeds the cost by a factor of five.

Figure 3 also displays the economic costs of an equivalently stringent C&T system. The difference between TPS and C&T is negligible until about 2028. After that year, the economic cost of TPS becomes increasingly higher than C&T due to the increased stringency. As noted earlier, the TPS's implicit output subsidy has two opposing influences on cost-effectiveness: (1) it causes covered facilities to rely too little (from an efficiency point of view) on output-reduction to achieve compliance, and (2) it reduces the efficiency costs from prior taxes on labor, capital, and intermediate inputs in production. The first influence works against cost-effectiveness; the second one promotes it. The TPS's costs relative to C&T reflect changes over time in the relative importance of these two factors. In the first years of the TPS, the two influences are of similar importance. As a result, there is little difference in the cost-effectiveness of the TPS and C&T. However, over time, the first factor gains more importance relative to the second. This reflects the increasing stringency of the benchmarks and the increase in allowance prices.[28] The eventual higher costs of the TPS compared to C&T reflect the increased relative importance of the first factor.

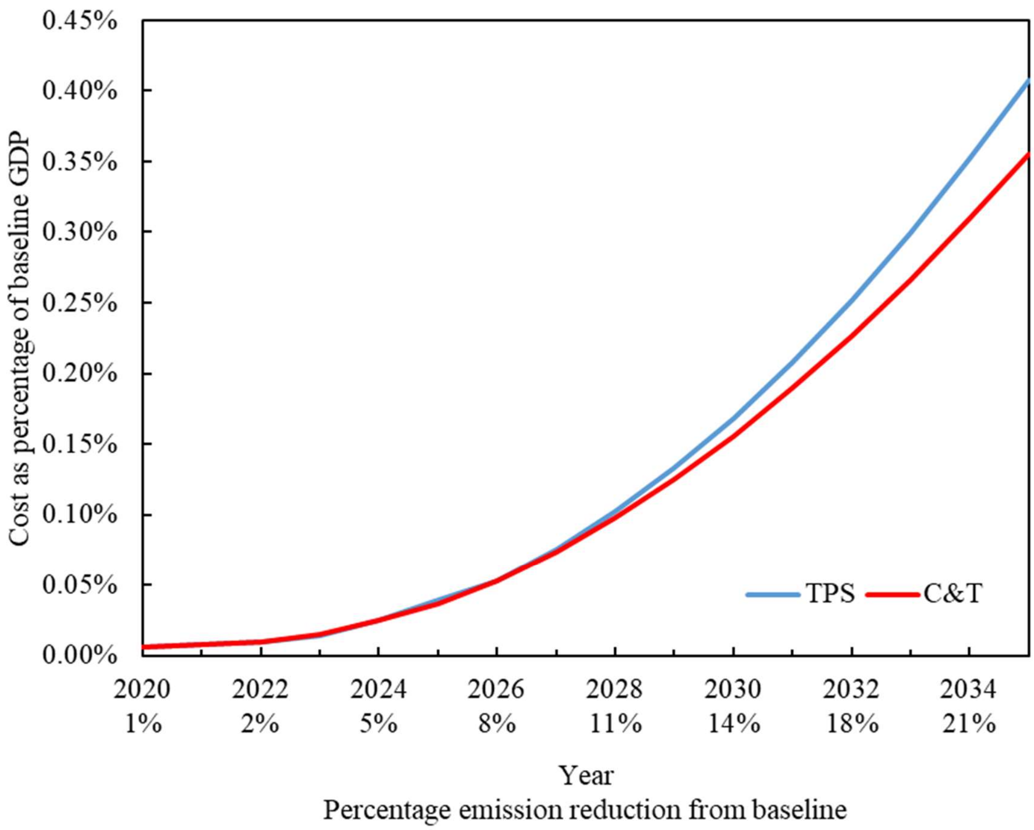


Figure 3. TPS and C&T Economic Costs Over Time

Table 8 summarizes the cumulative emissions reduction, cumulative costs, costs per ton, as well as impacts on renewables-based electricity during each phase.

---

[28] Several studies that the distortion related to the first factor is the product of the benchmark and the allowance price. See, for example, Goulder *et al*. (2020). In the policy simulations considered, allowance prices rise over time by a larger percentage than the percentage by which the benchmarks decline. Hence the product of the allowance price and benchmark grows, and the associated distortion increases. In contrast, the other contributing factor to the efficiency impact of the implicit subsidy – the beneficial impact from pre-existing taxes on labor, capital, and intermediate inputs -- does not change much over time, since the pre-existing tax rates do not change. Thus, the adverse efficiency influence from the TPS's implicit output subsidy increases while its beneficial influence does not change much, and the overall the TPS’s cost relative to C&T rises.

Table 8. Summary of Cumulative Results in Each Phase

	Phase 1 (2020-2022)		Phase 2 (2023-2025)		Phase 3 (2026-2035)	
	TPS	**C&T**	**TPS**	**C&T**	**TPS**	**C&T**
Cumulate reduction within the phase (Gt)	0.5	0.5	1.7	1.7	21.7	21.7
Percentage of baseline cumulative emissions	*1.69*	*1.69*	*4.60*	*4.60*	*15.46*	*15.46*
Present value of cumulative costs (billion RMB)	23	24	81	80	2,016	1,822
Percentage of baseline cumulative GDP	*0.0077*	*0.0078*	*0.0262*	*0.0257*	*0.2015*	*0.1820*
Economic costs per ton (RMB/ton)	43	44	49	48	93	84
Renewables-generated electricity increase	0.5	3.9	1.1	7.3	6.0	19.2

Sector-level emissions reductions

Figures 4, 5, and 6 offer details on sources of emission reductions from specific subsectors or technologies in 2021, 2023, and 2026.

Figure 4 identifies the contributions of the various generation technologies to reductions in 2021. The TPS causes emissions to decline for some generator types and to increase for others. This reflects differences in the business-as-usual (BAU) emissions intensities of the technologies. Table 2 above displayed the generator technologies within each of the broader technology classes. As the table indicates, the Large SC, Large SUB, Other coal, and Small CFB generators have higher BAU emissions intensities than the applicable benchmarks for their technology category; they reduce emissions intensities, outputs, and emissions to achieve compliance. The other generators have BAU intensities below their benchmarks. These units have excess allowances and do not need to reduce output. Indeed, they increase output in order to generate additional allowances that can be sold. Their increased output leads to higher emissions.

Figure 5 indicates the emission reductions in covered subsectors and uncovered sectors in 2023, the first year of Phase 2. The contributions to emission reductions from different electricity technology types are similar to those in Phase 1. In the cement, iron&steel, and aluminum sectors, high efficiency (i.e., low emissions intensity) subsectors have excess allowances and increase output and emissions. Emissions in the other subsectors have BAU intensities above their benchmarks and are induced to reduce emissions intensities, output, and emissions. The figure shows that in this phase, the electricity sector contributes significantly more to emissions reductions than do the sectors that were added at the beginning of Phase 2.

Figure 6 indicates the emission reduction in covered sectors and uncovered sectors in 2026, the first year of Phase 3. For readability, we do not display the emissions changes by the individual generation technologies within the electricity sector, but report the overall changes in the note to the figure. Among the five newly added sectors, the raw chemicals and the other non-metal products subsectors contribute the most emissions reductions. This reflects their relatively high baseline emissions and baseline emission intensities among the newly added sectors.[29]

The emissions of uncovered sectors continuously increase as the system expands over time, reflecting the widening coverage and increasing stringency of the benchmarks that lead to greater substitution from covered sectors to uncovered sectors due to the increased prices of covered sectors. These changes lead to ever larger declines in the demand for coal. Relative to the baseline, coal use in the covered sectors decreases by 5%, 6%, and 11% in 2021, 2023 and 2026. This then induces a larger decrease in the price of coal, making it more favorable to use coal in the uncovered sectors.

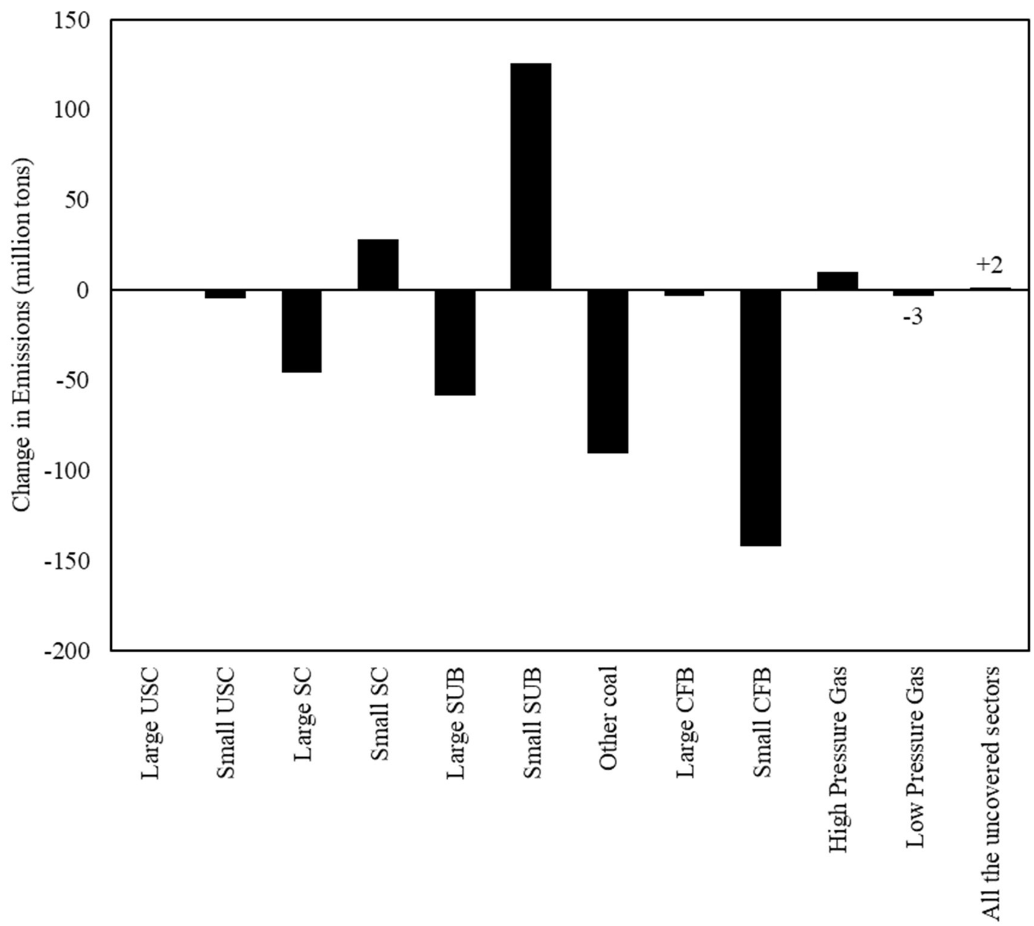


Figure 4. Emissions Changes by Electricity Sector's Subsectors and Other Sectors in 2021 (Phase 1)

*See Table 2 in Subsection III.B above for definitions of the abbreviations of the generator technologies.

[29] Because of limitations on the firm- and subsector-level data, the model does not disaggregate the newly added Phase 3 sectors.

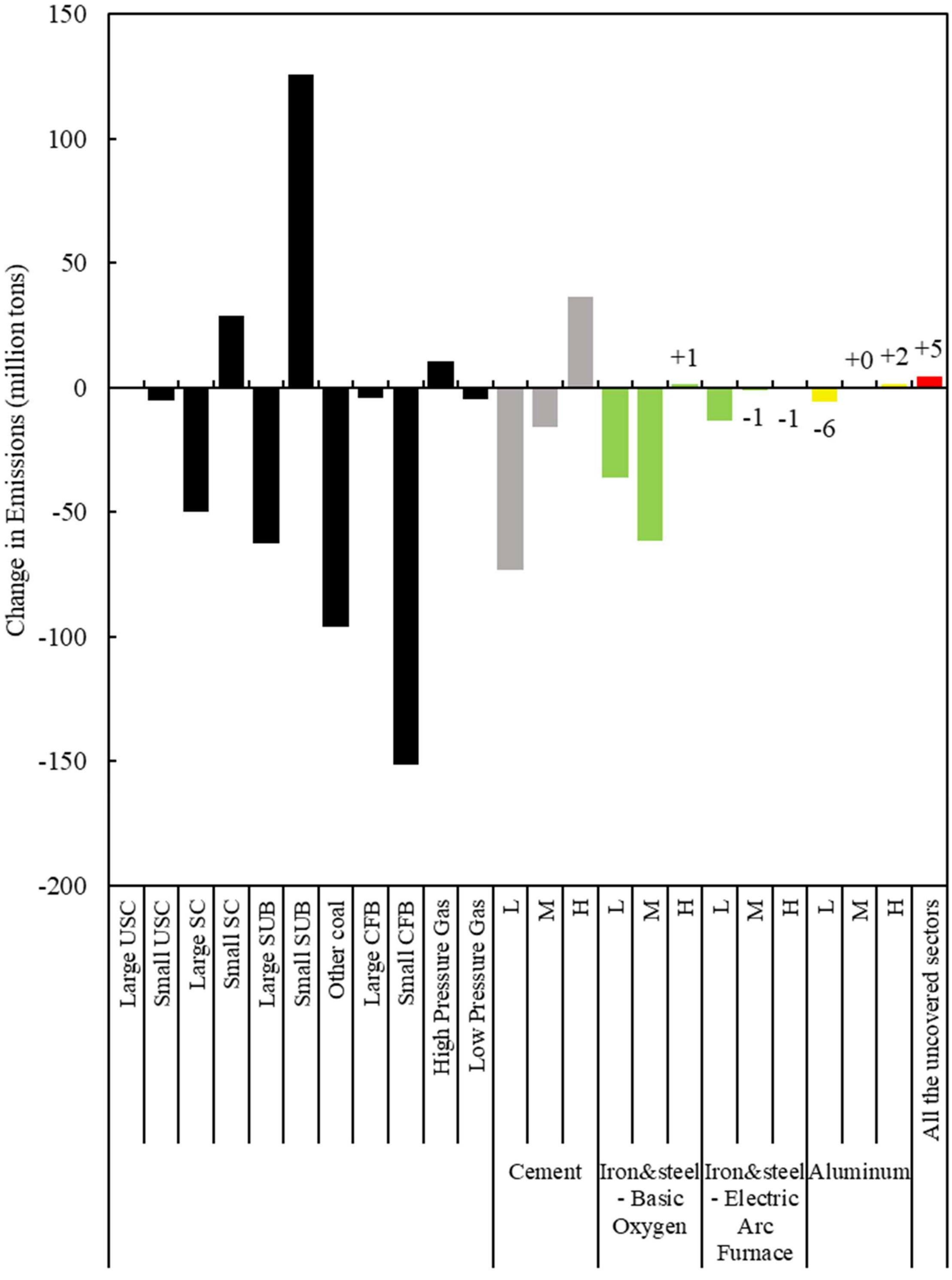


Figure 5. Emissions Changes by the TPS-covered Subsectors and Other Sectors in 2023 (Phase 2)

*L, M, H denote low, middle, and high efficiency, respectively.

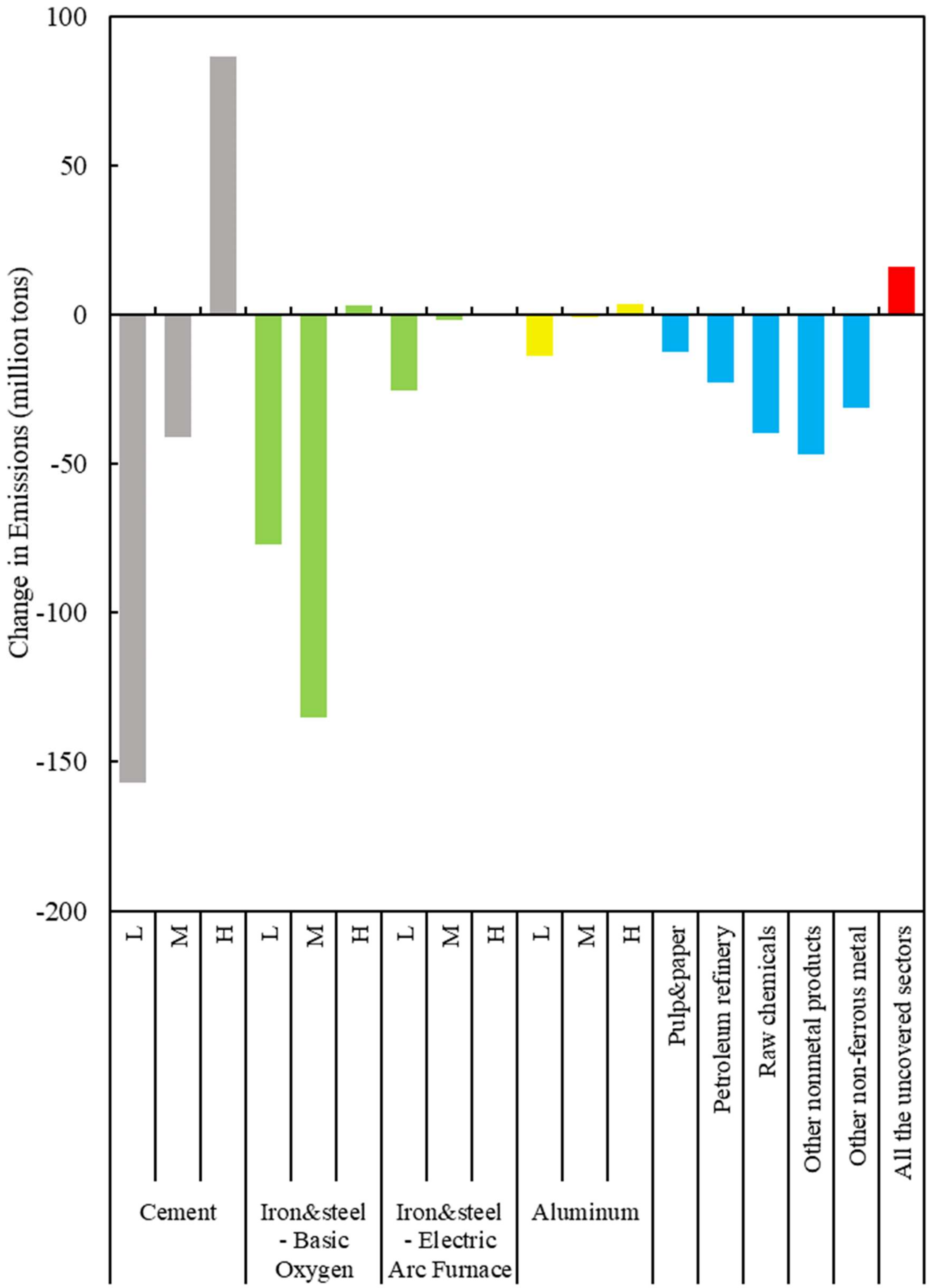


Figure 6. Emissions Changes by the TPS-covered Sectors and Other Sectors in 2026 (Phase 3)

* L, M, H denote low, middle, and high efficiency, respectively.

** In the electricity sector, the total emissions increase by the generators that increase emissions is 320 million tons; the total emissions decrease by generators that reduce emissions is 882 million tons. The net emissions reduction in the electricity sector is 562 million tons. The distribution of the emission change of subsectors within the electricity sector in Phase 3 is very similar to the distributions in Phase 1 and Phase 2.

Figure 7 shows the covered sectors' relative contributions to emissions reductions over the interval 2020-2035. The electricity sector makes by far the largest contribution. The iron&steel and cement sectors also make significantly larger contributions than do the other added sectors, because they are the biggest emitters.

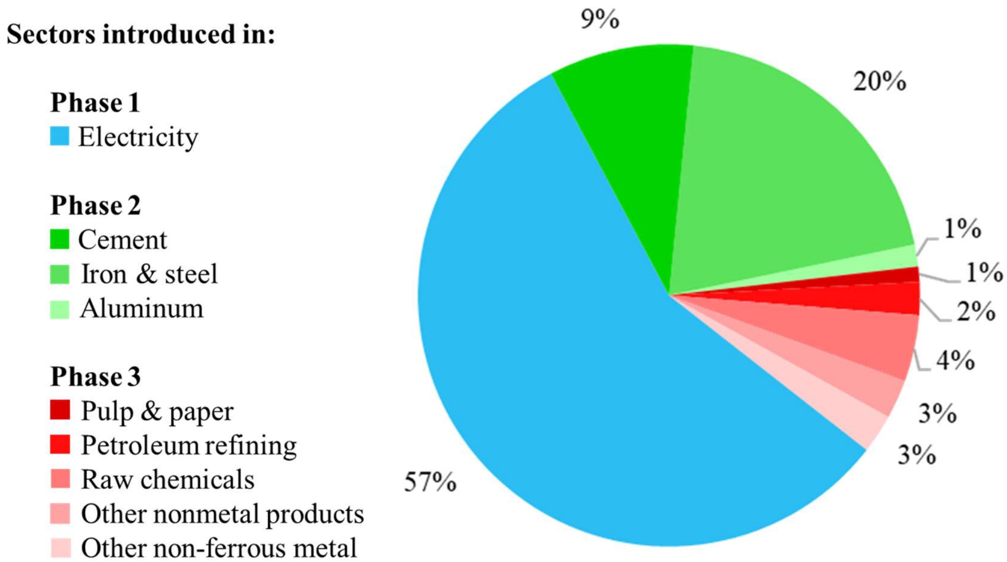


Figure 7. Covered-sectors' Cumulative Emissions Reductions over the Interval 2020-2035.

Sector and subsector prices, outputs, and profits

Table 9 displays for each sector the percentage changes in the output price, level of production and profit level, in 2021, 2023, and 2026. Prices and the profit are expressed in real terms, with the price of the composite produced good employed as the price index.

As expected, the covered sectors tend to experience the largest reductions in output. The electricity sector experienced the largest output reduction among covered sectors, because it is the first sector to be covered by the TPS and thus its benchmarks have been tightened by more than other sectors. As a result of the highest stringency level in any given year, the production cost of the electricity sector increases more than that of other sectors, relative to the baseline.

In each of the three years, the covered sectors experience increased profits. This reflects economic rents enjoyed by these sectors associated with the value of free allowances.[30] Among the covered sectors, the cement and electricity sectors experience the largest profit increases. The free allocation of allowances leads to especially large rents in these sectors. This is made possible by the fact that demands for their products are relatively inelastic, which is partly due to the fact that these sectors are less trade-exposed and thus less prone to

[30] Goulder et al. (2010) offer a detailed discussion of how free allowance allocation yields economic rent. Under the TPS, free allocation is an intrinsic characteristic of the system: a covered facility with benchmark β receives the quantity βq of free allowances. These have a value of $t\beta q$. As an example, in the TPS simulations here, the value of the allowanes offered free to the electricity sector in 2021 is 220 billion RMB. This is enough to offset the gross costs of abatement in the electricity sector in 2021, which is about 217 billion RMB.

substitution by imported goods. (Appendix D indicates trade exposure for each sector in terms of the ratio of traded goods to total output.)

The uncovered sectors also are affected by the TPS. The impacts on profits and outputs in these sectors depend on the impacts on production cost and output demand. The TPS raises costs of production for many uncovered sectors, particularly those that are electricity intensive due to the pass-through of carbon costs to higher electricity prices, and this leads to reductions in their outputs and profits. For example, in Phase 1, the aluminum sector is not yet covered by the TPS but experiences large declines in output and profits. This reflects its relatively intense use of electricity as an input: electricity accounts for about 40% of its total input costs. For the same reason, the raw chemicals and other non-ferrous metals sectors also experience reductions in outputs and profits before being covered by the TPS.

For the uncovered sectors, the TPS's impact on output demand can be positive or negative. The impact is negative in the coal sector, an important supplier of inputs to other sectors. This sector experiences large decreases in price and output as a result of significant TPS-induced reductions in the demand for coal. In contrast, the natural gas sector experiences large increases in output and price. This reflects the increased demand for natural gas, which substitutes for coal in response to the increased cost of coal-fired power generation. Natural gas has a CO_2 emissions factor much lower than that of coal; as a result, the TPS raises the price of coal-fired power generation relative to that of natural gas.

Table 9. Price, Quantity, and Profit Impacts of the TPS

Percentage Changes from Baseline

Sectors	Price Change (%)			Quantity Change (%)			Profit Change (%)		
	2021	2023	2026	2021	2023	2026	2021	2023	2026
Electricity	0.41	0.47	1.29	-0.30	-0.50	-2.37	1.35	2.06	4.40
Cement	-0.02	0.30	1.77	-0.02	-0.06	-0.22	-0.05	3.47	7.27
Iron&steel	-0.01	0.11	0.28	-0.05	-0.23	-0.46	-0.07	1.83	3.85
Aluminum	0.18	0.30	1.04	-0.20	-0.35	-1.16	-0.10	1.70	3.34
Pulp&paper	0.01	0.01	0.08	-0.02	-0.03	-0.13	-0.02	-0.03	0.99
Petroleum refining	0.01	0.01	0.05	-0.06	0.02	-0.01	-0.06	0.03	0.61
Raw chemicals	0.01	0.00	0.10	-0.04	-0.05	-0.30	-0.05	-0.06	0.95
Other non-metal products	0.01	0.03	0.16	-0.03	-0.06	-0.22	-0.03	-0.07	0.60
Other non-ferrous metal	0.03	0.04	0.15	-0.09	-0.15	-0.49	-0.10	-0.17	0.56
Agriculture	-0.01	-0.02	-0.05	0.00	0.00	0.00	-0.01	0.00	0.00
Coal	-0.28	-0.48	-1.17	-2.16	-3.64	-8.92	-3.22	-5.40	-13.1
Crude oil	0.01	0.01	0.09	-0.06	-0.04	0.12	-0.08	-0.04	0.25
Natural gas	0.30	0.30	0.73	0.60	0.59	1.48	0.98	0.97	2.41
Mining	0.02	0.00	0.01	-0.07	-0.30	-0.79	-0.07	-0.41	-1.10
Food	0.00	-0.01	-0.03	-0.01	-0.01	-0.03	-0.01	-0.02	-0.07
Textile	0.00	0.00	0.00	0.00	0.02	0.12	0.00	0.01	0.10
Clothing	0.00	-0.01	-0.03	0.00	0.02	0.11	-0.01	0.00	0.05
Log furniture	0.00	0.00	-0.01	-0.06	-0.09	-0.22	-0.06	-0.11	-0.28
Printing and stationery	0.00	0.00	0.02	-0.01	-0.02	-0.06	-0.03	-0.04	-0.14
Daily chemicals	0.00	-0.01	-0.01	-0.01	-0.02	-0.06	-0.02	-0.04	-0.13
Metal products	0.02	0.04	0.12	-0.07	-0.16	-0.42	-0.07	-0.17	-0.46
General equipment	0.01	0.01	0.04	-0.05	-0.12	-0.29	-0.06	-0.14	-0.37
Transport equipment	0.01	0.01	0.03	-0.02	-0.05	-0.12	-0.02	-0.06	-0.18
Electronic equipment	0.01	0.01	0.03	-0.04	-0.08	-0.22	-0.05	-0.11	-0.29
Other manufacturing	0.00	0.00	0.01	-0.03	-0.02	-0.05	-0.04	-0.03	-0.09
Gas distribution	0.20	0.19	0.45	0.17	0.27	0.65	0.27	0.36	0.87
Water	0.04	0.04	0.10	-0.03	-0.04	-0.15	-0.01	-0.03	-0.13
Heat distribution	-0.06	-0.03	0.03	-0.04	0.53	2.10	-0.09	0.57	2.36
Construction	0.00	0.02	0.09	-0.01	-0.03	-0.10	-0.02	-0.05	-0.17
Transport	0.00	0.00	-0.02	-0.02	-0.04	-0.08	-0.03	-0.05	-0.14
Services	-0.01	-0.01	-0.04	-0.01	-0.02	-0.07	-0.03	-0.05	-0.14

* Blue font identifies the covered sectors in the applicable phase on a given date.

Impacts on foreign trade

Table 10 shows the impacts of the TPS and C&T on net imports in 2021, 2023, and 2026. Both the TPS and C&T lead to an increase in the prices of domestic goods relative to foreign goods. This change is most pronounced in the covered sectors. This precipitates an increase in the net imports by the covered sectors. C&T tends to have larger impacts on both exports and imports. This reflects C&T's larger impact on domestic output prices.

For uncovered sectors, gross imports may increase or decrease because of two opposing effects: a *scale effect* and a *substitution effect*. On the one hand, the TPS and C&T lead to reductions in household income; this reduces overall demands, including industrial, commercial, and residential demands for imports. These scale effects tend to reduce import demands as well as demand for domestic goods. On the other hand, the TPS and C&T tend to raise the prices of goods from the domestic sectors relative to the prices of imported goods. This can lead to increased demand for imports.

Table 10. Percentage Changes in Net Imports

Sectors	2021		2023		2026	
	TPS	C&T	TPS	C&T	TPS	C&T
Electricity	7.41	36.87	8.92	50.68	24.66	108.28
Cement	-0.12	0.36	1.45	20.79	9.38	41.34
Iron&steel	-0.42	0.53	2.97	21.81	7.37	44.02
Aluminum	2.03	10.74	3.39	22.99	10.83	45.36
Pulp&paper	0.19	1.17	0.12	0.66	1.48	9.71
Petroleum refining	-0.01	0.15	0.05	0.11	0.53	1.46
Raw chemicals	0.09	1.65	-0.11	1.70	1.68	15.99
Other non-metal products	0.10	0.60	0.98	3.19	2.86	10.33
Other non-ferrous metal	0.22	1.33	0.26	2.23	1.13	7.73
Agriculture	-0.08	-0.38	-0.14	-0.73	-0.45	-1.90
Coal	-2.54	-3.20	-5.04	-5.94	-12.71	-14.80
Crude oil	-0.05	0.03	0.05	0.07	0.77	0.00
Natural gas	6.86	9.28	7.24	12.56	15.70	29.76
Mining	-0.04	-0.13	-0.26	-0.89	-0.74	-2.28
Food	-0.25	-1.66	-0.40	-2.94	-1.25	-6.55
Cement	-0.01	-0.24	-0.11	-1.11	-0.61	-3.58
Clothing	-0.04	-0.42	-0.11	-1.14	-0.51	-3.23
Log furniture	0.03	-0.01	0.01	-0.35	-0.11	-1.10
Printing and stationery	0.00	-0.14	-0.01	-0.33	0.00	-0.27
Daily chemicals	-0.38	-2.09	-0.77	-5.07	-2.06	-8.62
Metal products	0.23	1.36	0.73	3.93	1.84	8.39
General equipment	0.38	3.42	2.35	11.59	2.41	11.53
Transport equipment	-0.01	-0.06	0.05	0.13	0.00	-0.09
Electronic equipment	0.16	0.45	0.27	0.90	0.59	2.07
Other manufacturing	-0.12	-0.67	0.02	-1.66	-0.36	-4.51
Construction	-0.05	-0.05	0.45	3.78	1.47	7.86
Transport	-0.01	-0.48	-0.02	-0.90	-0.18	-1.95
Services	-0.86	-6.41	-2.30	-19.99	-20.34	-121.8

* Blue font identifies the covered sectors in the applicable phase on a given date.

B. Alternative Policy Cases

Impacts of benchmark variation

Benchmark Variation and Economic Costs

The alternative policy cases include cases with alternative specifications for the variation of the benchmarks. Cases 2a and Case 2b have fewer benchmarks than Case 1.

Case 2a involves two benchmarks. A single benchmark replaces what were three separate benchmarks for the coal-fired generators, while retaining a separate benchmark for the natural-gas-fired generators. The single benchmark for the coal-fired generators equals the weighted average benchmark of the three coal-fired categories in Case 1. Case 2b has one benchmark for all of the generators, and this benchmark equals the weighted average benchmark of the electricity sector in Case 1. In both cases, the benchmarks for other sectors are set in the same way as in Case 1. All benchmarks are scaled by a common factor so that the economy-wide emissions of each year are the same as in Case 1.

Figure 8 shows the economic costs under these alternative TPS cases and under an equally stringent C&T.[31] The cost is lower, the smaller the number (and greater uniformity) of benchmarks. Greater uniformity lowers the aggregate cost by reducing the variation in the marginal value of output. This leads to a more efficient allocation of production across generators. Under the one-benchmark TPS, the cost is sufficiently low to fall below that of C&T. We noted earlier that the TPS's implicit output subsidy partly offsets the distortions of pre-existing taxes. In the one-benchmark case, the combination of this partial offset and the lower distortions associated with the uniformity of the benchmarks is enough to cause the TPS's cost in this case to fall below the cost under C&T.[32]

---

[31] Different initial allocations under C&T do not alter the results (except for distributional effects), provided the total initial allocations are the same, because (in contrast to the TPS's allocations) the allocations are exogenous to covered facilities under C&T. Whether the initial allocation under the C&T matches the one-benchmark TPS case or the four-benchmark case makes no difference in total emissions and total economic costs. Therefore, in Figure 8 we compare the alternative TPS cases with the C&T case where the initial C&T allocations are the same as the four-benchmark TPS.

[32] We performed a counterfactual simulation with no pre-existing taxes. In this case, the cost of the one-benchmark TPS exceeds that of C&T.

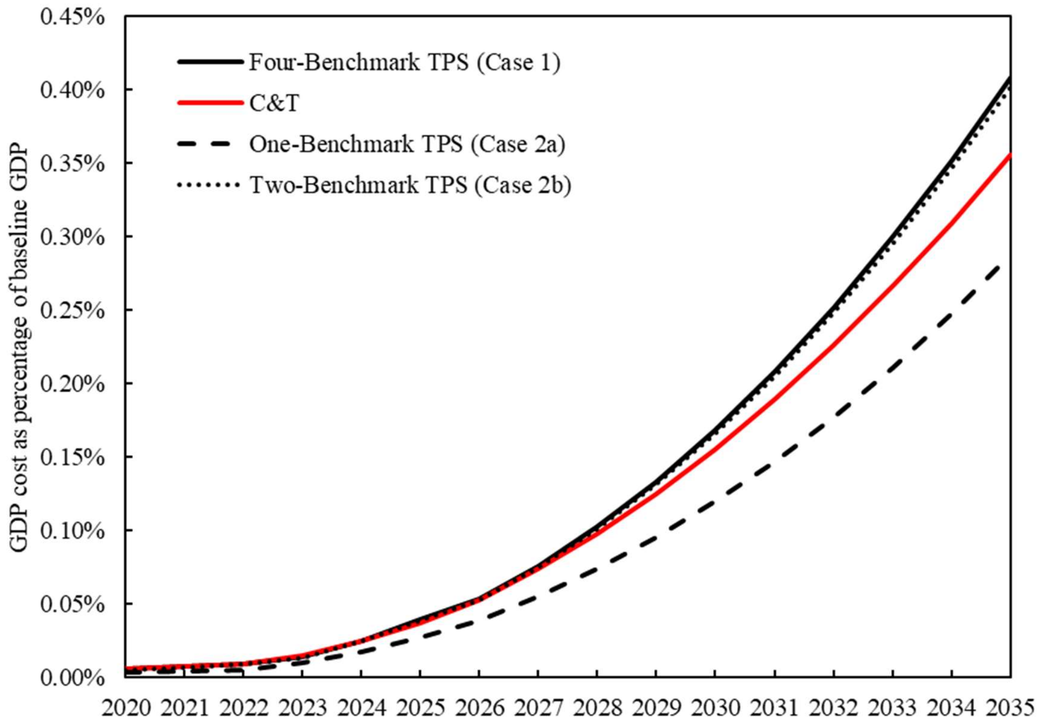


Figure 8. Economic Costs under Different Benchmark Variations

Benchmark Variation and Sector Impacts

Figure 9 shows the cumulative impacts of these alternative benchmark designs on electricity subsectors over the interval 2020-2035. In the two-benchmark Case (2a), the benchmarks are more stringent than in Case 1 for generators in the Small SC, Small SUB, Other Coal, and CFB categories, so these generators experience smaller increases or larger decreases in profit than in Case 1. For other coal-fired generators, the benchmarks are less stringent than in Case 1 and thus their profit impacts are more favorable.

In the one-benchmark case (2b), the benchmarks for the gas-fired generators are less stringent than in Case 1. The lower stringency implies higher profits for natural gas-fired generators than in Case 1. The greater output of natural gas competes for the production of electricity with output from the coal-fired and CFB generators, so the coal-fired and CFB generators experience larger profit losses (or smaller profit increases) in the one-benchmark case than in the two-benchmark case.

Compared with Case 1, the profit increases of low carbon electricity are smaller in cases 2a and 2b, in keeping with the smaller increases in electricity prices in these cases and the associated lower incentives for wind and solar electricity to increase output.

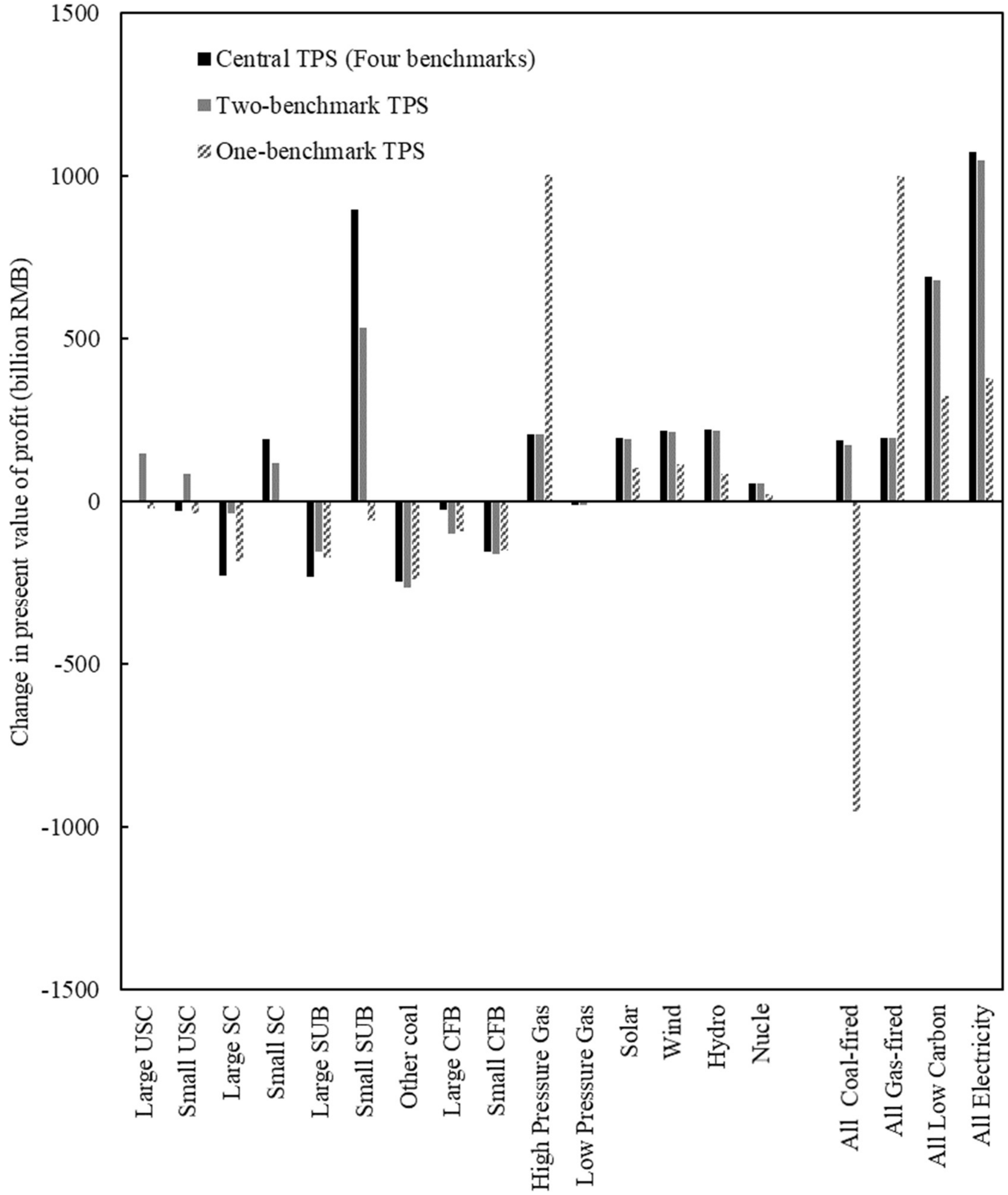


Figure 9. Impact of Changes to Benchmark Variation on Profits in the Electricity Sector, Present Value, 2020-2035

*The present value is calculated using a discount rate of 5%/year.

Impacts of benchmark stringency

Figure 10 reveals the implications of changes in stringency in benchmarks for emissions. The benchmarks are tightened more quickly in Case 3a and 3b than in Case 1, and the faster tightening leads to more extensive emissions reductions. As noted in Section III.B, Case 3a and 3b are consistent with the emission path toward achieving China's goal of net carbon neutrality by 2060 suggested by the literature.

The bumpy pattern of reductions between 2022 and 2026 reflects the discrete jumps in coverage and overall stringency accompanying the introduction of new phases. Cumulative economy-wide emissions over the entire 2020-2035 simulation interval are reduced by 12% (24 Gt) in Case 1, by 13% (26 Gt) in Case 3a, and by 19% (40 Gt) in Case 3b. Cumulative emissions from the covered sectors are reduced by 18% (24 Gt) in Case 1, by 20% (27 Gt) in Case 3a and by 37% (41 Gt) in Case 3b.

Figure 11 compares the annual costs under Cases 1, 3a and 3b, and reveals the costs of greater stringency. The present value of the economic costs of Cases 3a and 3b over the 2020-2035 interval is 19% and 160% higher than that of Case 1, respectively. The average cost per ton over the 2020-2035 interval is 96 RMB under Case 3a and 138 RMB under Case 3b, 9% and 56% higher than that of Case 1 (89 RMB).

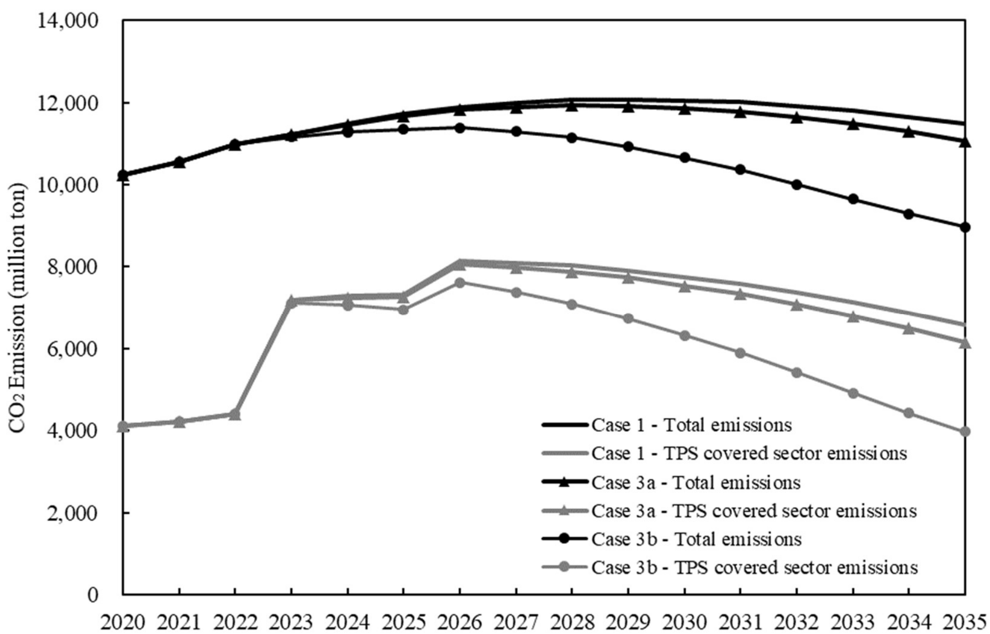


Figure 10. Emissions under Different Benchmark Stringency, 2020-2035

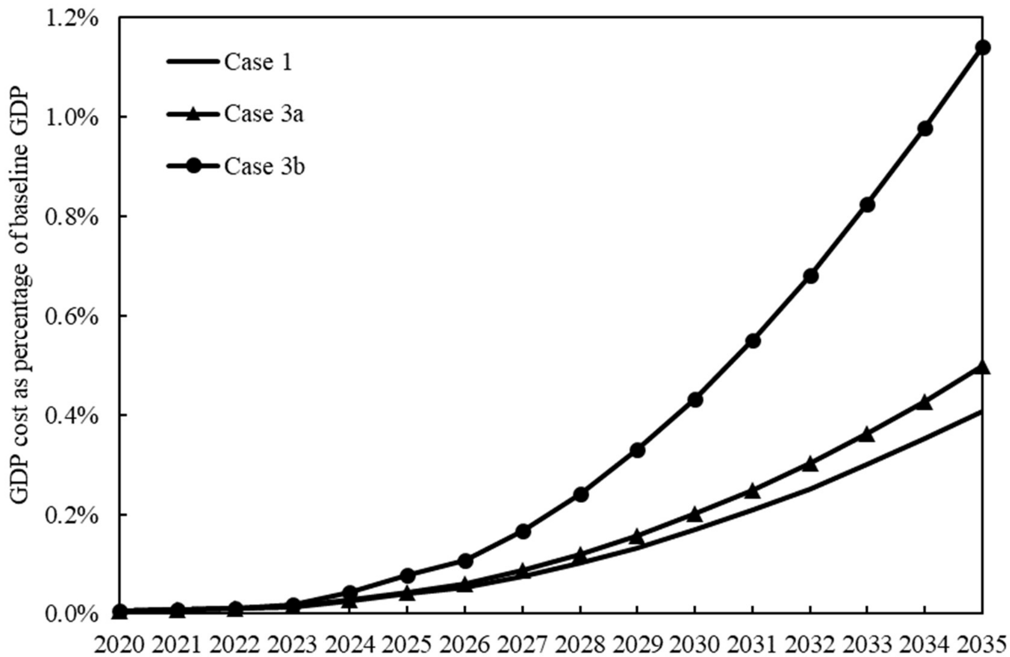


Figure 11. Economic Costs of Different Benchmark Stringencies, 2020-2035

Impacts of Auctioning

Here we consider the impacts of introducing auctioning as a source of supply of some of the emissions allowances. The policy simulations span a range of auctioning cases, differing in the share of the economy's emissions allowances provided through auctioning and in the ways that the auction revenues are recycled back to the economy. Table 3 in subsection IIIB displayed the five auctioning cases considered.

Impacts of Alternative Revenue Recycling Options

Figure 12 shows the economic costs under different revenue recycling options, and compares them with Case 1, which involves no auction. All the auctioning cases involve lower costs relative to Case 1. A main reason for the lower costs is that auctioning substitutes for the free allocation under the TPS, and only the free allocation component of allowance supply introduces the implicit subsidy to output, which over the long term has adverse impacts on cost-effectiveness. Thus, the significance of the output subsidy under the TPS declines, the larger the fraction of allowances supplied through auctioning. This general result provides support for introducing auctioning as part of China's CO_2 emissions trading system.[33]

Among all the auctioning cases, Case 5a has the highest economic costs. In Case 5a, all of the auction revenues are recycled as output subsidies to wind and solar electricity generation. This brings in new distortions, whereas the other auctioning cases only recycle half of the revenue

[33] Each allowance distributed via auction entitles the owner to a given quantity of emissions. In contrast with the TPS, covered facilities do not earn additional allowances from the auction component of the system by increasing the supply of intended output.

as subsidies to wind and solar electricity generations.

Case 5d has the lowest economic costs. This case differs from the other cases in that some of the auction revenues are recycled as subsidies to capital and labor inputs to the coal and mining sectors. As a result, it leads to the highest rates of capital accumulation. This lowers the costs of coal and mining and generally lowers the price of composite investment goods, which encourages higher capital accumulation.[34] With more capital, sectors in Case 5d can more easily use capital to substitute away from carbon-intensive inputs, which works toward lower economic costs of the TPS.

Cases 5b and 5c use half of the auction revenue to subsidize wind and solar electricity, recycling the other half as a lumpsum transfer. The only difference between the two cases is the recipient of the transfer, households in Case 5b and the coal and mining sectors in Case 5c, which has no marginal influence on the production and emission decisions. As a consequence, the economic costs are the same in the two cases.

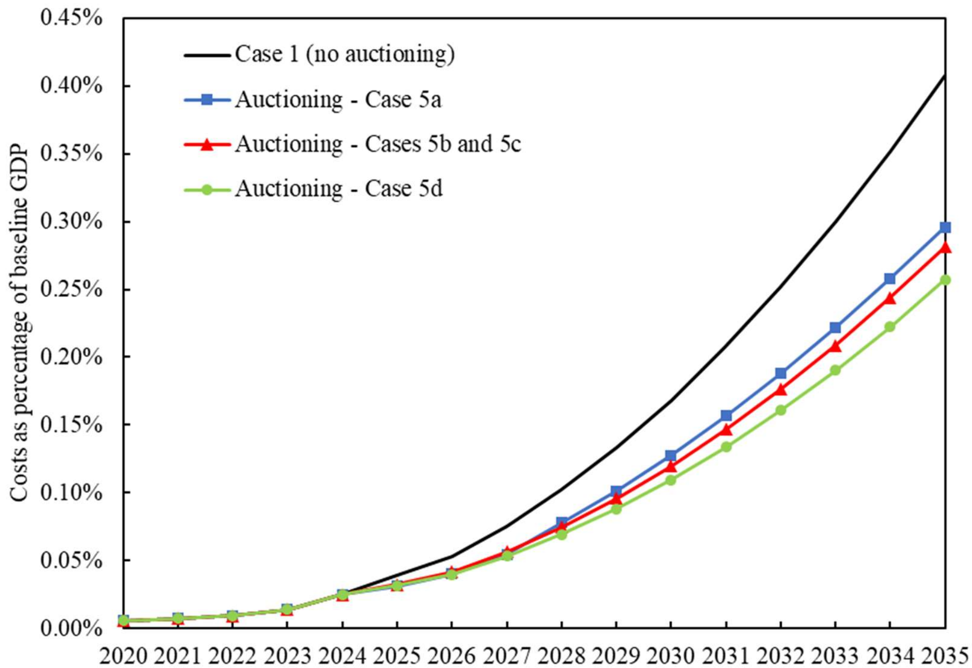


Figure 12. Economic Costs under Different Auction Revenue Recycling Options, 2020-2035

Figure 13 shows the wind and solar electricity generation under the different revenue-recycling options. As a response to the renewable subsidies, all the auction cases tend to involve higher wind and solar electricity generation than the TPS without an auction. By using all the auctioning revenue to subsidize wind and solar electricity, Case 5a has the largest impact on their generation levels. Case 5d leads to the highest production levels in nearly all

[34] As noted earlier, the labor endowment is exogenous and same across all cases, while the capital endowment is affected by the investments in previous periods. We assume the households devote a fixed share of income to buy investment goods, thus lower price of investment goods leads to higher investment quantity and capital accumulation. See Appendix B for related details.

of the other sectors because it leads to the highest levels of capital accumulation. The highest production levels lead to the highest demand for electricity, including wind and solar electricity, since electricity is a key input in many sectors.

Under Case 5c, the auctioning revenue that is transferred to the coal and mining sectors is 20 billion RMB in 2025 and increases to 345 billion in 2035. This transfer partially offsets the total profit loss in the coal and mining sectors in 2025-2027, and fully offsets their profit loss in 2028-2035 as the auctioning revenue increases over time.

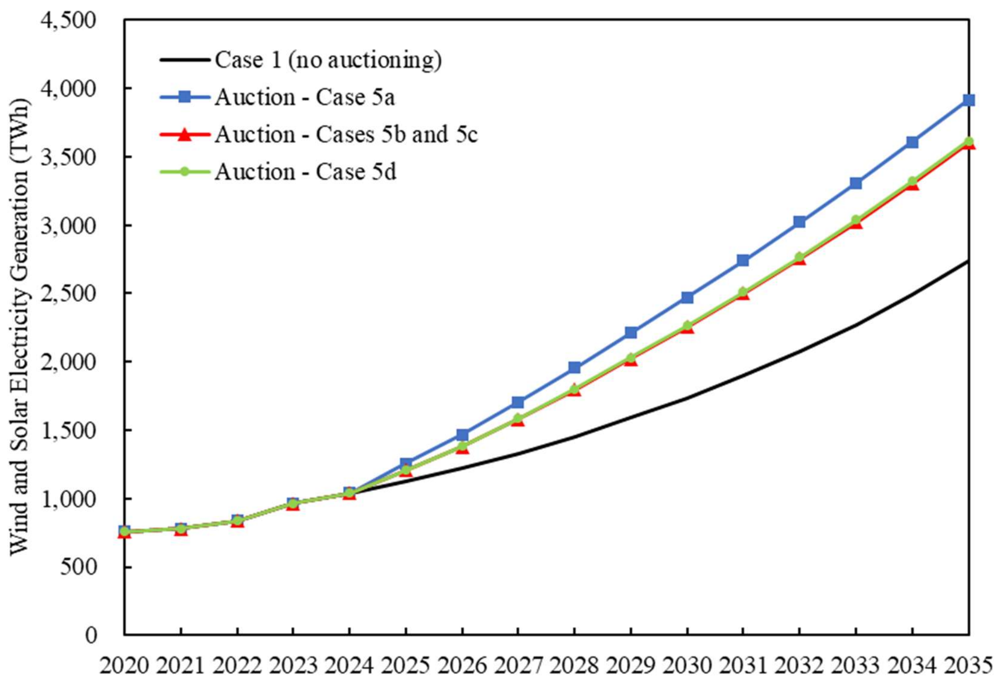


Figure 13. Wind and Solar Electricity Generation under Different Auction Revenue-Recycling Options, 2020-2035

Implications of the Scale of the Auction

In Case 5e, the auction's share of the total supply of allowances is lower than in the other cases. In the year 2026 when the auction is introduced, the economic costs of Case 5e is slightly higher than the cost in Case 5a because the lower auction share in Case 5e means that there are fewer auctioned allowances and more allowances provided through the TPS. Thus, the TPS's implicit output subsidy carries more weight and the policy is slightly less cost-effective at the beginning. On the other hand, the increased implicit output subsidy also lowers the prices of new capital goods, which accounts for the higher rate of investment under Case 5e. For this reason, in later years, the economy-wide cost of achieving the same amount of emission reduction under Case 5e becomes lower.

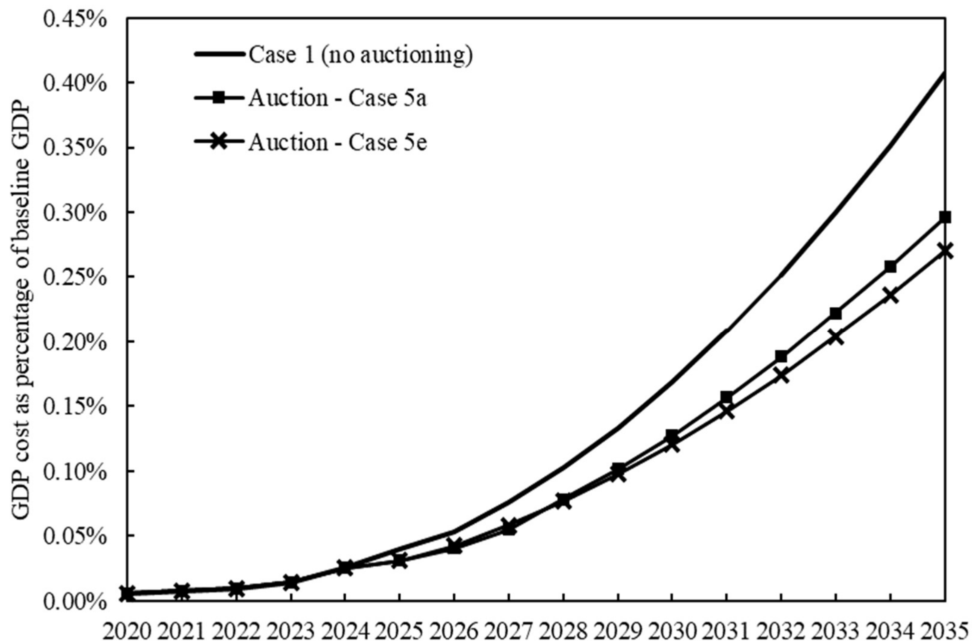


Figure 14. Economic Costs under Different Auction Shares, 2020-2035

Transition to C&T

In subsection IV B, we compared the costs of the TPS and an equally stringent C&T system when each policy is introduced in 2020 and maintained over the entire simulation interval. Here we consider scenarios in which the TPS converts to C&T at some future time. Such a transition is being contemplated by China's planners.

In Case 6a, the transition occurs and is completed in one year – 2028. In Case 6b, the transition is more gradual, starting in 2028 and completed by 2030. Thus, in Case 6b, the TPS and C&T are both in place in 2028 and 2029, and C&T is the only emissions trading system starting in 2030. During the transition period, the free allowances allocated by TPS's benchmarks account for 2/3 and 1/3 of total free allowances in 2028 and 2029. The benchmarks are scaled so that economy-wide emissions in cases 6a and 6b match those of the central case during the transition and thereafter.

Figure 15 shows the economic costs of the TPS and C&T under the various transition scenarios. As the figure shows, both transition cases have lower costs than the TPS and C&T as of 2028. Their economic costs are lower than TPS because of the reduction or absence (after the transition is completed) of the implicit output subsidy. In the years after the transition to the C&T, the costs are lower than under the central case C&T in the same years. This reflects differences in rates of capital accumulation before the transition period. Prior to the transition years, when the TPS applies, aggregate investment is higher than in the central C&T case. The higher investment reflects the TPS's implicit output subsidy, which implies lower prices of capital goods relative to the prices under C&T. As a result, during and after the transition, the economy's capital stock is higher than in the same years under C&T in the central case. The higher capital stock means that capital is more abundant and implies a lower rental price of capital, which in turn implies lower costs of CO_2 abatement, as covered facilities now can switch at a lower cost from carbon-based fuels to capital in production.

Table 11 contrasts the economic costs under the central case TPS and C&T scenarios and the two transition scenarios. When the transition starts, both the transition cases have the same capital endowment. For the reasons given above, the costs are lower in the transition cases than under the central case C&T (as well as under the TPS with no transition). The gradual transition case (6b) ultimately yields a slightly lower cost than the instant transition case (6a). This is because there is more investment in years 2028 and 2029 in Case 6a than in Case 6b, as capital goods prices are higher in Case 6b in those years. Consequently, after 2029 the economy's capital stock in each year is higher in Case 6b than in Case 6a, which accounts for 6b's slightly lower costs of abatement.

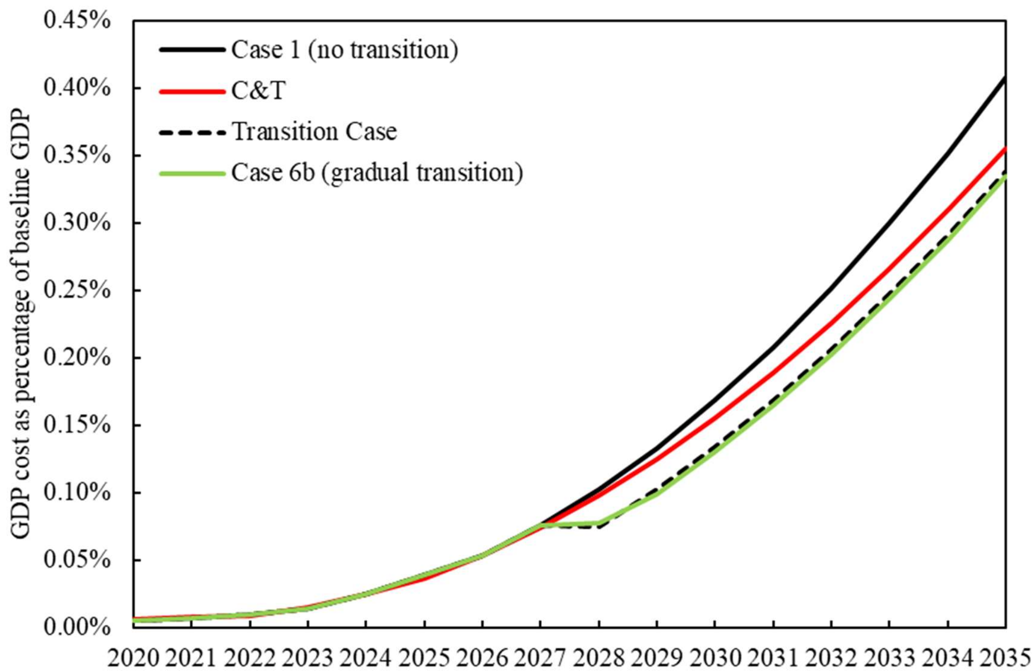


Figure 15. Economic Costs under Different Speeds of Transition to a Full C&T System, 2020-2035

Table 11. Economic Costs as Percentage of Baseline GDP for Two Transition Cases in Years after the Transition Starts

	Case 1 (no transition)	Case 6a (instant transition)	Case 6b (gradual transition)
2028	0.102	0.075	0.078
2029	0.133	0.103	0.100
2030	0.168	0.134	0.130
2031	0.208	0.169	0.165
2032	0.252	0.206	0.203
2033	0.300	0.247	0.244
2034	0.352	0.291	0.288
2035	0.408	0.338	0.334

Allowance Banking

China's TPS currently allows firms to bank allowances for future use. However, the detailed rules regarding the validation duration of the banked allowance have not yet been specified. Faced with these uncertainties, allowance banking is limited in the current system. We assume the detailed rules on allowance banking will be announced in 2024, and that banking will begin in that year.

Firms lower their costs by submitting banked allowances rather than purchasing them in periods of time when the discounted allowance price (which reflects marginal abatement costs) is particularly high. Firms' efforts to minimize the present value of their cumulative compliance costs lead to an equilibrium in which discounted allowance prices (and associated marginal abatement costs) are the same across periods. Details on the approach of incorporating allowance banking in the model are offered in Appendix E.

Figure 16 shows the CO_2 emissions of the covered sectors (i.e., the allowances submitted) in the no-banking and banking cases. The dashed line represents the total allowances available in that period. The difference between allowances available and allowances submitted is the amount of allowance banking. With banking, covered firms tend to reduce more CO_2 now in exchange for more allowance available in the future. Therefore, compared with Case 1, CO_2 emissions from TPS-covered sectors are lower over the interval 2024-2029 and higher over the interval 2030-2035.

Figure 17 shows the equilibrium allowance price in the cases with and without banking. In the absence of banking, the discounted value of allowances is increasing over time, a reflection of the continued tightening of benchmarks. As a result, covered facilities have incentives to bank some of their allowances in the first years of the TPS in order to reduce their needed purchases of future allowances. This reduces the early-period allowance supply and leads to higher allowance prices in early periods than in Case 1. The reverse is the case in later periods, as the banked allowances add to future supplies and yield lower allowance prices.

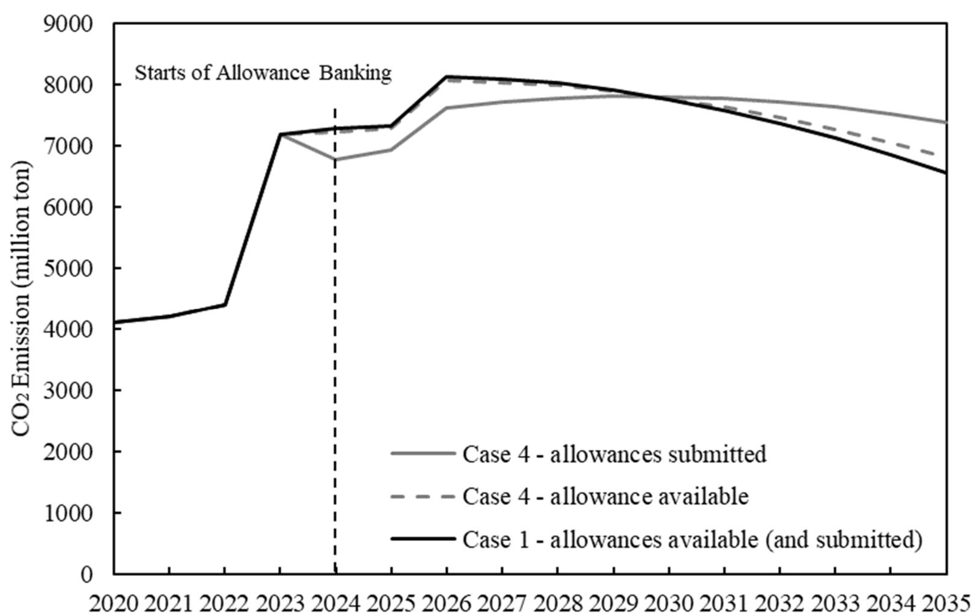


Figure 16. Covered Sectors' Emissions under the TPS, with and without Banking, 2020-2035

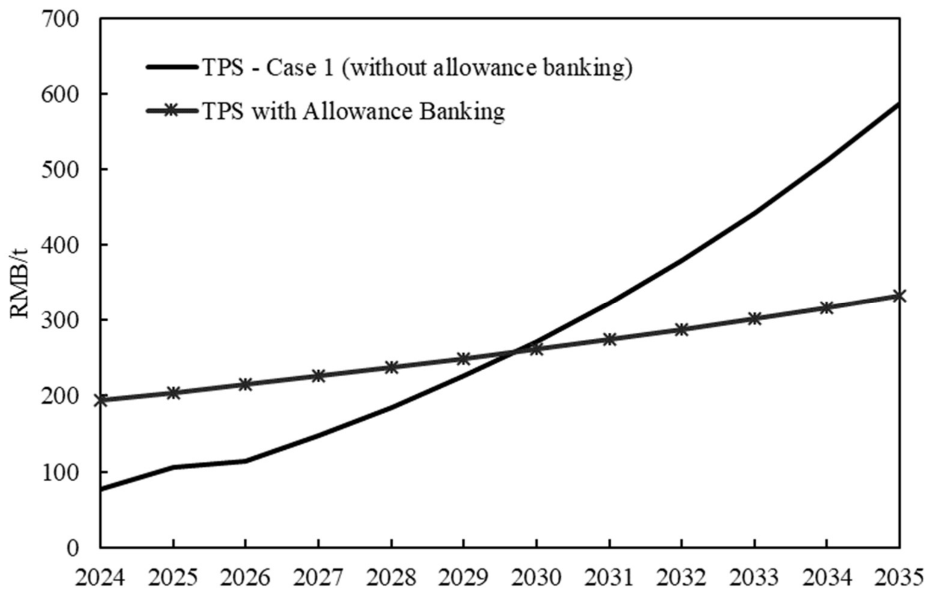


Figure 17. Carbon Price under TPS with and without Banking, 2020-2035

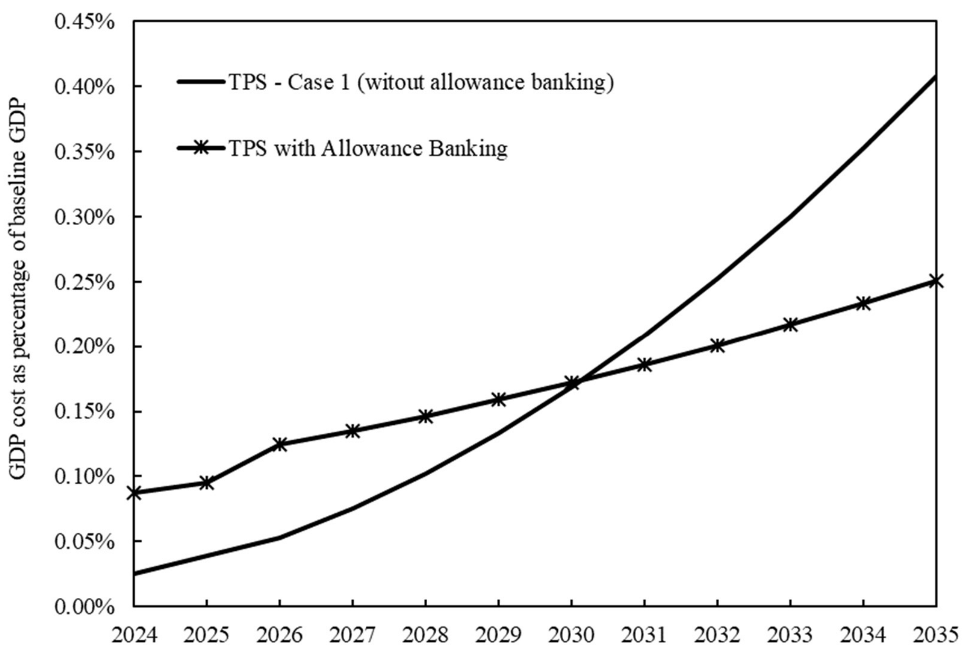


Figure 18. Economic Costs under TPS with and without Banking, 2020-2035

Figure 18 shows the economic costs as percentage of GDP in the absence and presence of banking. Banking raises compliance costs prior to 2030 and lowers costs after 2030, as previously banked allowances reduce the future abatement requirements. Overall, banking reduces the present value of economic costs over 2020-2035. The present value of economic costs is 2,037 billion RMB in the presence of banking, as compared with 2,121 billion RMB in its absence. Banking achieves lower costs in present value because it enables producers to reduce the variation in the discounted value of allowance prices over time. This tends to promote greater equality in discounted marginal costs of abatement, which contributes to cost-effectiveness in the form of a lower present value of discounted compliance costs.

C. Further Sensitivity Analysis

Here we examine the sensitivity of the model's results to the input substitution elasticities, capital transformation elasticities, and key parameters that determine the model's dynamics. Tables 12 and 13 summarize these results.

The substitution elasticity between energy and factor inputs (σ_{kle}) governs the ease of substituting away from energy input for capital or labor input. A higher elasticity of substitution implies lower costs of reducing emissions intensities. Allowance prices and economic costs per ton decline with higher elasticity.

The elasticity of capital transformation between different subsectors within a sector determines the ease of capital reallocation. A higher capital transformation elasticity implies lower transformation costs in response to a policy change. Thus, economic costs per ton decline with higher elasticity.

The autonomous energy efficiency improvement (AEEI) rate is the growth rate of energy efficiency in production sectors. The central case employs an AEEI of 0.7%/year. A higher AEEI rate reflects a higher growth rate of energy efficiency over time and implies a lower cost of using non-energy inputs to substitute away the carbon-intensive energy inputs. Thus, the economic costs per ton decline with a higher AEEI rate.

The savings rate determines the share of income that is used to buy investment goods. In the central case, the savings rate starts at 42% in 2020 and declines linearly to 32% in 2035. We consider an alternative savings rate case in which the baseline savings rate time-profile is shifted up by five percent. In this alternative simulation, the profile is shifted up but its shape does not change. Scaling up the saving rate time-profile implies a baseline with higher investment and lower consumption, and thus more capital accumulations, as well as higher GDP and higher emissions over time than in the central case. When applying the central case benchmarks to this alternative baseline, this alternative TPS has greater emission reductions because of the higher output level than the central case.[35] Along with the greater emissions reductions, the economic costs are also higher than the central case. Nevertheless, since greater capital accumulation makes it easier for firms to substitute carbon-intensive inputs with capital inputs, this alternative TPS has a slightly lower cost per ton than the central case.

Overall, our main findings on the impacts of the TPS are robust to changes in these parameters.

[35] With the same benchmarks, a higher output level implies greater emissions reductions because the reductions are the output level multiplied by the difference between baseline intensity and benchmark.

Table 12. Sensitivity Analysis – I

Significance of Production and Transformation Elasticities

	Energy-factor substitution elasticity			Capital transformation elasticity		
	0.3	**0.4** (central case)	**0.5**	**2**	**3** (central case)	**4**
Cumulative emission reduction (Gt)						
Phase 1 (2020-2022)	0.53	0.55	0.56	0.54	0.55	0.55
Phase 2 (2023-2025)	1.63	1.66	1.69	1.65	1.66	1.67
Phase 3 (2026-2035)	21.80	21.75	21.79	21.76	21.75	21.76
Present value of cumulative costs (billion RMB)						
Phase 1 (2020-2022)	23	23	24	26	23	22
Phase 2 (2023-2025)	84	81	79	87	81	77
Phase 3 (2026-2035)	2,216	2,016	1,866	2,146	2,016	1,914
Economic costs per ton (RMB/ton)						
Phase 1 (2020-2022)	44.1	42.9	41.9	47.7	42.9	39.2
Phase 2 (2023-2025)	51.5	48.9	47.0	52.3	48.9	46.2
Phase 3 (2026-2035)	101.7	92.7	85.6	98.6	92.7	88.0
Average allowance price (RMB/ton)						
Phase 1 (2020-2022)	60	54	49	60	54	49
Phase 2 (2023-2025)	97	86	78	91	86	80
Phase 3 (2026-2035)	459	382	326	401	382	360
Wind- and solar- electricity increase (percent)						
Phase 1 (2020-2022)	0.49	0.48	0.48	0.66	0.48	0.3
Phase 2 (2023-2025)	1.17	1.06	0.98	1.28	1.06	0.9
Phase 3 (2026-2035)	7.10	6.02	5.22	6.67	6.02	5.5

Table 13. Sensitivity Analysis – II
Significance of Key Dynamic Parameters

	AEEI rate			Saving rate	
	0.35%	0.7% (central case)	1.4%	42% in 2020 to 32% in 2035 (central case)	47% in 2020 to 37% in 2035
Cumulative emission reduction (Gt)					
Phase 1 (2020-2022)	0.55	0.55	0.54	0.55	0.56
Phase 2 (2023-2025)	1.74	1.66	1.50	1.66	1.75
Phase 3 (2026-2035)	23.80	21.75	17.89	21.75	23.83
Present value of cumulative costs (billion RMB)					
Phase 1 (2020-2022)	24	23	23	23	24
Phase 2 (2023-2025)	87	81	70	81	85
Phase 3 (2026-2035)	2,367	2,016	1,428	2,016	2,200
Economic costs per ton (RMB/ton)					
Phase 1 (2020-2022)	42.9	42.9	42.8	42.9	42.9
Phase 2 (2023-2025)	50.2	48.9	46.4	48.9	48.4
Phase 3 (2026-2035)	99.5	92.7	79.8	92.7	92.3
Average allowance price (RMB/ton)					
Phase 1 (2020-2022)	54	54	54	54	54
Phase 2 (2023-2025)	90	86	78	86	84
Phase 3 (2026-2035)	433	382	292	382	377
Wind- and solar- electricity increase (percent)					
Phase 1 (2020-2022)	0.48	0.48	0.48	0.48	0.48
Phase 2 (2023-2025)	1.09	1.06	1.00	1.06	1.03
Phase 3 (2026-2035)	6.30	6.02	5.36	6.02	5.90

V. Conclusion

This report describes recent improvements to the structure and data of a dynamic general equilibrium model designed to assess the impacts of China's national carbon emissions trading system. New features of the model include the expansion of the time-interval of the model to 2035 and further disaggregation of the model's production sectors. The extensions also include giving the model the capability to assess two policy changes that the Chinese planners are contemplating: the introduction of an auction as a potential source of supply of emissions allowances, and the possible future transition from the TPS to C&T. This report describes the results from applications of the extended model to these potential new policy approaches, as well as to other current or planned policies. The applications make use of an updated dataset.

Insights from the applications include the following. Unless otherwise indicated, these are results under our central case values for parameters:

- Over the 2020-2035 interval, the TPS is likely to reduce the cumulative CO_2 emissions (relative to baseline) by about 24 Gt, or 12 percent of the baseline emissions. Phase 1 (2020-2022) contributes 2 percent of the cumulative reductions, Phase 2 (2023-2025) contributes 7 percent, and Phase 3 (2026-2035) contributes 91 percent. The emissions reductions increase significantly over time due to the expansion of the TPS's coverage and the continued tightening of the benchmarks.
- The cumulative economic costs (measured as the change in real GDP from baseline) to achieve the emissions reductions over the 2020-2035 interval would amount to around 2.1 trillion RMB, or 0.13 percent of discounted cumulative baseline GDP in the same period. Annual aggregate economic costs of the TPS increase over time. The increase reflects the TPS's expanding coverage and the increasing stringency of its benchmarks.
- The climate-related benefits of the TPS exceed its economic costs. When a value of 353RMB/tCO_2 is employed in 2020 for the social cost of carbon, in our central case the benefits from avoided climate change associated with the TPS's induced emissions reductions over the 2020-2035 interval exceed the economic costs by a factor of 5.
- In the first years of implementation of the TPS, the policy's costs per ton of CO_2 abatement are very close to the costs under an equally stringent C&T program. However, the TPS's costs per ton begin to exceed those of C&T starting around 2028 and the excess of its costs over those of C&T continues to expand after that. The eventually higher cost of the TPS reflects the increasing stringency of the benchmarks over time, which augments the economic distortions associated with the TPS's implicit subsidy to output. Correspondingly, a transition from the TPS to C&T lowers the costs of CO_2 abatement in the longer run.
- Introducing an auction to complement the free allocation of emissions allowances lowers the aggregate costs of reducing CO_2 emissions. The presence of an auction reduces the share of allowances offered through free allocation and thereby reduces the importance of the TPS's implicit output subsidy, a key source of economic distortions under the TPS. The economic gains from introducing auctioning depend on the scale of the auction and how the auction's revenues are used. When the auction contributes 10 percent of the emissions allowances in circulation, using the revenues to offset pre-existing capital and labor taxes yield the largest cost reductions, lowering economic costs by 34 percent relative to the case with no auctioning. Using the revenues to finance output subsidies to wind and solar-generated electricity reduces costs by 25 percent relative to the no-

auctioning case, but has the attraction of increasing renewable electricity production by renewables-based electricity by 38 percent relative to the no-auctioning case.

- In all phases, the coal sector experiences the largest profit loss. This reflects the decreased demand for coal under TPS, a consequence of the high carbon intensity of coal. If ten percent of the emissions allowances were supplied via auction, recycling half of the auction revenue to the coal sector through a lumpsum transfer would fully compensate the coal sector's profit loss. Among the Phase 2-newly-added sectors, the aluminum sector is the most adversely affected, and among the Phase 3-newly-added sectors, the "other non-ferrous metal" sector is the most adversely affected. This reflects their relatively high emissions intensities, as well as the fact that they are more trade-exposed and thus more prone to substitution by imported goods.
- Although renewables-based electricity is not covered under the TPS, the TPS promotes the growth of renewables-based electricity by raising the relative cost of fossil-based electricity. The TPS increases the wind- and solar-generated electricity by 4% and 6% relative to baseline over the 2020-2035 interval. The C&T has larger positive effects on renewables-based electricity because the price of electricity rises more under C&T, giving larger incentives for the wind- and solar- electricity to increase output. The wind- and solar-generated electricity increases by 13% and 20% relative to the baseline.
- Reducing the number (and associated variation) of the benchmarks reduces the costs of meeting given aggregate targets for CO_2 emissions abatement. Lowering the number of electricity sector benchmarks from four to two (while maintaining the same average stringency) reduces costs by 1 percent in 2020-2035. Lowering the number to one reduces costs by 29 percent. While greater benchmark variation implies higher costs, it allows policymakers to customize the benchmarks in a way that avoids undesirable distributional impacts.

References

Cao, J., Ho, M. S., Hu, W., & Jorgenson, D. (2020). Effective labor supply and growth outlook in China. *China Economic Review*, *61*, 101398.

Fischer, C. (2003). Combining rate-based and cap-and-trade emissions policies. *Climate Policy*, *3*, S89–S103.

Fischer, C., & Newell, R. G. (2008). Environmental and technology policies for climate mitigation. *Journal of Environmental Economics and Management*, *55*(2), 142–162.

Goulder, L. H., Long, X., Lu, J., & Morgenstern, R. D. (2022). China's unconventional nationwide CO2 emissions trading system: Cost-effectiveness and distributional impacts. *Journal of Environmental Economics and Management*, *111*, 102561.

Goulder, L. H., Parry, I. W. H., Williams III, R. C., & Burtraw, D. (1999). The cost-effectiveness of alternative instruments for environmental protection in a second-best setting. *Journal of Public Economics*, *72*(3), 329–360.

He, J., Li, Z., Zhang, X., Wang, H., Dong, W., Chang, S., Ou, X., Guo, S., Tian, Z., Gu, A., Teng, F., Yang, X., Chen, S., Yao, M., Yuan, Z., Zhou, L., & Zhao, X. (2020). Comprehensive report on China's Long-Term Low-Carbon Development Strategies and Pathways. *Chinese Journal of Population, Resources and Environment*, *18*(4), 263–295.

Long, X., Zhang, D., Goulder, L., & Qu, C. (2022). *General Equilibrium Analysis of Cost-Effectiveness and Distributional Impacts of China's Nationwide CO_2 Emissions Trading System* (1). Asia Society Policy Institute.

MEE. (2021). *Interim Regulations for the Management of Carbon Emissions Trading (Draft)*.

National Bureau of Statistics. (2021). *The National Bureau of statistics on the final verification of GDP in 2020*.

Nordhaus, W. D. (2017). Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences*, *114*(7), Article 7.

Outline of the 14th Five-Year Plan (2021-2025) for National Economic and Social Development and Vision 2035 of the People's Republic of China. (2021). People's Publishing House.

Parry, I. W. H., & Bento, A. M. (2000). Tax Deductions, Environmental Policy, and the "Double Dividend" Hypothesis. *Journal of Environmental Economics and Management*, *39*(1), 67–96.

Appendices

Appendix A. Data details

In the model, the electricity, cement, aluminum, and iron & steel sectors include subsectors distinguished by technology or emissions-intensity considerations.

Electricity Sector

For the electricity sector, there are 15 subsectors, with each subsector representing a distinct technology used for electricity generation. The first 11 technologies differ in terms of fuel input (coal or gas), capacity (300MW, 600MW, etc.), and temperature & pressure (subcritical, supercritical, etc.). The 12th - 15th technologies are low-carbon (wind, solar, hydro, and nuclear power) generation. The differing fuel input intensities imply different emissions intensities.

In our data, there are 1,929 coal-fired and gas-fired units, generating 23 billion kWh in 2017, covering 49.7% of China's coal- and gas-fired electricity generation.

Table A1. Subsectors of the Electricity Sector

Technology Category	Subsector
Coal-fired (other than circulating fluidized bed)	LUSC- 1000MW Ultra-supercritical SUSC - 600MW Ultra-supercritical LSC - 600MW Supercritical SSC - 300MW Supercritical LSUB - 600MW Subcritical SSUB - 300MW Subcritical OTHC - install capacity less than 300MW
Circulating Fluidized Bed	LCFB - Circulating Fluidized Bed Units (with installed capacity greater than or equal to 300MW) SCFB - Circulating Fluidized Bed Units (with installed capacity less than 300MW)
Gas-fired	HPG - F-class LPG - Pressure lower than F-class
Other	Wind power Solar power Hydropower Nuclear power

Cement

For the cement sector, the subsectors reflect heterogeneity in emissions intensity, rather than along a technology dimension. We cluster by their base year emissions intensity.

In our data, there are 797 cement production lines from 631 cement firms, covering 57% of China's cement production. We have the CO_2 emissions intensity data for each production line.[36] We apply a clustering algorithm to group the production lines into five clusters, which are described in the section below. The lowest and highest clusters have very few production lines, so we include them in the closest intermediate groups. Each of the resulting three clusters represents a subsector of the cement sector. The clusters are indicated in Table A2 below. Figure A1 shows the cumulative density function that captures the relationship between the emissions intensities of the three emissions-intensity groups and cumulative cement production.

Table A2. Subsectors of the Cement Sector

Subsector	**CO_2 emissions intensity**
High-efficiency cement production	CO_2 emissions intensity < 0.845 tCO_2/ton cement production
Medium-efficiency cement production	0.914 > CO_2 emissions intensity ⩾ 0.845 tCO_2/ton cement production
Low-efficiency cement production	CO_2 emissions intensity ⩾ 0.914 tCO_2/ton cement production

[36] We do not have emissions data for the full cement production, but we have emissions data for cement clinkers for each production line of cement firms. Cement is produced by grinding cement clinker into a fine powder. Since emissions from the "clinker grinding" process accounts for only a small portion of the total emissions of producing cement, using the emissions intensity of cement clinker to define subsectors approximates fairly closely the emissions intensity of cement production.

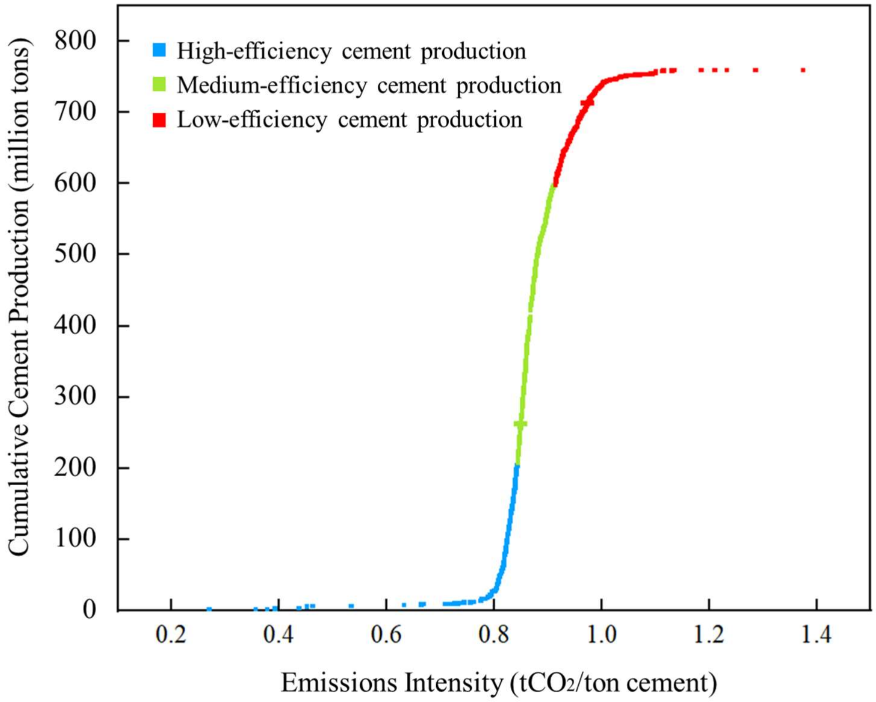


Figure A1. Clustering of Cement Sector by Emissions Intensity

Aluminum

As with cement, we cluster aluminum firms by their base year emissions intensity. In our data, there are 116 aluminum production lines from 64 aluminum firms, covering 42% of China's aluminum production. We use the same clustering method as cement – we take the logarithm of emissions intensities before using K-means to group the 116 production lines into 5 clusters, and then regroup the lowest and highest clusters to their closest groups, respectively. We end up with three clusters, each representing one subsector in the aluminum sector.

Table A3. Subsectors of the Aluminum Sector

Subsector	CO_2 emissions intensity
High efficiency	CO_2 emissions intensity < 8.00 (tCO_2/ ton aluminum)
Medium efficiency	8.33 > CO_2 emissions intensity ⩾ 8.00 (tCO_2/ ton aluminum)
Low efficiency	CO_2 emissions intensity ⩾ 8.33 (tCO_2/ ton aluminum)

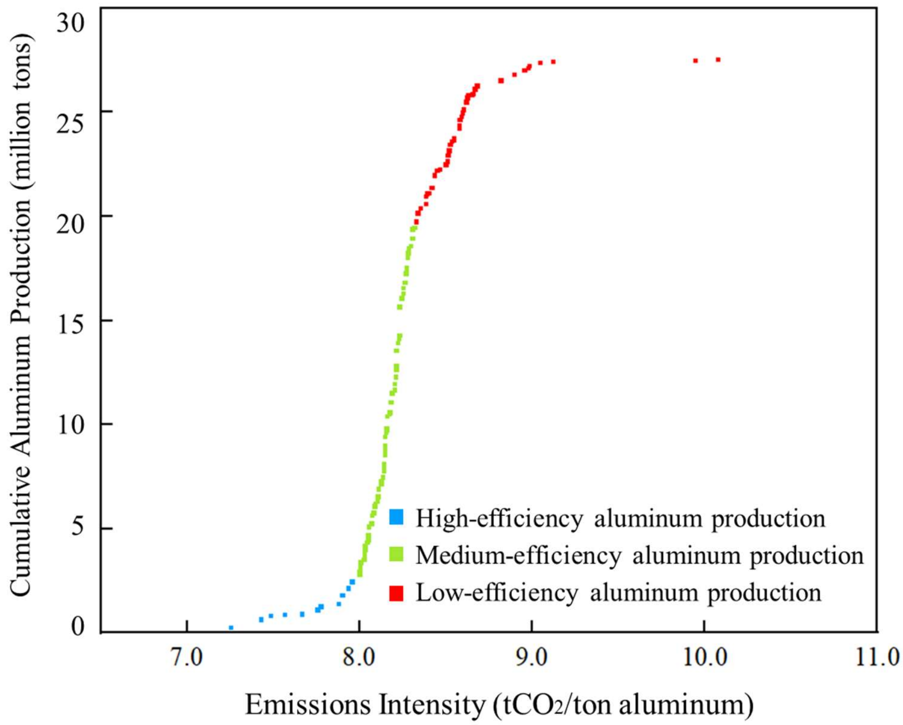


Figure A2. Clustering of Aluminum Sector by Emissions Intensity

Iron & Steel

We first classify iron & steel units into two technology categories: basic oxygen (BO) steelmaking and electric arc (EA) furnace steelmaking. Each technology category is further classified into subcategories based on its base-year emissions intensities.

There are 187 BO steelmaking units with a total production of 600 million tons of crude steel, and 262 EA steelmaking units with a total production of 133 million tons of crude steel. In total, our data cover 88% of the national crude steel production in 2017.

We use the same clustering method as cement and aluminum. We use K-means to cluster the 187 BO steelmaking units into 5 clusters, and then regroup the lowest and highest ones to their closest groups, respectively. We end up with three clusters, each representing one subsector in BO steelmaking units. Similarly, we cluster the 259 EA steelmaking units into 5 clusters, and then regroup the lowest and highest clusters to their closest groups, respectively, and we end up with three clusters, each representing one subsector in EA steelmaking units.

Table A4. Subsectors of the Iron & Steel Sector

Subsector	CO_2 emissions intensity
Basic oxygen steelmaking	CO_2 emissions intensity < 1.41 (tCO_2/t)
	1.98 > CO_2 emissions intensity ⩾ 1.41 (tCO_2/t)
	Carbon emissions intensity ⩾ 1.98 (tCO_2/t)
Electric arc furnace steelmaking	CO_2 emissions intensity < 0.125 (tCO_2/t)
	0.235 > CO_2 emissions intensity ⩾ 0.125 (tCO_2/t)
	CO_2 emissions intensity ⩾ 0.235 (tCO_2/t)

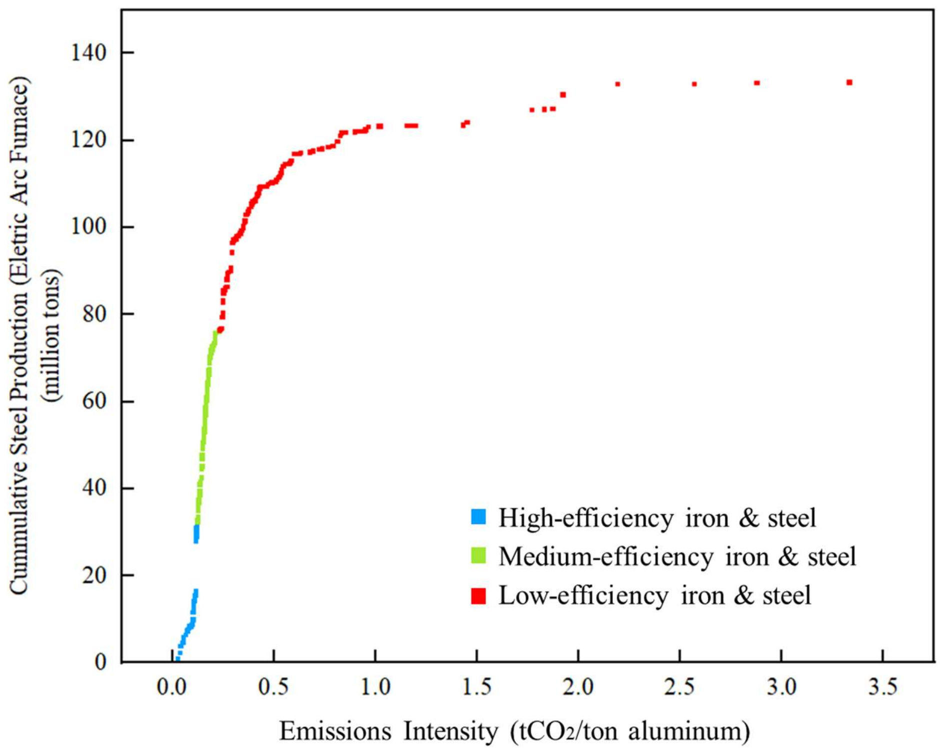


Figure A3. Clustering of Iron & Steel (EA) Sector by Emissions Intensity

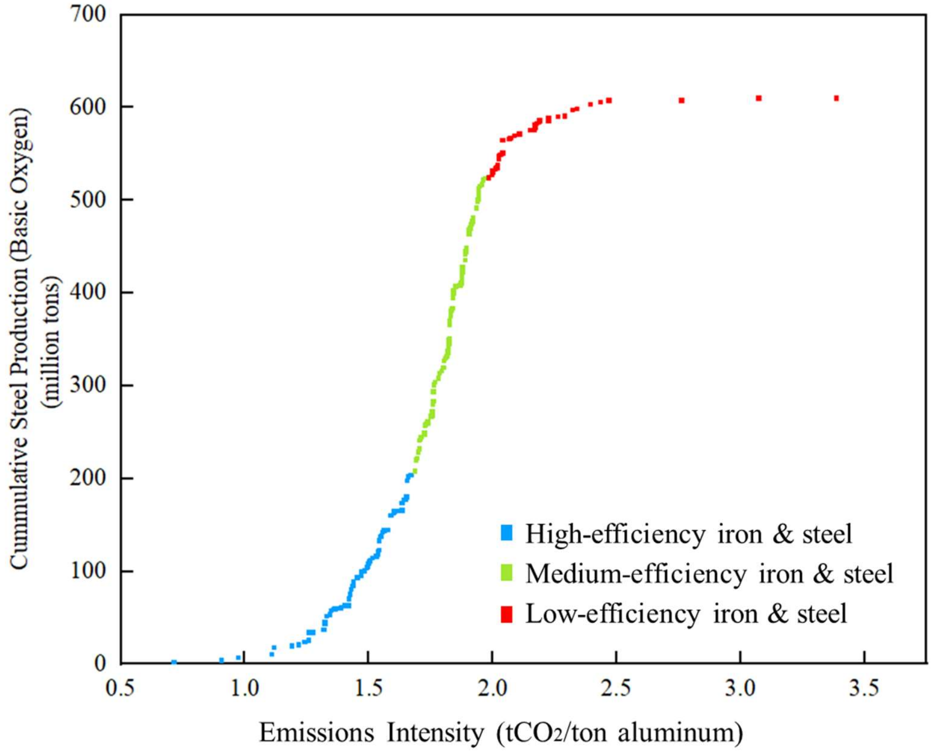


Figure A4. Clustering of Iron & Steel (BO) Sector by Emissions Intensity

The Clustering Algorithm

The clustering algorithm applies a machine-learning technique that groups data points into clusters. We cluster plants within a given sector into subsectors based on their base-year emissions intensities. The first step is to choose the sector to be disaggregated and the resulting number of subsectors. The second step is to employ the clustering algorithm to find cluster centers and assign plants to each cluster such that the distance (i.e., the difference between the center's emissions intensity and the plant's emissions intensity) is minimized. Various clustering algorithms differ in how "cluster center" and "distance" are defined. K-means clustering defines the center as the mean of all data points in the cluster, distance as the squared Euclidean deviation from the mean, while K-medians clustering defines the center as the median of all data points in the cluster, and distance as the Manhattan distance. Therefore, clustering is subject to the researcher's choice of the number of clusters (i.e., the number of subsectors) and the choice of the distance metric.

Data Processing

The data are processed in four steps. First, the 149 sectors' input-output data from China's 2017 input-output table are aggregated to the 31 production sectors in our study and scaled to 2020, the first simulation year. We use three scalars to translate these input and output data to 2020: one for the service sector, one for the agriculture sector, and one for other sectors. The data are scaled so that the GDP, as well as the value-added shares of the service sector and agriculture sectors, match the published statistics in 2020 (National Bureau of Statistics, 2021). Second, the sectors are then disaggregated into subsectors for electricity, cement, aluminum, and iron & steel according to the subsector-level information, which is obtained by aggregating the firm-level Ministry of Ecology and Environment (MEE) data. The disaggregation method is described in the next paragraph. Third, we scale all tax and subsidy rates reported in GTAP for 2014 (the latest version) by a common factor so that the total tax revenue net of subsidies matches that in 2020 (National Bureau of Statistics, 2021). Lastly, we re-balance the input-output data after these adjustments, as described in the subsection "Input-Output Table Rebalance" below.

Disaggregating Sector-level Data to Subsectors

The input-output table provides sector-level data on economic value variables. The sectors are then split into subsectors (for electricity, cement, aluminum, and iron & steel sectors) according to the subsector-level information, which is obtained by aggregating the firm-level data from the MEE. The disaggregation method is described below.

For factor inputs ($m_j,\ w_j$), material inputs (d, n), and exports (Y_{ex}), sector-level electricity, cement, and aluminum data are split into subsectors by assuming that each subsector's share of a corresponding input (or export) equals the subsector's output share. As for the material inputs of iron & steel, we consider the different technical properties of the basic oxygen (BO) steelmaking and electric arc furnace (EA) steelmaking subsectors: BO steelmaking converts iron ore into pig iron and then into steel, while the EA steelmaking directly converts scrap or direct reduced iron to steel by electric arcs. Therefore, we assume that the BO steelmaking subsector uses all the iron ore and mineral material inputs in the iron & steel sector. We also assume that the self-inputs of the EA steelmaking subsector account for 60% of its total input, while the self-inputs of the BO steelmaking subsector only account for 20%, according to Lu *et al.* (2015). Other material inputs, factor inputs, and exports of the iron & steel sector are split in the same way as the electricity, cement, and aluminum sectors.

For energy inputs in the electricity sector, the MEE data provides each coal-fired subsector's share of coal use, and each gas-fired subsector's share of gas usage. For energy inputs in the cement and the iron & steel sector, the MEE data provides each subsector's share of electricity, heat, and fuel composite. We assume that a subsector's share of the fuel composite applies to each fuel. For energy inputs in the aluminum sector, the MEE data provides each subsector's share of electricity input. We assume this share also applies to other energy inputs.

The MEE data provides the emissions in electricity, cement, iron & steel, and aluminum sectors. Note that the cement sector, in addition to emissions from consuming energy inputs, also emits CO_2 in the process of carbonate decomposition ($CaCO_3$ decomposed to CaO and CO_2). The data only covers a subset of the whole sector. For example, data on the cement sector covers 57% of China's cement production. We scale the emissions data up by the share of coverage for each of the three sectors. Then, for the electricity, cement, iron & steel, and aluminum sectors, the emissions data at the sector level are split into subsectors in the same way as we split energy inputs.

Input-Output Table Rebalance

After the processing of the original data, the original input-output table becomes unbalanced – the total inputs and total outputs of a sector may be different. We thus apply a least-square optimization method to obtain a balanced input-output table following Zhang *et al.*(2013). Specifically, Equation (A1) is applied to adjust the factor inputs and intermediate inputs so that the input and output of a sector are balanced.

$$
\begin{aligned}
&\min_{\{x_{ijk}, e_{ijk}, w_{jk}, m_{jk}\}} \sum_{i,j,k} \{(x_{ijk} - \overline{x_{ijk}})^2 + (w_{jk} - \overline{w_{jk}})^2 + (m_{jk} - \overline{m_{jk}})^2 + (e_{jk} - \overline{e_{jk}})^2\} \\
&s.t. \\
&\sum_i (x_{ijk} + w_{jk} + m_{jk} + e_{ljk}) \cdot (1 + \overline{\theta_{res_{jk}}}) = (\sum_{i,k} x_{jik} + \sum_{i,k} \overline{Y_{ex_{ijk}}}) \cdot \psi_{jk}, \forall j, k \\
&x_{ijk}, w_{jk}, m_{jk}, e_{ljk} > 0, \\
&x_{ijk} \equiv 0, \forall \overline{x_{ijk}} = 0 \\
&w_{jk} \equiv 0, \forall \overline{w_{jk}} = 0 \\
&m_{jk} \equiv 0, \forall \overline{m_{jk}} = 0 \\
&e_{ljk} \equiv 0, \forall \overline{e_{ljk}} = 0,
\end{aligned}
\tag{A1}
$$

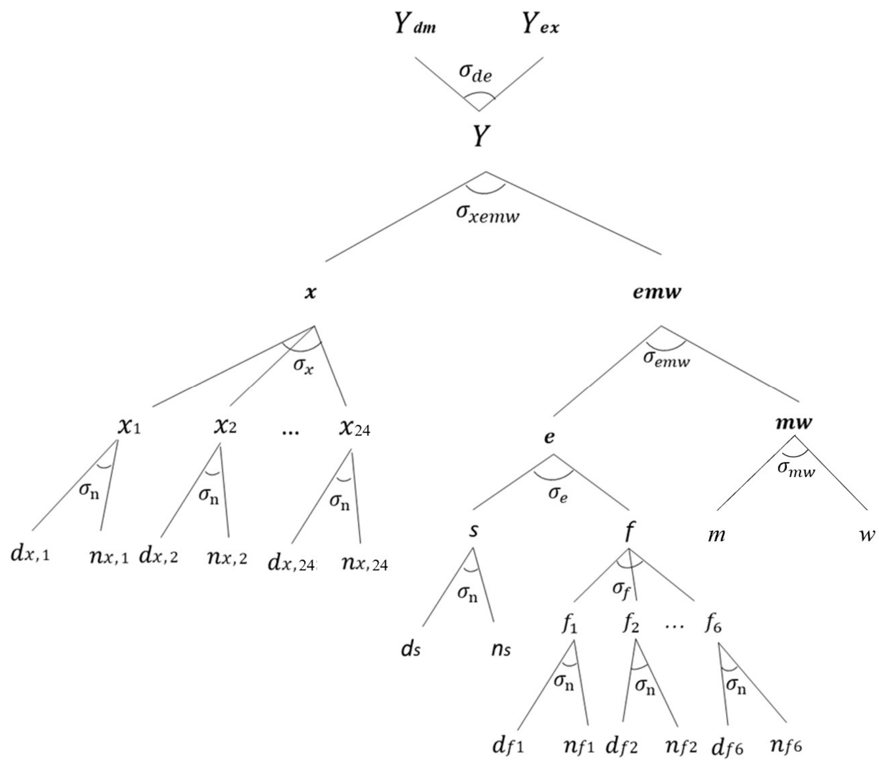
In Equation (A1), $x_{ijk}, e_{ljk}, w_{jk}, m_{jk}$ represent the adjusted material *i*, energy *l*, capital, and labor input of sector *j*, subsector *k*. $\overline{x_{ijk}}, \overline{e_{ljk}}, \overline{w_{jk}}, \overline{m_{jk}}$ represent the corresponding accounts before the rebalance. The objective function is to minimize the difference between the adjusted and unadjusted original value. The constraints for the objective function are the balance of the input and output of sector *j*, subsector *k*. The left-hand side represents the total inputs of sector *j*, subsector *k*. $\overline{\theta_{res_{jk}}}$ is the share of natural resources for renewable and nuclear electricity production subsectors. The right-hand side is the total output of sector *j*, subsector *k*, of which ψ_{jk} represents the subsector *k*'s output share in sector *j*.

Appendix B. Model and Parameters

Production

Production in each of the sectors in each modeling period is represented by a nested structure shown in Figure A5. The σ's in the nesting structure are elasticities that govern the ease with which inputs can be substituted for each other. This nesting structure includes a large number of distinct parameters, which allows the model to incorporate considerable variation in the ease of input substitution for differing inputs.

a. **Fossil-fuel based power sector and other sectors**



b. **Solar, wind, hydro, and nuclear power subsectors**

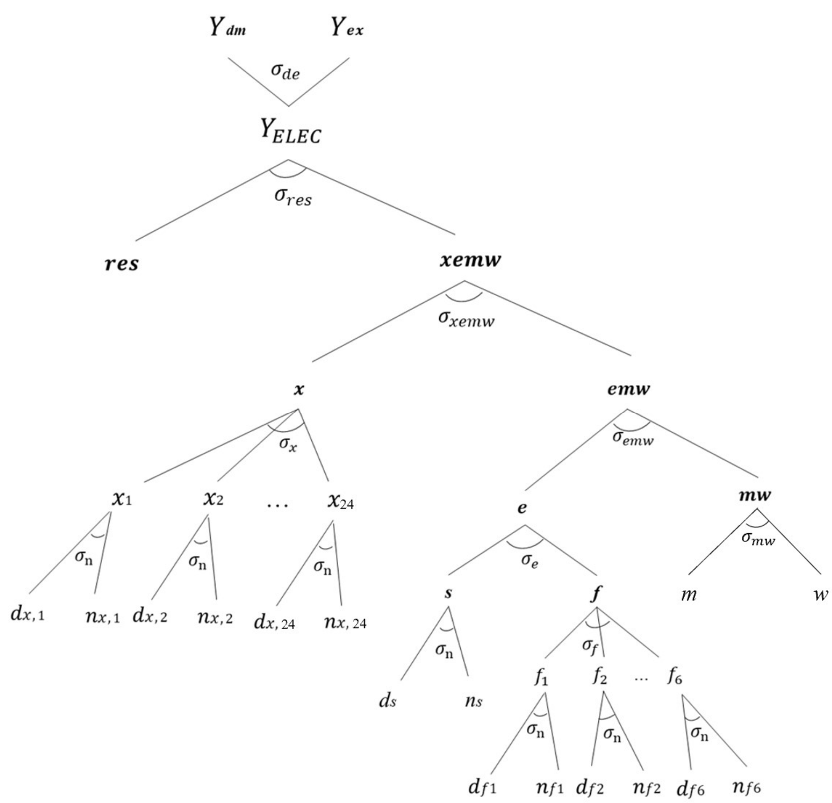


Figure A5. Nested CES Production Structure for Each Sector

Below we use fossil-based power sector and other sectors as an example to illustrate the production structure. The structure for solar, wind, hydro, and nuclear power subsectors are similar, except that they have natural resources (*res*) as their inputs.

In each sector, producers employ material inputs (***x***), energy inputs (***e***), and factors (***mw***) to produce output. As indicated in the left portion of the nested structure, the material inputs x_1, x_2, …, x_{24} combine to produce the composite material input ***x***. Each of the material inputs x_i is a composite of a domestically produced material input $d_{x,i}$ and, if any, a foreign-produced material input $n_{x,i}$.

The energy composite (*e*) is produced from electricity (*s*) and non-electricity fuels (*f*), and the non-electricity fuel is a composite of six fuel inputs f_1, f_2, …, f_6 (coal, crude oil, natural gas, gas manufacture & distribution, petroleum products, and heat). Distinguishing electricity from non-electricity fuels allows flexibility in setting different elasticities of substitution with regard to fuels and electricity, as a more realistic representation of the production technologies. Energy inputs f_i (*s*) is also a composite of a domestically produced energy $d_{f,i}$ (d_s) and, if any, a foreign-produced input $n_{f,i}$ (n_s)

Producers also employ factors of production labor (*m*) and capital (*w*). As discussed further below, labor is represented as perfectly mobile across sectors, while the other factors are imperfectly mobile. These factors combine to form the composite factor ***mw***. Additionally, producers of renewable and nuclear electricity employ a special factor of production, natural resource (***res)***, as Figure A5(b) above shows.

The composite ***mw*** combines with the energy composite ***e*** to produce the energy-factor composite ***emw***. The elasticity of substitution between ***e*** and ***mw*** controls the energy efficiency improvements achieved by substituting capital and labor for energy. The composite ***emw*** then combines with ***x*** to produce gross output (*Y*). The output *Y* is allocated toward the domestic market or the export market. Y_{dm} and Y_{ex} represent the output devoted to each of these markets.

The model employs the constant-elasticity-of-substitution (CES) functional form for the production functions at each stage of the production nest. A general equation for this functional form is:

$$V = \left[\sum_{i=1}^{n} \alpha_i v_i^{\rho} \right]^{\frac{1}{\rho}} \tag{A2}$$

where $\sum_{i=1}^{n} \alpha_i = 1$. The parameter ρ is equal to $1 - \frac{1}{\sigma}$, where σ is the elasticity of substitution among v_i in producing V.

Equation (A2) indicates the relationship, at any given point of the nest, between a given composite and its underlying elements. For example, the function that combines ***x*** and ***emw*** to produce *Y* is expressed by:

$$Y = \left[\alpha_{\boldsymbol{x}} \boldsymbol{x}^{\rho_{xemw}} + \alpha_{\boldsymbol{emw}} \boldsymbol{emw}^{\rho_{xemw}} \right]^{\frac{1}{\rho_{xemw}}} \tag{A3}$$

where $\alpha_{\boldsymbol{x}} + \alpha_{\boldsymbol{emw}} = 1$, $\rho_{\boldsymbol{xemw}} = 1 - \frac{1}{\sigma_{\boldsymbol{xemw}}}$, and $\sigma_{\boldsymbol{xemw}}$ is the elasticity of substitution between ***x*** and ***emw***.

A constant elasticity of transformation (CET) function maps the total output Y into the domestic supply Y_{dm} and export Y_{ex}.

$$Y_{dm} = \alpha_{dm}^{\sigma_{de}} \left[\frac{p_{dm}}{p} \right]^{-\sigma_{de}} Y \tag{A4}$$

$$Y_{ex} = \alpha_{ex}^{\sigma_{de}} \left[\frac{p_{ex}}{p} \right]^{-\sigma_{de}} Y \tag{A5}$$

where $\alpha_{dm} + \alpha_{ex} = 1$, and σ_{de} is the elasticity of transformation between Y_{dm} and Y_{ex}. p_{dm}, p_{ex} and p denote the domestic price, export price, and composite price of the produced good, respectively. As these functions indicate, the fraction of *Y* devoted to the domestic market and exports is a function of the real prices of goods sold to the domestic and foreign markets. Throughout, wherever there is a tax or subsidy, the price in all equations is the gross-of-tax price.

Factor Types and Supply

Labor (*m*) is perfectly mobile across sectors, capital (*w*) is imperfectly mobile, and natural resource (*res*) is immobile. The supplies of the imperfectly mobile factor capital in every single period to the 31 sectors are based on a transformation function. The transformation function allocates capital to the model's sectors. Changes in relative prices alter its allocation across sectors. The marginal returns to capital generally will differ across sectors, a reflection of its imperfect mobility. Consequently, the market price of capital will generally differ across sectors.

The transformation function, $\Gamma_{w_i}(\cdot)$, has the CET functional form and is expressed by:

$$\overline{w} = [\sum_{j=1}^{31} \alpha_{w,j} w_j^{S\rho_w}]^{1/\rho_w} \tag{A6}$$

where $\sum_{j=1}^{31} \alpha_{w,j} = 1$ and $\rho_w = 1 - \frac{1}{\sigma_w}$, where σ_w is the elasticity of transformation among sectors. The element $\overline{w}$ denotes the fixed endowment of capital and w_j^S the allocation of $\overline{W}$ to sector *j*.

Capital is allocated to maximize the return to their owners. The maximization problem is expressed by the following:

$$\max_{w_j^S} \sum_{j=1}^{j=31} w_j^S P_{wj}$$
$$s.t. \Gamma_w \left(w_j^S \right) = w \tag{A7}$$

where w_j^S denotes the allocation of capital to sector *j* and p_{wj} is the sector-specific price of the factor w. $\Gamma_w(\cdot)$ is the CET function for capital. As indicated earlier, the model distinguishes subsectors of the electricity, cement, aluminum, and iron & steel sectors, to reflect within-sector differences in technology or emissions intensities. The same maximization problem determines the allocation of capital across subsectors.

Inputs and Outputs

In each sector, managers of firms are assumed to aim to maximize profit. This objective determines firms' choices of input and output levels. Optimal choices of inputs and outputs are shown below. The sector subscript has been suppressed in this subsection.

Optimal input intensities

For any CES function of the form in Equation (A2), the Lagrangian equation for obtaining the composite V at minimum cost is given by:

$$L = \sum_{i=1}^{n} p_i v_i + \lambda \left\{ \left[\sum_{i=1}^{N} \alpha_i v_i^{\rho} \right]^{\frac{1}{\rho}} - V \right\} \tag{A8}$$

where p_i the price of input v_i.

The first-order conditions can be summarized as:

$$\frac{v_i}{v_j} = \left[\frac{\alpha_j}{\alpha_i} \frac{p_i}{p_j} \right]^{\frac{1}{\rho-1}} \tag{A9}$$

for all i and j in 1, … ,n.

From the first-order conditions and the CES production function, the optimal demand of input v_i per unit of the composite V is derived as:

$$\frac{v_i}{V} = \alpha_i^{\sigma} \left[\frac{p_i}{P} \right]^{-\sigma} \tag{A10}$$

where σ is the constant elasticity of substitution equal to $\frac{1}{1-\rho}$. P is the price of the composite V:

$$P = \left[\sum_{i=1}^{n} \alpha_i^{\sigma} p_i^{1-\sigma} \right]^{\frac{1}{1-\sigma}} \tag{A11}$$

The formulas in Equations (A10) and (A11) apply at every level of the production nest. As an example, the intensity of domestic material input d_{xl}, imported material input n_{xl} in the domestic-import material composite x_l, and the price of the composite x_l are:

$$\frac{d_{xl}}{x_l} = \alpha_{d_{xl}}^{\sigma_n} \left[\frac{p_{d_{xl}}}{p_{x_l}} \right]^{-\sigma_n} \tag{A12}$$

$$\frac{n_{xl}}{x_l} = \alpha_{n_{xl}}^{\sigma_n} \left[\frac{p_{n_{xl}}}{p_{x_l}} \right]^{-\sigma_n} \tag{A13}$$

$$p_{x_l} = \left[\alpha_{d_{xl}}^{\sigma_n} p_{d_{xl}}^{1-\sigma_n} + \alpha_{n_{xl}}^{\sigma_n} p_{n_{xl}}^{1-\sigma_n} \right]^{\frac{1}{1-\sigma_n}} \tag{A14}$$

Optimal output

The profit function is:

$$\begin{aligned} \Pi &= pY - C \\ &= pY - p_x x - p_{emw} emw \end{aligned} \tag{A15}$$

$$\Pi_k = pY - p_x x - p_{emw} emw - p_{rk} res_k \tag{A16}$$

where the C is the cost of production inputs, which equals the payment to $\boldsymbol{x}$ and $\boldsymbol{emw}$. For renewable and nuclear electricity supply, Equation (A16) is applied, where p_{rk} and $\boldsymbol{res_k}$ denote the price and endowment for natural resources in renewable and nuclear subsectors (wind, solar, hydro, and nuclear). The p denotes the composite price of the produced good:

$$p = \left[\alpha_{dm}^{\sigma_{de}} p_{dm}^{1-\sigma_{de}} + \alpha_{ex}^{\sigma_{de}} p_{ex}^{1-\sigma_{de}} \right]^{\frac{1}{1-\sigma_{de}}} \tag{A17}$$

where p_{dm} is the domestic price, p_{ex} the export price, σ_{de} the elasticity of transformation between domestic and export supply, and $\alpha_{dm} + \alpha_{ex} = 1$. Thus, the composite price is a function of the market prices for the sale of the output to the domestic and export markets.

Differentiating the profit function with respect to $\boldsymbol{x}$ gives the first-order condition for $\boldsymbol{x}$, where the left-hand side represents the marginal revenue of $\boldsymbol{x}$ and the right-hand side represents the marginal cost of $\boldsymbol{x}$:

$$p \frac{\partial Y}{\partial \boldsymbol{x}} = p_x \tag{A18}$$

From the first-order condition, we can solve the optimal quantity of $\boldsymbol{x}$ as a function of output.

$$\boldsymbol{x} = \alpha_{\boldsymbol{x}}^{\sigma_{xemw}} \left[\frac{p_{\boldsymbol{x}}}{p} \right]^{-\sigma_{xemw}} Y \tag{A19}$$

Similarly, differentiating the profit function with respect to $\boldsymbol{emw}$ gives the first-order condition for $\boldsymbol{emw}$. And from the first-order condition, we have the optimal quantity of $\boldsymbol{emw}$ as a function of output.

$$p \frac{\partial Y}{\partial \boldsymbol{emw}} = p_{\boldsymbol{emw}} \tag{A20}$$

$$\boldsymbol{emw} = \alpha_{\boldsymbol{emw}}^{\sigma_{xemw}} \left[\frac{p_{\boldsymbol{emw}}}{p} \right]^{-\sigma_{xemw}} Y \tag{A21}$$

Under the model's production structure, each firm's production exhibits constant returns to scale. The optimal output level, Y, is determined such that, when market equilibrium is achieved, price equals the constant marginal cost.

Applying the optimal $\boldsymbol{x}$ and optimal $\boldsymbol{emw}$ in Equations (A19) and (A21) to the optimal input intensities, we get the optimal levels of all inputs. As an example, the optimal level of $d_{x,l}$ is:

$$\begin{aligned} d_{x,l} &= \frac{d_{x,l}}{x_l} \frac{x_l}{\boldsymbol{x}} \boldsymbol{x} \\ &= \alpha_{d_{x,l}}^{\sigma_n} \left[\frac{p_{d_{x,l}}}{p_{x_l}} \right]^{-\sigma_n} \alpha_{x_l}^{\sigma_x} \left[\frac{p_{x_l}}{p_{\boldsymbol{x}}} \right]^{-\sigma_x} \alpha_{\boldsymbol{x}}^{\sigma_{xemw}} \left[\frac{p_{\boldsymbol{x}}}{p} \right]^{-\sigma_{xemw}} Y \end{aligned} \tag{A22}$$

Final Demand

Consumption

In the model, a representative household makes consumption choices to maximize utility. The nested structure of the utility function is below. The household chooses between material goods (x) and energy goods (e). At the next level, the material composite is a CES combination of material goods, x_1, x_2, …, x_{24}. The energy composite is a CES function of electricity (s) and fuel composite (f). The fuel composite is a CES function of six fuel goods, $f_1, f_2, \ldots, f_6$. Each x_l, f_l, and s is a composite based on the domestically and foreign supplied component.

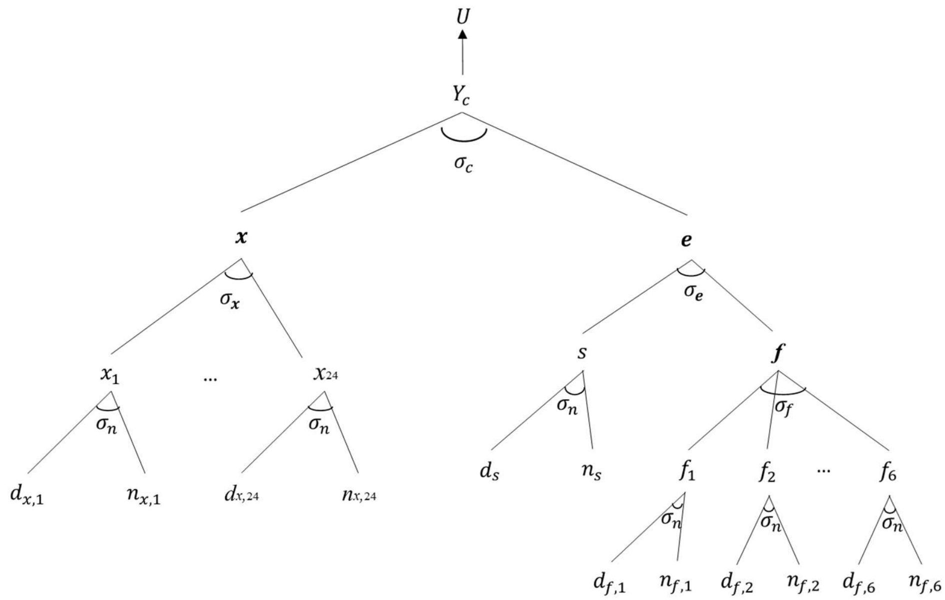


Figure A6. Household Demand Structure

The generalizable CES function form in Equation (A2) applies to all nests in the household demand structure. For example, the top level is expressed by

$$Y_C = \left[\alpha_{x_C} \boldsymbol{x}_C^{\rho_{xe}} + \alpha_{e_C} \boldsymbol{e}_C^{\rho_{xe}} \right]^{\frac{1}{\rho_{xe}}} \tag{A23}$$

where Y_C, $\boldsymbol{x}_C$, and $\boldsymbol{e}_C$ are the demand of the final private good, material composite, and energy composite, respectively. The distribution shares α_{x_C} and α_{e_C} sum to 1, and $\rho_{xe} = 1 - \frac{1}{\sigma_{xe}}$, where σ_{xe} is the elasticity between $\boldsymbol{x}$ and $\boldsymbol{e}$.

The generalizable form of the price function in Equation (A11) applies to the composite prices for all nests of the household demand structure. For example, the composite price of the final consumption good is a combination of the material composite price and energy composite price expressed as:

$$p_C = \left[\alpha_{x_C}^{\sigma_{xe}} p_{x_C}^{1-\sigma_{xe}} + \alpha_{e_C}^{\sigma_{xe}} p_{e_C}^{1-\sigma_{xe}} \right]^{\frac{1}{1-\sigma_{xe}}} \tag{A24}$$

where p_C, p_{x_C}, and p_{e_C} are the price of the final consumption good, the material composite, and energy composite, respectively.

The household maximizes utility subject to its budget constraint. The utility maximization problem is:

$$\max U\left(Y_C\right) = Y_C$$
$$s.t.\quad p_C Y_C \le p_m \bar{m} + p_w \bar{w} + p_{res} res + T - p_I Y_I \tag{A25}$$

where $p_C Y_C$ is the household expenditure,

$p_m \bar{m}$ is the income from the endowments of labor,

$p_w \bar{w}$ is the income from the endowments of capital,

$p_{res} res$ is the income from the endowments of natural resources,

T is the income from transfer from the government, and

$p_I Y_I$ is the private savings, which we discuss below.

Investment

In the model, the level of real investment is determined by the total savings and the price of investment goods of the economy. It is composed of private investment (i.e., investment by the household) and public investment (i.e., investment by the government). Private savings are determined by a fixed fraction of total after-tax households' income. Public savings are specified as a fixed share of government income.

Real investment is the quantity of a new capital good that is produced at minimum cost. The production of the capital goods derives from the nested structure in Figure A7 below. The intensities of the inputs used to produce the capital goods change in response to changes in their prices. The capital good is a CES aggregation of material and energy composites, and the material (energy) composite is a CES aggregation of material (energy) goods. Each material (energy) good is a domestic-import composite.

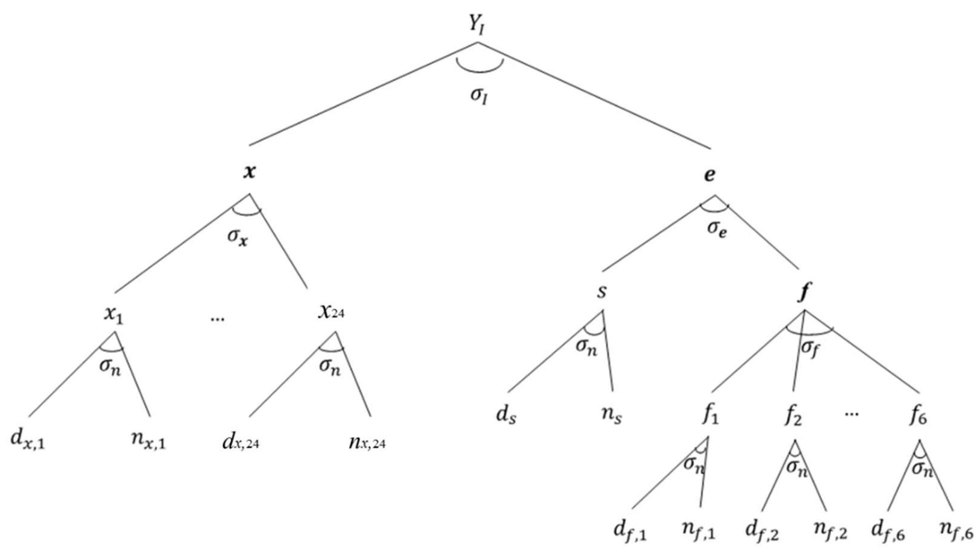


Figure A7. Nested Structure for Investment

The generalizable CES function form in Equation (A2) applies to all nests in the capital good production structure. For example, the top level is expressed by

$$Y_I = \left[\alpha_{x_I} \boldsymbol{x}_I^{\rho_{xe}} + \alpha_{e_I} \boldsymbol{e}_I^{\rho_{xe}} \right]^{\frac{1}{\rho_{xe}}} \tag{A26}$$

where Y_I, $\boldsymbol{x}_I$, and $\boldsymbol{e}_I$ are the investment composite, the material composite, and the energy composite, respectively. $\alpha_{x_I} + \alpha_{e_I} = 1$. $\rho_{xe} = 1 - \frac{1}{\sigma_{xe}}$, where σ_{xe} is the elasticity between $\boldsymbol{x}$ and $\boldsymbol{e}$.

The investment good is produced at the minimum cost. The minimum cost problem has the same form as that of the cost minimization problem of commodity goods. Hence the generalizable form in Equation (A11) applies to the investment good. The composite price of the final good is expressed as:

$$p_I = \left[\alpha_{x_I}^{\sigma_{xe}} p_{x_I}^{1-\sigma_{xe}} + \alpha_{e_I}^{\sigma_{xe}} p_{e_I}^{1-\sigma_{xe}} \right]^{\frac{1}{1-\sigma_{xe}}} \tag{A27}$$

where p_I, p_{x_I}, and p_{e_I} are the price of the final investment good, the material composite, and energy composite, respectively.

Plugging the equations for investment into the household's budget constraint in Equation (A25) yields:

$$\begin{aligned} p_C Y_C \leq\ & p_m \overline{m} + p_w \overline{w} + p_{res} res + \mathrm{T} \\ & - \left[\alpha_{x_I}^{\sigma_{xe}} p_{x_I}^{1-\sigma_{xe}} + \alpha_{e_I}^{\sigma_{xe}} p_{e_I}^{1-\sigma_{xe}} \right]^{\frac{1}{1-\sigma_{xe}}} \mathrm{Y}_I \end{aligned} \tag{A28}$$

Government Spending

Government spending in the model is characterized by a CES preference function defined over the material-energy composite. The structure is the same as the structure for household consumption, with the only difference being the values of the elasticities.

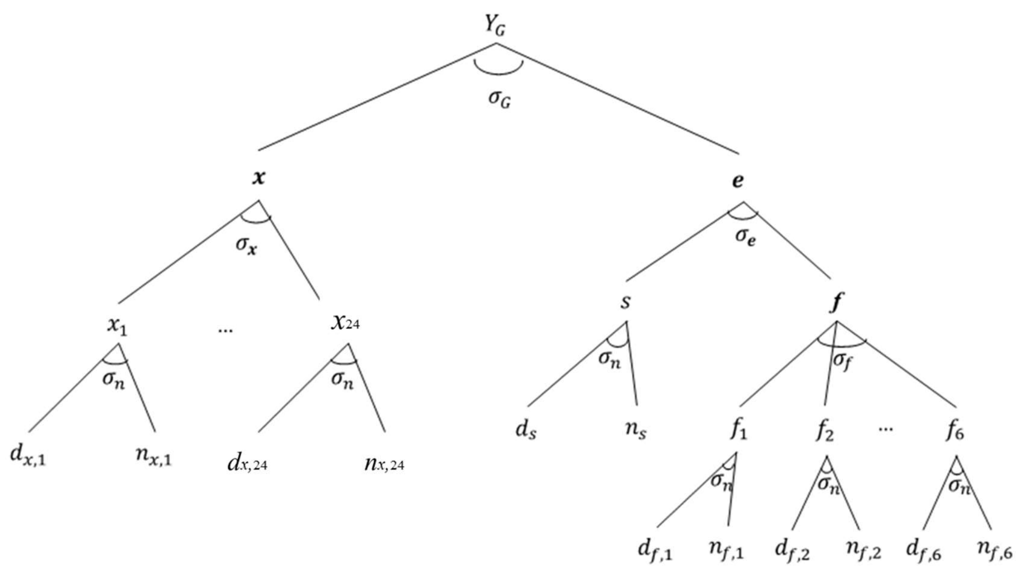


Figure A8. Nested Structure for Government Spending

The government's budget balance is:

$$p_G \overline{Y_G} = R - T - I_G \tag{A29}$$

where the left side is the expenditure on public consumption, and the right side is the total tax revenue *R* (consists of output taxes, intermediate demand taxes, factor taxes, and final demand taxes) minus transfer income to household *T* and public saving I_G.

The transfer *T* is endogenously determined by the government's budget balance requirement. Government consumption is set as a fixed share (17%, in 2017) of GDP and is characterized by a CES preference function defined over the material-energy composite. The transfer to households is then endogenously determined by the government's budget balance requirement.

The generalizable CES function form in Equation (A2) applies to all nests in the government demand structure. For example, the top level is expressed by

$$Y_G = \left[\alpha_{x_G} \boldsymbol{x}_G^{\rho_{xe}} + \alpha_{e_G} \boldsymbol{e}_G^{\rho_{xe}} \right]^{\frac{1}{\rho_{xe}}} \tag{A30}$$

where Y_G, $\boldsymbol{x}_G$, and $\boldsymbol{e}_G$ are the government's demand for the final good composite, the material composite, and the energy composite, respectively.

The composite government-provided final good is produced at minimum cost. The minimum cost problem has the same form as that of the cost-minimization problem for the outputs of the model's various sectors. Hence the generalizable form in Equation (A11) applies to the government's composite good. For example, the composite price of the final good is expressed as:

$$p_G = \left[\alpha_{x_G}^{\sigma_{xe}} p_{x_G}^{1-\sigma_{xe}} + \alpha_{e_G}^{\sigma_{xe}} p_{e_G}^{1-\sigma_{xe}} \right]^{\frac{1}{1-\sigma_{xe}}} \tag{A31}$$

where p_G, p_{x_G}, and p_{e_G} are the price of the final composite, the material composite, and the energy composite, respectively.

Parameters

Most elasticities employed in the production and utility functions are adopted from the GTAP database (Aguiar *et al.*, 2019), the MIT-EPPA model (Chen *et al*., 2017), the RTI-ADAGE model (RTI International, 2015), the DIEM model (Ross, 2014), and literature (Cossa, 2004; Hertel *et al.*, 2007; Hertel & Mensbrugghe, 2019; Jomini *et al.*, 1991). Values for these parameters are presented in Table A5.

Table A5. Elasticities

Parameter	Source	Values[1]
Production elasticities		
σ_r	Calibrated	Solar: 0.27; Wind: 0.28; Hydro, Nuclear: 0
σ_{xemw}	GTAP, EPPA, RTI-ADAGE, DIEM	0
σ_{emw}	EPPA	0.40
σ_e	Cossa (2004), RTI-ADAGE	Non-ELEC: 0.50; ELEC: 0.10
σ_f	Cossa (2004), RTI-ADAGE	Non-ELEC: 1.00; ELEC: 0.10
σ_{mw}	Jomini *et al.* (1991)	AGR: 0.24 COL, OIL, GAS, OMN: 0.20 FBT: 1.12 SER: 1.36 TRN: 1.48 Other sectors: 1.26
σ_x	GTAP, EPPA, DIEM	0
σ_n	Hertel *et al.* (2007)	OMN: 1.80 CON, TRN, SER: 3.80 OIL: 4.20 AGR: 4.84 FBT: 5.09 CMT, OTHNMP: 5.80 WTR, GDT, ELEC, HEAT: 5.60 PAP, IAS: 5.90 COL: 6.10 TEM: 6.31 CHP: 6.60 LOG: 6.80 TXT, MTP, OEM: 7.50 CLO: 7.63 GEM: 8.10 ALU, OTHNFM: 8.40 ELQ: 8.80 CRU: 10.40 GAS: 16.00
σ_{ds}	GTAP	Same as σ_n
Consumption elasticities		
σ_{xs}	GTAP	0
σ_s	DIEM	0.7
σ_f	DIEM	0.5
σ_x	GTAP	Household consumption: 1.00 Government consumption, investment: 0
Transformation elasticities[2]		
σ_w	GTAP	1.5 for capital, $+\infty$ for labor
σ_{w_k}	GTAP	3 for capital, $+\infty$ for labor

[1] We assume the elasticities are the same across subsectors within a sector.

[2] σ_w represents the factor transformation elasticities between sectors; σ_{w_k} represents the factor transformation elasticities between subsectors within a sector.

The parameters for the model's dynamics include the growth rate of effective labor, the rate of autonomous energy efficiency improvement, the saving rate, the reproducible capital depreciation rate, and the interest rate. Values for these parameters are displayed in Table A6.

The growth of capital derives from savings decisions. The saving consists of private savings and government savings. Private savings are assumed to be a fixed fraction of total after-tax household income, and public savings are specified as a fixed share of government income. Public savings takes account for about 5% of total savings in China, according to Zhang *et al.* (2018). We use this information and the total investment data from the China IO table to calculate private and public savings in the base year (2020). We calculate the two savings rates so that the resulting public and private savings match the data of the base year. For the following years, we assume the private saving rate decreases from 42% in 2020 to 32% in 2035 according to the projection by the People's Bank of China (2021). The public saving rate is assumed to remain constant at the level of 15%.

The total savings are used to buy the investment goods. The real investment level in period t is thus determined by the total savings and the unit price of the investment goods. The growth of capital from period t to $t+1$ is calculated as the investment of period t net of depreciation during period t. We apply a depreciation rate of 5% per year according to Herd (2020). The capital stock of the base year (2020) is adopted from Holz & Sun (2018).

The model incorporates technological progress. We assume a 0.7% annual autonomous energy efficiency improvement rate (AEEI) for production sectors but energy production sectors following Duan *et al.* (2014). The energy production sectors (Oil refinery, Coal, Natural Gas, Gas manufacture & distribution, Electricity) are unique in that they convert fossil fuel to produce other energy products. We assume zero AEEI rates in these sectors.

The model also considers the cost reduction of wind electricity and solar electricity and assumes Hicks-neutral technological change. Currently, wind and solar electricity have higher unit cost than fossil-based electricity. Therefore, China's government gives them subsidies to lower the unit cost of wind and solar electricity to a comparable level of conventional generation technologies, i.e., fossil-based electricity. We obtain the subsidy rates from Direct Trading Pilots of Green Power[37]. The model assumes technological progress in the production of wind- and solar-powered electricity generation through an exogenously specified productivity factor. This factor is calibrated to be 1 in the base year 2020. It linearly increases to 1.56 (= 1/(1-36%)) for wind and solar electricity by 2035, respectively, as the unit cost is projected to decrease by 36% according to IRENA (2019a, 2019b). Correspondingly, the subsidies are projected to decrease, too. Studies have projected that these existing subsidies will decrease to zero before 2025 (Tu *et al.*, 2019; Zhang *et al.,* 2021). Therefore, we assume the subsidy rates for wind and solar electricity will decrease linearly to zero in 2025.

We also incorporate important structural changes in China in the calibration of the reference scenario, i.e., the sectoral transition towards the service sector. This structural change is the result of differences in factor productivity growth between the service sector and other sectors. The manufacturing sector is projected to have the highest productivity growth rate while the service sector has the lowest, due to sector-biased technological change (Święcki, 2017). The lowest factor productivity growth rate in the service sector implies it would need more factor inputs per unit output, and as a result, driving factors to flow from industrial sectors to service sectors (Święcki, 2017). We use a multiplier on the factor input in the service sector to simulate this structural change and calibrate it to match the projection by the State Information Center (2020). During 2020-2035, the share of agriculture, industry, and service sector in GDP is calibrated to change from 7%, 37%, and 56% to 6%, 30%, and 64%.

[37] According to the statistics from Direct Trading Pilots of Green Power, the wind and solar electricity has a price markup of around 0.03-0.05 yuan/kWh over fossil fuel electricity, which implies an existing subsidy to the renewable electricity of about 8-13%. Therefore, in this study, we assume the pre-existing subsidy on wind and solar electricity to be 10%.

Table A6. Sources and values of dynamic module parameters

	Value	Method/Reference
Effective labor annual growth rate	Average level 3% /year	Calibrated
Autonomous energy efficiency improvement rate	0 for the energy production sectors 0.7% for other sectors	Duan *et al.* (2014)
Household saving rate	42% in 2020 and decreases to 32% in 2035 linearly	People's Bank of China (2021)
Government saving rate	15% and fixed over time	Calibrated
Factor productivity for wind and solar electricity	1-1.56 for wind and solar	IRENA (2019a, 2019b, 2020)

Appendix C. Method for Modeling the Allowance Auction

We assume that the auction price equals the market price of allowance. When the auction starts, each firm receives some free allowances according to their corresponding "benchmarks", which are lower than the benchmarks in the central case. Let the total number of allowances introduced under the TPS without auctioning in a given period be *N*. We consider a scenario in which some fraction *a* of *N* are auctioned.

In the cases with auctioning, we have two conditions to meet, each of which requires one scalar.

- The economy-wide emissions match the central case TPS. For this condition, we have a common factor for auctioned allowances and the benchmark-determined allowances.
- The share of auctioned allowances in total allowances equals *a*. For this condition, we have an additional scalar for auctioned allowances.
  The solver iterates on the two scalars until both conditions are met.

The specifics on the implementation of the different types of revenue recycling are as follows:

Case 5a:

All of the auction revenue is recycled as output subsidies for wind and solar electricity production. This is done by adding output subsidies (*s'*) to the wind- and solar-electricity generators so that the additional subsidies given to the wind- and solar- generators equal the auction revenue. Equation (A32) is the equation that determines this output subsidy rate *s'*. p_{elec} is the electricity price and *y* are the output of solar and wind electricity.

$$(p_{elec}y_{solar} + p_{elec}y_{wind}) \times s' = t \times A \tag{A32}$$

Case 5b:

Fifty percent of the auction revenue is recycled as output subsidies for wind and solar electricity production, and the other 50% is recycled as lumpsum transfer to households. This is modeled by adding two additional conditions: (1) a lumpsum transfer to the representative households that equals half of the auctioned revenue, and (2) adding output subsidies (*s'*) to the wind- and solar-electricity generators so that the additional subsidies given to the wind- and solar- generators equal half of the auction revenue.

Case 5c:

Fifty percent of the auction revenue is recycled as output subsidies for wind and solar electricity production, and the other 50% is recycled as lumpsum transfer to sectors that are hit most, which are the coal and mining sectors. This is modeled by adding two additional conditions: (1) a lumpsum transfer to the capital owners of the coal and mining sectors that equals half of the auctioned revenue, and (2) adding output subsidies (*s'*) to the wind- and solar-electricity generators so that the additional subsidies given to the wind- and solar- generators equal half of the auction revenue.

Case 5d:

Fifty percent of the auction revenue is recycled as output subsidies for wind and solar electricity production, and the other 50% is recycled as subsidies to capital and labor inputs in sectors that are hit most (the coal and mining sectors). This is modeled by adding two additional conditions: (1) adding subsidies (*s"*) to the capital and labor employed in the coal and mining sectors so that these subsidies add up to be equal to half of the auction revenue, and (2) adding output subsidies (*s'*) to the wind- and solar-electricity generators so that the additional subsidies given to the wind- and solar- generators equal half of the auction revenue.

Appendix D. Imports and Exports Relative to Total Sector Output

Table A7. Import and Export Shares

	Exports and Imports as Percent of Total Sector Output	
	Exports	**Imports**
Clothing	36	4
Electronic equipment	36	23
Printing and stationery	24	3
Log furniture	18	4
Textile	15	5
General equipment	15	16
Transport	14	6
Metal products	12	4
Other manufacturing	11	27
Daily chemicals	9	7
Aluminum	8	1
Raw chemicals	7	14
Transport equipment	7	17
Iron & steel	5	4
Other non-metal products	5	2
Pulp & paper	4	6
Natural gas	4	21
Services	4	3
Food	3	4
Other non-ferrous metal	3	14
Petroleum refining	2	6
Mining	1	63
Agriculture	1	7
Coal	1	12
Crude oil	1	238
Construction	0	0
Cement	0	0
Electricity	0	0

Appendix E. Modeling Allowance Banking

In a market with banking and borrowing, the allowance price path should reflect an intertemporal optimization process that minimizes abatement costs over time, such that the discounted marginal abatement cost is the same across periods.

With banking, instead of an allowance market equilibrium achieved in each period, there is a single equilibrium for the cumulative allowance demand and supply summing over the periods 2020-2035.

Specifically, we incorporate allowance banking in the model following these steps:

a) Intertemporal arbitrage in the allowance market will yield an increase rate of the allowance price that equals the expected rate of return. Therefore, we add one constraint in the model:

$$PC_{t+1} = PC_t(1+r_t) \tag{A33}$$

where r_t is the interest rate. PC_t is the allowance price of period t. The interest rate is endogenously determined by the model, i.e.,

$$r_t = PF_t \cdot \theta / PYI_{t-1} \tag{A34}$$

where PF_t represents the before-tax price of a unit of capital service (capital rent) of period t, PYI_{t-1} represents the before-tax price of a unit of new capital (i.e., a unit of investment) at time t-1. Note that we calibrate PF_t and PYI_{t-1} to be 1 in benchmark data. θ is the ratio of units of capital services to capital goods in the benchmark data which has a value of 5%.

b) We posit an initial allowance price PC_0. Given the posited allowance prices and the equation above, we let the model solve in each period for the supplies and demands for allowances by covered facilities in each sector. Supply in period *t* can be determined by the allowance allocations in that period. Demand in period *t* can be determined as a function of the allowance price and the marginal cost of abatement.in that period. In our policy simulations, we assume the same benchmarks are used in the cases with and without allowance banking. In general, in a given period, the supplies and demands will not be equal.

c) Calculate the cumulative supply and demand for allowances at the end of the last period (the year 2035). Let cumulative net demand (CND) refer to cumulative demand minus cumulative supply.

d) If CND is positive (negative), posit a new higher (lower) PC_0, and calculate again to get the new CND.

e) Repeat steps 2-4 until the CND is approximately zero in the final period. We use Newton's method for iteration.

f) Calculate and check the CND in each period. The TPS policy in China only allows for banking but not borrowing. Therefore, it is inconsistent with the reality that in any period there is a negative CND. Fortunately, negative CND doesn't happen in our simulation.

Appendix References

Aguiar, A., Chepeliev, M., Corong, E., & van der Mensbrugghe, D. (2019). The GTAP Data Base: Version 10. *Journal of Global Economic Analysis*, *4*(1), 1–27.

Chen, Y.-H. H., Paltsev, S., Reilly, J. M., & Karplus, V. (2017). *The MIT Economic Projection and Policy Analysis (EPPA) Model: Version 5* (Joint Program Technical Note TN #16, p. 32p).

Cossa, P. F. (2004). *Uncertainty analysis of the cost of climate policies* [PhD Thesis]. Massachusetts Institute of Technology.

Duan, H.-B., Zhu, L., & Fan, Y. (2014). Optimal carbon taxes in carbon-constrained China: A logistic-induced energy economic hybrid model. *Energy*, *69*, 345–356.

Herd, R. (2020). *Estimating Capital Formation and Capital Stock by Economic Sector in China: The Implications for Productivity Growth*. World Bank, Washington, DC.

Hertel, T., Hummels, D., Ivanic, M., & Keeney, R. (2007). How confident can we be of CGE-based assessments of Free Trade Agreements? *Economic Modelling*, *24*(4), 611–635.

Hertel, T., & van der Mensbrugghe, D. (2019). Chapter 14: Behavioral Parameters (Center for Global Trade Analysis). *Purdue University, West Lafayette, IN: Global Trade Analysis Project (GTAP).*

Holz, C. A., & Sun, Y. (2018). Physical capital estimates for China's provinces, 1952–2015 and beyond. *China Economic Review*, *51*, 342–357.

IRENA. (2019a). *Future of Solar Photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects* (A Global Energy Transformation: Paper). International Renewable Energy Agency.

IRENA. (2019b). *Future of wind: Deployment, investment, technology, grid integration and socio-economic aspects* (A Global Energy Transformation: Paper). International Renewable Energy Agency.

IRENA. (2020). *Renewable Power Generation Costs in 2019* (p. 144). International Renewable Energy Agency.

Jomini, P., Zeitsch, J. F., McDougall, R., Welsh, A., Brown, S., Hambley, J., & Kelly, J. (1991). SALTER: A General Equilibrium Model of the World Economy, vol. 1, Model Structure. *Database and Parameters, Industry Commission, Canberra*.

Lu, M., Zhu, R., & Lu, W. (2015). Optimization of material structure in converter steelmaking. *Chinese Journal of Engineering*, *S1*, 70–73.

Medium and long-term goals, strategies, and paths of China's economic and social development. (2020). The State Information Center.

People's Bank of China (PBC). (2021). *Research on the calculation of China's potential output and growth momentum during the 14th Five Year Plan Period*. No.2021/1 PBC Working Paper.

Ross, M. T. (2014). *Structure of the Dynamic Integrated Economy/Energy/Emissions Model: Computable General Equilbrium Component, DIEM-CGE.* (NI WP 14-12).

RTI International. (2015). *The Applied Dynamic Analysis of the Global Economy (RTI ADAGE) model* (U.S. Regional Module Final Release). RTI International.

Święcki, T. (2017). Determinants of structural change. *Review of Economic Dynamics*, *24*, 95–131.

Tu, Q., Betz, R., Mo, J., Fan, Y., & Liu, Y. (2019). Achieving grid parity of wind power in China – Present levelized cost of electricity and future evolution. *Applied Energy*, *250*, 1053–1064.

Zhang, D., Rausch, S., Karplus, V. J., & Zhang, X. (2013). Quantifying regional economic impacts of CO2 intensity targets in China. *Energy Economics*, *40*, 687–701.

Zhang, L., Du, Q., & Zhou, D. (2021). Grid Parity Analysis of China's Centralized Photovoltaic Generation under Multiple Uncertainties. *Energies*, *14*(7), 1814.

Zhang, M. L., Brooks, M. R., Ding, D., Ding, H., He, H., Lu, J., & Mano, R. (2018). *China's high savings: Drivers, prospects, and policies*. International Monetary Fund.