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CHINA'S NATIONWIDE CO2 EMISSIONS TRADING SYSTEM: A GENERAL EQUILIBRIUM ASSESSMENT

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ABSTRACT

China’s recently launched CO2 emissions trading system, already the world’s largest, aims to contribute importantly toward global reductions in greenhouse gas emissions. The system, a tradable performance standard (TPS), differs importantly from cap and trade (C&T), the principal emissions trading approach used in other countries. This paper presents the structure and results from a multi-sector, multi-period equilibrium model tailored to evaluate China’s TPS. The model incorporates distinctive features of China’s economy, including state-owned enterprises and electricity market regulation. It distinguishes between the TPS and C&T and considers a wide range of potential future TPS designs.

Key findings include the following. The TPS’s environmental benefits exceed its costs by a factor of five when only the climate-related benefits are considered and by a significantly higher factor when health benefits from improved air quality are included. The TPS’s interactions with China’s fiscal system substantially affect its costs relative to those of C&T. Employing a single benchmark (standard) for the electricity sector would lower costs by 34 percent relative to the four-benchmark system that is actually in place but increase the standard deviation of percentage income losses across provinces by more than 60 percent. Introducing an auction as a complementary source of allowance supply can lower economy-wide costs by at least 30 percent.

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A data appendix is available at http://www.nber.org/data-appendix/w31809

1. Introduction

China has launched an ambitious nationwide program to reduce emissions of carbon dioxide (CO_2) and address climate change. Introduced in 2021, the program has already become the world's largest emissions trading system. It is expected to make a major contribution toward halting aggregate emissions growth by 2030 and achieving net-zero CO_2 emissions before 2060.

The new system is a tradable performance standard (TPS), a system in which compliance depends on a covered facility's emissions intensity. In every compliance period, each covered facility receives from the government a certain number of emissions allowances based on its output and the government's assigned "benchmark" ratio of emissions per unit of output. In general, the benchmarks are set below the average initial emissions intensities across the covered facilities, which implies that the TPS will require an overall reduction in the emissions-output ratio.

China's TPS is an example of an output-oriented emissions intensity standard, as it imposes a ceiling on the ratio of emissions to output.[1] It can be contrasted with an input-oriented rate-based standard, which imposes a floor on the ratio of "clean" (low-polluting) to "dirty" (high-polluting) inputs to production. Examples include low-carbon fuel standards, which have been introduced in several US states, and renewable portfolio standards, which establish a floor on the ratio of renewables-generated to fossil-generated electricity purchased by electric utilities. These standards implicitly subsidize the cleaner inputs and tax the dirtier ones.[2]

China's TPS includes provisions under which covered facilities may trade emissions allowances. Such trades alter the distribution of abatement efforts across

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[1] Fischer (2001) offered a seminal theoretical study of the efficiency properties of TPS. Subsequent studies examining potential or actual rate-based climate policies in the US (include Fischer *et al.*(2017), Bushnell *et al.* (2017), Zhang *et al.* (2018), and Chen *et al.* (2018)). Recent studies of China's TPS include Pizer & Zhang (2018), Goulder *et al.* (2022), Wang *et al.* (2022), and Karplus & Zhang (2017).

[2] Studies of low-carbon fuel standards include Holland *et al.*(2009), Holland *et al.*(2015), and Bento *et al.* (2020). Analyses of renewable portfolio standards include Fischer (2010), Fischer & Preonas (2010), and Bento *et al.*(2018). A close cousin to a renewable portfolio standard is a clean electricity standard, which imposes a floor on the ratio of "clean" electricity to fossil-generated electricity used by utilities, where "clean" may include energy from nuclear power plants as well as renewable sources. Goulder *et al.*(2016) and Borenstein & Kellogg (2022) examine such standards. Fullerton & Metcalf (2001), Fischer& Newell (2008), Goulder & Parry (2008), Parry *et al.*(2016), Fischer *et al.*(2017), Metcalf (2019) and Dimanchev & Knittel (2020) survey the efficiency attractions and limitations of a wide range of climate policy instruments, including intensity standards and cap and trade.

facilities and bring about more abatement efforts by facilities that can achieve emissions reductions at the lowest cost. In this respect, the TPS shares a key feature of cap and trade (C&T), the principal type of emissions trading program used in other countries.

However, a TPS differs from C&T in important ways. Under C&T, a covered facility's compliance is based on the absolute quantity of its emissions over the compliance period. This quantity must not exceed the facility's allocated emissions allowances, an amount that usually is exogenous from the covered facility's perspective.[3] In contrast, under the TPS's intensity-based approach, the number of allowances granted to a covered facility is endogenous: it is the product of the facility's assigned benchmark and its chosen level of output. This intensity-based allocation method offers the covered facility just enough allowances to justify the emissions it would generate if its actual emissions-output ratio matched its benchmark. The endogeneity of the allowance allocation is an important difference from C&T -- a difference with important implications for the costs of achieving the nation's overall emission-reduction targets and the distributional impacts.

This paper presents the structure and results from a multi-sector, multi-period general equilibrium model designed to evaluate China's new effort. We apply the model to assess the TPS's impact on output levels, production costs, prices, and CO_2 emissions over the interval 2020-2035.

The model has several distinguishing features that enable it to identify economic forces and outcomes that have received relatively little prior recognition. First, it pays close attention to the structure and compliance obligations of China's TPS. Much of the earlier literature on China's emissions trading system did not consider the significant differences between the TPS and C&T. While some relatively recent studies of China's nationwide climate policy efforts recognize these differences[4], this paper makes a further contribution by considering how institutional and regulatory features of China's economy influence the outcomes of the TPS and C&T. These features include the administered pricing of some electricity output, supporting policies for renewable electricity, pre-existing taxes and subsidies, and the preferential treatment of state-owned enterprises

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[3] A few C&T systems include provisions for output-based allocation, in which case a facility's allowance allocation is connected to the facility's chosen level of output and thus is endogenous.

[4] See, for example, Geng & Fan (2021), Goulder *et al.*(2022), IEA (2022), Ma & Qian (2022), Wang *et al.* (2022), Yu *et al.*(2022), and Zhang *et al.*(2023).

(SOEs). The paper shows that these features influence the TPS's costs and the differences between its costs and those of C&T.

Second, the model employs a general equilibrium framework, which enables it to consider interactions among sectors covered by the TPS as well as between the covered and uncovered sectors. Earlier studies examining China's TPS have tended to employ partial equilibrium models.[5] We are aware of only one general equilibrium model that studied China's TPS: Yu *et al.* (2022).[6] Our model differs from that model in several ways. In addition to incorporating the institutional and regulatory features just described, it employs plant-level data, enabling it to account for heterogeneous production technologies within sectors and to consider the TPS with multiple benchmarks within each covered sector – consistent with the actual design of China's TPS. In addition, while Yu *et al.* focus only on the first phase of China's TPS, when it covers only the electricity sector, our analysis also considers the later phases during which coverage extends to several other sectors.

Third, the model is intertemporal, so it can capture changes in policy stringency and impacts over time. The few existing TPS studies that incorporate intertemporal dynamics tend to focus on individual sectors.[7] Our model's dynamic general equilibrium framework can assess how the absolute and relative costs of the TPS and C&T change over time with the changes in sector coverage and policy stringency.

Finally, the model has considerable flexibility in terms of the range of future TPS policy designs it can examine, dimensions that have not been comprehensively analyzed in the prior literature. These include alternative specifications for the variation and average stringency of benchmarks and the introduction of allowance auctioning. Although China has already introduced the first phase of the TPS, the Ministry of Environment and Ecology (MEE) – the ministry responsible for the design and implementation of the program – is continuing to make important decisions about the design of later phases. The model can incorporate the alternative potential policy designs,

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[5] The partial equilibrium studies include Geng & Fan (2021), Goulder *et al.*(2022), IEA (2022), Ma & Qian (2022), Wang *et al.*(2022), and Zhang *et al.*(2023).

[6] Lin & Jia (2019), Jin *et al.* (2020), and Wu *et al.* (2022) assess the general equilibrium impacts of a nationwide emissions trading system in China. However, the systems considered in these studies are C&T rather than a TPS.

[7] See, for example, Becker (2020) and Yu *et al.*(2022).

which have differing implications for aggregate costs, their distribution across sectors and regions, and the scale of emissions reductions. The flexibility makes this model poised to offer important policy recommendations for China's continually evolving carbon emissions trading system.

The results from our analysis yield several insights into the potential impacts of China's new nationwide climate policy effort. First, we find that the TPS's environmental benefits are likely to be well above its economic cost. Our central estimate is that the climate-related benefits from the TPS's emissions reduction over the interval 2020-2035 would exceed its cost by a factor of more than five. Taking account of the health benefits from improved local air quality increases the TPS's benefit-cost ratio to 26.[8] These ratios apply when we employ the Biden administration's estimates of the "social cost of carbon" (SCC) -- the discounted climate-related benefit from an incremental reduction in CO_2 emissions. Recent studies obtain considerably larger estimates of the SCC. Employing these estimates yields considerably higher benefit-cost ratios.[9]

Second, the planned stringency of China's TPS is less than the efficiency-maximizing level. Efficiency maximization requires that marginal abatement cost equal marginal environmental benefit. Our results indicate that over the interval 2020-2035, the average discounted marginal cost of abatement[10] is well below the central estimates by the Biden Administration of the marginal benefits from emissions abatement undertaken during this interval, as expressed by the SCC. With the Biden administration's SCC estimates, efficiency maximization would call for the use of benchmarks that are nine

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[8] The climate-related benefits from CO_2 reductions range from 6 trillion to 43 trillion RMB under a plausible range of values for the SCC, model parameters, and policy stringency over the 2020-2035 interval. When health co-benefits are considered, the TPS's total environmental benefits range from 19 to 122 trillion RMB, with 53 trillion RMB as the central estimate. This compares with economic costs of 1-3 trillion RMB under the same range of model parameters and policy stringency. We offer details in Section 6.3.

[9] The recent study by Rennert *et al.* (2022) estimates the SCC (evaluated in 2020) to be 1,277 RMB (185 US dollars) per ton of CO_2; Carleton and Greenstone (2022) suggest using 863 RMB (125 US dollars) per ton of CO_2. These recent estimations are much higher than the Biden administration's central estimate of 353 RMB (51 US dollars) per ton.

[10] We obtain the economy-wide marginal cost by evaluating the cumulative economy-wide cost from an incremental tightening of benchmarks relative to their values under the TPS in the central case. Specifically, the average marginal cost per ton is the present value of cumulative change in GDP over the 2020-2035 interval divided by the associated cumulative change in emissions relative to the baseline, using an annual discount rate of 5%. Note that the economy-wide marginal cost of abatement is different from the marginal abatement cost of individual covered facilities (or the allowance price, under assumptions of pure competition and a perfectly functioning allowance market), since emissions reductions achieved by covered facilities affect prices and input costs to non-covered firms.

percent tighter than the current and planned benchmarks under the TPS. Using the efficiency-maximizing benchmarks would lead to emissions reductions over the interval 2020-2035 twice as large as what seems likely to result from the current and projected benchmarks over this interval. Using the higher SCC estimates from recent studies would call for still greater stringency and associated emissions reductions.

Third, the relative costs of the TPS and an equivalent C&T system change significantly over time. In the early years, the TPS's costs are only slightly higher than those of an equivalently stringent C&T system, but its cost disadvantage becomes more significant over time. We identify three factors that explain this pattern, two of which have not been previously recognized. A first factor, recognized in prior literature, alludes to the TPS's method for allowance allocation. The TPS implicitly subsidizes intended output, since covered facilities receive free allowances for each additional unit of production. The implicit subsidy causes covered firms to rely too little (from an efficiency point of view) on output reduction to achieve compliance, as reducing output implies a reduction in the allowance allocation. This factor handicaps the TPS relative to C&T, which includes no such subsidy. This paper reveals two additional and significant determinants of the TPS's absolute costs and its costs relative to those under C&T. First, the TPS's excess cost over C&T increases with the stringency of the emissions-reduction target. Increased stringency leads to higher allowance prices and, as shown below, the higher allowance prices give greater importance to the TPS's implicit subsidy. This explains the observed growing gap over time in the TPS's aggregate abatement cost relative to the aggregate cost under C&T as stringency increases and allowance prices rise. Second, we find that the relative costs also depend on the extent of pre-existing taxes on capital, labor, and intermediate inputs. Both the TPS and C&T give rise to higher output prices by raising private production costs. The higher output prices exacerbate the economic distortions associated with these pre-existing taxes – this is the "tax-interaction" effect that has been examined in prior theoretical and empirical literature.[11] But the TPS's implicit output subsidy leads to smaller increases in output prices than those occurring under C&T. As a result, the adverse tax-interaction effect is smaller under the TPS than under C&T. This offsets what otherwise would be a larger

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[11] Lee and Misiolek (1986), Oates (1995), Bovenberg & Goulder (1996), Parry (1997), Goulder et al. (1997), Fullerton & Metcalf (2001), Williams (2002), and West & Williams (2007).

disadvantage of the TPS in terms of cost-effectiveness. We find that this offset is quantitatively important. In the shorter term, it eliminates almost all of the gap in costs that otherwise would apply.

Fourth, supplying some allowances under the TPS via an auction can lower the economic costs of achieving given emissions-reduction targets.[12] Our central estimate is that introducing an allowance auction would lower economy-wide costs by 30-43 percent relative to the no-auction case, depending on how auction revenues are recycled. Including auctioning lowers costs for two reasons. First, because allowance allocation via auction does not involve an implicit output subsidy, the distortionary cost of the emissions trading system is lowered the larger is the contribution of auctioning to the system. Second, the revenue from the auction can be recycled in ways that lower costs further. The cost-reduction is especially large when the auction revenue is used to finance cuts in pre-existing capital and labor tax rates. This lowers the distortionary effects of pre-existing labor and capital taxes on production decisions. Over the 2020-2035 simulation interval, such revenue-recycling reduces costs by 18 percent relative to a scenario where the revenue is returned in a lump-sum fashion. Introducing an auction also affects the sectoral distribution of output and profit. Using auction revenue to finance subsidies for wind- and solar-generated electricity leads to a significant increase in the market penetration by renewables-based electricity. And devoting the revenues toward compensation to the coal and mining sectors (which otherwise would suffer the largest profit losses) can fully offset what would otherwise be the TPS's adverse profit impact.

Fifth, the simulation results reveal important trade-offs between cost-effectiveness and distributional equity. Although distributional concerns can be addressed through the use of varying benchmarks, greater benchmark variation raises aggregate costs by widening the disparities in the marginal costs of production. The TPS currently in place has four different benchmarks for the electricity sector, and it is plausible that this will continue to be the case for this sector over the rest of the 2020-2035 interval. We find that employing a single benchmark for this sector over this interval would lower economy-

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[12] Strictly speaking, the system is no longer a TPS once an auction is introduced, because a covered facility's compliance will no longer depend on achieving its assigned emissions-output ratio. Rather, compliance will require that its total emissions not exceed the *level* of emissions authorized by its total allowance holdings – the sum of the allowances received free as a function of the prescribed benchmark and the allowances purchased at the auction or on the trading market.

wide costs by 34 percent relative to those in the four-benchmark case. At the same time, the one-benchmark case increases the standard deviation of percentage income losses across provinces by more than 60 percent.

The rest of this paper is organized as follows. Section 2 describes the basic features of the TPS and provides a simple analytical model of the incentives it yields for covered facilities' choices of inputs, levels of output, and purchases or sales of emissions allowances. Section 3 presents the numerical model's structure, and Section 4 indicates its data and parameters. Section 5 describes the policies examined, and Section 6 presents and interprets the outcomes from policy simulations. Section 7 provides a sensitivity analysis, and Section 8 offers conclusions.

2. The TPS

2.1 Basic Features

The TPS is a rate-based (or intensity-based) emissions trading system. As mentioned, emissions allowances are allocated to covered facilities in proportion to their levels of output. The endogeneity of the allowance allocation is a key difference from C&T – a difference with important implications for output choices, emissions, and economy-wide policy costs.

China's TPS includes provisions for emissions allowance trading within and across sectors. In the absence of provisions for trading, a performance standard would require each covered facility to achieve an emissions-output ratio not exceeding its assigned benchmark. With allowance trading as a possibility, the covered facility's initial allocation of allowances, plus (minus) any allowances it purchases (sells) on the trading market, must be sufficient to justify its emissions during the compliance period. Allowance trading can reduce aggregate costs of lowering emissions by helping to bring marginal abatement costs closer to equality.

The TPS will be introduced in phases. The first began in 2021 and covers only the power sector. The compliance is based on emissions performance in the previous year. In the second phase, which is likely to begin in late 2023 or early 2024, the TPS's coverage will expand to include the cement and aluminum sectors and possibly the iron & steel sector as well.[13] At least one further phase is expected, under which the TPS will expand to cover additional manufacturing sectors. The expected additional sectors are pulp & paper, other non-metal products, other non-ferrous metals, raw chemicals, and petroleum refining.

2.2 Producer Behavior and Efficiency Implications

The following framework indicates how covered facilities minimize costs of compliance under the TPS and C&T. Covered facilities can utilize three channels to minimize costs of compliance: (a) reducing emissions intensity (emissions per unit of output), (b) reducing output supply, and (c) purchasing or selling allowances (allowance trading). We start with a focus on the electricity sector, which faces administered prices for some of the electricity supplied.[14] We then briefly discuss the framework for other sectors, which is simpler because administered prices do not apply.

We assume that firms are price takers in both the product market and allowance trading market.[15] Under the TPS, the profit function π for electricity generators is:[16]

$$\pi_{ELEC}^{TPS} = \overline{p}\,\overline{q} + p(q - \overline{q}) - C(q, e) - t(e - \beta q) \tag{1}$$

where p denotes the market price, q the level of output, C the total cost of production, t the market price of carbon allowances, and β the benchmark. In China's electricity

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[13] At the time of this writing, there remains uncertainty as to whether the iron & steel sector will be covered under Phase 2. The simulations in this paper assume coverage of this sector in that phase.

[14] The structure of the analytical model is similar to that in Goulder *et al.* (2022), a partial equilibrium study of the electricity sector.

[15] There is no evidence suggesting the existence of market power in the national emission trading system. Some studies, e.g., Wang *et al.*, (2021) and Zhu *et al.* (2020), obtained evidence of the limited exercise of market power in the earlier regional pilots programs. We anticipate negligible exercise of market power in the national market in light of the market's greater scope and much larger number of participants.

[16] The profit function could be expressed as a function of input choices denoted by a vector x. That is, expression 2 could be re-written as: $\pi_{ELEC}^{TPS} = pq(x) + (\overline{p} - p)\overline{q} - C(x) - t(e(x) - \beta q(x))$, where emissions and output levels are functions of input choices. In this case the first-order condition with respect to x_i (with i indexing inputs) yields: $\partial\pi^{TPS} / \partial x_i : p\partial q / \partial x_i = C_{x_i} + t(\partial e / \partial x_i - \beta\partial q / \partial x_i)$, which indicates that the marginal benefit of input x_i must equal its marginal cost. Since the $\partial e / \partial x_i - \beta\partial q / \partial x_i$ term in the right-hand side differs across inputs, the TPS induces input substitution. The more emissions-intensive input has a higher $\partial e / \partial x_i$ than a less emissions-intensive one. Hence the TPS causes the low-intensity input's marginal cost (left-hand side) to decline relative to that of a high-intensity input, leading firms to substitute away from the emission-intensive inputs.

market, generators sell a fixed amount of their electricity $\overline{q}$ at a government-administered price $\overline{p}$ and sell the electricity beyond that production level at market prices. The profit function can be rewritten as:

$$\pi_{ELEC}^{TPS} = pq + (\overline{p} - p)\overline{q} - C(q,e) - t(e - \beta q) \tag{2}$$

For sectors other than electricity, outputs are sold at market prices, and thus the profit function is:

$$\pi_{NON-ELEC}^{TPS} = pq - C(q,e) - t(e - \beta q) \tag{3}$$

The number of allowances allocated to the covered facility is βq. Covered facilities with relatively low initial emissions intensities – that is, with intensities below their benchmarks – will receive allocations of allowances in excess of what is needed for compliance. For these facilities $t(e - \beta q)$ is negative. These facilities have incentives to increase output,[17] as this will expand their allowance allocation, giving them additional allowances to sell.

In contrast, the facilities with relatively high initial emissions intensities will have emissions above the levels authorized by their allowances. For these facilities $t(e - \beta q)$ is positive. Such facilities can reduce the costs of allowance purchases $t(e - \beta q)$ by reducing output. Importantly, the fact that reducing output leads to a reduction in allowance allocation means that the firm faces an implicit tax on the reduction in output. As a result, under the TPS the high-intensity facilities tend to exploit output-reduction less than under an equivalent C&T system to reduce emissions. Correspondingly, to achieve compliance these must rely relatively more on reductions in input intensity of production. The numerical results displayed in Section 6 show that the differences between the TPS and C&T in terms of reliance on output-reduction and on reduced input intensities are quite large.

For both electricity generators and firms in other sectors, the first-order conditions with respect to the two decision variables e and q are:

$$\partial \pi^{TPS} / \partial e: \ -C_e = t \tag{4}$$

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[17] Increasing output adds to profit when the increase in output does not raise production cost more than the value of the additional allowances gained.

$$\partial\pi^{TPS} / \partial q: \; C_q = p + \beta t \tag{5}$$

where $-C_e$ and C_q represent the private marginal cost of emissions reductions and production, respectively.[18] Condition 4 indicates that profit maximization requires that the marginal cost of abatement be equated to the marginal benefit of abatement. Condition 5 indicates that the marginal cost of production must equal the marginal benefit of production. The marginal benefit is the price of output plus βt, the increment to profit from selling the β additional allowances generated by a unit increase in output. The βt term is the implicit subsidy to an increase in output under the TPS. This term is also the implicit tax on a reduction in output under the TPS.

Under C&T, the profit function for electricity generators is:

$$\pi_{ELEC}^{C\&T} = \overline{pq} + p(q - \overline{q}) - C(q,e) - t(e - \overline{a}) \tag{6}$$

where $\overline{a}$ denotes the fixed number of allowances allocated to the firm. The difference from the TPS's profit function is in the far-right term, in which the allowance allocation is the exogenous quantity $\overline{a}$. The profit function is equivalent to:

$$\pi_{ELEC}^{C\&T} = pq + (\overline{p} - p)\overline{q} - C(q,e) - t(e - \overline{a}) \tag{7}$$

For non-electricity sectors, the profit function is:

$$\pi_{NON-ELEC}^{C\&T} = pq - C(q,e) - t(e - \overline{a}) \tag{8}$$

The profit-maximizing first-order conditions under C&T for both electricity generators and non-electricity firms are:

$$\partial\pi^{C\&T} / \partial e: \; -C_e = t \tag{9}$$

$$\partial\pi^{C\&T} / \partial q: \; C_q = p \tag{10}$$

Conditions 4 and 9 are identical: under both the TPS and C&T, profit-maximization requires that the marginal cost of emissions equal the allowance price *t*. Conditions 5 and 10 are different, however. In contrast with C&T, the TPS introduces the implicit subsidy to output (or tax on output-reduction) βt. For any given allowance

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[18] Despite the presence of administered pricing of electricity, only market price *p* appears in equation (5) because the marginal output of electricity is sold at market prices.

price, the subsidy gives firms incentives for higher output than under C&T. It is straightforward to show that the first-order conditions of the C&T match those of a social planner (Tietenberg, 1985), whereas the TPS encourages output levels above the socially optimal level.[19] Correspondingly, the TPS does not make sufficient use of output-reduction as a channel for achieving compliance and instead relies excessively (from the perspective of cost-effectiveness) on reductions in emissions intensities. This underlies the lower cost-effectiveness of the TPS relative to C&T.[20]

The size of the cost-disadvantage of the TPS depends on the variation of benchmarks. Higher variation leads to greater differences in the implicit output subsidy, which in turn tends to cause greater variation in the marginal cost of production across firms. This leads to a further sacrifice of cost-effectiveness. As noted above, the TPS's disadvantage in terms of cost-effectiveness is mitigated by pre-existing taxes on factors and other production inputs. Owing to its implicit output subsidy, the TPS leads to smaller increases in output prices compared to an equivalently stringent C&T system. Consequently, the distortions stemming from these pre-existing taxes are smaller under the TPS, and the associated cost-effectiveness disadvantage is smaller.

Notwithstanding its disadvantages in terms of cost-effectiveness, the TPS has certain attractions relative to C&T. First, it would likely give rise to lower emissions leakage. The implicit output subsidy under the TPS leads to smaller increases in the prices of the output of the covered facilities than under C&T. As a result, the TPS induces a smaller shift in demand toward the output of firms in the non-covered industries and less associated leakage. Second, the fact that allowance allocation under the TPS is endogenous to the level of output makes it responsive to macroeconomic conditions. When the economy is booming (contracting) and levels of production increase (decrease) in response to the demand, the number of allowances allocated automatically increases (decreases), helping moderate the potential changes in the allowance price. Third, the TPS's rate-based structure capitalizes on China's historical experience with intensity-based environmental regulation.

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[19] However, with pre-existing distortionary taxes, the first-order conditions for private cost minimization under C&T will not match the social planner's cost-minimization conditions. See, for example, Bovenberg and Goulder (1996).

[20] See, Fischer (2001) and Goulder *et al.* (2022) for further discussion of the significance of the implicit output subsidy.

3. The Numerical Model

3.1 Main Features

The multi-sector dynamic computable general equilibrium (CGE) model developed for this study enables us to consider a range of economic factors that determine the TPS's cost-effectiveness and distributional outcomes. As Figure 1 shows, the model captures the interactions among China's production, household, and government sectors. Representative firms in each of the 31 production sectors employ inputs of primary factors (capital, labor, and natural resources) along with intermediate inputs (energy and material goods) to produce goods for the domestic market and export. A representative household earns income from returns to the factors of production and devotes that income to consumption and savings. The government receives tax revenues that are devoted to government consumption, public savings, and transfers to households. Private and public savings finance investment. The final demand for goods and services consists of household consumption demand, public and private investment demand, and the government's demand for goods and services. The model also incorporates emissions allowance trading. For each year in the interval 2020 through 2035, it solves for the equilibrium factor prices and allowance prices as well as the prices of all produced goods.

A distinguishing feature of this CGE model is its recognition of the heterogeneity in production methods within sectors. Here it exploits information from a unique firm-level dataset on emissions, output, and energy use obtained from the MEE. This enables the model to analyze the impacts of the national emissions trading system on firms of different emissions intensities within a given sector.

The model considers several of the important government interventions in the market. These include various taxes on inputs and outputs, the administered pricing of some of the electricity supplied, subsidies targeted towards renewable electricity, and the favored treatment of SOEs.

3.2 Production

Here we briefly describe the structure of the production system. Details are provided in Appendix A.

3.2.1 Primary Factors

The primary factors are labor, capital, land, and "natural resources". Labor and capital are employed in production in all sectors. Labor is perfectly mobile across sectors. Capital is imperfectly mobile: there are costs to its reallocation across sectors or subsectors, or between SOEs and privately owned enterprises (POEs). Land is employed in the agriculture sector only and is not mobile across sectors. Natural resources are directly employed only in wind, solar, hydro, and nuclear electricity production and are not mobile across sectors or subsectors.

3.2.2 Sectors and Subsectors

Table 1 identifies the model's 31 production sectors. The outputs from these sectors divide into two major categories: materials and energy goods. The first 24 outputs in the table are in the first category; the remaining seven in the latter. As indicated below, some sectors subdivide into subsectors.

In the electricity sector, the model distinguishes renewable electricity (solar, wind, and hydro) and nuclear electricity from fossil-based electricity. Within the group of fossil-based electricity generators, the model recognizes heterogeneity across the fossil-electricity plants by distinguishing eleven technology categories. The cement, aluminum, and iron & steel sectors also have subsectors with differing production technologies and associated input intensities. Notwithstanding the differences in input intensities across subsectors, the outputs from subsectors of a given sector are treated as homogeneous and face the same market price. The rationale and method for subsector classifications are offered in Appendix B. Production is represented by nested constant elasticity of substitution (CES) functions. Each sector (and subsector in the electricity, cement, aluminum, and iron & steel sectors) employs material inputs, energy, and factor inputs for production.

3.2.3 State-Owned Enterprises and Administered Pricing

A critical feature of the Chinese economy is the presence of SOEs. These enterprises account for around 31 percent of the value of economy-wide output. SOEs receive favorable treatment relative to POEs through subsidies to their various inputs. They are especially important in the crude oil and electricity sectors, where they account for more than 87 percent of the output value (See Table A10 in Appendix C).

We model the SOEs and POEs as profit-maximizing firms that enjoy subsidies and face taxes. The functional forms of both types of firms are the same, though parameters differ. Both the subsidies and the taxes are regarded as exogenous from the point of view of the firm. SOEs benefit from preferential treatment through input subsidies. Also, individuals employed in SOEs often receive superior benefits, including higher social security payments and pensions.[21] Government-provided transfers defray a significant fraction of the costs of these benefits.

A challenge to the modeling of the SOEs and POEs is their co-existence in specific markets. Despite the SOEs' preferential treatment, which enables them to enjoy lower average costs of production, the SOEs do not take over the markets, as optimal supplies depend on marginal, not average, cost. In the model, marginal costs increase with supply, reflecting the fact that both types of firms rely on imperfectly mobile capital as an input and experience the associated diminishing marginal productivity of production. For a given type of output, both SOEs and POEs choose levels of output that bring their marginal costs up to the prevailing and common output price. Appendix A provides details.

The model incorporates the administered pricing in China's electricity market and the ongoing electricity market reform in China. As equation (2) indicates, in China's electricity market, generators sell a fixed amount of their electricity (the administered electricity) at a government-administered price (usually higher than the market price) and sell the production beyond that at market prices. The model reflects these features through a piece-wise marginal revenue function. For output levels up to the administered quantity, a government-determined price (the administered price) applies. Beyond this quantity, the market price applies. These characteristics will only apply until 2025, as ongoing reform indicates a fully liberalized Chinese electricity market by then. Further details can be found in Appendix A.

3.3 Household Behavior

A representative household's consumption choices reflect its utility maximization subject to a budget constraint. A nested CES utility function governs the allocation of

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[21] Prior literature that provides evidence on these preferential treatment to SOEs include Cull & Xu (2003), Hering & Poncet (2010), Guariglia *et al.*(2011), Song *et al.*(2011), Démurger *et al.*(2012), Hsieh & Song (2015), Berkowitz *et al.*(2017), Harrison *et al.*(2019), Han *et al.*(2021).

consumption expenditure across specific consumer goods.

The household receives income from labor, capital, land, and natural resource rents, and devotes its income to consumption and private savings. Private savings are devoted to investment -- expenditure on an investment good. The savings rate is a positive function of the return on investment.

3.4 Government Behavior

The government sector comprises government behavior at all levels: national, regional, and municipal. The model's taxes include output taxes and subsidies, intermediate taxes and subsidies, factor taxes and subsidies, final demand taxes, import tariffs, export subsidies, and subsidies for wind and solar electricity generation. Government expenditure consists of government savings, public consumption, and transfers to households. Public consumption is set as a fixed share of GDP and is characterized by a CES preference function defined over the material-energy composite. The government must balance its budget in each period. In each period, government transfers are endogenously determined and are adjusted to meet the government's budget balance requirement.

Appendix A offers details of the three CES preference structures for consumption, investment, and government spending, respectively.

3.5 Foreign Trade

The model has a simple treatment of China's trade with the rest of the world (ROW). We regard China as a price-taker on the world market: the foreign-currency prices of imports are exogenous, as are the foreign-currency prices at which exports can be sold. Domestically produced and imported goods in a given sector category are regarded as imperfect substitutes; hence their market prices can differ. Imports and exports quantities are functions of the relative prices of domestic and foreign goods.

The time-profile of international financial capital flows is specified exogenously, based on Ju *et al.* (2021). The exchange rate adjusts each year to equate the value of net exports with the net inflow of international financial capital.

3.6 Equilibrium

The general equilibrium requires supply-demand balance in each period for each factor and produced good. Under policies with emissions allowance trading, the allowance supply and demand must match as well. In each period, these requirements determine (a) the prices for the 31 sectors' produced goods; (b) the wage rate; (c) the pre-tax rental prices of capital, which differ across sectors (as well as subsectors in the electricity, cement, aluminum, and iron &steel sectors); (d) the rental prices of the natural resources employed in the solar, wind, hydro, and nuclear electricity production subsectors, respectively; and (e) the CO_2 allowance price.

3.7 Dynamics

The model solves at one-year intervals from 2020 through 2035.[22] Changes in equilibria from one period to the next depend on the increments to the stocks of labor and capital. There is one aggregate capital stock. The stock in the next period is aggregate real investment in the current period net of depreciation over that period. The stocks of land and the four kinds of natural resources (wind, solar, hydro, and nuclear) are treated as fixed at the base year level.

Technological progress takes two forms: autonomous energy efficiency improvement (AEEI) and Hicks-neutral technological change. In the model, AEEI is an exogenous increase in the productivity of the composite energy input into production. As indicated below, the AEEI rate differs across sectors. Hicks-neutral technological change applies to all sectors and is assumed to have different rates across sectors. These differences across sectors give rise to important structural change in China – in particular, the transition involving increased representation of the service sector (Święcki, 2017) and the increased penetration of renewable electricity. The rates of Hicks-neutral technological change are calibrated to match the projections in the State Information Center (2020) and IRENA (2019a, 2019b). Details can be found in Appendix C.

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[22] The model is solved as a mixed complementarity problem (MCP) with a Newton-based solver.

4. Data and Parameters

4.1 Data

We combine data from several sources to create a consistent database for inputs, outputs, and emissions. China's 2017 input-output table (National Bureau of Statistics, 2018) is the source of data on inputs and outputs of production sectors as well as levels of household consumption, government consumption, and investment. The Global Trade Analysis Project (GTAP 10) database (Aguiar *et al.*, 2019) offers needed information on taxes and subsidies on inputs and goods. CO_2 emissions from production are derived from the sectoral energy use data in the 2017 China energy balance table (National Bureau of Statistics, 2018). We update the input and output data so that the GDP, total CO_2 emissions, value-added shares of the service sector and agriculture sectors, and the total tax revenue net of subsidies match the published statistics in 2020 (National Bureau of Statistics, 2021).

The sectoral data are then disaggregated into subsectors for electricity, cement, aluminum, and iron & steel sectors according to the subsector-level information, which is obtained by aggregating firm-level data. The firm-level data are collected by the MEE, which provides production, fossil fuel energy consumption, electricity usage, heat rate, and CO_2 emissions at the plant level. This plant-level data spans the electricity, cement, aluminum, and iron & steel sectors.

Data on the costs associated with various measures for changing heat rates in fossil-based power plants are obtained from a series of reports by National Development and Reform Commission of China (NDRC, 2016, 2017). Data on the integration costs of renewable electricity at different shares of penetration are obtained from the estimations by Zhang *et al.*(2023).[23] Data related to administered electricity are obtained from the China Electricity Council (CEC, 2019), which offers the quantities and prices of administered electricity for different types of power plants.

Key data pertaining to SOEs and POEs were obtained Chinese Industrial Enterprise Database (NBS, 2017) and literature (Han *et al.*, 2021). The database offers

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[23] Wind and solar electricity generation incurs integration costs, which include grid integration, balancing services, the flexible operation of thermal plants and reserve costs. The integration costs increase as the wind and solar penetration levels rise. See Appendix C for details.

information on SOE and POE's output shares and capital-output ratios in each sector, and Han *et al.*(2021) offer information on the additional subsidies received by the SOEs as compared with POEs.

Data sources and processing steps are detailed in Appendix B.

4.2 Parameters

We make use of the data from the above sources and others to obtain key parameters of the model. Details are offered in Appendix C.

Elasticities of substitution among various fuel inputs are taken from Cossa (2004) and RTI-ADAGE (RTI International, 2015). The elasticities of substitution among various factor inputs are from Jomini *et al.* (1991). The elasticities of substitution between domestic and imported goods are from Hertel *et al.* (2007). Elasticities of capital transformation are taken from the GTAP database (Aguiar *et al.*, 2019).

Additional parameters are obtained through calibration. In general, the input share parameters of production functions are identified by the requirement that the inputs and outputs in each sector in the base year are consistent with the benchmark input-output table. Parameters for the shares of capital inputs in SOEs and POEs are identified by the condition that marginal costs of production are the same at the given market's output price.

In subsectors of the electricity sector, the substitution elasticities between the energy composite and factor composite are calibrated to ensure that, in the baseline simulations, subsector-level marginal costs of reducing the heat rate match points on a separately derived curve for subsector-level costs of reducing heat rates. We derive the separate cost curve from the series of reports by NDRC (2016, 2017), as mentioned in subsection 4.1 above. For renewable electricity production, both the elasticity of substitution between natural resource input and other input, and the share of natural resource input, are calibrated so that the marginal cost (the sum of generation cost and integration cost) at various renewable electricity supply levels matches the marginal cost curve inferred from the estimations by Zhang *et al.*(2023). The substitution elasticities between electricity and non-electricity inputs in all sectors are calibrated to yield a demand elasticity for electricity consistent with empirical evidence in China (Hu *et al.*, 2019). The substitution elasticities between consumption and private savings are calibrated so that the demand elasticity of investment goods matches the empirical evidence (Lian *et al.*, 2020).

The time-profile of effective labor is exogenously specified and set so that the model's GDP growth rate in the baseline scenario is consistent with official projections.[24]

5. Scenarios

We examine the TPS's impacts in its three planned phases. The first began in 2020 and covers only the electricity sector (which accounted for about 43% of China's total CO_2 emissions in 2020). For the future phases, the assumed coverage follows closely the approaches implied by discussions by decision-makers in the MEE and other administrative bodies. The second phase is assumed to begin in late 2023, with the TPS expanding to also cover the iron & steel, aluminum, and cement sectors (which currently account for about 67% of China's CO_2 emissions). The third phase begins in 2026, with coverage expanding further to include the pulp & paper, other non-metal products, other non-ferrous metals, raw chemicals, and petroleum refining industries (which account for nearly 75% of China's CO_2 emissions.[25]

Table 2 indicates the main features of the various policy cases considered. We consider cases that differ in terms of the number and stringency of benchmarks. We also consider cases in which some of the emissions allowances are supplied via auction. Table 3 indicates the benchmark values in these policy cases.

6. Results

6.1 Aggregate Impacts

6.1.1 Emission Reductions

Table 2 indicates the alternative policy cases considered. Case 1 (the central case) aligns most closely with current plans by the MEE in terms of initial benchmark values and rates of benchmark tightening over time.

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[24] These projections are in *Medium and Long-term Goals, Strategies, and Paths of China's Economic and Social Development* (The State Information Center, 2020). We calibrate the model to yield a GDP growth rate of 5.5% in 2020-2025, 4.5% in 2026-2030, and 3.5% in 2031-2035, consistent with these projections.

[25] Other non-metal products include ceramics, bricks, and glasses; other non-ferrous metals include copper and tin; raw chemicals include ethylene, methanol, synthetic ammonia, caustic soda, soda ash, synthetic fiber, and plastic; refined petroleum products include gasoline and diesel fuels.

Figure 2 displays the policy-induced emissions reductions (relative to the baseline) in this case. As indicated in the figure, the reductions in CO_2 emissions become progressively larger as the system's coverage expands and the benchmarks are tightened. The average annual reduction over the Phase 2 interval is about 441 million tons, more than three times the average annual reduction during Phase 1; the average annual reduction over the Phase 3 interval is about 1.9 billion tons, about four times the average annual reduction during Phase 2.[26] In 2035, the emissions reduction is about 20 percent relative to the baseline. Below we show that maximizing net benefits from emissions reductions would call for more stringent benchmarks and associated policy stringency.

In Phase 1, by far the largest changes in emissions are in the covered sector (electricity), where emissions decline annually by about 137 million tons, or three percent from the baseline. Emissions from uncovered sectors increase slightly – by 0.8 million tons annually. This increase mainly reflects the slightly higher use of coal in these sectors because of the lower coal prices stemming from the significant reduction in coal demand by the electricity sector.

Over the entire interval 2020-2035, the cumulative emissions reduction is estimated to amount to 21 billion tons, or 9.7 percent of the cumulative baseline emissions.

Figure 3 shows the covered sectors' relative contributions to emissions reductions over the interval 2020-2035. The largest reductions are from the electricity sector and the sectors added in Phase 2, with the former accounting for 48 percent and the latter collectively accounting for 37 percent of the total. Over the 2020-2035 interval, the TPS gives rise to a small amount of emissions leakage – a slight (0.2 percent) increase in emissions from uncovered sectors, reflecting the aforementioned increase in the demand for coal by these sectors.[27]

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[26] Under China's TPS, the emissions associated with electricity production are priced twice: the electricity sector faces the price of emissions from its generation of electricity, and non-electricity sectors are also charged for the emissions from the generation of the electricity 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 improve electricity-use efficiency because of the free allocation of allowances and the presence of administered prices for some electricity. The simulations in this study incorporate administered pricing and double-counting. The emissions reductions reported are the actual economy-wide reductions.

[27] This includes increased emissions from sectors that are eventually covered during the earlier periods in which they were not yet covered.

6.1.2 Aggregate Costs

1) Impacts under the TPS

Table 4 presents the aggregate costs of the TPS, measured both by the change in GDP and by the equivalent variation measure of the change in household utility. The GDP cost in Phase 1 is relatively small (less than 0.01 percent), but costs expand significantly over time, a consequence of increased benchmark stringency and broader sector coverage. The present value of the GDP cost over the period of 2020-2035 is 2.0 trillion RMB, 0.13 percent of the baseline GDP. When measured via the equivalent variation, the cost is smaller, largely because this measure is based on changes in consumption and disregards the significant declines in investment. The TPS's negative impacts on investment are substantial because the main inputs into the production of the composite investment good are iron & steel and cement, which are emissions-intensive and covered by the TPS. In subsection 6.3 below we compare these costs with estimates of the environmental benefits.

Figure 4 displays the allowance price under the TPS over time in Case 1, under central values for parameters. In 2020, the model-generated allowance price is 58 RMB/ton, close to the observed price in the first compliance period, which is in the range of 40-60 RMB/ton. The rising trajectory of the allowance price reflects the combination of benchmark tightening and broader coverage of the TPS over time.[28]

We have also explored the significance of the SOEs to aggregate costs. To do this, we considered the impact of the TPS in a counterfactual case in which the SOE firms do not receive favorable treatment. The TPS's GDP costs in this case are 0.8 percent higher than that in the case with preferential treatment. This stems from the fact that the distortionary impacts of the TPS's implicit output subsidy are smaller when the SOEs receive favorable treatment. Given that SOEs have lower output supply elasticities than POEs,[29] implementing TPS without SOE's preferential treatment reduces the ratio of SOE to POE output compared to the case with preferential treatment. This lowered ratio

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[28] The slight dip in the price from 2022 to 2023 reflects a short-term reduction in the overall stringency of the TPS during the transition from Phase 1 to Phase 2.

[29] This stems from the fact that SOEs have higher intensities of sector-specific (or subsector-specific) capital input than POEs, which makes it harder for SOEs to adjust their output in response to a change in producer price than POEs. Hence, within the same sector (or subsector), SOEs exhibit lower supply elasticities than POEs.

increases the average supply elasticity in covered sectors. As a result, the distortionary impacts of the implicit output subsidy are larger in the case without preferential treatment, leading to a higher GDP cost.

2) Comparison with C&T

An important policy choice for policymakers considering emissions trading is whether to adopt the rate-based TPS or the mass-based and more widely used alternative of C&T. China's policymakers continue to focus on this issue, as there have been serious discussions of switching from the TPS to C&T. The model employed in this paper reveals that the relative costs of the TPS and C&T follow a dynamic pattern that to our knowledge has received no prior attention. We focus on this issue here.

Figure 5 displays the economic costs of the two approaches, showing some important changes over time. The TPS's costs are close to those of an equally stringent C&T system during the first eight years of the program, but rise above the C&T costs in later years.[30] Three factors underlie this pattern.

First, as was noted in Section 2, the TPS introduces an implicit subsidy to output, which causes covered facilities to make relatively inefficient use of the output-reduction channel to reduce emissions. Figure 6 displays the relative contributions of the three key channels for emissions reductions over the interval 2020-2035 under the TPS and the equally stringent C&T system. Compared with C&T, covered facilities rely less on the output-reduction channel and more on reduced emissions-intensities in order to achieve emissions reductions. The TPS's lower reliance on output-reduction explains why allowance prices rise more under the TPS than under C&T (see Figure 4). The higher output relative to C&T is associated with a higher demand for allowances, which leads to higher allowance prices despite the TPS's lower emissions intensity.

While this first factor has been recognized in prior studies, our model reveals two other important factors at work. One additional factor is policy stringency, which explains the widening gap between the policies' costs over time. Equation (5) of the analytical model indicated that the inefficiency associated with the TPS's implicit subsidy is proportional to the product of the benchmark and the allowance price. Greater

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[30] In the simulations of C&T, emissions allowances are allocated for free in each year so that economy-wide emissions match those of the TPS in Case 1. The distributions of the allocations across sectors and subsectors are proportional to those under the TPS.

stringency generally implies a higher allowance price, which augments the importance of the implicit subsidy.[31] Figure 5's results suggest that the magnitude of this inefficiency is not great until Phase 3, when higher allowance prices cause this product to be considerably higher than in earlier years.

A further and important additional factor is the presence of taxes on factors of production. This factor reduces what otherwise would be a larger cost-disadvantage of the TPS. As mentioned in the introduction, although the TPS's implicit output subsidy leads to inefficiently small output-reductions relative to C&T, it also has the *beneficial* effect (in terms of efficiency) of reducing the distortionary effect of pre-existing taxes and renewable subsidies. This "tax-interaction" effect has been examined theoretically and numerically in the prior public economics and environmental economics literature.[32] This impact from the subsidy helps improve the cost-effectiveness of the TPS and offsets what otherwise would be a larger disadvantage relative to C&T. In the first years of the TPS, the two effects on cost-effectiveness are comparable; hence the costs of each policy are not much different. However, over time, as the product of the allowance price and benchmark increases, the adverse impact from this product becomes significantly more important than the beneficial impact of pre-existing taxes, and the gap between the TPS and C&T costs widens. We simulate counterfactual cases where the levels of pre-existing taxes differ from Case 1. The results displayed in Appendix D indicate that the ratio of TPS's costs to C&T's costs declines monotonically as the levels of pre-existing taxes are raised.

The impact of prior taxes has significant policy implications, suggesting that the TPS need not be viewed as having a large cost-disadvantage relative to C&T in settings with significant factor taxes. The disadvantage shown in Figure 5 is slight during the first decade of China's TPS. However, with increased stringency increases and associated increases in allowance prices, the disadvantage becomes more pronounced.

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[31] In our simulations of the TPS, 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, increasing the associated distortion.

[32] See, for example, Bovenberg & Goulder (1994), Goulder *et al.* (1999), Parry and Bento (2000), Fullerton & Metcalf (2001) and Parry and Williams (2010). 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 factors and other inputs are different. Details are in Appendix D.

China's planners are contemplating a transition from the TPS to C&T. We have performed simulations of such a transition and find that this can lower the cost per ton of emission reductions. Details are in Appendix E.

6.2 Sector Impacts

6.2.1 Sector and Subsector Prices, Outputs, and Profits

Table 5 displays for each sector and in each of the three phases the percentage changes in the output price, level of production, and profit.[33] Prices and profit are expressed in real terms, with the price of a composite produced good employed as the price index.

As expected, the covered sectors tend to experience the largest reductions in output, reflecting the use of output-reduction as a channel for reducing compliance costs. The reduction in output is highest in the electricity sector. This sector's carbon intensity is relatively high and its benchmarks are stringent relative to those of other sectors.[34] As a result, unit costs of electricity production increase significantly, prompting a significant reduction in electricity demand.

In all three phases, all of the sectors covered during the phase in question experience increased profits. This reflects the economic rents associated with the value of the free allowances these sectors receive under the TPS.[35] The rents are significant, as the demands for the products of these sectors are relatively inelastic.[36] The low elasticity in part reflects the fact that these sectors are not highly trade-exposed[37]; hence they are less

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[33] We measure the sectors' profit by the total after-tax return to the sectors' capital and the value of free allowances.

[34] The emissions intensities by sector are provided in Table A7 in Appendix B.

[35] Goulder *et al.* (2010) offer a detailed discussion of how free allowance allocation yields economic rents. Under the TPS, free allocation is an inherent 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 allowances offered free to the electricity sector in 2021 is 257 billion RMB. This fully offsets the TPS-induced increase in production cost to this sector of about 243 billion RMB in that year.

[36] Underlying the overall increase in profits in the electricity sector are differing impacts between the fossil-based and renewables-based electricity generators. The fossil-based electricity generators experience profit increases during 2020-2028 and profit reductions during 2029-2035, while the renewable electricity generators experience profit increases during the entire simulation interval.

[37] Appendix B indicates trade exposure for each sector in terms of the ratio of traded goods to total output.

vulnerable to imported substitutes. In the uncovered sectors, impacts on profits and output reflect changes in demand and production cost. The coal sector suffers the highest percentage losses of output and profit, reflecting a significant reduction in demand for coal by the contracting electricity sector. In contrast, the natural gas sector experiences percentage increases in prices, profits and output. The increased output reflects increased demand for natural gas, which has a lower emissions factor than coal and can substitute for coal in some covered sectors as a way to reduce emissions intensity. Also, the MEE sets less stringent benchmarks (measured by the difference between the benchmark and the baseline emissions intensity) for gas-fired plants than for coal-fired plants, which contributes to the substitution of gas-fired for coal-fired electricity.

For many other uncovered sectors, the TPS raises the costs of production by increasing the prices of their inputs. In Phase 1, this is especially important in the aluminum sector, which is intensive in its use of electricity.

6.2.2 Impacts on Renewables

Many policymakers and citizens hope that China's climate policies will help spur the transition away from fossil fuels and toward renewables-based energy. Both the TPS and C&T promote the substitution of renewable-based electricity for fossil-based power. This reflects the fact that both policies raise the prices of carbon-intensive fuel inputs, which raises the marginal costs of fossil-based generation relative to renewables-based generation.[38]

Figures 7a and 7b show the impacts of the two policies on renewables generation, as changes relative to the baseline (7a) and as shares of total generation (7b).[39] The shifts toward renewable electricity sources are smaller under the TPS than under C&T. The difference is due to the TPS's implicit output subsidy, which mitigates the increase in fossil-based electricity prices and moderates the substitutions toward renewables-based power.

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[38] Over the interval 2020-2035, profits to fossil-based electricity producers decrease by 0.5%, while the profits to wind and solar electricity suppliers increase by 10%.

[39] The extent of hydroelectric and nuclear electricity generation is mainly determined by government planning in China. Accordingly, the model assumes their outputs remain at the base year levels and are not influenced by the TPS and C&T policies.

6.3 Net Benefits

The TPS's climate-related benefits are estimated to be well above its economic costs. This conclusion holds under a plausible range of values for the climate-related benefits from CO_2 abatement (as implied by alternative assumed values for the social cost of carbon), for production parameters[40], and for assumed future levels of stringency of the TPS.[41]

For the SCC, we consider three paths[42]: one starting in 2020 at 307 RMB (44 dollars) per ton and increasing at 3% annually (following Nordhaus (2017)), one starting at 353 RMB (51 dollars) per ton and increasing by 3% annually (following the Biden Administration (2021)), and one starting at 1,277 RMB (185 dollars) per ton and increasing by 2% annually (following Rennert *et al.* (2022)).

Figure 8a shows the ranges and the central estimates of TPS's costs and climate benefits under Case 1. The estimated benefits from the cumulative CO_2 reductions over the 2020-2035 interval are in the range of 6-43 trillion RMB, 3-22 times the cumulative costs. The central estimate of the climate benefit is 10 trillion RMB, around five times the TPS's costs.

Figure 8b displays the costs and benefits when health benefits from reduced local pollution are taken into account. The health benefits are measured as the estimated values of avoided premature deaths. To estimate these benefits, we apply an emissions-inventory model (described in Zheng *et al.* (2019)), an air-quality model (Polynomial function-based Response Surface Model, Pf-RSM, described in Xing *et al.*(2018)), and the Global Exposure Mortality Model (GEMM) developed by Burnett *et al.* (2018) to calculate $PM_{2.5}$-related premature mortalities under the baseline and the TPS.[43] Details are provided

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[40] As indicated in Section 7 below, these include elasticities of substitution in production, elasticities of capital transformation, the elasticity of substitution between household consumption and private saving, and the rates of exogenous improvement in energy factor productivity.

[41] To address the uncertainty about future benchmark tightening rates, we consider a low stringency scenario in which benchmarks are 0.5 percentage points lower than in Case 1 and a high stringency scenario with benchmarks 0.5 percentage points higher than in Case 1. Section 7 below offers related details.

[42] The SCC at time *t* is the climate-change-related 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. It reflects the value of climate change impacts, including changes in net agricultural productivity, human mortality related to heat, energy expenditures for heating and cooling buildings, and the coastal impacts of rising sea levels, etc. (Rennert *et al.*, 2022).

[43] Studies indicate that $PM_{2.5}$ is a major contributor to premature mortality from air pollution (Burnett *et al.*, 2018; Zhou *et al.*, 2019; Wang *et al.,* 2021). For this reason we focus on the benefits from reduced $PM_{2.5}$.

in Appendix F. The mortality impacts are then monetized by considering three sets of assumptions for the value of a statistical life (VSL).[44]

Accounting for health benefits raises the benefit-cost ratio substantially. The central estimate is that under Case 1, the TPS could avoid 2.3-2.5 million $PM_{2.5}$-related deaths in total over the 2020-2035 interval, relative to the baseline.[45] Under plausible ranges of the parameters determining the benefits and costs, the present value of the TPS's climate and health benefits are in the range of 19-122 trillion RMB over the 2020-2035 interval. The central estimate is 53 trillion RMB, 26 times the central estimate for the TPS's costs.

The results in figures 8a and 8b are based on estimated *global* benefits from reductions in CO_2 emissions. Ricke *et al.* (2018) estimate that China would enjoy approximately six percent of the climate benefits from its CO_2 reductions. If only China's climate benefits are considered, the benefit-cost ratio ranges from 0.2 to 1.3. However, if local health benefits are considered along with the climate benefits to China, the TPS's benefit-cost ratio is consistently well above one – specifically, in the range of 10 to 68.

A related and important issue is how the TPS's abatement path over the 2020-2035 interval compares with the path that would maximize net benefits over this interval. This requires attention to marginal (rather than total) costs and benefits from abatement. Efficiency maximization requires that marginal costs per ton of emissions reduction equal the SCC. We assess the efficiency of the stringency level of the TPS by comparing marginal costs and benefits associated with the emissions reductions over the 2020-2035 interval.[46] We define the marginal benefit as the average value of the SCC[47] over the interval. The marginal cost is derived by decrementing the Case 1 benchmarks each year

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[44] We assume a constant elasticity of the VSL with respect to income: $VSL_t = VSL_0(INC_t\ /INC_0)^{\sigma_{VSL}}$, where INC_t and INC_0 are the per capita income in year *t* and in the base year 2020, and are calculated from the model's output. VSL_0 and σ_{VSL} are respectively the estimated VSL for base year 2020 and the income elasticity of the *VSL*. The three sets of assumptions for the VSL_0 and σ_{VSL} are: 6.5 million RMB in 2020 with an elasticity of the VSL with respect to per-capita GDP of 0.22, based on Hoffmann *et al.* (2017); 10.3 million RMB in 2020 with the elasticity of 1, based on OECD (2012); and 18.4 million RMB in 2020, with the elasticity of 0.8, based on the U.S. EPA (2010).

[45] The range is the 95 percent confidence interval implied by uncertainties in parameters in the GEMM model. See Appendix F for details.

[46] Note that while the costs are experienced within the interval 2020-2035, the climate benefits from abatement during this interval stretch into the indefinite future.

[47] We apply a weighted average of the SCC, with the weight equal to the period's share of the cumulative emissions reductions over the simulation interval.

and noting the associated incremental increase in costs per extra ton abated. The results are shown in Figure 9. We find that efficiency maximization would require benchmarks approximately 9-12 percent lower than the Case 1 benchmarks. The efficiency-maximizing benchmarks would give rise to emissions reductions of around 18-22 percent relative to the baseline, more than twice the scale of the reductions in Case 1.

6.4 Impacts of Auctioning

China's policymakers are seriously contemplating revising the allowance allocation method so that a share of allowances is supplied via auction rather than offered for free. Here we present results from simulations in which auctioning serves as a source of supply of some of the allowances. The policy simulations span a range of auctioning cases, differing in the ways that the auction revenues are recycled back to the economy. Auctioning is included with the TPS starting in year 2025. For comparability, the total number of allowances supplied in each year is the same in the cases with and without auctioning. To maintain the same allowance supply in the auctioning case, the benchmarks (which determine the amounts supplied outside of the auction) are reduced by a common factor across sectors and technology types.

Figure 10 shows the economic costs in cases involving auctioning and in Case 1, which involves no auction. In all of the auctioning cases, the costs are lower than in Case 1. Introducing auctioning lowers costs because supplying by auctioning does not involve the TPS's implicit output subsidy and its associated distortions. In addition, in the cases where the auction revenues are recycled through cuts in marginal rates of pre-existing income taxes, the costs are reduced further, since lowering the marginal tax rates reduces the economic distortions from such taxes. These results provide support for introducing auctioning as part of China's national emissions trading system.

Among all the auctioning cases, the highest costs are in the case where all of the auction revenues are recycled as output subsidies for wind and solar electricity generation. The cost in this case is higher than in the other cases because the subsidies introduce new distortions (holding fixed the aggregate reductions in emissions). The lowest cost is in the case in which auction revenues are recycled to finance cuts in taxes on capital and labor, which lowers the distortions from pre-existing capital and labor taxes. In the case where auction revenues are recycled as a lump-sum transfer, the cost lies between those of the other two auctioning cases.

The present value of the gross revenue from the auction is about 2.4 trillion RMB over the interval when the auction is in place (2025-2035). If used as compensation for the coal and mining sectors, which suffer the largest percentage profit losses, this revenue would fully offset their losses of profit over the same interval (0.9 trillion RMB).

Figure 11 shows the electricity produced from wind and solar electricity generators under the different revenue-recycling options. With auctioning, electricity prices increase more than in Case 1, as auctioning reduces the TPS's output subsidy. The higher prices promote greater substitution of renewables-based power generation for fossil-based generation and imply higher production of wind- and solar-based generation. Among the auctioning cases, the case involving recycling in the form of subsidies to renewables-based electricity generation yields as expected the greatest increase in wind and solar electricity generation.

6.5 Trade-offs between Efficiency and Distributional Impacts

One of the objectives of China's policymakers is to achieve emissions reductions at lower costs. Another is fairness – avoiding substantial differences in policy costs across sectors, regions, and demographic types. These objectives can compete with each other. We apply the model to assess the trade-offs.

As indicated in the analytical model, aggregate cost under the TPS depends on the variation of benchmarks. Figure 12 displays the economic costs in cases that differ in terms of such variation. It also shows the cost under an equally stringent C&T system. The smaller the number (and greater uniformity) of benchmarks, the lower the cost. Greater uniformity lowers the aggregate cost by reducing the variation in the implicit subsidy and associated wedge between the price of output (or marginal value to consumers) and the private marginal cost of production. This leads to a more efficient allocation of production across generators. Changing from separate benchmarks for coal-fired and gas-fired generators to a unified benchmark for both significantly lowers the costs by narrowing the gap in marginal production costs across generators. The marginal costs differ because of significant differences in the emissions intensities of the different types of generators. Under the one-benchmark TPS, the economy-wide cost is sufficiently low to fall below that of C&T. We noted earlier that the TPS's implicit output subsidy partly offset the distortions of pre-existing taxes. In the one-benchmark case, the combination of this offset and the lower distortions associated with the uniformity of the benchmarks is enough to cause the TPS's overall cost to fall below the cost under C&T.[48]

The use of multiple benchmarks can serve distributional objectives, however. Table 6 presents the cumulative income change of all sectors by province. Details of the estimation method are in Appendix G. Over the interval 2020-2035, the percentage losses of income are much more unevenly distributed in the one-benchmark case than in the four-benchmark case. The red (green) font identifies the five provinces with the largest (smallest) percentage income losses in a given benchmark case. In the one-benchmark case, the difference in the income percentage change between the best-off province and the worst-off province is 2.4, higher than the difference (1.7) in the four-benchmark case. The standard deviation of percentage losses across provinces in the one-benchmark case is 0.502, 69 percent higher than the standard deviation of 0.297 in the four-benchmark case. These results reveal a significant trade-off between cost-effectiveness and distributional equity (and associated political acceptability) in the choice of TPS design.

7. Sensitivity Analysis

Here we examine the sensitivity of the model's results to input substitution elasticities, capital transformation elasticities, the parameters that determine the model's dynamics, and the assumed rates of increase in policy stringency.

The significance of input substitution and transformation elasticities is examined in Table 7. A higher elasticity of substitution between energy and other inputs lowers the cost of reducing emissions intensities through the substitution of material inputs for high-carbon fuels. Similarly, a higher capital transformation elasticity implies lower costs of reallocating capital from the low-efficiency subsectors to the high-efficiency subsectors in response to a changing policy environment. Thus, costs per ton decline with a higher value for this elasticity.

Table 8 focuses on parameters that directly influence the dynamics. The autonomous energy efficiency improvement (AEEI) rate is the growth rate of exogenous energy factor productivity in production. The central case employs an AEEI of 1.0 percent annually. A higher AEEI rate implies faster growth of energy efficiency and

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[48] To confirm the underlying determinants of this outcome, 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.

lower baseline emissions. Thus, the economic costs per ton decline with a higher AEEI rate.

The elasticity of substitution between household consumption and private saving determines the responsiveness of saving to changes in the return to capital. Under the TPS, the price of investment goods increases relative to that of consumption goods, reflecting the greater emissions intensity of investment goods. This relative price change leads to a lower saving rate and rate of capital accumulation relative to the baseline. A higher elasticity amplifies this effect. Greater capital accumulation facilitates firms in substituting carbon-intensive inputs with capital inputs. Therefore, in cases with a higher (lower) elasticity between consumption and saving, the TPS incurs a slightly higher (lower) cost per ton compared to the central case.

Table 9 examines the significance of assumptions about the future extent of policy stringency, as determined by the rate of benchmark tightening after 2022. In the central case, benchmarks are tightened by 1.5% and 2.5% annually for the electricity and non-electricity sectors, respectively. We consider two alternative scenarios. In the low (high) stringency scenario, electricity sector benchmarks are tightened by 1% (2%) annually and non-electricity sectors' benchmarks by 2% (3%). The cumulative emissions reductions in the high stringency case are approximately 29 percent higher than in the central case. Costs per ton of abatement are higher, the greater the level of stringency, reflecting rising marginal costs of abatement.

The bottom row in Tables 7, 8, and 9 indicates how the ratio of the TPS's costs to those under C&T depends on key parameters. As discussed in Section 2, the TPS's implicit output subsidy is the product of the allowance price and the applicable benchmark. Thus a lower carbon price implies a smaller implicit output subsidy and a smaller associated distortion under the TPS. A higher energy-factor substitution elasticity, higher AEEI rate, and lower benchmark tightening rate all work toward lower allowance prices by implying lower costs of reducing emissions and lower demands for allowances. Hence they lead to a lower ratio of TPS costs to C&T costs.

In contrast, the influence of capital transformation elasticity on the ratio of TPS costs to C&T is ambiguous. It depends on differences in the extent to which the two policies rely on changes in sector composition to reduce emissions.[49] The relative reliance changes over time. The TPS relies more on these changes in Phase 1, while C&T relies more in phases 2 and 3.[50] Correspondingly, easier capital transformation would benefit the TPS more in the first few years, and C&T more after that.

Overall, our main findings on the impacts of the TPS are robust to changes in these parameters. This includes the findings that the TPS's environmental benefits significantly exceed its economic costs, that the planned stringency of China's TPS is less than the efficiency-maximizing level, and that the TPS's costs become higher than those of an equivalently stringent C&T system once the system reaches a critical level of stringency.[51]

8. Conclusions

This paper presents and interprets results from a multi-sector, multi-period general equilibrium model designed to evaluate the impacts of China's recently implemented nationwide tradable performance standard to reduce CO_2 emissions. The model indicates this new venture's potential costs and benefits over the interval 2020-2035, both in the aggregate and across sectors and provinces, and identifies the relative attractions and limitations of alternative specific policy designs.

The model differs from earlier studies because of its general equilibrium framework, its attention to changes in impacts over time; its recognition of differences between the TPS and C&T in terms of structure, incentives, and impacts; its recognition of the institutional and regulatory features of China's economy; and its ability to consider a range of potential future TPS designs. The potential designs include alternative

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[49] As indicated in Subsection 6.1.2, shifts in sectoral composition provide one of three main channels through which the TPS can yield reduced economy-wide emissions, with the others being reduced output supply and reduced emissions intensity at the firm level.

[50] In Phase 1, under the TPS and C&T, the contributions from changes in sector composition to emission reductions are 54% and 47%, respectively. The two policies' reliance on change in sector-composition is 31% and 39% in Phase 2 and 25% and 38% in Phase 3.

[51] Tables 8 and 9 show that the TPS can involve lower costs than C&T in all three phases in certain cases. This occurs in three cases: when there is a modest benchmark tightening rate (1% for electricity and 2% for the non-electricity sector), when the AEEI rate is high (1.5%), or when the energy-factor substitution elasticities are twice those of the central case. These alternative parameter values lower the marginal abatement cost compared to the central case. This effect is more significant under the TPS, because of the decrease in the distortionary effects of TPS's implicit output subsidy. Consequently, the differences in abatement costs between TPS and C&T are sufficiently low. Hence, with the tax-interaction effect explained in section 6.1.2, the TPS can have a lower cost than C&T.

specifications for the variation and average stringency of government-specified benchmarks, the introduction of an allowance auction as a supplementary source of allowance supply. With this flexibility, the model can offer useful information to China's planners as they continue to make decisions about the design of later phases of the TPS.

The results from our analysis yield unique insights into the potential impacts of China's new and evolving policy effort. First, we find under plausible parameters and levels of policy stringency over the 2020-2035 interval, the TPS's environmental benefits are well above its economic costs. Our central estimate is that the benefits exceed costs by a factor of more than five when only the climate-related benefits are considered and by a much higher factor when health benefits from reduced emissions of local pollutants are also considered.

Second, the currently planned stringency of China's TPS is considerably weaker than the efficiency-maximizing level. Based on distributions of marginal environmental benefits and economic costs, we find that efficiency maximization would require using benchmarks approximately 9-12 percent tighter than the current and projected benchmarks over the interval 2020-2035 interval.

Third, the relative cost of the TPS and an equivalently stringent C&T system depends importantly on the level of stringency of the system and on pre-existing taxes. Earlier literature had identified a cost-effectiveness handicap of the TPS relative to C&T because of its implicit subsidy to output. We show that the subsidy also yields an offsetting benefit by causing the increase in output prices under the TPS to be smaller than under C&T. As a result, the TPS generates a smaller adverse tax-interaction effect than under C&T. This offsets what otherwise would be a larger disadvantage of the TPS in terms of cost-effectiveness. Indeed, in the short run, when the stringency of the emissions trading system is relatively low, the cost per ton of abatement under the TPS is very close to that under C&T. In the longer run, greater stringency yields higher allowances prices, which increase the distortionary cost of the TPS's implicit subsidy and widens the gap between the TPS's costs and those of C&T.

Fourth, introducing an auction as a complementary source of allowance supply can lower the economic costs of China's emissions trading system by 30-43 percent relative to the no-auction case. Auctioning lowers costs because there is no implicit subsidy to allowances introduced via auction. A further cost advantage arises to the extent that the auction revenues are used to finance cuts in pre-existing distortionary taxes.

Finally, the simulation results reveal important trade-offs between cost-effectiveness and distributional equity. Distributional concerns can be addressed through the employment of varying (customized) benchmarks, but greater benchmark variation raises aggregate costs by widening the disparities in marginal costs of production. Employing a single benchmark for the electricity sector would lower costs by 34 percent relative to the four-benchmark system that is in place but would increase the standard deviation of percentage income losses across provinces by more than 60 percent.

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Table 1. Sectors

Name	Description
Cement*	Cement
Iron & steel**	Iron and steel
Aluminum***	Aluminum products
Pulp & paper	Pulp and paper
Other non-metal products	Non-metal processing other than cement
Other non-ferrous metals	Non-ferrous metals other than aluminum
Raw chemicals	Raw chemical materials, chemical products
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
Printing & stationery	Printing and stationery
Daily chemical products	Chemical fibers, medicines, rubber & plastics products
Metal products	Metal products
General equipment	General equipment manufacturing
Transport equipment	Transport equipment manufacturing
Electronic equipment	Electronic equipment manufacturing
Other manufacturing	Other manufacturing
Water	Water
Construction	Construction
Transport	Transport and post
Services	Services
Electricity****	Electricity generation
Petroleum refining	Petroleum refining
Heat	Heat distribution
Coal	Coal mining and processing
Crude oil	Extraction of crude oil
Natural gas	Primary production of natural gas
Gas manufacture & distribution	Manufacture, processing, and distribution of natural or synthetic gas

* The cement divides into 3 subsectors: high, medium, and low-efficiency cement production.

** The iron&steel sector divides into 6 subsectors: high, medium, and low-efficiency basic oxygen steel production, and high, medium, and low-efficiency electric-arc furnace steel making.

*** The aluminum sector divides into 3 subsectors, including high, medium, and low-efficiency aluminum production.

**** The electricity sector divides into 15 subsectors, distinguishing the following generation technologies: LUSC (1000MW Ultra-supercritical); SUSC (600MW Ultra-supercritical); LSC (600MW Supercritical); SSC (300MW Supercritical); LSUB (600MW Subcritical); SSUB (300MW Subcritical); OTHC (Installed capacity less than 300MW); LCFB (Circulating Fluidized Bed Units with installed capacity greater than or equal to 300MW); SCFB (Circulating Fluidized Bed Units with installed capacities less than 300MW); HPG (Gas fired plants, F-class); LPG (Gas fired plants, Pressure lower than F-class); Wind power; Solar power; Hydropower; and Nuclear power.

Table 2. Policy Cases Considered

Case	Specification
Case 1: Central case	- Number of benchmarks. Four benchmarks apply to the electricity sector: three for coal-fired and one for gas-fired generators. Two benchmarks apply to the iron & steel sector.* One benchmark applies to each of all other covered sectors. - Initial benchmarks. Initial benchmarks for the electricity sector are set according to the MEE's released documents. Initial benchmarks for other sectors are set to be 2.5% below their emissions intensity in the year before they are included in the TPS. - Tightening rates of benchmarks. The tightening rate for the electricity sector is 0.5 %/year during Phase 1 according to the MEE. We assume the tightening rate for the electricity sector in Phases 2 and 3 is 1.5%, and the rate for other sectors is 2.5%.**
Case 2: Fewer benchmarks for the electricity sector	- Case 2a: Two-benchmark case: One benchmark for coal-fired generators; a different benchmark for gas-fired generators. All other benchmark assumptions are the same as in Case 1. The coal-fired generators' benchmark is the weighted average of their differing benchmarks in Case 1. All benchmarks are scaled by a common factor to match Case 1's economy-wide emissions each year. - Case 2b: One-benchmark case: A single benchmark applies to all generators. The settings of all other benchmark assumptions are the same as in Case 2a.
Case 3: Allowance auction	- Auction share. The auction starts in 2025. The initial share of auctioned allowances is 10% for the electricity sector and 0% for others. The auction share increases by a constant rate in the electricity sector and a different constant rate in the other sectors, reaching 100% for the electricity sector and 30% for other covered sectors by 2035. The benchmarks that determine free allowances are lowered to match Case 1's economy-wide emissions in each year. - Recycling of auction revenues. Case 3a: recycled as output subsidies for wind and solar electricity. Case 3b: recycled as lump-sum transfers. Case 3c: recycled to finance cuts in capital and labor taxes in all sectors.

* One for the basic oxygen process and one for the electric arc furnace process.

** The lower tightening rate for the electricity sector is consistent with the MEE's view that there is less room for future energy-efficiency improvements in this sector than in others.

Table 3. Initial Benchmarks

Sectors and Subsectors	Policy Cases					
	Case 1	Case 2a	Case 2b	Case 3a	Case 3b	Case 3c
Electricity (tCO_2/MWh):						
Coal-fired generators with capacity < 300 MW (SSC, SSUB, and OTHC)	0.882	0.859	0.833	0.882	0.882	0.882
Coal-fired generators with capacity >= 300 MW (LUSC, SUSC, LSC, and LSUB)	0.824	0.859	0.833	0.824	0.824	0.824
Circulating fluidized bed generators (LCFB, SCFB)	0.940	0.859	0.833	0.940	0.940	0.940
Gas-fired generators (HPG, LPG)	0.394	0.393	0.833	0.394	0.394	0.394
Cement (tCO_2/ton)	0.849	0.848	0.848	0.849	0.849	0.849
Iron & steel (tCO_2/ton):						
Basic oxygen furnace	0.017	0.017	0.017	0.017	0.017	0.017
Electric arc furnace	0.004	0.004	0.004	0.004	0.004	0.004
Aluminum (tCO_2/ton)	7.911	7.910	7.905	7.911	7.911	7.911
Other non-metal products (tCO_2/*k*RMB)	0.058	0.058	0.058	0.057	0.057	0.057
Other non-ferrous metals (tCO_2/*k*RMB)	0.051	0.051	0.051	0.050	0.050	0.050
Pulp & paper (tCO_2/*k*RMB)	0.050	0.050	0.050	0.049	0.049	0.049
Petroleum refining (tCO_2/*k*RMB)	0.039	0.039	0.039	0.038	0.038	0.038
Raw chemicals (tCO_2/*k*RMB)	0.092	0.091	0.091	0.090	0.089	0.089

Note. "Initial benchmarks" refers to the benchmark values when they are first introduced under the TPS. For the electricity sector, the benchmarks first apply in 2020. For sectors first covered in Phase 2, they first apply in 2023. For the sectors first covered in Phase 3, they first apply in 2026.

Table 4. Summary of Costs of Case 1

	Cost (billion RMB)		CO_2 Emissions Abatement (billion tons)	Cost Per Ton of CO_2 Abatement (RMB/t)	
	Measured By the Change in GDP	Measured by the Equivalent Variation of Consumption		Measured By the Change in GDP	Measured By the Equivalent Variation of Consumption
Phase 1 (2020-2022)	17	8	0.4	41	21
Phase 2 (2023-2025)	63	10	1.3	48	8
Phase 3 (2026-2035)	1,939	477	19.1	102	25
Overall (2020-2035)	2,019	495	20.8	97	24

Table 5. Percentage Changes of Price, Quantity, and Profit Impacts of the Case 1

Sectors	Price			Output			Profit		
	Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3
Electricity	0.222	0.472	3.802	-0.394	-0.864	-6.742	0.734	1.486	4.354
Cement	-0.016	0.746	9.958	-0.016	-0.099	-0.818	-0.035	5.181	16.84
Iron & steel	-0.007	0.143	0.571	-0.038	-0.283	-0.760	-0.042	2.41	7.903
Aluminum	0.097	0.426	4.115	-0.122	-0.506	-4.980	-0.061	2.537	6.605
Pulp & paper	0.005	0.002	0.238	-0.019	-0.038	-0.396	-0.016	-0.041	2.424
Petroleum refining	-0.001	0.004	0.125	-0.043	0.040	-0.189	-0.053	0.042	0.581
Raw chemicals	0.001	-0.01	0.542	-0.026	-0.042	-1.373	-0.029	-0.061	2.019
Other non-metal products	0.005	0.045	0.663	-0.020	-0.088	-0.753	-0.019	-0.104	1.275
Other non-ferrous metal	0.014	0.039	0.509	-0.061	-0.189	-1.532	-0.061	-0.208	1.078
Coal	-0.176	-0.539	-2.088	-1.398	-4.146	-16.52	-2.024	-5.918	-21.78
Natural Gas	0.032	0.085	0.526	0.071	0.185	1.217	0.110	0.287	1.779
Mining	0.007	-0.011	0.054	-0.038	-0.33	-1.545	-0.044	-0.302	-1.077
Agriculture	-0.004	-0.017	-0.086	-0.006	-0.004	0.009	-0.015	-0.015	-0.053
Uncovered manufacturing sectors[*]	0.001	0.004	0.057	-0.024	-0.075	-0.390	-0.026	-0.088	-0.521
Construction	0.002	0.034	0.333	-0.007	-0.047	-0.455	-0.004	-0.059	-0.584
Service sectors[**]	-0.002	-0.015	-0.158	-0.014	-0.034	-0.143	-0.015	-0.054	-0.360

Note: The prices and outputs are weighted average percentage changes relative to the baseline in the corresponding period, with annual output levels used as weights. The profits are the present value of cumulative changes in the corresponding period. The blue font identifies the covered sectors in the applicable phase.

[*] Elements in this row are percentage changes for the aggregate of all the manufacturing sectors not covered by the TPS. These sectors include Food, Textile, Clothing, Log furniture, Printing and stationery, Daily chemicals, Metal products, General equipment, Transport equipment, Electronic equipment, and Other manufacturing.

[**] Here we display the results after aggregating the results from the specific service sectors: gas manufacture and distribution, heat distribution, water, transport, and other services.

Table 6. Cumulative Income Change by Province, 2020-2035

Provinces	Four-Benchmark (Case 1)		Two-Benchmark (Case 2a)		One-Benchmark (Case 2b)	
	Absolute Change (billion RMB)	Percent Change (%)	Absolute Change (billion RMB)	Percent Change (%)	Absolute Change (billion RMB)	Percent Change (%)
East:						
Hebei	44	0.062	-46	-0.065	-202	-0.275
Shandong	-229	-0.154	-287	-0.193	-704	-0.458
Liaoning	-30	-0.061	-28	-0.056	-139	-0.270
Jiangsu	-96	-0.055	-92	-0.053	622	0.346
Hainan	-11	-0.119	-19	-0.195	-19	-0.197
Zhejiang	-47	-0.045	-3	-0.003	79	0.073
Fujian	14	0.022	61	0.092	133	0.195
Shanghai	-104	-0.162	-56	-0.086	74	0.111
Guangdong	-210	-0.115	-205	-0.111	573	0.301
Tianjin	-40	-0.109	-20	-0.055	214	0.566
Beijing	-123	-0.193	-122	-0.190	214	0.323
Regional Total	-833	-0.086	-817	-0.084	844	0.084
Central:						
Shanxi	-298	-0.889	-393	-1.169	-420	-1.208
Heilongjiang	-158	-0.453	-175	-0.498	-193	-0.534
Henan	-74	-0.079	-64	-0.068	-156	-0.161
Anhui	-83	-0.144	51	0.089	-197	-0.332
Jilin	-35	-0.121	-30	-0.102	-26	-0.086
Hubei	14	0.018	1	0.001	-53	-0.068
Hunan	-51	-0.074	-34	-0.048	-18	-0.025
Jiangxi	38	0.096	76	0.189	18	0.043
Inner Mongolia	-155	-0.487	-150	-0.470	-586	-1.771
Regional Total	-802	-0.173	-718	-0.154	-1631	-0.339
West:						
Ningxia	54	0.790	21	0.298	-70	-0.986
Guizhou	-133	-0.492	-114	-0.422	-217	-0.775
Shaanxi	-222	-0.490	-249	-0.547	-114	-0.243
Yunnan	15	0.043	-7	-0.021	-66	-0.187
Guangxi	8	0.020	24	0.061	-38	-0.094
Xinjiang	16	0.059	17	0.064	-17	-0.063
Chongqing	-57	-0.141	-41	-0.101	-38	-0.092
Gansu	-14	-0.083	-45	-0.269	-112	-0.642
Sichuan	-85	-0.103	-69	-0.084	82	0.097
Qinghai	34	0.587	41	0.690	41	0.667
Regional Total	-384	-0.119	-423	-0.130	-550	-0.164
National Total	-2019	-0.115	-1958	-0.111	-1338	-0.073
Standard deviation		0.297		0.307		0.502

Note: The red font identifies the five provinces with the largest percentage income losses in a given benchmark case; the green font identifies the five with the smallest percentage losses (or largest percentage increases). Hong Kong, Macao, Tibet and Taiwan are not included in this table due to input-output data limitations.

Table 7. Sensitivity Analysis: Significance of Production and Capital Transformation Elasticities

		Energy-Factor Substitution Elasticity				Capital Transformation Elasticity	
	Central Case	of All Sectors		of the Electricity Sector		Halved	Doubled
		Halved	Doubled	Halved	Doubled		
Cumulative emissions reduction (billion tons):							
Phase 1 (2020-2022)	0.41	0.38	0.45	0.39	0.43	0.42	0.40
Phase 2 (2023-2025)	1.32	1.25	1.45	1.28	1.40	1.32	1.33
Phase 3 (2026-2035)	19.08	18.30	20.89	19.09	19.35	19.08	19.13
Present value of cumulative cost (billion RMB):							
Phase 1 (2020-2022)	17	19	16	19	15	20	14
Phase 2 (2023-2025)	63	70	59	66	60	68	57
Phase 3 (2026-2025)	1,939	2,451	1,593	2,076	1,727	2,064	1,776
Economic cost per ton (RMB/ton):							
Phase 1 (2020-2022)	41	49	35	49	34	47	34
Phase 2 (2023-2025)	48	56	40	51	42	51	43
Phase 3 (2026-2025)	102	134	76	109	89	108	93
Average allowance price (RMB/ton):							
Phase 1 (2020-2022)	61	84	41	84	41	74	47
Phase 2 (2023-2025)	88	120	61	98	75	98	76
Phase 3 (2026-2025)	408	636	244	454	335	445	357
Wind- and solar- electricity increase (%):							
Phase 1 (2020-2022)	0.30	0.31	0.28	0.31	0.28	0.43	0.18
Phase 2 (2023-2025)	0.70	0.93	0.50	0.75	0.65	0.84	0.53
Phase 3 (2026-2025)	5.63	8.70	3.34	6.81	4.14	5.94	4.88
Ratio of TPS cost to C&T cost:							
Phase 1 (2020-2022)	0.97	1.19	0.80	1.12	0.86	1.01	0.93
Phase 2 (2023-2025)	1.03	1.18	0.91	1.08	0.97	1.00	1.07
Phase 3 (2026-2025)	1.10	1.29	0.98	1.14	1.03	1.05	1.19

Note: The words “halved” and “doubled” indicate how the parameters in the sensitivity analysis are changed relative to the value of that parameter in the central case.

Table 8. Sensitivity Analysis: Significance of Key Dynamic Parameters

	AEEI Rate			Elasticity Between Private Saving and Consumption		
	0.5%	1%	1.5%	1	1.5	2
		(Central case)		(Constant saving rate)	(Central case)	
Cumulative emissions reduction (billion tons):						
Phase 1 (2020-2022)	0.41	0.41	0.41	0.41	0.41	0.41
Phase 2 (2023-2025)	1.39	1.32	1.26	1.32	1.32	1.33
Phase 3 (2026-2035)	21.31	19.08	16.87	18.99	19.08	19.17
Present value of cumulative cost (billion RMB):						
Phase 1 (2020-2022)	17	17	17	17	17	17
Phase 2 (2023-2025)	69	63	57	63	63	63
Phase 3 (2026-2035)	2,475	1,939	1,495	1,884	1,939	1,992
Economic cost per ton (RMB/ton)						
Phase 1 (2020-2022)	41	41	41	41	41	41
Phase 2 (2023-2025)	50	48	45	47	48	48
Phase 3 (2026-2035)	116	102	89	99	102	104
Average allowance price (RMB/ton):						
Phase 1 (2020-2022)	61	61	61	61	61	61
Phase 2 (2023-2025)	94	88	83	88	88	88
Phase 3 (2026-2035)	496	408	330	407	408	408
Wind- and solar- electricity increase (%):						
Phase 1 (2020-2022)	0.29	0.30	0.31	0.30	0.30	0.30
Phase 2 (2023-2025)	0.69	0.70	0.71	0.70	0.70	0.70
Phase 3 (2026-2035)	5.76	5.63	5.34	5.63	5.63	5.63
Ratio of TPS cost to C&T cost:						
Phase 1 (2020-2022)	0.97	0.97	0.97	0.98	0.97	0.96
Phase 2 (2023-2025)	1.08	1.03	0.98	1.07	1.03	1.00
Phase 3 (2026-2035)	1.24	1.10	0.99	1.19	1.10	1.03

Table 9. Sensitivity Analysis: Significance of Policy Stringency

	Benchmark Annual Tightening Rate		
	Low*	Central**	High***
Cumulative emissions reduction (billion tons)			
Phase 1 (2020-2022)	0.41	0.41	0.41
Phase 2 (2023-2025)	1.08	1.32	1.57
Phase 3 (2026-2035)	13.62	19.08	24.93
Present value of cumulative cost (billion RMB)			
Phase 1 (2020-2022)	17	17	17
Phase 2 (2023-2025)	45	63	85
Phase 3 (2026-2035)	1,032	1,939	3,203
Economic cost per ton (RMB/ton)			
Phase 1 (2020-2022)	41.2	41.2	41.2
Phase 2 (2023-2025)	41.7	47.6	53.9
Phase 3 (2026-2035)	75.8	101.6	128.5
Average allowance price (RMB/ton)			
Phase 1 (2020-2022)	61	61	61
Phase 2 (2023-2025)	68	88	111
Phase 3 (2026-2035)	242	408	629
Wind- and solar- electricity increase (%)			
Phase 1 (2020-2022)	0.30	0.30	0.30
Phase 2 (2023-2025)	0.42	0.70	1.08
Phase 3 (2026-2035)	2.00	5.63	11.56
Ratio of TPS cost to C&T cost			
Phase 1 (2020-2022)	0.97	0.97	0.97
Phase 2 (2023-2025)	0.91	1.03	1.13
Phase 3 (2026-2035)	0.92	1.10	1.23

* 1% for electricity; 2% for other sectors.
** 1.5% for electricity; 2.5% for other sectors.
*** 2% for electricity; 3% for other sectors.

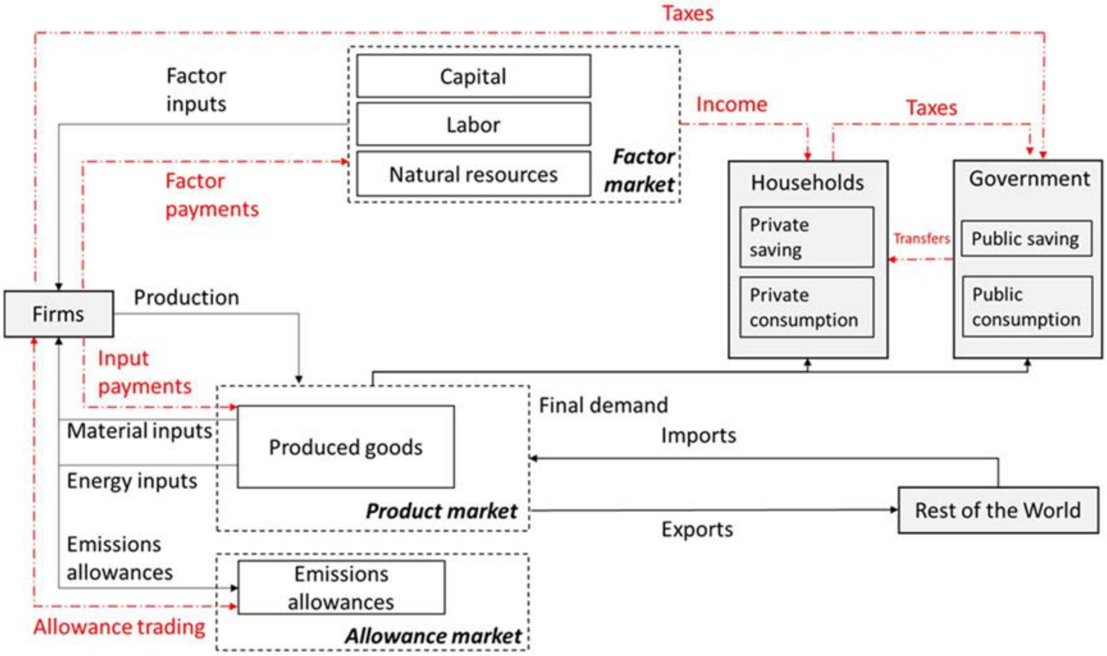


Figure 1. Goods and Financial Flows[1]

[1] The solid and dashed lines with arrows indicate the material flow and cash flow in the economy, respectively.

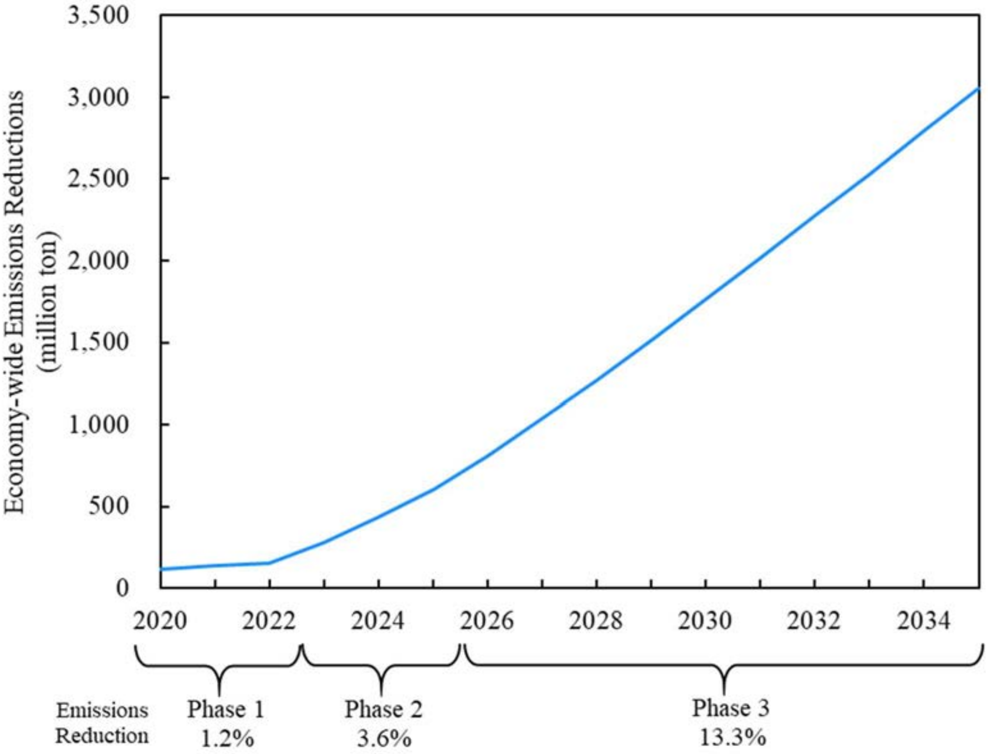


Figure 2. Emissions Reductions Relative to the Baseline, Over Time

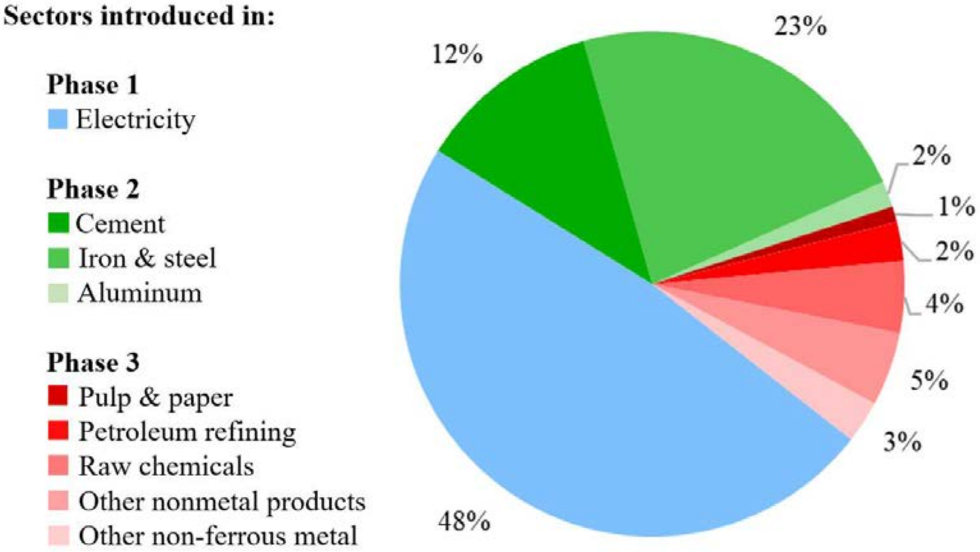


Figure 3. Covered-Sectors' Cumulative Emissions Reductions Over the Interval 2020-2035

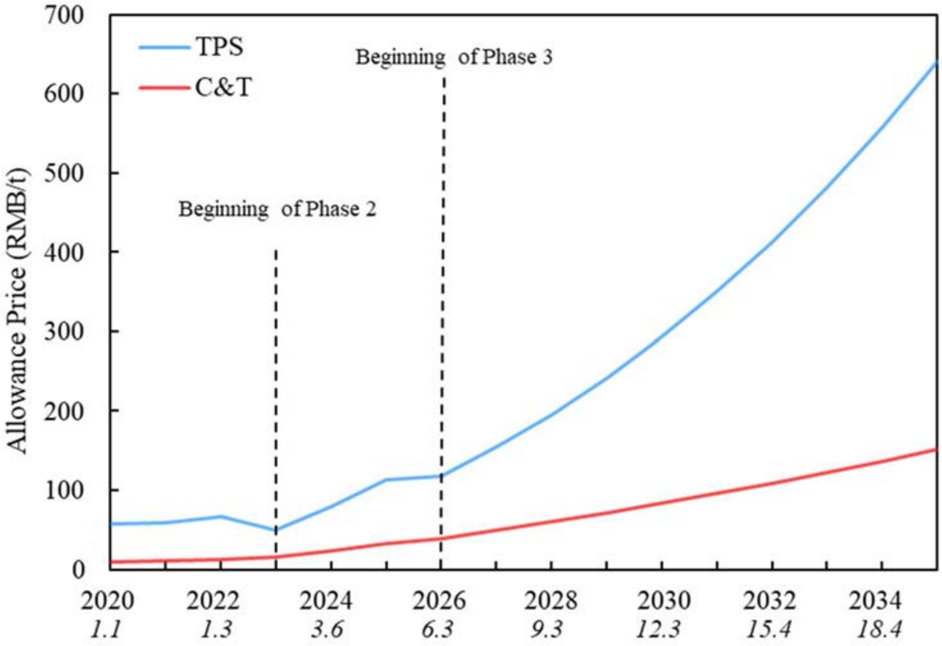


Figure 4. Allowance Prices Over Time

Numbers in italics are percentage emission reductions from the baseline

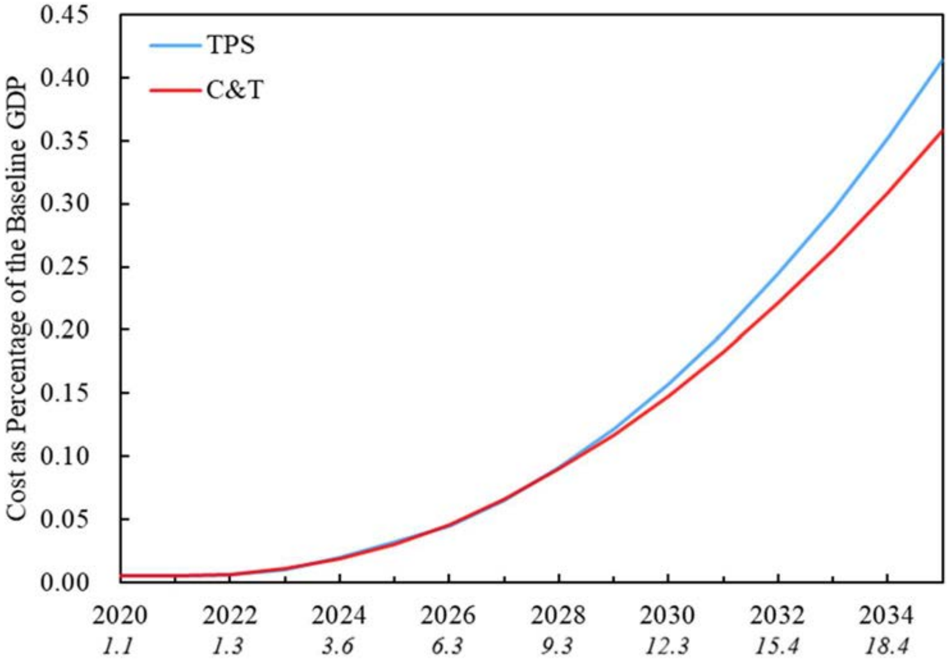


Figure 5. TPS and C&T Economic Costs Over Time

Numbers in italics are percentage emission reductions from the baseline

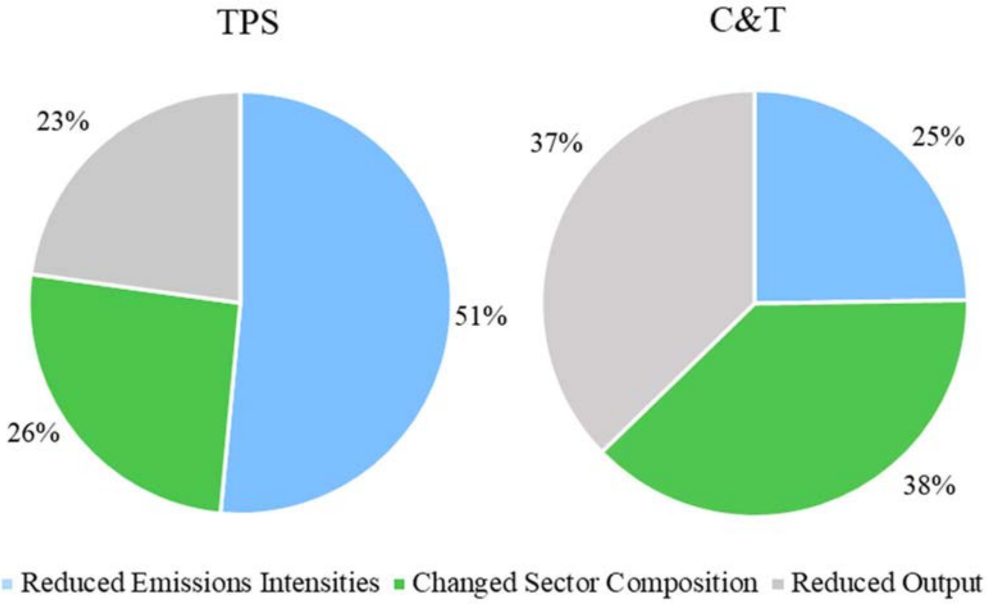


Figure 6. Sources of Emissions Reductions Under the TPS and C&T, 2020-2035

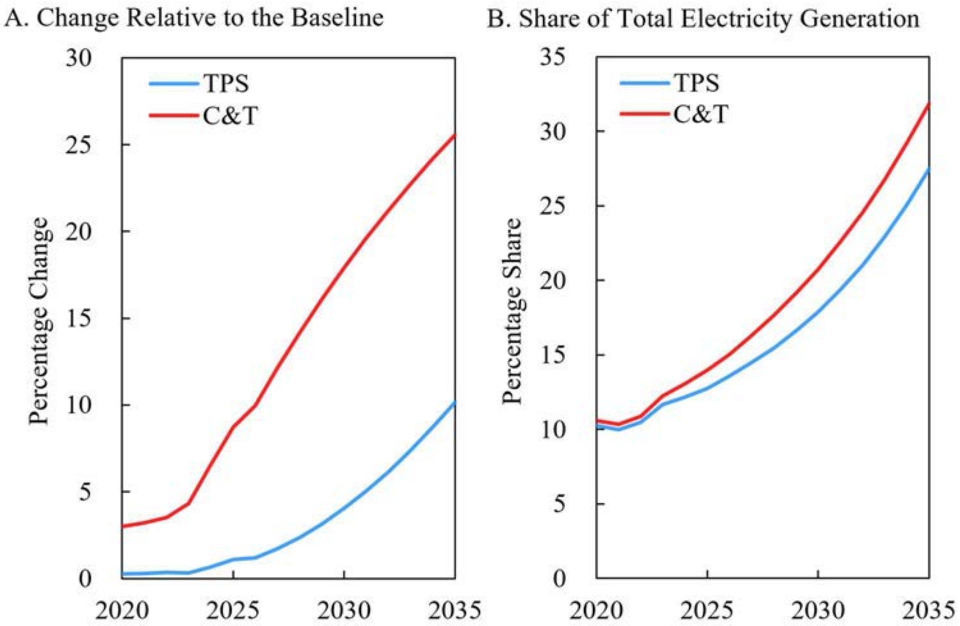
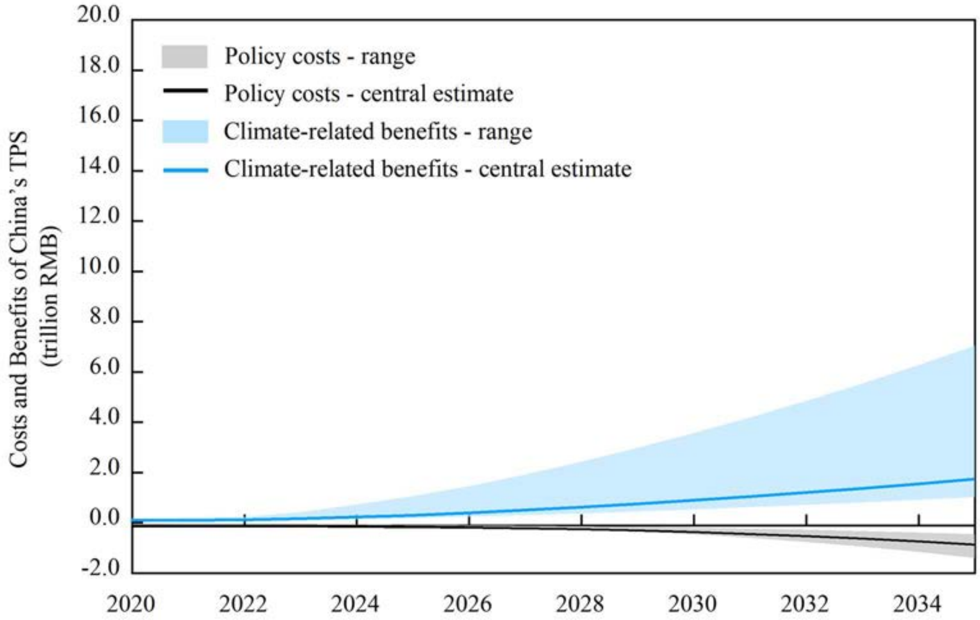


Figure 7. Change in Wind- and Solar- Electricity Generation Relative to the Baseline

A. Costs and Benefits, Excluding Health Benefits from Improved Air Quality



B. Costs and Benefits, Including Health Benefits from Improved Air Quality

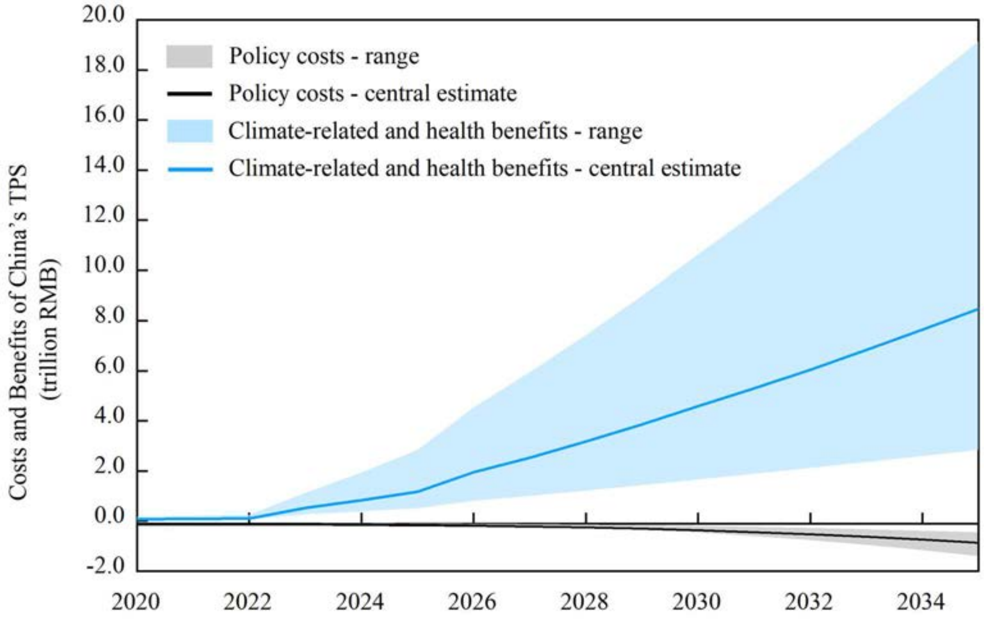


Figure 8. Costs and Benefits of China’s TPS

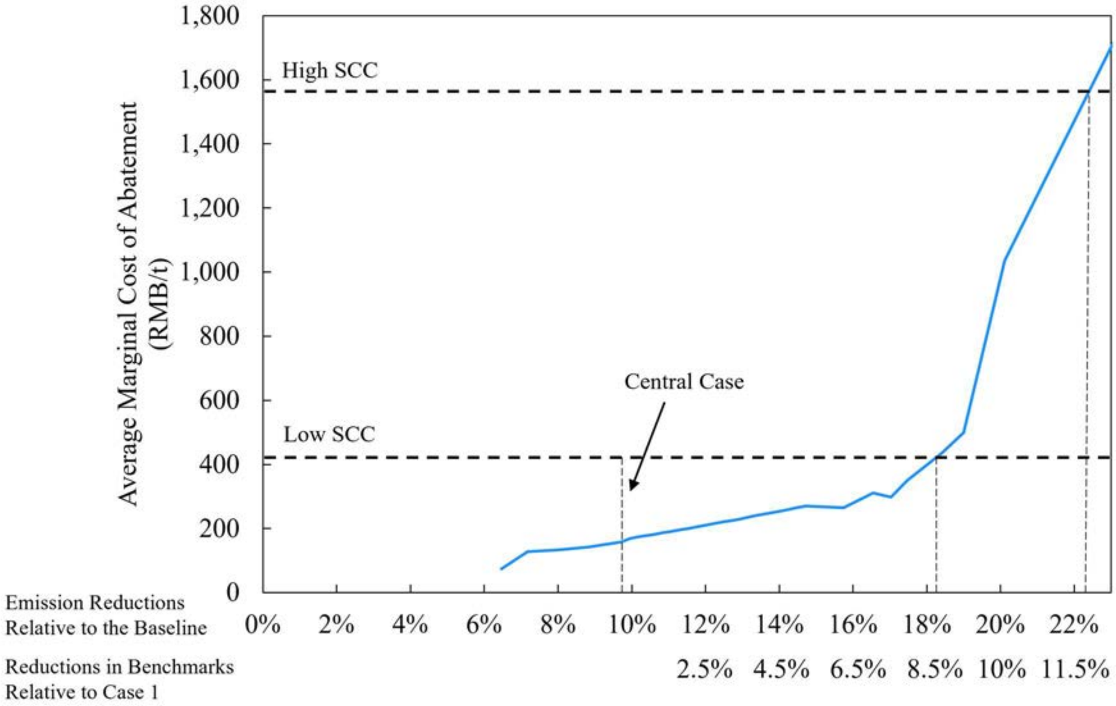


Figure 9. Average Marginal Cost of Abatement Under Alternative Benchmark Stringencies

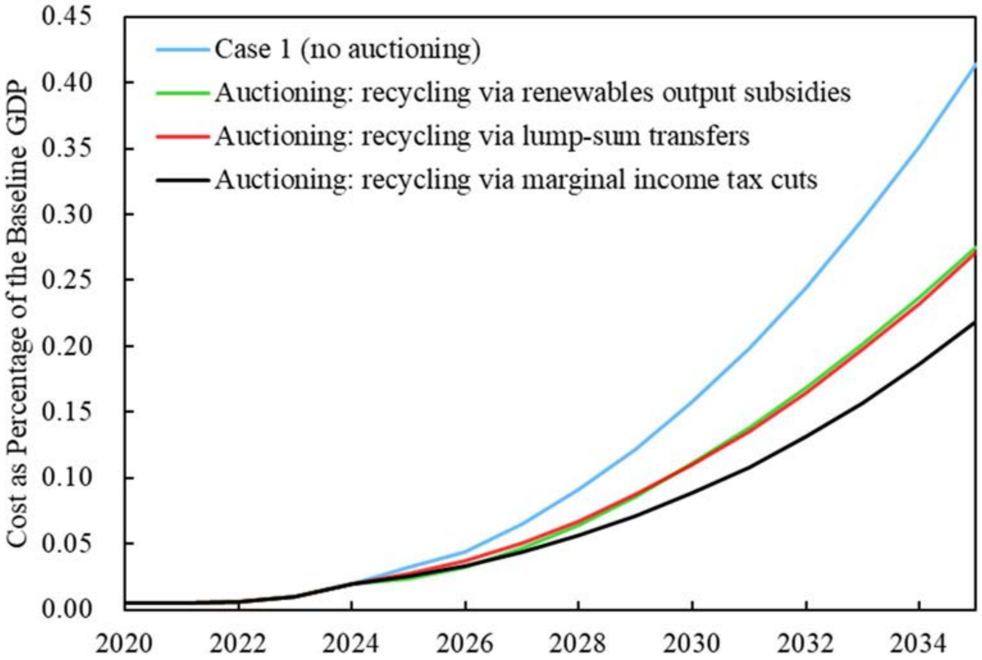


Figure 10. Economic Costs under Different Auction Revenue Recycling Options, 2020-2035

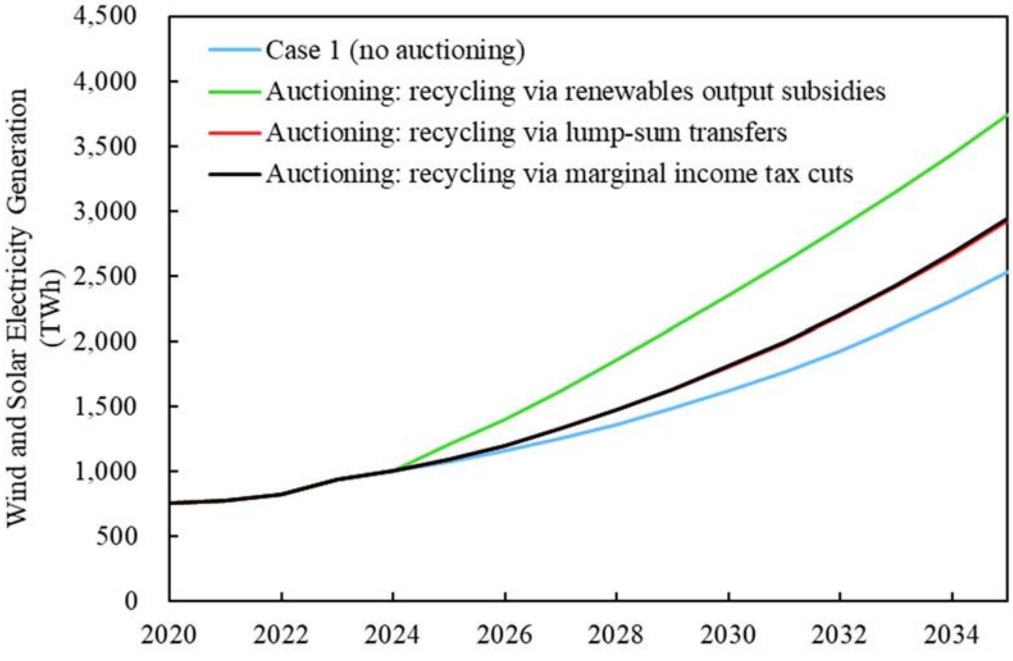


Figure 11. Wind and Solar Electricity Generation under Different Auction Revenue Recycling Options, 2020-2035

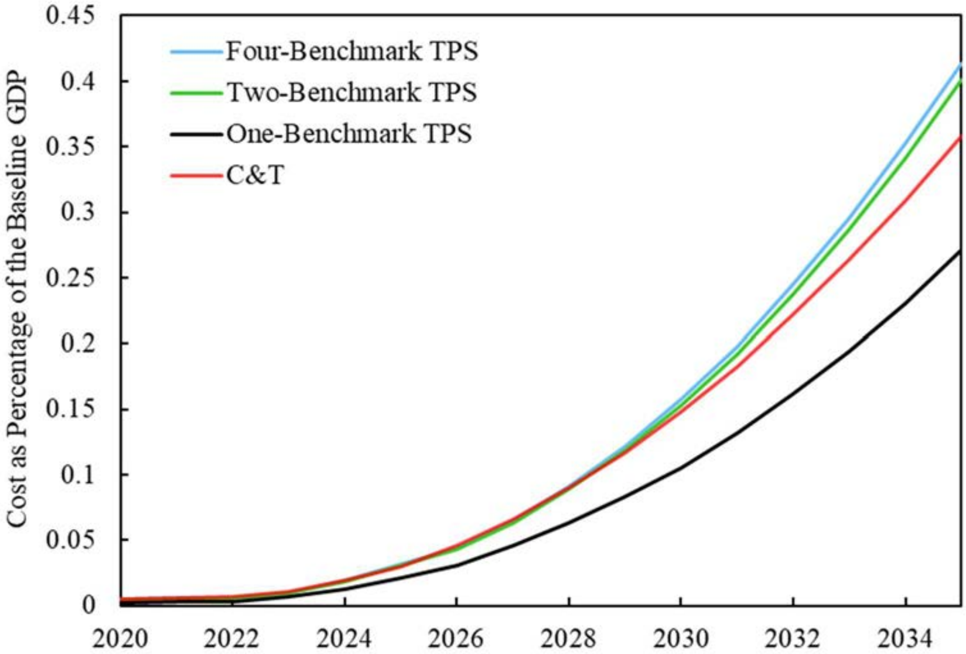


Figure 12. Economic Cost as Function of Number (and Variation) of Benchmarks