Supplemental Appendix for China's Nationwide CO_2 Emissions Trading System: A General Equilibrium Assessment

Lawrence H. Goulder[1], Xianling Long[2], Chenfei Qu[3], Da Zhang[3]

[1] Stanford University, NBER, and Resources for the Future

[2] China Center for Economic Research, National School of Development, Peking University

[3] Institute of Energy, Environment, and Economy, Tsinghua University

Table of Contents

Appendix A. Proofs for Analytical Model **3**

Appendix B. Numerical Model Structure and Functional Forms **13**

Appendix C. Data **29**

Appendix D. Parameters and Calibration Methods **41**

Appendix E. Equilibrium Conditions and Solution Method **56**

Appendix F. Evaluation of Health Co-benefits **69**

Appendix G. Distributional Impacts **74**

Appendix H. Sensitivity Analysis **77**

Appendix I. Aggregate Costs under a Transition from the TPS to C&T **88**

Appendix J. Countries That Have Implemented or Are Seriously Considering a TPS (Partial List) **90**

Appendix References **91**

Appendix A. Proofs for Analytical Model

A.1 Outcomes in the Presence of Administered Pricing

In China's electricity market, generators sell some of their electricity (referred to as "guaranteed production level") at a government-administered price. The administered price is above the market price. The administered price applies to output below the guaranteed level, and the market price applies to output beyond that level.

Under most circumstances, firms produce beyond the guaranteed level, so the market price generally applies at the margin and the administered prices apply inframarginally.

Firms maximize profits, yielding the equality of market price and marginal cost. Section I displayed total derivatives for the market price p_X and government lump-sum transfer G with respect to t_E. These expressions continue to apply in the case with administered pricing.

However, in the presence of administered pricing, total profits are no longer zero due to the inframarginal price paid by consumers. The total profit becomes:

$$p_X(X-\overline{X})+\overline{p_X}\,\overline{X}$$

where $\bar{X}$ is the guaranteed production level and $\bar{p}_X$ is the administered price, both of which are exogenous. This profit enters household income, as households own the firms.

The household budget constraint under both business as usual (BAU) and the TPS is:

$$\left(p_X+t_X\right)\left(X-\bar{X}\right)+\left(\bar{p}_X+t_X\right)\bar{X}+\left(1+t_Y\right)Y=L+T+\left(\bar{p}_X-p_X\right)\bar{X} \tag{A1}$$

Rearranging the above expression yields:

$$\left(p_X+t_X\right)X+\left(1+t_Y\right)Y=L+T \tag{A2}$$

This is the same as in the case without administered pricing, and consequently, the subsequent expressions in Section A.2 are unchanged as well. Thus, the results in the main text hold under administered pricing.

A.2 Economic Cost Expressions

We first derive the economic cost of C&T in the presence of output taxes. Differentiating $p_X = 1 + c(a) + t_E(e_0 - a)$, substituting $t_E = c'(a)$ and using $E = X(e_0 - a)$, we obtain:

$$\frac{dp_X}{dt_E} = \frac{E}{X} \tag{A3}$$

From the utility maximization problem, we obtain the demand functions for X and Y: $X(p_X, \pi, T)$, $Y(p_X, \pi, T)$.

Differentiating $t_X X + t_Y Y = G$, we obtain:

$$t_X\left(\frac{\partial X}{\partial p_X}\frac{dp_X}{dt_E} + \frac{\partial X}{\partial \pi}\frac{d\pi}{dt_E} + \frac{\partial X}{\partial G}\frac{dG}{dt_E}\right) + t_Y\left(\frac{\partial Y}{\partial p_X}\frac{dp_X}{dt_E} + \frac{\partial Y}{\partial \pi}\frac{d\pi}{dt_E} + \frac{\partial Y}{\partial G}\frac{dG}{dt_E}\right) = \frac{dG}{dt_E} \tag{A4}$$

Arranging this equation yields:

$$\frac{dG}{dt_E} = \frac{\left(t_X\frac{\partial X}{\partial p_X} + t_Y\frac{\partial Y}{\partial p_X}\right)\frac{dp_X}{dt_E} + \left(t_X\frac{\partial X}{\partial \pi} + t_Y\frac{\partial Y}{\partial \pi}\right)\frac{d\pi}{dt_E}}{1 - t_X\frac{\partial X}{\partial G} - t_Y\frac{\partial Y}{\partial G}} \tag{A5}$$

The utility function is:

$$v(p_X, \pi, G) = \max u(X, Y) - \lambda\left((p_X + t_X)X + (1 + t_Y)Y - L - T - \pi\right) \tag{A6}$$

From Roy's identity:

$$\frac{\partial v}{\partial p_X} = -\lambda X, \quad \frac{\partial v}{\partial \pi} = \lambda, \quad \frac{\partial v}{\partial T} = \lambda \tag{A7}$$

Differentiating v:

$$\frac{\partial v}{\partial t_E} = \frac{\partial v}{\partial p_X}\frac{dp_X}{dt_E} + \frac{\partial v}{\partial \pi}\frac{d\pi}{dt_E} + \frac{\partial v}{\partial T}\frac{dT}{dt_E} \tag{A8}$$

Substituting Equations (A7) and (A5) into (A8), and noting that $T \equiv G$, we obtain:

$$-\frac{1}{\lambda}\frac{dv}{dt_E} = E - \frac{d\pi}{dt_E} + \frac{1}{M_G}\left[\left(-t_X\frac{\partial X}{\partial p_X} - t_Y\frac{\partial Y}{\partial p_X}\right)\frac{dp_X}{dt_E} + \left(-t_X\frac{\partial X}{\partial \pi} - t_Y\frac{\partial Y}{\partial \pi}\right)\frac{d\pi}{dt_E}\right] \tag{A9}$$

where $M_G \equiv 1 - t_X \frac{\partial X}{\partial G} - t_Y \frac{\partial Y}{\partial G}$, $E - \frac{d\pi}{dt_E} = E - \frac{d\left(t_E A_0\right)}{dt_E} = E - A_0 - t_E \frac{dA_0}{dt_E}$. We have $E = A_0$ because of allowance market equilibrium (A_0 is the initial allowance, and E is the emission after abatement). This term is then:

$$\begin{aligned} -t_E \frac{dA_0}{dt_E} &= -t_E \frac{dE}{dt_E} = -t_E \frac{dX\left(e_0 - a\right)}{dt_E} = -t_E \left[-\frac{da}{dt_E} X + \left(e_0 - a\right) \frac{dX}{dt_E} \right] \\ &= t_E \frac{da}{dt_E} X + \left(-\frac{dX}{dt_E} \right) t_E \left(e_0 - a\right) = c'(a) \frac{da}{dt_E} X + \left(-\frac{dX}{dt_E} \right) t_E \left(e_0 - a\right) \end{aligned} \tag{A10}$$

Substituting Equation (A10) into (A9), we can obtain the cost expression for C&T:

$$\begin{aligned} -\frac{1}{\lambda} \frac{dv}{dt_E} = & \underbrace{c'(a) \frac{da}{dt_E} X}_{\text{MC Abatement } (W_1)} + \underbrace{\left(-\frac{dX}{dt_E} \right) t_E \left(e_0 - a\right)}_{\text{MC Allowances} (W_2)} \\ & + \underbrace{\frac{1}{M_G} \left[\left(-t_X \frac{\partial X}{\partial p_X} - t_Y \frac{\partial Y}{\partial p_X} \right) \frac{dp_X}{dt_E} + \left(-t_X \frac{\partial X}{\partial \pi} - t_Y \frac{\partial Y}{\partial \pi} \right) \frac{d\pi}{dt_E} \right]}_{\text{TI effect} (W_3)} \end{aligned} \tag{A11}$$

We then derive the economic cost of TPS in the presence of output taxes. Differentiating $p_X = 1 + c(a) + t_E(e_0 - a - \beta)$, substituting $t_E = c'(a)$ and $E = X(e_o - a)$, we obtain:

$$\frac{dp_X}{dt_E} = e_0 - a - \beta - t_E \frac{d\beta}{dt_E} \tag{A12}$$

From the utility maximization problem, we obtain the demand functions for X and Y: $X(p_X, \pi, T)$, $Y(p_X, \pi, T)$.

Differentiating $t_X X + t_Y Y = G$, we obtain:

$$t_X \left(\frac{\partial X}{\partial p_X} \frac{dp_X}{dt_E} + \frac{\partial X}{\partial G} \frac{dG}{dt_E} \right) + t_Y \left(\frac{\partial Y}{\partial p_X} \frac{dp_X}{dt_E} + \frac{\partial Y}{\partial G} \frac{dG}{dt_E} \right) = \frac{dG}{dt_E} \tag{A13}$$

Arranging this equation yields:

$$\frac{dG}{dt_E} = \frac{\left(t_X \frac{\partial X}{\partial p_X} + t_Y \frac{\partial Y}{\partial p_X} \right) \frac{dp_X}{dt_E}}{1 - t_X \frac{\partial X}{\partial G} - t_Y \frac{\partial Y}{\partial G}} \tag{A14}$$

The utility function is:

$$v\left(p_X, G\right) = \max u\left(X, Y\right) - \lambda\left(\left(p_X + t_X\right)X + \left(1 + t_Y\right)Y - L - T\right) \tag{A15}$$

From Roy's identity:

$$\frac{\partial v}{\partial p_X} = -\lambda X, \quad \frac{\partial v}{\partial T} = \lambda \tag{A16}$$

Differentiating v:

$$\frac{dv}{dt_E} = \frac{\partial v}{\partial p_X}\frac{dp_X}{dt_E} + \frac{\partial v}{\partial T}\frac{dT}{dt_E} \tag{A17}$$

Substituting Equations (A16) and (A14) into (A17), and noting that $T \equiv G$, we obtain:

$$-\frac{1}{\lambda}\frac{dv}{dt_E} = E - \beta X - t_E X\frac{d\beta}{dt_E} + \frac{1}{M_G}\left[\left(-t_X\frac{\partial X}{\partial p_X} - t_Y\frac{\partial Y}{\partial p_X}\right)\frac{dp_X}{dt_E}\right] \tag{A18}$$

where $E - \beta X - t_E X\frac{d\beta}{dt_E} = -t_E X\frac{d\beta}{dt_E}$ because of the allowance market equilibrium $\left(E = \beta x\right)$.

Then we have:

$$-t_E X\frac{d\beta}{dt_E} = -t_E\left(\frac{d\left(\beta X\right)}{dt_E} - \beta\frac{dX}{dt_E}\right) = -t_E\frac{dE}{dt_E} + t_E\beta\frac{dX}{dt_E} \tag{A19}$$

Substituting (A19) into (A18), we can obtain the cost expression for TPS:

$$-\frac{1}{\lambda}\frac{dv}{dt_E} = \underbrace{c'(a)\frac{da}{dt_E}X}_{\text{MC Abatement }(W_1)} + \underbrace{\left(-\frac{dX}{dt_E}\right)t_E\left(e_0 - a - \beta\right)}_{\text{MC Allowances }(W_2)} + \underbrace{\frac{1}{M_G}\left(-t_X\frac{\partial X}{\partial p_X} - t_Y\frac{\partial Y}{\partial p_X}\right)\frac{dp_X}{dt_E}}_{\text{TI effect }(W_3)} \tag{A20}$$

A.3 C&T Achieves the First-best in the Absence of Pre-existing Taxes

Below we demonstrate that, in the absence of pre-existing taxes or other market failures besides the emissions externality, the economic cost expression under C&T is equivalent to that of a social planner.

A social planner chooses the optimal levels of X and a to maximize social welfare; the level of Y is then automatically determined because L is exogenous. The total unit

cost of producing X is $1+c(a)$, which indicates that $1+c(a)$ unit of L is consumed to produce each unit of X. Thus we have the constraint that $(1+c(a))X+Y \le L$. The constrained maximization problem is:

$$\max u\left(X,Y\right)-\varphi\left(E\right)$$

$$s.t.\left(1+c\left(a\right)\right)X+Y \le L$$

Therefore, the social welfare function is given by:

$$V\left(X,a\right)=u\left(X,Y\right)-\varphi\left(E\right)-\lambda\left(\left(1+c\left(a\right)\right)X+Y-L\right) \tag{A21}$$

The representative household maximizes utility according to observed price:

$$\frac{\partial u}{\partial X}=\lambda p_X=\lambda\left(1+c\left(a\right)\right) \tag{A22}$$

From Roy's identity:

$$\frac{\partial V}{\partial X}=\frac{\partial u}{\partial X}-\frac{\partial \varphi}{\partial E}\frac{\partial E}{\partial X}-\lambda\left(1+c\left(a\right)\right)=\frac{\partial u}{\partial X}-\frac{\partial \varphi}{\partial E}\left(e_0-a\right)-\lambda\left(1+c\left(a\right)\right) \tag{A23}$$

$$\frac{\partial V}{\partial a}=-\frac{\partial \varphi}{\partial E}\frac{\partial E}{\partial a}-\lambda c'\left(a\right)X=\frac{\partial \varphi}{\partial E}X-\lambda c'\left(a\right)X \tag{A24}$$

Substituting Equation (A22) into (A23), we obtain:

$$\frac{\partial V}{\partial X}=-\frac{\partial \varphi}{\partial E}\left(e_0-a\right) \tag{A25}$$

Differentiating V with respect to the social cost of carbon t_E^*:

$$\frac{dV}{dt_E^*}=\frac{\partial V}{\partial a}\frac{da}{dt_E^*}+\frac{\partial V}{\partial X}\frac{dX}{dt_E^*} \tag{A26}$$

Substituting Equations (A24) and (A25) into (A26), we obtain:

$$\frac{dV}{dt_E^*}=\left(\frac{\partial \varphi}{\partial E}X-\lambda c^{'}\left(a\right)X\right)\frac{da}{dt_E^*}-\frac{\partial \varphi}{\partial E}\left(e_0-a\right)\frac{dX}{dt_E^*} \tag{A27}$$

Social planner maximizes social welfare given any social cost of carbon, $dV/dt_E^*=0$. Reorganizing it yields:

$$\lambda c'\left(a\right)X\frac{da}{dt_E^*}=\frac{\partial \varphi}{\partial E}X\frac{da}{dt_E^*}-\frac{\partial \varphi}{\partial E}\left(e_0-a\right)\frac{dX}{dt_E^*} \tag{A28}$$

The utility function of the household (assuming no internalization of the impact of emissions) is thus given by:

$$v = \max u(X,Y) - \lambda\left(\left(1+c(a)\right)X + Y - L\right) \tag{A29}$$

From the household's utility function,

$$\frac{dv}{dt_E^*} = \frac{\partial u}{\partial X}\frac{dX}{dt_E^*} - \lambda X\frac{d\left(1+c(a)\right)}{dt_E^*} - \lambda\left(1+c(a)\right)\frac{dX}{dt_E^*} \tag{A30}$$

Given (A22), (A30) simplifies to:

$$\frac{dv}{dt_E^*} = -\lambda c'(a)X\frac{da}{dt_E^*} \tag{A31}$$

Substituting (A28) into (A31):

$$-\frac{dv}{dt_E^*} = \frac{\partial\varphi}{\partial E}X\frac{da}{dt_E^*} - \frac{\partial\varphi}{\partial E}(e_0 - a)\frac{dX}{dt_E^*} \tag{A32}$$

By definition, $\frac{1}{\lambda}\frac{\partial\varphi}{\partial E} = t_E^*$. From this, (A32) simplifies to:

$$-\frac{1}{\lambda}\frac{dv}{dt_E^*} = t_E^* X\frac{da}{dt_E^*} - t_E^*(e_0 - a)\frac{dX}{dt_E^*} \tag{A33}$$

At the social optimum, $c'(a) = t_E^*$, so (A33) becomes:

$$-\frac{1}{\lambda}\frac{dv}{dt_E^*} = c'(a)\frac{da}{dt_E^*}X + \left(-\frac{dX}{dt_E^*}\right)t_E^*(e_0 - a) \tag{A34}$$

which is identical to the result under C&T when the allowance price under C&T equals the social cost of carbon.

A.4 The Cost Wedge between TPS and C&T in a Setting with Pre-existing Taxes

We now compare the TPS and C&T. In the case of pre-existing taxes, the expressions for marginal abatement cost (W_1) and marginal allowance cost (W_2) remain unchanged, but their magnitudes will vary. In this subsection, we focus on the tax-interaction effect. We discuss the changes in abatement and allowance costs due to pre-existing taxes in the next subsection.

The tax-interaction effect, W_3, can be expressed in terms of a price effect and an income effect:

$$C\&T: \quad W_3 = \underbrace{\frac{1}{M_G}\left[t_X\left(-\frac{\partial X}{\partial p_X}\right)-t_Y\left(\frac{\partial Y}{\partial p_X}\right)\right]\frac{E}{X}}_{\text{Price effect}} + \underbrace{\frac{1}{M_G}\left(-t_X\frac{\partial X}{\partial \pi}-t_Y\frac{\partial Y}{\partial \pi}\right)\frac{d\pi}{dt_E}}_{\text{Income effect}} \quad \text{(A35)}$$

$$TPS: \quad W_3 = \underbrace{\frac{1}{M_G}\left[t_X\left(-\frac{\partial X}{\partial p_X}\right)-t_Y\left(\frac{\partial Y}{\partial p_X}\right)\right]\left(\frac{E}{X}-\frac{d(t_E\beta)}{dt_E}\right)}_{\text{Price effect}} \quad \text{(A36)}$$

The price effect represents the impact of the TPS or C&T on tax-interaction costs via p_X. The impact of the price effect on the cost wedge between the TPS and C&T depends on the sign of $t_X\left(\partial X/\partial p_X\right)-t_Y(\partial Y/\partial p_X)$, the weighted difference between the tax rates, with the own price elasticity $\left(-\partial X/\partial p_X\right)$ and cross price elasticity $\left(\partial Y/\partial p_X\right)$ as weights. As discussed in Section I, the price effect is smaller under the TPS if $t_X > t_Y$.

A second difference in the TI effect between the two policies is that C&T includes an income effect absent in TPS. In C&T, this income effect arises from free allowances, which reduce tax-interaction costs. In contrast, TPS treats free allowances as an output subsidy, lowering firms' marginal costs, so no rent is generated. The income effect in C&T offsets the negative impacts of pre-existing taxes by increasing demand for goods, thus reducing C&T's tax-interaction costs.[1] Therefore, C&T's income effects reduce its tax-interaction costs.

Therefore, the tax-interaction effect on policy costs depends on the price and income effect wedges. Our numerical model shows that the price effect wedge exceeds the income wedge, thereby narrowing the overall wedge between TPS and C&T.

A.5 Analysis with Pre-existing Labor Taxes

In the main text, we consider pre-existing output taxes and assume an exogenous labor supply. In this subsection, we consider a pre-existing labor tax instead of prior

[1] With the assumption that $A_0 - t_E\left(dA_0/dt_E\right) > 0$, i.e., the increase in t_E raises rent, avoiding a Laffer-Curve-type of response.

output taxes and we allow labor supply to be endogenous. We assume the labor tax rate is uniform in the two sectors.

The representative household's utility function is given by:

$$U = u(X, Y, \bar{L} - L) - \varphi(E) \tag{A37}$$

where leisure is equal to the household time endowment ($\bar{L}$) less labor supply (L). All other notations are the same as in the main text.

The budget constraint for C&T is:

$$p_X X + Y = (1 - t_L) L + T + \pi \tag{A38}$$

Differentiating $t_L L = G$ we obtain:

$$t_L \left(\frac{\partial L}{\partial p_X} \frac{dp_X}{dt_E} + \frac{\partial L}{\partial \pi} \frac{d\pi}{dt_E} + \frac{\partial L}{\partial G} \frac{dG}{dt_E} \right) = \frac{dG}{dt_E} \tag{A39}$$

Arranging this equation yields:

$$\frac{dG}{dt_E} = \frac{t_L \left(\frac{\partial L}{\partial p_X} \frac{dp_X}{dt_E} + \frac{\partial L}{\partial \pi} \frac{d\pi}{dt_E} \right)}{1 - t_L \frac{\partial L}{\partial G}} \tag{A40}$$

The utility function is:

$$v(p_X, \pi, G) = \max u(X, Y, \bar{L} - L) - \lambda (p_X X + Y - (1 - t_L) L - T - \pi) \tag{A41}$$

From Roy's identity:

$$\frac{\partial v}{\partial p_X} = -\lambda X, \quad \frac{\partial v}{\partial \pi} = \lambda, \quad \frac{\partial v}{\partial T} = \lambda$$

Differentiating v:

$$\frac{dv}{dt_E} = \frac{\partial v}{\partial p_X} \frac{dp_X}{dt_E} + \frac{\partial v}{\partial \pi} \frac{d\pi}{dt_E} + \frac{\partial v}{\partial T} \frac{dT}{dt_E} \tag{A42}$$

We still have $\frac{dp_X}{dt_E} = \frac{E}{X}$, and note that $T \equiv G$,we obtain:

$$-\frac{1}{\lambda} \frac{dv}{dt_E} = E - \frac{d\pi}{dt_E} + \frac{1}{M_G} \left[-t_L \left(\frac{\partial L}{\partial p_X} \frac{dp_X}{dt_E} + \frac{\partial L}{\partial \pi} \frac{d\pi}{dt_E} \right) \right] \tag{A43}$$

where $M_G \equiv 1 - t_L \frac{\partial L}{\partial G}$. As in the case under output taxes, this expression can be simplified to:

$$-\frac{1}{\lambda}\frac{dv}{dt_E} = \underbrace{c'(a)\frac{da}{dt_E}X}_{\text{MC Abatement } (W_1)} + \underbrace{\left(-\frac{dX}{dt_E}\right)t_E(e_0 - a)}_{\text{MC Allowances } (W_2)} + \underbrace{\frac{1}{M_G}\left[-t_L\left(\frac{\partial L}{\partial p_X}\frac{dp_X}{dt_E} + \frac{\partial L}{\partial \pi}\frac{d\pi}{dt_E}\right)\right]}_{\text{TI effect } (W_3)} \quad \text{(A44)}$$

For TPS, the only difference from C&T is the expression for $\frac{dp_X}{dt_E}$:

$$\frac{dp_X}{dt_E} = e_0 - a - \beta - t_E\frac{d\beta}{dt_E} \quad \text{(A45)}$$

With this, we have:

$$-\frac{1}{\lambda}\frac{dv}{dt_E} = E - \beta X - t_E X\frac{d\beta}{dt_E} - \frac{d\pi}{dt_E} + \frac{1}{M_G}\left[-t_L\frac{\partial L}{\partial p_X}\frac{dp_X}{dt_E}\right] \quad \text{(A46)}$$

where $E - \beta X - t_E X\frac{d\beta}{dt_E} = -t_E X\frac{d\beta}{dt_E}$ because of the allowance market equilibrium ($E = \beta X$). Then we have:

$$-t_E X\frac{d\beta}{dt_E} = -t_E\left(\frac{d(\beta X)}{dt_E} - \beta\frac{dX}{dt_E}\right) = -t_E\frac{dE}{dt_E} + t_E\beta\frac{dX}{dt_E} \quad \text{(A47)}$$

Substituting this to $-\frac{1}{\lambda}\frac{dv}{dt_E}$, we obtain:

$$-\frac{1}{\lambda}\frac{dv}{dt_E} = \underbrace{c'(a)\frac{da}{dt_E}X}_{\text{MC Abatement } (W_1)} + \underbrace{\left(-\frac{dX}{dt_E}\right)t_E(e_0 - a - \beta)}_{\text{MC Allowances } (W_2)} + \underbrace{\frac{1}{M_G}\left(-t_L\frac{\partial L}{\partial p_X}\frac{dp_X}{dt_E}\right)}_{\text{TI effect } (W_3)} \quad \text{(A48)}$$

The pre-existing labor tax causes an undersupply of labor even before the introduction of any carbon pricing policy. Implementing a carbon pricing policy further exacerbates this labor undersupply problem. However, because the TPS leads to a smaller output reduction and thus a smaller reduction in labor supply, the problem is less severe under the TPS. This can be observed in equations (A44) and (A48), which are similar to those in the main text where the pre-existing taxes are output taxes. The difference from the main text is that the price elasticity of product demand is now replaced by the elasticity of labor supply with respect to the change in the product price

of X (i.e., $\partial L / \partial p_X$). This elasticity is negative because a higher p_X indicates higher abatement and compliance costs, which results in reduced production levels and lower labor supply. This negative elasticity causes both the TPS and C&T to exacerbate the adverse tax-interaction effect. However, because the price of X increases by less under the TPS than under C&T, the tax-interaction effect is smaller under the TPS. Thus, the predictions regarding the wedge between TPS and C&T resemble those under output taxes.

Appendix B. Numerical Model Structure and Functional Forms

The notation used in this appendix is summarized below.

Table B1. Notation

Symbol	Definition
Y	Output
R	Tax revenue
T	Lump-sum transfer
E	CO_2 emissions
p	Price of goods and factors
t	Price of allowances
x	Material inputs
e	Energy inputs (electricity and fuels)
s	Electricity inputs
f	Fuel inputs
d	Domestic intermediate inputs
n	Imported intermediate inputs
m	Labor inputs
w	Capital inputs
res	Natural resources inputs
lnd	Land inputs
$\overline{m}, \overline{w}, \overline{res}, \overline{lnd}$	Factor endowments
σ	The elasticity of substitution between inputs
α , ϕ	Parameters of CES functions
i,j,l	Sectors
k	Subsectors

B.1 Structure

Figure B1 presents the goods and financial flows in the model. As described in the main text, representative firms in each of the 31 production sectors (Table B2) employ inputs of primary factors (land, 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.

The model solves at one-year intervals from 2020 through 2035 for the equilibrium factor prices and allowance prices as well as the prices of all produced goods. Below we describe the model's production and demand structure in detail.

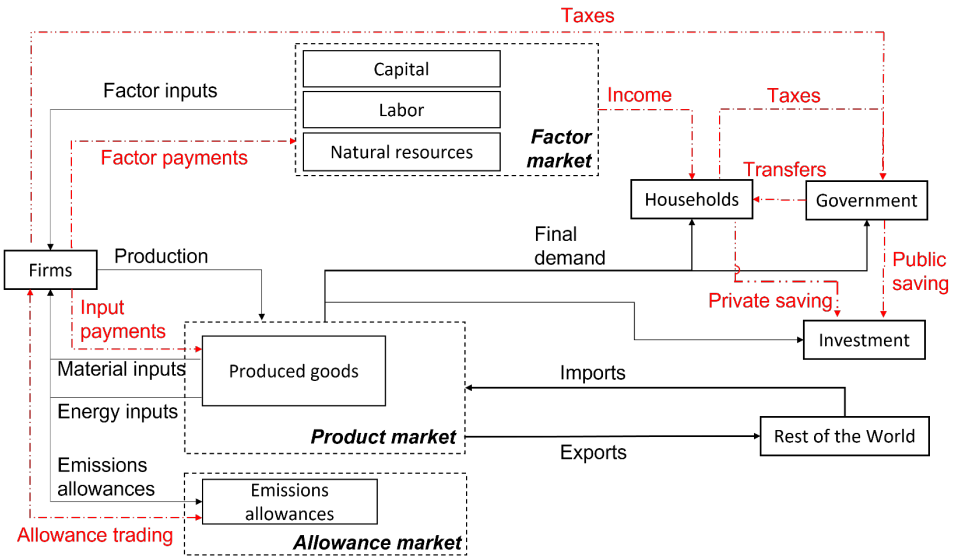


Figure B1. Goods and Financial Flows

Note: The solid and dashed lines with arrows indicate the economy's material flows and cash flows, respectively.

Table B2. Sectors

Name	Description
Cement[a]	Cement
Iron & steel[b]	Iron and steel
Aluminum[c]	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 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[d]	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

[a] The cement divides into 3 subsectors: high, medium, and low-efficiency cement production.
[b] 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.
[c] The aluminum sector divides into 3 subsectors, high, medium, and low-efficiency aluminum production.
[d] 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.

B.2 Factor Types and Supply

Labor (*m*) is perfectly mobile across sectors, capital (*w*) is imperfectly mobile, and land (*lnd*) and natural resources (*res*) are immobile. In all sectors and in each period, the supplies of the imperfectly mobile factor are captured via a transformation function that allocates capital across sectors and subsectors. Changes in relative prices alter this allocation. The marginal returns to capital and the associated market price of capital generally will differ across sectors and subsectors, a reflection of imperfect capital mobility.

The capital transformation function, $\Gamma_{w_i}(\bullet)$, has the constant elasticity of transformation (CET) functional form and is expressed by:

$$\overline{w} = \left[\sum_{j=1}^{31} \alpha_{w,j} w_j^{S\rho_w} \right]^{1/\rho_w} \tag{B1}$$

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

The model assumes that owners of capital make investments so as to maximize their returns from the capital. The maximization problem is expressed by the following:

$$\begin{aligned} &\max_{w_j^S} \sum_{j=1}^{j=31} w_j^S P_{wj} \\ &s.t. \quad \Gamma_w\left(w_j^S\right) = \overline{w} \end{aligned} \tag{B2}$$

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

As indicated in the main text, the government's preferential treatment of SOEs influences both the average return to capital and its relative returns across sectors. These interventions affect the capital owner's optimizing investment decisions and the allocation of capital across sectors. The same maximization problem in Equation (B2) determines the allocation of capital between SOEs and POEs within a subsector.

B.3 Production

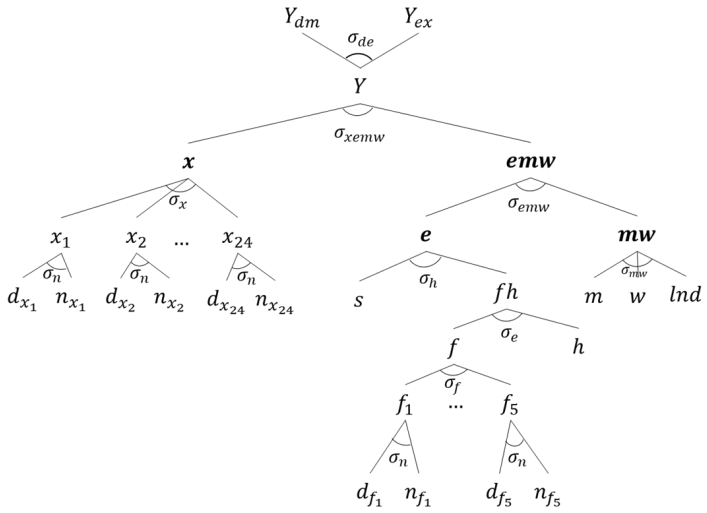
Here we first present how firms determine their optimal input structure based on cost minimization for a given level of output. Subsequently, we explain how firms choose their output level, and how the output is allocated between domestic supply and exports. We will then present how SOEs and administered pricing are considered in our model.

Production in each sector is represented by the nested structure shown in Figure B2. The σ parameters in the figure are elasticities of substitution in production.

The structure described below applies to all sectors other than renewables-based and nuclear electricity. It also applies to subsectors of the electricity, iron & steel, aluminum, and cement sectors. The structures for solar, wind, hydro, and nuclear electricity subsectors are similar, except that they have natural resources (*res*) as their inputs.

In each sector or subsector, producers employ material inputs (***x***), energy inputs (***e***), and factors (***mw***) to produce output. As indicated in Figure B2, the material inputs x_1, x_2, …, x_{24} combine to produce the composite material input ***x***. Each of the material inputs x_i is a composite of a domestically produced material input $d_{x,i}$ and, if any, a foreign-produced material input $n_{x,i}$. The energy composite (***e***) is produced from electricity (*s*), heat (*h*) and fossil fuels (*f*), and the fossil fuel is a composite of five fuel inputs f_1, f_2, …, f_5 (coal, crude oil, natural gas, gas manufacture & distribution and petroleum products). Producers also employ factors of production labor (*m*), capital (*w*) and, if any, land (*lnd*). The output Y is allocated toward the domestic market or the export market. Y_{dm} and Y_{ex} represent the output devoted to each of these markets.

A. Fossil-fuel based electricity sector and other sectors



B. Solar, wind, hydro, and nuclear electricity subsectors

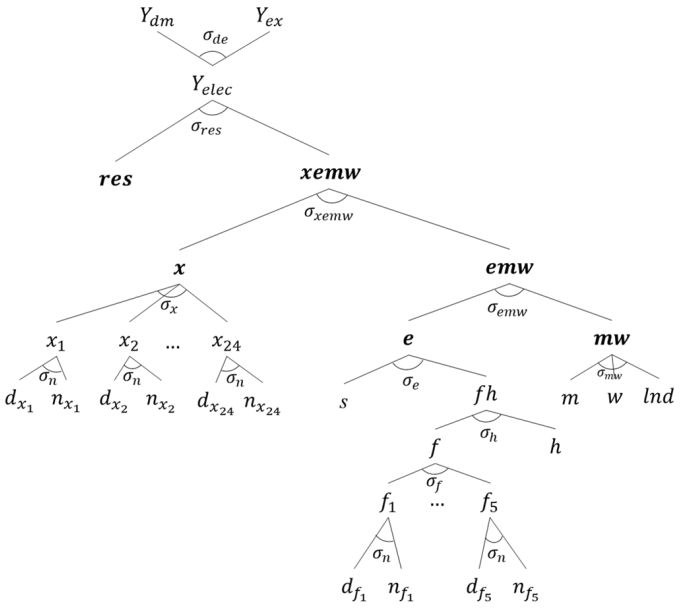


Figure B2. Nested CES Production Structure for Each Sector

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

$$V = \phi \left[\sum_{i=1}^{n} \alpha_i v_i^{\rho} \right]^{\frac{1}{\rho}} \tag{B3}$$

where $\sum_{i=1}^{n}\alpha_i = 1$. The parameter ρ is equal to $1-\frac{1}{\sigma}$, where σ is the elasticity of substitution among v_i in producing V. Equation (B3) indicates the relationship, at any given point of the nest, between a given composite and its underlying elements.

Firms make choices of variable inputs and levels of output consistent with the objective of profit maximization. The modeling of these choices is shown below. For convenience, the sector subscript has been suppressed in this subsection.

Cost-Minimizing Input Intensities

For any CES function of the form in Equation (B3), the Lagrangian equation for obtaining the composite V at minimum cost is given by:

$$L = \sum_{i=1}^{n} p_i v_i + \lambda \left\{ \phi \left[\sum_{i=1}^{N} \alpha_i v_i^{\rho} \right]^{\frac{1}{\rho}} - V \right\} \tag{B4}$$

where p_i is the price of input v_i. For simplicity, in all equations in this appendix, the price shown is inclusive of any tax and net of any subsidy. In Appendix E where we listed all the equilibrium conditions of the model, all taxes and subsidies are shown explicitly.

From this minimization problem, the optimal demand of input v_i per unit of the composite V is derived as:

$$\frac{v_i}{V} = \phi^{\sigma-1} \alpha_i^{\sigma} \left[\frac{p_i}{p} \right]^{-\sigma} \tag{B5}$$

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

$$p = \frac{1}{\phi} \left[\sum_{i=1}^{n} \alpha_i^{\sigma} p_i^{1-\sigma} \right]^{\frac{1}{1-\sigma}} \tag{B6}$$

Cost-Minimizing Output Supply

For fossil-based electricity subsectors and other sectors, the profit function is:

$$\begin{aligned} \Pi &= pY - C \\ &= pY - p_x x - p_{emw} emw \end{aligned} \tag{B7}$$

For solar, wind, hydro, and nuclear electricity subsectors, the profit function is:

$$\Pi_k = pY - p_x x - p_{emw} emw - p_{rk} res_k \tag{B8}$$

where the C is the cost of production inputs, which equals the payment to $\boldsymbol{x}$ and $\boldsymbol{emw}$, p_{rk} and res_k denote the price and endowment for natural resources. The p denotes the composite price of the produced good.

$$p = \left[\alpha_{dm}^{\sigma_{de}} p_{dm}^{1+\sigma_{de}} + \alpha_{ex}^{\sigma_{de}} p_{ex}^{1+\sigma_{de}} \right]^{\frac{1}{1+\sigma_{de}}} \tag{B9}$$

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

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

$$p \frac{\partial Y}{\partial \boldsymbol{x}} = p_x \tag{B10}$$

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

$$\boldsymbol{x} = \alpha_{\boldsymbol{x}}^{\sigma_{xemw}} \left[\frac{p_{\boldsymbol{x}}}{p} \right]^{-\sigma_{xemw}} Y \phi^{\sigma_{xemw}-1} \tag{B11}$$

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

$$p \frac{\partial Y}{\partial \boldsymbol{emw}} = p_{emw} \tag{B12}$$

$$\boldsymbol{emw} = \alpha_{\boldsymbol{emw}}^{\sigma_{xemw}} \left[\frac{p_{\boldsymbol{emw}}}{p} \right]^{-\sigma_{xemw}} Y \phi^{\sigma_{xemw}-1} \tag{B13}$$

Under the model's production structure, each firm's production exhibits constant returns to scale. The firm chooses the level of output at which the marginal production

cost equals the price. Applying the optimal $\boldsymbol{x}$ and optimal $\boldsymbol{emw}$ in equations (B11) and (B13) to the optimal input intensities, we get the optimal levels of all inputs.

Allocation of Supply to Domestic and Foreign Markets

A CET function maps the total output Y into the domestic supply Y_{dm} and export Y_{ex}.

$$Y_{dm} = \alpha_{dm}^{-\sigma_{de}} \left[\frac{p_{dm}}{p} \right]^{\sigma_{de}} Y \tag{B14}$$

$$Y_{ex} = \alpha_{ex}^{-\sigma_{de}} \left[\frac{p_{ex}}{p} \right]^{\sigma_{de}} Y \tag{B15}$$

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

State-Owned Enterprises

State-owned enterprises (SOEs) and privately-owned enterprises (POEs) are modeled as profit-maximizing firms that enjoy subsidies and face taxes. SOEs receive favorable treatment relative to POEs through input subsidies. Despite the SOEs' favorable treatment, the two types of firms share the markets for specific products and receive the same prices for these products. For a given product, both SOEs and POEs choose levels of output that bring the marginal costs from their differing marginal cost functions up to the common output price.

SOEs benefit from preferential treatment through lower interest rates in capital markets due to government subsidies (Cull and Xu, 2003; Guariglia *et al.*, 2011; Song *et al.*, 2011; Harrison *et al.,* 2019). These are modeled as subsidies to their capital inputs. SOEs also offer superior benefits to their employees, including higher social security and pensions, implying higher labor costs (Hering & Poncet, 2010; Démurger *et al.*, 2012; Berkowitz *et al.*, 2017). This is captured via a higher tax rate on the labor input of SOEs than POEs.

The model assumes there are two representative firms in each sector (or in each subsector, when subsectors are identified), with one representing SOEs and one representing POEs.

Administered Pricing of Electricity

In China's electricity markets, generators sell some of their electricity at a government-administered price and some at market prices. The market price applies at the margin, that is, for the supply beyond a government-specified quantity to which the administered price applies. As mentioned in Appendix A, the data indicate that the government-administered price is higher than the market price (CEC, 2019) to guarantee the production of the administered electricity. We assume the share of the administered electricity will decrease linearly to zero before 2025, following the expectation that China's electricity market will be fully liberalized by 2025. Thus, the model incorporates administered pricing only through 2024.

A piecewise marginal revenue function captures the hybrid pricing structure. Let Y_A represent the level of output at which administered pricing no longer applies. There are three cases:

Case i) For firms that produce output above Y_A, the marginal cost is below the market price at the quantity Y_A, so firms have incentives to exceed Y_A and face the market price at the margin. Total expenditure on electricity by consumers exceeds pY: this total is $p \cdot Y + (p_A - p) \cdot Y_A$. The electricity consumers effectively face a lump-sum tax of $(p_A - p) \cdot Y_A$.

Case ii) For firms that would produce less than Y_A, the marginal cost at the level Y_A is higher than the administered price p_A. The profit-maximizing output level is $Y < Y_A$. However, the firms still need to produce to the guaranteed level, Y_A. All of their electricity is sold at the price p_A. In this case, the electricity generating firms incur a loss of $(c - p_A) \cdot Y_A$.

Case iii) For firms that would produce Y_A, the marginal cost at the level Y_A is lower than or equal to the administered price p_A but higher than the market price p. These firms could earn rents if p_A exceeds their marginal cost, yet they have no incentive to

exceed Y_A because output beyond Y_A would need to be sold at the market price p, which is below marginal cost.

B.4 Household Behavior

Consumption

In the model, a representative household makes consumption choices to maximize utility. The nested structure of the utility function is below. The household chooses between material goods (***x***) and energy goods (***e***). At the next level, the material composite is a CES combination of material goods, x_1, x_2, …, x_{24}. The energy composite is a CES function of electricity (s), heat (h) and fuel composite (f). The fuel composite is a CES function of five fuel goods, f_1, f_2, …, f_5. Each x_i, f_i, and s is a composite based on the domestically and foreign supplied component.

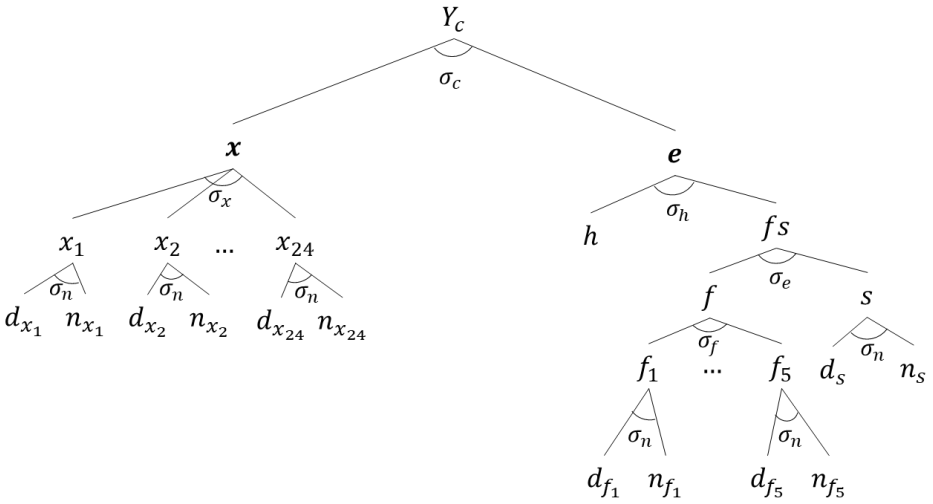


Figure B3. Household Demand Structure

The CES functional form in Equation (B3) applies to all nests in the household demand structure. The form of the price function in Equation (B6) applies to the composite prices for all nests of the household demand structure. The household maximizes utility subject to its budget constraint. The maximization problem is:

$$\begin{aligned} &\max U\left(Y_C\right) = Y_C \\ &s.t. \quad p_C Y_C \le p_m \overline{m} + p_w \overline{w} + p_{res} \overline{res} + p_{lnd} \overline{lnd} + T - S \end{aligned} \tag{B16}$$

where

$p_C Y_C$ is the household expenditure,

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

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

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

$p_{lnd} \overline{lnd}$ is income from the endowments of land,

T is the transfer from the government, and

S is private saving (discussed below).

Investment

Production of the investment involves the CES nested structure in Figure B4.

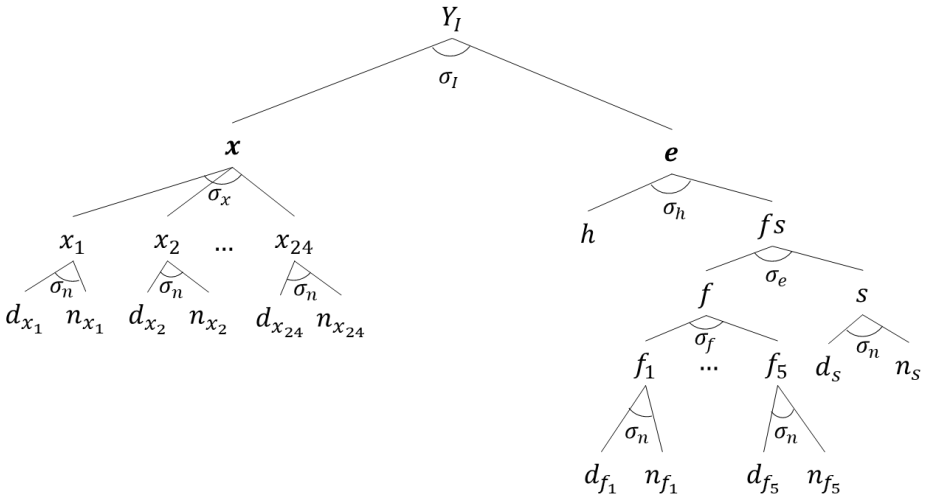


Figure B4. Nested Structure for Investment

The generalizable CES function form in Equation (B3) applies to all nests in the investment good production structure. The investment good is produced at the minimum cost. The minimum cost problem has the same form as that of the cost minimization problem of commodity goods. Hence the generalizable form in Equation (B6) applies to the investment good.

Household spends money on consumption and investment. Household's expenditure on the investment good is determined by the price of the investment good and the substitution elasticity between consumption and investment, as Figure B5 shows.

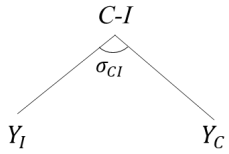


Figure B5. Structure for Household Saving and Consumption Decisions

Household's expenditure on investment derives from private saving. The structure displayed in Figure B5 leads to the private saving according to:

$$\frac{\frac{S_t}{INC_t}-\frac{S_0}{INC_0}}{\frac{S_0}{INC_0}}=-\varepsilon_I\frac{\frac{p_{I,t}}{p_{C-I,t}}-\frac{p_{I,0}}{p_{C-I,0}}}{\frac{p_{I,0}}{p_{C-I,0}}} \tag{B17}$$

where S_t represents private saving and INC_t is total household income. The left-hand side represents the change in private saving rate relative to the benchmark data. $p_{I,t}$ the cost of investment good in period *t*. $p_{C-I,t}$ the price of consumption-investment composite. S_0, INC_0, $p_{I,0}$, and $p_{C-I,0}$ represent them in the benchmark data. The ε_I is the elasticity between private saving rate and the price of investment good relative to the consumption-investment composite, and $\varepsilon_I=-\sigma_{CI}(1-\frac{S_0}{INC_0})$. In keeping with Zhang *et al.* (2018), we assume the saving rate decreases over time (see further discussion below).

B.5 Government Behavior

Government spending in the model derives from a CES preference function defined over a material-energy composite.

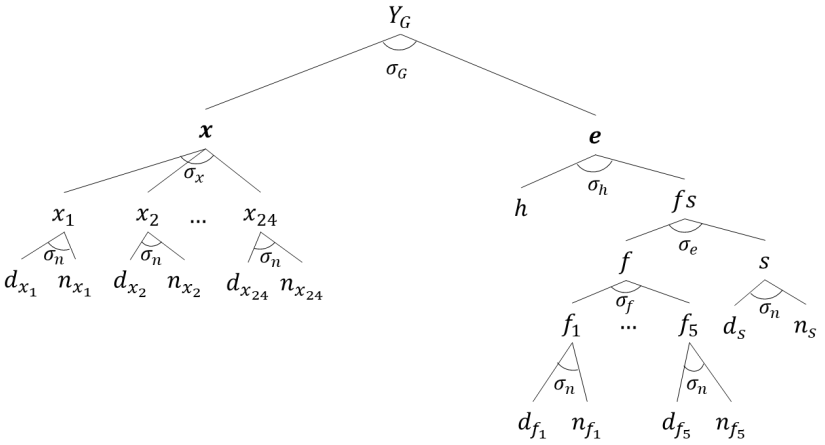


Figure B6. Nested Structure for Government Spending

The government is assumed to balance its budget each year:

$$p_G Y_G = R - T - I_G \tag{B18}$$

where $p_G Y_G$ is the expenditure on public consumption, R the total tax revenue (consists of output taxes, intermediate demand taxes, factor taxes, and final demand taxes), T the transfers to households, and I_G the public saving. Government consumption is set as a fixed share of GDP and characterized by a CES preference function defined over the material-energy composite. The transfer to households is endogenously determined by the government's budget balance requirement. Public saving is also specified as a fixed share of GDP.

The generalizable CES function form in Equation (B3) applies to all nests in the government demand structure. The composite final good is produced at minimum cost. The minimum cost problem has the same form as that of the cost-minimization problem for the outputs of the model's various sectors. Hence the generalizable form in Equation (B6) applies to the government's composite good.

B.6 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. A CES function aggregates the domestically produced and imported goods to an Armington composite. Imported goods also incur international transport service, which is set as proportional to the quantity of imports, as Equation (B19) shows. In this way, imports and exports quantities are functions of the relative prices of domestic and foreign goods and the international transportation cost.

$$P_{i,r}^{M} = P_{i,s}^{E} \times (1 - \theta_{i,s,r}^{t}) + P^{T} \times \theta_{i,s,r}^{t} \tag{B19}$$

where $P_{i,r}^{M}$ is the price of import goods *i* in region *r*, $P_{i,s}^{E}$ is export price in rest of the world (*s*), and P^{T} the price of international transportation services. $\theta_{i,s,r}^{t}$ is the share of international transportation service in the import activity of goods *i*.

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

B.7 Equilibrium

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.

A full description of the equation system and solution method is provided in Appendix E.

B.8 Dynamics

The model solves at one-year intervals from 2020 through 2035. 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.

$$\bar{w}_{t+1} = \bar{w}_t(1-\delta) + I_t \tag{B20}$$

where $\bar{w}_t$ is the capital stock in period *t*. δ is the depreciation rate. I_t is the real investment (total savings divided by the price of investment goods) in period *t*.

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. AEEI is an exogenous increase in the productivity of the composite energy input into production. As indicated below, the AEEI rate differs across sectors. The changes to the rates are achieved via time-varying technological change parameters that apply to the benchmark energy input shares.

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. The rates of Hicks-neutral technological change are calibrated to match the projections in the State Information Center (2020) and IRENA (2024). Similarly, these technology changes are achieved by time-varying Hicks-neutral technological change parameters in the production function (ϕ in Equation B3).

Appendix C. Data

C.1 Subsector Classification

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

Electricity Sector

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

Table C1. Subsectors of the Electricity Sector

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

In our data, there are 1,929 coal-fired and gas-fired units, generating 23 billion kWh in 2017, covering 49.7% of China's coal- and gas-fired electricity generation.[2]

The cement and aluminum sectors include subsectors categorized according to their observed emissions intensities. Iron & steel sector includes subsectors categorized by their production technologies and observed emissions intensities. We use a machine-learning method to cluster plants with varying emissions intensities into distinct subsectors. The first step is to decide the resulting number of subsectors. The second step is to employ the clustering algorithm to find cluster centers and assign plants to each cluster such that the distance (i.e., the difference between the center's emissions intensity and the plant's emissions intensity) is minimized. Various clustering algorithms differ in how "cluster center" and "distance" are defined. We employ the k-means algorithm. Below we document this clustering process for cement, aluminum, and iron & steel, respectively.

Cement

In our data, there are 797 cement production facilities from 631 cement firms, covering 57% of China's cement production.[3] We have the CO_2 emissions intensity data for each facility.[4] We apply a clustering algorithm to group the production facilities into five clusters. The lowest and highest clusters have very few production facilities, so we include them in the closest intermediate groups. Each of the resulting three clusters represents a subsector of the cement sector. The

[2] The Ministry of Ecology and Environment (MEE) provided us with data based on a sampling of the transactions in each sector. The average emissions intensity of fossil-based electricity production in our dataset is 0.78 tCO_2/MWh. This closely aligns with the national average emission intensity of fossil-based electricity for the corresponding year, which was reported as 0.77 tCO_2/MWh in the Energy Balance Table of 2017.

[3] The average emissions intensity of cement in our data is 0.87 tCO_2/ton cement. This value closely aligns with the published national-average emissions intensity of 0.87 tCO_2/ton cement (Ding, 2021), making the dataset representative.

[4] The cement production process is primarily divided into two steps: cement clinking and clinker grinding. The emissions data here are emissions in the cement clinking process. Given that the emissions from the clinker grinding step account for a minor fraction of the total emissions in cement production, using the emissions intensity of cement clinker to define subsectors approximates fairly closely the emissions intensity of cement production.

clusters are indicated in Table C2 below. Figure C1 shows the cumulative distribution function that captures the relationship between the emissions intensities of the three emissions-intensity groups and cumulative cement production.

Table C2. Subsectors of the Cement Sector

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

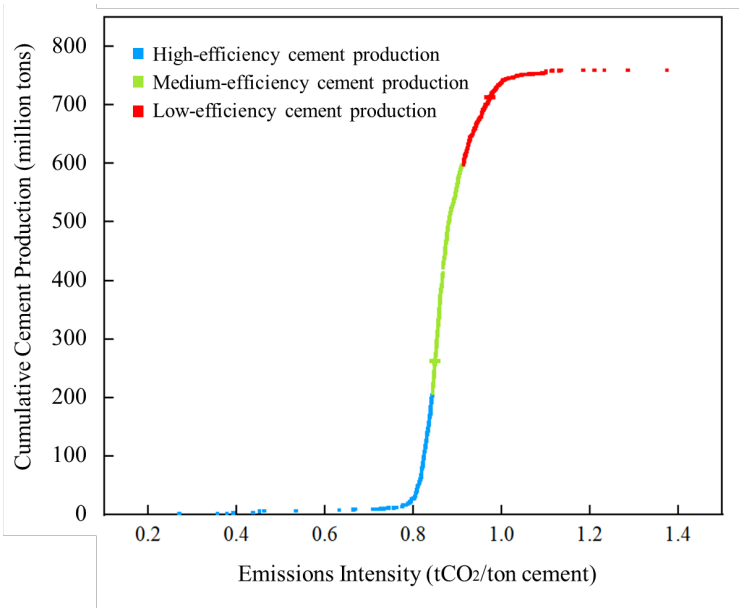


Figure C1. Clustering of Cement Sector by Emissions Intensity

Aluminum

In our data, there are 116 aluminum production facilities from 64 aluminum firms, covering 42% of China's aluminum production.[5] We use the same clustering method

[5] The average electricity intensity of aluminum in the data is recorded at 13,218 kWh/ton aluminum, which closely aligns with the published national average level of 13186 kWh/ton aluminum (NDRC, 2021b).

as cement – we first group the 116 production facilities into 5 clusters, and then regroup the lowest and highest clusters to their closest groups, respectively. We end up with three clusters, each representing one subsector in the aluminum sector, as shown in Table C3 and Figure C2.

Table C3. Subsectors of the Aluminum Sector

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

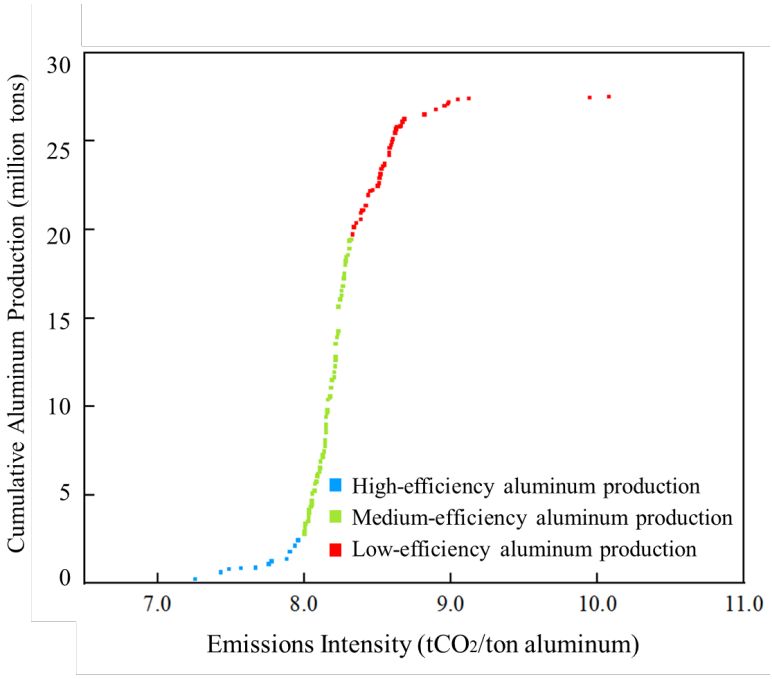


Figure C2. Clustering of Aluminum Sector by Emissions Intensity

Iron & Steel

We first classify iron & steel units into two technology categories: basic oxygen (BO) steelmaking and electric arc (EA) furnace steelmaking. Units within each technology category are further classified into subcategories based on their observed emissions intensities.

There are 187 BO steelmaking units with a total production of 600 million tons of crude steel, and 262 EA steelmaking units with a total production of 133 million tons of crude steel. In total, our data cover 88% of the national crude steel production in 2017.[6]

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

Table C4. Subsectors of the Iron & Steel Sector

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

[6] The average emissions intensity of BO and EA iron and steel production in our data is 1.40 tCO_2/ton, which closely aligns with the published national average level of 1.37 tCO_2/ton (NBS, 2018).

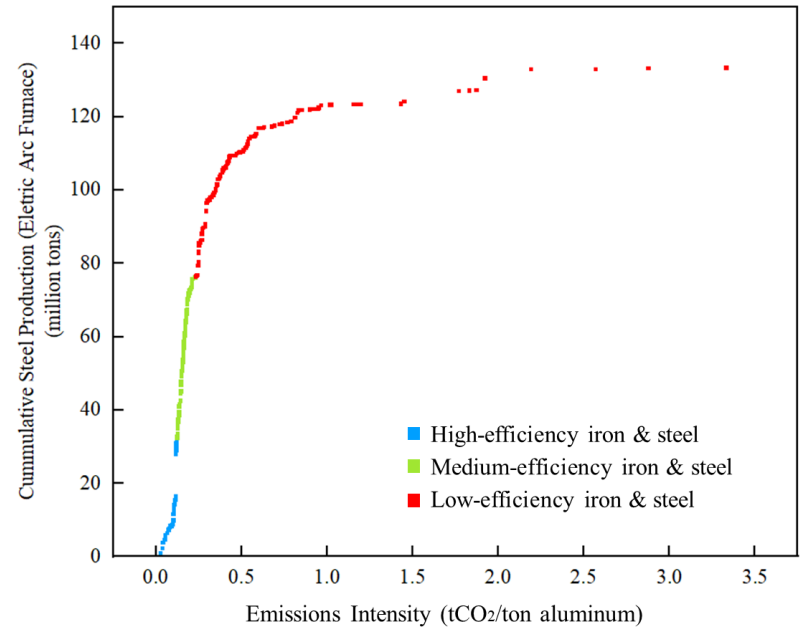


Figure C3. Clustering of Electric Arc Furnace Steelmaking by Emissions Intensity

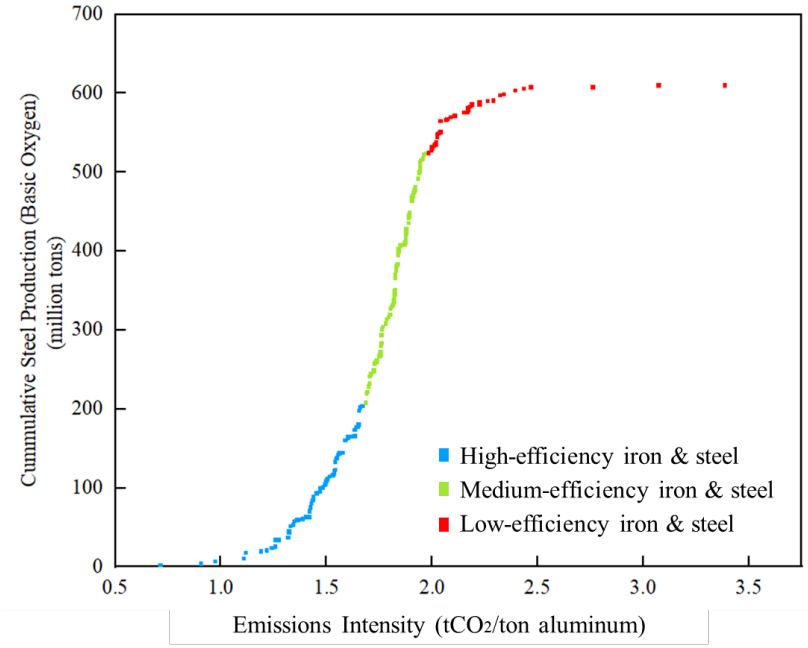


Figure C4. Clustering of Basic Oxygen Steelmaking by Emissions Intensity

C.2 Data Aggregation and Consistency Procedures

The data are processed in five steps. First, the 149 sectors' input-output data from China's 2017 input-output table are aggregated to the 31 production sectors in our study and scaled to 2020, the first simulation year. We use three scalars to translate these input and output data to 2020: one for the service sector, one for the agriculture sector, and one for other sectors. The data are scaled so that the GDP, as well as the value-added shares of the service sector and agriculture sectors, match the published statistics in 2020 (NBS, 2021). Second, the sectors are disaggregated into subsectors for electricity, cement, aluminum, and iron & steel according to the subsector-level information, which is obtained by aggregating the firm-level Ministry of Ecology and Environment (MEE) data. The disaggregation method is described in the next paragraph. Third, we scale all tax and subsidy rates reported in GTAP v10 so that the total tax revenue net of subsidies matches that in 2020 (NBS, 2021).[7] Fourth, we re-balance the input-output data after these adjustments, as described in the subsection "Input-Output Table Rebalance" below. Lastly, we further disaggregate the sectors (or subsectors for electricity, cement, aluminum, and iron & steel) into SOEs and POEs. This disaggregation ensures that the inputs and outputs of SOEs and POEs match the empirical evidence while maintaining the balance of the input-output data. Details about the parameters related to SOEs and POEs are provided in Appendix D.

Disaggregating Sector-Level Data to the Subsector Level

The input-output table provides sector-level data on economic values. The sectors are then split into subsectors (for electricity, cement, aluminum, and iron & steel sectors) as described below.

For factor inputs (m_j, w_j), material inputs d, n, and exports (Y_{ex}), sector-level electricity, cement, and aluminum data are split into subsectors by assuming that each

[7] Wind and solar electricity have higher unit cost than fossil-based electricity. China's government incentivizes solar and wind electricity generators through various forms of subsidies. We obtain the current subsidy rates for wind and solar electricity from Direct Trading Pilots of Green Power (Hao et al., 2023) and project these rates to decline over time. Following the official announcement by NDRC (2021a), we assume that the subsidy rates for wind and solar electricity will decrease linearly over time and reach zero in 2025.

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

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

The MEE data include emission data in electricity, cement, aluminum, and iron & steel sectors. The emission data only cover a subset of the whole sector. We scale the emissions data up by the share of coverage for each of the four sectors. Then, for the electricity, cement, aluminum, and iron & steel sectors, the emissions data at the sector level are split into subsectors in the same way as we split energy inputs. Note that the cement sector, in addition to emissions from consuming energy inputs, also emits CO_2 in the process of carbonate decomposition ($CaCO_3$ decomposed to CaO and CO_2).

Input-Output Table Re-balancing

After data processing described above, the original input-output table is unbalanced: the total inputs of a sector differ from the sector's total outputs. We apply a least-square optimization method to obtain a balanced input-output table, following Zhang *et al.*(2013):

$$
\begin{aligned}
&\min_{\{d_{x_{ijk}},e_{ijk},w_{jk},m_{jk}\}} \sum_{i,j,k} \{(d_{x_{ijk}} - \overline{d_{x_{jik}}})^2 + (w_{jk} - \overline{w_{jk}})^2 + (m_{jk} - \overline{m_{jk}})^2 + (e_{jk} - \overline{e_{jk}})^2\} \\
&s.t. \\
&\sum_i (d_{x_{ijk}} + w_{jk} + m_{jk} + e_{ljk}) \cdot (1 + \overline{\theta_{res_{jk}}}) = (\sum_k Y_{dm_{jk}} + \sum_k \overline{Y_{ex_{jk}}}) \cdot \psi_{jk}, \forall j,k \\
&\sum_{i,k} d_{x_{jik}} \equiv \sum_k Y_{dm_{jk}} \\
&d_{x_{jik}}, w_{jk}, m_{jk}, e_{ljk} > 0, \\
&d_{x_{jik}} \equiv 0, \forall \overline{d_{x_{jik}}} = 0 \\
&w_{jk} \equiv 0, \forall \overline{w_{jk}} = 0 \\
&m_{jk} \equiv 0, \forall \overline{m_{jk}} = 0 \\
&e_{ljk} \equiv 0, \forall \overline{e_{ljk}} = 0,
\end{aligned}
\tag{C1}
$$

where $d_{x_{ijk}}$ represent the adjusted domestic material input *i* of sector *j*, subsector *k*, e_{ljk} the energy input *l*, w_{jk} the capital input, and m_{jk} the labor input. $\overline{d_{x_{ijk}}}$, $\overline{e_{ljk}}$, $\overline{w_{jk}}$, $\overline{m_{jk}}$ represent the corresponding accounts before the re-balance. $\overline{\theta_{res_{jk}}}$ is the share of natural resources for low-carbon electricity production subsectors. The objective function assesses the difference between the adjusted and unadjusted original value. In the first constraint, the left-hand side represents the total inputs of sector *j*, subsector *k*. The right-hand side is the total output of sector *j*, subsector *k*, where ψ_{jk} represents the subsector *k*'s output share in sector *j*.

C.3 Sector-level Data Details

Here we present the sector-level data that are important to understand the TPS's sector-level impacts. Table C5 presents the tax rates in the dataset produced through the aforementioned steps. Table C6 shows the import and export ratios to sectors' total output, which are calculated using the import, export, and output data in the same dataset. Additionally, Table C7 presents the sector emissions intensities, derived from the emissions data and the output data in the produced dataset.

Table C5. Tax Rates

	Labor	Capital	Output	Imported Goods	Weighted-Average
Electricity	20.4	-10.0	2.3	N/A	1.0
Cement	8.7	-2.0	2.9	9.7	1.4
Iron & steel	5.1	-0.7	1.3	8.8	0.7
Aluminum	3.8	-0.3	1.7	6.4	0.8
Pulp & paper	3.4	0.1	2.2	7.6	1.1
Petroleum refining	19.4	-4.6	8.9	10.9	4.2
Raw chemical	5.2	-0.9	1.4	8.5	0.7
Other non-metal products	5.3	-2.0	3.0	10.5	1.4
Other nonferrous metal	3.3	-0.3	1.7	7.3	0.9
Agriculture	0.8	-2.8	0.0	10.1	-0.3
Coal	3.6	-1.7	4.6	4.5	2.1
Crude oil	24.6	-10.0	0.8	0.0	0.6
Natural gas	7.5	-0.7	3.4	2.2	1.5
Mining	3.0	-1.2	4.5	6.6	2.1
Food	2.3	0.3	4.2	11.3	2.0
Textile	1.4	1.1	1.4	9.5	0.7
Clothing	1.3	1.1	1.6	11.5	0.7
Log furniture	1.5	0.9	2.5	8.0	1.1
Printing and stationery	2.0	0.0	2.9	10.3	1.3
Daily chemicals	2.2	0.3	1.8	9.5	0.9
Metal products	1.9	0.4	1.7	10.4	0.9
General equipment	2.3	-0.2	1.8	9.1	0.9
Transport equipment	4.4	-1.5	2.0	15.3	1.0
Electronic equipment	1.8	0.6	1.1	8.8	0.5
Other manufacturing	3.8	0.2	1.5	8.1	0.8
Gas distribution	1.3	1.3	1.0	N/A	0.5
Water	1.2	1.3	2.4	N/A	1.2
Construction	2.7	-2.5	1.9	6.8	1.0
Transport	4.0	-1.4	0.6	8.5	0.1
Services	5.1	-3.8	4.6	5.2	2.0
Heat	20.4	-10.0	2.6	N/A	1.3
Average tax rate [1]					
Phase 1:					
Covered sectors	20.4	-10.0	2.3	N/A	1.1
Noncovered sectors	4.2	-2.7	3.0	7.8	1.2
Phase 2:					
Covered sectors	12.0	-4.5	1.7	8.6	0.9
Noncovered sectors	4.2	-2.8	3.1	7.7	1.2
Phase 3:					
Covered sectors	8.3	-2.8	3.0	8.6	1.4
Noncovered sectors	4.1	-2.8	3.0	7.6	1.1

[1] For labor (capital) taxes, the weights are the share of labor (capital) inputs in each sector relative to the total labor (capital) endowments in the benchmark data. For outputs, the weights are the share of each sector's domestic production in the total domestic production in the benchmark data. For taxes on imported goods, the weights are the proportion of imports of each sector's product in the total imports in the benchmark data. Tax rates are assumed to remain constant at base year levels throughout the simulation period, except for declining output subsidies for wind and solar electricity production (see footnote 7 in the appendix). The tax rates for the electricity sector presented in this table represent the average over the entire simulation period.

Table C6. Import and Export as Ratios to Sectors' Total Output

Sector	Export to total output (%)	Import to total output (%)
Cement	0	0
Gas distribution	0	0
Iron & steel	5	4
Aluminum	8	1
Pulp & paper	4	6
Other non-metal products	5	2
Other non-ferrous metals	3	14
Raw chemicals	7	14
Agriculture	1	7
Mining	1	63
Food	3	4
Textile	16	5
Clothing	39	4
Log & furniture	19	4
Printing & stationery	25	3
Daily chemical products	9	7
Metal products	12	4
General equipment	16	16
Transport equipment	7	17
Electronic equipment	38	22
Other manufacturing	11	27
Water	0	0
Construction	0	0
Transport	14	6
Services	4	3
Electricity	0	0
Petroleum refining	2	5
Heat	0	0
Coal	1	12
Crude oil	1	238
Natural gas	4	21

Table C7. Sector Emissions Intensities

Sector	Emissions intensity (t/*k*RMB)
Cement	1.945
Iron & steel	0.235
Aluminum	0.446
Pulp & paper	0.053
Other non-metal products	0.062
Other non-ferrous metals	0.054
Raw chemicals	0.098
Agriculture	0.013
Mining	0.018
Food	0.008
Textile	0.007
Clothing	0.002
Log & furniture	0.003
Printing & stationery	0.001
Daily chemical products	0.003
Metal products	0.003
General equipment	0.005
Transport equipment	0.002
Electronic equipment	0.001
Other manufacturing	0.004
Water	0.038
Construction	0.003
Transport	0.072
Services	0.001
Electricity	0.858
Petroleum refining	0.041
Heat	0.945
Coal	0.029
Crude oil	0.043
Natural gas	0.007
Gas manufacture & distribution	0.003

Appendix D. Parameters and Calibration Methods

D.1 Production Parameters

The balanced input-output table described in Appendix C provides benchmark data for output, material, energy and factor inputs. Based on the values in this table we calibrate the share parameters of CES functions. Specifically, we obtain the parameter α_i for each sector or subsector by inverting the optimal input intensity function, Equation (B5), normalizing ϕ to one in the base year:

$$\alpha_i = (\frac{v_i}{V})^{1/\sigma} \cdot \frac{p_i}{p} \tag{D1}$$

where V is the output quantity, v_i the quantity of input i, p_i the benchmark price of input i and p the benchmark price of output. To calibrate α_i, we also need the elasticities of substitution (σ) at different levels of the nested CES structure. In the subsections below, we discuss how we obtain them.

Substitution Elasticity between Electricity and Other Fuels (σ_e)

We calibrate the elasticity of substitution between electricity and other fuels (σ_e) based on data for the price elasticity of demand for electricity. Estimates for this price elasticity in China range from -0.1 (Shi *et al.*, 2012) to -2.9 (He & Reiner, 2016), with most of the long-run values (consistent with the scope of our model) around -0.5. In our central case we employ the estimate of -0.5 in Hu *et al.*(2019). This estimate is relatively recent and derives from an especially rich dataset.

Substitution Elasticity between the Energy Composite and Factor Composite (σ_{emw})

A generator's heat rate measures the energy used by a power plant to generate one kilowatt-hour (kWh) of electricity. It serves as an efficiency indicator for power plants. Our model aims to capture the ease of changing the heat rate for generators in each of the fossil-based electricity subsectors.

The NDRC reports provide estimates of the costs and potential heat rate reductions across different measures for both coal-fired and gas-fired power plants in China.[8] The coal-fired power plants data include 26 measures, and gas-fired power plants include 11 measures. These measures can be categorized into improvements for the boiler island, turbine island, flue gas system, air pollution controls and water treatment system, etc. We rank these measures by their unit cost, which yields marginal cost curves for heat rate reduction for coal-fired and gas-fired power plants, respectively, as shown in Figure D1.

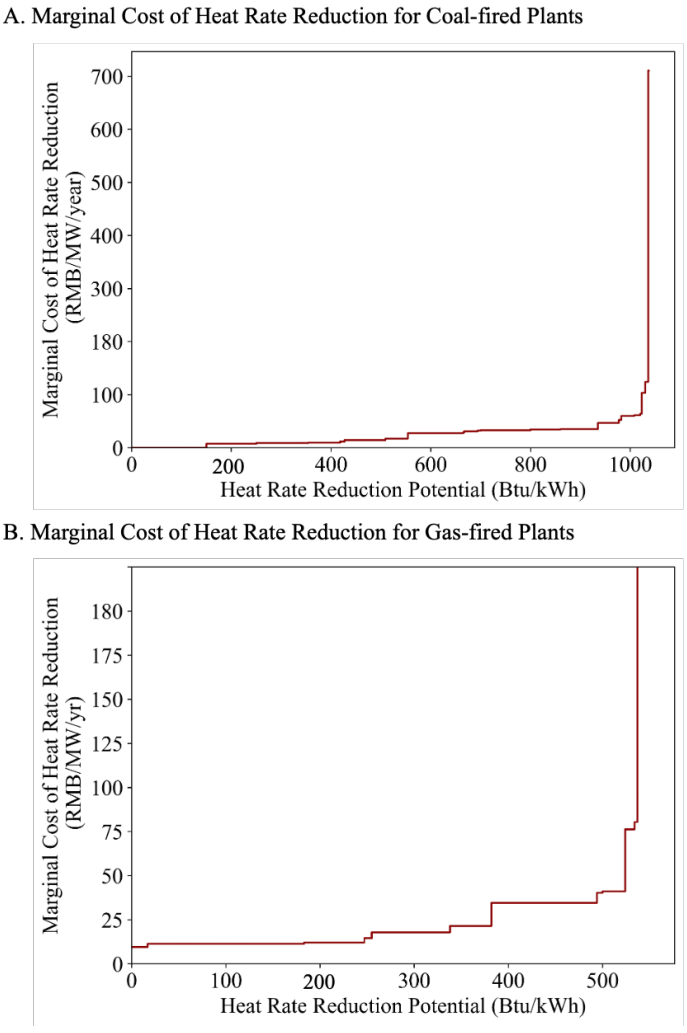


Figure D1. Marginal Cost of Heat Rate Reduction with All Measures

[8] The NDRC reports estimate the costs of these measures based on the pilot energy conservation programs in China.

Estimating the marginal cost curve presents a key challenge: it should exclude measures that have already been adopted, since their (historical) costs are not marginal. Following Burtraw *et al.* (2012), we assume that the observed heat rates are inversely correlated with the adoption of identified measures. Specifically, the power plants with higher emissions intensities have adopted fewer efficient techniques than the plants with lower intensities.

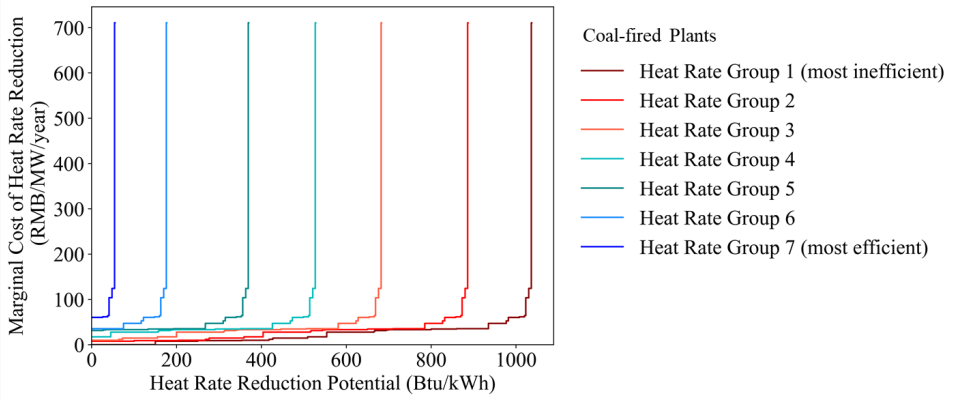
We first categorize all power plants according to their heat rates, as in Table D1.[9] We consider the most inefficient (highest heat rate) group as having access to all heat rate reduction measures shown in Figure D2, resulting in a marginal cost curve identical to that in Figure D1. On the other hand, the most efficient group (lowest heat rate) is assumed to have only two measures with the two highest unit costs available, leading to its marginal cost curve matching the two far-right segments of Figure D2. For the groups that lie between these two extremes, we assume a linear relationship between their heat rate reduction potentials and their differences from the lowest heat rate group in terms of median heat rate. The resulting curves are in Figure D2.

Table D1. Heat Rate Range by Heat Rate Group

Heat rate group	Heat rate range (Btu/kWh)
Coal-fired Power Plants	
1 (most inefficient)	(13015, 14000]
2	(11435, 13015]
3	(10182, 11435]
4	(9260, 10182]
5	(8535, 9260]
6	(7624, 8535]
7 (most efficient)	[7000, 7624]
Gas-fired Power Plants	
1 (most inefficient)	(11278, 13000]
2	(8593, 10435]
3	(7177, 8593]
4 (most efficient)	[6000, 7177]

[9] We employ the k-means clustering algorithm to cluster all coal-fired power plants into seven groups with different heat rates, and gas-fired power plants into four groups.

A. Marginal Cost of Heat Rate Reduction for Coal-fired Plants



B. Marginal Cost of Heat Rate Reduction for Gas-fired Plants

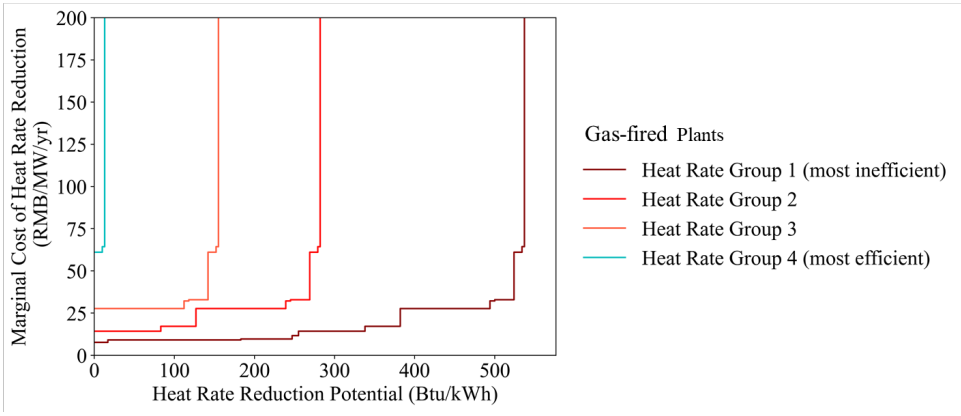


Figure D2. Marginal Cost of Heat Rate Reduction by Heat Rate Group

For each heat rate group, we then calibrate the price elasticity of the demand for fossil fuel input to fit the marginal cost curve for each heat rate group, as indicated in Table D2. The elasticity in each subsector is then calculated, considering the distribution of plants among the heat rate groups:

$$\varepsilon_k = \sum_h \vartheta_{kh} \varepsilon_h \tag{D2}$$

where ε_k is the price elasticity of coal for subsector k, ε_h is the price elasticity of fossil fuel for heat rate group h, ϑ_{kh} is the output share of heat rate group h in subsector k.

Finally, we use ε_k to calibrate the energy-factor elasticity in production, σ_{emw}, for each fossil-based electricity subsector.

Table D2. Calibrated Energy-Factor Elasticity of Substitution for Fossil-based Electricity Subsectors

Fossil-based subsectors	Energy-factor elasticity of substitution
Coal-fired Subsectors	
LUSC	0.229
SUSC	0.219
LSC	0.259
SSC	0.253
LSUB	0.299
SSUB	0.295
LCFB	0.373
SCFB	0.340
OTHC	0.361
Gas-fired Subsectors	
HPG	0.041
LPG	0.161

Parameters related to Renewable Energy Supply

The calibration of the elasticity of substitution between the resource and other input, σ_{res}, as well as the share of natural resource input, θ_{res}, leads to a detailed representation of renewable and nuclear electricity supply in China.

We use the Renewable Electricity Planning and Operation (REPO) Model,[10] a model of China's power system, to get the information on the marginal costs as a

[10] The REPO model (IEA and Tsinghua University, 2021; Zhang et al., 2023) captures China's power sector in great detail. The marginal cost is a combination of the marginal generation cost and the cost of integration. Generation costs depend on technology-specific investment and operation costs, as well as site-specific wind and solar conditions. Integration costs include grid integration, balancing services, more flexible operation of thermal plants, reserve costs, etc., and increase as the wind and solar penetration level rises (Hirth et al., 2015). The integration cost of wind or solar is complex and highly context-specific. Therefore, the existing empirical studies, which focused on the US and the EU, may not be applicable to China. We thus rely on the REPO model for deriving the curves.

function of supply for renewable and nuclear electricity, and then perform simulations of the model with different values of σ_{res} and θ_{res} and identify the combinations that lead to similar marginal costs in the REPO model. The derived curves are shown in Figure D3.

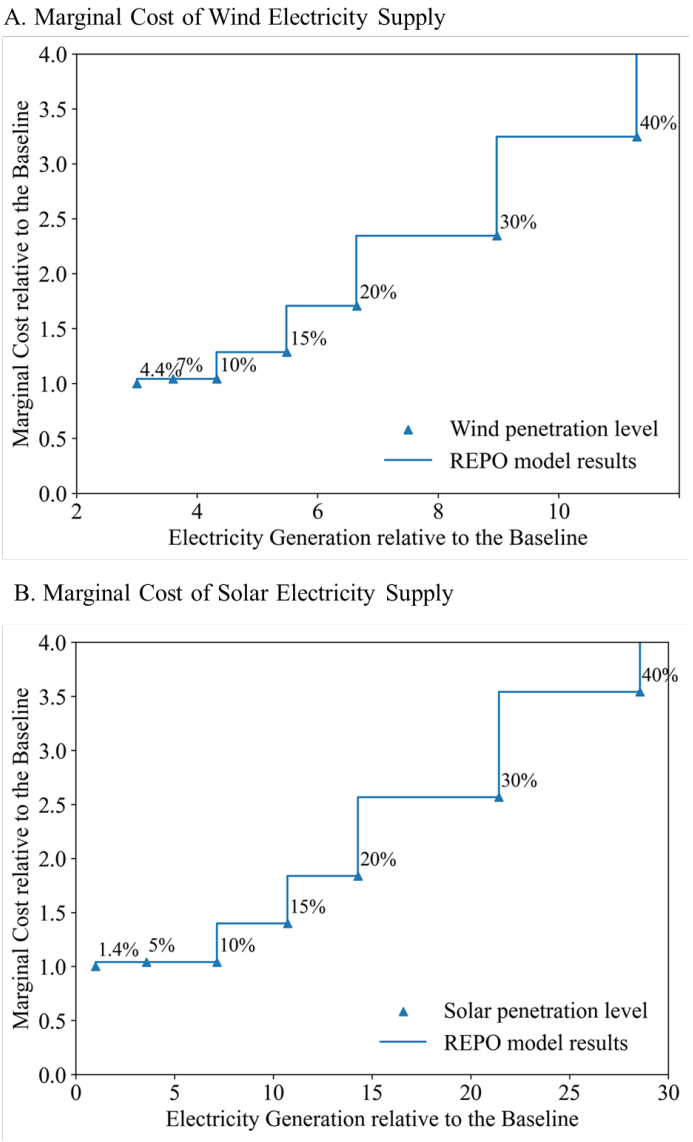


Figure D3. Marginal Cost for Wind and Solar Supply from the REPO Model

We use the following equation from the top-level nest of the production function to calibrate the parameters σ_{res} and θ_{res} in that function.

$$Y = Y_0 \left(\frac{1-(1-\theta_{res})\cdot(p/p_0)^{\sigma_{res}-1}}{\theta_{res}} \right)^{\frac{\sigma_{res}}{1-\sigma_{res}}} \quad \text{(D3)}$$

We obtain the values for σ_{res} and θ_{res} that best fit (using ordinary least squares) the supply curve in Figure D3.

For hydroelectricity and nuclear electricity, we use Leontief production functions, consistent with the fact that supplies of hydro and nuclear electricity in China are mainly constrained by planning and largely insensitive to electricity prices. Hence, for these subsectors, $\sigma_{res} = 0$. The θ_{res} parameter, representing the resource-related input not accounted for by other intermediate inputs or factor inputs, is derived from the literature. For hydroelectricity, it is calculated as the price difference between the hydroelectricity on-grid price (258.93 yuan/MWh) and the average on-grid electricity price (376.28 yuan/MWh) (NEA, 2018). The resulting θ_{res} is 0.3119 ($= \frac{376.28 - 258.93}{376.28}$). For nuclear electricity, θ_{res} equals 0.006 according to the share of payment for regional society in its total cost (IAEA, 2018).

Parameters related to State-Owned Enterprises

As indicated in the main text and Appendix B, the model considers two representative firms in each sector (or subsector, when subsectors are identified), with one representing SOEs and one representing POEs. Table D3 presents for each sector the total output value and the SOE value share, based on data from the China Industrial Enterprise Database and the China Input-Output Table.

Table D3. State-Owned Enterprises - Shares of Output

Sector	Benchmark-year output (trillion RMB)	SOE share (percent)
Cement	0.71	36
Iron & steel	5.89	36
Aluminum	0.72	31
Pulp & paper	1.92	8
Other non-metal products	5.89	36
Other non-ferrous metals	4.21	31
Raw chemicals	8.49	20
Agriculture	11.89	5
Mining	1.98	51
Food	13.22	23
Textile	4.04	3
Clothing	4.26	2
Log & furniture	2.66	6
Printing & stationery	2.39	8
Daily chemical products	7.06	8
Metal products	4.49	16
General equipment	8.26	19
Transport equipment	8.93	40
Electronic equipment	18.35	9
Other manufacturing	1.21	15
Water	0.26	53
Construction	23.02	39
Transport	14.97	77
Services	93.15	30
Electricity	4.88	87
Petroleum refining	5.77	69
Heat	0.60	87
Coal	2.34	69
Crude oil	0.81	92
Natural gas	0.37	46
Gas manufacture & distribution	0.43	46
Average	2.62	31

To achieve consistency with specific benchmark (year 2020) data, several conditions must be met. We express the conditions as they apply to subsectors. In the sectors without subsectors, they apply only at the sector level. Definitions of symbols are indicated in Table D4 below.

The co-existence of SOEs and POEs with outputs of the same type of good implies that their marginal costs of production are the same at the given market's output price. The marginal cost curves for SOEs and POEs exhibit different slopes. We calibrate the production functions of the SOEs and POEs so that the differing marginal cost curves yield the same marginal cost at the benchmark levels of output. The differences in the slopes of the marginal cost curves are attributable in significant part to the fact that the share of reproducible capital (an imperfectly mobile factor) differs at given output levels for the two types of firms.

The calibration method is as follows. The parameter $\theta_{w_{jk}}$ denotes the observed benchmark share of reproducible capital inputs in marginal cost:

$$\theta_{w_{jk}} = \frac{w_{jk} p_{w_{jk}} (1 + \tau_{w_{jk}} - o_{w_{jk}})}{p_{jk} \overline{Y_{jk}}} \tag{D4}$$

We identify the values of w_{jk} consistent with equal marginal costs at the observed benchmark input and output levels. Equation systems below denote the conditions.

(1) The equal-marginal-cost condition is:

$$\underbrace{\frac{w_{jk}{}^{S}}{\overline{Y_{jk}{}^{S}}}(1 - \overline{o_{wjk}{}^{S}}) + \frac{m_{jk}{}^{S}}{\overline{Y_{jk}{}^{S}}}(1 + \iota_{mjk}{}^{S})}_{\text{marginal factor costs of SOEs}} = \underbrace{\frac{w_{jk}{}^{P}}{\overline{Y_{jk}{}^{P}}}(1 + \overline{\iota_{wjk}{}^{P}}) + \frac{m_{jk}{}^{P}}{\overline{Y_{jk}{}^{P}}}(1 + \overline{\iota_{mjk}{}^{P}})}_{\text{marginal factor costs of POEs}} \tag{D5}$$

(2) In each subsector, the ratio of SOE to POE capital intensities matches the observed level in the data.

$$\frac{w_{jk}{}^{S}}{\overline{Y_{jk}{}^{S}}} \Big/ \frac{w_{jk}{}^{P}}{\overline{Y_{jk}{}^{P}}} = \overline{B_j} \tag{D6}$$

(3) In each subsector, the combined capital used by SOEs and POEs matches the data.

$$w_{jk}{}^{S} + w_{jk}{}^{P} = \overline{w_{jk}} \tag{D7}$$

(4) In each subsector, the combined labor used by SOEs and POEs matches the data.

$$m_{jk}{}^{S} + m_{jk}{}^{P} = \overline{m_{jk}} \tag{D8}$$

(5) The combined tax revenue of SOEs and POEs, after deducting subsidies to each subsector matches the data.

$$\overline{\iota_{wjk}}^{P} w_{jk}^{P} + \overline{\iota_{mjk}}^{P} m_{jk}^{P} + \iota_{mjk}^{S} m_{jk}^{S} - \overline{o_{wjk}}^{S} w_{jk}^{S} + \sum_{X} \overline{X_{jk}}\,\overline{\iota_{Xjk}} + \overline{Y_{jk}}\,\overline{\iota_{Yjk}} = \overline{T_{jk}} \qquad \text{(D9)}$$

The five sets of conditions correspond to five types of parameters. For the cases where a subsector *k* applies, the five parameters are: (1) w_{jk}^{S}, the benchmark capital input quantity of SOEs of sector *j*, subsector *k*; (2) w_{jk}^{P}, the benchmark capital input quantity of POEs of sector *j*, subsector *k*; (3) m_{jk}^{S}, the benchmark labor input quantity of SOEs of sector *j*, subsector *k*; (4) m_{jk}^{P}, the benchmark labor input quantity of POEs of sector *j*, subsector *k*; and (5) ι_{mjk}^{S}, the labor tax rate of SOEs of sector *j*, subsector *k*.

The relationship between parameters and conditions is not a simple one-to-one mapping, since some conditions (e.g., conditions 1 and 5) are met by combinations of parameters. The conditions and parameters imply a *5jk* simultaneous equation system, which we solve by Gaussian Elimination.

Table D4. Parameters Related to State-Owned Enterprises

Symbol	Definition
j	Index for sector
k	Index for subsector
P	Superscript for POEs
S	Superscript for SOEs
$\overline{Y_{jk}}$	Total output quantity
$\theta_{w_{jk}}$	Benchmark share of capital input in marginal cost
$\overline{Y_{jk}^{S}}$	Output quantity of the SOEs
$\overline{Y_{jk}^{P}}$	Output quantity of the POEs
$\overline{X_{jk}}$	SOE and POE total quantity of intermediate inputs
$\overline{m_{jk}}$	SOE and POE total quantity of labor inputs
$\overline{w_{jk}}$	SOE and POE total quantity of capital inputs
w_{jk}^{S}	Quantity of SOEs' capital inputs
w_{jk}^{P}	Quantity of POEs' capital inputs
m_{jk}^{S}	Quantity of SOEs' labor inputs
m_{jk}^{P}	Quantity of POEs' labor inputs
$\overline{T_{jk}}$	Total taxes paid by SOEs and POEs
$\overline{\iota_{Xjk}}$	Tax rate of intermediate inputs
$\overline{\iota_{mjk}^{P}}$	Tax rate on POEs' labor inputs
ι_{mjk}^{S}	Tax rates on SOEs' labor inputs
$\overline{\iota_{wjk}^{P}}$	Tax rate on POEs' capital inputs
$\overline{o_{wjk}^{S}}$	Subsidy rate on SOEs' capital inputs
$\overline{\iota_{Yjk}}$	Tax rate per unit of output
$\overline{B_{j}}$	The ratio of capital input intensity of SOEs to that of POEs

Note: Symbols with bars represent the data or parameters that are observed or obtained from other studies. Symbols without bars are the parameters that require calibration.

Other Parameters

We obtain other elasticities mainly from the GTAP database after close consideration of the quality of existing empirical estimates and the applicability to our model. The GTAP database offers an extensive and consistent collection of elasticity

estimates across various sectors in China. However, given its emphasis on trade with less attention to energy and climate, we adapted the energy-related elasticities based on a comprehensive literature review of China's empirical estimations. The selection criteria for elasticity values are the empirical literature's reported ranges for Chinese sectors and their applicability to our model.

For the substitution elasticities between the energy composite and the factor composite for non-electricity sectors, the existing literature's estimates range from 0.4 to 1.2 in China (Cao et al., 2020; Feng & Zhang, 2018; Su et al., 2012; Zha & Zhou, 2014). We adopt the lower bound of this range because of our model's detailed sectoral disaggregation, recognizing the increased challenge of input substitution at more disaggregated levels, as highlighted by recent empirical studies (Oberfield & Raval, 2021).

For substitution elasticities among fossil fuels in non-electricity sectors, Li & Lin (2016) suggested a range of 0.6-1 for China. However, their study only focused on oil-coal substitution and did not consider the broader substitution potential between coal and gas. Therefore, building on the findings of Li & Lin (2016) and recognizing the significant substitution potential between coal and gas in China, we have opted for a value of 1 in our central case.[11] For electricity sectors where generators are categorized by fuel type, we assign a smaller value of 0.01 to reflect limited fuel-switching capabilities.

Substitution elasticities among factor inputs, elasticities of factor transformation and the substitution elasticities between domestic and imported products are all derived from the GTAP databases.

Table D5 below summarizes the values and sources of these elasticities.

[11] A similar value is employed in the well-established EPPA and ADAGE models (Chen et al., 2017; RTI International, 2013) .

Table D5. Elasticities

Parameter	Source	Values
Production elasticities		
σ_{res}	Calibrated	Solar: 0.27 Wind: 0.28 Hydro, Nuclear: 0
σ_{xemw}	GTAP	0
σ_{emw}	Electricity calibrated; others from literature (Cao et al., 2020;etc.)	Electricity: 0.04 - 0.37, see Table D2 Other sectors: 0.4
σ_e	Calibrated	Other sectors: 0.50; Electricity: 0.01
σ_h	Hu *et al.* (2019)	0.30
σ_f	Li & Lin (2016)，RTI-ADAGE	Other sectors: 1.00; Electricity: 0.10
σ_{mw}	GTAP	Agriculture: 0.24 Coal, Crude oil, Natural gas, Mining: 0.20 Food: 1.12 Services: 1.36 Transportation: 1.48 Other sectors: 1.26
σ_x	GTAP	0
σ_n	GTAP	Mining: 1.80 Construction, Transportation, Services: 3.80 Petroleum refining: 4.20 Agriculture: 4.84 Food: 5.09 Cement, Other non-metal products: 5.80 Water, Gas manufacture & distribution, Electricity, Heat: 5.60 Pulp & paper, Iron & steel, Printing & stationery: 5.90 Coal: 6.10 Transport equipment: 6.31 Raw chemicals, Daily chemical products: 6.60 Log & furniture: 6.80 Textile, Metal products, Other manufacturing: 7.50 Clothing: 7.63 General equipment: 8.10 Aluminum, Other non-ferrous metals: 8.40 Electronic equipment: 8.80 Crude oil: 10.40 Natural gas: 16.00
σ_{ds}	GTAP	Same as σ_n
Consumption elasticities		
σ_{xs}	GTAP	0
σ_s	Calibrated	0.55
σ_f	GTAP	0.50
σ_x	GTAP	Household consumption: 1.00 Government consumption, investment: 0
Saving elasticity		
σ_{CS}	Calibrated	1.50
Transformation elasticities*		
σ_{w}	GTAP	1.50 for capital, $+\infty$ for labor
σ_{w_k}	GTAP	3.00 for capital, $+\infty$ for labor
$\sigma_{w_{ksp}}$	GTAP	6.00 for capital, $+\infty$ for labor

* σ_w represents the factor transformation elasticities between sectors; σ_{w_k} represents the factor transformation elasticities between subsectors within a sector; $\sigma_{w_{ksp}}$ represents the factor transformation elasticities between state-owned enterprises and private-owned enterprises within a subsector.

D.2 Parameters Influencing Economic Growth

Other parameters connect closely with intertemporal choices and economic growth. These include the growth rate of effective labor, the rate of autonomous energy efficiency improvement, the savings rate, the reproducible capital depreciation rate, and the interest rate.

Capital growth stems from private and public savings. According to Zhang *et al.* (2018), China's public saving has been around 3% of GDP in recent years. Utilizing this data along with total investment data from the China IO table, we calculate private and public savings for the base year (2020). Then the two saving rates are determined to ensure that the resulting public and private savings match the base year data. The private saving rates for subsequent years assume a private saving rate annual reduction factor of 0.6%. This yields a baseline path for private saving rates consistent with the projected declining trends in China's saving rates, according to Zhang *et al.* (2018). The public saving rate is assumed to remain constant at 3% of GDP, following Zhang *et al.* (2018).

The level of aggregate real investment level in each period t is determined by total savings and the unit price of investment goods in that period. Capital growth from period t to t+1 is calculated as the investment of period t net of depreciation during period t. We apply an annual depreciation rate of 5%, following Herd (2020). The initial capital stock for the base year (2020) is derived from Holz & Sun (2018).

Technological progress takes two forms: autonomous energy efficiency improvement (AEEI) and Hicks-neutral technological change. Regarding AEEI: for sectors excluding the fossil-based electricity sector, we follow Chen *et al.* (2017), applying a 1% annual AEEI rate. For the fossil-based electricity subsectors, we again follow Chen *et al.* (2017), applying an annual AEEI rate of 0.4%.

Hicks-neutral technological change applies to all sectors but at different rates across sectors. These differences give rise to important structural changes 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 changes are set so that the model's baseline path is consistent with the projections by the State Information Center (2020) and

IRENA(2024). In keeping with these requirements, in the baseline, the GDP contributions from agriculture, industry, and service sectors are projected to change from 7%, 37%, and 56%, to 6%, 30%, and 64%, respectively, over the interval 2020-2035; and wind and solar energy costs decline by 36% over this interval.

D.3 Initial TPS Benchmarks in the Policy Cases

The TPS benchmarks for each sector in the different cases are shown in Table D6.

Table D6. 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)	0.847	0.847	0.847	0.847	0.847	0.847
Iron & steel (tCO_2/ton):						
Basic oxygen furnace	1.685	1.684	1.684	1.685	1.685	1.685
Electric arc furnace	0.381	0.381	0.381	0.381	0.381	0.381
Aluminum (tCO_2/ton)	7.841	7.840	7.838	7.841	7.841	7.841
Other non-metal products (tCO_2/*k*RMB)	0.058	0.058	0.058	0.055	0.055	0.055
Other non-ferrous metals (tCO_2/*k*RMB)	0.051	0.051	0.050	0.049	0.049	0.049
Pulp & paper (tCO_2/*k*RMB)	0.050	0.050	0.050	0.048	0.047	0.047
Petroleum refining (tCO_2/*k*RMB)	0.039	0.039	0.038	0.037	0.037	0.037
Raw chemicals (tCO_2/*k*RMB)	0.091	0.091	0.091	0.087	0.086	0.086

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 2024. For the sectors first covered in Phase 3, they first apply in 2027.

Appendix E. Equilibrium Conditions and Solution Method

Our numerical model incorporates three types of conditions for a general equilibrium: conditions for zero profit, market-clearing, and income balance. The equilibrium of the model is framed as a Mixed Complementarity Problem (MCP), as conceptualized by Mathiesen (1985) and Rutherford (1995). To find solutions that yield non-negative prices and quantities, we employ the PATH solver, as developed by Dirkse and Ferris (1995).

Below we list the conditions for solving the equilibrium of the TPS for numerical modelling. We adhere to the convention of using a calibrated share form of the function for numerical modeling (Böhringer et al., 2003; Kiuila and Rutherford, 2013), where each variable is defined relative to its reference benchmark level. This form is an alternative expression of the traditional functional form which we described in Appendix B, and they are fundamentally equivalent (see Kiuila and Rutherford, 2013, for proof).

Tables E1-E8 indicate the notation.

Producer's profit maximization condition:

Equations E1-E11 below are derived from profit maximization and determine, for each firm in each sector, the production level associated with a given market price. For each level of production, import, export, or factor use in the model, there is a corresponding inequality representing the first-order condition for profit maximization. In a mixed complementarity problem, achieving non-zero output (import, export, or factor use) levels in equilibrium requires that this first-order condition holds as an equality. Equations E1-E11 list these conditions. These equations not only include the profit maximization conditions for representative firms, which determine the production level of each sector, but also for aggregating sector products into final goods (e.g., composite consumption goods and investment goods), and for capital allocation to each sector.

1. Production of goods of sector *i*, subsector *t* in region *r*:

$$\begin{aligned}\Pi^{Y}_{g,r,k} = &\left((1-\theta^{ex}_{g,r,k})\times P_{g,r}^{\ 1+\sigma^{de}_{g}} + \theta^{ex}_{g,r,k}\times P^{E\ 1+\sigma^{de}_{g}}_{g,r}\right)^{\frac{1}{1+\sigma^{de}_{g}}}\\ &\times\left(1-rto_{g,r,k}\right)\times vom_{g,r,k}\times Y_{g,r,k}\\ &+t\times\beta_{g,r,k}\times q_{g,r,k}\times Y_{g,r,k}\\ &-cy_{g,r,k}\times C^{Y}_{g,r,k}\times Y_{g,r,k}\\ &\le 0 \perp Y_{g,r,k}\ge 0\end{aligned} \tag{E1}$$

where:

$$C^{Y}_{g,r,k} = \left((1-\theta^{res}_{g,r,k})\times (C^{KLEM}_{g,r,k})^{1-\sigma^{res}_{k}} + \theta^{res}_{g,r,k}\times (P^{res}_{g,r,k})^{1-\sigma^{res}_{k}}\right)^{\frac{1}{1-\sigma^{res}_{k}}}$$

$$C^{KLEM}_{g,r,k} = \theta^{kle}_{g,r,k}\times C^{KLE}_{g,r,k} + (1-\theta^{kle}_{g,r,k})\times C^{M}_{g,r,k}$$

$$C^{M}_{g,r,k} = \left(\sum_{i\in x}\theta^{M}_{i,g,r,k}\times C^{A}_{i,g,r,k}{}^{1-\sigma^{x}_{g,k}}\right)^{\frac{1}{1-\sigma^{x}_{g,k}}}$$

$$C^{KLE}_{g,r,k} = \left((\theta^{kl}_{g,r,k}\times C^{F}_{g,r,k})^{1-\sigma^{emw}_{g,k}} + \left((1-\theta^{kl}_{g,r,k})\times C^{ENG}_{g,r,k}\right)^{1-\sigma^{emw}_{g,k}}\right)^{\frac{1}{1-\sigma^{emw}_{g,k}}}$$

$$C^{F}_{g,r,k} = \left(\sum_{f}(\theta^{F}_{f,g,r,k}\times\frac{P^{F}_{f,g,r,k}\times(1+rtf^{1}{}_{f,g,r,k})}{1+rtf^{0}{}_{f,g,r,k}})^{1-\sigma^{mw}_{g}}\right)^{\frac{1}{1-\sigma^{mw}_{g}}}$$

$$C^{ENG}_{g,r,k} = \left((\theta^{e}_{g,r,k}\times P^{ELEC}_{g,r,k})^{1-\sigma^{e}} + \left((1-\theta^{e}_{g,r,k})\times C^{FL}_{g,r,k}\right)^{1-\sigma^{e}}\right)^{\frac{1}{1-\sigma^{e}}}$$

$$C^{FL}_{g,r,k} = \left((\theta^{e}_{g,r,k}\times P^{HEAT}_{g,r,k})^{1-\sigma^{h}_{g}} + \left((1-\theta^{e}_{g,r,k})\times C^{FLNH}_{g,r,k}\right)^{1-\sigma^{h}_{g,k}}\right)^{\frac{1}{1-\sigma^{h}_{g,k}}}$$

$$C^{FLNH}_{g,r,k} = \left(\sum_{i\in nenh}\theta^{nenh}_{i,g,r,k}\times C^{A}_{i,g,r,k}{}^{1-\sigma^{f}_{g,k}}\right)^{\frac{1}{1-\sigma^{f}_{g,k}}}$$

$$C^{A}_{i,g,r,k} = \left((\theta^{d}_{i,g,r,k}\times P^{D}_{i,g,r,k})^{1-\sigma^{n}_{i}} + \left(\left(1-\theta^{d}_{i,g,r,k}\right)\times P^{I}_{i,g,r,k}\right)^{1-\sigma^{n}_{i}}\right)^{\frac{1}{1-\sigma^{n}_{i}}}$$

$$P^{I}_{i,g,r,k} = \frac{P^{M}_{i,r}\times(1+rtfi^{1}_{i,g,r,k}) + t\times rti_{i,g,r,k}}{(1+rtfi^{0}_{i,g,r,k})}$$

$$P^{D}_{i,g,r,k} = \frac{P_{i,r}\times(1+rtfd^{1}_{i,g,r,k}) + \tau\times rtd_{i,g,r,k}}{(1+rtfd^{0}_{i,g,r,k})}$$

2. Production of goods for export in sector *i*, subsector *t* in region *r*:

$$\begin{aligned}\Pi^{X}_{i,r} = &(1-rtxs_{i,s})\times P^{FX}\\ &-P^{E}_{i,r}\times(1-rtxs_{i,r})\le 0\perp X_{i,r}\ge 0\end{aligned} \tag{E2}$$

3. Import aggregate:

$$\Pi_{i,r}^{MM} = P_{i,r}^{M} - \left(\begin{array}{l} \dfrac{P_{i,s}^{X} \times \left(1 - rtxs^{1}{}_{i,s,r}\right) \times \left(1 + rtms^{1}{}_{i,s,r}\right)}{\left(1 - rtxs^{0}{}_{i,s,r}\right) \times \left(1 + rtms^{0}{}_{i,s,r}\right)} \times (1 - \theta_{i,s,r}^{t}) \\ + \dfrac{P^{T} \times \left(1 + rtms^{1}{}_{i,s,r}\right)}{1 + rtms^{0}{}_{i,s,r}} \times \theta_{i,s,r}^{t} \end{array} \right) \leq 0 \quad \perp M_{i,r} \geq 0 \qquad \text{(E3)}$$

4. Factor allocation

$$\Pi_{f \in sf,r}^{FT} = \sum_{j} \left(\theta_{f \in sf,j,r}^{wj} \times P_{f \in sf,j,r}^{wj \left(1+\sigma^{wj}\right)} \right)^{\frac{1}{1+\sigma^{wj}}} - P_{f \in sf,r}^{PF} \leq 0 \perp FT_{sf,r} \geq 0 \qquad \text{(E4)}$$

where:

$$P_{f \in sf,j,r}^{wj} = \left(\sum_{k} \theta_{f \in sf,j,r,k}^{wjk} \times P_{f \in sf,j,r}^{wjk \left(1+\sigma^{wjk}\right)} \right)^{\frac{1}{1+\sigma^{wjk}}}$$

$$P_{f \in sf,j,r}^{wjk} = \left(\sum_{tsp} \theta_{sf,j,r,ksp}^{wjksp} \times P_{sf,j,r,ksp}^{S \left(1+\sigma^{wjksp}\right)} \right)^{\frac{1}{1+\sigma^{wjksp}}},$$

where *s* and *p* refer to the SOEs and POEs in subsector *k*, respectively.

5. Private consumption and private saving

$$\Pi_{r}^{W} = P_{r}^{W} - \left(\left(\theta^{s1} \times P_{r}^{YI}\right)^{1-\sigma^{CI}} + \left((1-\theta^{s1}) \times P_{r}^{YC}\right)^{1-\sigma^{CI}} \right)^{\frac{1}{1-\sigma^{CI}}} \leq 0 \perp W \geq 0 \qquad \text{(E5)}$$

6. Composite investment goods:

$$\Pi_{r}^{I} = P_{r}^{YI} - C_{i \in I,r}^{Y} \leq 0 \perp Y_{r}^{I} \geq 0 \qquad \text{(E6)}$$

7. Composite consumption goods:

$$\Pi_{r}^{C} = P_{r}^{YC} - C_{i \in C,r}^{Y} \leq 0 \perp Y_{r}^{C} \geq 0 \qquad \text{(E7)}$$

8. Composite government consumption:

$$\Pi_{r}^{GC} = P_{r}^{GC} - C_{i \in GC,r}^{Y} \leq 0 \perp Y_{r}^{GC} \geq 0 \qquad \text{(E8)}$$

9. Composite government investment

$$\Pi_{r}^{GI} = P_{r}^{GI} - C_{i \in GI,r}^{Y} \leq 0 \perp Y_{r}^{GI} \geq 0 \qquad \text{(E9)}$$

10. Government consumption and government investment

$$\Pi_r^G = P_r^G - (P_r^{GI})^{\theta^{gs}} (P_r^{GC})^{1-\theta^{gs}} \le 0 \perp Y_r^G \ge 0 \tag{E10}$$

11. Composite output

$$\Pi_r^{WG} = P_r^{WG} - (P_r^G)^{1-\theta^W} (P_r^W)^{\theta^W} \le 0 \perp WG \ge 0 \tag{E11}$$

Market-clearing condition:

Equations E12-E27 are the market-clearing conditions that determine the market price variables. Each type of good—domestic, imported, exported, and composite final goods—is associated with its market clearing condition. Additionally, there are market clearing conditions for each production factor, international transportation service, and emissions allowances. In a mixed complementarity problem, achieving a non-zero market price in equilibrium requires that the supply of a good (or factor, or allowance) equals its aggregate demand, otherwise supply is greater than demand and price equals 0. For all the inequalities listed in this subsection, the left-hand side represents the aggregate supply of the goods, while the right-hand side represents the aggregate demand.

12. Domestic goods market:

$$\begin{aligned} &\sum_k \left(\frac{P_{i,r}}{\left((1-\theta_{i,r,k}^{ex}) \times P_{i,r}^{(1+\sigma_g^{de})} + \theta_{i,r,k}^{ex} \times P_{i,r}^{E(1+\sigma_g^{de})} \right)^{\frac{1}{1+\sigma_g^{de}}}} \right)^{\sigma_{de}} \\ &\quad \times (vom_{i,r,k} - vxm_{i,r,k}) \times Y_{i,r,k} \\ &\ge \sum_{g,k} D_{i,g,r,k}^{DFM} \perp P_{i,r} \ge 0 \end{aligned} \tag{E12}$$

For non-energy products, i.e., $i \in nf$

$$D_{i,g,r,k}^{DFM} = vdfm_{i,g,r,k} \times Y_{g,r,k} \times \left(\frac{C_{g,r,k}^{Y}}{C_{g,r,k}^{KLEM}} \right)^{\sigma_k^{res}} \times \left(\frac{C_{g,r,k}^{M}}{C_{i,g,r,k}^{A}} \right)^{\sigma_{g,k}^{x}} \times \left(\frac{C_{i,g,r,k}^{A}}{P_{i,g,r,k}^{D}} \right)^{\sigma_i^n}$$

For electricity, i.e., $i \in el$

$$D_{i,g,r,k}^{DFM} = vdfm_{i,g,r,k} \times Y_{g,r,k} \times \left(\frac{C_{g,r,k}^{Y}}{C_{g,r,k}^{KLEM}} \right)^{\sigma_k^{res}} \times \left(\frac{C_{g,r,k}^{KLE}}{C_{g,r,k}^{ENG}} \right)^{\sigma_{g,t}^{emw}} \times \left(\frac{C_{g,r,k}^{ENG}}{P_{g,r,k}^{ELEC}} \right)^{\sigma_{g,t}^{e}} \times \left(\frac{P_{g,r,k}^{ELEC}}{P_{i\in el,g,r,k}^{D}} \right)^{\sigma_i^{n}}$$

For heat, i.e., $i \in ht$

$$D_{i,g,r,k}^{DFM} = vdfm_{i,g,r,k} \times Y_{g,r,k} \times \left(\frac{C_{g,r,k}^{Y}}{C_{g,r,k}^{KLEM}} \right)^{\sigma_k^{res}} \times \left(\frac{C_{g,r,k}^{KLE}}{C_{g,r,k}^{ENG}} \right)^{\sigma_{g,k}^{emw}} \times \left(\frac{C_{g,r,k}^{ENG}}{C_{g,r,k}^{FL}} \right)^{\sigma_{g,t}^{e}} \times \left(\frac{C_{g,r,k}^{FL}}{C_{g,r,k}^{HEAT}} \right)^{\sigma_{g,t}^{h}}$$

For fossil fuel products, i.e., $i \in nenh$

$$D_{i,g,r,k}^{DFM} = vdfm_{i,g,r,k} \times Y_{g,r,k} \times \left(\frac{C_{g,r,k}^{Y}}{C_{g,r,k}^{KLEM}} \right)^{\sigma_k^{res}} \times \left(\frac{C_{g,r,k}^{KLE}}{C_{g,r,k}^{ENG}} \right)^{\sigma_{g,k}^{emw}} \times \left(\frac{C_{g,r,k}^{ENG}}{C_{g,r,k}^{FL}} \right)^{\sigma_{g,t}^{e}} \times \left(\frac{C_{g,r,k}^{FL}}{C_{g,r,k}^{FLNH}} \right)^{\sigma_{g,t}^{h}} \times \left(\frac{C_{g,r,k}^{FLNH}}{C_{i\in nenh,g,r,k}^{A}} \right)^{\sigma_{g,k}^{f}} \times \left(\frac{C_{i\in nenh,g,r,k}^{A}}{P_{i\in nenh,g,r,k}^{D}} \right)^{\sigma_i^{n}}$$

13. Export goods market:

$$\sum_k \left(\frac{P_{i,r}^{E}}{\left((1-\theta_{i,r,k}^{ex}) \times P_{i,r}^{(1+\sigma_i^{de})} + \theta_{i,r,k}^{ex} \times P_{i,r}^{E(1+\sigma_i^{de})} \right)^{\frac{1}{1+\sigma_i^{de}}}} \right)^{\sigma_i^{de}} \times vxm_{i,r,k} \times Y_{i,r,k} \quad \text{(E13)}$$

$$\geq X_{i,r} \times vxm_{i,r} + Y^{T} \times vst_{i,r} \perp P_{i,r}^{X} \geq 0$$

14. Import goods market:

$$M_{i,r} \times vim_{i,r} \geq \sum_{g,t} D_{i,g,r,t}^{IFM} \perp P_{i,r}^{M} \leq 0 \quad \text{(E14)}$$

For non-energy products, i.e., $i \in nf$

$$D_{i,g,r,k}^{IFM} = vifm_{i,g,r,k} \times Y_{g,r,k} \times \left(\frac{C_{g,r,k}^{Y}}{C_{g,r,k}^{KLEM}} \right)^{\sigma_k^{res}} \times \left(\frac{C_{g,r,k}^{M}}{C_{i,g,r,k}^{A}} \right)^{\sigma_{g,k}^{x}} \times \left(\frac{C_{i,g,r,k}^{A}}{P_{i,g,r,k}^{I}} \right)^{\sigma_i^{n}}$$

For electricity, i.e., $i \in el$

$$D_{i,g,r,k}^{IFM} = vifm_{i,g,r,k} \times Y_{g,r,k} \times \left(\frac{C_{g,r,k}^{Y}}{C_{g,r,k}^{KLEM}} \right)^{\sigma_k^{res}} \times \left(\frac{C_{g,r,k}^{KLE}}{C_{g,r,k}^{ENG}} \right)^{\sigma_{g,t}^{emw}} \times \left(\frac{C_{g,r,k}^{ENG}}{C_{g,r,k}^{ELEC}} \right)^{\sigma_{g,t}^{e}} \times \left(\frac{C_{g,r,k}^{ELEC}}{P_{i\in el,g,r,k}^{I}} \right)^{\sigma_i^{n}}$$

For fossil fuel products, i.e., $i \in nenh$

$$D_{i,g,r,k}^{IFM} = vifm_{i,g,r,k} \times Y_{g,r,k} \times \left(\frac{C_{g,r,k}^{Y}}{C_{g,r,k}^{KLEM}} \right)^{\sigma_k^{res}} \times \left(\frac{C_{g,r,k}^{KLE}}{C_{g,r,k}^{ENG}} \right)^{\sigma_{g,k}^{emw}} \times \left(\frac{C_{g,r,k}^{ENG}}{C_{g,r,k}^{FL}} \right)^{\sigma_{g,t}^{e}} \times \left(\frac{C_{g,r,k}^{FL}}{C_{g,r,k}^{FLNH}} \right)^{\sigma_{g,t}^{h}} \times \left(\frac{C_{g,r,k}^{FLNH}}{C_{i\in nenh,g,r,k}^{A}} \right)^{\sigma_{g,k}^{f}} \times \left(\frac{C_{i\in nenh,g,r,k}^{A}}{P_{i\in nenh,g,r,k}^{D}} \right)^{\sigma_i^{n}}$$

15. Trade transportation market clear:

$$Y^T \times vtw \geq \sum_{i,s,r} vtwr_{i,s,r} \times M_{i,r}$$
$$\perp P^T_{i,r} \geq 0 \tag{E15}$$

16. Aggregate factor markets

$$evom_{f,r} \geq \sum_{j,k} D^{FM}_{f,j,r,k} \perp P^{PF}_{f,r} \geq 0 \tag{E16}$$

For labor

$$D^{FM}_{f,j,r,k} = vfm_{f,j,r,k} \times Y_{j,r,k} \times \left(\frac{C^Y_{j,r,k}}{C^{KLEM}_{j,r,k}} \right)^{\sigma^{res}_k} \times \left(\frac{C^{KLE}_{j,r,k}}{C^F_{j,r,k}} \right)^{\sigma^{emw}_{j,k}} \times \left(\frac{C^F_{j,r,k}}{P^F_{f,g,r,k} \times \frac{1+rtf^1_{f,g,r,k}}{1+rtf^0_{f,g,r,k}}} \right)^{\sigma^{mw}_j}$$

For capital

$$D^{FM}_{f,j,r,k} = FT_{f,r} \times vfm^0_{f,j,r,k}$$

17. Capital market

$$vfm^0_{f,g,r,k} \times FT_{sf,r} \times \left(\frac{P^S_{f,j,r,ksp}}{P^{wjk}_{f,j,r,k}} \right)^{\sigma^{wjksp}} \times \left(\frac{P^{wjk}_{f,j,r}}{P^{wj}_{f,j,r}} \right)^{\sigma^{wjk}} \times \left(\frac{P^{wj}_{f,j,r}}{P^F_{f,r}} \right)^{\sigma^{wj}}$$
$$\geq D^{FM}_{f,j,r,k} \perp P^S_{f,j,r,ksp} \geq 0 \tag{E17}$$

18. Natural resource market

$$res_{j,r,k} \geq res_{j,r,k} \times Y_{j,r,k} \times \left(\frac{C^Y_{j,r,k}}{P^{RES}_{j,r,k}} \right)^{\sigma^{res}_k} \perp P^{RES}_{g,r,k} \geq 0 \tag{E18}$$

19. Foreign exchange market

$$\sum_{i,s,r} vst_s \times Y^T \times \frac{P^T_{i,s,r}}{P^{FX}} + \sum_{i,s} X_{i,s} \times vxm_{i,s} + \frac{ROW}{P^{FX}}$$
$$\geq \sum_{i,r \in rm} X_{i,r} \times (1 - rtxs_{i,r}) \times vxm_{i,r} + rowfx \perp P^{FX} \geq 0 \tag{E19}$$

20. Emission allowance market

$$\sum_{g \in cv, k \in cv} \beta_{g,r,k} \times q_{g,r,k} \times Y_{g,r,k} \geq$$
$$\sum_{i,g \in cv, t \in cv} rtd_{i,g,r,k} \times D^{DFM}_{i,g,r,k} + \sum_{i,g \in cv, t \in cv} rti_{i,g,r,k} \times D^{IFM}_{i,g,r,k} \perp t \geq 0 \tag{E20}$$

where $g \in cv, k \in cv$ represent the covered sectors and covered subsectors.

21. Private consumption and savings

$$W_r \geq WG_r \times \frac{P_r^{WG}}{P_r^W} \perp P_{i,r}^W \geq 0 \quad \text{(E21)}$$

22. Private consumption

$$Y_r^C \geq W_r \times \left(\frac{1-\theta^{s1}}{1-\theta^{s0}}\right) \times \left(\frac{P_r^W}{P_r^{YC}}\right)^{\sigma_r^{CI}} \perp P_r^{YC} \geq 0 \quad \text{(E22)}$$

23. Private investment

$$Y_r^I \geq W_r \times \left(\frac{\theta^{s1}}{\theta^{s0}}\right) \times \left(\frac{P_r^W}{P_r^{YI}}\right)^{\sigma_r^{CI}} \perp P_r^{YI} \geq 0 \quad \text{(E23)}$$

24. Government consumption and investment

$$Y_r^G \geq WG_r \times \frac{P_r^{WG}}{P_r^G} \perp P_r^G \geq 0 \quad \text{(E24)}$$

25. Government consumption

$$Y_r^{GC} \geq Y_r^G \times \frac{P_r^G}{P_r^{GC}} \perp P_r^{GC} \geq 0 \quad \text{(E25)}$$

26. Government investment

$$Y_r^{GI} \geq Y_r^G \times \frac{P_r^G}{P_r^{GI}} \perp P_r^{GI} \geq 0 \quad \text{(E26)}$$

27. Aggregate output

$$WG_r \times wg_r^0 \geq \frac{INC_r^G - T_r + RA_r}{P_r^{WG}} \perp P_r^{WG} \geq 0 \quad \text{(E27)}$$

Income balance:

Equations E28-E29 represent income balance conditions for the government and the representative household.

28. Government income balance. The left-hand side of the equation represents the total expenditure on government consumption, investment, and transfers to households, while the right-hand side represents the total income of the government from tax revenue.

$$
\begin{aligned}
& Y_r^G \times P_r^G \times g_r + T_r \\
& = INC_r^G \\
& = \sum_{i,k} rto_{i,r,k} \times R_{i,r,k}^Y \times vom_{i,r,k} \times Y_{i,r,k} \\
& + \sum_{f,g,k} rtf^1{}_{f,g,r,k} \times P_{f,g,r,k}^F \times D_{f,j,r,k}^{FM} \\
& + \sum_{i,g,k} rtfi^1{}_{i,g,r,k} \times P_{i,r}^M \times D_{f,g,r,k}^{IFM} \\
& + \sum_{i,g,k} rtfd^1{}_{i,g,r,k} \times P_{i,r} \times D_{f,g,r,k}^{DFM} \\
& + \sum_{i,s} rtms^1{}_{i,s,r} \times P_{i,s}^E \times \left(1 - rtxs^1{}_{i,s,r}\right) \times (X_{i,s} \times vxmd_{i,s,r} + P_{i,r}^T \times vtwr_{i,s,r}) \\
& - \sum_{i,s} rtxs^1{}_{i,r,s} \times P_{i,r}^E \times X_{i,s} \times vxmd_{i,r,s}
\end{aligned}
\tag{E28}
$$

29. Domestic household income balance. The left-hand side of the equation represents the total expenditure on private consumption and investment, whereas the right-hand side represents the total income of the households.

$$
\begin{aligned}
w_r \times P_r^W \times W_r &= RA \\
&= vb_r \times P_r^{WG} + \sum_f P_{f,r}^F \times evom_{f,r} + \sum_{i,k} P_{i,,r,k}^{res} \times res_{i,r,k} + T_r
\end{aligned}
\tag{E29}
$$

Table E1. Sets in the Numerical Model

Symbol	Description
$i(j), g$	Sectors. *i* and *j* represent the production sectors, while *g* represents the production sectors as well as the final demand sectors, C (household consumption), I (household investment), GC (government consumption), and GI (government investment).
r, s	Regions. *r* denotes the modeling region, China; while s represents the rest of the world.
k	Subsectors.
ksp	SOEs and POEs in subsector *k.*
f	Capital, labor and land. Capital and land belong to the category of sluggish factor (*sf*) while labor belongs to the mobile factor (*mf*).

Table E2. Activity Variable in the Numerical Model

Symbol	Description
$Y_{i,r,k}$	Output of production of sector *i*, region *r*, subsector *k*.
$X_{i,r}$	Exports of sector *i*, region *r*.
$M_{i,r}$	Imports of sector *i*, region *r*.
$FT_{f,r}$	Factor transformation activity
$D_{i,g,r,k}^{DFM}$	Domestic demand of domestic goods *i* in sector *g*, subsector *k* in region *r*.
Y^{T}	Exports for international transportation.
$D_{i,g,r,k}^{IFM}$	Domestic demand of imported goods *i* in sector *g*, subsector *k* in region *r*.
$D_{f,j,r,k}^{FM}$	Demand for factor *f* in sector *j*, subsector *k* in region *r*.
Y_{r}^{I}	Private saving in region *r*.
Y_{r}^{C}	Private investment in region *r*.
Y_{r}^{GC}	Government consumption in region *r*.
Y_{r}^{GI}	Public investment in region *r*.
Y_{r}^{G}	Governments' consumption and investment in region *r*.
W_{r}	Households' consumption and investment in region *r*.
WG_{r}	Aggregate output in region *r*.

Table E3. Price and Cost in the Numerical Model

Symbol	Description
$P_{g,r}$	Domestic goods' price
t	Allowance price
$C^{Y}_{i,r,k}$	Cost of production
$C^{KLEM}_{g,r,k}$	Cost of factor-energy-intermediate input composite
$P^{RES}_{g,r,k}$	Price of resource input
$C^{KLE}_{g,r,k}$	Cost of factor-energy input composite
$C^{M}_{g,r,k}$	Cost of material input composite
$C^{A}_{i,g,r,k}$	Cost of Armington composite
$C^{F}_{g,r,k}$	Cost of factor input composite
$C^{ENG}_{g,r,k}$	Cost of energy input composite
$C^{FLNH}_{g,r,k}$	Cost of fossil fuel input
$P^{ELEC}_{g,r,k}$	Price of electricity
$C^{FL}_{g,r,k}$	Cost of non-electricity fuel input
$P^{HEAT}_{g,r,k}$	Price of heat
$C^{FLNH}_{g,r,k}$	Cost of non-electricity, non-heat fuel input
$P^{D}_{i,g,r,k}$	Domestic goods' price
$P^{I}_{i,g,r,k}$	Imported goods' price
$P^{F}_{f,g,r,k}$	User price of factor
$P^{wj}_{f\in sf,j,r}$	Aggregate price of factor *f* in sector *j* in region *r*.
$P^{wjk}_{f\in sf,j,r}$	Price of factor *f* in sector *j*, subsector *k* in region *r*.
$P^{E}_{g,r}$	Export goods' price
P^{FX}	Foreign exchange price
$P^{M}_{i,r}$	User price of imported goods
$P^{T}_{i,s,r}$	Price of international transportation service
$P^{PF}_{f,r}$	Aggregate factor price
P^{YC}_{r}	Price of composite household consumption good
P^{YI}_{r}	Price of composite household investment good
P^{W}_{r}	Price index of households' welfare
P^{GC}_{r}	Price of composite government consumption
P^{GI}_{r}	Price of composite government investment
P^{G}_{r}	Price index of composite government consumption and investment
P^{WG}_{r}	Composite output price

Table E4. Cost Share in the Numerical Model

Symbol	Description
$\theta^{res}_{g,r,k}$	Value share of resource input in sector *g*, region *r*, subsector *k*.
$\theta^{kle}_{g,r,k}$	Value share of factor-energy input in factor-energy-material input composite in sector *g*, region *r*, subsector *k*.
$\theta^{M}_{i,g,r,k}$	Value share of material input *i* in total material input composite of sector *g*, region *r*, subsector *k*.
$\theta^{kl}_{g,r,k}$	Value share of factor input in the factor-energy composite of sector *g*, region *r*, subsector *k*.
$\theta^{F}_{f,g,r,k}$	Value share of factor *f* input in total factor input composite of sector *g*, region *r*, subsector *k*.
$\theta^{e}_{g,r,k}$	Value share of electricity input in total energy input of sector *g*, region *r*, subsector *k*.
$\theta^{h}_{g,r,k}$	Value share of heat input in total energy input of sector *g*, region *r*, subsector *k*.
$\theta^{nenh}_{i,g,r,k}$	Value share of fossil fuel input "*i*" in total fossil fuel in total energy input of sector *g*, region *r*, subsector *k*.
$\theta^{d}_{i,g,r,k}$	Value share of domestic produced goods in material input *i* of sector *g*, region *r*, subsector *k*.
$\theta^{ex}_{g,r,k}$	Value share of exports in total output of sector *g*, region *r*, subsector *k*.
$\theta^{t}_{i,s,r}$	Value share of international transportation service in total import activity of *i* import from *s* to *r*.
$\theta^{wj}_{f,j,r}$	Value share of factor *f* in sector *j* in all sectors in region *r*.
$\theta^{wjk}_{f,j,r,k}$	Value share of factor *f* in subsector *k* of sector *j* in region *r*.
$\theta^{wjksp}_{sf,j,r,ksp}$	Value share of factor *f* in SOE or POE in subsector *k*, sector *j* in region *r*.
θ^{s1}, θ^{s0}	Value share of saving in total household income.
θ^{gs}	Value share of saving in total government spending.
θ^{W}	Value share of households income in GDP.

Table E5. Substitution Elasticities in the Numerical Model

Symbol	Description
σ_k^{res}	Substitution elasticity between factor-energy-material input and resource input
$\sigma_{g,k}^{x}$	Substitution elasticity between material inputs
$\sigma_{g,k}^{emw}$	Substitution elasticity between factor and energy inputs
σ_g^{mw}	Substitution elasticity between different factors
$\sigma_{g,k}^{e}$	Substitution elasticity between electricity and fuel
$\sigma_{g,k}^{h}$	Substitution elasticity between heat and fossil fuels
σ_i^{n}	Substitution elasticity between domestic and imported goods
σ^{de}	Transformation elasticity between domestic and exported goods
σ^{wj}	Transformation elasticity of factors across sectors
σ^{wjk}	Transformation elasticity of factors across subsectors within a sector
σ^{wjksp}	Transformation elasticity of factors between SOEs and POEs within a subsector
σ_r^{CI}	Substitution elasticity between household's consumption and investment

Table E6. Tax Rates in the Numerical Model

Symbol	Description
$rto_{i,r,k}$	Output tax rate of production of sector *i*, subsector *k* in region *r*.
$rtf^{1}_{f,g,r,k}, rtf^{0}_{f,g,r,k}$	The factor tax rate of factor *f* of sector *i*, subsector *k* in region *r* in policy cases and in reference level.
$rtfi^{1}_{i,g,r,k}, rtfi^{0}_{i,g,r,k}$	Tax rate of imported good *i* in sector *g*, subsector *k* in region *r*.
$rtfd^{1}_{i,g,r,k}, rtfd^{0}_{i,g,r,k}$	Tax rate of domestic good *i* in sector *g*, subsector *k* in region *r*.
$rtxs_{i,r}$	Exports subsidy of goods *i* in region *r*.
$rtms^{1}_{i,s,r}, rtms^{0}_{i,s,r}$	Imported tariff of good *i* from *s* to *r*.

Table E7. Benchmark Level

Symbol	Description
$vom_{g,r,k}$	Benchmark output level in sector *g*, region *r*, subsector *k*.
$cy_{g,r,k}$	Benchmark cost of production in sector *g*, region *r*, subsector *k*.
$q_{i,r,k}$	Benchmark production quantity in sector *g*, region *r*, subsector *k*.
w_r	Benchmark level of households' consumption and investment in region *r*.
g_r	Benchmark level of government's consumption and investment in region *r*.
wg_r^0	Benchmark level of aggregate output in region *r*.
$vxm_{i,r,k}$	Benchmark export in sector *i*, region *r*, subsector *k*.
$vdfm_{i,g,r,k}$	Benchmark domestic demand of domestic goods *i* in sector *g*, subsector *k* in region *r*.
$vim_{i,r}$	Benchmark import of goods *i* in region *r*.
$vifm_{i,g,r,k}$	Benchmark domestic demand of imported goods *i* in sector *g*, subsector *k* in region *r*
vtw	Aggregate international transportation services
$vst_{i,r}$	Exports for international transportation services in region *r* for goods *i*.
$vtwr_{i,s,r}$	Margins for international transportation at world prices for goods *i*.
vb_r	China's endowment of foreign exchange.
$evom_{f,r}$	Endowment of production factor *f* (capital, labor, and land)
$res_{g,r,t}$	Endowment of natural resources

Table E8. Others

Symbol	Description
$rti_{i,g,r,k}$	Emissions per unit imported fuel input *i* consumed in sector *g*, region *r*, subsector *k*.
$rtd_{i,g,r,k}$	Emissions per unit domestic fuel input *i* consumed in sector *g*, region *r*, subsector *k*.
$\beta_{i,r,k}$	Benchmarks for free allowance allocation under the TPS.
T_r	Government lump-sum transfer to households

Appendix F. Evaluation of Health Co-benefits

To calculate the health co-benefits from avoided pre-mature deaths, we apply an emission 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 pre-mature mortalities under the baseline and the TPS.

The emissions inventory model is the Air Benefit and Cost and Attainment Assessment System – Emission Inventory (ABaCAS-EI) model, which was jointly developed by the School of Environment at Tsinghua University, the Southern China University of Technology, and the University of Tennessee. It is widely used in China's air quality research. It covers six major categories of anthropogenic emissions sources, each of which is further divided top-down into industry-level, fuel-level, and technology-level subsectors.

The air quality model is the Polynomial function-based Response Surface Model (Pf-RSM), which was developed by the School of Environment at Tsinghua. Pf-RSM combines mathematical and statistical methods and performs stable emissions concentration-response simulation.

To link the dynamic general equilibrium model to the air quality model, we first run the general equilibrium model to obtain results for sectoral fuel consumption and sectoral outputs. These results are then multiplied by the energy emission factors in the ABaCAS-EI emissions inventory to yield sectoral pollutant emissions at the provincial level.[12] The air pollutants we consider include SO_2, NOx, NH_3, non-methane volatile organic compounds (NMVOCs), and primary particulate matter (PM). Then, the provincial sectoral emissions are employed as inputs to the RSM model. Using these inputs, the RSM model simulates the local air pollution concentrations for each province for each year. We focus on changes in provincial $PM_{2.5}$ concentration because studies suggest that $PM_{2.5}$ is responsible, and will continue to be responsible for a large fraction of premature mortality from air pollution in the next several decades (Burnett

[12] We assume that over the interval 2020-2035, the spatial distribution of firms within an industry and the energy emission factors do not change.

et al., 2018; Zhou *et al.*, 2019; Wang *et al.,* 2021). Figure F1 represents the results for the year 2035. Similar patterns can be observed for other years, with the only difference being the magnitudes.

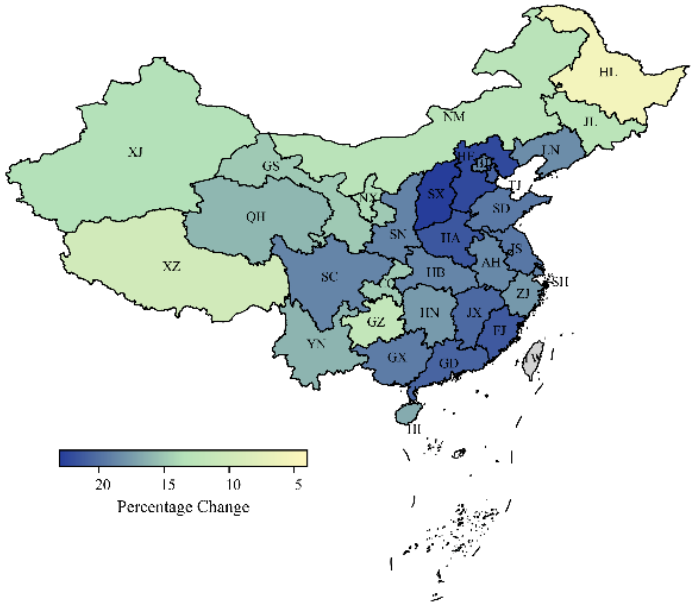


Figure F1. Changes in $PM_{2.5}$ Concentrations under the TPS Relative to the Baseline, 2035

Note: The abbreviations for provinces are AH-Anhui, BJ-Beijing, CQ-Chongqing, FJ-Fujian, GS-Gansu, GD-Guangdong, GX-Guangxi, GZ-Guizhou, HI-Hainan, HE-Hebei, HL-Heilongjiang, HA-Henan, HB-Hubei, HN-Hunan, JS-Jiangsu, JX-Jiangxi, JL-Jilin, LN-Liaoning, NM-Inner Mongolia, NX-Ningxia, QH-Qinghai, SN-Shaanxi, SD-Shandong, SH-Shanghai, SX-Shanxi, SC-Sichuan, TJ-Tianjin, XJ-Xinjiang, XZ-Tibet, YN-Yunnan, ZJ-Zhejiang. Results for Hong Kong, Macao, and Taiwan are not included in this figure due to data limitations in their emissions inventories. The map is from Tianditu (2024).

We calculate the health-related benefits from reduced air pollution concentrations as follows. First, we apply the GEMM NCD+LRI method (Burnett *et al.*, 2018) to estimate avoided pre-mature death related to reductions in chronic exposure to outdoor fine particulate matter ($PM_{2.5}$) under different scenarios. The GEMM NCD+LRI adopts the following equation to quantify the relationship between the hazard ratio (RR) and ambient $PM_{2.5}$ concentration (c):

$$RR(c) = \exp\left(\theta \times \frac{\ln\left(\frac{\max(0, c - c_f)}{\alpha} + 1 \right)}{1 + \exp\left(-\frac{\max(0, c - c_f) - \mu}{\nu} \right)} \right) \quad \text{(F1)}$$

where θ, α, μ, ν, and c_f are shape parameters and are adopted from Burnett *et al.* (2018). Avoided deaths can then be calculated using Equation (F2).

$$\Delta M_t = \sum_{m,p} M_m^B \times pop_{p,t} \times \left(\frac{1}{RR(c_{TPS,t})} - \frac{1}{RR(c_{BS,t})} \right) \quad \text{(F2)}$$

where $c_{BS,t}$ is the $PM_{2.5}$ concentration under the baseline in period t, and $c_{TPS,t}$ is the $PM_{2.5}$ concentration under the TPS in period *t*. M_m^B are the mortality rates with the lowest level of exposure to $PM_{2.5}$ for age group *m* in China, and are retrieved from the Global Health Data Exchange. We follow the convention to divide the national population into 12 subgroups (adults with ages 25 to 85 and above in five-year intervals). $pop_{p,t}$ are baseline provincial population projections in period *t* and are sourced from Chen *et al.* (2020).

We consider the uncertainties related to the hazard ratio from equation (F1). Following Burnett *et al.* (2014), we assume that θ has a normal distribution. We sample 1,000 points from the normal distribution and calculate the mean and 95% confidence interval of avoided death, using Equation (F2). The results for avoided deaths are presented in Table F1. The confidence interval for total avoided premature deaths during the period 2020-2035 is 1.9-2.1 million; the interval for the average number of deaths annually is 119,000-133,000.

Table F1. Average Annual Avoided Deaths under the TPS, 2020-2035 (thousand)

Provinces	Annual avoided deaths	95% confidence interval
Beijing	2.2	(2.1,2.3)
Tianjin	1.7	(1.6,1.8)
Hebei	9.2	(8.7,9.6)
Shanxi	4.8	(4.5,5.1)
Inner Mongolia	1.4	(1.4,1.5)
Liaoning	3.9	(3.7,4.1)
Jilin	1.7	(1.6,1.8)
Heilongjiang	0.8	(0.8,0.9)
Shanghai	2.1	(2,2.2)
Jiangsu	8.0	(7.5,8.4)
Zhejiang	4.5	(4.2,4.7)
Anhui	5.7	(5.3,6)
Fujian	3.1	(2.9,3.3)
Jiangxi	4.4	(4.2,4.7)
Shandong	10.4	(9.9,10.9)
Henan	12.3	(11.6,12.9)
Hubei	6.4	(6.1,6.8)
Hunan	6.3	(6,6.7)
Guangdong	9.4	(8.8,10)
Guangxi	4.9	(4.6,5.2)
Hainan	0.5	(0.5,0.5)
Chongqing	2.1	(1.9,2.2)
Sichuan	6.7	(6.3,7.1)
Guizhou	2.0	(1.9,2.2)
Yunnan	3.1	(2.9,3.3)
Tibet	0.1	(0.1,0.1)
Shaanxi	3.6	(3.4,3.8)
Gansu	1.7	(1.6,1.8)
Qinghai	0.5	(0.4,0.5)
Ningxia	0.4	(0.4,0.5)
Xinjiang	1.9	(1.8,2)

Note: Hong Kong, Macao, and Taiwan are not included in this table due to data limitations in their emissions inventories.

We monetize the benefits from avoided premature death by using the value of a statistical life (VSL). We assume a constant elasticity of the VSL with respect to income: $VSL_t = VSL_0 \left(INC_t / INC_0 \right)^{\sigma_{VSL}}$, 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 the 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 an 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).

Appendix G. Distributional Impacts

G.1 Impacts on Renewables

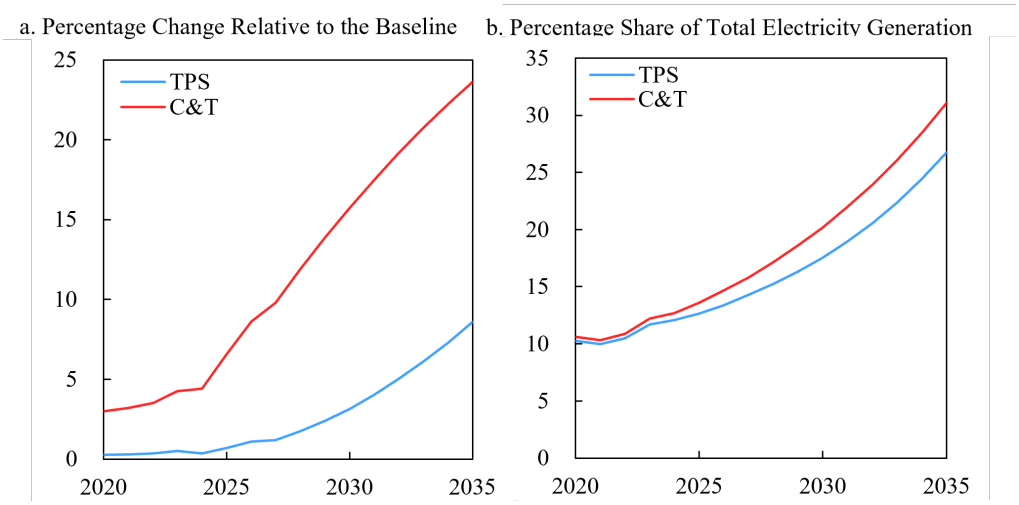


Figure G1. Impacts on Wind- and Solar- Electricity Generation

Here we show the impacts on wind and solar electricity generation, as 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.

G.2 Distribution of Impacts Across Provinces

To assess the geographical distributional impacts, we use the following method. Let INC_{ikp} be the income of sector *i* subsector *k* in province *p*, and INC_p be the income of all sectors in province *p*.

$$INC_p = \sum_{ik} INC_{ik} \frac{INC_{ikp}}{INC_{ik}} \tag{G1}$$

In Equation (G1), the term $\frac{INC_{ikp}}{INC_{ik}}$ represents the share of the income from sector *i* subsector *k* in province *p* in the national income from sector *i* subsector *k*. We assume these shares are the same and remain at the base year's level for all years and in all scenarios. $\frac{INC_{ikp}}{INC_{ik}}$ in the base year can be calculated from the provincial input-output tables and the firm-level MEE data as we described in Appendix C.

Let ΔINC_p be the change of income of province *p*, then

$$\Delta INC_p = \sum_{ik} \Delta INC_{ik} \frac{INC_{ikp}}{INC_{ik}} \tag{G2}$$

Equation (G2) is used to calculate the absolute change of the provincial income presented in Table G1. The percentage change can then be calculated by $\frac{\Delta INC_p}{INC_p}$.

Table G1. 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	33	0.051	-37	-0.057	-149	-0.229
Shandong	-166	-0.122	-221	-0.162	-520	-0.382
Liaoning	-18	-0.040	-18	-0.038	-100	-0.219
Jiangsu	-72	-0.045	-69	-0.044	456	0.287
Hainan	-8	-0.095	-14	-0.164	-15	-0.172
Zhejiang	-36	-0.037	-2	-0.002	56	0.058
Fujian	15	0.025	51	0.084	101	0.167
Shanghai	-79	-0.133	-41	-0.069	53	0.091
Guangdong	-164	-0.097	-160	-0.095	415	0.247
Tianjin	-30	-0.090	-15	-0.044	157	0.469
Beijing	-97	-0.165	-95	-0.163	153	0.261
Regional Total	-621	-0.070	-621	-0.070	609	0.068
Central:						
Shanxi	-307	-0.977	-378	-1.205	-405	-1.291
Heilongjiang	-125	-0.390	-137	-0.429	-146	-0.457
Henan	-54	-0.063	-46	-0.054	-108	-0.127
Anhui	-49	-0.093	58	0.110	-131	-0.250
Jilin	-27	-0.101	-22	-0.084	-19	-0.071
Hubei	13	0.019	3	0.004	-39	-0.057
Hunan	-40	-0.063	-26	-0.041	-14	-0.022
Jiangxi	32	0.088	61	0.166	16	0.043
Inner Mongolia	-152	-0.513	-148	-0.499	-479	-1.619
Regional Total	-707	-0.166	-637	-0.149	-1327	-0.311
West:						
Ningxia	45	0.723	21	0.332	-46	-0.740
Guizhou	-95	-0.384	-78	-0.315	-152	-0.615
Shaanxi	-161	-0.388	-178	-0.429	-64	-0.155
Yunnan	11	0.035	-5	-0.017	-46	-0.150
Guangxi	6	0.016	17	0.047	-29	-0.080
Xinjiang	18	0.075	19	0.080	-5	-0.020
Chongqing	-43	-0.116	-31	-0.083	-28	-0.076
Gansu	-9	-0.059	-35	-0.229	-82	-0.535
Sichuan	-65	-0.086	-52	-0.069	66	0.088
Qinghai	27	0.508	32	0.593	33	0.606
Regional Total	-265	-0.089	-289	-0.098	-355	-0.120
National	-1593	-0.099	-1547	-0.096	-1073	-0.067
Standard deviation	79	0.288	93	0.299	203	0.461

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.

Appendix H. Sensitivity Analysis

This appendix presents the results of the sensitivity of the model's results to alternative parameter specifications. We consider the parameters that influence the degree of input substitution and capital mobility, the rates of investment and technological change, the nature of the favorable treatment of SOEs, and the nature of administered pricing of electricity. We also offer a closer look at how the time-path for the imposed stringency of the TPS affects the costs of this policy as well as its costs relative to those under C&T.

H.1 Alternative Specifications for Input-Substitution, Capital Mobility, Savings Behavior, Investment and Technological Change

The significance of input substitution and transformation elasticities is examined in Table H1. 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 H2 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 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 H3 examines the significance of assumptions about the future extent of policy stringency, as determined by the rate of benchmark tightening after 2024. 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 28 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 H1, H2, and H3 indicates how the ratio of the TPS's costs to those under C&T depends on key parameters. As discussed in Section I, the cost-effectiveness of the TPS relative to C&T decreases as policy stringency increases. A higher energy-factor substitution elasticity, higher AEEI rate, and lower benchmark tightening rate all work toward lower costs of reducing emissions and lower demands for allowances, and thus lower policy stringency. Hence, they increase the cost-effectiveness of TPS relative to C&T, leading 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. On the one hand, it lowers the allowance price and reduces the size of the distortionary implicit output subsidy of TPS. On the other hand, 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. According to our simulations, 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.[13]

Table H1. Sensitivity Analysis: Significance of Production and Capital Transformation Elasticities

		Energy-Factor Substitution Elasticity				Capital Transformation Elasticity	
		of All Sectors		of the Elec Sector			
	Central Case	Halved	Doubled	Halved	Doubled	Halved	Doubled
Emission reduction (billion tons):							
Phase 1 (2020-2023)	0.61	0.57	0.67	0.58	0.65	0.62	0.60
Phase 2 (2024-2026)	1.39	1.31	1.54	1.34	1.48	1.39	1.41
Phase 3 (2027-2035)	16.34	15.60	17.98	16.26	16.66	16.32	16.42
Present value of cost (billion RMB):							
Phase 1 (2020-2023)	26	29	24	30	23	31	22
Phase 2 (2024-2026)	64	71	60	67	61	69	59
Phase 3 (2027-2035)	1,503	1,878	1,257	1,602	1,349	1,597	1,389
Economic cost per ton (RMB/ton):							
Phase 1 (2020-2023)	43	52	36	52	35	49	36
Phase 2 (2024-2026)	46	54	39	50	41	50	42
Phase 3 (2027-2035)	92	120	70	99	81	98	85
Allowance price (RMB/ton):							
Phase 1 (2020-2023)	70	95	47	95	47	83	55
Phase 2 (2024-2026)	89	122	61	99	76	99	78
Phase 3 (2027-2035)	361	550	220	400	299	393	321
Wind- and solar- elec increase (%):							
Phase 1 (2020-2023)	0.35	0.38	0.33	0.37	0.33	0.50	0.23
Phase 2 (2024-2026)	0.73	0.96	0.53	0.78	0.69	0.87	0.57
Phase 3 (2027-2035)	4.87	7.39	2.95	5.80	3.70	5.14	4.28
Ratio of TPS to C&T cost:							
Phase 1 (2020-2023)	1.00	1.23	0.83	1.17	0.88	1.04	0.97
Phase 2 (2024-2026)	1.01	1.15	0.90	1.06	0.95	0.98	1.05
Phase 3 (2027-2035)	1.06	1.24	0.95	1.10	0.99	1.01	1.13

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.

[13] Tables H1, H2 and H3 show that the TPS can involve lower costs than C&T in all three phases 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 sufficiently high (1.5%). These alternative parameter values imply lower policy stringency, which enhances the relative cost-effectiveness of TPS and allows it to exceed C&T in the presence of pre-existing taxes, as explained in Sections I and V.A.

Table H2. Sensitivity Analysis: Significance of Key Dynamic Parameters

	AEEI Rate			Elasticity Between Private Saving and Consumption		
	0.5%	**1% (Central case)**	**1.5%**	**1 (Constant saving rate)**	**1.5 (Central case)**	**2**
Cumulative emissions reduction (billion tons):						
Phase 1 (2020-2023)	0.60	0.61	0.61	0.61	0.61	0.61
Phase 2 (2024-2026)	1.46	1.39	1.32	1.39	1.39	1.39
Phase 3 (2027-2035)	18.25	16.34	14.46	16.26	16.34	16.41
Present value of cumulative cost (billion RMB):						
Phase 1 (2020-2023)	26	26	26	26	26	26
Phase 2 (2024-2026)	71	64	58	64	64	65
Phase 3 (2027-2035)	1,906	1,503	1,167	1,462	1,503	1,541
Economic cost per ton (RMB/ton)						
Phase 1 (2020-2023)	43	43	43	43	43	43
Phase 2 (2024-2026)	48	46	44	46	46	46
Phase 3 (2027-2035)	104	92	81	90	92	94
Average allowance price (RMB/ton):						
Phase 1 (2020-2023)	69	70	71	70	70	70
Phase 2 (2024-2026)	95	89	84	89	89	89
Phase 3 (2027-2035)	435	361	295	360	361	361
Wind- and solar- electricity increase (%):						
Phase 1 (2020-2023)	0.34	0.35	0.37	0.35	0.35	0.35
Phase 2 (2024-2026)	0.71	0.73	0.75	0.73	0.73	0.73
Phase 3 (2027-2035)	4.97	4.87	4.64	4.87	4.87	4.87
Ratio of TPS cost to C&T cost:						
Phase 1 (2020-2023)	1.00	1.00	1.00	1.02	1.00	0.99
Phase 2 (2024-2026)	1.06	1.01	0.96	1.05	1.01	0.97
Phase 3 (2027-2035)	1.19	1.06	0.96	1.15	1.06	0.99

Table H3. Sensitivity Analysis: Significance of Policy Stringency

	Benchmark Annual Tightening Rate		
	Low[a]	**Central[b]**	**High[c]**
Cumulative emissions reduction (billion tons)			
Phase 1 (2020-2023)	0.61	0.61	0.61
Phase 2 (2024-2026)	1.23	1.39	1.55
Phase 3 (2027-2035)	12.07	16.34	20.84
Present value of cumulative cost (billion RMB)			
Phase 1 (2020-2023)	26	26	26
Phase 2 (2024-2026)	52	64	78
Phase 3 (2027-2035)	852	1,503	2,390
Economic cost per ton (RMB/ton)			
Phase 1 (2020-2023)	43	43	43
Phase 2 (2024-2026)	42	46	50
Phase 3 (2027-2035)	71	92	115
Average allowance price (RMB/ton)			
Phase 1 (2020-2023)	70	70	70
Phase 2 (2024-2026)	75	89	106
Phase 3 (2027-2035)	225	361	539
Wind- and solar- electricity increase (%)			
Phase 1 (2020-2023)	0.35	0.35	0.35
Phase 2 (2024-2026)	0.56	0.73	0.95
Phase 3 (2027-2035)	2.04	4.87	9.29
Ratio of TPS cost to C&T cost			
Phase 1 (2020-2023)	1.00	1.00	1.00
Phase 2 (2024-2026)	0.92	1.01	1.09
Phase 3 (2027-2035)	0.89	1.06	1.20

[a] 1% for electricity; 2% for other sectors.
[b] 1.5% for electricity; 2.5% for other sectors.
[c] 2% for electricity; 3% for other sectors.

H.2 Alternative Cases with Imperfect Competition

Here we examine our results in the presence of imperfect competition. Specifically, we model market power using markups that differ across sectors. Following the approach of Baqaee and Farhi (2020), we assume that the markups are not altered by

the introduction of the TPS. Since the TPS's carbon prices are a small fraction of input costs, this seems to be a reasonable assumption.

Specifically, under the baseline, the profit function for firms possessing market power is:

$$\pi = p(q)q - C(q)$$

where π is the profit, p and q represent the price and production. C is the cost of the firm. The resulting first-order condition is then:

$$\frac{\partial p}{\partial q}q + p = C'(q) \rightarrow \left(1 + \frac{1}{\varepsilon}\right)p = C'(q) \tag{H1}$$

where ε denotes the demand elasticity of the firm's product. Combining the definition for markup ($mkp = \left[p - C'(q)\right] / C'(q)$) and equation (H1), we have the relationship between demand elasticity and markup, which is:

$$mkp = -\frac{1}{\varepsilon} \tag{H2}$$

Then Equation H1 becomes:

$$(1 - mkp)\,p = C'(q) \tag{H3}$$

Similarly, we can derive the first-order-condition under the TPS:

$$(1 - mkp)\,p + \beta t = C'(q) \tag{H4}$$

where β and t represents the benchmark under the TPS and allowance price, respectively. The sector-level markups are estimated following Xie et al. (2024).

To incorporate markups, we modify the original first-order conditions of firms for both the baseline scenario and the TPS. The results under imperfect competition are presented in Table H4. Imperfect competition reduces output levels and leads to inefficient factor allocation even before the introduction of TPS or C&T. Consequently, the conclusions regarding the effects of pre-existing taxes remain valid in this context. With markups, the economic cost per ton of emissions reduction increases under both policies, resembling the effects of an output tax.

Markups improve the relative cost-effectiveness of TPS compared to C&T. This is because the TPS's implicit output subsidy for covered sectors partially offsets the

distortions caused by markups. Although the quantitative results change, our main findings do not. For example, it remains the case that the ratio of the TPS's costs per ton to those of C&T increases with the increase in policy stringency.

Table H4. Sensitivity Analysis: Imperfect Competition

	Central	With markups on all sectors
Cumulative emissions reduction (billion tons)		
Phase 1 (2020-2023)	0.61	0.63
Phase 2 (2024-2026)	1.39	1.46
Phase 3 (2027-2035)	16.34	17.21
Economic cost per ton (RMB/ton)		
Phase 1 (2020-2023)	43	98
Phase 2 (2024-2026)	46	88
Phase 3 (2027-2035)	92	120
Ratio of TPS cost to C&T cost		
Phase 1 (2020-2023)	1.00	0.84
Phase 2 (2024-2026)	1.01	0.86
Phase 3 (2027-2035)	1.06	0.96

Note: In this sensitivity analysis, the benchmarks remain the same as in the central case. The economic costs are evaluated by comparing the TPS under these markups to the baseline with the same markups.

H.3 Implications of Preferential Treatment of SOEs

Table H5 presents TPS's results of the central case and the results from an alternative case where the SOE does not receive the preferential treatment.

Table H5. Results with Alternative Settings of SOEs' Preferential Treatment

	With SOEs' preferential treatment	Without SOEs' preferential treatment
Cumulative Emissions Reduction (billion tons)		
Phase1	0.61	0.61
Phase2	1.39	1.39
Phase3	16.34	16.33
All years	18.34	18.32
Economic cost per ton (RMB/ton)		
Phase1	43	40
Phase2	46	46
Phase3	92	94
All years	87	88

H.4 Alternative Cases Regarding Administered Pricing

To evaluate the impact of administered pricing, we conducted counterfactual simulations assuming the absence of such pricing. Our analysis focuses on Phase 1 (2020–2023), because as mentioned, administered pricing is primarily applied during this period and will be discontinued starting in 2025.

Table H6. Results of the TPS under Alternative Settings Regarding the Administered Pricing (Phase 1)

	Central Case	No administered pricing
Market price of electricity (change from baseline, %)	0.260	0.263
Average price of electricity (change from baseline, %)	0.186	0.263
Emissions reduction (billion tons)	0.608	0.607
Allowance price (RMB/ton)	69.9	69.6
Economic cost per ton (RMB/ton)	43.0	42.9

The results for Phase 1 are very close to the results in the absence of administered pricing. Since administrative pricing was limited to inframarginal production, electricity prices were still effectively passed through, even in its presence.

H.5 Alternative Cases Regarding International Trade

In the model, there are four types of elasticities that influence the prices of internationally traded goods and services. These are the elasticities for:

(a) the rest-of-world demand for China's exports,
(b) China's supply of its exports,
(c) China's demand for its imports, and
(d) the rest-of-world supply of China's imports.

In both the main text's simulations and the simulations reported here that relax the price-taking assumption, (b) above is determined by firms' profit maximization conditions: firms allocate their output between the domestic and international markets

based on the relative prices in these markets; and (c) above is determined by the input choice of firms and consumption choices of consumers, who choose between imported and domestic products based on their relative prices.

The assumptions about price-taking relate to (a) and (d) above. In simulations for the main text, our central case, we have assumed that (1) China's exports can only be sold at a given exogenous world price and that (2) China must pay a given exogenous world price for its imports. These assumptions effectively treat China as a price taker in the international market.

To assess the significance of China's potential impact on prices of internationally traded goods and services, we assume that in international markets, the prices of China's exports are a negative function of their supply, and the prices of its imports are a positive function of their import demand. We implement these following the method developed by Schreiber et al. (2024). To facilitate comparison, we calibrate the model to ensure that, under the baseline scenario (i.e., no policy intervention), the equilibrium prices and quantities of exports and imports align with the data we observe. We use the elasticities of import and export for China provided by Schreiber et al. (2024).

The results of this analysis are presented in the table below.

Table H7. Sensitivity Analysis: Significance of Trade Assumption

	Trade Assumption			
	Central Case	**Alternative Assumptions of Price Elasticity**		
	Infinite Elasticities	Finite Elasticity of World's Demand for China's Export	Finite Elasticity of World's Supply of China's Import	Both
Cumulative emissions reduction (billion tons)				
Phase 1 (2020-2023)	0.61	0.60	0.60	0.60
Phase 2 (2024-2026)	1.39	1.37	1.38	1.36
Phase 3 (2027-2035)	16.34	15.84	16.18	15.75
Economic cost per ton (RMB/ton)				
Phase 1 (2020-2023)	43	36	40	34
Phase 2 (2024-2026)	46	40	44	39
Phase 3 (2027-2035)	92	86	90	85

Note: The world's supply elasticity for China's import is estimated to be 200, and the world's demand elasticity for China's export is estimated to be -6 (Schreiber et al., 2024).

The graphs below provide intuition for the results. Graph (a) below indicates that the introduction of a downward-sloping rather than perfectly flat curve for exports has a positive welfare impact (assuming the TPS raises costs of exports). In the graph, the original demand curve is flat. In the alternative (no-price-taker) case, the export *D* curve slopes down (*D'*). Introducing the TPS shifts up the export *S* curve to *S'*. Under the assumption of price-taking, the equilibrium quantity of exports drops to Q_1. In contrast, if China can affect the world price, the equilibrium supply of exports drops by less – to Q_2. China is better off in this case (that is, its cost or reduction in welfare is smaller) because some of the TPS-induced export cost increase is shifted to foreigners. Consequently, under this scenario, the policy cost is lower compared to the central case where this positive terms-of-trade effect is not considered. Similar positive term-of-trade impacts from domestic carbon policies have been observed in other countries, such as Germany and the United States, as discussed in Böhringer *et al.* (2021) and Schreiber *et al.* (2024).

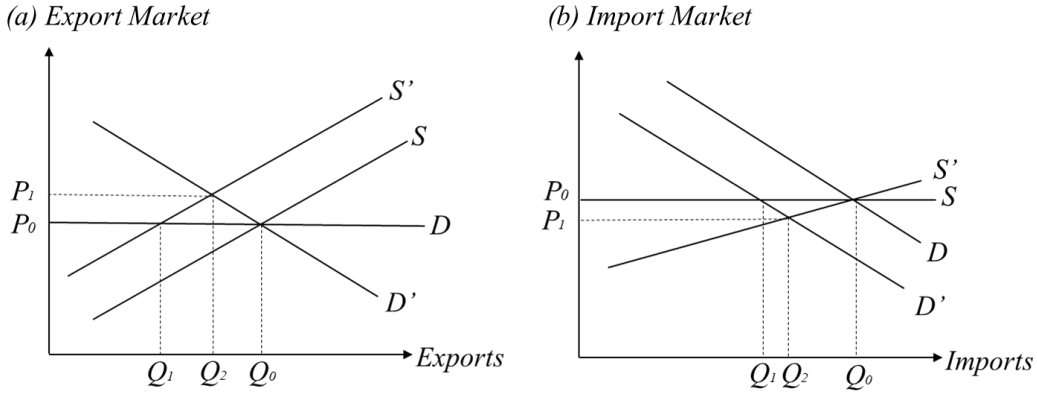


Figure H1. Graphical Illustration of Influence of Alternative Trade Settings

Graph b helps explain the impact of changing only the world's price elasticity of supply for China's imports. Introducing the TPS lowers the demand for imports. On the one hand, the TPS lowers total economic output and households' income and leads to decreased demand for imports. On the other hand, due to substitution effects, the factor costs for sectors not covered by the TPS decrease. For certain non-covered sectors (e.g., services and transportation), this reduction in production costs makes domestic production more competitive compared to imported goods, leading to

decreased demand for imports. These two effects result in an inward shift in the demand for imports (as shown in the graph). Having an endogenous import price (i.e., dropping the price-taking assumption for imports) increases welfare – that is, the cost of the TPS is lower than in the price-taker case. This is because the decreased demand for imports leads to lower import prices (P_I in the graph).

Since the absolute value of the world's supply elasticity of China's imports is much larger (closer to the central case assumption of infinity) than the world's demand elasticity for China's exports and China's export is larger than total import, the overall impact of relaxing the price-taker assumption is dominated by the effects on the export market.

As shown in the table above, the assumptions regarding China's international trade have a relatively minor impact on the main results for cumulative emissions reductions and unit costs. Our primary conclusions remain robust under alternative trade assumptions.

Appendix I. Aggregate Costs under a Transition from the TPS to C&T

In Section V.A, we compared the costs of the TPS and an equally stringent C&T system when each policy is introduced in 2020 and maintained over the entire simulation period. In this appendix, we consider a scenario in which the TPS transitions to C&T at some future time, a transition currently under consideration by China's planners.

In this transition scenario, the system is a TPS system before 2028 and a C&T system since 2028. That is, the transition is completed in one year, and there is no transition period during which the TPS and C&T co-exist.[14]

Figure I1 shows the costs of Case 1, C&T, and the transition case. The transition case has lower costs than both Case 1 (TPS) and C&T since 2028. Its economic cost is lower than the TPS because of the absence of the implicit output subsidy. Its economic cost is lower than the C&T because of the differences in capital accumulation before the transition. Prior to the transition year, when the TPS system applies in the transition case, the aggregate investment is higher than in the C&T case. The higher investment reflects TPS's implicit output subsidy, which implies lower prices of the more emission-intensive capital goods relative to the prices under C&T. As a result, during and after the transition, the economy's capital endowment in the transition case is higher than in the C&T. The higher capital endowment implies a lower rental price of capital, which in turn implies a lower cost of CO_2 abatement, as covered facilities can switch at a lower cost from carbon-based fuels to capital in production.

[14] In an alternative scenario, we assume the transition is gradual, starting in 2028 and completed by 2030. The TPS and C&T are both in place in 2028 and 2029, and C&T is the only ETS starting in 2030. During the transition period, the free allowances allocated by TPS's benchmarks account for 2/3 and 1/3 of total free allowances in 2028 and 2029. This scenario yields results similar to those in the immediate transition case.

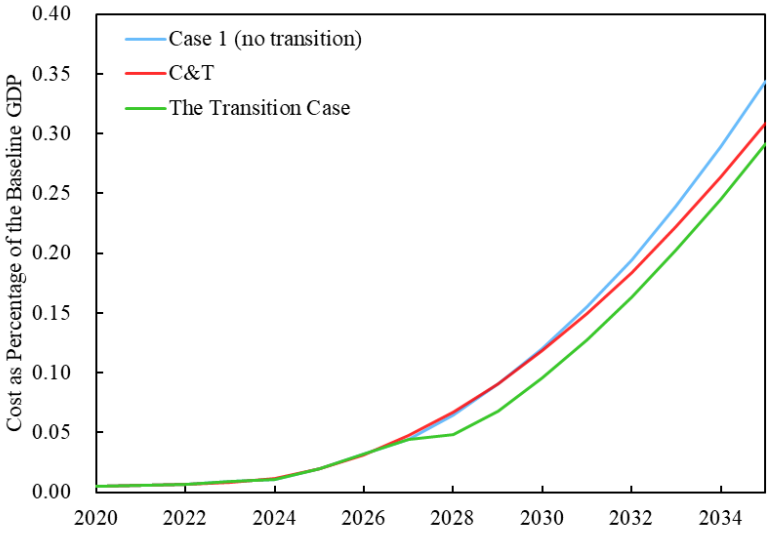


Figure I1. Economic Cost under Transition to a Full C&T System, 2020-2035

Appendix J. Countries That Have Implemented or Are Seriously Considering a TPS (Partial List)

Table J1. Countries Implementing or Seriously Considering Implementing a TPS: ***Five Developing Countries and Two More Developed Regions (The EU and US)***

	Value-added share of emissions-intensive industries	Average growth rate of primary energy consumption in 2013-2023	Average growth rate of electricity generation in 2013-2023	Average growth rate of CO_2 in 2012-2022
China	10%	3.4%	5.7%	2.0%
Vietnam	9%	7.5%	7.9%	4.6%
Kazakhstan	8%	1.2%	2.1%	0.0%
Indonesia	2%	4.5%	4.5%	2.7%
India	8%	4.2%	5.6%	2.3%
The EU	7%	-1.1%	-0.4%	-1.3%
The US	4%	0.2%	0.5%	-0.4%

Source: Energy Institute - Statistical Review of World Energy (2024); World Bank Group (2025)

Table J2. Tax rates in countries actually or potentially implementing a TPS

	Share of govt. tax revenue from output taxes	Average tax rates in emissions intensive sectors	Average tax rates in other sectors
China	86%	6%	5%
Vietnam	76%	2%	4%
Kazakhstan	34%	1%	5%
Indonesia	45%	-9%	2%
India	68%	5%	2%
EU	46%	17%	13%
US	46%	14%	13%

Source: Data are collected based on the GTAP11 data (Aguiar *et al.*, 2022) for year 2017.

Appendix References

Aguiar, Angel, Maksym Chepeliev, Erwin L. Corong, Robert McDougall, and Dominique Van Der Mensbrugghe. 2019. "The GTAP Data Base: Version 10." *Journal of Global Economic Analysis*, 4(1): 1-27.

Aguiar, A., Chepeliev, M., Corong, E., & van der Mensbrugghe, D. 2022. "The GTAP Data Base: Version 11". *Journal of Global Economic Analysis,* 7(2): 1-37.

Baqaee, David Rezza, and Emmanuel Farhi. "Productivity and misallocation in general equilibrium." *The Quarterly Journal of Economics* 135.1 (2020): 105-163.

Berkowitz, Daniel, Hong Ma, and Shuichiro Nishioka. 2017. "Recasting the Iron Rice Bowl: The Reform of China's State-Owned Enterprises." *The Review of Economics and Statistics* 99 (4): 735–747.

Burnett, Richard, Hong Chen, Mieczysław Szyszkowicz, Neal Fann, Bryan Hubbell, C. Arden Pope, Joshua S. Apte, *et al.* 2018. "Global Estimates of Mortality Associated with Long-Term Exposure to Outdoor Fine Particulate Matter." *Proceedings of the National Academy of Sciences* 115 (38): 9592–97.

Burnett, Richard T, C Arden Pope III, Majid Ezzati, Casey Olives, Stephen S Lim, Sumi Mehta, Hwashin H Shin, *et al.* 2014. "An Integrated Risk Function for Estimating the Global Burden of Disease Attributable to Ambient Fine Particulate Matter Exposure." *Environmental Health Perspectives* 122 (4): 397–403.

Burtraw, Dallas, Matt Woerman, and Anthony Paul. 2012. "Retail Electricity Price Savings from Compliance Flexibility in GHG Standards for Stationary Sources." *Energy Policy* 42 (March): 67–77.

Böhringer, Christoph, Thomas F. Rutherford, and Wolfgang Wiegard. 2003. "Computable General Equilibrium Analysis: Opening a Black Box." ZEW Discussion Paper 03-56. Mannheim: Centre for European Economic Research.

Böhringer, Christoph, Andreas Löschel, and Thomas F. Rutherford. 2006. "Efficiency gains from "what"-flexibility in climate policy an integrated CGE assessment." *The Energy Journal* 27.3_suppl (2006): 405-424.

Böhringer, Christoph, Thomas F. Rutherford, and Jan Schneider. 2021. "The Incidence of CO_2 Emissions Pricing under Alternative International Market Responses." *Energy Economics* 101: 105404.

Cao, Jing, Mun S. Ho, and Rong Ma. "Analyzing carbon pricing policies using a general equilibrium model with production parameters estimated using firm data." Energy Economics 92 (2020): 104958.

Cull, Robert, and Lixin Colin Xu. 2003. "Who Gets Credit? The Behavior of Bureaucrats and State Banks in Allocating Credit to Chinese State-Owned Enterprises." *Journal of Development Economics* 71 (2): 533–559.

Chen, Y. H. H., S. Paltsev, J. Reilly, J. Morris, V. Karplus, A. Gurgel, N. Winchester, P. Kishimoto, E. Blanc, and M. Babiker. 2017. "The MIT Economic Projection and Policy Analysis (EPPA) Model: Version 5." *MIT Joint Program on the Science and Policy of Global Change, Technical Note* 16: 1-34.

Chen, Yidan, Fang Guo, Jiachen Wang, Wenjia Cai, Can Wang, and Kaicun Wang. 2020. "Provincial and Gridded Population Projection for China under Shared Socioeconomic Pathways from 2010 to 2100." *Scientific Data* 7 (1): 83.

CEC. *Analysis of Trading Information in the National Electricity Market*. Beijing: China Electricity Council, 2019.

Démurger, Sylvie, Shi Li, and Juan Yang. 2012. "Earnings Differentials between the Public and Private Sectors in China: Exploring Changes for Urban Local Residents in the 2000s." *China Economic Review* 23 (1): 138–53.

Ding, M. R. 2021. "Analysis of the Current Situation of Carbon Emissions in the Cement Industry and Exploration of Key Paths for Emission Reduction." *China Cem* 7: 46-49.

Dirkse, Steven P., and Michael C. Ferris. 1995. "The PATH Solver: A Non-Monotone Stabilization Scheme for Mixed Complementarity Problems." *Optimization Methods and Software* 5 (2): 123–156.

Energy Institute. 2024. *Statistical Review of World Energy*. Accessed Feb 9, 2025. https://www.energyinst.org/statistical-review.

Guariglia, Alessandra, Xiaoxuan Liu, and Lina Song. 2011. "Internal Finance and Growth: Microeconometric Evidence on Chinese Firms." *Journal of Development Economics* 96 (1): 79–94.

Hao, Y., Jiang, Y., Lu, S., & Li, T. (2023). *Annual report on the green power procurement mechanism in China's market: Progress, analysis, and outlook for 2022*. RMI, Beijing.

Harrison, Ann., Marshall Meyer, Peichun Wang, Linda Zhao, and Minyuan Zhao. 2019. "Can a Tiger Change Its Stripes? Reform of Chinese State-Owned Enterprises in the Penumbra of the State." *National Bureau of Economic Research*. Accessed August 21, 2023.

He, Xiaoping, and David Reiner. 2016. "Electricity Demand and Basic Needs: Empirical Evidence from China's Households." *Energy Policy* 90 (March): 212–21.

Hering, Laura, and Sandra Poncet. 2010. "Market Access and Individual Wages: Evidence from China." *Review of Economics and Statistics* 92 (1): 145–159.

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

Hirth, Lion, Falko Ueckerdt, and Ottmar Edenhofer. 2015. "Integration Costs Revisited–An Economic Framework for Wind and Solar Variability." *Renewable Energy* 74: 925-939.

Hoffmann, Sandra, Alan Krupnick, and Ping Qin. 2017. "Building a Set of Internationally Comparable Value of Statistical Life Studies: Estimates of Chinese Willingness to Pay to Reduce Mortality Risk." *Journal of Benefit-Cost Analysis* 8 (2): 251–289.

Holz, Carsten A., and Yue Sun. 2018. “Physical Capital Estimates for China’s Provinces, 1952–2015 and Beyond.” *China Economic Review* 51 (October): 342–57.

Hu, Wenhao, Mun S. Ho, and Jing Cao. 2019. “Energy Consumption of Urban Households in China.” *China Economic Review* 58 (December): 101343.

IAEA. *Economic Assessment of the Long-Term Operation of Nuclear Power Plants: Approaches and Experience*. IAEA Nuclear Energy Series, No.NP-T-3.25. Vienna: Austria, 2018.

IEA/Tsinghua University. *The Role of China’s ETS in Power Sector Decarbonization*. Paris: OECD Publishing, 2021.

IRENA (2024). Renewable power generation costs in 2023. Abu Dhabi: International Renewable Energy Agency, 2024.

Kiuila, Olga, and Thomas F. Rutherford. 2013. “Piecewise smooth approximation of bottom–up abatement cost curves.” Energy Economics 40: 734-742.

Lian, Weicheng, Natalija Novta, Evgenia Pugacheva, Yannick Timmer, and Petia Topalova. 2020. “The Price of Capital Goods: A Driver of Investment under Threat.” *IMF Economic Review* 68: 509-549.

Li, Jianglong, and Boqiang Lin. “Inter-Factor/Inter-Fuel Substitution, Carbon Intensity, and Energy-Related CO_2 Reduction: Empirical Evidence from China.” Energy Economics, vol. 56, 2016, pp. 483–494.

Lu, Ming, Rong Zhu, and Wengang Lu. 2015. “Optimization of Material Structure in Converter Steelmaking.” *Chinese Journal of Engineering*, no. S1: 70–73.

The State Information Center. *Medium and Long-Term Goals, Strategies, and Paths of China’s Economic and Social Development.* Beijing: State Information Center, 2020.

Mathiesen, Lars. 1985. “Computational Experience in Solving Equilibrium Models by a Sequence of Linear Complementarity Problems” *Operations Research* 33(6): 1225–50.

NBS. *Energy Statistic Yearbook 2017*. Beijing: National Bureau of Statistics, 2018

NBS. *Input-output Table 2017*. Beijing: National Bureau of Statistics, 2021

NEA. *2017 Regulatory Report on National Electricity Pricing*. Beijing: National Energy Administration, 2018.

NDRC. *National Key Energy Conservation and Low Carbon Technology Promotion Catalogue*. Beijing: National Development and Reform Commission of China, 2016.

NDRC. *National Key Energy Conservation and Low Carbon Technology Promotion Catalogue*. Beijing: National Development and Reform Commission of China, 2017.

NDRC. *Practical Experience in Energy Efficiency in the Aluminum Industry*. Beijing: National Development and Reform Commission of China, 2021b.

NDRC. *Notice of the National Development and Reform Commission on Issues Related to the 2021-New Energy Feed-in-Tariff Policy.* Beijing: National Development and Reform Commission of China, 2021a.

Oberfield, Ezra, and Devesh Raval. "Micro Data and Macro Technology." Econometrica, vol. 89, no. 2, 2021, pp. 703–732.

OECD. 2012. *Mortality Risk Valuation in Environment, Health and Transport Policies.* Paris: OECD Publishing. https://doi.org/10.1787/9789264130807-en.

Paltsev, Sergey, John M. Reilly, Henry D. Jacoby, Richard S. Eckaus, James McFarland, Marcus Sarofim, Malcolm Asadoorian and Mustafa Babiker. *The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4.* Cambridge MA: MIT Joint Program on the Science and Policy of Global Change, 2005.

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

Rutherford, Thomas F. 1995. "Extensions of GAMS for Complementarity Problems Arising in Applied Economic Analysis." *Journal of Economic Dynamics and Control* 19 (8): 1299–1324.

Song, Zheng, Kjetil Storesletten, and Fabrizio Zilibotti. 2011. "Growing like China." *American Economic Review* 101 (1): 196–233.

Schreiber, Andrew, Alex Marten, and Ann Wolverton. "Approximating Terms of Trade Effects in Single Country CGE Models." Journal of Global Economic Analysis 9.2 (2024): 70-111.

Su, Xuanming, Weisheng Zhou, Ken'Ichi Nakagami, Hongbo Ren, and Hailin Mu. 2012. "Capital Stock-Labor-Energy Substitution and Production Efficiency Study for China." Energy Economics 34 (4): 1208–1213.

Shi, Guoqing, Xiaojian Zheng, and Fangfang Song. 2012. "Estimating Elasticity for Residential Electricity Demand in China." *The Scientific World Journal*.

Święcki, Tomasz. 2017. "Determinants of Structural Change." *Review of Economic Dynamics* 24 (March): 95–131.

Tianditu. 2024. Tianditu Map Data: China Administrative Division. https://cloudcenter.tianditu.gov.cn/administrativeDivision.

Wang, Yiyi, Jianlin Hu, Jia Zhu, Jingyi Li, Momei Qin, Hong Liao, Kai Chen, and Meng Wang. 2021. "Health Burden and Economic Impacts Attributed to $PM_{2.5}$ and O_3 in China from 2010 to 2050 under Different Representative Concentration Pathway Scenarios." *Resources, Conservation and Recycling* 173 (October): 105731.

World Bank Group. *World Development Indicators* 2025. Accessed Feb 9, 2025. https://data.worldbank.org.

Xie, Chunping, Kerui Du, Yingru Zhao, and Nigel P Brandon. 2016. "Possibilities of coal–gas substitution in East Asia: A comparison among China, Japan and South Korea." Natural Gas Industry B 3.4: 387-397.

Xie, Enze, Mingzhi Xu, and Miaojie Yu. 2024. “Trade liberalization, labor market power, and misallocation across firms: Evidence from China's WTO accession.” *Journal of Development Economics*, 171, p.103353.

Xing, Jia, Dian Ding, Shuxiao Wang, Bin Zhao, Carey Jang, Wenjing Wu, Fenfen Zhang, Yun Zhu, and Jiming Hao. 2018. “Quantification of the Enhanced Effectiveness of NOx Control from Simultaneous Reductions of VOC and NH_3 for Reducing Air Pollution in the Beijing–Tianjin–Hebei Region, China.” *Atmospheric Chemistry and Physics* 18 (11): 7799–7814.

Zha, Donglan, and Dequn Zhou. “The Elasticity of Substitution and the Way of Nesting CES Production Function with Emphasis on Energy Input.” Applied Energy, vol. 130, 2014, pp. 793–798.

Zhang, Da, Sebastian Rausch, Valerie J. Karplus, and Xiliang Zhang. 2013. “Quantifying Regional Economic Impacts of CO_2 Intensity Targets in China.” *Energy Economics* 40 (November): 687–701.

Zhang, Hongyu, Da Zhang, and Xiliang Zhang. 2023. “The Role of Output-Based Emission Trading System in the Decarbonization of China’s Power Sector.” *Renewable and Sustainable Energy Reviews* 173: 113080.

Zhang, Longmei, Ray Brooks, Ding Ding, Haiyan Ding, Hui He, Jing Lu, and Rui Mano. 2018. “China’s High Savings: Drivers, Prospects, and Policies”. *International Monetary Fund*.

Zheng, Haotian, Bin Zhao, Shuxiao Wang, Tong Wang, Dian Ding, Xing Chang, Kaiyun Liu, *et al.* 2019. “Transition in Source Contributions of PM2.5 Exposure and Associated Premature Mortality in China during 2005–2015.” *Environment International* 132 (November): 105111.

Zhou, Maigeng, Haidong Wang, Xinying Zeng, Peng Yin, Jun Zhu, Wanqing Chen, Xiaohong Li *et al.* 2019. “Mortality, Morbidity, and Risk Factors in China and its Provinces, 1990–2017: A Systematic Analysis for the Global Burden of Disease Study 2017.” *The Lancet* 394, no. 10204: 1145-1158.