China's Nationwide CO_2 Emissions Trading System: A General Equilibrium Assessment[*]

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Abstract

China's CO_2 emissions trading system, the world's largest, aims to significantly reduce CO_2 emissions. The system is a tradable performance standard (TPS), differing from cap and trade (C&T). We provide a dynamic general equilibrium assessment that uniquely considers institutional and fiscal features of China that affect policy costs and distributional impacts. Key findings: the TPS's environmental benefits exceed its costs by a factor of five or more. Interactions with the fiscal system reduce or eliminate the TPS's cost disadvantage relative to C&T. Introducing auctioning as a complementary source of allowance supply can reduce costs by 30%.

Keywords: carbon pricing, tradable performance standard, general equilibrium policy analysis.

JEL Codes: D58, D61, H23, Q52, Q54, Q58.

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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 aims to make a major contribution toward halting aggregate emissions growth by 2030 and achieving the nation's goal of net-zero CO_2 emissions before 2060 (MEE, 2024).

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 a reduction in the nation's 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.[2]

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[1] Goulder et al. (1999) and Fischer (2001) offered initial theoretical studies of the efficiency properties of performance standards. Subsequent studies examining potential or actual rate-based climate policies in the US include Fischer et al. (2017) and Bushnell et al. (2017). Recent studies of China's TPS include Pizer and Zhang (2018), Goulder et al. (2022), and Yu et al. (2022).

[2] Examples of input-oriented intensity standards 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. Input-oriented intensity standards implicitly subsidize the cleaner inputs and tax the dirtier ones. Studies of low-carbon fuel standards include Holland et al. (2009) and Bento et al. (2020). Analyses of renewable portfolio standards include Fischer (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 and Kellogg (2022) examine such standards. Fullerton and Metcalf (2001), Fischer and Newell (2008), Goulder and Parry (2008), Metcalf (2019), and Dimanchev and Knittel (2023) survey the efficiency attractions and limitations of a wide range of climate policy instruments, including intensity standards and cap and trade.

China's TPS includes provisions under which covered facilities may trade emissions allowances. Trades alter the distribution of abatement efforts across facilities and bring about more abatement 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 amount authorized by the facility's allocated emissions allowances, an amount that usually is exogenous from the facility's perspective.[3] In contrast, under the TPS's intensity-based approach, the number of allowances granted to a covered facility is endogenous – the product of the facility's assigned benchmark and its chosen level of output. 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 emissions-reduction targets and the distributional impacts.

This paper offers an analytical model that assesses the economic costs of the TPS and C&T under a range of conditions, including different characteristics of the tax system. If prior taxes on factors (capital and labor) or goods are ignored, the model indicates that the TPS is less cost-effective than C&T, paralleling a central finding from prior studies.[4] This disadvantage reflects the TPS's implicit subsidy to output stemming from the fact that a firm's allowance allocation is proportional to its output. However, in contrast with prior studies, our analytical model shows that the TPS's cost-disadvantage can decline or even disappear when prior taxes are accounted for.

These and other analytical results are reinforced by the results from our numerical model, a multi-sector, multi-period general equilibrium model that yields quantitative outcomes. We apply the numerical model to assess the

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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 in the previous year and thus is endogenous.

[4] See Goulder et al. (1999), Fischer (2001), and Goulder et al. (2022).

TPS's impact on production costs, supplies, prices, and CO_2 emissions over the 2020-2035 interval.

The numerical model has several distinguishing features that enable it to identify economic forces and outcomes with 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 disregards significant differences between the TPS and C&T.[5] In contrast, this paper considers how institutional and regulatory features of China's economy influence the TPS's costs and the differences between its costs and those of C&T. Key features include the pre-existing taxes and subsidies, administered pricing of some electricity output, direct support of renewable electricity, and the preferential treatment of state-owned enterprises (SOEs).

Second, the model employs a general equilibrium framework, enabling it to account for interactions among sectors covered by the TPS as well as between the covered and non-covered sectors. Earlier studies examining China's TPS have tended to employ partial equilibrium models.[6] We are aware of only one general equilibrium model that studied China's TPS: Yu et al. (2022).[7] 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 within- and across-sector variation of TPS benchmarks – consistent with the actual design of China's TPS. In addition, while Yu et al. (2022) 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, capturing changes in policy stringency

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[5] Some relatively recent studies recognize these differences. See, for example, Goulder et al. (2022), Ma and Qian (2022),Yu et al. (2022), Fischer et al. (2024) and Long et al. (2024).

[6] The partial equilibrium studies include Goulder et al. (2022), Ma and Qian (2022), and Geng and Fan (2024).

[7] Jin et al. (2020), 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.

and impacts over time. The few existing TPS studies that incorporate intertemporal dynamics tend to focus on individual sectors.[8] 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 previously. 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, its regulatory authority, the Ministry of Environment and Ecology (MEE), continues to make decisions about the design of later phases. The model can incorporate alternative potential policy designs, which have differing implications for aggregate costs, their distribution across sectors and regions, and the scale of emission reductions.

Our analysis yields significant new 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 2020-2035 interval would exceed its cost by a factor of six. Taking account of the health benefits from improved local air quality increases the benefit-cost ratio to 28.[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 2020-2035 interval, the average discounted marginal cost of abatement is well below the average marginal benefit from emissions abatement. Using a low SCC (307 RMB, i.e., 44 dollars) per ton in 2020, the efficiency max-

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[8] See, for example, Becker (2023) and Yu et al. (2022).

[9] 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. Its estimate for 2020 was 353 RMB per ton (51 dollars). In Section 6 below we consider results under a range of SCC estimates.

imization would call for the use of benchmarks 8% tighter than the current and projected 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.[10]

Third, the TPS's costs relative to those of an equivalent C&T system change significantly over time. As mentioned, prior analytical studies have recognized the TPS's disadvantage stemming from the fact that it implicitly subsidizes intended output, as covered facilities receive free allowances for each additional unit of production. Consequently, they rely too little (from an efficiency point of view) on output-reduction to achieve compliance, since reducing output implies a reduction in the allowance allocation. Our analytical and numerical models reveal two additional and significant determinants of the TPS's absolute costs and its costs relative to those of C&T. Pre-existing taxes are one additional and critical determinant. 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.[12] This offsets what otherwise would be a larger disadvantage of the TPS in terms of cost-effectiveness. Numerical simulations indicate that this offset is quantitatively important. A second key determinant is policy stringency. The TPS's cost relative to C&T's increases with the stringency of the emissions-reduction target. In the shorter term, pre-existing output taxes eliminate

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[10] Using the higher SCC estimates from recent studies would call for still greater stringency and associated emissions reductions. See Section 6.

[11] See Lee and Misiolek (1986), Bovenberg and Goulder (1996), Goulder et al. (1997), Fullerton and Metcalf (2001), Williams III (2002), and West and Williams III (2007). Goulder et al. (2024) find that because of tax-interaction effects, a narrower US climate policy – one that excludes certain sectors – can be more cost-effective than a broader one.

[12] This result is akin to the findings in Goulder et al. (2016), which found that prior taxes reduce the costs of a US Clean Energy Standard relative to an equally stringent C&T policy.

almost all of the gap in costs that otherwise would apply. However, the situation changes over the longer term. As shown below, increased stringency implies higher allowance prices; the higher prices expand the distortionary impact of the implicit subsidy and overwhelm the benefit from pre-existing taxes. This underlies our finding that while the costs of the TPS and C&T are quite similar in the near term, the TPS's costs per ton become significantly higher than those of C&T over time as stringency increases and allowance prices rise.

Fourth, supplying some allowances via an auction can lower the economic costs of achieving given emissions-reduction targets. Under central values for production parameters, introducing an allowance auction lowers economy-wide costs by 29–43% relative to the no-auction case, depending on how auction revenues are recycled. Introducing 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 lower when auctioning contributes to allowance supply. 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.

Fifth, the simulation results reveal important trade-offs between cost-effectiveness and distributional equity across provinces and sectors. 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 has four different benchmarks for the electricity sector. We find that employing a single benchmark for this sector over the 2020-2035 interval would lower economy-wide costs by 33% 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%.

The rest of this paper is organized as follows. Section 2 describes the basic features of the TPS and conveys the analytical model's structure and results.

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 discusses results from our sensitivity analysis. Section 8 offers conclusions.

2 The TPS

2.1 Basic Features

A 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.

2.2 An Analytical Model

The analytical model is static, with a representative household deriving utility from a polluting good (X) and a non-polluting good (Y) produced using labor (L). The marginal product of labor is assumed to be constant, and units are defined so that under the status quo ante (i.e., in the absence of regulation), the unit costs of producing X and Y are unity. Any tax revenues received by the government are assumed to be returned to the private sector in the form of lump-sum transfers.

The household's utility function is given by:

$$U = u\left(X, Y\right) - \varphi\left(E\right) \tag{1}$$

where $u\left(\cdot\right)$ is utility from consumption and $\varphi(\cdot)$ is the disutility from emissions E. The household budget constraint is $p_X X + Y = L$, where p_X denotes the price of X.[13] For simplicity, the analysis below makes no reference to administered pricing of electricity. Appendix A.1 shows that such pricing (as structured in China) has inframarginal impacts that do not alter the efficiency outcomes.

The gross cost to firms of emissions abatement is given by $C = c\left(a\right) X$, where a is the emission reduction per unit of output, and $c(a)$ is the per-unit

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[13] Labor supply is treated as exogenous. We consider endogenous labor supply in Appendix A.5.

cost. Total emissions after abatement are $E = (e_0 - a)\,X$, where e_0 denotes the baseline emissions per unit of output.

An important feature of the model is its consideration of pre-existing taxes.[14] We first compare the costs of the TPS and C&T in the absence of such taxes and then consider the implications of their presence. Detailed proofs are provided in Appendix A.2.

2.2.1 No pre-existing taxes

Under C&T, the free initial allocation of allowances generates rent $\pi = t_E A_0$, where t_E is the price of allowances and A_0 the initial allocation. This rent contributes to household income since households own firms; thus the household budget constraint is now $p_X X + Y = L + \pi$. From this setup, we obtain the indirect utility function $V = v\,(p_X, \pi) - \varphi(E)$. Producers are assumed to be competitive, supplying output to the point where marginal cost equals the price:

$$P_X = \underbrace{1}_{\text{MC production}} + \underbrace{c\,(a)}_{\text{MC abatement}} + \underbrace{t_E(e_0 - a)}_{\text{MC allowance}} \tag{2}$$

Firms choose a to maximize profits, yielding the condition $t_E = c'(a)$.

Here we address the economic costs of the TPS and C&T. The price of an emissions allowance functions as a virtual tax t_E on emissions. We examine the effects of a marginal change in t_E. The change can be relative to an initial value of zero (indicating the introduction of a carbon pricing policy) or from an initially positive value. Although the focus is on marginal changes, the impact of a significant change to the virtual emission tax can be viewed as the integral of successive marginal changes.

Under C&T, the economic cost of a marginal increase in t_E is:

$$\text{C\&T:} \quad -\frac{1}{\lambda}\frac{dv}{dt_E} = \underbrace{c'\,(a)\,\frac{da}{dt_E}X}_{\text{MC abatement }(W_1)} + \underbrace{\left(-\frac{dX}{dt_E}\right)t_E\,(e_0 - a)}_{\text{MC allowances }(W_2)} \tag{3}$$

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[14] Goulder et al. (2016) and Landis et al. (2019) compared the cost-effectiveness of intensity standards and carbon pricing in the presence of other taxes. Our analytical model is distinct in its focus on cost-differences between China's TPS and an equivalent cap-and-trade system and the significance of differing prior tax rates in covered and non-covered sectors.

where λ represents the marginal utility of income. The regulatory cost on the right-hand side includes the marginal cost of abatement (W_1) and the marginal cost of (additional) allowances (W_2), where the latter is the product of the change in output ($-\frac{dX}{dt_E}$) and the allowance cost associated with the change in output ($t_E\left(e_0-a\right)$).

Under the TPS, the price equation is $p_X = 1 + c\left(a\right) + t_E\left(e_0 - a - \beta\right)$, where β is the applicable TPS benchmark. In this case, the economic cost is :

$$\text{TPS:} \quad -\frac{1}{\lambda}\frac{dv}{dt_E} = \underbrace{c'\left(a\right)\frac{da}{dt_E}X}_{\text{MC abatement }(W_1)} + \underbrace{\left(-\frac{dX}{dt_E}\right)t_E\left(e_0-a-\beta\right)}_{\text{MC allowances }(W_2)} \tag{4}$$

The difference from C&T is the presence of the benchmark β, which implicitly subsidizes output. This implicit subsidy, equal to $t_E\beta$, distorts output levels under a TPS. The subsidy-induced distortion leads to relatively inefficient use of output-reduction as a channel for emissions abatement under the TPS, increasing the TPS's overall costs relative to C&T.[15] Appendix A.3 replicates the well-known result that absent other taxes or market failures, C&T minimizes the costs of achieving a given emissions-reduction target. The TPS outcome differs from the C&T outcome, implying that the TPS is less cost-effective.

2.2.2 Pre-existing taxes

We now contrast the outcomes in the presence of per-unit taxes on output.[16] Government expenditure (G) is financed through tax revenue:

$$t_X X + t_Y Y = G \tag{5}$$

where t_X and t_Y represent the output tax rates applying to the two goods. The tax rates are net of applicable subsidies. Net tax revenue is returned to the private sector via lump-sum transfers (T). Under C&T, the budget constraint is $\left(p_X + t_X\right)X + \left(1 + t_Y\right)Y = L + \pi + T$. Under the TPS, it is $\left(p_X + t_X\right)X + \left(1 + t_Y\right)Y = L + T$. The government is assumed to run a

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[15] See Fischer et al. (2017) and Goulder et al. (2022) for detailed discussions of this issue.

[16] We consider existing output taxes instead of factor taxes because output taxes account for a significantly larger share of China's tax revenues. As shown in Appendix A.5, the qualitative results are the same when factor (labor) taxes are considered.

balanced budget: $T = G$.

Now consider how prior taxes affect the relative costs of the two policies. Under pre-existing taxes, the economic costs of a marginal change in t_E are:

$$\text{C\&T:} \quad -\frac{1}{\lambda}\frac{dv}{dt_E} = \underbrace{c'(a)\frac{da}{dt_E}X}_{\text{MC abatement }(W_1)} + \underbrace{\left(-\frac{dX}{dt_E}\right)t_E\left(e_0 - a\right)}_{\text{MC allowances }(W_2)}$$

$$+ \underbrace{\frac{1}{M_G}\left[t_X\left(-\frac{\partial X}{\partial p_X}\right) - t_Y\left(\frac{\partial Y}{\partial p_X}\right)\right]\frac{E}{X} + \frac{1}{M_G}\left(-t_X\frac{\partial X}{\partial \pi} - t_Y\frac{\partial Y}{\partial \pi}\right)\frac{d\pi}{dt_E}}_{\text{TI effect }(W_3)}$$

$$\text{TPS:} \quad -\frac{1}{\lambda}\frac{dv}{dt_E} = \underbrace{c'(a)\frac{da}{dt_E}X}_{\text{MC abatement }(W_1)} + \underbrace{\left(-\frac{dX}{dt_E}\right)t_E\left(e_0 - a - \beta\right)}_{\text{MC allowances }(W_2)}$$

$$+ \underbrace{\frac{1}{M_G}\left[t_X\left(-\frac{\partial X}{\partial p_X}\right) - t_Y\left(\frac{\partial Y}{\partial p_X}\right)\right]\left(\frac{E}{X} - \frac{d(t_E\beta)}{dt_E}\right)}_{\text{TI effect }(W_3)}$$

where $M_G \equiv 1 - t_X\frac{\partial X}{\partial G} - t_Y\frac{\partial Y}{\partial G}$.

The tax-interaction effect (W_3 above) enters as a third term in the cost expressions. This effect differs across policies and influences their relative costs. Excluding the very last term for the C&T,[17] the impact of tax-interactions on the cost wedge between the TPS and C&T now depends on the sign of $t_X\left(-\frac{\partial X}{\partial p_X}\right) - t_Y\left(\frac{\partial Y}{\partial p_X}\right)$, which is the weighted difference between the tax rates, with the own price elasticity $\left(-\frac{\partial X}{\partial p_X}\right)$ and cross price elasticity $\left(\frac{\partial Y}{\partial p_X}\right)$ as the weights. If the weighted difference $t_X\left(-\frac{\partial X}{\partial p_X}\right) - t_Y\left(\frac{\partial Y}{\partial p_X}\right)$ is greater than zero, the TPS has a smaller adverse tax-interaction effect than C&T. Our data show that for all of the major categories of taxes we consider, the covered sectors

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[17] The additional C&T term $\frac{1}{M_G}\left(-t_X\frac{\partial X}{\partial \pi} - t_Y\frac{\partial Y}{\partial \pi}\right)\frac{d\pi}{dt_E}$ is an income effect. This effect tends to be negative, so it favors C&T. Therefore, the influence of the tax-interaction effect on relative policy costs depends on the price effect wedge through the impacts on p_X, which (as shown below) tends to favor the TPS, and the income effect wedge, which favors C&T. In our numerical simulations the price effect has a larger impact on the wedge than the income effect, implying that pre-existing taxes narrow the overall wedge between the TPS and C&T. See Appendix A.4 for details.

are overtaxed relative to its non-covered sectors.

Higher net taxes in the covered sector underlie the TPS's smaller tax-interaction effect and the result that prior taxes lower the TPS-to-C&T cost ratio. Because the X sector faces a higher tax burden – as $t_X\left(-\frac{\partial X}{\partial p_X}\right) - t_Y\left(\frac{\partial Y}{\partial p_X}\right)$ is positive – labor is under-allocated to X prior to the introduction of either environmental policy.[18] Both the TPS and C&T further reallocate labor away from the X sector, worsening the allocation on efficiency grounds (abstracting from the environmental externality). However, the extent of the reallocation differs across the two policies. The TPS's implicit subsidy to output moderates the further reallocation: because of this subsidy, output is higher and more factors are employed in X under the TPS than under C&T. This accounts for the smaller adverse tax-interaction effect under the TPS. The smaller tax-interaction effect reduces the disadvantage of the TPS in terms of cost-effectiveness. Thus, in China's case, pre-existing taxes reduce the cost wedge. Appendix A.4, A.5, C.3 provide comparative statics and other details.

The cost wedge also depends on policy stringency. As indicated above, the distortion from the TPS's implicit output subsidy is related to $t_E\beta$. Higher stringency reduces the relative cost-effectiveness of the TPS if the relative increase in t_E exceeds the relative reduction in β (*i.e.*, if $\frac{d(t_E\beta)}{dt_E} > 0$). It is theoretically ambiguous whether the rate of increase in emissions allowance prices t_E stemming from the tightening of the benchmarks β exceeds or falls short of the rate at which the benchmarks are tightened. In Section 6 we address this question with numerical simulations using plausible functional forms, parameters, and fiscal conditions.

3 The Numerical Model

3.1 Main Features

Our multi-sector dynamic computable general equilibrium (CGE) model considers key economic factors that determine the TPS's aggregate costs and

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[18] This analytical model focuses on labor, but it is straightforward to show that the result will hold for capital to the extent that net tax rates on the capital are higher in the X sector than the Y sector.

their distribution. We briefly describe the model's structure here. A complete description is in Appendix B.

The model captures the interactions among the production, household, and government sectors. It distinguishes 31 production sectors (see Appendix Table B1), including nine that are expected to be included in China's TPS. A distinguishing feature of our model is its recognition of the heterogeneity in production processes within sectors. It accomplishes this by exploiting information from a unique firm-level dataset on emissions, output, and energy use obtained from the MEE. This enables the model to capture the differing impacts of the TPS on facilities of different emissions intensities within a given sector. This enables the model to capture closely the TPS's designs, which involves different benchmarks for differing facilities within a given sector.

Another important feature of the model is its consideration of important government interventions in the market, including taxes on and subsidies to productive inputs, subsidies to renewable electricity output, the preferential treatment of SOEs, and administered pricing of some of the electricity supplied.

3.2 Production

The primary production factors are labor, capital, land, and "natural resources." 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 an immobile factor employed in the agriculture sector. Natural resources are primary factors in the wind, solar, hydro, and nuclear electricity production sectors; these resources are not mobile across sectors or subsectors. Details are in Appendix Figure B2.

The electricity, cement, aluminum, and iron & steel sectors subdivide into subsectors.[19] The rationale and method for subsector classifications are offered

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[19] In the electricity sector, the model distinguishes renewable electricity (solar, wind, and hydro), nuclear electricity, and fossil-based electricity. Within the group of fossil-based electricity generators, the model distinguishing eleven generation technologies. The cement, aluminum, and iron&steel sectors also have subsectors with differing production technologies and associated input intensities. Notwithstanding the differences in input

in Appendix C. Production is represented by nested constant elasticity of substitution (CES) functions. Each sector (or subsector, where applicable) employs material inputs, energy, and factor inputs for production.

SOEs are an important feature of the Chinese economy. In 2014 (the most recent year with available SOE data), they accounted for about 31% of the value of economy-wide output. They are especially important in the crude oil and electricity sectors, where they account for more than 87% of the output value (see Appendix Table D3).

The model distinguishes the SOEs and POEs within a sector or subsector. We model SOEs and POEs as profit-maximizing firms that enjoy subsidies and face taxes.[20] The functional forms of both types of firms are the same, though parameters differ. The subsidies and the taxes are regarded as exogenous from the firm's point of view. SOEs benefit from preferential treatment through capital subsidies. Workers in SOEs often receive higher social security payments and pensions, resulting in a higher cost for labor input in these enterprises.[21] The model addresses the coexistence of SOEs and POEs in markets, noting that market dominance is not solely due to preferential treatment but also marginal cost considerations. In the model, marginal costs increase with supply, reflecting the reliance on imperfectly mobile capital as input and 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.

As was noted, the model also incorporates the administered pricing in

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intensities across subsectors, the outputs from subsectors of a given sector are treated as homogeneous and face the same market price.

[20] At the beginning of this century, profit-maximization conditions played a limited role in decisions regarding production and investment in SOEs (Whalley and Zhang, 2006). This is because China implemented central planning across all industries in the early days of the PRC, rather than using SOEs as a policy instrument to address market failures (Chen et al., 2021). Over the past two decades, the Chinese government has implemented multiple rounds of reforms to improve the governance of SOEs and strengthen profit motives. Despite their state-sponsored origins, today the behavior of Chinese SOEs is quite similar to that of other profit-maximizing firms (Chen et al., 2021).

[21] Prior literature that provides evidence on these preferential treatment to SOEs include Song et al. (2011), Hsieh and Klenow (2009), Berkowitz et al. (2017), and Han et al. (2021).

China's electricity market and the ongoing electricity market reform in China. As Appendix B indicates, electricity generators must sell a fixed amount of their electricity at a government-administered price (usually higher than the market price); production beyond that level is sold at market prices. Administered pricing is expected to apply only until 2025, as ongoing reform suggests a fully liberalized Chinese electricity market.[22]

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 consumption expenditure across specific consumer goods.

The household derives income from its ownership of labor, capital, land, and natural resources, and from a lump-sum transfer from the government. The income is used for consumption and private saving, where the latter finances investment, that is, expenditure on an investment good. The savings rate is a positive function of the return on current investment, as households have static expectations.

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, import tariffs, and export subsidies. 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.

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[22] China has been advancing electricity market reforms, pushing all the fossil- and renewable-based power plants to enter the market, eliminating the administered pricing by 2025 (NDRC, 2021; NDRC and NEA, 2022, 2025).

3.5 Foreign Trade

The model regards 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.[23]

3.6 Equilibrium

General equilibrium requires supply-demand balances 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 uses the year 2020 as the base year and solves at one-year intervals from 2020 through 2035.[24] 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 capital stock in the next period is the current stock plus aggregate real investment net of current-period depreciation. The

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[23] In Appendix H.5, we examine the implications of relaxing the assumption that China is a price taker in the international market. This has a minor impact on overall emissions reductions and policy costs. Thus, our primary conclusions remain robust under alternative trade assumptions.

[24] The model is solved as a mixed complementarity problem with a Newton-based solver. The formulation of the mixed complementarity problem is provided in Appendix E.

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. AEEI is an exogenous increase in the productivity of a composite energy input into production. As indicated below, the AEEI rate differs across sectors. Hicks-neutral technological change applies to all sectors but at different rates across sectors. These differences give rise to structural change in China – in particular, the transition involving increased representation of the service sector (Święcki, 2017) and the increased penetration of renewable electricity.

4 Data and Parameters

4.1 Data

Data from several sources to create a consistent database for inputs, outputs, and emissions. Details on data sources and processing steps are in Appendix C.

Input-output data as well as data on household consumption, government consumption, and investment in China are obtained for the year 2017 from the National Bureau of Statistics (National Bureau of Statistics, 2018a). Information on taxes and subsidies on inputs and goods are obtained from the Global Trade Analysis Project (GTAP 10) database (Aguiar et al., 2019) and are scaled using China's input-output tables to ensure the tax rates reflect China's actual conditions. CO_2 emissions from production are derived from the sectoral energy use data in the 2017 China energy balance table (National Bureau of Statistics, 2018b). We updated the input and output data so that the GDP, total CO_2 emissions, value-added shares of the service sector and agriculture sectors, and total tax revenue net of subsidies match the published statistics in 2020 (National Bureau of Statistics, 2021). The sectoral data were then disaggregated into subsectors for electricity, cement, aluminum, and iron & steel sectors according to the subsector-level information obtained by aggregating firm-level data collected by the MEE. These data provide production, fossil fuel energy consumption, electricity usage, heat rate, and CO_2 emissions at the plant level. The plant-level data spans the electricity, cement, aluminum, and iron & steel sectors.

Data on the costs of changing the heat rates of fossil-based power plants were obtained from a series of reports by the National Development and Reform Commission of China (2016, 2017). Data on the costs of adding renewable electricity capacity were obtained from Zhang et al. (2023).[25] Data on administered pricing of electricity were obtained from the China Electricity Council (2019). Key data pertaining to SOEs and POEs were obtained from the Chinese Industrial Enterprise Database (NBS, 2017) and literature (Han et al., 2021). The database offers 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.

4.2 Parameters

We outline the parameterization methods here; details are in Appendix D.

The nested production structure requires share parameters and substitution elasticities for the production function or subfunction at each nest or subnest. Input share parameters were identified from the requirement of consistency between base-year data on sector inputs and outputs and the benchmark input-output table. Parameters for the shares of capital inputs in SOEs and POEs were identified by equating marginal costs of production and the given market's output price.

Several important elasticities are obtained via calibration. For fossil electricity production, the substitution elasticities between the energy and the factor composite are calibrated to ensure that, in the baseline simulations, subsector-level marginal costs of reducing heat rates match points on separately derived curves for subsector-level costs of reducing heat rates. For renewable electricity production, the substitution elasticities between the natural resource input and other inputs and the share of the natural resource

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[25] 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 D for details.

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 of adding renewable electricity capacity. Substitution elasticities between electricity and non-electricity input and the substitution elasticities between consumption and private savings are based on empirical estimates of Hu et al. (2019). The time-profile of effective labor and the rate of Hicks-neutral technological changes are calibrated to match the historical data during 2020-2023, and projections for the future (SIC, 2020; IRENA, 2024; NBS, 2024).

Other substitution elasticities are derived from the GTAP database, which offers an extensive and consistent collection of elasticity estimates spanning China's major sectors. The database concentrates on trade relationships. To enhance the database to capture more closely some critical energy flows, we selected energy-related elasticities based on a comprehensive literature review of empirical estimates for China (Feng and Zhang, 2018; Li and Lin, 2016).

5 Scenarios

The TPS will be introduced in phases. The first began in 2021 and covers only the power sector. In the second phase which began in late 2024, coverage expands to include the cement, aluminum and the iron & steel sector.[26] 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.

We examine the TPS's impacts in each phase. Table 1 describes the policy cases considered. The cases differ in terms of the number of benchmarks and in terms of the presence or absence of an auction to supply some of the emissions allowances. Case 1 aligns most closely with current plans by the MEE in terms of initial benchmark values and rates of benchmark tightening over time. Table D6 in Appendix D provides the benchmark values in all

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[26] The first compliance cycle of Phase 1 requires firms to submit allowances for their emissions in 2019 and 2020, and the second compliance cycle of Phase 1 corresponds to emissions in 2021 and 2022.

policy cases.

TABLE 1 Policy Cases Considered

Case	Specification
Case 1: Central case	- *Number of benchmarks.* 4 benchmarks apply to the electricity sector: 3 for coal-fired and 1 for gas-fired. 2 benchmarks apply to the iron & steel sector.a 1 benchmark applies to each of 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[a] 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 from 2020 to 2022, and is 1.0%/year for 2023 and 2024, according to the MEE. We assume the tightening rate for the electricity sector is 1.5%/year from 2025 to 2035. The rate for other sectors is 2.5%/year.[b]
Case 2: Fewer electricity sector benchmarks	- *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: Introduction of an 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.

[a] One for the basic oxygen process and one for the electric arc furnace process.

[b] 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.

6 Results

6.1 Aggregate Impacts

6.1.1 Emissions Reductions

Figure 1a compares CO_2 emissions under the baseline with emissions under the TPS in Case 1. As indicated in the figure, the emission reductions become progressively larger as the system's coverage expands and the benchmarks are tightened. Relative to the baseline, the emissions reduction over the Phase

2 interval is almost three times the reduction during Phase 1; the reduction over the Phase 3 interval is more than three times the reduction during Phase 2. Over the entire interval 2020-2035, the cumulative emissions reduction is estimated to amount to 18 billion tons, or 8.6% of the cumulative baseline emissions.

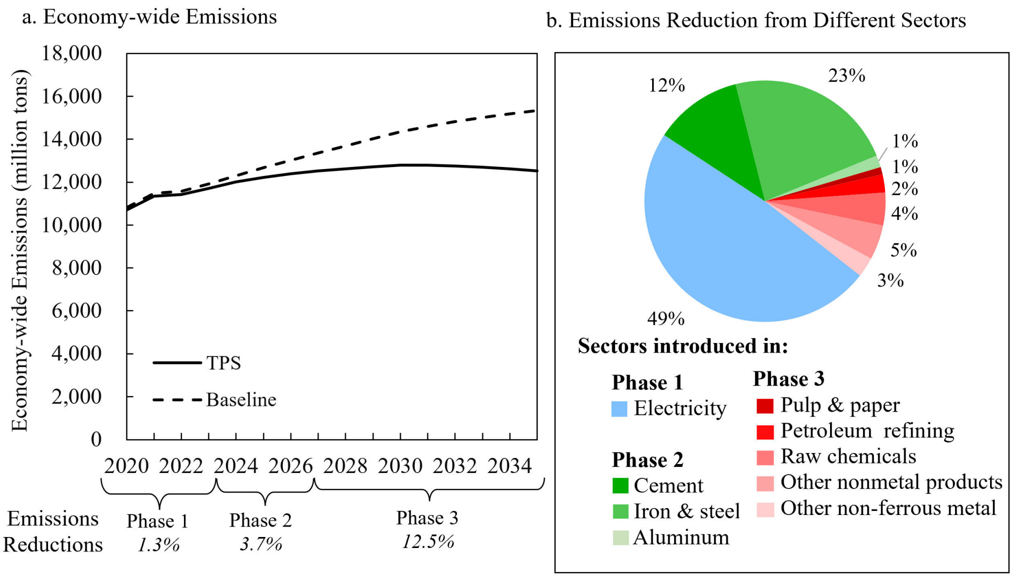

FIGURE 1 Economy-wide Emissions under the TPS and the Baseline

Figure 1b 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 49% and the latter collectively accounting for 36% of the total. Over the 2020–2035 interval, the TPS gives rise to a small amount of emissions leakage – a slight (0.2%) increase in emissions from non-covered sectors – reflecting the increase in the demand for coal by these sectors because of the lower coal prices.[27]

6.1.2 Aggregate Costs under the TPS

Table 2 presents the TPS's aggregate costs, measured both by the change in GDP and by the equivalent variation measure of the change in household

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[27] This includes leakage to ultimately covered sectors in years before their coverage begins.

utility. The GDP cost in Phase 1 is relatively small (less than 0.01%), 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 interval 2020–2035 is 1.6 trillion RMB, 0.10% 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 negative impacts on investment are substantial because the main inputs into the production of investment goods are iron & steel and cement, which are covered by the TPS.

TABLE 2 Summary of Costs in 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 (2020-2023)	26	13	0.6	43	21
Phase 2 (2024-2026)	64	11	1.4	46	8
Phase 3 (2027-2035)	1,503	364	16.3	92	22
Overall (2020-2035)	1,593	388	18.3	87	21

Note: The costs in the table are expressed in 2020 constant prices. In this paper, we use an exchange rate of 6.9 RMB per dollar, which represents the average exchange rate for the year 2020.

We explore the significance of the SOEs on aggregate costs by examining a counterfactual case where SOEs do not receive favorable treatment. Preferential treatment has mixed efficiency impacts, reflecting its effects on the allocation of capital across sectors. We diagnose the impact of favorable treatment through counterfactual simulations. As indicated in Appendix H.3, the effect of preferential treatment varies across sectors and, depends on the preexisting tax rates on capital. In the electricity sector, preferential treatment tends to raise overall policy costs because that sector's capital already faces relatively low taxes and is overallocated (in terms of efficiency) toward that sector. In contrast, in several industrial sectors, preferential treatment works toward lower overall policy costs, as the sectors face high capital tax rates and capital is underallocated toward those sectors. The overall cost-impact of preferential treatment over the 2020–2035 interval is relatively small, as the positive and negative impacts largely cancel out.

We also examine the significance of administered electricity pricing, with results summarized in Appendix Table H7. Administered pricing applies only to Phase 1, as it is to be phased out by 2025. The limited presence of such pricing, combined with the previously mentioned fact that such pricing only affects inframarginal production, implies that such pricing has a relatively small impact on the TPS's costs. We consider the potential quantitative impact of such pricing through a comparison with a counterfactual simulation in which administered pricing is absent in Phase 1. In the counterfactual case, the TPS's cost per ton is 0.2% lower during that phase. In the absence of administered price, generators with relatively high emissions intensities no longer are compelled to achieve "guaranteed-hour" levels. The associated lower output of these generators has a positive yet slight efficiency impact.

6.1.3 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 C&T alternative. China's policymakers have been seriously considering switching from the TPS to C&T.

Figures 2a and 2b display the allowance prices and economic costs of both approaches, showing some important changes over time. In 2020, the model-generated allowance price is 58 RMB/ton, close to the observed price range of 40–60 RMB/ton during the first compliance period. The rising allowance price reflects the combination of benchmark tightening and broader coverage of the TPS over time.[28] Figure 2b reveals that the relative costs of the TPS and C&T follow a dynamic pattern that to our knowledge has received no prior attention. During the first two phases of the program, the TPS's costs

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[28] The slight price dips from 2023 to 2024 and 2026 to 2027 reflect a short-term reduction in the overall stringency of the TPS during the expansion of coverage.

are close to (and, in some years, slightly below) those of an equally stringent C&T system. But in later years they rise above the C&T costs.[29]

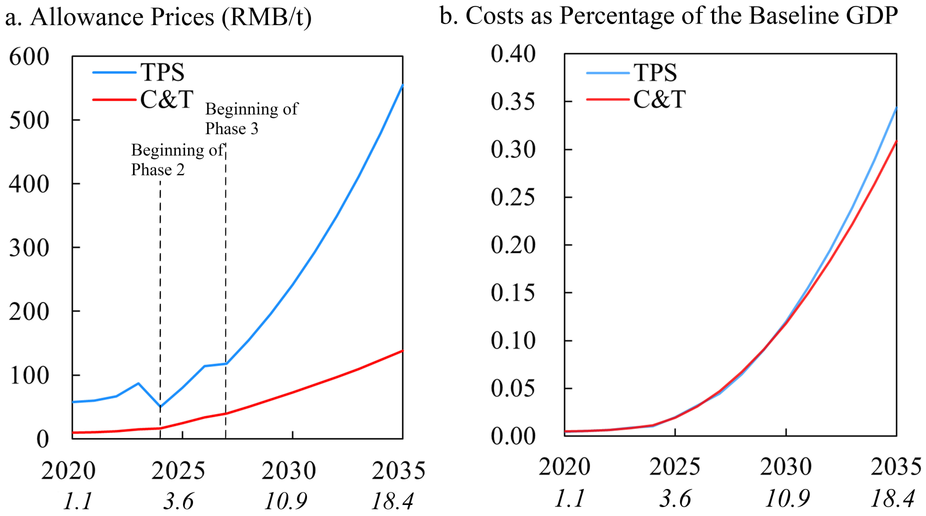

FIGURE 2 Allowance Prices and Economic Costs Over Time

Notes: Numbers in italics are percentage emissions reductions from the baseline. The prices in the table are expressed in 2020 constant prices. In this paper, we use an exchange rate of 6.9 RMB per dollar, which represents the average exchange rate for the year 2020.

Three factors underlie this pattern. First, the TPS's implicit subsidy to output causes covered facilities to make relatively inefficient use of the output-reduction channel to reduce emissions. Figure 3 displays the relative contributions of the three key channels for emissions reductions over the 2020–2035 interval 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 and economic costs rise more under the TPS than under C&T (see Figure 2a).

While this first factor has been recognized in prior studies, our model reveals two other important factors at work. One is policy stringency, which explains the widening gap between the policies' costs over time. The analytical model indicated that the inefficiency associated with the TPS's implicit

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[29] In the simulations of C&T, emissions allowances are allocated for free, and in each year the total quantities allocated are set to match those of the TPS in Case 1. The distributions of the allocations across sectors and subsectors are proportional to those under the TPS.

subsidy is proportional to the product of the benchmark and the allowance price. Greater stringency generally implies a higher allowance price, which augments the importance of the implicit subsidy.[30] By 2030, the allowance prices are high enough to make the inefficiency from the implicit subsidy large enough to cause the TPS's costs to rise significantly above those of C&T.

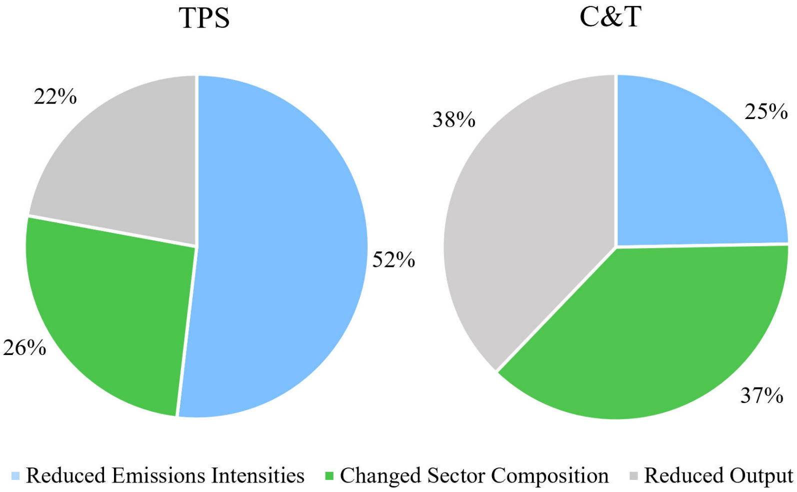

FIGURE 3 Sources of Emissions Reductions Under the TPS and C&T, 2020–2035

Notes: "Reduced Emissions Intensities" identifies the emission reduction that would occur if emissions intensities changed but industry production levels remained at baseline levels. "Changed Sector Composition" designates the reduction that would occur if the only change from the policy were in the shares of production from the different technology classes. "Reduced Output" identifies the reduction that would stem from differences between output under the TPS and the baseline, if emissions intensities and sector composition remained the same as in the baseline.

A further and important additional factor is the presence of taxes. The significance of these taxes can be seen from the results in Table 3. Row 1 indicates results under actual tax rates; rows 2-5 show outcomes when a particular prior tax is lower than their actual values; and row 6 shows outcomes when all prior taxes are lower than actual values. For purposes of brevity, "tax rates" in the labels refers to the pre-existing rates net of applicable subsidies.

During Phase 1, pre-existing taxes tend to lower the ratio of TPS to C&T costs: in the actual case (Row 1), the cost ratio is 1.003 – lower than the ratio of 1.105 in the counterfactual case in which all pre-existing tax rates are

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[30] 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.

lower (Row 6). All of the specific prior taxes considered contribute to this result: in each case the cost-ratio is lower in the actual higher-tax case than the counterfactual case.[31]

TABLE 3 Results under Alternative Prior Tax Rates

	Scenario:	Phase 1					2020–2035				
		%Δ in ratio q_c to q_{nc}[a]		Cost per ton (RMB/t)		Cost ratio	%Δ in ratio q_c to q_{nc}		Cost per ton (RMB/t)		Cost ratio
		TPS	C&T	TPS	C&T		TPS	C&T	TPS	C&T	
1	Actual tax rates	-0.685	-2.131	43	43	1.003	-1.340	-2.999	87	82	1.058
2	Labor tax rates reduced[b]	-0.685	-2.132	44	43	1.027	-1.340	-3.000	87	82	1.061
3	Capital tax rates reduced	-0.690	-2.142	43	43	1.003	-1.342	-3.007	87	82	1.056
4	Output tax rates reduced	-0.691	-2.141	38	36	1.058	-1.333	-3.000	88	83	1.058
5	Import tax rates reduced	-0.687	-2.133	42	41	1.017	-1.341	-2.995	86	81	1.063
6	All tax rates reduced	-0.699	-2.155	39	35	1.105	-1.337	-3.005	82	77	1.062

[a] q_c and q_{nc} represent the weighted average output level of covered (c) and non-covered (nc) sectors, respectively, with their output share in the data as weights.
[b] In the counterfactual cases (rows 2-6), tax rates are reduced by 20%.

These results are consistent with the findings of the analytical model. For most types of taxes, the covered sector is overtaxed relative to the non-covered sector. In terms of efficiency (when assessed without consideration of the environmental externality),[32] this works toward an under-allocation of factors to the covered sector. Both the TPS and C&T compound this problem by causing a further shifting of factors away from the covered sectors. However, the compounding is less extensive under the TPS, as indicated by the differences in the changes in the ratios of covered sector output (q_c) to non-covered sector output (q_{nc}). This difference is a consequence of the TPS's implicit subsidy to output, which leads to less extensive output reductions

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31. The impact of a change in initial capital taxes is insignificant, as indicated in Row 3. This reflects the fact that the magnitudes of the initial net taxes on capital are relatively small, so that absolute changes in the net taxes are small as well.

32. The narrower notion of efficiency is appropriate since the focus here is on policy costs apart from environmental benefits.

compared with C&T. Hence the presence of these taxes reduces the TPS's cost-disadvantage.

The right-hand set of columns displays the results over the full 2020-2035 simulation interval. Averaged over this interval, the magnitudes of the impacts are much smaller than in Phase 1. This stems from the fact that the differences between covered and non-covered sector pre-existing taxes are somewhat smaller in the later years. Consequently, the initial misallocation of factors declines over time, which reduces the impact of the TPS's smaller compounding of the misallocation.

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 prior taxes, particularly in the earlier phases of the policy, when stringency is fairly modest.[33] But by Phase 3, the greater stringency gives C&T a cost advantage. Thus the efficiency case for a transition from the TPS to C&T becomes stronger to the extent that longer-run relative costs are given more weight.[34]

6.2 Sector Impacts

6.2.1 Prices, Outputs, and Profits

Table 4 displays for each sector and phase the percentage changes in the output price, level of production, and profit.[35] Figures in blue font represent results applying to a sector that is covered during the phase in question. Prices and profits are expressed in real terms, with the price of a composite produced good employed as the price index.

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[33] In Appendix H, we examine the sensitivity of the TPS-to-C&T cost-ratio to alternative specifications for benchmark tightening rates. The results confirm the analytical model's result that higher rates of benchmark tightening (i.e., higher policy stringency) imply a higher cost-ratio.

[34] 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 emissions reductions. Details are in Appendix I.

[35] Each sector's profit is defined as the total after-tax return to the sector's capital and land and natural resources (if any), as well as the value of free emissions allowances.

TABLE 4 Percentage Changes of Price, Quantity, and Profit of 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	0.26	0.50	3.36	-0.44	-0.89	-6.21	0.89	1.73	4.24
Cement	-0.02	0.74	8.44	-0.02	-0.10	-0.72	-0.04	5.22	15.6
Iron & steel	-0.01	0.14	0.53	-0.04	-0.28	-0.73	-0.05	2.43	7.29
Aluminum	0.11	0.44	3.57	-0.14	-0.54	-4.48	-0.07	2.56	6.14
Pulp & Paper	0.01	0.00	0.21	-0.02	-0.04	-0.35	-0.02	-0.04	2.24
Petroleum Refining	0.00	0.01	0.11	-0.05	0.04	-0.15	-0.06	0.05	0.56
Raw Chemicals	0.00	-0.01	0.46	-0.03	-0.04	-1.18	-0.03	-0.06	1.91
Other Non-Metal Products	0.01	0.05	0.57	-0.02	-0.09	-0.66	-0.02	-0.11	1.20
Other Non-Ferrous Metal	0.02	0.04	0.45	-0.07	-0.19	-1.34	-0.07	-0.21	1.04
Coal	-0.19	-0.56	-1.99	-1.54	-4.26	-15.6	-2.22	-6.08	-20.8
Natural Gas	0.04	0.09	0.46	0.08	0.19	1.07	0.12	0.29	1.57
Mining	0.01	-0.01	0.05	-0.04	-0.33	-1.38	-0.05	-0.31	-0.96
Agriculture	0.00	0.04	0.29	-0.01	-0.05	-0.39	-0.01	-0.06	-0.51
Non-Covered Manufacturing Sectors[a]	0.00	-0.02	-0.14	-0.02	-0.03	-0.13	-0.02	-0.06	-0.32
Construction	-0.01	-0.02	-0.07	-0.01	0.00	0.01	-0.02	-0.01	-0.04
Service Sectors[b]	0.00	0.01	0.05	-0.03	-0.08	-0.34	-0.03	-0.09	-0.46

Notes: 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.

[a] Elements in this row are percentage changes for the aggregate of all the manufacturing sectors not covered by the TPS. These sectors include food, textiles, clothing, log furniture, printing and stationery, daily chemicals, metal products, general equipment, transport equipment, electronic equipment, and other manufacturing.

[b] 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.

As expected, the TPS-covered sectors tend to experience the largest reductions in output, reflecting the use of output-reduction as a channel for reducing compliance costs. Among them, 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.[36] 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

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36. Emissions intensities by sector are displayed in Table C7 of Appendix C.

the value of the free allowances these sectors receive under the TPS.[37] The rents are significant, as the demands for the products of these sectors are relatively inelastic. The low elasticity in part reflects the fact that these sectors are not highly trade-exposed;[38] Hence they are less vulnerable to imported substitutes. In non-covered 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 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 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 than for coal-fired plants, which contributes to the substitution of gas-fired for coal-fired electricity.

For many other non-covered 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 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 for fossil-based electricity. 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.[39]

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[37] See Goulder et al. (2010) for 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.

[38] Table C6 in Appendix C expresses the trade exposure of each sector in terms of the ratio of traded goods to total output.

[39] Over the interval 2020–2035, profits to fossil-based electricity producers decrease by 1.2%, while the profits to wind and solar electricity suppliers increase by 9.0%.

Appendix G.1 shows the impacts of the two policies on wind and solar generation. The shifts toward renewable electricity are smaller under the TPS than under C&T. Under the TPS, over the interval 2020-2035 the combined electricity output from wind and solar generation increases by 4% relative to the baseline, while under C&T, it increases by 14%. This is due to TPS's implicit output subsidy, which mitigates the increase in fossil-based electricity prices and moderates the substitutions toward renewables-based power.

6.3 Net Benefits

The TPS's climate-related benefits are estimated to be well above its economic costs. This holds under a plausible range of values for the climate-related benefits from CO_2 abatement (implied by alternative values for the SCC), for production parameters,[40] and for future levels of stringency of the TPS.[41] We consider three SCC paths:[42] 307 RMB (44 dollars) per ton in 2020, increasing 3% annually (Nordhaus, 2017); 353 RMB (51 dollars) in 2020, increasing 3% annually (Biden Administration, 2021); and 1,277 RMB (185 dollars) in 2020, increasing 2% annually (Rennert et al., 2022).

Figure 4a 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 6–37 trillion RMB, 4–27 times the cumulative costs. The central estimate of the climate benefit is 9 trillion RMB, around six times the TPS's costs.

Figure 4b displays the costs and benefits when health benefits from reduced local pollution are accounted for. The health benefits are estimated values of avoided premature deaths. To estimate these benefits, we apply an emissions-

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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 at time t. The most recent SCC estimates are still higher. For example, Moore et al. (2024) arrive at an SCC of 283 dollars.

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

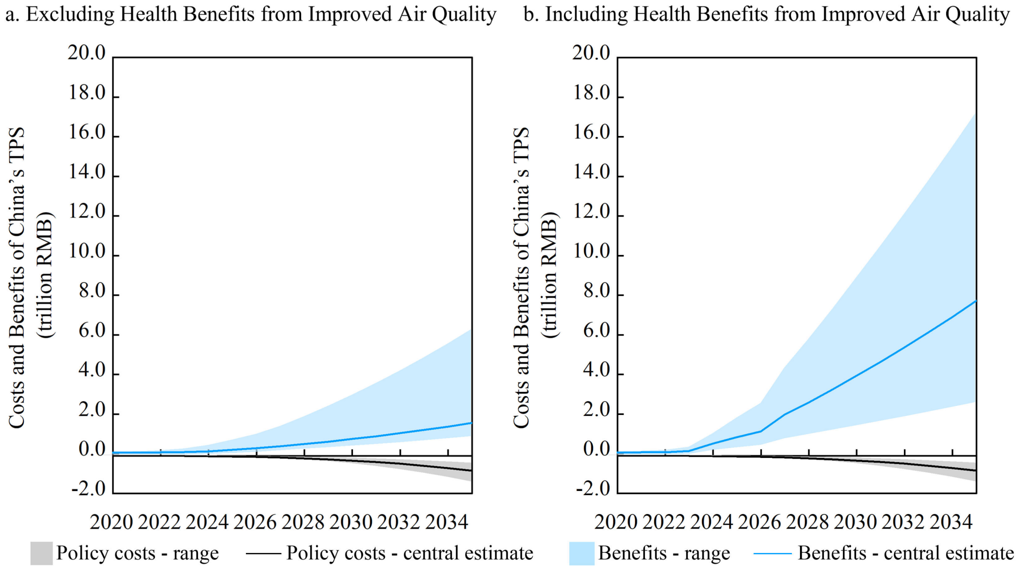

FIGURE 4 Costs and Benefits of China's TPS

Accounting for health benefits raises the benefit-cost ratio substantially. The central estimate is that under Case 1, the TPS could avoid 1.9–2.1 million $PM_{2.5}$-related deaths in total over the 2020–2035 interval, relative to the baseline.[44] 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 17–102 trillion RMB over the 2020–2035 interval. The central estimate is 45 trillion RMB, 28 times the central estimate for the TPS's costs.

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

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

The results in Figure 4 are based on estimated *global* benefits from reductions in CO_2 emissions. Ricke et al. (2018) estimate that China would enjoy approximately 6% of the climate benefits from its CO_2 reductions. If this percentage is assumed and only China's climate benefits are considered, the benefit-cost ratio ranges from 0.2 to 1.6. However, if local health benefits are considered along with China's own climate benefits, the TPS's benefit-cost ratio is consistently well above one – specifically, in the range of 7 to 65.

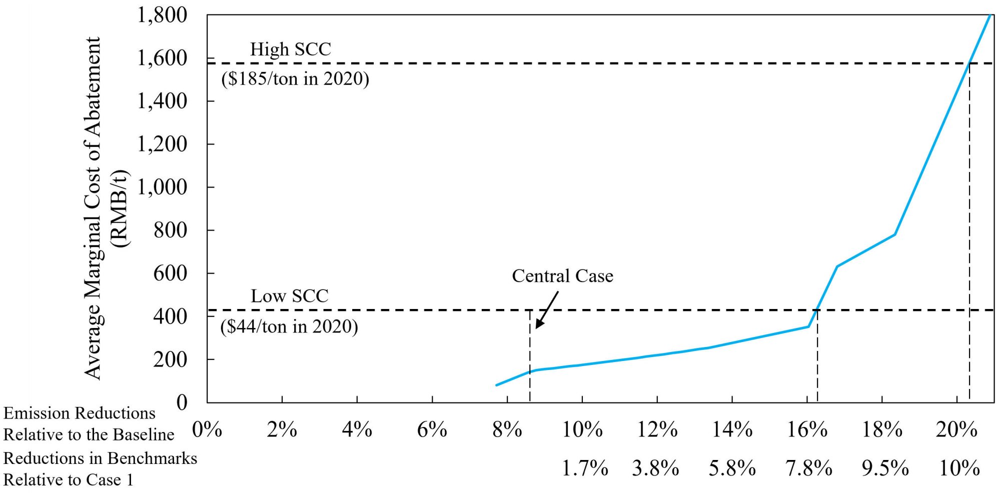

FIGURE 5 Estimated Marginal Costs of Abatement

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.[45] We define the marginal benefit as the average value of the SCC over the interval.[46] Marginal cost is derived by decrementing the Case 1 benchmarks each year and noting the associated incremental increase in costs per extra ton abated. The

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

[46] 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. This measure of marginal benefit is conservative in that it does not include health-related co-benefits.

results are in Figure 5. We find that efficiency maximization would require benchmarks approximately 8–10% lower than the Case 1 benchmarks. The efficiency-maximizing benchmarks would give rise to emissions reductions of around 16–20% 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 free. Here we present results from simulations in which auctioning serves as an additional source of the allowance supply. The policy simulations include auctioning cases differing in the ways that the auction revenues are recycled back to the economy. Auctioning is introduced in 2025.

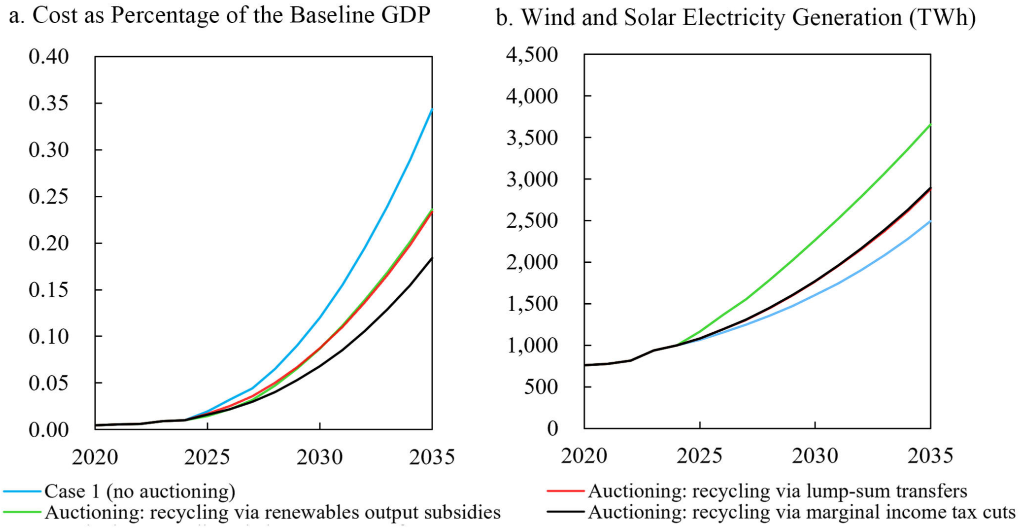

FIGURE 6 Economic Costs and Wind and Solar Electricity Generation under Different Auction Revenue-Recycling Options, 2020–2035

Notes: In Figure 6b, the red line and black line overlap with each other, indicating that recycling in the form of income tax cuts has a very slight impact on renewables.

Figure 6 shows economic costs and renewables output in cases involving auctioning and in Case 1, which involves no auctioning. As Figure 6a indicates, 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 on cost-effectiveness grounds for introducing auctioning as part of China's national emissions trading system.

The present value of the gross revenue from the auction is about 2.3 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 of profit losses, this revenue would fully offset their losses of profit over the same interval (0.7 trillion RMB). As shown in Figure 6b, recycling the auction revenues through subsidies to renewables output can yield significant increases in such output.

6.5 Tradeoffs between Efficiency and Distributional Impacts

One of the objectives of China's policymakers is to achieve emissions reductions at low cost. 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 tradeoffs.

As indicated in the analytical model, aggregate cost under the TPS depends on the variation of benchmarks. Table 5 displays the economic costs in cases that differ in terms of such variation. The smaller the number (and greater uniformity) of benchmarks, the lower the aggregated 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 uniform benchmark 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. By 2035, the costs in the one-benchmark case are 33% lower than in the four-benchmark case.

TABLE 5 Regional Income Change under Alternative Benchmarks

Regions	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 China	-621	-0.070	-621	-0.070	609	0.068
Central China	-707	-0.166	-637	-0.149	-1327	-0.311
West China	-265	-0.089	-289	-0.098	-355	-0.120
National	-1593	-0.099	-1547	-0.096	-1073	-0.067
Across province Std. dev	79	0.288	93	0.299	203	0.461

Note: East China includes Hebei, Shandong, Liaoning, Jiangsu, Hainan, Zhejiang, Fujian, Shanghai, Guangdong, Tianjin, and Beijing; Central China includes Shanxi, Heilongjiang, Henan, Anhui, Jilin, Hubei, Hunan, Jiangxi, and Inner Mongolia; West China includes Ningxia, Guizhou, Shaanxi, Yunnan, Guangxi, Xinjiang, Chongqing, Gansu, Sichuan, and Qinghai. Changes refer to the change in the net present value of cumulative income during 2020-2035. Standard deviations (std.) measure the variability in income changes across provinces. Full results for all provinces are in Table G1 in Appendix G.

The use of multiple benchmarks can serve distributional objectives, however. As Table 5 shows, the regional distribution of the TPS's impacts depends on the number (and variation) of benchmarks. Compared with the one-benchmark case, the four-benchmark case imposes less stringent benchmarks on high-carbon-intensity electricity generators, which are highly represented in China's central provinces. The less stringent benchmarks produce income losses in central China that are 47% smaller than in the one-benchmark case, and the associated distribution of losses across regions is considerably more even. The standard deviation of percentage losses across provinces in the four-benchmark case is 0.288, about 40% lower than the standard deviation of 0.461 in the four-benchmark case. The difference in the standard deviation of absolute losses is even higher. 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

We examine the sensitivity of the model's results to alternative policy designs and market structures, as well as parameter values including input substitution elasticities, capital transformation elasticities, savings rates, and the technological progress rate (AEEI). We briefly summarize the findings here; details are offered in Appendix H.

First, higher input substitution elasticities, higher AEEI rates, or lower future policy stringency levels lower the costs of the TPS and lead to lower allowance prices. As discussed in subsection 6.13, lower allowance prices imply a smaller gap between the costs of the TPS and C&T. However, our central case conclusions about relative costs of the TPS and C&T do not change. The impact of higher capital transformation elasticity on the cost gap is ambiguous. On the one hand, it lowers the allowance price and reduces the size of the implicit output subsidy. On the other hand, a higher capital transformation elasticity increases the supply elasticity, which increases the response of output to the distortionary implicit output subsidy, thereby increasing distortions. The net effect depends on which influence prevails.

Second, the TPS's costs per ton rise with the savings rate. 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 capital accumulation rate relative to the baseline. A higher savings elasticity amplifies this effect. It implies less capital accumulation, which reduces the firms' opportunities to substitute carbon-intensive inputs with capital inputs, increasing costs.

Third, imperfect competition in product markets leads to restricted supplies and inefficient factor allocation prior to the introduction of TPS or C&T, increasing the costs of emission reduction under both policies, similar to the effects of an output tax. However, market power partially offsets the distortions caused by the implicit output subsidy under TPS, so it improves the relative cost-effectiveness of TPS to C&T. Under low policy stringency, it may even eliminate TPS's cost disadvantage.

Our main qualitative findings on the impacts of the TPS are robust to parameter, stringency, and market structure changes. These include 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, that pre-existing taxes reduce the cost-disadvantage of the

TPS, 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.

8 Conclusions

China's recently implemented nationwide CO_2 tradable performance standard has the potential to contribute importantly to global reductions in CO_2 emissions. This paper assesses 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 specific alternative specific policy designs.

Our analytical model's general equilibrium framework shows that the relative cost-effectiveness of the TPS and C&T depends importantly pre-existing tax rates, with the direction of the impact on the cost-differential depending on differences in prior tax rates between covered and non-covered sectors. In particular, taxes on covered sectors favor the TPS while taxes on non-covered sectors favor C&T.

Our numerical model offers a unique combination of features well-suited to evaluating the TPS. These include its general equilibrium framework, attention to changes in impacts over time, recognition of differences between the TPS and C&T in terms of structure and induced incentives, and incorporation of significant institutional and regulatory features of China's economy. The model reveals that the TPS's climate-related benefits significantly exceed its costs, that accounting for health benefits from reduced local pollutants significantly augments the benefit-cost ratio, and that a more stringent policy relative to what is currently planned would significantly increase net benefits. Earlier work had suggested that the TPS has a significant disadvantage relative to C&T in terms of cost-effectiveness. Building on the analytical model's findings, the numerical model finds that China's pre-existing taxes reduce substantially and in some circumstances eliminate the TPS's claimed cost-disadvantage relative to cap and trade. It also identifies quantitatively significant trade-offs between the TPS's cost-effectiveness and the evenness of its impacts across provinces. In addition, it shows that introducing an auction as a complementary source of allowance supply can lower the economic costs of China's emissions trading system substantially.

Our findings are significant for decision-makers not only in China but in several other countries as well.[47] Several countries have recently introduced a nationwide TPS, including Kazakhstan and Indonesia (ICAP, 2025), which face development challenges similar to those in China. Countries seriously considering implementing the TPS include India (ICAP, 2024) and Vietnam (Veyt, 2014). These four countries collectively represent about 10% of global CO_2 emissions and this share has been expanding quickly. They have several economic features similar to those in China (see Appendix J), including a relatively high share of emissions-intensive industries and high growth rates of energy and CO_2 emissions. And, as in China, their tax systems rely significantly on output taxes, with rates that differ significantly across sectors. Like China, these nations face severe challenges related to air pollution – a problem that the TPS can help address. These considerations make our modeling framework and findings significant for decisionmakers not only in China but in these major developing countries as well.

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[47] Decision-makers appear attracted to the way that a TPS automatically adjusts stringency to business-cycle conditions, as the allocation of allowances is proportional to the level of production. See, for example Pizer and Zhang (2018).

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