

**Rate-Based Emissions Trading with Overlapping Policies:
Insights from Theory and an Application to China**

APPENDIX

A. Additional Mathematical Proofs

Mathematical Proof of Proposition 6. With CAT, the introduction of the renewables subsidy does not affect total emissions, which are determined by the cap. The average emissions intensity of production can change, however. The numerator in \bar{a} is fixed by the emissions target, so average embodied emissions change only with total output: $d\bar{a}^{\text{CAT}-2} = \bar{a}(dY/Y)$. Solving our system of equations with the new definition of db :

$$\frac{dt^{\text{CAT}-2}}{ds} = (S'_g m_f + S'_f m_g)(t\bar{a} + D'Y) / \Psi^{\text{CAT}-2} < 0 \text{ if } t\bar{a} < -D'Y \quad (\text{A1})$$

$$\frac{dY^{\text{CAT}-2}}{ds} = (S'_g m_f (m_f + \bar{a}) + S'_f (m_g + \bar{a}))Y / \Psi^{\text{CAT}-2} > 0 \quad (\text{A2})$$

$$\frac{db^{\text{CAT}-2}}{ds} = -\bar{a}(S'_g m_f (m_f t - D'Y) + S'_f m_g (m_g - D'Y)) / \Psi^{\text{CAT}-2} < 0 \quad (\text{A3})$$

where $\Psi^{\text{CAT}-2} = Y S'_r (S'_g m_f (m_f + \bar{a}) + S'_f (m_g + \bar{a})) - (t\bar{a} + D'Y) (S'_g m_f^2 + S'_r (m_f - m_g)^2 + S'_f m_g^2) > 0$ if t is not too large (for which $t\bar{a} < -D'Y$ is a sufficient but not necessary condition).□

Mathematical Proof of Proposition 7. With USPS, since average emissions always equal the standard, $d\bar{a}^{\text{UTPS}-2} = 0$. Solving our system of equations, we find that:

$$\frac{dt^{\text{USPS}-2}}{ds} = -\left(a S'_f S'_g - (S'_g m_f + S'_f m_g) D'\right) / \Psi^{\text{USPS}-2} < 0 \quad (\text{A4})$$

$$\frac{dE^{\text{USPS}-2}}{ds} = a \frac{dY^{\text{USPS}-2}}{ds} = a (S'_g m_f^2 + S'_f m_g^2) / \Psi^{\text{USPS}-2} > 0 \quad (\text{A5})$$

where $\Psi^{\text{USPS}-2} = S'_r M^{\text{USPS}} - D' (S'_g m_f^2 + S'_r (m_f - m_g)^2 + S'_f m_g^2) > 0$. □

In the presence of linked embodied emissions pricing, an overlapping renewable subsidy has the same effect on the numerator of the emissions price response (which is negative) as in the case without such taxes, but the denominator is altered. The effect on emissions and output still takes the opposite sign of the emissions price effect.

Mathematical Proof of Proposition 8. With an EPS, substituting the equilibrium change in emissions, we see the change in average embodied emissions

$d\bar{a}^{\text{EPS-2}} = ((\bar{a} - a_f)df + (\bar{a} - a_g)dg + (\bar{a} - a_r)dr) / Y$. Assuming $a_r = 0$ as in the EPS and solving for the change in emissions and their price from a change in the renewable subsidy, we get

$$\frac{dt^{\text{EPS-2}}}{ds} = \frac{\Delta_f S'_g - \Delta_g S'_f}{Z^{\text{EPS-2}}} (t\bar{a} + D'Y) < 0 \text{ if } t\bar{a} < -D'Y \quad (\text{A6})$$

$$\frac{dE^{\text{EPS-2}}}{ds} = \frac{(\Delta_f + \Delta_g)(\Delta_g m_f + \Delta_f m_g)}{Z^{\text{EPS-2}}} (t\bar{a} + D'Y) < 0 \text{ if } t\bar{a} < -D'Y \quad (\text{A7})$$

$$\frac{db^{\text{EPS-2}}}{ds} = \frac{t(D'(\Delta_f + \Delta_g)(\Delta_g m_f + \Delta_f m_g) - \bar{a}(S'_f \Delta_g^2 + S'_g \Delta_f^2)) + \bar{a}D'Y(\Delta_f S'_g - \Delta_g S'_f)}{Z^{\text{EPS-2}}} < 0 \quad (\text{A8})$$

where

$$\begin{aligned} Z^{\text{EPS-2}} &= t(\Delta_f + \Delta_g)(\Delta_g(m_f - \bar{a}) + \Delta_f(m_g - \bar{a}))S'_r - t\bar{a}(\Delta_f^2 S'_g + \Delta_g^2 S'_f) \\ &\quad + Y(\bar{a}S'_r(\Delta_f S'_g - \Delta_g S'_f) + (S'_r - D')(\Delta_f^2 S'_g + \Delta_g^2 S'_f) - S'_r D'(\Delta_f + \Delta_g)^2) \end{aligned}$$

is positive with a (possibly unnecessary) restriction on the size of t , which ensures that the direction of change in the embodied emissions tax follows the first-order effects of the renewable subsidy ($db/ds < 0$). The range restriction of $t\bar{a} < -D'Y$ is sufficient. Recall that $\bar{\mu}^{\text{EPS}} > 0$ implies $\Delta_f S'_g - \Delta_g S'_f > 0$.

This fact also allows us to demonstrate that the numerator of $dY^{\text{EPS-2}} / ds$ is also positive:

$$\frac{dY^{\text{EPS-2}}}{ds} = \frac{t(\Delta_f + \Delta_g)(\Delta_g m_f + \Delta_f m_g) + Y((S'_f \Delta_g (\Delta_g + \bar{a}) + S'_g \Delta_f (\Delta_f - \bar{a}))}{Z^{\text{EPS-2}}} > 0$$

since $(S'_f \Delta_g (\Delta_g + \bar{a}) + S'_g \Delta_f (\Delta_f - \bar{a})) > (S'_g \Delta_f (\Delta_g + \bar{a}) + S'_f \Delta_g (\Delta_f - \bar{a})) = S'_g \Delta_f \Delta_g + S'_f \Delta_g^2 > 0$. \square

B. Numerical Model

Here we briefly describe the structure of the numerical model used in this study. This version is adapted from Goulder *et al.* (2023). Figure B1 presents the economic flows represented in the model.

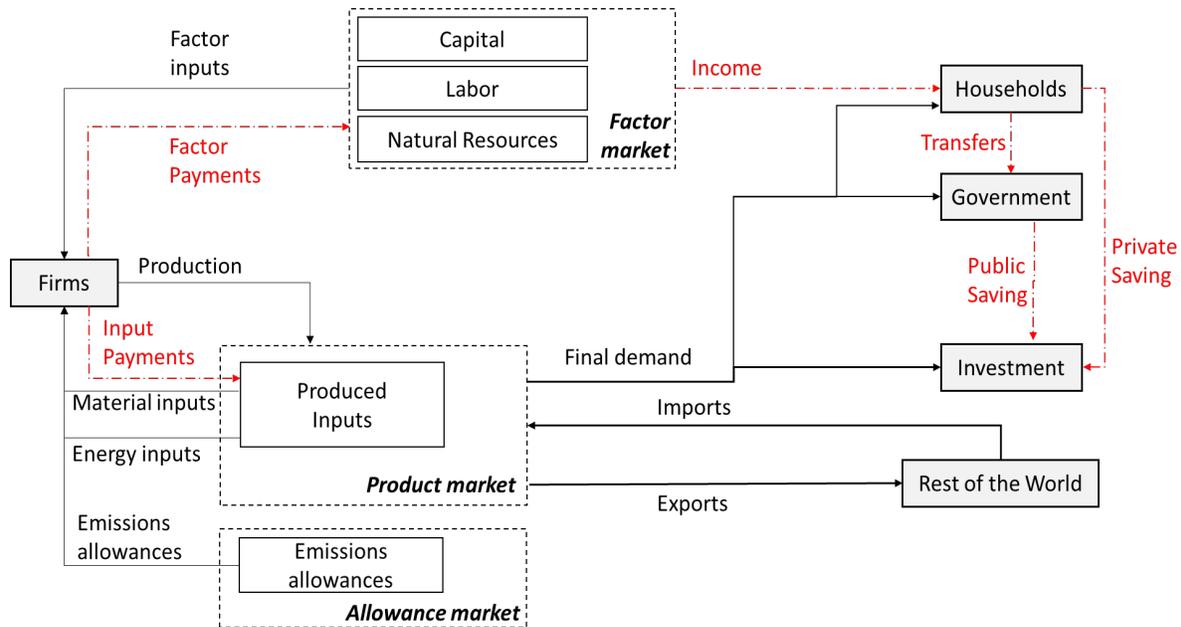


Figure B1. Structure of the Numerical Model

1. Production

Primary Factors

The primary factors are labor, capital, land, and “natural resources”. Labor and capital are employed in production in all sectors. Labor is perfectly mobile across sectors. Capital is imperfectly mobile: there are costs to its reallocation across sectors and subsectors. Land is employed in the agriculture sector only and is not mobile across sectors. Natural resources are employed only in wind, solar, hydro, and nuclear electricity production and are not mobile across sectors or subsectors.

Sectors and Subsectors

There are 31 production sectors (listed in Table B1). The first 24 outputs in the table are in the material category, while the remaining seven are in the energy category. As indicated

below, some sectors subdivide into subsectors. The representative firm of each of the sectors (and subsectors) employs inputs of primary factors along with intermediate inputs (energy and material goods) to produce goods for the domestic market and export.

In the electricity sector, the model differentiates between renewable sources of electricity (such as solar, wind, and hydro) as well as nuclear power, and the conventional fossil-based sources of electricity. To capture the diversity among fossil-based electricity generators, the model takes into account eleven distinct subsectors, listed in the Figure B2. The cement, aluminum, and iron & steel sectors also distinguish subsectors with production technologies differing in their emissions intensities and production technologies. The model treats the outputs from subsectors of a given sector as homogeneous; thus they have the same market price.

Production is represented by nested constant elasticity of substitution (CES) functions. A general equation for this functional form is shown as Equation B1.

$$V = \left[\sum_{i=1}^n \alpha_i v_i^\rho \right]^{\frac{1}{\rho}} \quad (\text{B1})$$

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 (B1) indicates the relationship between a given composite and its underlying elements at any given point of the nest.

In each sector, including the subsectors within the electricity, cement, aluminum, and iron & steel sectors, producers employ material inputs (\mathbf{x}), energy inputs (\mathbf{e}), and factors (\mathbf{mw}) to produce output. Figure B3 illustrates how the material inputs x_1, x_2, \dots, x_{24} combine to produce the composite material input \mathbf{x} . Each of the material inputs x_i is a composite of a domestically produced material input $d_{x,i}$ and, if applicable, a foreign-produced material input $n_{x,i}$. The energy composite (\mathbf{e}) is a composite of electricity (s), heat (h) and fossil fuels (f), and the fossil fuel is a composite of five fuel inputs f_1, f_2, \dots, 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 applicable, land (lnd). Equation B1 applies in each level of the structure in Figure B3.

Output Y is allocated toward the domestic market, which is represented by Y_{dm} , and to export, which is represented by Y_{ex} .

Table B1. Sectors

Name	Description
Cement ¹	Cement
Iron & steel ²	Iron and steel
Aluminum ³	Aluminum products
Pulp & paper	Pulp and paper
Other non-metal products	Non-metal processing other than cement
Other non-ferrous metals	Non-ferrous metals other than aluminum
Raw chemicals	Raw chemical materials, chemical products
Agriculture	Crop cultivation, forestry, livestock and livestock products, and fishery
Mining	Metal minerals mining and non-metal minerals, and other mining
Food	Food and tobacco
Textile	Textile
Clothing	Clothing
Log & furniture	Log and furniture
Printing & stationery	Printing and stationery
Daily chemical products	Chemical fibers, medicines, rubber & plastics products
Metal products	Metal products
General equipment	General equipment manufacturing
Transport equipment	Transport equipment manufacturing
Electronic equipment	Electronic equipment manufacturing
Other manufacturing	Other manufacturing
Water	Water
Construction	Construction
Transport	Transport and post
Services	Services
Electricity	Electricity generation
Petroleum refining	Petroleum refining
Heat	Heat distribution
Coal	Coal mining and processing
Crude oil	Extraction of crude oil
Natural gas	Primary production of natural gas
Gas manufacture & distribution	Manufacture, processing, and distribution of natural or synthetic gas

¹ The cement is divided into 3 subsectors: high, medium, and low-efficiency cement production.

² The iron & steel sector is divided into 6 subsectors: high, medium, and low-efficiency basic oxygen steel production, and high, medium, and low-efficiency electric-arc furnace steel making.

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

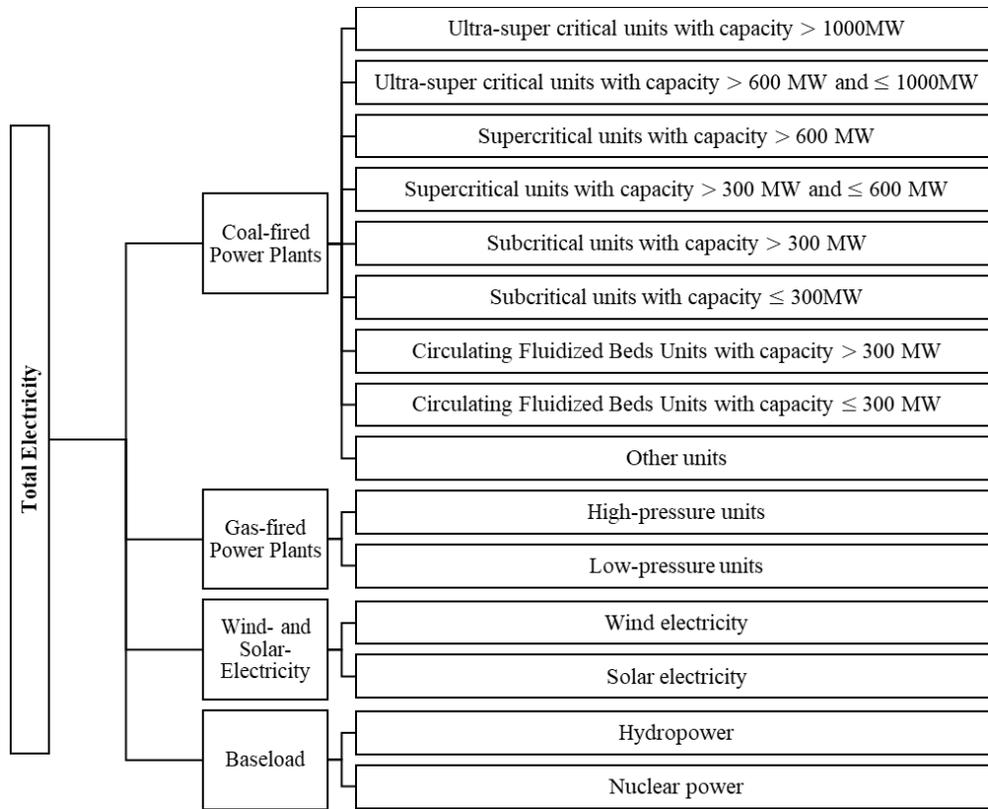
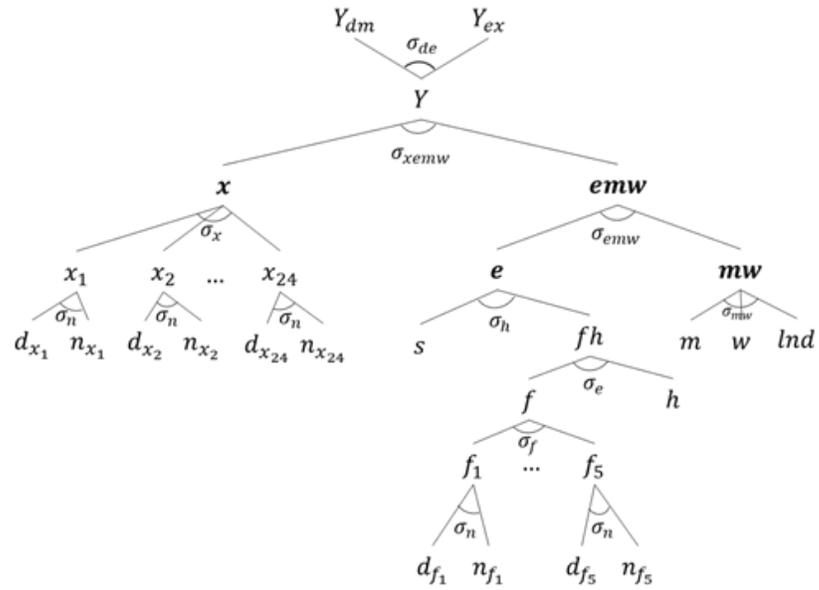


Figure B2. Subsectors in the Electricity Sector in the Numerical Model

A. Fossil-fuel based electricity sector and other sectors



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

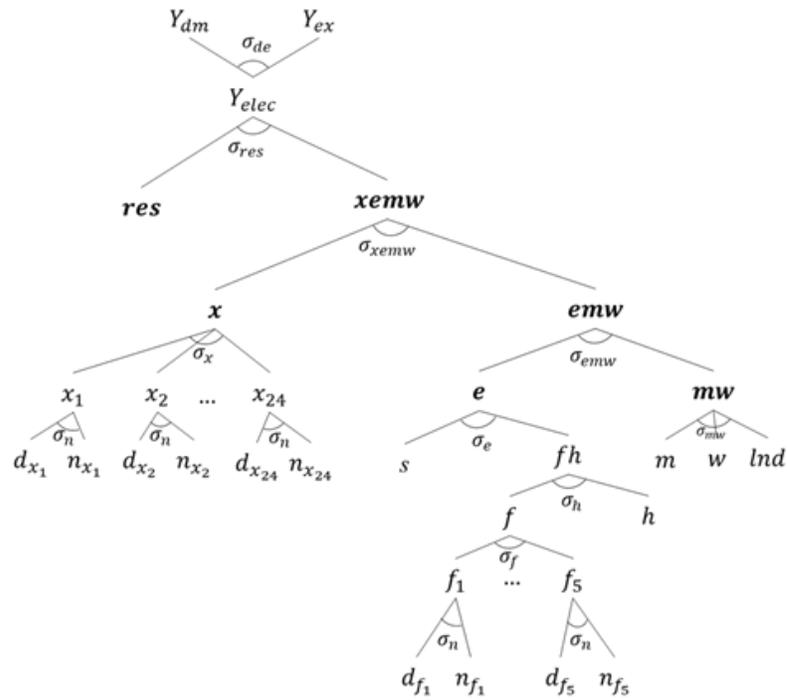


Figure B3. Nested CES Production Structure for Each Sector

2. Household Behavior

A representative household earns income from returns to the factors of production and devotes that income to consumption, savings, and transfers to the government.

Real private investment is set as a fixed share of real gross domestic production (GDP) and remains unaffected by the real return on investment. The value of savings is used to finance the real private investment.

Lumpsum transfers are endogenously determined to finance government expenditure, which is described in the following subsection.

Consumption choices reflect its utility maximization subject to a budget constraint. A nested CES utility function governs the allocation of consumption expenditure across specific consumer goods and energy.

3. Government Behavior

We did not include pre-existing taxes and subsidies in the version of the model, so the tax revenue that finances the government's activity in the input-output table is modeled as lump sum transfers from the households to the government. The government receives transfers from households that are devoted to government consumption and public savings.

Public consumption is set as a fixed share of GDP and is characterized by a CES preference function defined over the material-energy composite. Government saving finance public investment, which is also set as a fixed share of GDP.

In each period, an endogenously determined lumpsum transfer from the households finances these government expenditures.

4. Foreign Trade

The model regards China as a price-taker on the world market: the foreign-currency prices of imports are exogenous, as are the foreign-currency prices at which exports can be sold. Domestically produced and imported goods in a given sector category are regarded as imperfect substitutes; hence their market prices can differ. Import and export quantities are functions of the relative prices of domestic and foreign goods.

The emissions leakage rate to foreign countries is calculated by multiplying the change in net exports in sector j between China and country c by the emissions intensity of j in c , and

dividing the sum across sectors and countries by the change in domestic emissions, using the following equation:

$$\text{Emission_Leakage_rate} = \frac{\sum_j (\sum_{c \in IC} \Delta \text{Import}_{j,c} \times \text{Intensity}_{j,c} - \sum_{c \in EC} \Delta \text{Export}_{j,c} \times \text{Intensity}_{j,c})}{\Delta \text{Emission}_D},$$

IC denotes import-origin countries, and *EC* denotes export-destination countries. $\Delta \text{Emission}_D$ is the domestic emissions abatement. This formula assumes that any decrease in China's bilateral exports will be perfectly offset by an equivalent increase in foreign production by the trade partner. This assumption tends to over estimate the leakage rate: In a more complicated model with trade response, the leakage rate would be even smaller. The data on emission intensities of each sector by country is from the Global Trade Analysis Project database (version 10) (2019).

5. Equilibrium

The general equilibrium requires supply-demand balance in each period for each factor and produced goods. 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 rental prices of capital, which differ across sectors (as well as subsectors in the electricity, cement, aluminum, and iron & steel sectors); (d) the four different rental prices of the natural resources, for these resources employed in the solar, wind, hydro, and nuclear electricity production subsectors, respectively; and (e) the CO₂ allowance price.

6. Dynamics

The model is solved as a mixed complementarity problem (MCP) with a Newton-based solver, and 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. As discussed earlier, domestic real investment in each period is set as a fixed share of GDP. The stock in the next period is aggregate real domestic investment in the current period net of depreciation over that period. The stocks of land and the four kinds of natural resources (wind, solar, hydro, and nuclear) are treated as fixed at the base year level.

The model incorporates technological progress as exogenous improvements in energy factor productivity, as well as the cost reduction trend in renewable electricity generation.

7. Parameters and Calibration Methods

In this section, we provide a brief overview of the calibration process for our model. For a more comprehensive understanding of the data sources, data processing methods, and calibration techniques, we recommend referring to Goulder *et al.* (2023).

For any CES function of the form in Equation (A1), the Lagrangian equation for obtaining the composite V at minimum cost is given by:

$$L = \sum_{i=1}^n p_i v_i + \lambda \left\{ \left[\sum_{i=1}^N \alpha_i v_i^\rho \right]^{\frac{1}{\rho}} - V \right\} \quad (\text{B2})$$

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

$$\frac{v_i}{V} = \alpha_i^\sigma \left[\frac{p_i}{p} \right]^{-\sigma} \quad (\text{B3})$$

Therefore, the share parameters of CES functions that have the functional form of Equation (A1), α_i can be calibrated by inverting the optimal input intensity function:

$$\alpha_i = \left(\frac{v_i}{V} \right)^{1/\sigma} \cdot \frac{p_i}{p} \quad (\text{B4})$$

where α_i is the share parameter of the CES production function, V 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.

Data for calibration includes the 2017 China's input-output table and a firm-level dataset from the Ministry of Ecology and Environment of 2017, which can be used to derive the “ $\frac{v_i}{V}$ ” component in Equation (A4). The elasticities of substitution (σ) at different levels of the nested CES structure are obtained from calibrations and various sources. Table B2 provides the

summary of the value and sources of these elasticities of substitution used in the version of the model in this study.

Table B2. Elasticities

Parameter	Source	Values
Production elasticities		
σ_{res}	Calibrated	Solar: 0.27 Wind: 0.28 Hydro, Nuclear: 0
σ_{xemw}	GTAP, EPPA, RTI-ADAGE, DIEM	0
σ_{emw}	Calibrated	Electricity: 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 HPG: 0.041 LPG: 0.161 Other sectors: 0.4
σ_e	Calibrated	Other sectors: 0.50; Electricity: 0.01
σ_h	Hu <i>et al.</i> (2019)	0.30
σ_f	Cossa (2004), RTI-ADAGE	Other sectors: 1.00; Electricity: 0.10 Agriculture: 0.24 Coal, Crude oil, Natural gas, Mining: 0.20
σ_{mw}	Jomini <i>et al.</i> (1991)	Food: 1.12 Services: 1.36 Transportation: 1.48 Other sectors: 1.26
σ_x	GTAP, EPPA, DIEM	0
σ_n	Set to zero to suppress international leakage	0
σ_{ds}	GTAP	0
Consumption elasticities		
σ_{xs}	GTAP	0
σ_s	Calibrated	0.55
σ_f	DIEM	0.50
σ_x	GTAP	Household consumption: 1.00 Government consumption, investment: 0
Transformation elasticities¹		
σ_w	GTAP	1.50 for capital, $+\infty$ for labor
σ_{wk}	GTAP	3.00 for capital, $+\infty$ for labor

Note: σ_w represents the factor transformation elasticities between sectors; σ_{wk} represents the factor transformation elasticities between subsectors within a sector.

Other parameters are closely related to intertemporal choices and economic growth. 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 percent according to 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 percent annual AEEI rate. For the fossil-based electricity subsectors, we again follow Chen *et al.*(2017), applying an annual AEEI rate of 0.4 percent.

Hicks-neutral technological change applies to all sectors but at different rates across sectors. The rates of Hicks-neutral technological change are set in a way that aligns the model's reference path with the projections provided by the State Information Center (2020) and the International Renewable Energy Agency (IRENA) (2019a, 2019b). Specifically, the projections indicate that the contributions of agriculture, industry, and service sectors to GDP are expected to change from 7%, 37%, and 56% to 6%, 30%, and 64%, respectively, over the period of 2020-2035.

The growth rate of effective labor is calibrated so that the resulting GDP is consistent with the government projection, averaging 5.5% during 2020-2025, 4.5% during 2026-2030, and 3.5% during 2031-2035.

C. Additional Numerical Results

1. Results of DEPS in Scenarios of Various Overlaps

In Figure 2 in the main text, we compared the cost per ton of abatement associated with DEPS with various overlapping policy cases. Table C1 includes more details of the results, from which we can further understand why the stated policy overlaps – R2 – could help improve the cost-effectiveness of emissions reductions under a DEPS.

Table C1. Results of Policy Overlaps under DEPS in Scenarios of Various Overlaps

	Electricity Price	Marginal Revenue of Renewables	Marginal Revenue of Fossil-based Electricity	Unit Cost of Electricity Used by Covered Sectors	Allowance Price	Cost Per Ton of Abatement
	(yuan/kWh)	(yuan/kWh)	(yuan/kWh)	(yuan/kWh)	(yuan/t)	(yuan/t)
Phase 1						
R2	0.692	0.769	0.746	0.711	65	15.3
RN	0.692	0.769	0.746	0.701	65	15.3
SN	0.690	0.767	0.747	0.690	68	19.4
NO	0.695	0.695	0.695	0.695	152	19.6
Phase 2						
R2	0.686	0.798	0.743	0.747	71	17.3
RN	0.687	0.799	0.744	0.706	72	17.5
SN	0.685	0.798	0.685	0.685	101	22.9
NO	0.695	0.695	0.695	0.695	152	19.6
Phase 3						
R2	0.675	0.745	0.821	0.790	207	22.5
RN	0.673	0.754	0.838	0.694	227	24.2
SN	0.673	0.760	0.673	0.673	263	29.0
NO	0.681	0.681	0.681	0.681	313	32.0

2. DEPS with Optimized Renewable Subsidy and Electricity Taxes

Additional cost savings are possible with exogenous renewable subsidies and electricity taxes by optimizing tax and subsidy rates together. Figure C1 presents the relationship between cost per ton, a broad-based electricity consumption tax rate, and renewable subsidy rates with DEPS. As the existence of an optimal level of renewable subsidy, there also exists an optimal level of electricity tax that corrects the incomplete cost passthrough just correctly. The optimal rate of the tax also depends on the rate of overlapping renewable subsidies. The higher the renewable subsidy rates, the lower the electricity price, the higher the needed overlapping electricity tax. Therefore, the two overlapping policies (electricity tax and renewable subsidies) are interdependent.

The red triangles in the graphs represent the optimized electricity taxes and renewable subsidy rates in each phase. In comparison to the implicit electricity tax rates introduced by the RPS, which are approximately 1% in Phase 1 and 3% in Phases 2 and 3, the optimal tax rates are significantly higher, indicating the potential impact of implementing electricity taxes to reduce abatement costs.

By optimizing both tax rates and renewable subsidy rates together, the cost of abatement can be further reduced by 50%, 30%, and 11% in Phases 1, 2, and 3, respectively, compared to DEPS-R*2. In Phase 3, the IEP policy in DEPS-R*2 covers 25% of electricity consumption, effectively addressing incomplete passthrough. Therefore, in Phase 3, the additional need for an electricity tax rate is not substantial.

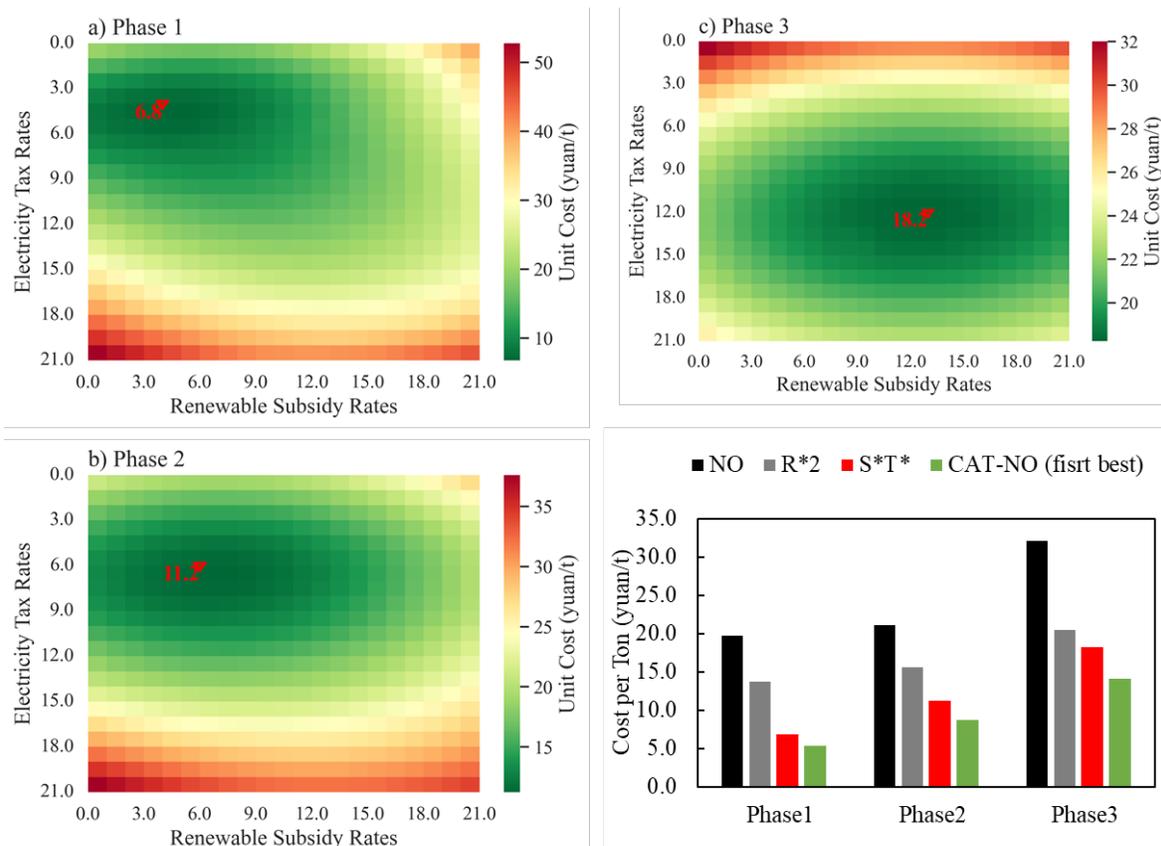


Figure C1. Relationship between Cost Per Ton Abatement, Electricity Tax Rates, and Renewable Subsidy Rates with DEPS.

Note: red triangles indicate the optimized electricity taxes and renewable subsidy rates.

3. Cost Per Ton Abatement of All Cases

Table C2 includes the cost per ton abatement under all scenarios listed in section III C.

Table C2. Cost Per Ton Abatement of Different ETS in Different Scenarios

		CAT	USPS	UEPS	DEPS
NO	Phase1	5.4	9.5	12.7	19.7
	Phase2	8.8	12.7	16.3	21.0
	Phase3	14.1	18.2	25.5	32.1
R2	Phase1	12.1	13.5	13.7	15.3
	Phase2	14.2	15.8	15.9	17.3
	Phase3	15.1	17.8	18.5	22.5
R*2	Phase1	5.4	9.4	10.0	13.7
	Phase2	8.9	12.4	12.9	15.6
	Phase3	14.4	17.3	17.8	20.4
RN	Phase1	12.1	13.5	13.7	15.3
	Phase2	14.1	15.9	16.0	17.5
	Phase3	14.8	18.4	19.1	24.2
R*N	Phase1	5.4	9.4	10.0	13.7
	Phase2	8.8	12.7	13.1	16.0
	Phase3	14.1	17.9	18.5	21.7
S2	Phase1	12.3	15.1	17.2	20.0
	Phase2	14.3	17.9	20.3	22.4
	Phase3	15.1	18.2	22.0	25.5
SN	Phase1	12.3	15.1	17.2	20.0
	Phase2	14.4	18.1	20.7	22.9
	Phase3	14.9	19.0	23.9	29.0
S*2	Phase1	5.4	9.4	11.4	16.7
	Phase2	8.9	12.4	14.5	18.2
	Phase3	14.4	17.4	21.2	24.8
S*N	Phase1	5.4	9.4	11.4	16.7
	Phase2	8.8	12.7	14.9	18.9
	Phase3	14.1	18.1	23.1	25.0
N2	Phase1	5.4	9.4	12.6	19.6
	Phase2	8.9	12.4	15.8	20.1
	Phase3	14.4	17.4	23.2	27.5

D. Sensitivity Analysis

We conducted a sensitivity analysis around the key parameters of the numerical model. Results are summarized in Tables D1 – D3. We focus on three parameters: the substitution elasticity between energy and factor inputs; the capital transformation elasticity within a sector; and the substitution between electricity and non-electricity inputs.

The substitution elasticity between energy and factor inputs determines how easily energy intensity can be reduced within a given subsector or sector. Higher elasticity indicates that production facilities can more easily substitute factor inputs for energy inputs. In the central case of our numerical model, the elasticity values for different electricity generation technologies are calibrated based on data on the cost of reducing the heat rate in the electricity sector, ranging from 0.16 to 0.37, depending on the specific technology. For industrial sectors, the elasticity value is sourced from the literature and is set at 0.4.¹

To account for uncertainties associated with these parameter choices, we considered two alternative settings: doubling and halving the elasticity. The results are summarized in Table D1. Higher energy-factor input substitution elasticity facilitates the use of factor inputs to replace energy inputs, thereby reducing abatement costs and achieving greater emissions reductions, as shown in Table D1. Additionally, increased elasticity correlates with a lower relative cost of DEPS-NO compared to CAT-NO. Greater elasticity signifies less difficulty in reducing emissions from fossil-based power plants, enabling more substantial emissions reductions by these plants. As a result, the need for augmenting renewable energy sources and reducing electricity demand diminishes, mitigating the distortive effects associated with DEPS's exclusion of renewables and its implicit subsidy on output.

Consequently, with higher elasticity, the need for overlapping renewable subsidies or indirect emissions pricing to support DEPS decreases. This is evident from the diminishing difference in the relative cost of DEPS-R2 and DEPS-NO compared to CAT-NO in Table D1.

¹ The estimated substitution elasticities between the energy composite and the factor composite for non-electricity sectors in China range from 0.4 to 1.2 (Cao et al., 2020; Feng & Zhang, 2018; Su et al., 2012; Zha & Zhou, 2014). This wide range is due to the level of sector aggregation and the time scope of the empirical studies. The model adopts 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). More information on the parameter settings can be found in Goulder *et al.* (2023).

Table D1. Sensitivity Analysis with Different Settings of Energy-Factor Elasticities

Policy Case	Emissions Reduction (%)	Cost per Ton Abatement (yuan/t)			Cost Ratio	
		CAT-NO	DEPS-R2	DEPS-NO	DEPS-R2/CAT-NO	DEPS-NO/CAT-NO
Halved						
Phase 1	-2.4	6.7	18.6	29.2	2.8	4.3
Phase 2	-5.1	10.5	20.8	28.9	2.0	2.7
Phase 3	-10.2	16.4	29.5	43.0	1.8	2.6
All	-8.0	15.2	28.0	40.7	1.8	2.7
Central						
Phase 1	-2.6	5.4	15.3	19.6	2.8	3.6
Phase 2	-5.5	8.8	17.3	21.0	2.0	2.4
Phase 3	-11.0	14.1	22.5	32.0	1.6	2.3
All	-8.7	13.1	21.5	30.2	1.6	2.3
Doubled						
Phase 1	-2.9	4.0	12.2	12.2	3.0	3.0
Phase 2	-6.3	8.8	13.9	14.3	1.6	1.6
Phase 3	-12.7	14.1	16.3	22.4	1.2	1.6
All	-10.0	13.1	15.9	21.0	1.2	1.6

Capital transformation elasticities determine the flexibility of shifting production across different subsectors within a sector. In our central case, the capital transformation elasticity is set at 3 for different subsectors within a sector and 1.5 for different sectors, based on estimates from the GTAP database (Aguiar, 2019). This indicates that capital incurs adjustment costs when reallocating across subsectors and sectors, and the adjustment cost is lower for capital between firms producing the same product (subsectors within a sector) than between firms producing different products (sectors).

We explore the uncertainties related to this parameter. Higher capital transformation elasticity leads to lower abatement costs by reducing the capital adjustment cost of shifting from plants with higher emission intensity to plants with lower emission intensity. However, its influence on the cost gap between DEPS-NO and CAT-NO is uncertain. Increased elasticity increases the response of subsector electricity output to the implicit output subsidy under DEPS, implying greater distortion. However, it also reduces the allowance price, which in turn lowers

the size of the implicit output subsidy under the DEPS. The net impact depends on which effect predominates.

We found that changing this parameter does not significantly affect the importance of overlapping policies. Overlapping policies such as RPS and IEP improve the cost-effectiveness of DEPS by enabling more renewable electricity production and increasing cost pass-through. Changing capital transformation elasticity within a sector does not significantly impact these channels, because the supply elasticity of renewables is also affected by their own subsector-specific resource input. This resource input accounts for the special integration costs associated with renewables and is a fixed factor, limiting the extent of renewables' output change due to capital transformation elasticity. Also, capital transformation elasticity within a sector affects the supply elasticity of output from a subsector but does not directly affect the elasticity of the total output from that sector. Consequently, the response of results to overlapping policies does not vary significantly with changes in capital transformation elasticity.

Table D2. Sensitivity Analysis with Different Settings of Capital Transformation Elasticities

	Emissions Reduction (%)	Cost per Ton Abatement (yuan/t)			Cost Ratio	
		CAT-NO	DEPS-R2	DEPS-NO	DEPS-R2/CAT-NO	DEPS-NO/CAT-NO
Halved						
Phase 1	-2.7	6.3	17.2	22.4	2.7	3.6
Phase 2	-5.8	10.2	20.1	23.7	2.0	2.3
Phase 3	-11.8	16.9	24.5	36.6	1.4	2.2
All	-9.3	15.7	23.7	34.6	1.5	2.2
Central						
Phase 1	-2.6	5.4	15.3	19.6	2.8	3.6
Phase 2	-5.5	8.8	17.3	21.0	2.0	2.4
Phase 3	-11.0	14.1	22.5	32.0	1.6	2.3
All	-8.7	13.1	21.5	30.2	1.6	2.3
Doubled						
Phase 1	-2.5	4.7	14.1	17.2	3.0	3.7
Phase 2	-5.4	8.8	15.7	18.8	1.8	2.1
Phase 3	-10.7	14.1	21.1	28.9	1.5	2.1
All	-8.4	13.1	20.1	27.2	1.5	2.1

Table D3 presents the results with varying settings for electricity-non-electricity substitution elasticity. In our central parameter setting, this elasticity is calibrated based on data for the price elasticity of demand for electricity, which is -0.5 following Hu et al. (2019). To account for uncertainties, we consider two alternative cases: (1) Setting the electricity-non-

electricity substitution elasticity to zero, which implies an electricity demand elasticity of around 75% of the central case. (2) Setting the electricity-non-electricity substitution elasticity to five times the central parameter value, which implies an electricity demand elasticity twice that of the central case.

Higher electricity demand elasticity generally lowers the cost per ton abatement, except in Phase 1, where it raises unit costs due to greater emissions leakage under CAT-NO. The effect of higher electricity demand elasticity on the cost gap of DEPS-NO and CAT-NO is also ambiguous. It depends on the combined influences of carbon price changes and supply elasticity. A higher elasticity increases the impact of the implicit output subsidy under DEPS but also reduces the size of the implicit output subsidy by lowering the carbon price.

Additionally, higher elasticity makes electricity use more sensitive to price changes, enhancing the benefits of implementing an electricity consumption tax. Consequently, overlapping policies become more critical when the substitution elasticity is larger.

Table D3. Sensitivity Analysis with Different Settings of Substitution Elasticity between Electricity and Non-Electricity Inputs

Policy Case	Emissions Reduction (%)	Cost per Ton Abatement (yuan/t)			Cost Ratio	
		CAT-NO	DEPS-R2	DEPS-NO	DEPS-R2/CAT-NO	DEPS-NO/CAT-NO
Zero						
Phase 1	-2.5	5.2	15.9	20.0	3.1	3.9
Phase 2	-5.4	9.0	18.4	21.7	2.0	2.4
Phase 3	-11.0	14.6	24.5	32.6	1.7	2.2
All	-8.6	13.5	23.4	30.8	1.7	2.3
Central						
Phase 1	-2.6	5.4	15.3	19.6	2.8	3.6
Phase 2	-5.5	8.8	17.3	21.0	2.0	2.4
Phase 3	-11.0	14.1	22.5	32.0	1.6	2.3
All	-8.7	13.1	21.5	30.2	1.6	2.3
Five times of the central						
Phase 1	-2.7	5.8	13.6	18.8	2.4	3.2
Phase 2	-5.6	8.8	14.2	17.9	1.6	2.0
Phase 3	-11.1	14.1	16.6	27.4	1.2	1.9
All	-8.7	13.1	16.2	25.9	1.2	2.0

Overall, the sensitivity analysis underscores the key insight of our paper: current overlapping policies can significantly reduce the cost disparity between China's DEPS and CAT largely for the period of 2020-2035. This conclusion remains valid across a range of parameter settings, although the extent to which overlapping policies interact with China's ETS is influenced by these settings.

Appendix References

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