Synergy between Pollution and Carbon Emissions Control: Comparing China and the United States

Kyung-Min Nam[1,2], Caleb J. Waugh[*], Sergey Paltsev[*], John M. Reilly[*], and Valerie J. Karplus[*]

Abstract

In this study, we estimate potential synergy between pollution and climate control in the U.S. and China and conduct a cross-country comparison. When measured as cross-emissions elasticity, ancillary CO_2 abatement from unit % reduction of NO_x and SO_2 emissions is substantially greater in China under stringent targets, though comparable between the two countries under moderate targets. In contrast, NO_x and SO_2 abatement from unit % reduction of CO_2 emissions is much greater in the U.S. than in China, regardless of the stringency of the policy shock. These results are primarily driven by China's higher dependence on coal, as coal has larger unit emission-reduction effects than other fossil fuels and its intensive use creates more room for less costly fuel-switching and abatement options. In addition, pollution-abatement co-benefits of carbon mitigation tend to be greater than carbon-mitigation co-benefits of NO_x and SO_2 reduction in the U.S., while the opposite is the case for China. The relatively low pollution-abatement effects of carbon mitigation policy in China are primarily due to the expanded role of carbon capture and storage technology, which keeps coal from being crowded out of the energy market by reducing its carbon emission factors, but without affecting NO_x and SO_2 emissions. Our study suggests that some countries like China may consider it more appealing to pursue the synergy from a pollution-control perspective than from a carbon-mitigation standpoint, given the former's greater synergistic effects. In this sense, future co-benefit studies need to pay more attention to carbon co-benefits of pollution abatement—the opposite logic of the currently dominant focus.

Contents

1. INTRODUCTION

In this study, we explore synergistic effects of controlling emissions of nitrogen oxides (NO_x) and sulfur dioxides (SO_2) and of carbon dioxides (CO_2) in the United States and China—the world's largest carbon emitters. The primary motivation for this research comes from the fact that NO_x and SO_2, two criteria air pollutants, and CO_2, a primary greenhouse gas, are co-

[1] Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology, Cambridge, MA, USA.
[2] Corresponding author (Email: kmnam@mit.edu).

generated from combustion of fossil fuels, so their emissions are closely linked (Agee *et al*., 2012). The close link of emissions, in turn, suggests potential synergy between two different policies—pollution abatement and carbon mitigation policies (Nam *et al*., 2012). Carbon-mitigation policy can achieve a substantial reduction in NO_x and SO_2 emissions, and control of the two air pollutants may lead to a substantial cutback in carbon emissions.

In this study, we are interested in the following two questions: one is what extent of potential synergy exists between pollution and carbon policies in the two countries; the other is what strategies are needed to maximize this synergy. A substantial body of the literature has demonstrated the existence of such synergy, but for two reasons, it fails to offer complete answers. First, in many cases, a parallel comparison of national study results is not feasible. Different studies use different measures for co-benefits and focus on different production sectors. Their conclusions are also based on different methods: some use dynamic analytic tools, while others adopt static, point estimation methods. Cross-country comparison, however, is important, as the magnitude or direction of the dominant synergistic effects may differ, depending on certain country-specific conditions. The other reason is that the existing literature, leaning toward one direction of the pollution-climate interactions, provides only partial answers, at best. Fewer empirical studies explore carbon-mitigation effects of pollution abatement, compared to air-quality co-benefits of climate policy. In this study, we pay equal attention to the pollution-abatement effects of carbon-mitigation policy and the carbon-reduction effects of NO_x and SO_2 control, providing the basis for their parallel comparison in each country.

2. Synergy between Pollution Control and Climate Policy

Numerous studies explore air-quality co-benefits of climate mitigation, by recognizing that criteria air pollutants and GHGs are co-generated by fossil-fuel combustion (Smith, 2013). In most cases, ancillary benefits from GHG control are estimated to be substantially large, though central estimates from different studies show a fairly high standard deviation. For example, 10 selected national co-benefits studies, placing emphasis on health benefits from unintended air-quality improvement, present a co-benefits range of 2008 US$2-128 per ton of CO_2 emissions mitigated (Nemet *et al*., 2010). In general, co-benefits estimates for developing countries tend to be larger than those for developed countries. From the review of 37 peer-reviewed studies, for example, Nemet *et al*. (2010) draw the mean and median co-benefits of $44/t$CO_2$ and $31/t$CO_2$, respectively, for the developed world and those of $81/t$CO_2$ and $43/t$CO_2$ for developing countries. However, cross-country comparison of this kind lacks validity, as different studies use different measures of co-benefits and different methods to evaluate them by considering different sets of air pollutants and GHGs (Bollen *et al*., 2009).

Many co-benefits studies have been motivated to convince the global community that carbon emissions control is less costly than conventionally imagined. The central logic behind this argument is that GHG-reduction policy carries not only long-term benefits from mitigated climate change but also short-term benefits associated with air-quality improvement from the policy-led, reduced use of fossil energy. However, a large part of the developing world is still skeptical about potential benefits from climate control, taking a conservative attitude toward legally binding GHG mitigation targets (Bodansky, 2010). In this situation, GHG mitigation through pollution control may be more appealing to developing countries than targeting GHG mitigation directly, given that many of them confront imminent pressure to reduce local air pollution.

In contrast to air-quality mitigation co-benefit analysis, however, sparse is the literature on its reversed policy logic—carbon co-benefits from pollution control (Morgenstern *et al*., 2004; Nam *et al*., 2012; Xu and Masui, 2009). So far, we have found only six studies exploring the latter topic (**Table 1**). Three of them focus on a particular city or a sector and the others are China's national level studies without a specific sectoral focus. Despite difference in terms of focus and method, all these studies found substantial carbon-mitigation effects of pollution control, presenting the cross-emissions elasticity of 0.14-0.99. These ancillary effects beyond direct benefits from improved air quality are expected to contribute to substantial reduction of policy compliancy costs, such as the costs associated with reduced economic output or abatement technology adoption. Generalization of this finding, however, needs further empirical validation, as the size of carbon benefits depends largely on various local conditions, such as pollution levels, industrial mix, or emission intensity.

Table 1: Studies of carbon-mitigation co-benefits from pollution control.

Study	City or Country	Sectors	Pollutants	Policy Considered	Climate Co-benefits ($\%\Delta CO_2/\%\Delta$Pollution)
Morgenstern *et al*. (2004)	Taiyuan (China)	Electric	SO_2	Shut down small boilers, switch to low sulfur fuels	0.76-0.97
Xu and Masui (2009)	China	All	SO_2	Emission caps, energy efficiency, sulfur tax	0.90-0.97
Chae (2010)	Seoul (Korea)	Transportation (public buses)	NO_x, PM_{10}	Switch to low sulfur fuels	0.14-0.88
Agee *et al*. (2012)	U.S.	Electric	NO_x, SO_2	Cap and trade	n/a
Cao *et al*. (2012)	China	All	SO_2	Emission caps	0.23
Nam *et al*. (2012)	China	All	NO_x, SO_2	Emission caps	0.41-0.99

3. Current Regulations in the U.S. and China

In this section, we briefly review current NO_x, SO_2, and CO_2 regulations in the U.S. and China. Leaders in both countries recognize the cost of environmental damages, which have been estimated at around 4-7% of GDP in China (World Bank and China SEPA, 2007). In the United States the impacts of degraded air quality have been the subject of numerous studies (e.g. Chay and Greenstone, 2003).

3.1 NO_x and SO_2 Emissions Control

Both the United States and China regulate air pollutant emissions, including both NO_X and SO_2. China's first controls on air pollution were embodied in the Air Pollution Prevention and Control Law China of 1987. Since then, China has regulated air pollution as part of its comprehensive national economic planning, which is set forth and updated through Five-Year Plans. The most recent is the Twelfth Five-Year Plan (2011-2015), which separately regulates emissions from the electric power sector and mobile sources. For the electric power sector, it calls for a reduction of 8% in SO_2 and of 10% in NO_x (which was regulated under the Twelfth Five-Year Plan for the first time) (Li, 2011). Longer term, China's stated goal is for ambient air quality in all Chinese cities to attain the National Ambient Air Quality Standards (NAAQS) and similar guidelines implemented by the World Health Organization. Targets for reducing pollutant emissions include 60% for SO_2, 40% for NO_x, 50% for PM_{10}, and 40% for VOCs, relative to 2005 (Wang and Hao, 2012). Efficient and cleaner use of coal and the improvement of vehicle fuel quality are major targets of regulatory efforts. Regulators have also articulated that air quality measures should be harmonized with climate policies. Many climate policy instruments, such as a carbon tax, are considered on the basis of any "green" co-benefits (Tian, 2012).

The United States has regulated air pollution from stationary and mobile sources under the Clean Air Act, which was first passed in 1970 and last amended in 1990 (EPA, 2013). Pollution sources are required to implement Maximum Achievable Control Technologies (MACT) for each polluting activity, which are defined by the U.S. Environmental Protection Agency (EPA) and revisited every eight years. In principle, implementation of control technologies is expected to support the achievement of air quality targets, which are set forth by the EPA's National Ambient Air Quality Standards (NAAQS). These standards set acceptable limits for ambient levels of six "criteria" pollutants: carbon monoxide, lead, nitrogen dioxide, ozone, particulate matter, and sulfur dioxide, and geographies across the U.S. are classified in terms of whether they do or do not meet the standards (attainment or non-attainment areas).

3.2 CO_2 Emissions Control

In both the U.S. and China there is growing recognition of the need to control greenhouse gas emissions, although neither country has adopted controls on the absolute level of such emissions. China has currently pledged to reduce its carbon intensity by 40% in 2020, relative to its 2005 level, as part of its commitment at the Copenhagen climate negotiations in 2009 (NRDC, 2009). As part of the country's Twelfth-Five Year Plan, leaders are targeting a 17% reduction in national carbon intensity, the first explicit target assigned for carbon in national law and designed to be consistent with the country's Copenhagen commitment. In Copenhagen the United States committed to reducing carbon emission by 17% by 2020 and suggested a goal of achieving an 83% reduction by 2020, although no legislation has yet been passed into law (NRDC, 2009). Meanwhile the growing availability of inexpensive, domestically-produced natural gas has displaced coal in the power sector and led to a reduction in total U.S. CO_2 emissions in recent years (NPR, 2012; Paltsev *et al*., 2011).

4. METHOD

To explore our research questions, we have extended the fifth version of the MIT Emissions Prediction and Policy Analysis (EPPA5) model. This updated version of EPPA4, whose methodological details are well documented in Paltsev *et al*. (2005), is a recursive dynamic, multi-regional computable general equilibrium (CGE) model having 16 global regions and 14 production sectors. As the standard version of EPPA5 already includes a CO_2 abatement module, our modeling work for this study focuses on developing a comparable structure for NO_x and SO_2. Below we briefly introduce the CO_2 abatement structure of EPPA5 and the pollution abatement structure of the extended model, which is described in detail by Nam *et al*. (2012).

4.1 CO_2 Abatement Structure in EPPA5

EPPA5 supposes three primary channels of CO_2 emissions: fossil-fuel burning, cement production, and deforestation and biomass burning. Among them, CO_2 emissions from the combustion of a fossil energy (X_E) are proportional to the total amount of that energy source used for production (X_F). We consider four kinds of fossil energy—coal, crude oil, refined oil, and natural gas—and each of them has a constant CO_2 emission factor with regard to a unit of heat energy that it generates. If a CO_2 emissions cap is imposed under this structure, economic agents within the economy are incentivized to switch to less CO_2-intensive fossil energy sources or electricity (ELEC) or to substitute capital (or labor) for energy inputs—i.e., adoption of less carbon-intensive technology—in order to minimize output reduction from such a policy shock. Carbon capture and storage (CCS), which is the main carbon-abatement technology considered in the model, comes into play when increased prices of conventional energy inputs under policy constraints justify sizable capital investment for its adoption. CCS is modeled to abate not only CO_2 but also NO_x and SO_2 emissions, as implementation of standard post-combustion CCS technology with an up to 90% CO_2 capture capability requires an additional desulfurization process prior to carbon capture, which removes over 99% of NO_x and SO_2 emissions from the flue gas (Deutch and Moniz, 2007). In the case of non-fuel-related emissions—i.e., emissions from cement production, and deforestation and biomass burning—CO_2 emissions are considered as direct inputs to production, which are not substitutable. Accordingly, the lower level of CO_2 allowances under the CO_2 emissions constraint will reduce outputs from the agricultural sector (AGRI) and the cement-production sector, which is aggregated under the energy-intensive industry (EINT) in EPPA5.[3] **Figure 1** briefly illustrates the model's CO_2 emissions structure, explained above.

[3] EINT includes the sectors that produce paper products, chemical products, ferrous and non-ferrous metals, metal products, and mineral products.

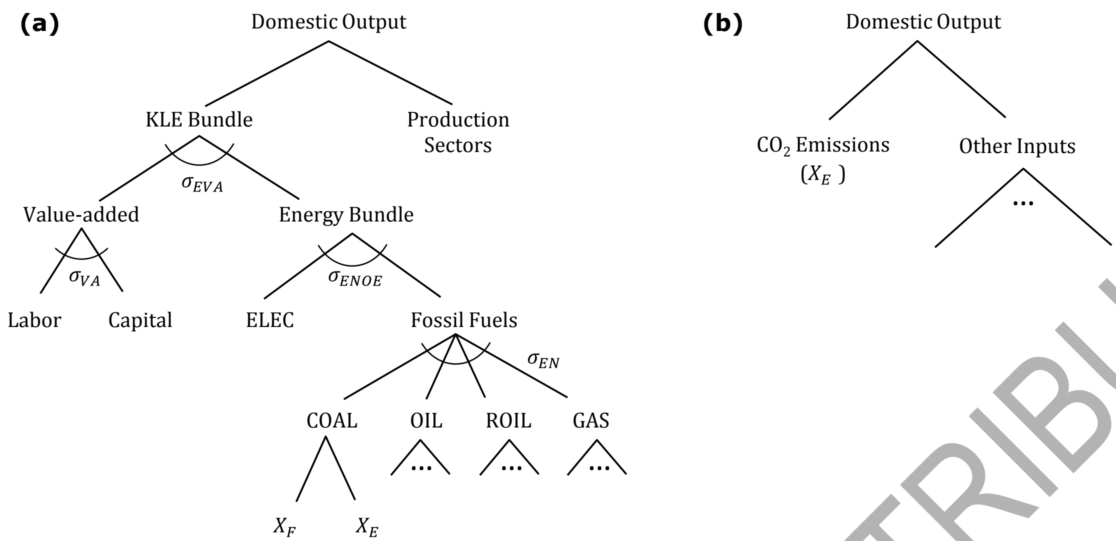

Figure 1. CO_2 emissions structure in EPPA5: **(a)** Fuel-related CO_2 emissions, **(b)** Non-fuel-related CO_2 emissions, AGRI and EINT sectors only. Source: Modified from Paltsev *et al*. (2005), p. 18.

4.2 Pollution Abatement Structure in Extended EPPA5

We consider fuel-related and non-fuel-related pollutions separately (**Figure 2**). On the one hand, each fuel bundle of the extended model has a fuel-related pollution sub-nest, so that fuel (X_F), precursor pollution (X_E), and pollution abatement (X_A) are considered as direct production inputs. Under the Leontief production structure, each sector requires X_F in a fixed proportion of its total output and each unit of X_F begets a unit of X_E. We then adopt a constant elasticity of substitution (CES) production structure with the elasticity (σ_{Fuel}) between X_E and X_A. As X_A is the capital cost of a unit of abatement, increasing X_A requires additional capital and reduces the amount of capital that can be used for other production activities. We estimate σ_{Fuel} from the technology cost and emissions data generated by the baseline scenario of the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model (Nguyen *et al*., 2011).

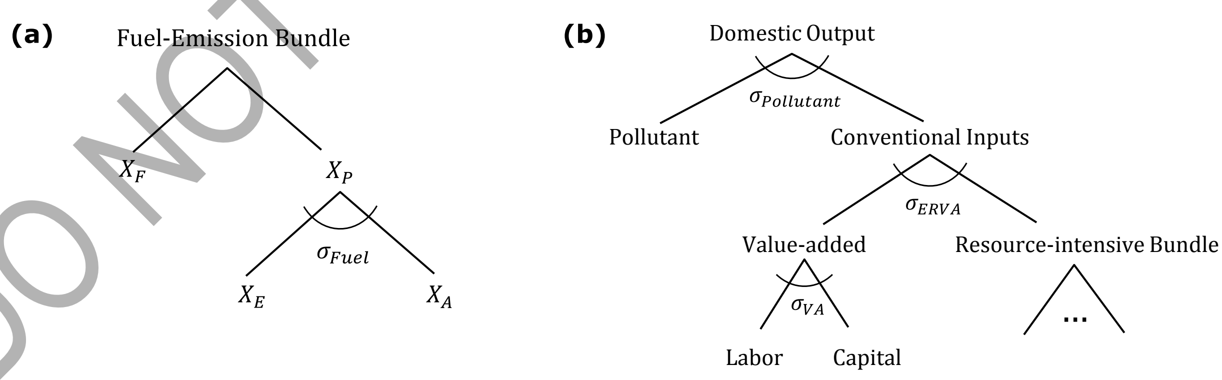

Figure 2. Pollution abatement structure: **(a)** Fuel-related pollution, **(b)** Non-fuel-related pollution. Source: Adopted from Nam *et al*. (2012), pp. 6-7.

While all pollution (X_p) will be emitted in the absence of policy, the extent to which pollution is emitted (X_E) or abated (X_A) is largely determined by the stringency of pollution control and cost of abatement, if a policy sets prices of pollution emissions. In other words, emitting under pollution control carries a cost, and its existence creates an incentive to abate until the marginal price for abating equals the marginal price for emitting. As emitting and abating become overly costly, economic agents will shift toward less pollution-intensive fuels or reduce energy consumption to meet emissions constraints.

On the other hand, non-fuel-related pollution is represented as a production input, which can be substituted by other conventional inputs, and associated pollution-abatement decisions are determined by $\sigma_{Pollutant}$. In this structure, adoption of abatement inputs results in a proportionally increased use of all other inputs, given all other prices unchanged. As NO_x and SO_2 cases are solved separately by sector and by fuel, the initial levels of pollution emissions and marginal abatement costs are unique to the fuel source, sector, and pollutant.

5. RESULTS

We simulate the model developed above by imposing a few different levels of nationwide emissions caps. Below we present our simulation results on carbon cobenefits from NO_x and SO_2 control and air-quality cobenefits from CO_2 emissions reduction, and discuss their policy implications.

5.1 Carbon Co-benefits of SO_2 and NO_x Control

For the comparative analysis of climate co-benefits, we simulate a total of five scenarios. One is a baseline scenario, which we call *REFERENCE*. In this scenario, we do not impose any further policy constraint beyond existing NO_x and SO_2 emissions regulations. The other four are policy scenarios imposing further reduction targets for NO_x and SO_2 emissions at the national level between 2015 and 2050. Each of the four scenarios ensures either 10%, 25%, 50%, or 75% reduction from the baseline NO_x and SO_2 emissions levels.

We, in particular, test these four policy targets to see how carbon-mitigation co-benefits from SO_2 and NO_x control may differ, depending on the relative stringency of policy shock. Obviously, 10% and 25% reductions represent relatively modest targets, while 50% and 75% reductions exemplify more stringent goals. We set the policy targets relative to the reference emissions levels, instead of imposing constant emissions caps, for a fair cross-country comparison. That is, fixed SO_2 and NO_x emissions caps almost always translate into more stringent policy shocks to China, leading to greater carbon co-benefits from the policy in China than in the U.S., given that future baseline SO_2 and NO_x levels grow much faster in China. We intend to avoid this situation by imposing caps relative to baseline levels.

We use cross emissions elasticity to measure "unit" carbon co-benefits from NO_x and SO_2 control. As shown in Equation 1, cross emissions elasticity ($\varepsilon_{i,j}$) is defined as % emissions change of gas *j* associated with unit % emissions change of gas *i*, where X_i^k denotes emissions of gas *i* under scenario *k*, and *REF* and *POL* mean *REFERENCE* and *POLICY* scenarios, respectively.

$$\varepsilon_{i,j} = \frac{X_j^{REF} - X_j^{POL}}{X_i^{REF} - X_i^{POL}} \cdot \frac{X_i^{REF}}{X_j^{REF}} \tag{1}$$

Our results show that unit carbon-reduction effects from NO_x and SO_2 emissions control are substantial in both countries, but are substantially greater in China than in the U.S. under relatively stringent pollution-control targets. When NO_x emissions caps are imposed without SO_2 emissions constrained, ε_{NO_x,CO_2} shows ranges of 0.12-0.67 in the U.S. and of 0.06-1.03 in China (**Table 2**). Similarly, when SO_2 emissions caps are imposed without NO_x emissions constrained, ε_{SO_2,CO_2} shows ranges of 0.11-0.54 in the U.S. and of 0.08-0.93 in China (**Table 3**). The cross-country gap in these cross-elasticities is particularly large under the 75% reduction targets, where China presents 45-69% higher ε_{NO_x,CO_2} values and 79-133% higher ε_{SO_2,CO_2} values than the U.S. As will be explained in detail, this fact is closely related to China's higher dependency on coal.

Table 2: Cross elasticity between NO_x and CO_2 ($\boldsymbol{\varepsilon}_{NO_x,CO_2}$).

	USA				China			
	10%	**25%**	**50%**	**75%**	**10%**	**25%**	**50%**	**75%**
2015	0.12	0.21	0.44	0.59	0.13	0.37	0.73	0.94
2020	0.15	0.25	0.48	0.62	0.12	0.36	0.74	0.94
2025	0.18	0.28	0.52	0.67	0.11	0.35	0.69	0.97
2030	0.19	0.30	0.61	0.61	0.10	0.33	0.64	0.98
2035	0.21	0.32	0.65	0.61	0.09	0.30	0.58	0.99
2040	0.22	0.33	0.67	0.61	0.08	0.28	0.52	1.02
2045	0.23	0.34	0.63	0.61	0.07	0.25	0.47	1.03
2050	0.23	0.34	0.60	0.61	0.06	0.22	0.42	1.03

Table 3: Cross elasticity between SO_2 and CO_2 ($\boldsymbol{\varepsilon}_{SO_2,CO_2}$) when only SO_2 emissions caps are imposed.

	USA				China			
	10%	**25%**	**50%**	**75%**	**10%**	**25%**	**50%**	**75%**
2015	0.11	0.29	0.34	0.44	0.10	0.33	0.66	0.83
2020	0.13	0.25	0.35	0.47	0.11	0.34	0.63	0.84
2025	0.15	0.33	0.35	0.47	0.11	0.35	0.60	0.87
2030	0.15	0.35	0.39	0.40	0.11	0.35	0.59	0.89
2035	0.14	0.37	0.39	0.40	0.10	0.33	0.54	0.90
2040	0.13	0.39	0.50	0.40	0.10	0.31	0.49	0.92
2045	0.12	0.33	0.48	0.40	0.09	0.28	0.45	0.93
2050	0.11	0.35	0.54	0.40	0.08	0.24	0.41	0.92

Several tendencies can be further identified from the same results. One is that ε_{NO_x,CO_2} and ε_{SO_2,CO_2} are comparable in each country, in terms of magnitude or time trend, although the former tend to be slightly higher than the latter. This is primarily because NO_x and SO_2 emissions share similar sources, such as fossil-fuel combustion or energy-intensive production. Another tendency is that in each country, unit carbon-reduction effects from pollution control are greater under more stringent pollution-control targets. This coincides with our expectation, as stringent pollution-control targets make fuel-switching or pollution-abatement options costly, increasing the need for cutting energy use. Finally, both ε_{NO_x,CO_2} and ε_{SO_2,CO_2} in China present declining tendencies over time, while those in the U.S. show increasing or constant trends. This is primarily because NO_x and SO_2 baseline emissions, which continue to grow over time in China, allow China to have more room to comply with the given policy without reducing energy use in later time periods. In contrast, NO_x and SO_2 baseline emissions in the U.S. grow only marginally over time, leading to relatively constant unit carbon-reduction effects over time.

For simplicity, we discuss the remainder of this section with the results based on ε_{POLL,CO_2}, instead of those based on ε_{NO_x,CO_2} or ε_{SO_2,CO_2}, as they are similar in terms of magnitude and time trend. ε_{POLL,CO_2}, shown in Equation 2, measures ancillary carbon-mitigation effects when NO_x and SO_2 are constrained at the same time. As illustrated in **Figure 3**, ε_{POLL,CO_2} is somewhere between ε_{NO_x,CO_2} and ε_{SO_2,CO_2}, presenting trends similar to those of the latter. China's dominance over the U.S. becomes clearer under more stringent targets, and the stringency of the policy shock is positively associated with the elasticity in each country.

$$\varepsilon_{POLL,CO_2} = \frac{X_{CO_2}^{REF} - X_{CO_2}^{POL}}{\sum_i \left(X_i^{REF} - X_i^{POL}\right)} \cdot \frac{\sum_i X_i^{REF}}{X_{CO_2}^{REF}} \tag{2}$$

where $i \in \{NO_x, SO_2\}$

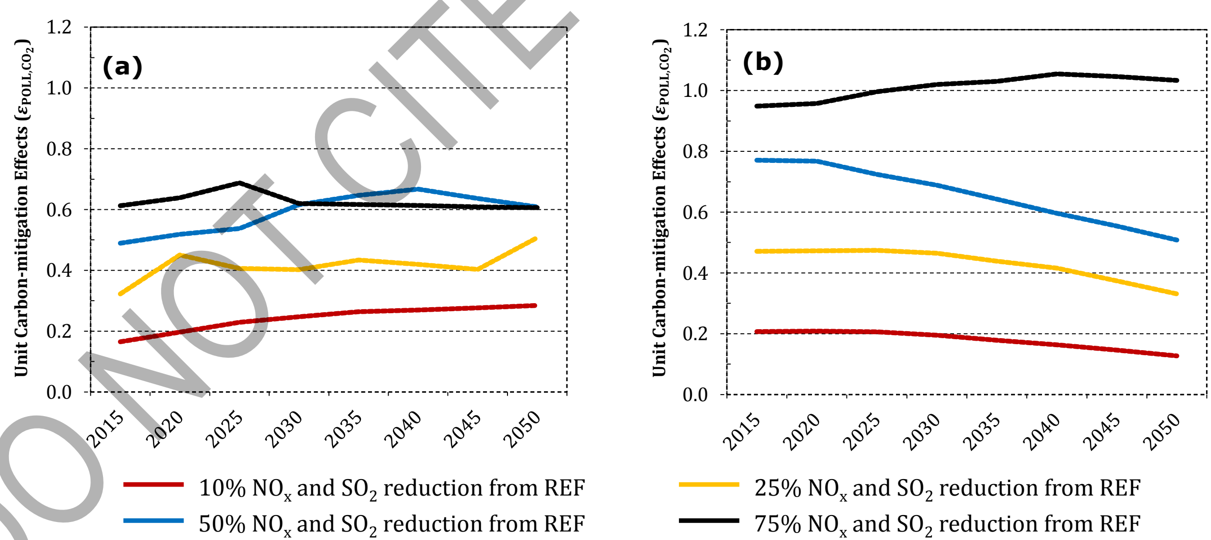

Figure 3. Cross emissions elasticity (ε_{POLL,CO_2}) by scenario: **(a)** USA, **(b)** China.

However, two aspects in the same figure may look puzzling to some readers. One of them is why in the U.S. ε_{POLL,CO_2} presents lower values under the 75% reduction targets than the 50% case in 2030 and thereafter. As hinted earlier, the answer is closely related to the changed mix of energy demand in the presence of policy shocks. Due to its high emission factors, coal is affected more greatly by NO_x and SO_2 regulations than other fossil energy sources. We see an increasing role of other energy sources in meeting the given emissions-reduction targets, as energy demand from coal converges to the minimal level that an economy can afford (**Figure 4**). Under the 75% targets, for example, the U.S. is expected to remove over 98% of its baseline coal use by 2025 and to comply with the policy by cutting an increased portion of energy demand from refined oil and natural gas since then (**Figure 5**). The reduced role of coal and the expanded role of refined oil and natural gas in policy compliance lowers unit carbon-mitigation effects from SO_2 and NO_x control, leading to a sudden decline of $\varepsilon_{\mathrm{POLL,CO_2}}$ in 2030, even below the 50% target level. The 50% $\varepsilon_{\mathrm{POLL,CO_2}}$ line for the U.S. suddenly hikes up in 2030, because a massive cut of coal use, beyond a quasi-linear reduction schedule, is achieved in the electricity sector by increased substitution of natural gas combined cycle (NGCC) for conventional coal-fired power-generation technology (**Figure 6**).

The other puzzling trend found in Figure 3 is why $\varepsilon_{\mathrm{POLL,CO_2}}$ for China presents an increasing tendency over time only under the 75% targets. This trend is related to the relative magnitude of the policy constraint imposed on each time period. Due to constantly growing baseline emission levels, China under each policy scenario tends to have increasing flexibility over time, in terms of choosing policy-compliance options beyond a cutback of energy use. Under the 10% targets, for example, avoided energy demand cut through adoption of pollution-abatement technology increases over time from 7.6 EJ in 2015 to 23.7 EJ in 2050 (Figure 4 (c)). Accordingly, China can comply with the 10% targets without increasing the absolute amount of energy demand cut in later periods. Due to this increasing flexibility, in terms of response to a given policy shock, $\varepsilon_{\mathrm{POLL,CO_2}}$ for China tends to decline over time under relatively moderate targets. However, this is not the case under the 75% targets, where China confronts increasingly strong pressure for energy demand cut over time. This is because the increased stringency of policy shock leaves China limited room for other pollution-abatement options than less use of energy (Figure 4 (d)). In contrast to the corresponding U.S. case, however, China still has capacity to cut its coal use under the 75% targets, as shown in Figure 5 (b), and thus presents an increasing trend of $\varepsilon_{\mathrm{POLL,CO_2}}$ over time.

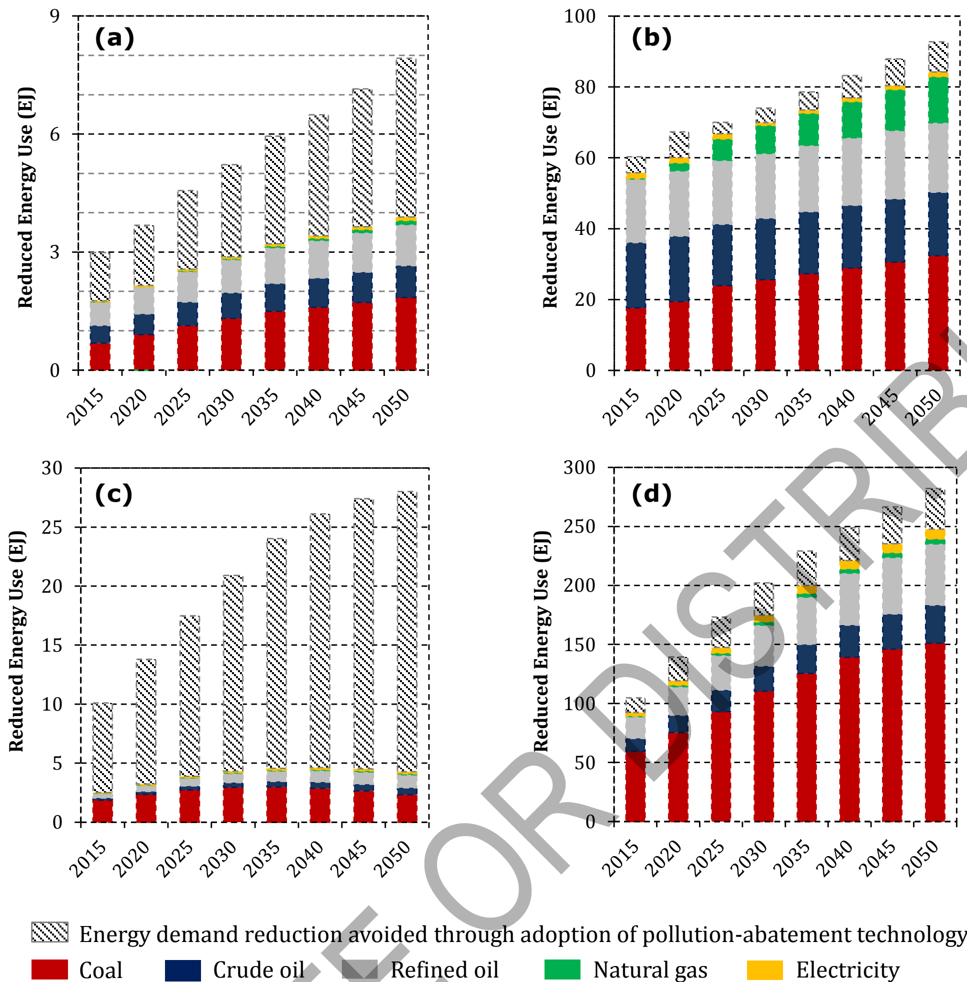

Figure 4. Reduced demand for energy inputs under selected policy scenarios: **(a)** USA: 10%, **(b)** USA: 75%, **(c)** China: 10%, **(d)** China: 75%.

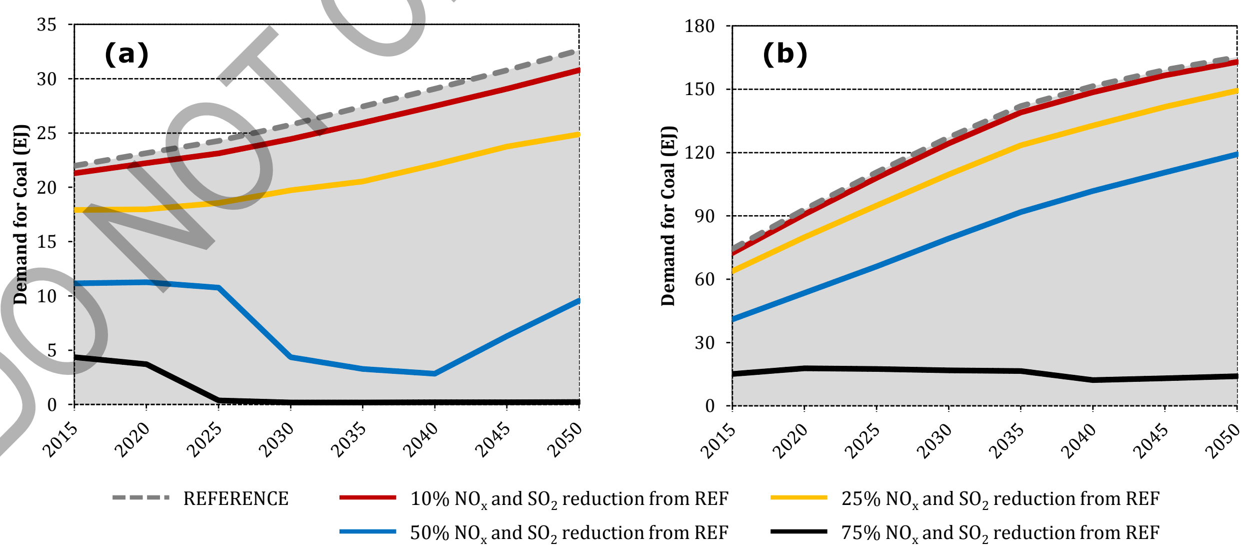

Figure 5. Demand for coal under policy scenarios: **(a)** USA, **(b)** China.

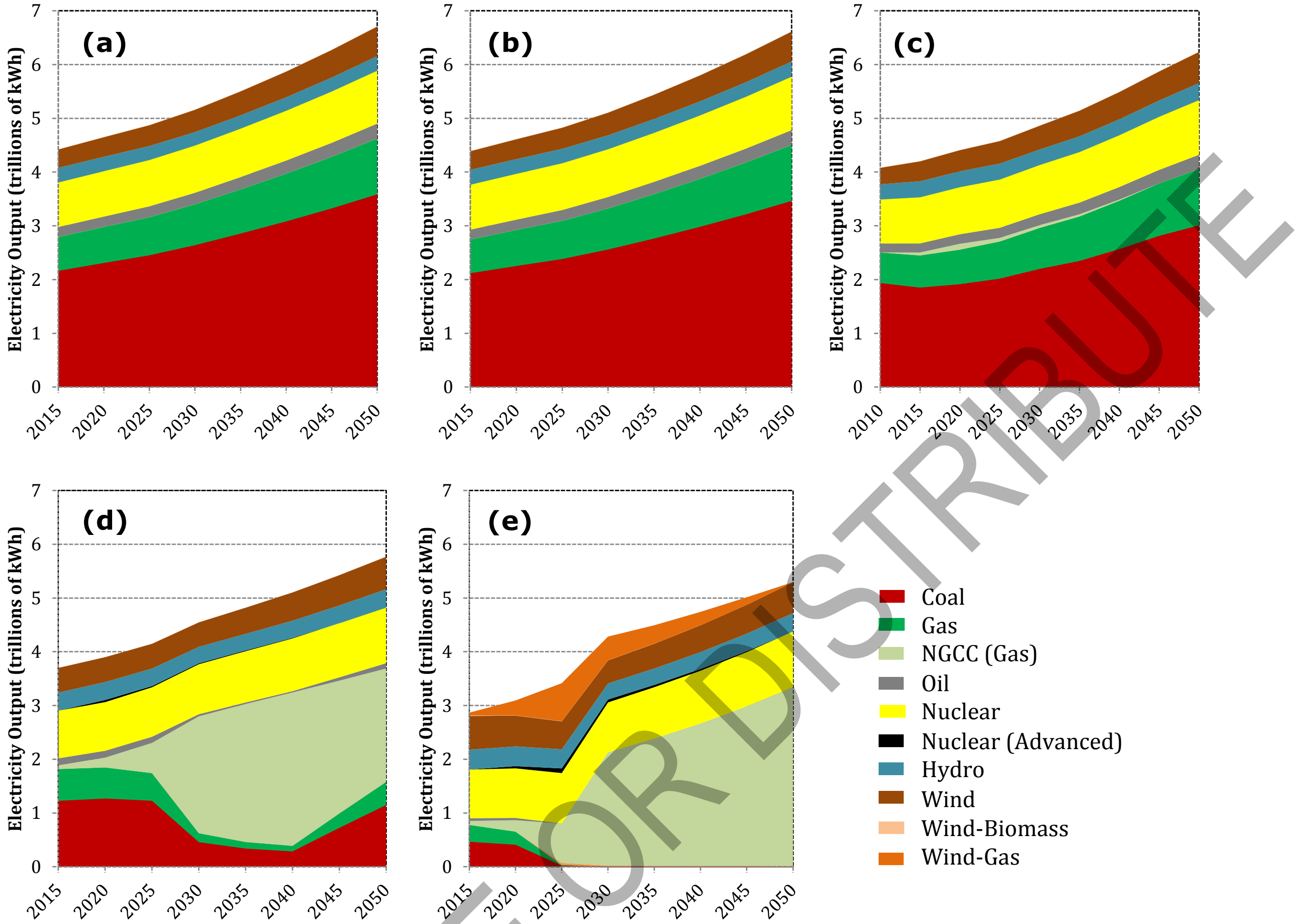

Figure 6. Electricity output mix in the U.S. under pollution-abatement policy: **(a)** REFERENCE, **(b)** 10% targets, **(c)** 25% targets, **(d)** 50% targets, **(e)** 75% targets.

In terms of total ancillary CO_2 reduction, China exhibits substantially greater carbon co-benefits from NO_x and SO_2 control (**Figure 7**). This is because the same percentage reductions from baseline levels translate into larger absolute amounts of NO_x and SO_2 reductions—and thus greater amounts of associated CO_2 reductions—in China than in the U.S. Under the 75% reduction targets, for example, the U.S. and China are expected to reduce 3.0-5.1 bmt and 6.8-18.1 bmt of CO_2 emissions in any year between 2015 and 2050, respectively. Meanwhile, the two countries show somewhat different sectoral compositions of the total emissions reductions. The U.S. economy complies with national NO_x and SO_2 caps primarily through reductions from the EINT and ELEC sectors, with the relative importance of the former in NO_x reduction and that of the latter in SO_2 reductions. On the other hand, EINT is the single dominant contributor to national NO_x and SO_2 emissions reductions in China. In both countries, however, associated CO_2 emissions are mostly from the ELEC sector.

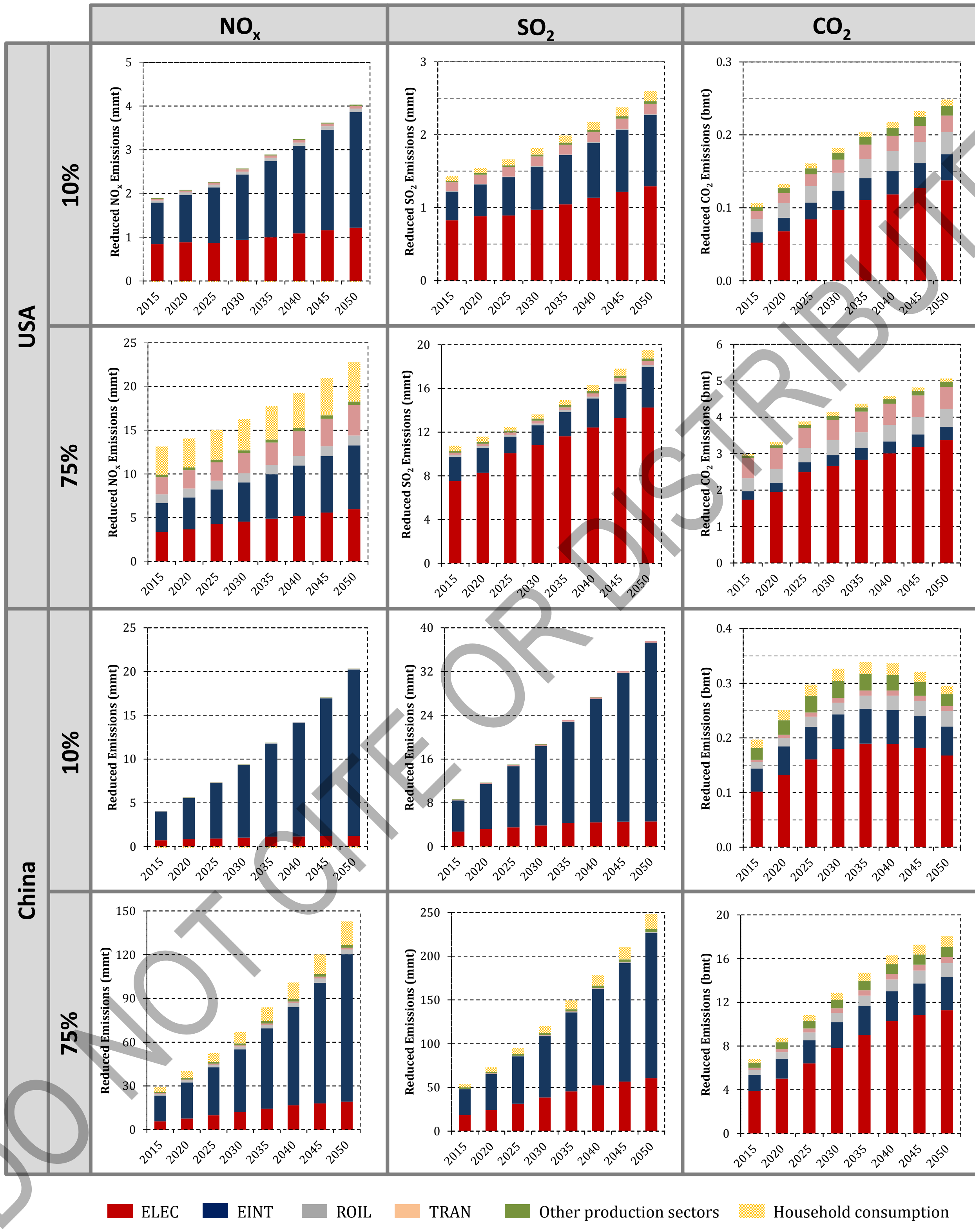

Figure 7. Reduced emissions by gas under NO_x and SO_2 control scenarios.

Policy compliance costs, measured as consumption loss, are comparable under the 10% targets but are substantially higher in China under more stringent targets (**Table 4**). For example, under the 10% reduction targets, net present value (as of 2010) of policy compliance costs for the period of 2015-2050 is $76 billion in the U.S. and $75 billion in China, presenting a marginal cross-country gap of $1 billion. But the gap increases to $5 trillion under the 75% targets, when corresponding compliance costs become $13 trillion in the U.S. and $18 trillion in China. The gap increases further if measured in relative terms. Higher policy compliance costs in China are primarily due to larger absolute amounts of emissions requirement and higher NO_x and SO_2 intensity, compared with the U.S. cases.

Table 4: Economic costs of complying NO_x and SO_2 reduction targets.

Scenario	USA		China	
	NPV* (bn 2004US$)	% of *REF*	NPV* (bn 2004US$)	% of *REF*
10% Reduction	76	0.03	75	0.09
25% Reduction	507	0.22	701	0.82
50% Reduction	2,944	1.26	5,272	6.17
75% Reduction	13,264	5.66	18,433	21.56

Note: * Net present value of consumption loss for the period of 2015-2050, evaluated in 2010 at 4% discount rate. Linearity is assumed within each five-year period.

5.2 Air Quality Co-benefits of CO_2 Control

We also run one reference and four climate policy scenarios for a cross-country comparison of ancillary NO_x and SO_2 reductions from carbon mitigation. Each policy scenario sets a national CO_2 emissions cap, which imposes either a 10%, 25%, 50%, or 75% reduction from the reference level.

When measured as cross-emissions elasticity (ε_{CO_2,NO_x} and ε_{CO_2,SO_2}), unit pollution abatement effects of carbon mitigation are substantially higher in the U.S. than in China under all policy scenarios (**Tables 5** and **6**). ε_{CO_2,NO_x} shows ranges of 0.43-0.85 for the U.S. and of 0.29-0.65 for China; ε_{CO_2,SO_2} is distributed between 0.74 and 1.30 in the U.S. and between 0.34 and 0.74 in China. This is because a policy shock of comparable stringency tends to require the U.S. to cut a relatively large amount of energy input reduction. As explained in Section 4.1, the carbon constraint in our model is met primarily through fuel switching and output reduction, although it may also trigger adoption of CCS technologies to a certain extent. Complying with a given carbon regulation through fuel switching is harder in the U.S., as the U.S. economy has already been utilizing less carbon-intensive fuels to a greater extent than the Chinese economy, even in the absence of such policy shocks. Under the 25% carbon reduction targets, for example, oil and gas account for a larger share of the total policy-driven energy demand cut in the U.S. than in China, reflecting that the U.S. economy is in general less dependent on coal than the Chinese economy (**Figure 8 (a)** and **(b)**). This low dependence on coal translates into limited room for fuel switching and increased pressure for energy demand reduction in the presence of a policy shock, asking the U.S. to cut a greater amount of energy demand, in relative terms. Under the 25% targets, for example, the U.S. is estimated to reduce 20.7-22.8% of its baseline energy use, while China is to reduce 9.3-18.7% (**Figure 9 (c)**). A greater magnitude of energy demand cut in the U.S., in turn, results in a higher unit pollution abatement effects.

Table 5: Cross elasticity between CO_2 and NO_x (ε_{CO_2,NO_x}).

	USA				China			
	10%	**25%**	**50%**	**75%**	**10%**	**25%**	**50%**	**75%**
2015	0.78	0.79	0.82	0.85	0.45	0.49	0.55	0.65
2020	0.68	0.73	0.73	0.77	0.40	0.45	0.51	0.61
2025	0.60	0.67	0.68	0.72	0.37	0.42	0.49	0.55
2030	0.54	0.61	0.70	0.68	0.35	0.39	0.47	0.53
2035	0.49	0.56	0.68	0.65	0.33	0.37	0.45	0.50
2040	0.47	0.51	0.66	0.63	0.32	0.36	0.41	0.45
2045	0.45	0.52	0.64	0.61	0.31	0.35	0.39	0.43
2050	0.43	0.48	0.61	0.60	0.29	0.33	0.37	0.41

Table 6: Cross elasticity between CO_2 and SO_2 (ε_{CO_2,SO_2}).

	USA				China			
	10%	**25%**	**50%**	**75%**	**10%**	**25%**	**50%**	**75%**
2015	1.21	1.13	1.10	1.02	0.61	0.64	0.67	0.74
2020	1.10	1.17	1.05	0.97	0.54	0.57	0.61	0.70
2025	0.99	1.12	1.15	0.95	0.48	0.53	0.58	0.65
2030	0.91	1.03	1.30	0.92	0.44	0.48	0.55	0.62
2035	0.84	0.92	1.27	0.90	0.41	0.45	0.53	0.59
2040	0.80	0.80	1.24	0.88	0.39	0.43	0.50	0.55
2045	0.77	0.87	1.21	0.86	0.37	0.42	0.49	0.52
2050	0.74	0.77	1.19	0.85	0.34	0.39	0.47	0.49

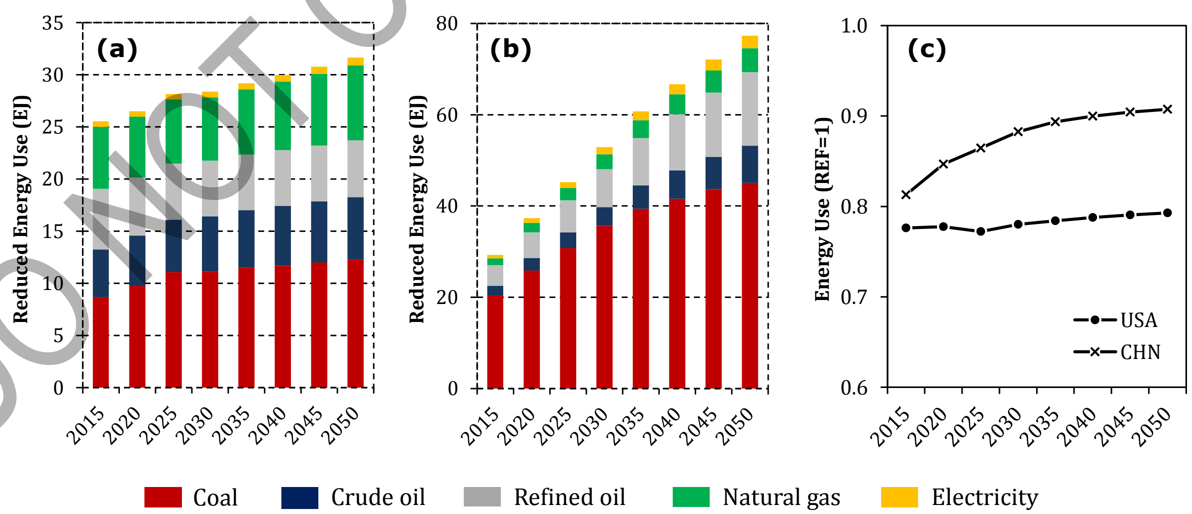

Figure 8. Reduced energy demand under 25% CO_2 reduction scenario: **(a)** USA, **(b)** China, **(c)** Energy input demand relative to baseline levels.

Another trend generalized from Tables 5 and 6 is that ε_{CO_2,NO_x} and ε_{CO_2,SO_2} tend to be higher under more stringent carbon reduction targets. This result makes sense, given that the increased stringency of a policy shock is likely to limit room for fuel switching and place a greater pressure for energy demand cut on an economy. As illustrated in **Figure 9**, however, ε_{CO_2,SO_2} for the U.S. deviates from this trend. In contrast to the case of China, where the level of ε_{CO_2,SO_2} increases according to the level of stringency of carbon reduction targets, a consistent relationship between the cross elasticity and the policy stringency does not exist for the U.S. What causes this inconsistency for the U.S. case?

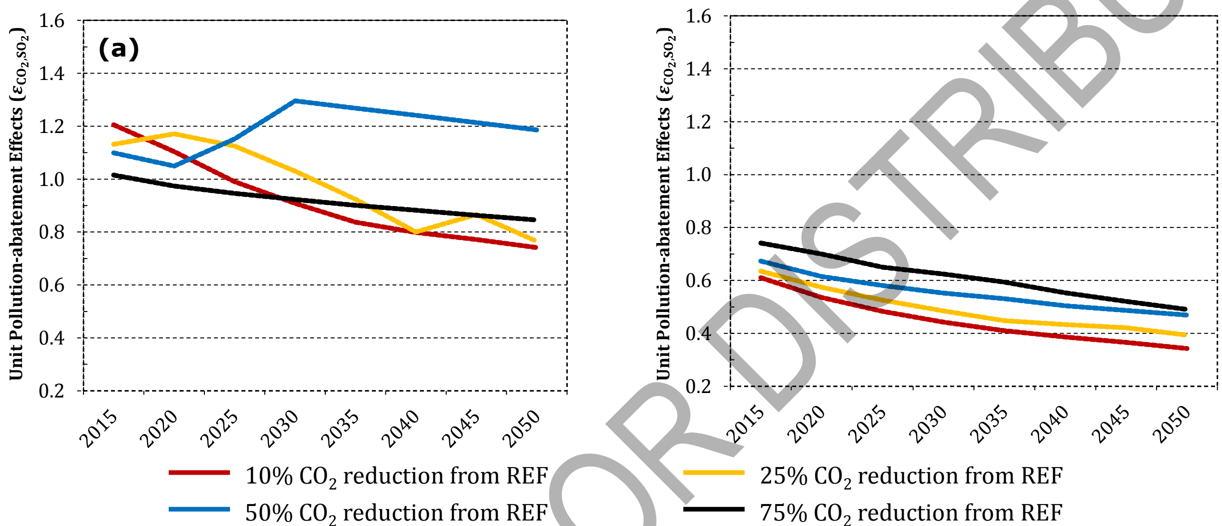

Figure 9. Cross emissions elasticity (ε_{CO_2,SO_2}) by scenario: **(a)** USA, **(b)** China. Source: graphed from Table 6.

The result is in part explained by policy-driven changes in coal demand (**Figure 10**). The U.S. ε_{CO_2,SO_2} line for the 75% target case is located below that for the 50% case because coal completely exits the market from the initial year of carbon constraint under the 75% targets, while demand for coal remains until 2025 under the 50% targets. In other words, a larger share of the total energy demand cut is from oil and gas under the 75% targets—thus, leading to relatively lower pollution-abatement effects—than under the 50% targets. In contrast, even the 75% carbon reduction policy does not drive coal completely out of China's energy market, causing less drastic changes in the trend of cross-emissions elasticities.

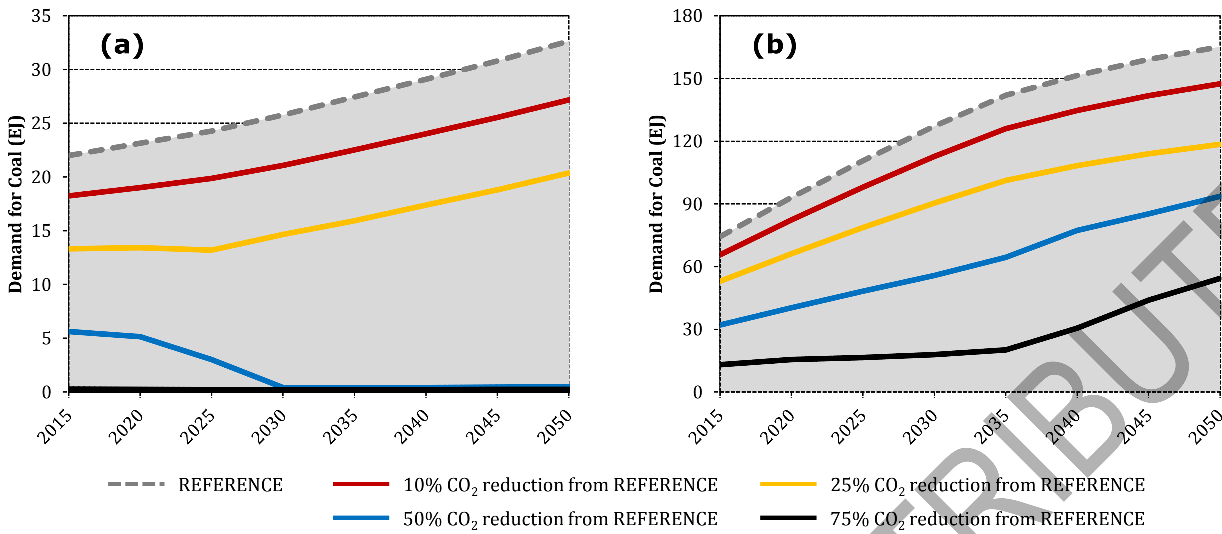

Figure 10. Reduced demand for coal-based energy: **(a)** USA, **(b)** China.

But the remaining puzzle is why part of the U.S. 75% line stays below the 10% and 25% lines in later periods. Decomposition of the electricity sector is helpful to understand why this happens, as it is the single most important production sector in complying with carbon-mitigation in both countries (**Figure 11**). First, the 10% targets are not stringent enough to incentivize adoption of low carbon technology, such as NGCC, so the targets are met primarily through fuel switching and energy demand cut (**Figure 12**). The 25% targets, however, allows NGCC to penetrate the market substantially and its substitution for coal-fired power generation technology achieves a further reduction of coal use, more than expected levels. Therefore, the 25% line tends to be located above the 10% line, in general. Under the 50% targets, NGCC and other advanced technologies, such as advanced nuclear[4] and wind power with a back-up capacity from natural gas (wind-gas), are competitive in the market and crowd out conventional coal at the pace beyond the expected level. The 50% line is above the 10% and 25% lines in later periods, as the 50 targets drive conventional coal completely out of the market in 2030 and later while the 10% and 25% targets allow gradual increase of coal use. Finally, the 75% targets completely crowd out conventional coal-fired power-generation technology from 2015, allowing expanded roles of advanced nuclear and wind-gas. But reduction of fossil energy use in the electricity alone is not enough to comply with the policy, and further energy use reduction should come from other sectors, which in general depend on coal less than the electricity sector does. As shown in Figure 11, the 75% targets in particular require increased energy demand cut from the household sector, which mainly consumes refined oil and natural gas for vehicle operations and heating. Thus, unit pollution-abatement effects are relatively low under the 75% targets, compared with other cases. However, the 75% line crosses with the 10% and 25% lines in later periods and is eventually located above them, as the latter cases allow gradual increase use of coal over time while the

[4] *Advanced nuclear* refers to generation 3+ nuclear technologies, which are based on reprocessing or breeder-type fuel cycles.

former case does not.

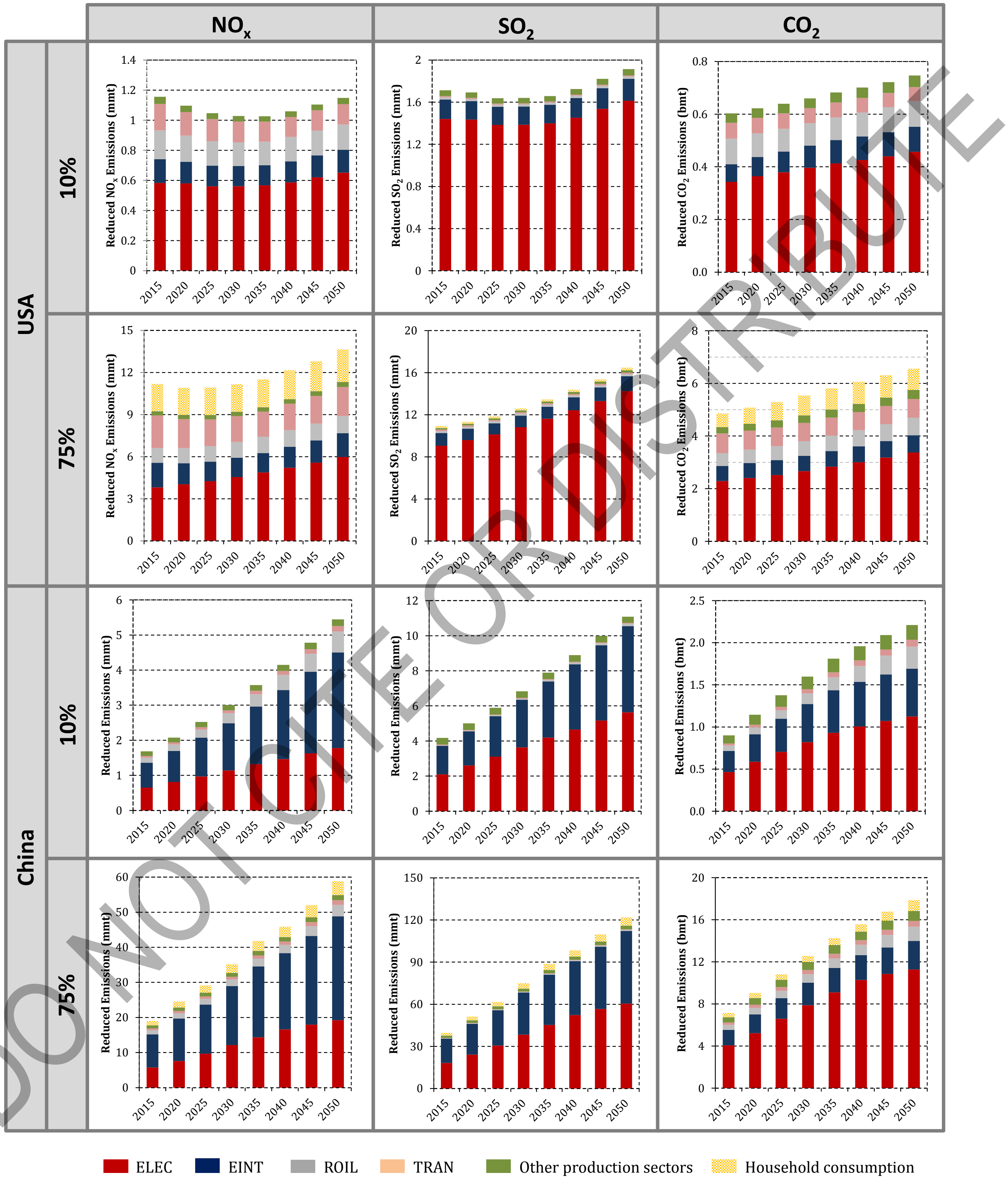

Figure 11. Reduced emissions by gas and sector under CO₂ control scenarios.

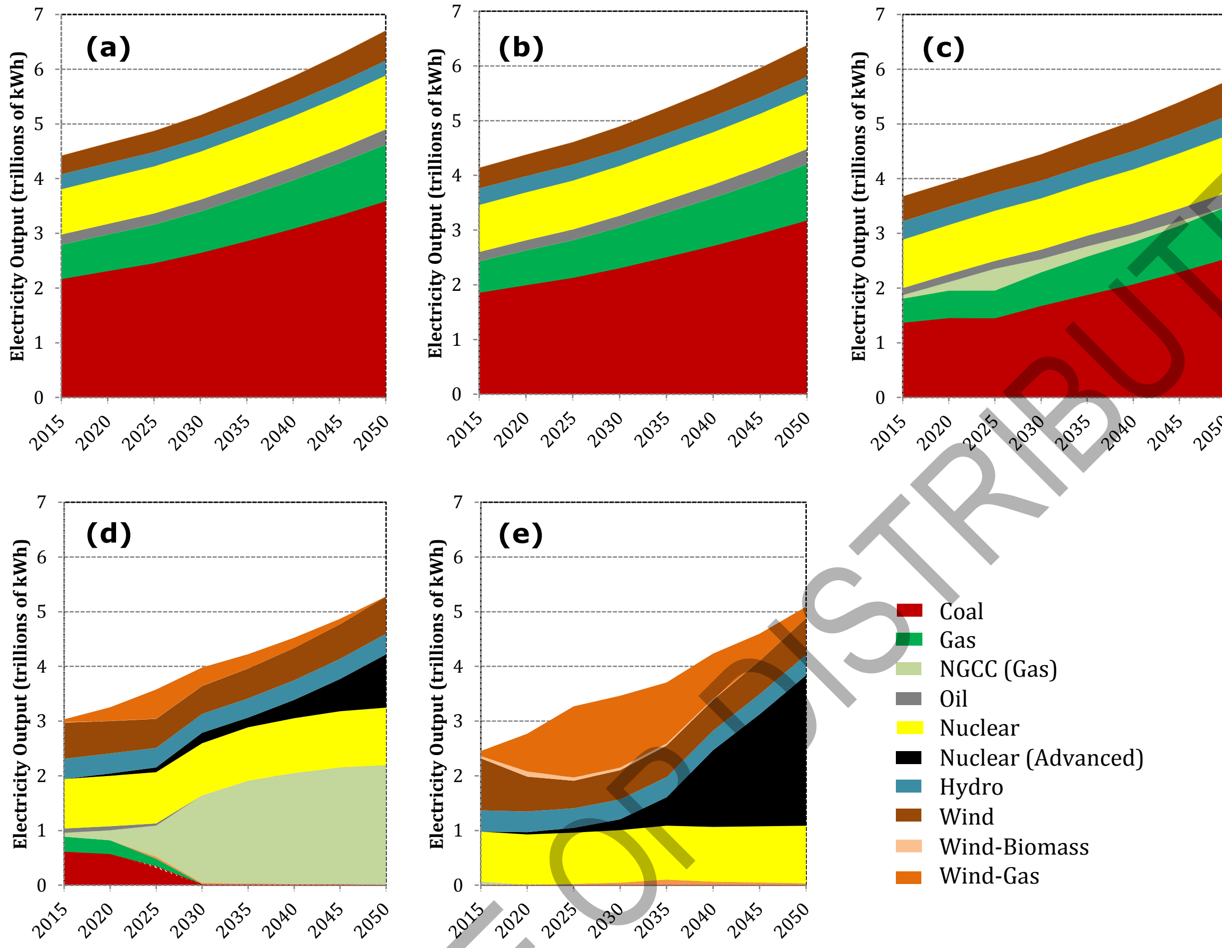

Figure 12. Electricity output mix in the U.S. under carbon-mitigation policy: **(a)** REFERENCE, **(b)** 10% targets, **(c)** 25% targets, **(d)** 50% targets, **(e)** 75% targets.

When measured in total ancillary NO_x and SO_2 reductions, air quality cobenefits from CO_2 control are substantially greater in China than in the U.S. (Figure 11). Under the 10% reduction targets, ancillary annual NO_x and SO_2 reductions are 1.2-1.4 mmt and 1.6-1.9 mmt in the U.S., respectively, and 1.8-5.6 mmt and 4.4-11.4 mmt in China. Under the 75% reduction targets, the ranges go up to 10.9-13.6 mmt and 10.9-16.5 mmt in the U.S. and 19.0-58.9 mmt and 39.7-121.8 mmt in China. The gap in terms of total ancillary pollution reduction primarily reflects China's higher and faster-growing baseline CO_2 emissions trend for future time periods, translating into a larger absolute amount of reduction CO_2 requirement for China than for the U.S. In terms of production sectors, the largest portion of the total ancillary reductions is from the ELEC sector in both countries, and the EINT is also a main contributor to the reductions in China.

Economic costs of complying with CO_2 reduction targets, measured as consumption loss, are higher in the U.S. in absolute terms, but are higher in China in relative terms (**Table 7**). When the 10-75% CO_2 reduction targets are imposed, cumulative compliance costs for the period of 2015-2050, discounted at 4%, are estimated \$225-16,767 billion in the U.S. and \$156-11,294 billion in China. On annual average, these correspond to a 0.10-7.15% loss of baseline consumption in the U.S. and a 0.18-13.21% loss in China. These results reflect the larger size of the U.S. economy and the higher carbon intensity of China's economy.

Table 7: Economic costs of complying CO_2 reduction targets.

Scenario	USA		China	
	NPV* (bn 2004US$)	% of *REF*	NPV* (bn 2004US$)	% of *REF*
10% Reduction	225	0.10	156	0.18
25% Reduction	1,176	0.50	997	1.17
50% Reduction	5,163	2.20	4,547	5.32
75% Reduction	16,767	7.15	11,294	13.21

Note: * Net present value of consumption loss for the period of 2015-2050, evaluated in 2010 at 4% discount rate. Linearity is assumed within each five-year period.

Compared with the results displayed in Table 4, policy compliance costs shown above are relatively large in the U.S. under all comparable reduction targets, suggesting that the U.S. economy has in reality sought pollution abatement more intensively than carbon mitigation. In contrast, compliance costs of meeting CO_2 targets in China are substantially lower than those of achieving comparable NO_x and SO_2 reduction targets, under relatively stringent targets, although the other way around under relatively moderate targets. Under relatively moderate targets, pollution control carries less economic cost than carbon control, as the former provides greater room for abatement technologies to play in than the latter. Under relatively stringent targets, however, the opposite is the case, as stringent pollution control increasingly drives up the costs of adopting pollution-abatement technologies and increases the pressure for cutting energy demand, while stringent carbon control increasingly justifies the adoption of CCS technologies and provides China more options to comply with the policy shock. In particular, even the 75% carbon-mitigation targets may allow China to keep using coal, combined with CCS technology, while pollution-abatement targets of comparable stringency are likely to completely crowd coal out of the electricity market (**Figure 13**). This relative role of coal partly explains why pollution-abatement targets may generate a more drastic policy shock to the Chinese economy than carbon-mitigation targets.

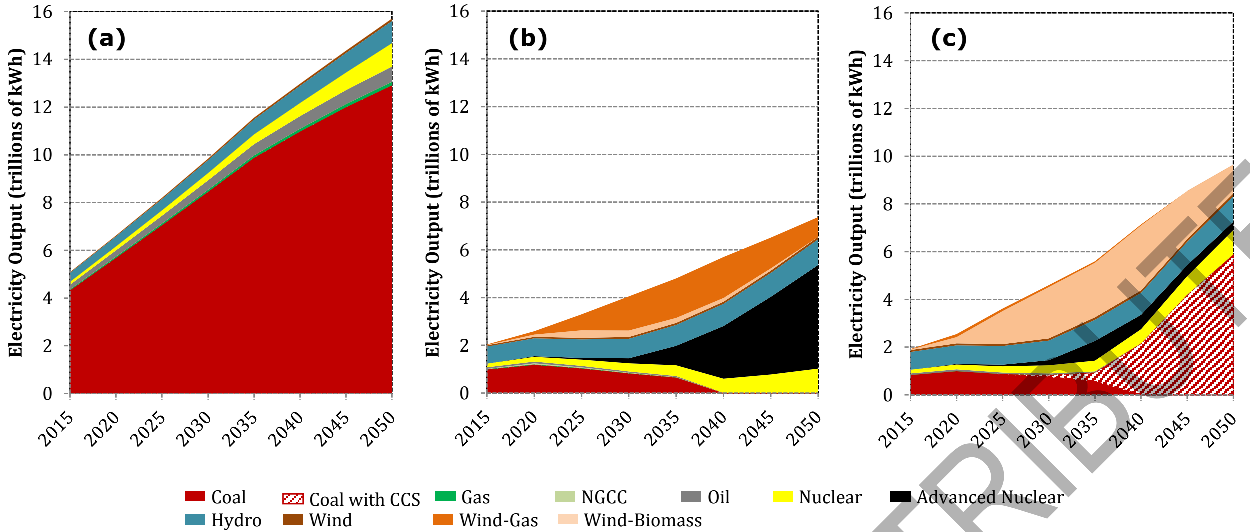

Figure 13. Electricity output mix in China under policy scenarios: **(a)** REFERENCE, **(b)** 75% NO_x and SO_2 reduction targets, **(c)** 75% CO_2 reduction targets.

6. CONCLUSIONS

In this study, we first introduce an analytic framework for pollution-climate control synergy and then apply the methodology to the U.S. and China. Primary contributions of this study to the literature and the policy debate include—but are not limited to—the following three aspects. First, our analysis is based on a new methodological approach, which endogenizes pollution emissions-abatement decisions within a CGE structure, incorporating bottom-up engineering details. This is a substantial improvement on conventional methods assuming fixed emission factors or exogenous abatement opportunities. Second, our study enriches the literature on carbon co-benefits of pollution abatement, which is sparse despite growing attention to the topic. Finally, we offer two sets of comparative analyses within the same framework, conveying significant policy implications. A cross-country comparison of the U.S. and China, the world's two largest GHG emitters, is one of them, and a parallel comparison of the carbon cobenefits of local pollution control and the air quality co-benefits of CO_2 abatement is the other.

Our results only partially support the conventional view that pollution-climate control synergy is greater in developing countries than in developed nations. Under relatively stringent targets that we tested, carbon mitigation effects per unit % abatement of NO_x and SO_2 emissions are larger in China than in the U.S. In reality, carbon co-benefits measured as cross emissions elasticity may be even greater than our estimates, given that these stringent targets are substantially moderate compared with China's recently announced NO_x and SO_2 reduction targets. In contrast, pollution abatement effects with regard to unit % CO_2 reduction are much greater in the U.S. than in China. This finding conflicts with the conclusions from most of the existing studies measuring the air quality co-benefits in dollar terms, such as $/tCO_2$. As explained earlier, these results are closely related to China's high dependence on coal, which has greater pollution and carbon emissions factors than other fossil fuels.

In addition, pollution-abatement co-benefits of carbon mitigation tend to be greater than carbon-mitigation co-benefits of NO_x and SO_2 reduction in the U.S., while the opposite is the case for China. This result suggests that the U.S. economy has more room for further improvement in terms of carbon intensity than of pollution intensity, while the Chinese economy is relatively pollution-intensive. But higher cross-emissions elasticities are associated with greater economic costs. Complying with pollution-abatement targets are relatively more costly in China than complying with carbon-mitigation targets of comparable stringency, while the opposite is the case for the U.S.

One thing to be noted is the potential nonlinearity underlying the relationship between policy stringency and unit synergistic effects from the policy. In general, increased stringency of pollution or carbon control targets tends to raise unit synergistic effects of the policies. The Chinese case coincides with this tendency, but the U.S. case does not always do, due to an expanded role of advanced technology. This result demonstrates that market responses to policy may vary, depending on socioeconomic conditions that each country confronts, and linearity between policy stringency and associated unit synergistic effects should not be assumed. Accordingly, raising policy effectiveness needs a careful analysis of potential pollutant-carbon emissions interactions before policy implementation.

The final key message from this study is that carbon-mitigation co-benefits of pollution-abatement policy need to receive more attention than they do now, so that the co-benefit analysis literature can keep increased balance between pollution- and climate-centered perspectives. As discussed throughout, local pollution abatement not only takes China's policy priority over carbon mitigation but is also likely to produce unit synergistic effects substantially greater than those expected from carbon-mitigation policy of comparable stringency. Given strong pressure for pollution-abatement actions and their great carbon-mitigation potential, placing emphasis on local pollution control over carbon-mitigation policy in co-benefit analysis, which is very rare by now, may be more appealing to some countries like China than the opposite case. Accordingly, this increased balance of study may also incentivize a large portion of the developing world to step forward to be part of the global effort to mitigate climate change.

Acknowledgments

The authors are grateful to Howard Herzog and Henry Chen for their valuable inputs for this study. We acknowledge the support of ENI, ICF, and Shell, initial Founding Sponsors of the China Climate and Energy Project, for this application of the EPPA model, and BP's support of Waugh's thesis, which provided the foundation work for representing air pollution control in the EPPA model. We also acknowledge general industrial and government sponsors of the Joint Program on the Science and Policy of Global Change (http://globalchange.mit.edu/sponsors/all) through which we have developed and maintain the EPPA modeling framework.

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