A Global Perspective on Coal-Fired Power Plants, Climate Change and Disease Burden

A GLOBAL PERSPECTIVE ON COAL-FIRED POWER PLANTS, CLIMATE CHANGE AND DISEASE BURDEN

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Abstract

This dissertation investigates the disease burden from coal-fired power plants from global perspective. First, the study estimated changes in national lung cancer incidence decades after building or closing coal-fired power plants. The study secondly estimated the relative risks and incident cases of cardiovascular diseases (CVD), particularly ischemic heart disease (IHD), attributable to sulfate oxide (SO_x) emission from coal-fired power plants from a global perspective. Since China is one of the most greenhouse gas (GHG) emitting country, we proposed “flying S” pattern to examine and forecast carbon dioxide (CO_2) emission in the next decades.

For the chapter one, standardized lung cancer incidence from every country with electrical plants using coal as primary energy supply were followed from 2000 to 2016. We applied a Poisson regression longitudinal model to estimate the association between lung cancer incidence and per capita coal capacity. We fund that with 1 kilowatts (KW) increase of coal capacity per person in a country, the relative risk of lung cancer increase by a factor of 85.1% (95%CI=1.217~2.816) among males and 58.5% (95%CI=1.070~2.347) among females. Based on the model, we estimate a total of 1.41 million standardized incident cases from lung cancer were associated with coal-fired power plants in 2015.

Chapter two analyzed the relative risk of CVD incidence associated with national SO_x reduction for 13,581 coal-fired power-generating units in 79 countries. A 10% decrease in SO_x

emission was associated with 0.28% (males; 95%CI=-0.39%~0.95%) and 1.69% (females; 95%CI=0.99%~2.38%) lower CVD risk. The effects on IHD were >2 times stronger among males than females (2.78%, 95%CI=1.99%~3.57% vs. 1.18%, 95%CI=0.19%~2.17%). Further, 1.43% (males) and 8.00% (females) of CVD cases were attributable to suboptimal SOx reduction. Thus, enhancing regulations on SO_x emission control represents a target for national and international intervention to prevent CVD.

In chapter three, we applied mixed effect model to examine the ex post data and predict per capita emission for selected countries in the same flying geese (FG) group in Asia. The "flying S" hypothesis says the trajectories of per capita CO_2 emission would just mirror each other for countries within a same FG and having relatively constant energy matrix across time, *ceteris paribus*.

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Introduction

Climate change is one of the most important environmental issues globally. Overwhelming majority of countries has devoted great efforts to curb greenhouse gas (GHG) but still way beyond being called effective. The impacts of climate change are wide but understudied. Coal-fired power plants, is one of the most important contributor of both GHG emission and $PM_{2.5}$ emission. As many scholars believed health is a crucial driver for climate policy, and frame the problem as shutting down coal-fired power plants provides "co-benefit" of health outcomes from carbon dioxide (CO_2) emission control.

From disease-specific angle of point, some non-communicable diseases are strongly associated to $PM_{2.5}$, such as lung cancer, and/or cardiovascular diseases. However, the diseases burden specifically associated with coal-fired power plant from global scale remains unknown. Chapter 1 investigates coal-fired power plants and burden of lung cancer and chapter 2 discusses sulfur oxide controls in coal-fired power plants and CVD.

China, as the top CO_2 emitting country, contributed almost 30% CO_2 emission globally. China set up its Intergovernmental Panel on Climate Change (IPCC) goal that its emission will peak before 2030 and its energy intensity (CO_2/GDP) will be 60% of 2015 level. Chapter 3 proposes a novel "flying S" hypothesis and forecast China's CO_2 emission up to 2050 by examining the ex post data.

The dissertation aims to provide scientific evidences of "co-benefit" of health outcomes by controlling the most important CO_2 emitting contributor from global perspective. We further turn the scope to East Asia and focus on newly developing countries as they are top GHG emitting countries recently. With such strong evidence provided in the dissertation, we offer a clear scientific data to support public health implication of changing climate. International bodies should take immediate steps to curb GHG emission globally.

Chapter 1. A Global Perspective on Coal-fired Power Plants and Burden of Lung Cancer

1.1 Introduction

Coal-fired power plants are the dominant source of energy production, yielding >40% of global electrical power since the 1970s (International Energy Agency 2017). Indeed, global production of coal increased nearly 2.2-fold from 1,958 million tons of oil equivalent (Mtoe) in 1980 to 4,270 Mtoe in 2010 (International Energy Agency 2017). However, air pollutants emitted from coal power plants and their potential impact on population health have aroused widespread concerns; fine particulate matter ($PM_{2.5}$) can cause both short-term and long-term adverse health outcomes (Cui et al. 2015; Dockery et al. 1993). Long-term exposure to $PM_{2.5}$ is associated with shorter life expectancy and higher mortality risks from lung cancer-related cardiopulmonary diseases (Miller et al. 2007; Pope et al. 2002; Pope et al. 2009). In fact, the International Agency for Research on Cancer (IARC) has listed several coal-fired power plant-related agents, including coal combustion, coal production, outdoor air pollution, and radon, as human carcinogens(International Agency for Research on Cancer (IARC) 2016). While lung cancer is prevalent, the proportion of cases attributed to environmental factors such as air pollution varies by country and is difficult to estimate(Global Burden of Disease Collaborative Network 2016). Nonetheless, improved air quality has been correlated to better health(Jerrett et al. 2005), prompting many countries to implement regulations on air pollution(US supreme Court 2001).

Most available estimates of health risk associated with electricity generation are oversimplified since they are calculated by multiplying a factor to air pollution levels (either $PM_{2.5}$ or PM_{10}) without considering the heterogeneous compositions of particles from different sources(Markandya and Wilkinson 2007; Padula et al. 2012; Sarah Penney 2009). Moreover, lower global levels of $PM_{2.5}$ are not necessarily associated with reduced adverse health effects, likely due to regional variations in composition (Harrison and Yin 2000; William M. Hodan). For example, satellite-driven $PM_{2.5}$ measurement showed a high level of air pollution concentrated in sub-Saharan Africa(National Aeronautics and Space Administration 2010). Yet, a major component of that PM was dust from the earth's crust rather than from human activities. Therefore, simply using PM to estimate health effects may result in misguided conclusions.

To clarify the long-term health effects from coal-fired power plants at the national level, and linking the capacity market in energy economic to health externality, we aim to estimate changes in national lung cancer incidence decades after building or closing coal-fired power plants.

1.2 Methods

1.2.1 Study period and design

Annual lung cancer incidence rates from 2000 to 2016 among males and females from countries which have had coal-fired power plants were included in the analyses. Most countries in the study are located in Europe (38.55%) and Asia (27.71%) (Supplementary Table 1). Country names and geographical categories reflect the United Nations' country classification(United Nations Statistics Division).

1.2.2 Dependent variables & independent variables

Annual lung cancer incidence rates were obtained from Global Burden of Disease Study(Global Burden of Disease Collaborative Network 2016). Lung cancer codes were B101 or 162 in International Classification of Diseases version 9 (ICD-9); C028, 162, 231.1, or 231.2 in ICD-9C; and 1034, C33, or C34 in ICD-10. Calculated age-adjusted incidence rates were based on the WHO 2000–2025 standard population for each country(Omar B. Ahmad 2001). We use "independent variables" and "covariates" interchangeably throughout.

Electrical capacity of power plants that primarily relied on coal as generating fuel was the study of interest. *Coal capacity* was defined as the annual accumulation of generating capacity from every coal-fired power plant in a given country. Similarly, we define *plant capacity* as the accumulation of total generating capacity from all power plants in a country. *Non-coal capacity* was plant capacity minus coal capacity. *Coal percentage* was defined as the ratio of coal capacity to plant capacity for each country. *Per capita coal capacity* is the coal capacity divided by total population in the corresponding country. Total coal consumption is the annual coal usage in all sectors (including electricity, industrial and residential use, units in Quadrillion Btu) in a given country(US Energy Information Administration 2015). Capacity data was derived from the Utility Data Institute World Electric Power Plants Data Base (UDI World Electric Power Plants Database (WEPP) 2016); we merged the WEPP database with incidence data by country and year. After matching, a total of 83 countries were included in the study.

We collected data on covariates of smoking prevalence, economic indexes, industrial indexes, and traffic indexes for each country. Annual smoking prevalence within each country was estimated, sex- and age-adjusted (Ng et al. 2014). Per capita gross domestic product adjusted for purchasing power parity [GDP(PPP)] and inflation to base year 2011 USD was used to capture the country's standard of living and healthcare level (The World Bank 2016). The indicator of CO_2 emissions only from manufacturing industries and construction (% of total fuel combustion) was used to characterize industrialization(The World Bank 2016). Traffic index, or the level of urbanization, measured as the proportion of a country's population living in urban areas, was applied to capture air pollutants emitted from all mechanical vehicles and public transports (The World Bank 2016). The missing data in North Korea and Taiwan were obtained from supplementary sources(Groningen Growth and Development Centre Faculty of Economics and Business 2016; National Statistics Taiwan 2016).

1.2.3 Data analysis

The longitudinal model for which we predict lung cancer incidence is the following Poisson regression:

$$\begin{aligned}\log E[\lambda_{it}|\boldsymbol{X}_{it}] = \beta_0 + {} & \beta_1[\text{Per capita Coal Capacity}]_{i(t-T)} + \beta_2[\text{Smoking Prevalence}]_{i(t-10)} \\ & +\beta_3[\text{Non Coal Capacity}]_{i(t-10)} + \beta_4[\text{Traffic Index}]_{i(t-10)} \\ & +\beta_5[\text{Industrialization Index}]_{i(t-10)} + \beta_6[\text{Per capita GDP (PPP)}]_{it} \\ & +\beta_7[\text{Total Coal Cunsumption}]_{i(t-10)}\end{aligned}$$

where index i denotes the country, t denotes the year, and T is the believed lag of per capita coal capacity before affecting the current lung cancer incidence rate λ_{it}. For completeness, we consider three lags at $T = 5, 10, 15$ years for coal capacity and assume an adequate lag of 10 year for smoking(Ezzati and Lopez 2003) and other covariates, except for per capita GDP.

The model stated above is a marginal model; specifically, we are not concerned with how the effect varies across individual countries, but rather with the “overall” effect averaged over all countries. We must, however, account for this within-country variation across the years, for which generalized estimating equations (GEE)(Zeger 1986) is perfectly suited to handle. GEE’s strengths lie in its semiparametric properties; it produces unbiased estimates for the beta coefficients, regardless of the within-country correlation structure specified, although a specification closer to the truth leads to lower standard errors.

The GEE fit was performed using the geepack package within R version 3.2.5 to estimate the effect of the selected covariates on standardized lung cancer incidence. We use an independence correlation structure, and fit for males and females separately, each weighted by the corresponding male and female populations. Figures were also drawn in R version 3.2.5.

1.2.4 Falsification test

To investigate the possibility that general health improvements correlated with coal capacity may obscure our lung-cancer results, we identify colorectal and anal cancer (CRC) as falsification outcomes (possible markers for general cancer trends that are not expected to be correlated with air pollution). CRC was coded as B093, B094, 153 or 154 in ICD-9; and C18, C19, C20, C21, and 1030 in ICD-10(Global Burden of Disease Collaborative Network 2016). We applied the same models to CRC to examine any association with coal capacity.

1.2.5 Burden of diseases analysis

We estimate the population attributable factor (PAF) of lung cancer to coal-fired power plants in 2015 and predict the PAF in 2025 among studied countries. The PAF is the proportion of lung cancer incidence attributable to anthropogenic coal capacity. Detailed step-by-step calculations are summarized in the GBD study(Global Burden of Disease Collaborative Network 2016) and our previous work(Lee et al. 2016). Briefly, to calculate PAF_{it}, the PAF for country i in year t, we need the quantity RR_{it}, the relative risk of lung cancer incidence given coal capacity at year $t-10$, holding all other covariates, including smoking, fixed. This can be deduced immediately from our data analysis portion using the relationship

$$RR_{it} = RR_0^{\text{Per capita coal capacity}_{\text{i(t−10)}}}$$

$$PAF_{it} = \frac{P_{it-10} \times (RR_{it} - 1)}{1 + P_{it-10} \times (RR_{it} - 1)}$$

where RR_0 is the relative risk for every KW/capita unit increase in lag 10 coal capacity (1.585 for males, 1.851 for females) as we obtained from the 10 year-lag model (Table 2). P_{it-10} is the proportion of males or females. PAF_{it} is useful, because we can then calculate the standardized attributable cases:

$$\text{Standardized attributable cases}_{it} = \text{PAF}_{it} \times \text{Population}_{it} \times \text{standardized incidence rate}_{it}$$

Supplementary Table 3 shows the PAFs in 2015 and 2025 and the standardized attributable cases for countries using coal as power generation in 2015.

1.3 Results

Coal capacities were calculated from a total of 13,581 generating units among 83 countries. All countries has complete 17-year follow-up data from 2000 to 2016. Coal capacities in four time points (years 2000, 2005, 2010, 2015) are mapped in Figure 1. Coal capacity varied widely both within and between countries across time. Supplementary Figure 1.1 shows coal capacity, plant capacity, coal percentage and total coal consumption of the top 5 countries with the highest levels of coal capacity in the world: China, Germany, Russia, the United Kingdom (UK), and the United States (US). Coal capacity in China has been more than the sum of the other four countries over many years, reaching 434.87GW after 2006. China caught up to the US in terms of plant capacity after 2013. Also, coal percentages in China (65%~75%) was significantly higher than the other four countries, which reflects the fundamental difference of energy matrices in different countries.

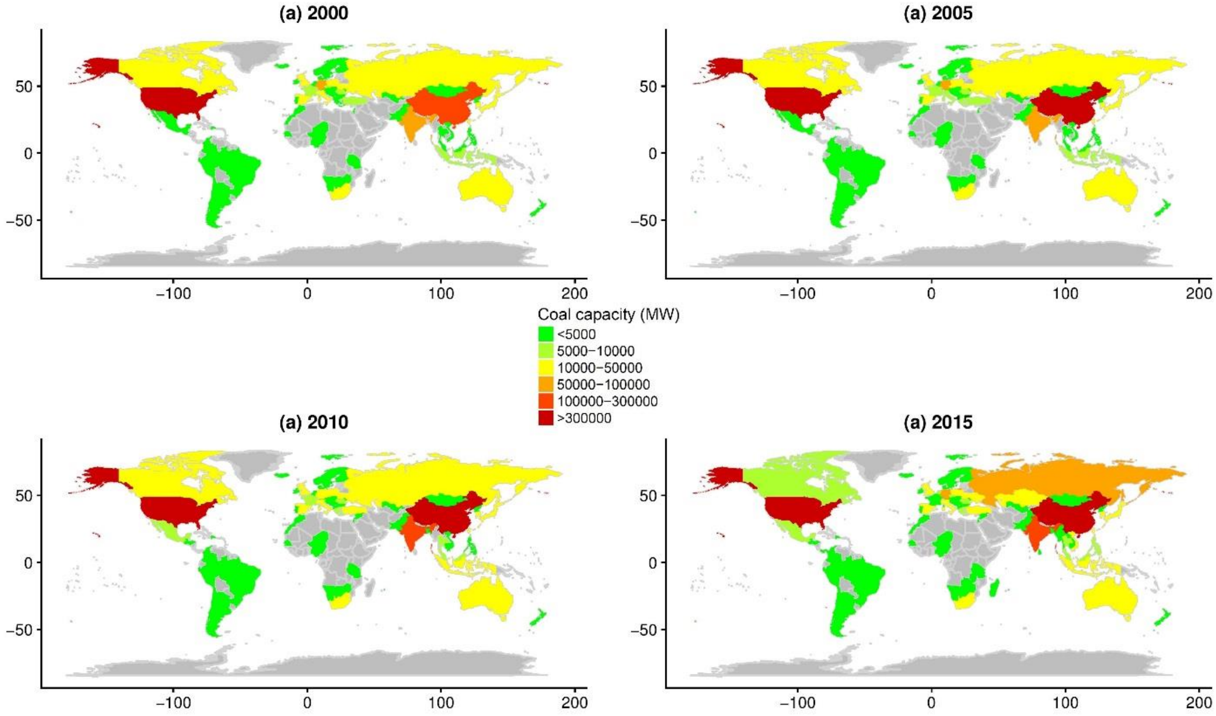

Figure 1.1 National coal capacity* in 2000, 2005, 2010 and 2015

Table 1 displays the mean and 95% confidence intervals (CIs) of all covariates during the three periods of 2000~2004, 2005~2009 and 2010~2016; note that these estimates are averaged over countries and time. From the first period to the last, average age-standardized incidence rates from lung cancer decreased by 45.68 per hundred thousand (10.06%) in males but increased by 11.36 per hundred thousand (7.92%) in females. Coal capacity increased by 1.43 times from 15.99 GW to 22.82 GW. Smoking prevalence decreased by 9.31% in males and 10.74% in females, respectively.

Table 1.1 Basic characteristics of analyzed countries across years

Year	2000~2004		2005~2010		2011~2016	
	Mean	(95%CI)	Mean	(95%CI)	Mean	(95%CI)
Lung cancer incidence [a]						
Males	454.07	(428.81~479.34)	434.87	(410.95~458.78)	408.39	(389.82~426.95)
Females	143.50	(133.16~153.83)	151.10	(140.06~162.13)	154.86	(145.37~164.35)
Coal capacity [b]	15987.86	(10836.73~21138.99)	19331.72	(12134.39~26529.05)	22821.17	(14725.02~30917.31)
Smoking prevalence [c]						
Males	32.23	(31.16~33.3)	30.09	(29.02~31.15)	29.23	(27.87~30.58)
Females	13.13	(12.17~14.1)	12.33	(11.4~13.26)	11.72	(10.57~12.87)
Traffic index [c]	27.76	(26.3~29.23)	28.32	(26.96~29.69)	29.91	(28.47~31.36)
Industrialization index [c]	17.65	(16.77~18.54)	17.23	(16.34~18.13)	16.39	(15.51~17.28)
GDP (PPP) [d]	742.85	(573.38~912.31)	910.6	(705.71~1115.49)	1113.37	(891.63~1335.1)
Total coal consumption [e]	1.24	(0.82~1.66)	1.53	(0.93~2.14)	1.75	(0.77~2.73)
Population [f]						
Males	326.71	(235.21~418.21)	345.06	(248.65~441.46)	367.16	(281.07~453.26)
Females	321.77	(235.49~408.05)	339.36	(248.68~430.03)	360.74	(279.91~441.57)

95%CI: 95% confidence interval; GDP (PPP): gross domestic product adjusted by (Purchasing Power Parity)

[a] Unit: case per hundred thousands

[b] Unit: megawatts (MW)

[c] Unit: %

[d] Unit: Billion 2011 USD

[e] Unit: Quadrillion British Thermal Unit (QBtu)

[f] Unit: hundred thousands

Figures 2 (males) and Figure 3 (females) show the relationship between 10-year-lag log coal capacity and log incidence rates of lung cancer in 2000, 2005, 2010 and 2015. Among both sexes, coal capacity was significantly positively correlated with lung cancer incidence rate (male, slopes = 0.10 to 0.13, all p-values < 0.05; females, slopes = 0.09 to 0.11, all p-values <0.05).

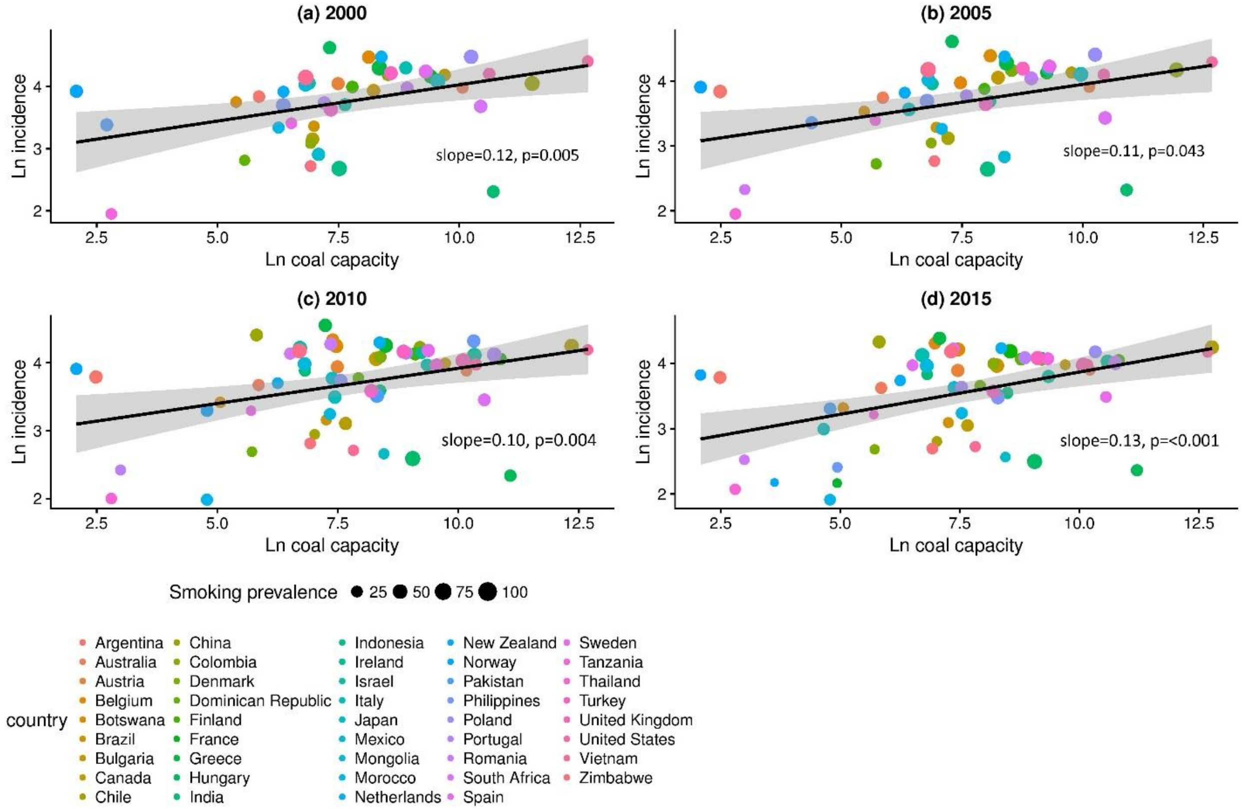

Figure 1.2 Incidence rates of lung cancer vs. coal capacity in 2000, 2005, 2010 and 2015 among males

Legend: y axis: ln(lung cancer incidence rate), unit: ln(case/100 thousands); x axis: ln(*coal capacity*), unit: ln(MW); smoking prevalence: unit: %

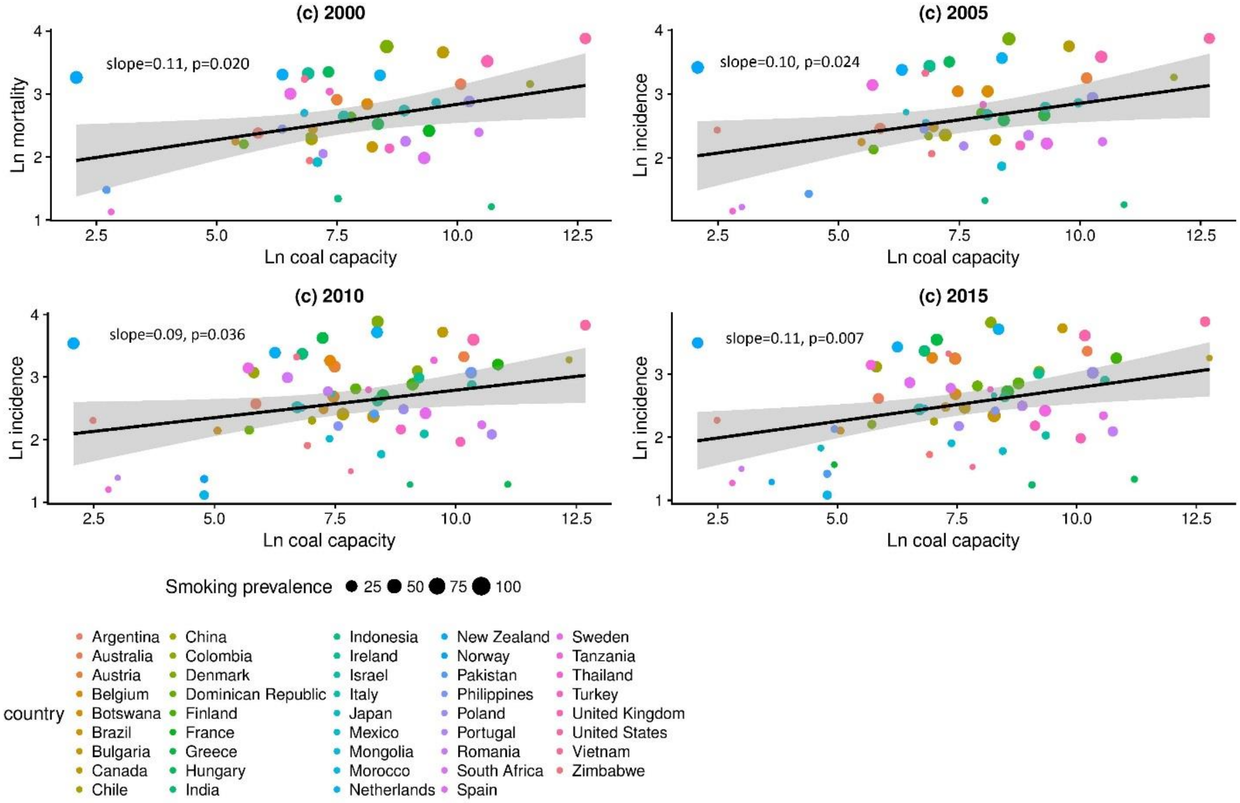

Figure 1.3 National incidence rates of lung cancer vs. coal capacity in 2000, 2005, 2010 and 2015 among females

Legend: y axis: ln(lung cancer incidence rate), unit: ln(case/100 thousands); x axis: ln(*coal capacity*), unit: ln(MW); smoking prevalence: unit: %

Univariate, behavior-environmental, 5-year-lag, 10-year-lag and 15-year-lag models were applied to examine the effect among males and females, respectively. The point estimates of per capita coal capacity among the year-lag models were similar, so we picked the 10-year-lag model as our primary model. With a 1 KW increase of coal capacity per person in a country, the relative risk of lung cancer increases by a factor of 85.1% (95%CI=1.217~2.816) among males and 58.5% (95%CI=1.070~2.347) among females. Meanwhile, a 1% increase of smoking prevalence is associated with an increase of lung cancer incidence by a factor of 3.1% (95%CI=1.009 ~ 1.054) and 2.2% (95%CI=0.998 ~ 1.046), among males and females, respectively.

Table 1.2 Relative risk (RR) and 95% confidence intervals (CIs) of the increase in lung cancer incidence with change in coal capacity, adjusted for different variables in different models among males and females.

	Univariate		**5-year lag**		**10-year-lag**		**15-year-lag**	
Males	RR	95%CI	RR	95%CI	RR	95%CI	RR	95%CI
Intercept	3.16×10^{-4}	$(1.82 \sim 5.49)\times10^{-4}$	3.20×10^{-5}	$(0.77 \sim 13.2)\times10^{-5}$	3.12×10^{-5}	$(0.74 \sim 13.2)\times10^{-5}$	2.82×10^{-5}	$(0.60\sim13.3)\times10^{-5}$
Per capita coal capacity [a]	2.620	(1.400 ~ 4.903)	1.681	(1.103 ~ 2.562)	1.585	(1.070 ~ 2.347)	1.571	(1.05~2.351)
Smoking prevalence [b]			1.031	(1.009 ~ 1.053)	1.031	(1.009 ~ 1.054)	1.032	(1.009~1.056)
Non-coal capacity [a]			0.935	(0.785 ~ 1.115)	0.915	(0.762 ~ 1.099)	0.897	(0.727~1.107)
Traffic index [b]			1.001	(0.983 ~ 1.020)	1.002	(0.983 ~ 1.020)	1.003	(0.981~1.025)
Industrialization index [b]			1.025	(1.001 ~ 1.049)	1.025	(1.001 ~ 1.049)	1.026	(1.001~1.052)
GDP (PPP) per capita [c]			1.000	(1.000 ~ 1.000)	1.000	(1.000 ~ 1.000)	1.000	(1.000~1.000)
Total coal consumption [d]			1.008	(1.001 ~ 1.015)	1.010	(1.003 ~ 1.017)	1.011	(1.004~1.018)
QIC	-5828520		-5134366		-5133338		-5043156	
Females	RR	95%CI	RR	95%CI	RR	95%CI	RR	95%CI
Intercept	1.03×10^{-4}	$(0.58\sim 1.86)\times10^{-4}$	1.21×10^{-5}	$(0.35 \sim 4.13)\times10^{-5}$	1.16×10^{-5}	$(0.34 \sim 3.99)\times10^{-5}$	1.08×10^{-5}	$(0.33\sim3.57)\times10^{-5}$
Per capita coal capacity [a]	3.872	(2.238 ~ 6.697)	1.842	(1.159 ~ 2.927)	1.851	(1.217 ~ 2.816)	1.852	(1.223~2.803)
Smoking prevalence [b]			1.023	(1.000 ~ 1.047)	1.022	(0.998 ~ 1.046)	1.021	(0.996~1.047)
Non-coal capacity [a]			1.002	(0.796 ~ 1.261)	0.986	(0.784 ~ 1.240)	0.981	(0.771~1.247)
Traffic index [b]			1.002	(0.986 ~ 1.017)	1.002	(0.987 ~ 1.017)	1.002	(0.986~1.018)
Industrialization index [b]			1.060	(1.027 ~ 1.094)	1.062	(1.029 ~ 1.096)	1.064	(1.030~1.100)
GDP (PPP) per capita [c]			1.000	(1.000 ~ 1.000)	1.000	(1.000 ~ 1.000)	1.000	(1.000~1.000)
Total coal consumption [d]			1.018	(1.002 ~ 1.035)	1.020	(1.005 ~ 1.035)	1.021	(1.006~1.035)
QIC	-1623308		-1488001		-1488392		-1459133	

RR: relative risk; 95%CI: 95% confidence interval; GDP (PPP): gross domestic product adjusted by (Purchasing Power Parity)

[a] Unit: KW/capita

[b] Unit: %

[c] Unit: Year 2011 USD/capita

[d] Unit: Quadrillion British Thermal Unit (QBtu)

No statistically significant interactions between smoking and coal capacity, or any other time-varying effects on the estimates, were discovered, and thus these results were omitted. In the falsification test, coal capacity was not associated with CRC incidence rates in either males or females for any lag model (Supplementary Table 2).

Supplementary Table 3 presents the PAFs and standardized lung cancer cases attributable to coal-fired power plants among males and females, respectively, in 2015. PAFs are higher for females than males in most countries due to higher RRs. Australia (39.26%) and US (32.65%) had the highest PAFs in 2015, corresponding to 13,539 and 244,617 standardized lung cancer among females, respectively. In China, we estimated 139,345 standardized lung cancer among females (PAF=8.09%) and 314,524 among males (PAF=6.39%) in 2015. We estimated the attributable factor will jump up to 19.24% and 15.22% for females and males in 2025, respectively, due to the dramatic increase of per capita coal capacity from 2005 to 2015 in China.

1.4 Discussion

Calculating per capita coal capacities as a determinant of lung cancer is useful for several reasons. Firstly, per capita coal capacities could be regarded as averaged individual energy consumption from coal for every citizen within a country, thus may provide a meaningful approach to energy policy compared to PM. As countries compose their Intended Nationally Determined Contributions (INDC) goals for the coming decades, an analysis on reducing construction of or shutting down existing coal power plants may reveal further co-benefits of mitigating global warming and adverse health outcomes (Buonocore et al. 2016). Secondly, most coal-fired power plants were built closer to areas with a high population density, rather than coal mining areas(Brett 2012). Thirdly, since all pollutants related to lung cancer are not known, and known pollutants compose a small fraction of $PM_{2.5}$, per capita coal capacity could serve as a better estimate of externality then pollutant composition measurements. Fourthly, although capacity factors varied among countries, the range of capacity was approximately 40%–60% (Kwon 2015); this indicates that the quantity of coal combustion remained fixed after a plant was built. Finally, coal prices in a local market reflect coal quality. Although coal quality might vary between countries, it remains constant within a plant across time.(Mernier 2010) Country-specific effects, such as coal quality, are marginalized out by GEE in the analysis. By weighting the model by country population, we are reflecting the individual data by exploiting aggregated mean values of per capita coal capacity for each individual.

The association between per capita coal capacity and lung cancer incidence can be used to understand the potential number of lives affected by different levels of reliance on coal power. In 2015, we estimate a total of 865,805 male and 542,848 female standardized lung cancer cases can be attributed to anthropogenic power plants using coal as primary energy source. There is little difference between the lag 5 and lag 10 models in terms of quadratic information criterion (QIC)(Pan 2001) and coefficients, so for sake of consistency with the other covariates, we fix lag 10 for coal capacity as primary model and estimate PAFs. These numbers should be interpreted as the total attributable cases given every country has WHO 2000-2025 standardized population and should not be compared directly to other estimations. However, these numbers adjust for age distributions in different countries and can be a valuable tool for country-to-country comparisons of the effect from coal capacity.

The model also provides a hint of the effect sizes from coal fired power plant and smoking prevalence. Comparing 2005 to 2015 in U.S., 10-year-lag coal capacity increased from 321.06 GW to 322.29 GW, corresponding to an increase of 0.12 KW/person. Meanwhile, 10-year-lag smoking prevalence decreased 3.5% among males (data not shown). The increased per capita coal capacity is associated with the higher risk of lung cancer by a factor of 5.68% (=$1.585^{0.12}$) while the decreasing smoking prevalence prevented the risk by a factor of 11.28% (=$1.031^{3.5}$). This is meant as a quick numerical check; however, one should not try to surmise any statistical results from this.

1.5 Study Limitations

Despite using an ecological study design, the potential for "ecological fallacy" (Robinson 2009) is unlikely because our analysis on aggregated data is meant to infer policy decisions at the national level and for international comparison, but not at the individual level (Idrovo 2011). To address concerns of data quality and other country-specific biases, we fitted a Poisson regression longitudinal model with GEE (Zeger 1986) to account for time-independent confounders such as underreporting and/or over-diagnosis of diseases. GEE is a semiparametric technique in that it makes no assumptions about the correlation structure among outcomes. One disadvantage regarding GEE is potential efficiency losses compared to mixed models, if we could have correctly specified the true correlation structure properly in a parametric form. However, we are willing to sacrifice some efficiency for statistical robustness, a property GEE possesses while mixed models do not(John E. Overall 2004). Regardless, this disadvantage would be germane had we failed to reject that coal capacity has a significant effect on lung cancer, but since we did reject, fitting with a correctly specified mixed model would only serve to increase the significance of the effect.

Our identified confounders associated with both coal capacity and lung cancer at the national level included adjustments for the appropriate latency period and strong temporality justifications for causal inference (Hill 1965). However, significant residual and unmeasured confounders, such as national-level educational attainment, may exist; adding more parameters to our analysis would destabilize estimates and cause loss of statistical power. Potential misclassifications of lung cancer diagnosis must also be considered across countries even GBD study is the best available data we can obtained(Global Burden of Disease Collaborative Network 2016). Another potential misclassification is meteorological factor, which cannot be adjusted in our model. Since neither the electricity matrix nor meteorological factor is relevant to a country's healthcare system, misclassification is non-differential and more likely biases toward the null.

Our estimates may be conservative since they do not account for all time-varying covariates in the model, such as indoor biomass combustion (Richard Hosier 1987). Although most countries included in this study were high-income countries and used a limited proportion of indoor biomass combustion, the true effect of coal power plants might be even higher if biomass combustion remained constant rather than decreasing. We adjusted total coal consumption in the model, which included the indoor combustion. Furthermore, the association between increasing lung cancer incidence and coal capacity may be underestimated since the calculations do not account for the improvement of techniques for controlling air pollutants across time. Further studies should address the effectiveness of pollutant controls in terms of incidence from lung cancer.

1.6 Conclusion

We demonstrated an association between lung cancer incidence and coal-fired power plants via a novel approach that measures per capita coal capacity rather than PM. The study may be helpful in addressing a key policy question about the externality cost of coal power plants and estimates of the global disease burden from preventable lung cancer attributable to coal-fired power plants. Further studies might focus on the effectiveness of pollutant controls on health outcomes, quality of coal, synergistic effects between tobacco smoking and environmental exposure, and the financial burden of coal on healthcare expenditures.

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1.8 Supplementary material

Supplementary Table 1.1 Countries included in the analysis, by geographical region a (N = 83)

Regions	N	Countries
Africa	**14**	
Eastern Africa	6	Kenya, Madagascar, Mauritius, Tanzania, Zambia, Zimbabwe
Northern Africa	1	Morocco
Southern Africa	5	South Africa, Botswana, Namibia, Niger, Pakistan
Western Africa	2	Nigeria, Senegal
Oceania	**2**	Australia, New Zealand
Asia	**23**	
Eastern Asia	6	China, Japan, Mongolia, North Korea, South Korea, Taiwan,
South-Eastern Asia	8	Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Thailand, Vietnam
Western Asia	3	Israel, Syria, Turkey
Central Asia	3	Kazakhstan, Tajikistan, Uzbekistan

Supplementary Table 1.1 (continued)

Southern Asia	3	Bangladesh, India, Sri Lanka
America	**12**	
Caribbean	1	Dominican Republic
Central America	4	Guatemala, Honduras, Mexico, Panama
South America	5	Argentina, Brazil, Chile, Colombia, Peru
North America	2	Canada, United States of America
Europe	**32**	
Eastern Europe	9	Bulgaria, Czech Republic, Hungary, Poland, Republic of Moldova, Romania, Russian Federation Slovakia, Ukraine
Southern Europe	11	Albania, Bosnia and Herzegovina, Croatia, Greece, Italy, Montenegro, Portugal, Serbia, Slovenia, Spain, TFYR Macedonia
Western Europe	6	Austria, Belgium, France, Germany, Iceland, Netherlands
North Europe	6	Denmark, Finland, Ireland, Norway, Sweden, United Kingdom

N = number of countries

[a] Based on the United Nations' geographical regions

Supplementary Table 1.2 Relative risk (RR) and 95% confidence intervals (CIs) of the increase in colorectal cancer with change in coal capacity, adjusted for different variables in different models among males and females.

	5-year lag		**10-year-lag**		**15-year-lag**	
Males	RR	95%CI	RR	95%CI	RR	95%CI
Intercept	3.08×10^{-5}	(0.96 ~ 9.84) $\times10^{-5}$	3.21×10^{-5}	(0.98 ~ 10.6) $\times10^{-5}$	3.20×10^{-5}	(0.80 ~ 12.2) $\times10^{-5}$
Per capita coal capacity [a]	1.088	(0.731 ~ 1.618)	0.986	(0.674 ~ 1.442)	0.952	(0.648~1.398)
Smoking prevalence [b]	1.023	(1.005 ~ 1.041)	1.022	(1.004 ~ 1.041)	1.022	(1.003~1.042)
Non-coal capacity [a]	0.898	(0.764 ~ 1.055)	0.890	(0.758 ~ 1.045)	0.884	(0.744~1.050)
Traffic index [b]	0.999	(0.984 ~ 1.015)	0.999	(0.983 ~ 1.015)	1.000	(0.980~1.020)
Industrialization index [b]	1.014	(0.991 ~ 1.039)	1.013	(0.989 ~ 1.036)	1.012	(0.988~1.036)
GDP (PPP) per capita [c]	1.000	(1.000 ~ 1.000)	1.000	(1.000 ~ 1.000)	1.000	(1.000~1.000)
Total coal consumption [d]	1.001	(0.990 ~ 1.011)	1.002	(0.992 ~ 1.012)	1.002	(0.993~1.012)
QIC	-3939681		-3937742		-3875775	
Females	RR	95%CI	RR	95%CI	RR	95%CI
Intercept	4.61×10^{-5}	(0.16 ~ 1.38) $\times10^{-4}$	4.82×10^{-5}	(0.16 ~ 1.43) $\times10^{-4}$	5.15×10^{-5}	(0.17 ~ 1.57) $\times10^{-4}$
Per capita coal capacity [a]	1.124	(0.821 ~ 1.539)	1.002	(0.737 ~ 1.361)	0.928	(0.678~1.269)
Smoking prevalence [b]	1.021	(1.006 ~ 1.036)	1.021	(1.006 ~ 1.036)	1.022	(1.007~1.038)
Non-coal capacity [a]	0.949	(0.816 ~ 1.104)	0.940	(0.806 ~ 1.098)	0.946	(0.804~1.112)
Traffic index [b]	0.998	(0.986 ~ 1.009)	0.997	(0.986 ~ 1.009)	0.996	(0.984~1.009)
Industrialization index [b]	1.026	(0.999 ~ 1.053)	1.024	(0.997 ~ 1.051)	1.021	(0.994~1.049)
GDP (PPP) per capita [c]	1.000	(1.000 ~ 1.000)	1.000	(1.000 ~ 1.000)	1.000	(1.000~1.000)
Total coal consumption [d]	1.001	(0.992 ~ 1.010)	1.003	(0.994 ~ 1.012)	1.004	(0.995~1.013)
QIC	-2372015		-2370885		-2323628	

RR: relative risk; 95%CI: 95% confidence interval; GDP (PPP): gross domestic product adjusted by (Purchasing Power Parity)

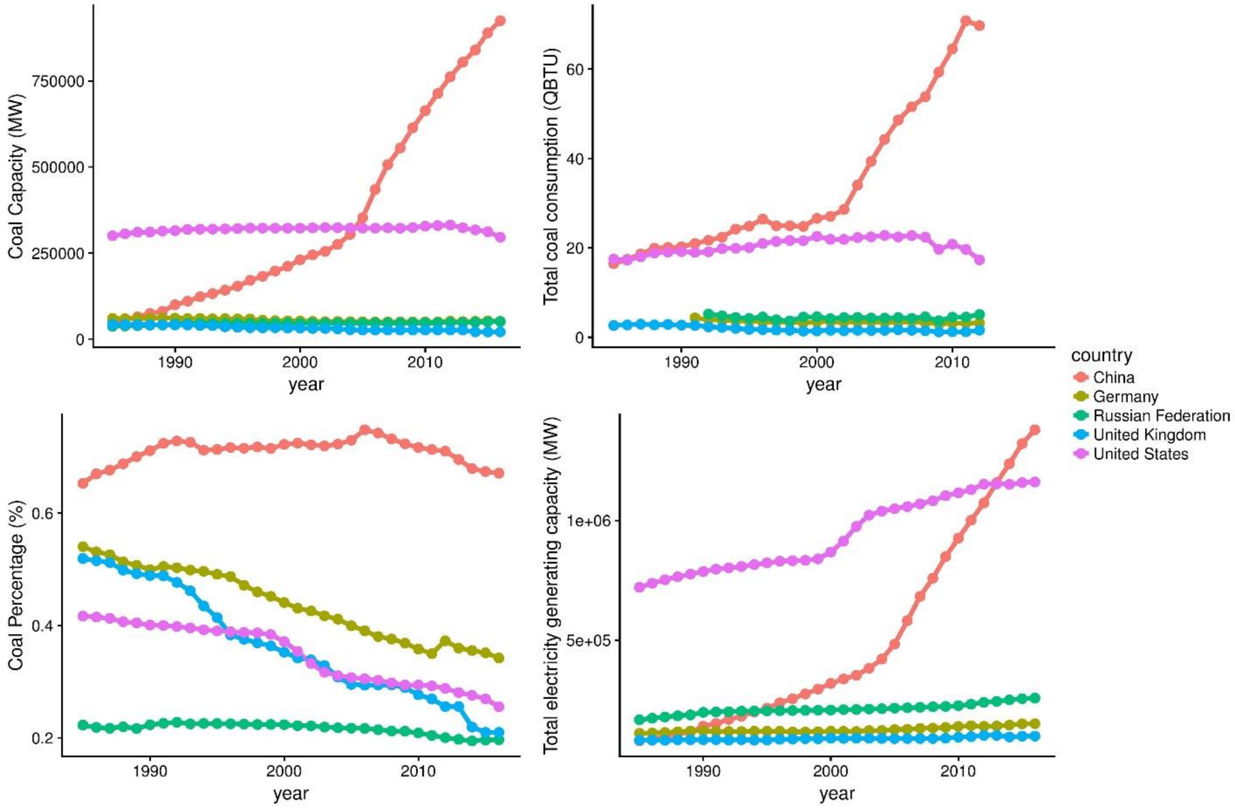
[a] Unit: KW/capita

[b] Unit: %

[c] Unit: Year 2011 USD/capita

[d] Unit: Quadrillion British Thermal Unit (QBtu)

Supplementary Table 1.3 Estimated population attributable factors (2015, 2025) and standardized attributable cases (2015) among males and females of studied countries



Supplementary Figure 1.1 Annual coal capacity, coal capacity, log coal capacity and coal percentage of countries with the 5 highest coal capacities

Chapter 2. Sulfur Oxide Controls in Coal-Fired Power Plants and Cardiovascular Disease

2.1 Introduction

CVD has been a leading cause of death globally for decades[1]. Treating CVD is costly, especially in the United States (US). For the US, the burden of medical cost for CVD was 656 billion United States Dollars (USD) in 2015 and is projected to reach 1,208 billion USD in 2030[2].

Controlling emissions from power-generating plants is important for human health as well as climate. Among the health problems linked to sulfur oxides (SO_x) exposures in air is cardiovascular disease (CVD)[3,4]. Various air pollutants initiate and promote atherosclerotic progression[5,6] and are associated with transient increases in plasma viscosity and thrombus formation[7]. Clear links have been drawn between SO_2 and CVD[8,9]. Indeed, total suspended particles (TSP) and SO_2 are associated with changes in vasomotor tone[10] and thus alter heart rate[11,12] and cardiac function[13]. Such mechanisms may underlie the association between SO_2 and CVD.

Coal-fired power-generating facilities have long been known to emit pollutants that fuel climate change and adversely impact human health. Among these emissions are SO_x, including sulfur dioxide (SO_2). Global SO_2 emissions, measured by the bottom-up mass balance method, peaked in the early 1970s and decreased for decades[14]. After the 2000s, these emissions increased again, mostly from developing countries[15]. The majority of SO_x in the air is anthropogenic emission from coal-fired power plants[16]. For example, in the US, 65% of SO_2 emission were from electric utilities, and more than 90% of those were coal-fired power plants[17]. Similarly, in the European Union, more than 70% of the emission was from electricity sectors[18].

To control these emissions, dozens of methods with relatively high efficiencies have been developed for fitting of coal-fired power plants. SO_x emissions are determined by (1) the sulfur content in coals burned and (2) the emission control system used[19]. The principle technology of emission control systems is the use of sorbents to scrub SO_x from the flue gas, called a flue gas desulfurization (FGD) system. Another method to reduce SO_x emission is the use of low sulfur coal, such as sub-bituminous coal mined in the Powder River Basin of Montana and Wyoming[19]. However, this method is not efficient and has a limited application globally. Indeed, FGD products represent an efficient and economically feasible approach to control emissions on a large scale. The cost to retrofit US plants with FGD equipment was estimated at about $407 (2008 USD) per kilowatt (kW) for a 500-megawatt (MW) plant in 2009; this cost escalates yearly by $16[20]. For most nations, coal-fired power plants are either state-owned or government-funded, giving governments direct authority on implementing emission controls; privately-owned power-generating units can be required to follow emissions regulations.

Here, we estimated the relative risks and incident cases of CVD, particularly ischemic heart disease (IHD), attributable to SO_x emission from coal-fired power plants from a global perspective. This study sought to determine the potential reduction in preventable CVD that could be attributed to reduced global SO_x emissions.

2.2 Methods

2.2.1 Data source

A total of 79 countries with data available for analyses were included in 2012. We obtained the age- and sex-adjusted CVD incidence rates from the Global Burden of Disease (GBD) Study[22]. CVD data included two subcategories, ischemic heart diseases (IHD) and rheumatic heart diseases (RHD). The former was coded as 410–410.9, 411–411.1, 411.8–411.9 in the International

Classification of Diseases version 9 (ICD-9) and I21.0–I21.4, I21.9, I22.0–I22.2, and I22.8–I22.9 in ICD-10. The latter was coded as 391.0–391.2, 391.8–391.9, 392.0, 394.0–394.2, 394.9, 395.0–395.2, 395.9, 396.0–396.3, 396.8–396.9, 397.0–397.1, 397.9, 398.8–398.9 in ICD-9 and I01.0–I01.2, I01.8–I01.9, I02.0, I05.0–I05.2, I05.8–I05.9, I06.0–I06.2, I06.8–I06.9, I07.0–I07.2, I07.8–I07.9, I08.0–I08.3, I08.8–I08.9, I09.0–I09.2, I09.8–I09.9 in ICD-10[22]. The GBD study has thorough estimation of incidence rates of CVD in 2010 and 2015, respectively. For CVD incidence rates data between 2011 and 2014, we estimated using linear interpolation.

Coal capacity is defined as the generating capacity of a coal-fired power plant [unit: megawatt (MW)]. The estimation for reduction of each unit is based on the representative SO_x reduction percentage of the corresponding control technology from literature review, summarized in Supplementary table 1. National SO_x reduction is the coal-capacity-weighted average SO_x reduction in a given country. The formula is written as follows:

$$National\ SO_x\ reduction\ (\%) = \frac{\sum_{i=1}^{n} SO_x\ reduction_i(\%) \times coal\ capacity_i\ (MW)}{\sum_{i=1}^{n} coal\ capacity_i\ (MW)}$$

where *i* is a coal-fired power unit and *n* is the total units in a country. Coal capacities are the weight for the reductions in different power units. Missing data on SO_x control are assigned 0. Data on the coal capacity of every plant were derived from the Utility Data Institute World Electric Power Plants Data Base (UDI WEPP)[21].

We also collected data exclusively on both behavior and economic covariates at the national level, including smoking prevalence, economy, traffic index, and macroeconomic indicators, and industrialization. Annual smoking prevalence within each country was estimated and sex- and age-adjusted[32]. The macro level indicator was the annual per capita gross domestic product adjusted for purchasing power parity [GDP (PPP)] and inflation to the base year 2011 to capture a country's standard of living level[33]. Traffic index, measured as the proportion of a country's population living in urban areas, was applied to capture air pollutants emitted from all mechanical vehicles and public transports associated with human activities[34]. The industrialization level was measured using the shares of CO_2 emissions from manufacturing industries and construction in total CO_2 emissions (% of total fuel combustion)[35]. We further grouped studied countries into 6 WHO regions (combination of geographical distribution and mortality): Africa, the Americas, Southeast Asia, Europe, Eastern Mediterranean, and the Western Pacific[36].

2.2.2 Data analysis

We took a natural logarithm of coal capacity to approximate normal distribution in the model. A Poisson regression was performed for count data of incidence cases of diseases. Our primary model is as following:

$$\begin{aligned} ln(E[\lambda_i]) = {} & \beta_0 + \beta_1 \times SO_2\ reduction_i + \beta_2 \times Smoking\ prevalence_i \\ & + \beta_3 \times Traffic\ index_i + \beta_4 \times Industrialization_i + \beta_5 \\ & \times log(National\ coal\ capacity)_i + \beta_6 \times I\_Region_i \end{aligned}$$

where *i* denotes each country; $ln(E[\lambda_i])$ denotes the natural log of expected standardized incident rates for CVD conditioned on covariates X_i; β_0 is the intercept; $\beta_1\ to\ \beta_6$ are coefficients of individual covariates; and *I_Region* is indicator variable for the six WHO regions to consider the underlying difference in hygiene and healthcare status.

In addition to the above primary model, four other models were specified to assess sensitivity to the inclusion of different adjustment covariates. They were: (1) Univariate model with SO_x reduction only; (2) Behavior-adjusted model with smoking prevalence and healthcare index of per capita GDP (PPP); (3) Economic-adjusted model with per capita GDP (PPP), traffic index, and industrialization; and (4) non-regional model with combination of behavior and economics. All models were analyzed for both sexes combined, males, and females, respectively, and weighted by nationwide sex-specific population[34] for all multivariate models.

Under the assumption that every country could hypothetically reach an optimal national SO_x reduction by a factor of 95%, we estimated the proportional attributable factor (PAF) for IHD for every country. The formula for PAF is written as follows[37]:

$$PAF = \frac{P_i \times (RR_i - 1)}{1 + P_i \times (RR_i - 1)}$$

where P_i is the proportion of people exposed to suboptimal SO_x reduction. In the estimation, we applied WHO mortality strata and assumed the P_i is 0.1 in strata A countries and 0.5 in stratum B to E countries[38], respectively, as often used in other studies[39-41]. RR_i is the relative risks from the primary model, comparing existing national SO_x reduction in 2012 vs. the counterfactual optimal reduction (95%). Supplementary Table 2 shows the step-by-step calculation for PAFs. The incident cases of IHD attributable to SO_x controls in coal-fired power plants were estimated by multiplying the standardized incidence rates by sex-specific population and PAF.

$$SOx\ associated\ IHD = Population \times \text{Standardized Incidence Rate} \times PAF$$

We performed the PROC GENMOD procedure with a log link function, using SAS version 9·4 (SAS Institute, Cary, NC, US) to estimate the effect of selected factors on standardized incidences of CVD, IHD, and RHD, respectively.

2.2.3 Additional analysis and falsification test

To investigate the possibility that general health improvements correlated with SO_x reduction in coal-fired power plants might be obscuring our CVD results, we further analyzed two subcategories of CVD: IHD and RHD. Since the latter is related to previously unsatisfactorily-treated streptococcus infection, we identified RHD as a falsification outcome that might be a marker that are not expected to bear any relationship to air pollution. We applied the primary model for IHDs and rheumatic heart diseases, respectively, as the additional analysis and examined whether the relationship between RHD and SO_x reduction existed as a falsification test.

2.3 Results

Data on the coal capacities of power plants across the globe were derived from the Utility Data Institute World Electric Power Plants Data Base (UDI WEPP)[21]. We identified a total of 13,581 generating units in 79 countries that used coal as the primary energy source (Table 1). Most were in Europe (*N*=36), the Americas (*N*=12), and the Western Pacific (*N*=11).

Table 2.1 Countries included in the analysis, by geographical region (N = 79)

Regions	N	Countries
Africa	10	Botswana, Madagascar, Mauritius, Namibia, Niger, Nigeria, Senegal, South Africa, Swaziland, Tanzania, Zambia, Zimbabwe
Americas	12	Argentina, Brazil, Canada, Chile, Colombia, Dominican Republic, Guatemala, Honduras, Mexico, Panama, Peru, United States

Table 2.1 (continued)

Europe	36	Albania, Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Israel, Italy, Kazakhstan, Kyrgyzstan, Macedonia, Moldova, Montenegro, Netherlands, Norway, Poland, Portugal, Romania, Russia, Serbia, Slovakia, Slovenia, Spain, Sweden, Turkey, Ukraine, United Kingdom, Uzbekistan
South East Asia	7	Bangladesh, India, Indonesia, Myanmar, North Korea, Sri Lanka, Thailand
Western Pacific	11	Australia, Cambodia, China, Japan, Malaysia, Mongolia, New Zealand, Philippines, South Korea, Taiwan, Vietnam
Eastern Mediterranean	3	Morocco, Pakistan, Syria

To calculate SO_x emission controls, the efficiencies of different SO_x reduction control systems in coal-fired power plants were extracted from the literature. Most SO_x control systems in the studied countries had relatively high SO_x reduction efficiency, by 80% or more (Supplementary table 1). Data on SOx control technology were only available for larger power plants. As a consequence, 19 countries had no data on control technologies. However, the total capacity of plants with missing control technology data is only 14.15 GW, representing 0.78% of the total coal capacity in the study. We assigned those missing as 0 reduction in the following analysis. We defined national SO_x reduction as the average SO_x reduction percentage weighted by generating capacities of individual plants in a given country. Total coal capacities and national SO_x reduction in included countries in 2012 are summarized in Figure 1. The lack of installing control systems in small units in many countries produced a bimodal distribution of national SO_x reduction, with a median of 58.49% (Supplementary Figure 1).

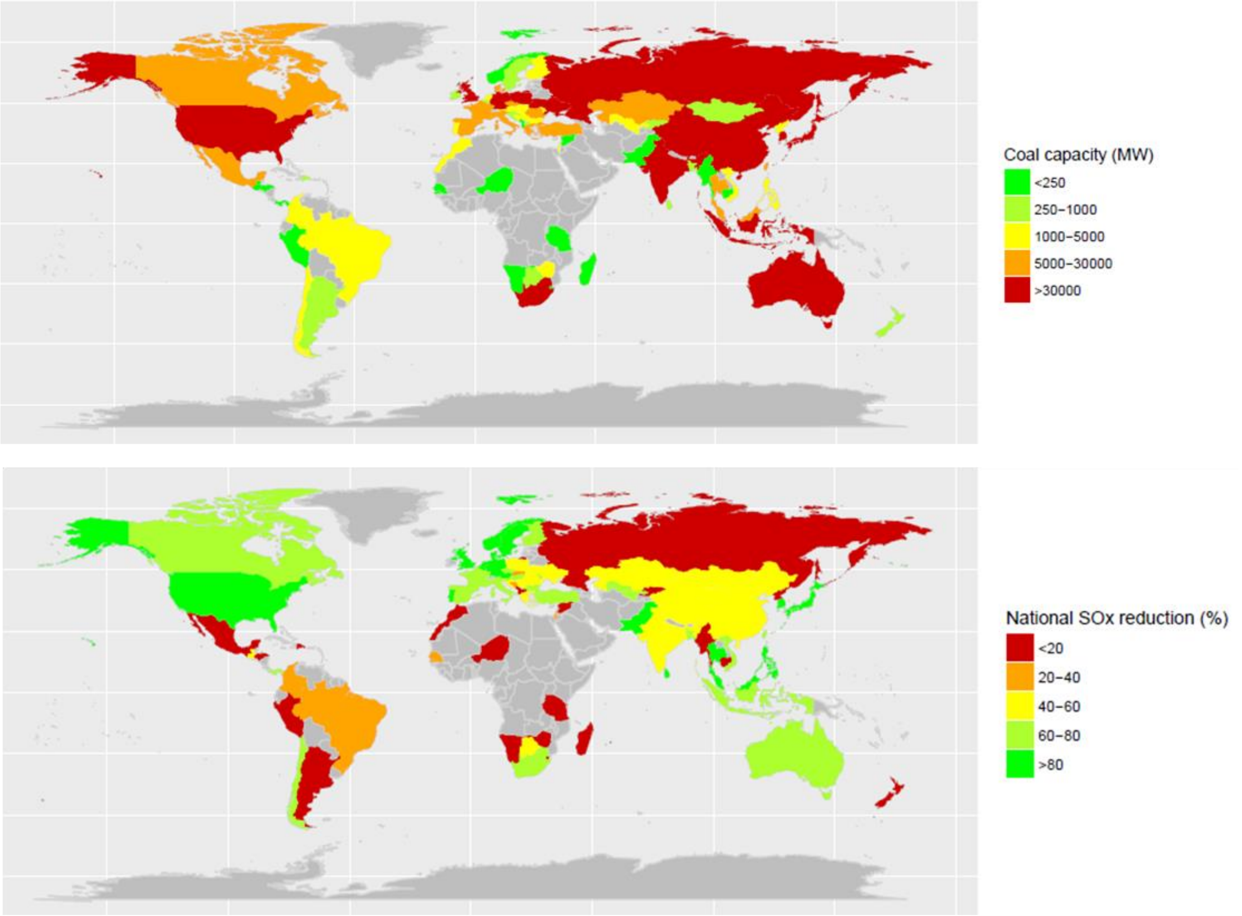


Figure 2.1 Total coal capacity (upper panel) and national SO_x reduction by country (lower panel) in 2012

The map is created by using R version 3.2.5, Package'rworldmap'[31]

To determine effects of SO_x emission controls on CVD, we extracted age- and sex-adjusted CVD incidence rates from the Global Burden of Disease (GBD) Study[22], including two subcategories: ischemic heart diseases (IHD) and rheumatic heart diseases (RHD). The former reflects coronary artery disease, which may have a stronger association with air pollution; the latter is a contagious disease that we used as a falsifying outcome. Table 2 summarizes these and other covariates included in the study. IHD was more common among males, while RHD, accounting for less than 1% of CVD, was more common among females. One behavior risk factor for CVD—smoking prevalence—was almost three times higher among males than females.

Table 2.2 Mean, range, and 95% CI of covariates among studied countries in 2012

	Mean	**Range**	**95% CI**
CVD incidence [a]			
Males	873.90	(293.16~1994.66)	(780.30~967.51)
Females	820.61	(305.85~1819.81)	(731.31~909.91)
Ischemic heart diseases			
Males	461.28	(156.69~859.76)	(422.06~500.50)
Females	311.61	(89.37~603.3)	(285.75~337.48)
Rheumatic heart diseases			
Males	5.42	(0.63~32.32)	(4.10~6.75)
Females	7.04	(0.72~42.60)	(5.07~9.02)
SO_x reduction [b]	47.00	(0.00~95.00)	(39.50~54.51)
Smoking prevalence [b]			
Males	29.61	(8.80~57.00)	(27.24~31.99)
Females	11.80	(0.70~34.70)	(9.74~13.86)

Table 2.2 (continued)

Per capita GDP (PPP) [c]	20.44	(0.84~63.8)	(17.01~23.88)
Traffic index [b]	61.29	(17.99~97.73)	(56.76~65.82)
Industrialization [b]	18.67	(2.55~62.09)	(16.45~20.90)
Coal capacity [d]	22726.01	(10.10~780959.5)	(1495.29~43956.73)
Population [e]			
All	72150.04	(623.86~1355386.95)	(25955.69~118344.39)
Males	36378.31	(308.06~697964.30)	(12550.04~60206.57)
Females	35771.73	(315.80~657422.65)	(13401.46~58142.00)

[a] Unit: incident case per 100,000

[b] Unit: %

[c] Unit: thousands United States Dollars

[d] Unit: megawatt

[e] Unit: thousand people

We applied a Poisson regression to analyze the relative risk of age-standardized CVD incidence associated with national SO_x reduction, adjusted for behavior, economic, and regional factors. A 10% decrease in SO_x emission from coal-fired power plants is associated with a 0.75% lower standardized CVD incidence rate [relative risk (RR)=0.9925, 95% confidence interval (CI)=0.9892–0.9959], after adjustments (primary model, sex combined, Table 3). The association of SO_x reduction was stronger for lower CVD in females (RR=0.9831, 95% CI=0.9762–0.9901) than in males (RR=0.9972, 95% CI=0.9905–1.0039).

Table 2.3 The effects of sulfate oxide controls in coal-fired power plants on cardiovascular diseases in different models, among sex combined, males, and females.

	Primary model		Behavior model		Economics model		Non-regional model	
Sex combined	RR	95%CI	RR	95%CI	RR	RR	95%CI	95%CI
Intercept	0.0041	(0.0038~0.0043)	0.0060	(0.0059~0.0061)	0.0049	(0.0047~0.0052)	0.0049	(0.0046~0.0051)
SO_x reduction [a]	0.9925	(0.9892~0.9959)	0.9847	(0.9815~0.9878)	0.9861	(0.9824~0.9898)	0.9793	(0.9756~0.9830)
Smoking prevalence [b]	1.0037	(1.0033~1.0041)	1.0070	(1.0066~1.0075)			1.0068	(1.0063~1.0072)
Per capita GDP(PPP) [c]			1.0092	(1.0087~1.0097)	1.0083	(1.0071~1.0095)	1.0095	(1.0083~1.0107)
Traffic index [b]	1.0018	(1.0011~1.0024)			1.0017	(1.0011~1.0024)	1.0005	(0.9998~1.0011)
Industrialization [b]	1.0038	(1.0026~1.005)			1.0032	(1.0018~1.0047)	1.0022	(1.0008~1.0037)
Ln coal capacity [d]	1.0450	(1.0413~1.0487)			1.0177	(1.0146~1.0208)	1.0159	(1.0128~1.0190)
Region								
Africa	0.7909	(0.7389~0.8464)						
America	0.8082	(0.7655~0.8533)						
Europe	1.5187	(1.4466~1.5945)						
South-East Asia	0.8046	(0.7693~0.8415)						
Western Pacific	0.8099	(0.7715~0.8502)						

Table 2.3 (Continued)

Eastern Mediterranean	1.0000	-						
Males								
Intercept	0.0043	(0.0038~0.0049)	0.0052	(0.0050~0.0055)	0.0049	(0.0045~0.0054)	0.0053	(0.0048~0.0058)
SO_x reduction [a]	0.9972	(0.9905~1.0039)	0.9775	(0.9710~0.9840)	0.9898	(0.9825~0.9972)	0.9686	(0.9612~0.9761)
Smoking prevalence [b]	1.0032	(1.0016~1.0048)	1.0104	(1.0092~1.0116)			1.0104	(1.0090~1.0117)
Per capita GDP(PPP) [c]			1.0117	(1.0106~1.0128)	1.0085	(1.0061~1.0109)	1.0148	(1.0123~1.0173)
Traffic index [b]	1.0012	(0.9999~1.0026)			1.0011	(0.9998~1.0023)	0.9976	(0.9963~0.9990)
Industrialization [b]	1.0019	(0.9994~1.0043)			1.0046	(1.0017~1.0075)	1.0004	(0.9975~1.0033)
Ln coal capacity [d]	1.0489	(1.0417~1.0562)			1.0203	(1.0144~1.0264)	1.0108	(1.0048~1.0169)
Region								
Africa	0.7261	(0.6342~0.8314)						
America	0.8101	(0.7272~0.9024)						
Europe	1.4162	(1.2879~1.5573)						
South-East Asia	0.7813	(0.7164~0.8521)						
Western Pacific	0.7753	(0.7040~0.8539)						
Eastern Mediterranean	1.0000	-						

Table 2.3 (Continued)

Females								
Intercept	0.0039	(0.0034~0.0044)	0.0058	(0.0056~0.0060)	0.0049	(0.0044~0.0055)	0.0027	(0.0024~0.0030)
SO_x reduction [a]	0.9831	(0.9762~0.9901)	0.9983	(0.9919~1.0049)	0.9821	(0.9746~0.9895)	0.9898	(0.9822~0.9973)
Smoking prevalence [b]	1.0124	(1.0079~1.0168)	1.0347	(1.0320~1.0375)			1.0485	(1.0452~1.0517)
Per capita GDP(PPP) [c]			0.9965	(0.9950~0.9981)	1.0080	(1.0056~1.0105)	0.9951	(0.9926~0.9976)
Traffic index [b]	1.0010	(0.9996~1.0025)			1.0025	(1.0011~1.0038)	1.0000	(0.9986~1.0013)
Industrialization [b]	1.0072	(1.0047~1.0097)			1.0017	(0.9987~1.0047)	1.0113	(1.0082~1.0143)
Ln coal capacity [d]	1.0417	(1.0343~1.0492)			1.0149	(1.0086~1.0212)	1.0461	(1.0392~1.0531)
Region								
Africa	0.8605	(0.7504~0.9867)						
America	0.7909	(0.707~0.8847)						
Europe	1.5105	(1.3538~1.6854)						
South-East Asia	0.8229	(0.7493~0.9038)						
Western Pacific	0.8689	(0.7853~0.9614)						
Eastern Mediterranean	1.0000	-						

[a] Unit: 10%, [b] Unit: %, [c] Unit: thousands United States Dollars, [d] Unit: Natural log of MW

Results of analysis of IHD and RHD as different outcomes are presented in Table 4. Unlike the effects on CVD, the effects of SO_x reduction on IHD were stronger in males than in females. A 10% decrease in SO_x emission from coal-fired power plants was associated with 0.9722-fold (95% CI=0.9643–0.9801) lower IHD incidence among males, while females had an analogous association of 0.9882 (95% CI=0.9783–0.9981). No statistically significant relationships between SO_x reduction and RHD incidence rate among either males or females were found.

Table 2.4 The effects of sulfur oxide controls in coal-fired power plants on the incidence of ischemic heart disease and rheumatic heart disease, among sex combined, males, and females, in the primary model.

	Ischemic heart disease		**Rheumatic heart disease**	
Sex combined	RR	95%CI	RR	95%CI
Intercept	0.0107	(0.0096~0.0120)	0.0006	(0.0004~0.0010)
SO_x reduction [a]	0.9739	(0.9679~0.9800)	0.9691	(0.9408~0.9984)
Smoking prevalence [b]	1.0099	(1.0091~1.0107)	0.9917	(0.9884~0.9950)
Traffic index [b]	0.9847	(0.9833~0.9860)	0.9673	(0.9607~0.9739)
Industrialization [b]	0.9987	(0.9964~1.0010)	1.0170	(1.0066~1.0274)
Ln coal capacity [c]	1.0318	(1.0253~1.0382)	1.1302	(1.0981~1.1633)
Region				
Africa	0.6639	(0.5980~0.7370)	0.3802	(0.2475~0.5841)
America	0.6673	(0.6079~0.7326)	0.1734	(0.1084~0.2773)
Europe	0.8163	(0.7533~0.8846)	0.1628	(0.1088~0.2437)
South-East Asia	0.5692	(0.5308~0.6104)	0.2765	(0.2094~0.3652)

Table 2.4 (continued)

Western Pacific	0.4523	(0.4190~0.4882)	0.1938	(0.1430~0.2626)
Eastern Mediterranean	1.0000	-	1.0000	-
Males				
Intercept	0.0114	(0.0098~0.0133)	0.0004	(0.0001~0.0014)
SO_x reduction [a]	0.9722	(0.9643~0.9801)	0.9738	(0.9108~1.0410)
Smoking prevalence [b]	1.0067	(1.0046~1.0089)	1.0052	(0.9849~1.0259)
Traffic index [b]	0.9857	(0.9839~0.9876)	0.9629	(0.9446~0.9816)
Industrialization [b]	0.9972	(0.9941~1.0004)	1.0151	(0.9918~1.0390)
Ln coal capacity [c]	1.0388	(1.0299~1.0477)	1.1540	(1.0717~1.2426)
Region				
Africa	0.6654	(0.5796~0.7641)	0.3902	(0.1517~1.0038)
America	0.6884	(0.6065~0.7814)	0.2347	(0.0789~0.6980)
Europe	0.8850	(0.7962~0.9837)	0.1670	(0.0703~0.3969)
South-East Asia	0.5698	(0.5184~0.6262)	0.2349	(0.1163~0.4747)
Western Pacific	0.4312	(0.3868~0.4808)	0.1556	(0.0662~0.3660)
Eastern Mediterranean	1.0000	-	1.0000	-
Females				
Intercept	0.0099	(0.0083~0.0117)	0.0008	(0.0003~0.0019)
SO_x reduction [a]	0.9882	(0.9783~0.9981)	0.9500	(0.8969~1.0064)
Smoking prevalence [b]	0.9827	(0.9758~0.9896)	1.0208	(0.9650~1.0798)
Traffic index [b]	0.9886	(0.9864~0.9909)	0.9628	(0.9498~0.9760)
Industrialization [b]	0.9990	(0.9954~1.0026)	1.0180	(0.9989~1.0374)
Ln coal capacity [c]	1.0178	(1.0080~1.0277)	1.1351	(1.0764~1.1971)
Region				

Table 2.4 (continued)

Africa	0.6625	(0.5654~0.7764)	0.3681	(0.1655~0.8187)
America	0.6212	(0.5397~0.7151)	0.1511	(0.0593~0.3855)
Europe	0.9703	(0.8480~1.1104)	0.1102	(0.0403~0.3009)
South-East Asia	0.6014	(0.5409~0.6688)	0.2629	(0.1558~0.4438)
Western Pacific	0.4908	(0.4365~0.5519)	0.1870	(0.1051~0.3326)
Eastern Mediterranean	1.0000	-	1.0000	-

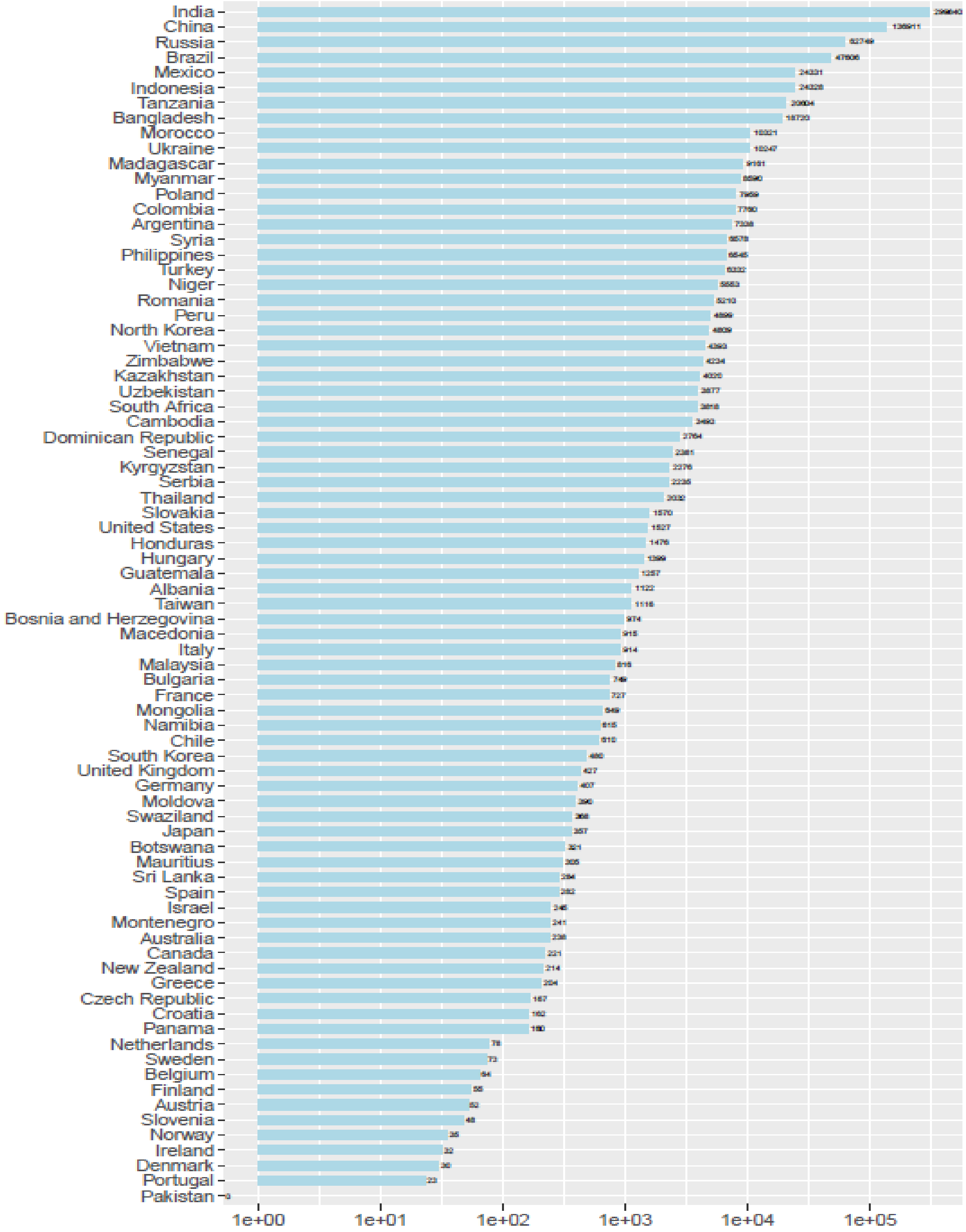
[a] Unit: 10%

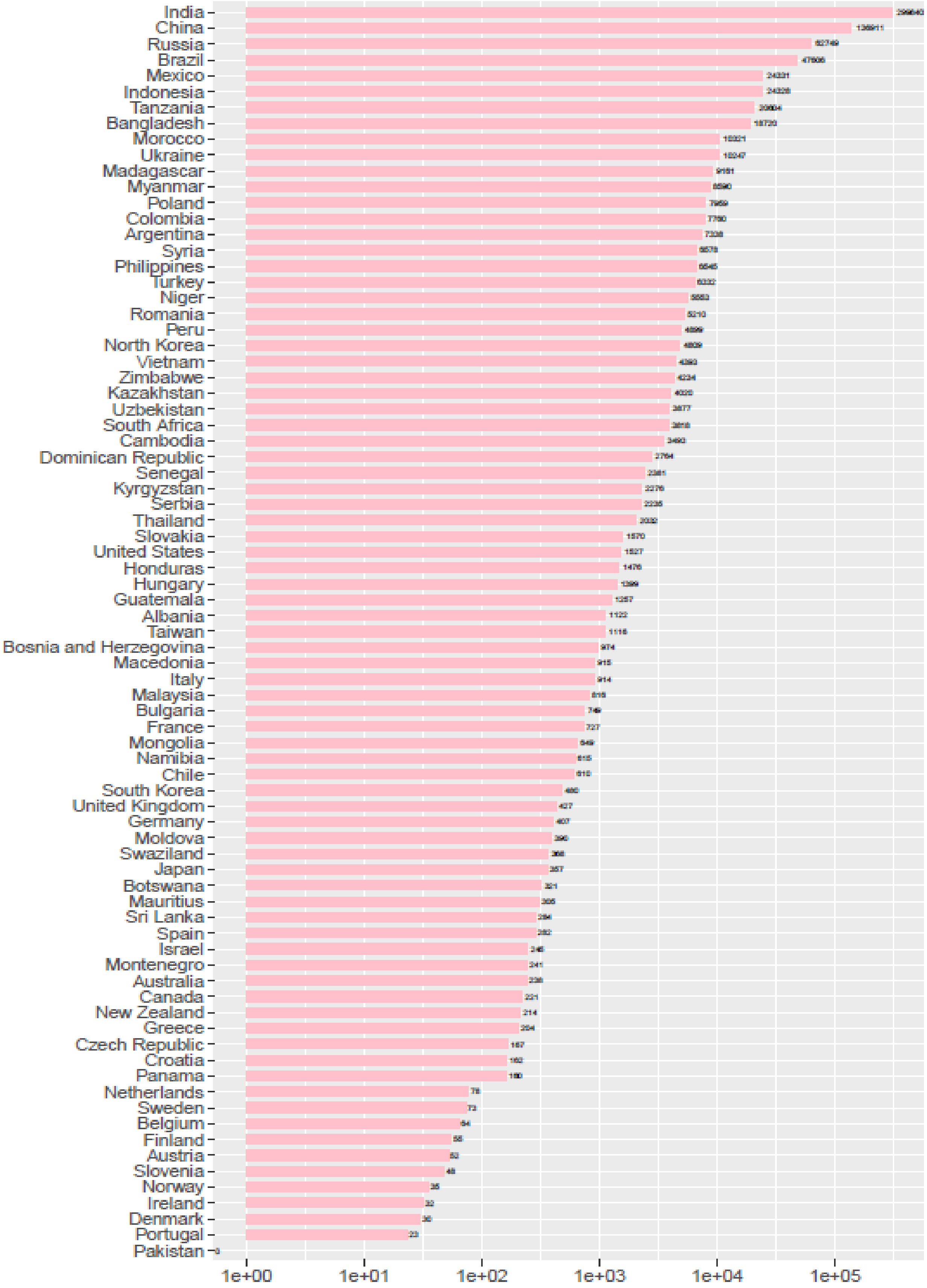
[b] Unit: %

[c] Unit: Natural log of MW

CVD incident cases attributable to suboptimal emission controls were estimated in all studied countries, assuming every country can reach 95% emission reduction. The fractions of CVD attributable to suboptimal SO_x reduction (PAF) were up to 1.43% and 8.00% for males and females, respectively (Supplementary Table 2). Similarly, the PAFs of IHD from suboptimal SO_x reduction were up to 13.24% and 5.70% for males and females, respectively. The number of attributable cases varied widely between countries. Take IHD for example, India and China had the highest preventable cases from optimizing SO_x reductions in coal-fired power plants, with estimations of 381,843 and 177,756 preventable cases, respectively (Figure 2).

Figure 2.2 The IHD incidence cases attributable to suboptimal SO_x emission control in studied countries among males (upper panel) and females (lower panel) in 2012




India
299840
China
136911
Russia
62749
Brazil
47606
Mexico
24331
Indonesia
24028
Tanzania
20604
Bangladesh
18720
Morocco
10021
Ukraine
10247
Madagascar
9161
Myanmar
8590
Poland
7959
Colombia
7760
Argentina
7338
Syria
6579
Philippines
6546
Turkey
6332
Niger
5553
Romania
5210
Peru
4899
North Korea
4809
Vietnam
4393
Zimbabwe
4234
Kazakhstan
4020
Uzbekistan
3877
South Africa
3818
Cambodia
3493
Dominican Republic
2764
Senegal
2381
Kyrgyzstan
2276
Serbia
2235
Thailand
2032
Slovakia
1570
United States
1527
Honduras
1476
Hungary
1399
Guatemala
1257
Albania
1122
Taiwan
1116
Bosnia and Herzegovina
974
Macedonia
915
Italy
914
Malaysia
818
Bulgaria
749
France
727
Mongolia
649
Namibia
615
Chile
610
South Korea
480
United Kingdom
427
Germany
407
Moldova
390
Swaziland
368
Japan
357
Botswana
321
Mauritius
305
Sri Lanka
284
Spain
282
Israel
248
Montenegro
241
Australia
238
Canada
221
New Zealand
214
Greece
204
Czech Republic
167
Croatia
162
Panama
160
Netherlands
78
Sweden
73
Belgium
64
Finland
56
Austria
53
Slovenia
48
Norway
35
Ireland
32
Denmark
30
Portugal
23
Pakistan
0
1e+00
1e+01
1e+02
1e+03
1e+04
1e+05

2.4 Discussion

To our knowledge, this is the first study showing the preventable CVD incidence attributable to SO_x reductions from coal-fired power plants from a global perspective. We found that 10% reductions in SO_x emissions were associated with CVD incidence rates that were 0.28% lower for males and 1.69% lower for females. Up to 13.24% and 5.70% of incident IHD cases are attributable to suboptimal SO_x emissions control in coal-fired power plants among males and females, respectively, given a country can reach 95% SO_x reduction in the electricity sector. Our falsifying test (see Methods) revealed no relationship between RHD and air pollution, supporting SO_x as a risk factor on air pollution related CVD.

Taking SO_x reduction in coal-fired power plants as a determinant of CVD incidence was reasonable and adequate from several perspectives: (1) The majority of SO_2 emission was from fossil fuel combustion, mostly coal-fired power units. Therefore, using the reduction percentage in coal-fired plants could capture the largest amount of SO_x reduction. (2) The implication of national SO_x reduction provides an alternative for policy application at the national level. By summarizing a national SO_x reduction, policy makers could use the results presented here to help estimate the counterfactual outcome given a country has improved its SO_x control system in coal-fired power plants. (3) Our approach provides a direct method to estimate the externality costs from coal-fired power plants, specifically from SO_x control systems, by comparing the costs of treatment for CVD attributable to SO_x emissions from coal-fired power plants.

Considering the magnitude of estimated costs of CVD, retrofitting FGD equipment in coal-fired power plants could be economically justifiable. Take the US as an example: the national SO_x reduction is 82.60% in the US. The US needs to install FGD in a total capacity of 42,093.37 MW (=339462.7MW*(95%-82.6%)) to reach optimal reduction. Given the the cost of installing FGD at \$455 per kW and 30 years lifetime of coal-fired power plants[19], the annual cost of SO_x emissions control would be \$638.42 million, nominal price. In contrast, the estimated cost of CVD is \$1,067.96 million (=564.32 billion dollars*(2,756/1,456,342))[2,23] under the estimated PAF=0.0003 for males and 0.002 for females, respectively, in the US (Supplementary Table 2). Yet, for many countries, the situation is more nuanced. For example, China has much higher CVD incidence and PAF than the US, so the health benefits per unit of SO_x reduction could be much higher, making FGD installation a cost-effective strategy to improve public health. Moreover, developing countries usually have relatively low SO_x reduction rates, such as in the cases of China (59.44%) and India (44.45%). Marginal costs of FGD might rise, while marginal benefits might decrease, when these countries increase their SO_x reduction rates. It is possible to find an efficient level of SO_x reduction rates (below 95%) when the marginal costs equal marginal benefits. The above examples illustrate the applications of SO_x reduction rate and PAF as helpful analytical tools to illuminate policy-making in public health and SOx emissions control.

The log-linear model also provides an interpretation of elasticity. For example, the elasticity of IHD on demanding SO_x emission control systems is 0.07 (=ln(0.9722)×2.5) and 0.03 (=ln(0.9882)×2.5) among males and females, respectively, given the national SO_x reduction is 25% in a given country *ceteris paribus* (Table 4). This implies the change of IHD is more sensitive to SO_x reduction among males than females. Similarly, the elasticity is 0.21 (=ln(0.9722)×7.5) and 0.09 (=ln(0.9882)×7.5) among males and females, respectively, given the national SO_x reduction is 75% in a given country *ceteris paribus*. The elasticity becomes larger when SO_x reduction improves, which means the incidence of IHD would be even more sensitive to additional improvement of the emission controls for countries having already had better SO_x control systems in coal-fired power plants.

Several limitations or concerns should also be addressed. (1) The cross-sectional study did not provide a temporal interpretation of the causal effect of SO_x reduction on CVD prevention. However, since the national SO_x reduction in 2012 remained relatively constant compared to our 2016 data, it could be deemed as a marker for what has happened over many previous years. (2) Despite using an ecological study design, the potential for "ecological fallacy"[24] is unlikely because our analysis on aggregated data is meant to inform policy decisions at the national level and for international comparison, but not at the individual level[25]. (3) This approach can be regarded as conservative in the sense that some of these plants may have actually reduced emissions more than our approach recognizes, implying that our approach actually underestimates the association between SO_x and CVD/IHD. Countries with national SO_x controls equal to 0 had lower CVD incidence rates (631 vs. 960 cases per hundred thousand males, on average). However, note that plants with missing control data amount to less than 1% of the total global coal capacity, so different assumptions about these missing data are not expected to have a meaningful impact on the analysis. (4) The study did not adjust for meteorological, geographical and/or other covariates[26]. If we assume the lack of considering meteorological effect misclassified our exposure, we might underestimate the true effect as well. Other covariates, such as socioeconomic status has an impact on cardiovascular disease at individual[27] and national levels[28]. Also, we've adjusted per capita GDP(PPP) and the geographic region as proxy indicators of healthcare expenditure and living standard. However, similar to previous report[29], we didn't find any statistically significant relationship between coal capacity and socioeconomic status at the national level. (5) It is noteworthy that even though the study does not explicitly calculate the effects of detailed secondary formation and/or byproduct of SO_2, retrofitting SO_x control system reduces both SO_2 and its secondary products. It is the cumulative effect that is of interest in this study. We did not consider the influence of seasonal differences on SO_x emission, either. Instead, we focused on the aggregate effect of SO_x emission from coal-fired power plants. Higher incidence rate of CVD might be associated with higher amount of coal combustion in winters within a country[30]. (6) The outcome data were obtained and interpolated from the GBD estimation[22]. Although we acknowledged the possible inconsistency of over- or under-reports from the global incidence data, GBD estimation provided the most thorough CVD incidences that we could access for a better international comparison.

2.5 Conclusion

In conclusion, CVD is a common, costly, and often fatal condition. Improvement in SO_x controls in coal-fired power plants has a marked association with lower incidence of CVD and IHD. Although the causality and biological mechanisms need further exploration, SO_x emission is a pervasive public health issue with major cardiovascular and healthcare economic consequences. Since SO_x emission is primarily from coal combustion, regulations on SO_x emission do present a key target for national and international intervention.

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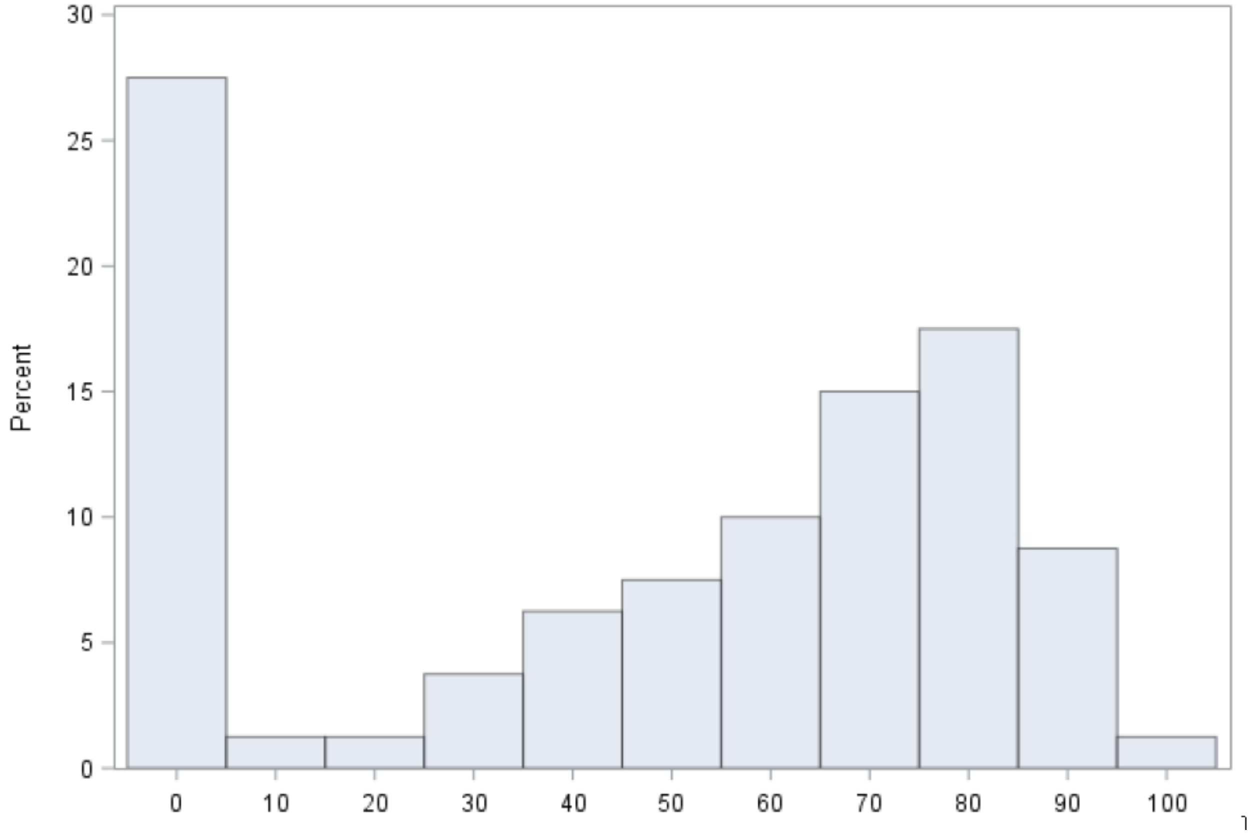
2.7 Supplementary Material



Supplementary Figure 2.1. Distribution of national reduction in sulfur oxide (SO_x) emissions

Legend: X-axis unit: percentage

Supplementary table 2.1 Reduction percentage of sulfur oxide control systems in coal-fired power plants

Reduction percentage	Emission control system
>= 95%	Noxso Corp or NOXSO process, Regenerative activated coke technology system (SO_2 and NO_X control), Flash dryer absorber system, Wellman-Lord process for FGD, sodium-sulfite based, Atmospheric circulating fluidized bed boiler, also used to code for SO2CTL for ACFB units, Compliance fuel/bubbling fluidized bed boiler, Combined SO_X and NO_X removal system, Pressurized fluidized-bed combustor, Spray-dry scrubber with activated carbon injection, Spray dry FGD with activated carbon injection, SNOX flue gas cleaning system, Wet limestone FGD plus activated carbon injection for mercury control
90%~95%	CANSOLV (regenerable aqueous amine FGD system), Circulating-bed FGD scrubber, aka Circoclean, Circulating dry FGD scrubber, First generation wet sulfuric acid FGD system developed by Chiyoda Corp, Wet limestone bubbling reactor FGD system developed by Chiyoda Corp, licensed elsewhere, Double alkali FGD scrubber, Dry FGD with activated carbon injection, Wet/dry lime spray FGD system, FGD scrubber (unspecified), Wet limestone FGD scrubber design, Lime injection, Limestone injection, Magnesium oxide FGD scrubber, Novel integrated desulphurization scrubber, generally supplied by Alstom (dry lime), NID FGD scrubber with activated carbon injection, Reflux circulating fluidized bed FGD scrubber with activated carbon injection, Spray dry FGD scrubber (typically using lime reagent), Spray dry FGD scrubber system, Spray dry circulating FGD, Spray dry rotary-atomizer FGD, Semi-dry lime FGD or other semidry gas cleaning system, Dry sorbent injection (typically lime or limestone) with activated carbon, Dry sorbent injection (typically lime or limestone) for acid gas or mercury control, Simplified Wet FGD (FGD design), Seawater FGD scrubber, Trona injection system for SO_2 control, Wet calcium carbonate FGD scrubber, Wet carbide sludge FGD scrubber, Wet FGD (unspecified), Wet FGD with sorbent injection for mercury control, Wet lime FGD scrubber, Wet lime-alkaline fly ash FGD scrubber, Wet lime/limestone FGD scrubber, Wet lime/magnesium FGD scrubber, Wet limestone FGD scrubber, Wet limestone FGD with sorbent injection for mercury control, Wet soda ash FGD scrubber, Wet sodium carbonate FGD scrubber, Wet scrubber (unspecified)
80%-90%	Ammonia or ammonium sulfate FGD scrubber, Bubbling fluidized bed boiler, Coal blending, Semi-dry circulating fluidized-bed FGD scrubber, Turbosorp scrubber, Semi-dry circulating fluidized-bed FGD scrubber/activated carbon injection, Dry aqueous carbonate FGD scrubber, Dry FGD scrubber (unspecified), Dry lime FGD scrubber, hydrated lime injection, Dry lime FGD scrubber, Hydrated lime injection with activated carbon or carbon filters, Dry scrubber, Reflux circulating fluidized bed FGD scrubber (semi-dry design)
<80%	Compliance fuel (fuel or fuels that allow plant to meet applicable air quality standards), Compliance fuel for SO_2 control, activated carbon injection for mercury control, Dalkia/Clarke, Limestone injection into furnace with CAO activation, Dry scrubber with additional sorbent injection for mercury control, Coal washing

Supplementary table 2.2 Estimated CVD and IHD incident cases attributable to suboptimal SO_2 controls in coal-fired power plants

			CVD				IHD			
Country	Sex	Population	Incidence	RR	PAF	Cases	Incidence	RR	PAF	Cases
Albania	Female	1436.63	948.0166	1.175434	0.080643	1098.32	332.6994	1.120829	0.056972	272.309
Argentina	Female	21503.12	512.0833	1.175434	0.080643	8879.937	138.2494	1.120829	0.056972	1693.673
Australia	Female	11453.16	596.1879	1.05574	0.005543	378.4986	135.7733	1.039021	0.003887	60.44336
Austria	Female	4322.8	1146.167	1.01978	0.001974	97.8099	251.4756	1.013919	0.00139	15.10961
Bangladesh	Female	76841.37	523.5315	1.055616	0.027056	10884.15	451.6289	1.038935	0.019096	6626.898
Belgium	Female	5644.75	1003.844	1.018798	0.001876	106.3196	235.4248	1.01323	0.001321	17.55785
Bosnia and Herzegovina	Female	1922.5	1349.059	1.10076	0.047964	1243.971	378.5058	1.070096	0.033861	246.4012
Botswana	Female	1067.29	414.3959	1.086453	0.041435	183.2599	294.6526	1.060262	0.029249	91.98368
Brazil	Female	102776.8	653.5399	1.123265	0.058054	38994.45	292.071	1.085489	0.040993	12305.18
Bulgaria	Female	3750.7	1819.806	1.034603	0.017007	1160.825	422.5572	1.024297	0.012003	190.2268
Cambodia	Female	7601.34	434.9973	1.175434	0.080643	2666.518	285.1735	1.120829	0.056972	1234.993
Canada	Female	17573.55	506.5908	1.039706	0.003955	352.0876	112.2493	1.02786	0.002778	54.80387
Chile	Female	8812.06	449.0074	1.044512	0.021771	861.4258	94.74023	1.03121	0.015365	128.2794
China	Female	657422.7	700.6195	1.062369	0.030242	139293.8	291.0682	1.043621	0.021345	40844.56
Colombia	Female	23779.63	537.3459	1.114032	0.053941	6892.487	322.2299	1.079185	0.038085	2918.254
Croatia	Female	2220.1	1641.567	1.067848	0.006739	245.6016	408.4573	1.047416	0.004719	42.7948
Czech Republic	Female	5365.17	1562.365	1.029876	0.002979	249.6866	446.0002	1.020992	0.002095	50.12648
Denmark	Female	2821.74	948.4362	1.016656	0.001663	44.50046	240.9256	1.011725	0.001171	7.961936
Dominican Republic	Female	5089.68	546.4754	1.175434	0.080643	2242.998	339.5946	1.120829	0.056972	984.728
Finland	Female	2759.47	1132.373	1.032421	0.003232	100.9806	242.2363	1.022772	0.002272	15.18731
France	Female	32612.88	864.7902	1.051859	0.005159	1455.044	156.0029	1.036324	0.003619	184.1362
Germany	Female	41004.3	1257.307	1.014896	0.001487	766.8374	269.0345	1.01049	0.001048	115.5947
Greece	Female	5671.2	1134.841	1.062683	0.006229	400.9089	226.2468	1.043838	0.004365	56.00309
Guatemala	Female	7857.16	305.8522	1.094385	0.045066	1082.985	220.9685	1.065719	0.031814	552.3477

Supplementary table 2.2 (Continued)

Honduras	Female	3869.12	419.2517	1.175434	0.080643	1308.142	353.301	1.120829	0.056972	778.7932
Hungary	Female	5224.77	1646.099	1.050101	0.024438	2101.815	420.8019	1.035101	0.017248	379.2129
India	Female	608395.9	580.7915	1.089801	0.042971	151838.6	444.3354	1.062566	0.030334	82003.18
Indonesia	Female	123023.8	585.1935	1.046935	0.022929	16507.51	395.3609	1.032898	0.016183	7871.139
Ireland	Female	2341.03	598.7613	1.02585	0.002578	36.14122	187.2539	1.018174	0.001814	7.952419
Israel	Female	3888.91	552.2559	1.103438	0.010238	219.8759	170.4386	1.071932	0.007142	47.33768
Italy	Female	30725	1137.151	1.052391	0.005212	1820.952	215.937	1.036694	0.003656	242.5618
Japan	Female	65248.03	789.7363	1.021489	0.002144	1104.952	89.37061	1.015118	0.001509	88.02237
Kazakhstan	Female	8704.79	997.3705	1.087462	0.041899	3637.603	548.851	1.060957	0.029577	1413.073
Kyrgyzstan	Female	2859.59	712.2386	1.175434	0.080643	1642.469	506.4876	1.120829	0.056972	825.159
Macedonia	Female	1038.72	1160.361	1.175434	0.080643	971.9844	373.8786	1.120829	0.056972	221.2555
Madagascar	Female	11185.48	476.2166	1.175434	0.080643	4295.631	452.8014	1.120829	0.056972	2885.542
Malaysia	Female	14643.78	452.7075	1.016588	0.008226	545.3192	348.5941	1.011678	0.005805	296.3342
Mauritius	Female	635.31	689.6669	1.175434	0.080643	353.3401	260.5811	1.120829	0.056972	94.31778
Mexico	Female	61356.42	436.2411	1.175434	0.080643	21585.12	249.4816	1.120829	0.056972	8720.947
Moldova	Female	2114.75	1085.014	1.039555	0.019394	445.0032	353.1582	1.027755	0.013687	102.2229
Mongolia	Female	1416.31	676.6552	1.08641	0.041416	396.9071	552.5462	1.060232	0.029236	228.7907
Montenegro	Female	315.8	1232.065	1.175434	0.080643	313.7714	325.4218	1.120829	0.056972	58.54958
Morocco	Female	16729.86	595.8472	1.175434	0.080643	8038.87	378.9147	1.120829	0.056972	3611.593
Myanmar	Female	26888.9	495.2436	1.175434	0.080643	10738.9	185.8823	1.120829	0.056972	2847.581
Namibia	Female	1179.11	417.027	1.175434	0.080643	396.5394	272.2096	1.120829	0.056972	182.8617
Netherlands	Female	8448.54	882.9135	1.016605	0.001658	123.6596	206.078	1.01169	0.001168	20.32932
New Zealand	Female	2261.65	692.0615	1.172589	0.016966	265.5531	183.0352	1.118914	0.011752	48.6472
Niger	Female	8752.39	318.5734	1.175434	0.080643	2248.558	296.7433	1.120829	0.056972	1479.696
North Korea	Female	12661.38	757.933	1.175434	0.080643	7738.908	266.6374	1.120829	0.056972	1923.389
Norway	Female	2501.19	866.7973	1.021024	0.002098	45.48486	213.2068	1.014791	0.001477	7.876089
Panama	Female	1864.78	495.4316	1.039555	0.019394	179.1761	245.4675	1.027755	0.013687	62.65292
Peru	Female	15091.89	409.406	1.175434	0.080643	4982.71	190.0625	1.120829	0.056972	1634.199
Philippines	Female	47460.39	521.6102	1.025829	0.01275	3156.284	452.8583	1.018159	0.008998	1933.872

Supplementary table 2.2 (Continued)

Poland	Female	19929.08	1533.488	1.065471	0.031698	9687.2	471.7375	1.04577	0.022373	2103.367
Portugal	Female	5507.9	1148.982	1.008544	0.000854	54.02133	265.6694	1.006022	0.000602	8.806075
Romania	Female	10269.04	1675.739	1.087629	0.041976	7223.256	443.641	1.061072	0.029631	1349.926
Russia	Female	76810.58	1673.768	1.143144	0.066792	85869.31	493.7753	1.099011	0.04717	17890.41
Senegal	Female	7027.06	358.2085	1.101841	0.048453	1219.643	306.0559	1.070838	0.034207	735.6847
Serbia	Female	4594.36	1583.284	1.08439	0.040487	2945.071	450.0703	1.058841	0.02858	590.9629
Slovakia	Female	2790.32	1202.691	1.109546	0.051929	1742.673	339.2174	1.076117	0.036663	347.0242
Slovenia	Female	1039.39	1361.105	1.045342	0.004514	63.85665	348.9872	1.031789	0.003169	11.49429
South Africa	Female	26900.78	660.7661	1.04024	0.019723	3505.83	353.3818	1.028232	0.01392	1323.242
South Korea	Female	24946.71	491.4082	1.015178	0.007532	923.3148	107.5745	1.010687	0.005315	142.641
Spain	Female	23641.93	894.8819	1.026422	0.002635	557.5256	174.296	1.018574	0.001854	76.39721
Sri Lanka	Female	10530.37	653.7116	1.008544	0.004254	292.8098	308.987	1.006022	0.003002	97.67073
Swaziland	Female	624.76	446.7208	1.175434	0.080643	225.0698	352.3253	1.120829	0.056972	125.4071
Sweden	Female	4783.81	1105.629	1.02004	0.002	105.7803	248.541	1.014101	0.001408	16.74185
Syria	Female	9877.31	387.4803	1.175434	0.080643	3086.428	354.5751	1.120829	0.056972	1995.317
Taiwan	Female	11642.5	667.9627	1.039454	0.019346	1504.457	244.2822	1.027684	0.013653	388.3024
Tanzania	Female	24484.47	445.9267	1.175434	0.080643	8804.85	483.4825	1.120829	0.056972	6744.294
Thailand	Female	34016.01	708.4309	1.022367	0.01106	2665.142	263.3032	1.015733	0.007805	699.0552
Turkey	Female	38068.52	614.7887	1.046147	0.022553	5278.409	336.825	1.03235	0.015917	2040.995
Ukraine	Female	24367.26	1798.855	1.078803	0.037908	16616.25	484.9034	1.054988	0.026758	3161.697
United Kingdom	Female	32296.93	916.5584	1.020999	0.002096	620.3132	237.5749	1.014774	0.001475	113.1913
United States	Female	158948.6	682.1426	1.021319	0.002127	2306.571	178.3509	1.014998	0.001498	424.534
Uzbekistan	Female	14528.69	628.6064	1.06019	0.029216	2668.222	467.7144	1.04211	0.020621	1401.231
Vietnam	Female	45692.84	649.6496	1.035247	0.017318	5140.752	280.4182	1.024747	0.012222	1566.026
Zimbabwe	Female	7378.07	356.9898	1.162583	0.07518	1980.168	335.7487	1.112167	0.053105	1315.514
Albania	Male	1444.04	1212.813	1.028914	0.014251	249.5881	586.6516	1.305222	0.132405	1121.663
Argentina	Male	20592.11	555.4942	1.028914	0.014251	1630.163	269.1305	1.305222	0.132405	7337.814
Australia	Male	11458.21	721.3166	1.009611	0.00096	79.36159	224.278	1.093506	0.009264	238.0691
Austria	Male	4132.68	1147.374	1.00346	0.000346	16.40108	383.7217	1.032805	0.00327	51.85251

Supplementary table 2.2 (Continued)

Bangladesh	Male	78416.02	594.7236	1.00959	0.004772	2225.602	535.6515	1.093294	0.044568	18720.2
Belgium	Male	5434.77	1048.155	1.00329	0.000329	18.73324	381.1493	1.031167	0.003107	64.36098
Bosnia and Herzegovina	Male	1905.92	1516.399	1.017074	0.008465	244.6371	647.4209	1.171408	0.078939	974.051
Botswana	Male	1065.53	437.8371	1.01473	0.007311	34.10805	442.0412	1.146422	0.068217	321.3069
Brazil	Male	99624.81	755.1746	1.02071	0.010249	7710.669	500.4346	1.211136	0.095488	47606.07
Bulgaria	Male	3553.04	1994.66	1.006017	0.002999	212.5724	752.2874	1.057661	0.028022	749.0136
Cambodia	Male	7230.92	413.7959	1.028914	0.014251	426.4129	364.8571	1.305222	0.132405	3493.168
Canada	Male	17294.6	651.7526	1.00689	0.000689	77.61155	193.9813	1.066272	0.006584	220.867
Chile	Male	8576.38	532.684	1.007709	0.00384	175.4265	198.2241	1.074407	0.035869	609.7868
China	Male	697964.3	819.8808	1.010726	0.005335	30527.07	393.8039	1.104845	0.049811	136911.3
Colombia	Male	23101.39	529.5706	1.019226	0.009521	1164.812	378.5253	1.194775	0.088745	7760.257
Croatia	Male	2066.92	1717.613	1.011644	0.001163	41.28878	694.5043	1.11425	0.011296	162.1513
Czech Republic	Male	5179.99	1552.708	1.005205	0.00052	41.84131	650.1549	1.04971	0.004946	166.5845
Denmark	Male	2779.24	1063.527	1.002917	0.000292	8.620235	393.1528	1.027596	0.002752	30.07003
Dominican Republic	Male	5065.36	595.2152	1.028914	0.014251	429.6699	412.1656	1.305222	0.132405	2764.3
Finland	Male	2665.18	1155.499	1.005643	0.000564	17.36693	386.0834	1.053988	0.00537	55.25441
France	Male	30948.92	891.618	1.008956	0.000895	246.91	272.6403	1.086889	0.008614	726.8461
Germany	Male	39473.65	1298.837	1.002611	0.000261	133.8281	418.9371	1.024667	0.002461	406.9125
Greece	Male	5438.46	1179.098	1.010779	0.001077	69.04572	359.3702	1.105382	0.010428	203.8132
Guatemala	Male	7511.6	293.1578	1.016032	0.007952	175.1187	225.6057	1.160248	0.07418	1257.106
Honduras	Male	3867.01	380.0417	1.028914	0.014251	209.4388	288.2117	1.305222	0.132405	1475.672
Hungary	Male	4733.57	1655.07	1.008658	0.00431	337.6979	734.1844	1.083897	0.04026	1399.153
India	Male	655193.7	688.6374	1.015281	0.007582	34210.8	646.9255	1.15225	0.07074	299840
Indonesia	Male	125014.1	638.0974	1.008121	0.004044	3226.123	515.1483	1.078517	0.037776	24327.76
Ireland	Male	2326.84	722.6209	1.004511	0.000451	7.581175	319.6768	1.042956	0.004277	31.81552
Israel	Male	3805.6	692.5598	1.017509	0.001748	46.0673	372.6577	1.176107	0.017306	245.4307
Italy	Male	29012.72	1169.195	1.009046	0.000904	306.57	362.1395	1.087795	0.008703	914.4083
Japan	Male	61891.8	868.3823	1.003757	0.000376	201.8202	162.5391	1.03566	0.003553	357.4582
Kazakhstan	Male	8116.67	917.8064	1.014896	0.007393	550.7367	718.0521	1.148178	0.068978	4020.193

Supplementary table 2.2 (Continued)

Kyrgyzstan	Male	2788.64	691.5559	1.028914	0.014251	274.8339	616.5091	1.305222	0.132405	2276.328
Macedonia	Male	1030.55	1366.235	1.028914	0.014251	200.6527	670.7576	1.305222	0.132405	915.2456
Madagascar	Male	11108.24	503.3256	1.028914	0.014251	796.7918	622.8854	1.305222	0.132405	9161.285
Malaysia	Male	14378.16	560.2147	1.002905	0.001451	116.8464	418.772	1.027483	0.013555	816.1922
Mauritius	Male	623.02	752.6469	1.028914	0.014251	66.82576	369.7969	1.305222	0.132405	305.0481
Mexico	Male	60714.54	450.5739	1.028914	0.014251	3898.606	302.6634	1.305222	0.132405	24330.76
Moldova	Male	1960	1156.163	1.006864	0.003421	77.51126	622.2282	1.066017	0.031954	389.6992
Mongolia	Male	1392.03	716.5069	1.014723	0.007308	72.88547	683.5988	1.146348	0.068185	648.8369
Montenegro	Male	308.06	1381.742	1.028914	0.014251	60.66146	590.5636	1.305222	0.132405	240.8824
Morocco	Male	16254.34	631.9166	1.028914	0.014251	1463.793	479.5488	1.305222	0.132405	10320.6
Myanmar	Male	25654.94	530.9697	1.028914	0.014251	1941.294	252.8733	1.305222	0.132405	8589.681
Namibia	Male	1112.54	426.1546	1.028914	0.014251	67.56682	417.5239	1.305222	0.132405	615.0352
Netherlands	Male	8300.78	993.3111	1.002908	0.000291	23.9742	341.3324	1.027512	0.002744	77.73664
New Zealand	Male	2174.24	901.6272	1.028475	0.002839	55.66217	337.2858	1.30002	0.029128	213.6079
Niger	Male	8883.39	394.0691	1.028914	0.014251	498.8864	472.0997	1.305222	0.132405	5552.844
North Korea	Male	12101.98	597.3016	1.028914	0.014251	1030.151	300.1489	1.305222	0.132405	4809.458
Norway	Male	2517.18	1047.397	1.003676	0.000367	9.687679	402.0075	1.034882	0.003476	35.17549
Panama	Male	1878.98	512.1484	1.006864	0.003421	32.91604	266.1825	1.066017	0.031954	159.8179
Peru	Male	15066.88	423.1158	1.028914	0.014251	908.5172	245.5731	1.305222	0.132405	4898.996
Philippines	Male	48556.93	589.0865	1.004507	0.002248	643.1612	641.5885	1.04292	0.021009	6545.075
Poland	Male	18680.41	1633.741	1.011246	0.005592	1706.512	816.1393	1.110166	0.052207	7959.4
Portugal	Male	5007.12	1061.784	1.001501	0.00015	7.980705	328.3564	1.014118	0.00141	23.17957
Romania	Male	9675.92	1821.362	1.014924	0.007406	1305.271	779.1578	1.148469	0.069105	5209.853
Russia	Male	66476.96	1581.859	1.023873	0.011796	12403.82	859.7572	1.246661	0.10979	62749.46
Senegal	Male	6753.05	366.3644	1.01725	0.008551	211.5602	442.105	1.173304	0.079742	2380.751
Serbia	Male	4388.22	1753.068	1.01439	0.007143	549.5375	763.9817	1.142838	0.066658	2234.729
Slovakia	Male	2625.18	1373.119	1.0185	0.009165	330.3861	699.8922	1.186856	0.085445	1569.918
Slovenia	Male	1023.5	1485.079	1.007851	0.000784	11.92339	618.6222	1.075814	0.007524	47.64119
South Africa	Male	25936.5	583.3448	1.006981	0.003479	526.3051	453.0044	1.067175	0.032496	3818.07

Supplementary table 2.2 (Continued)

South Korea	Male	24661.75	494.1631	1.00266	0.001328	161.8693	156.685	1.025135	0.012412	479.6007
Spain	Male	22995.16	874.8691	1.00461	0.000461	92.6901	280.2877	1.043914	0.004372	281.7985
Sri Lanka	Male	9891.49	713.5176	1.001501	0.00075	52.94107	409.7195	1.014118	0.00701	284.0848
Swaziland	Male	606.94	420.0358	1.028914	0.014251	36.33144	457.9608	1.305222	0.132405	368.0248
Sweden	Male	4759.65	1346.091	1.003505	0.00035	22.4492	462.085	1.033239	0.003313	72.86172
Syria	Male	10101.45	449.0501	1.028914	0.014251	646.4413	491.8048	1.305222	0.132405	6577.783
Taiwan	Male	11673.32	731.0352	1.006847	0.003412	291.1618	299.8653	1.065847	0.031874	1115.725
Tanzania	Male	24161.24	483.8605	1.028914	0.014251	1666.057	644.0696	1.305222	0.132405	20604.16
Thailand	Male	33148.12	770.8165	1.003908	0.00195	498.3502	336.4214	1.037126	0.018225	2032.357
Turkey	Male	36780.67	632.743	1.007988	0.003978	925.7582	463.3225	1.07718	0.037156	6331.932
Ukraine	Male	20952.69	1648.774	1.013466	0.006688	2310.473	783.4735	1.133151	0.06242	10246.74
United Kingdom	Male	31276.84	1017.431	1.003672	0.000367	116.7919	393.3242	1.034841	0.003472	427.1197
United States	Male	155850.9	774.1997	1.003727	0.000373	449.5184	277.9723	1.035374	0.003525	1527.099
Uzbekistan	Male	14063.76	621.3741	1.01036	0.005154	450.3594	572.9078	1.101112	0.048123	3877.389
Vietnam	Male	44642.71	569.426	1.006127	0.003054	776.4211	344.8591	1.058746	0.028535	4393.044
Zimbabwe	Male	7187.41	389.5593	1.026922	0.013282	371.8881	477.036	1.28179	0.123495	4234.217

CVD: cardiovascular diseases; IHD: ischemic heart diseases; PAF=population attributable factor; RR: relative risk.

Chapter 3. Are Per Capita Carbon Emissions Predictable Across Countries?

3.1 Introduction

The flying geese model (FG) of economic development was proposed and widely accepted to describe the industrial migration and economic developmental pattern in East Asian[1]. Like the first goose in a V-shaped formation, one economy can lead others toward industrialization, passing low value-added and labor-intensive industries down to the followers as its own incomes rise and moves into higher value-added industries[1]. Regional economics can exploit their comparative advantage through an orderly migration of industrial activities. Japan, East Asian newly industrialized economies (NIEs: Korea, Taiwan, Hong Kong, and Singapore), and some Association of Southeast Asian Nations (ASEAN) followed the industrial ladder and obtain great economic success in different eras of late 20th century[2]. Although the market size and detailed industrial structures are different in China and the other NIEs, this pattern of both economic growth and industrial transition still holds strongly in China[3,4].

Logistic curve (S-shaped, sigmoid curves) have been regularly used in economics to describe the evolution of the economic growth[5]. This natural phenomenon illuminates the economic growth coincident with Rostow's theory of five stages of growth[6]. As one of the major historical models of macroeconomic growth, Walt Whitman Rostow postulated the five basic stages, of varying length: (1) traditional society, (2) preconditions for take-off, (3) take-off, (4) drive to maturity, and (5) age of high mass consumption. Rostow also asserts that "countries go through each of these stages fairly linearly, and set out a number of conditions that were likely to occur in investment, consumption, and social trends at each state."[6]

The economic growth pattern in East Asian is similar within the region, but very unique compared to Western history, or Latin American[7] or African countries[8] either. Except Japan, most countries in East Asia went through industrialization after World War II [9,10]. Mirroring to Rostow's theory of five stages, most East Asian countries in the FG group went through producing labor-intensive consumer goods, such as textile industry initially. Followed by energy-intensive industry, such as concrete and steel industries, the earlier stage of industries lost competitive advantage due to a rise in wage [11]. Those energy-intensive industries would be subsequently replaced by capital intensive industries, such as finance, service and high techs [1]. Although scales might vary widely, the stages are followed constantly by every country in the FG group[3]. As a matter of fact, both theories could be regarded as two sides of a coin in the context of explaining economic growth pattern in East Asia[11]. Both provides the microeconomic understanding to the macroeconomic phenomenon and successfully explaining the economic growth of countries in East Asia.

Following the similar pattern, China has witnessed a very rapid and large scaled economic development. Concomitant with the massive industrial growth, China became the largest emitter of carbon dioxide (CO_2), contributing 25% of total emission in the world [12]. Chinese government pledged to cut the emission and stated in its intended nationally determined contribution (INDC). That is, by 2030, China peaks its CO_2 emission and lowers CO_2 emissions per unit of GDP by 60% to 65% from the 2005 level [13].

The per capita CO_2 emission in a country is proportional to its per capita energy consumption, given the energy matrix is constant across time. Furthermore, if the energy matrix is constant within individual country, the same logic in the similarity of industrial migration patterns between countries in a same FG group can apply to the similar patterns of per capita CO_2 emission. That is, the trajectories of per capita CO_2 emission for countries within a same FG and having relatively constant energy matrix across time, *ceteris paribus*, would just mirror each other. Indeed, limited to energy source, domestic politics and policy, facility inflexibility, and/or national security, most countries we studied countries have relative constant energy matrix during the period we studied. For example, coal consumption (production plus import) in China accounted for 66%±3.4% (mean±standard devitation (SD)) of total energy consumption; and 19%±2.9% in Japan in studied period (table 1).

Based on the theories explained above, we hypothesize per capita CO2 emission trajectory in one country can forecast per capita CO2 emission in another under two assumptions: (1) the studied countries fit into the same FG group, and (2) both predictor and predicted countries have relatively constant energy matrix across time. The theory would still hold even if there are substantial differences in industrial compositions and policies between the compared countries, as long as the life cycle of most industries follow the patterns described in the FG theory. We called this pattern "flying S" and applied this to predict emission in China.

In the study, we examine empirical data from leading goose of Japan, 2nd tier NIEs of Taiwan, Korea, Singapore, and Hong Kong, ASEAN of Thailand, Malaysia, Philippines, Indonesia and Vietnam, and next tier of China and India to validate our hypothesis. Subsequently, by exploiting the empirical data to the theory, we predict CO_2 emission of selected countries in 2030 and beyond.

3.2 Methods

3.2.1 Study period and data extraction

All data were obtained from World Bank[14], except Taiwan and China. Emission data in Taiwan is not available from World Bank and Chinese emission data from World Bank might be overestimated by up to 14% (2.49 gigatonnes of carbon)[15]. Therefore, data from the two countries are obtained from supplementary sources. Historical emission data were collected from China Energy Statistical Yearbook[16] and Bureau of Energy, Ministry of Economic Affairs[17], for China (1980-2015) and Taiwan (1961-2015), respectively. All unit conversions and step-by-step calculation are summarized in Appendix 1. In short, we followed the 2006 IPCC guidelines for National greenhouse gas (GHG) inventory from bottom-up method. That is:

$$\mathrm{CO_2\ Emission} = \mathrm{Emission\ from\ electricity\ \&\ heat} + \sum_{\mathrm{i}} \mathrm{Fuel\ consumption_i} \times \mathrm{Emission\ factor_i} \times \mathrm{Oxidation\ factor_i}$$

where i denotes different types of fossil fuel. Oxidation factor is set one by default and emission factors are IPCC default values for Taiwan. Since applying IPCC default values of emission factors might lead to substantial error in China, we carefully select most suitable factors for China from different sources and summarized in Appendix 1.

Nominal GDP and chain GDP (GDP[PPP]) were obtained and calculated deflated at 2011 values in both countries[18,19]. By sector emission data and GDP were only available from the national Bureau of Statistics and Statistical Bureau in China[18] and Taiwan[19], respectively. Sectoral classification are different and were summarized into four comparable categories of primary (farming), secondary (industry), tertiary (trade and transport), and residential consumption in two countries (Appendix 2). For data consistency, population and education, as the other possible predictors, were also collected from the same database for both countries[18,20].

3.2.2 Assumptions check

A total of 12 countries/economies in East Asia are well known in the same FG group from literature review[2]. To check up the constant energy matrix assumption, the percentages of energy consumption (production plus import) of major brown energy (namely, coal, gas and oil) are calculated across time[21]. The mean and standard deviation (SD) of the percentages are reported on table 1. We defined the energy matrix is relatively constant in a country If its mean-to-SD ratio of the dominant brown energy is larger than 6 in a given country.

3.2.3 Analytic model

We applied non-linear mixed effect modeling to examine the ex post data and predict per capita emission for selected countries. Our model is written as follows:

$$(\text{Per capita CO}_2\text{ emisison})_{it} = \frac{P_0 + P_1 \times (\text{Coal consumption})_i}{1 + \mathrm{e}^{-\left(\frac{t-\text{year}_i}{s}\right)}} + \varepsilon_{it}$$

The formula is a modified sigmoid curve for country i in year t. $P_0 + P_1 \times (\text{Coal consumption})_i$ is the country-specific plateau for per capita CO_2 consumption, which is regressed on average coal consumption percentage for country i (over years in which data is available). The scale factor s, addressing the "catching up" process is assumed fixed and estimated as 11.32 years from the regression model. Year_i denotes country-specific transition years when growth rate begins slowing down, i.e. the inflection point in the sigmoid curve.

Due to the difficulty in obtaining confidence bands in nonlinear mixed effects least squares, we simulate 1000 predictions from the model fit and construct 95% pointwise confidence bands from these fits. Specifically, the initial model fit provides estimates $\left(\hat{P}_0, \hat{P}_1, \widehat{\mathrm{year}}_i, \hat{s}\right)$ with respective covariance matrix, say, $\hat{\Sigma}$. We sample replicates $\left(\hat{P}_0^{(b)}, \hat{P}_1^{(b)}, \widehat{\mathrm{year}}_i^{(b)}, \hat{s}^{(b)}\right)$, for $b = 1, \cdots, 1000$, from a multivariate normal distribution with mean $\left(\hat{P}_0, \hat{P}_1, \widehat{\mathrm{year}}_i, \hat{s}\right)$ and covariance $\hat{\Sigma}$, which in turn are used to predict $(\text{Per capita CO}_2\text{ emisison})_{it}^{(b)}$ for each i and t, using the modified sigmoid model. We construct bands by taking the 2.5 and 97.5 percentile observations $(\text{Per capita CO}_2\text{ emisison})_{it}^{(b)}$ over replicates $b = 1, \cdots, 1000$ for each i and t. We further multiply the estimated population[22] by per capita CO2 emission to obtain the total emission from one country. All the analysis were performed in R 3.2.

3.3 Results

Among the 12 selected countries of the FG group, table 1 demonstrates the mean, standard deviation (SD) and mean-to-SD ratio of the percentage of three major brown energy production & consumption. Not every country had a relatively constant energy matrix. For example, 25% of total energy produced and imported in Korea were from coal, however, as the highest percentage of brown energy, the 95% confidence interval (CI) ranges widely from 11.28% to 38.72%, corresponding to the mean-to-SD ratio as low as 3.84. In contrast, coal accounted for 66% of energy product and import in China, which was relatively constant (95%CI=60.12%~71.88%) across decades. Based on table 1, we selected six countries of Japan, Taiwan, Thailand, Malaysia, China and India for further analysis.

Table 3.1 Mean, standard deviation (SD) and ratio of three major brown energy production & consumption in selected countries

Country	Studied year	Energy production &import	Mean	SD	Ratio
Japan	1971-2015	Coal	19%	3%	6.445126
		Gas	11%	6%	1.800871
		Oil	10%	2%	5.020363
Taiwan	1991-2015	Coal	31%	4%	8.180533
		Gas	7%	3%	2.532968
		Oil	40%	4%	9.486339
Korea	1971-2015	Coal	25%	7%	3.84191
		Gas	5%	5%	1.063375
		Oil	8%	4%	1.875851
Singapore	2000-2015	Coal	0%	0%	0.519467
		Gas	4%	1%	3.627806
		Oil	56%	10%	5.665901
Hong Kong	1991-2015	Coal	22%	14%	1.591906
		Gas	4%	5%	0.901509
		Oil	72%	15%	4.731587
Thailand	2000-2015	Coal	11%	1%	10.21173
		Gas	24%	1%	23.69161
		Oil	2%	1%	1.409736
Malaysia	1991-2015	Coal	6%	4%	1.45201
		Gas	41%	6%	6.957869
		Oil	39%	8%	4.596107
China	2000-2015	Coal	66%	3%	19.074
		Gas	3%	1%	2.65566
		Oil	2%	0%	6.497731

Table 3.1 (Continued)

Vietnam	1991-2015	Coal	21%	8%	2.633551
		Gas	5%	4%	1.27257
		Oil	24%	5%	4.444757
India	2000-2015	Coal	36%	3%	11.29546
		Gas	6%	1%	7.65874
		Oil	2%	1%	3.694636
Indonesia	2000-2015	Coal	38%	13%	2.944042
		Gas	18%	4%	4.8922
		Oil	6%	1%	7.918975
Philippines	1991-2015	Coal	14%	7%	2.009664
		Gas	3%	3%	1.078001
		Oil	31%	10%	3.222504

Foot note: data source: International Energy Agency[21]

Per capita CO_2 emission in Japan took off earliest among the studied countries and reached the plateau after 1970. Followed by Taiwan, with a complete classical S-shaped trajectories observed during the studied period. Taiwan's per capita CO_2 emission exceeded Japan after 2000 and gradually reached plateau thereafter. Meanwhile, the per capita emission in China mirrors the other countries and took off after 2000 (Figure 1). The historical record of per capita CO_2 emission in the other countries are shown in the Supplementary Figure 1.

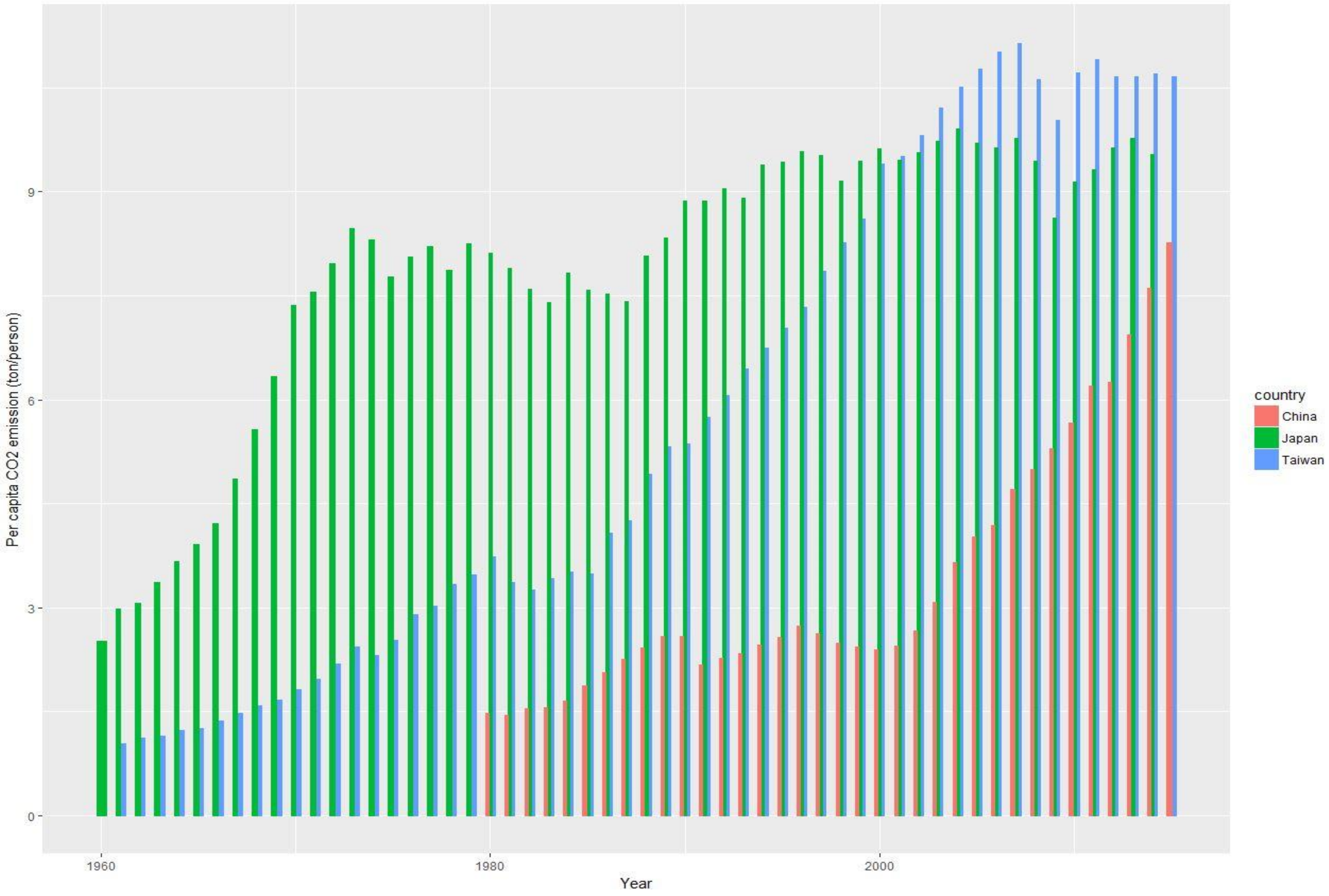


Figure 3.1. CO2 emission per capita in Japan, Taiwan and China, 1960~2015

.Figure 2 demonstrates the per capita CO2 emission from different sectors in Taiwan and China, respectively. “Flying S” model of per capita emission fits best in secondary and tertiary industrial sectors as they are the major economic drives in FG theory. Total CO2 emission (data not shown) and per capita CO2 emission from secondary industrial sector dropped in 2009 in Taiwan, corresponding to the financial crisis globally. The crisis did not affect the total emission in China, possibly reflecting the giant domestic market. The emissions in both countries do not mirror to each other in primary industrial sector, however, the scales are relatively negligible compared to the other sectors (less than 0.2 ton/person in Taiwan and 0.15 ton/person in China). Per capita emission in residential consumption were higher before 1990 in China, most probably reflects the indoor combustion for heat in the early age. As a tropical country, Taiwan, in contrast, do not use coal heaters in most families. During 1990 to 2000, electrical heaters and electrification of household appliance replaced the old coal-combustion heater gradually[23]. After that, the emission trajectory mirrored Taiwan as living standard elevated.

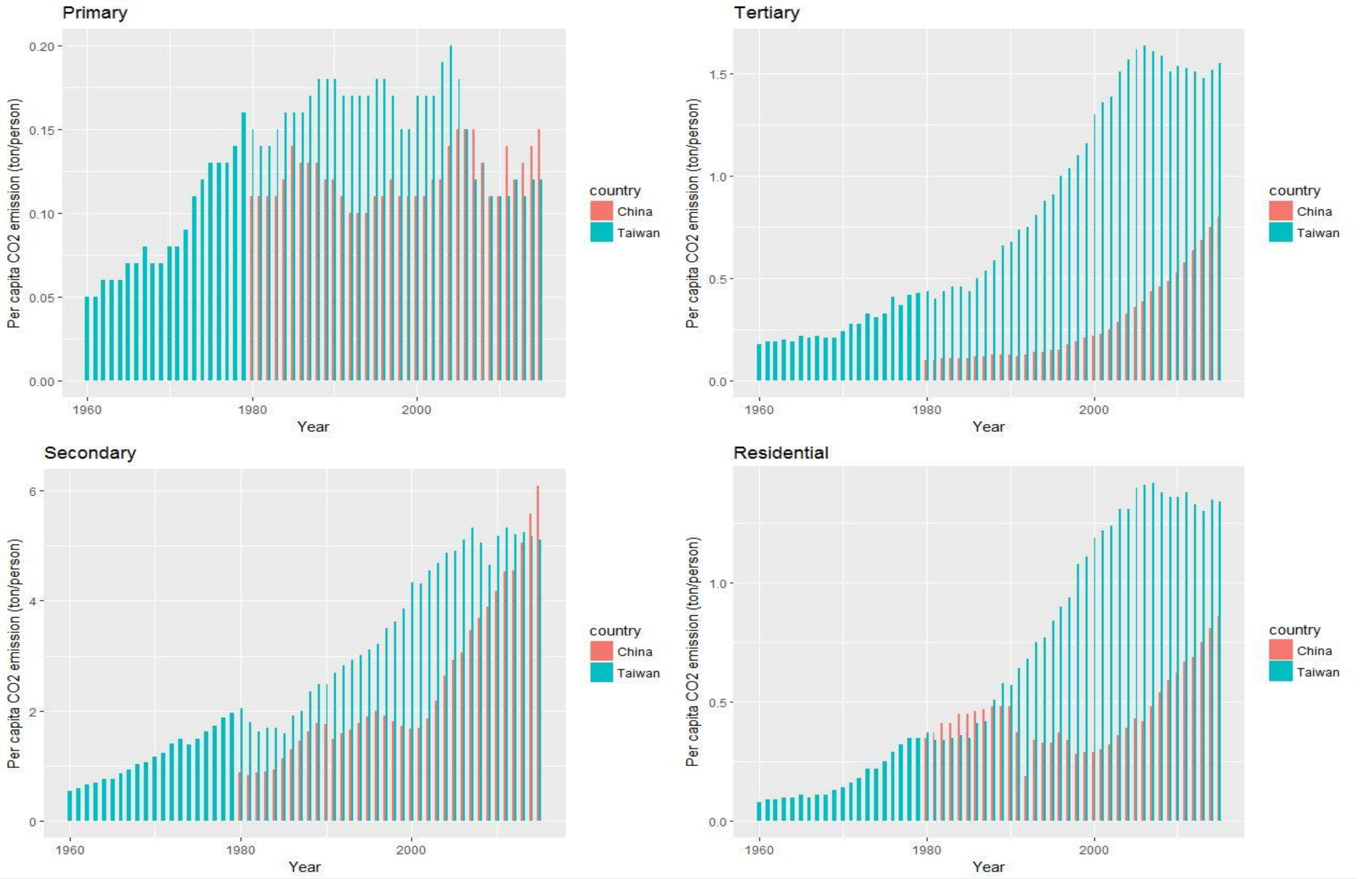


Figure 3.2. Per capita CO2 emission from different industrial sectors and residential consumption in Taiwan and China, 1960-2015

Per capita CO_2 emission vs. per capita nominal GDP illuminates the CO2 emission at different levels of economic development in a country. We observed the similar emission vs. GDP relationship of the six countries, which further validate the assumptions of our FS hypothesis (Supplementary Figure 2).

Table 2 summarized country-specific parameters of selected countries from our analysis. In the model, Japan reaches the transition year in 1966, which is 24 years earlier than Taiwan. In China, the transition year is 2018, which implies the growth rate of per capita CO2 emission will slow down since then. Meanwhile, India is still accelerating the rate of per capita CO2 emission until 2032 under our prediction. China has the highest plateau of 17.62 tons of CO2 per capita, due to its great dependent on coal consumption (66%, table 1). In our analysis, China will emit 13.17 (95%CI=6.90-16.68) tons of CO2 per capita in 2030, corresponding to 18648.72 $MtCO_2$/year, given China's population is 1.42 billion in 2030[22]. The total emission from China will be twice higher as India and 15 times higher than Japan. The historical records of per capita CO_2 emission and predicted emissions of the 6 selected countries are illustrated in Figure 3.

Table 3.2 Summary of country-specific parameters and predicted emissions of 6 selected countries

	Transition year	Plateau[a]	Per capita CO2 emission in 2030[a]	Population in 2030[b]	Total CO2 emission in 2030[c]
China	2018	17.62	13.17 (6.90-16.68)	1416	18648.72 (9770.40-23618.88)
India	2032	12.88	5.91 (1.89-10.26)	1528	9030.48 (2887.92-15677.28)
Japan	1966	10.19	10.15 (9.87-10.42)	120	1218 (1184.40-1250.40)
Malaysia	1991	8.13	7.88 (7.01-8.43)	36	283.68 (252.36-303.48)

Table 3.2 (continued)

Taiwan	1990	12.09	11.74 (10.67-12.32)	24	281.76 (256.08-295.68)
Thailand	2009	8.92	7.71 (5.12-8.72)	68	524.28 (348.16-592.96)

a Unit: tons/person

b Unit: million people

c Unit: Million tons

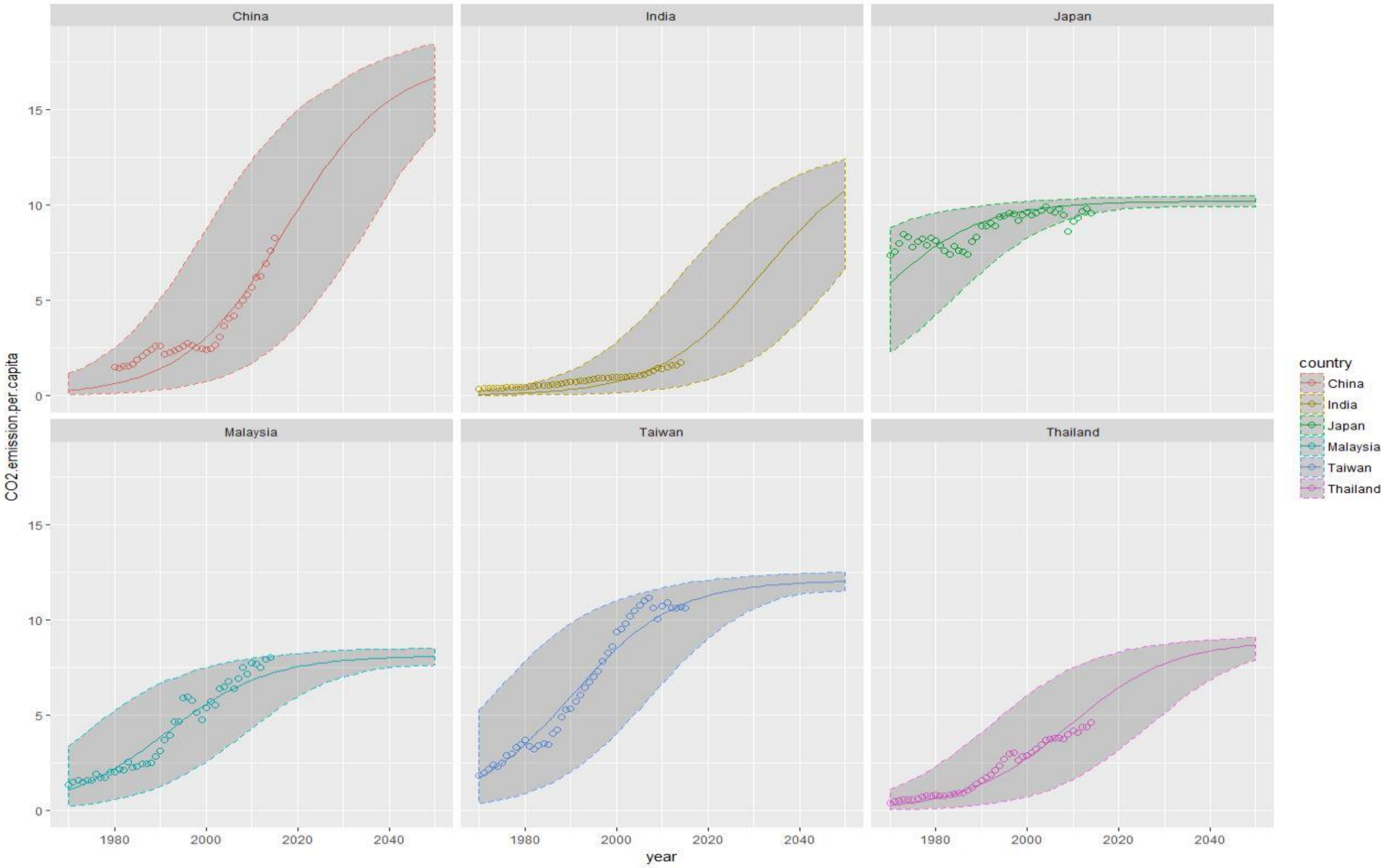


Figure 3.3. Historical and predicted per capita CO2 emission in selected countries, 1960-2040

3.4 Discussion

We predict China will emit 18648.72 $MtCO_2$/year (95%CI=9770.40-23618.88) in 2030. We also predict the CO_2 emissions per unit of GDP in China will be 0.49 kg/USD in 2030, which number easily meets Chinese INDC goal as lower CO_2 emissions per unit of GDP by 60-65% from 2005 level (1.82 kg/USD) by 2030. Our study proposed another approach to predict GHG emission for countries in the same FG group and could be an important application of FG paradigm in climate change.

Our prediction of China's CO_2 emission is comparable to the other studies. Most studies predicted annual CO_2 emission from fossil fuel and industry will range from 8000 $MtCO_2$/year up to 19000 $MtCO_2$/year in different scenarios[24-26].

The question can be deemed as transformation of economic growth pattern to GHG emission pattern. The energy consumption patterns of two countries mirror each other if they are both in the same FG group, because they follow the same industrial ladders from previous macroeconomic theories[1,6]. Since emission factor of any brown energy is fixed across time, as physical principle, the energy consumption pattern in one country is exactly proportional to its GHG emission, if, and only if the energy matrix is constant across time within the country.

3.5 Limitations

Many critiques and discussions on FG model will also rise concerns on FS hypothesis [2,27,28]. However, most of them are not quite relevant to CO_2 emissions. For example, some suggested the inward-looking Chinese economy would be very different from the economic structures in Japan and first-tier NIEs [2,29]. Also, the regionalization of East Asia has not been self-contained. While technology and capital might have been outsourced dominantly from Japan, final products are exported to third-party markets outside the region [2]. Those concerns are mainly from consumption side, rather than production side. No matter the markets are inside or outside the region, the industrial process incur GHG emission, not the location of market.

Constant energy matrix across time might be a strong assumption. For example, U.S. energy mix changed significantly since 2007 due to the shale gas revolution, which brought dramatic impacts on economics, geopolitics and national security[30]. However, the global energy mix did not change much over the last 50 years, especially in many East Asian counties[31]. We examine the assumption carefully on the historic data before fitting the model. Calculation of emission data might be hazy in some countries. For example, emission from various international organizations and Chinese Year book are different due to different scopes, methods and underlying data of fossil fuel consumption and emission factors[32]. We used the IPCC bottom-up method with the country-specific emission factor, consistent across time in the study.

In the analysis, we did not consider policy or advanced technology in the future. The effect of those challenges, however, remain unknown. The predictions could be interpreted as business as usual (BAU), driven and limited to macroeconomic growth in the region. Indeed, most scholars still believe the scale effect of economic growth might still be the dominant drive to CO_2 emission, outweighing any magic bullet of technology[33,34]. For example, some scholar forecasted the total capacity of CCS will increase to 2000GW by 2030 and 2500GW by 2050[35]. However, it may still not be mature enough to mitigate GHG emission, especially in such large scale in China [36]. Although the costs on renewable energy dropped dramatically in the recent decade, the total replacement of renewable is still limited in economically based world and mismatch the consumption and production [37].

3.6 Conclusions

Our study bridges a well-known FG paradigm in macroeconomics to Climate change study and proposes “flying S” hypothesis to predict and explain GHG emissions of the same FG countries in Asia. The “flying S” hypothesis provides a framework to describe and understand GHG emissions trajectories of developing countries under Asian development context, such as China and India.

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3.8 Supplementary materials

3.8.1 Appendix 1 Bottom-up calculation of CO2 emission in China

We applied the following formula to estimate CO_2 emission in China.

$$CO_2\ Emission = Emisison\ from\ electricity\ and\ heat + \sum_i Fuel\ consumption_i \times Emission\ factor_i \times Oxidation\ factor_i$$

Table 1 and Table 2 summarize the emission factors and oxidation factors of different energy sources in China and Taiwan, respectively.

To estimate CO_2 emission from electricity and heat, we use the following formula:

$$CO_2\ Emisison\ from\ electricity\ and\ heat_i = \frac{electricity\ and\ heat\ consumption_i}{total\ electricity\ consumption} \times total\ CO_2\ Emisison\ from\ electricity\ and\ heat$$

Supplementary Table 3.1. Emission factors and Oxidation factors for different energy sources in China

Item	Chinese name	Emission factor (CO_2/TJ)	Oxidation factor(1.0 = 100%)
raw coal	原煤	99.77	0.94
cleaned coal	洗精煤	93.17	0.90
other coal	其他洗煤	93.17	0.90
Briquette	型煤	123.20	0.90
Gangue coal	煤矸石	87.30	1.00
Coke	焦炭	108.17	0.93
Coke oven gas	焦炉煤气	49.79	0.99
Blast furnace gas	高炉煤气	259.60	0.99
Oxygen steel furnace gas	转炉煤气	181.87	0.99
Other coal gas	其他煤气	44.73	0.99
Other coking chemicals	其他焦化产品	108.17	0.93
Crude oil	原油	73.30	0.98
Gasoline	汽油	70.00	0.98
Kerosene	煤油	71.90	1.00
Diesal oil	柴油	74.10	0.98
Fuel oil	燃料油	77.40	0.98

Supplementary Table 3.1. (continued)

Naphtha	石脑油	73.33	0.98
Lubricants	润滑油	80.67	0.98
Paraffin waxes	石蜡	73.30	1.00
Solvents	溶剂油	73.30	1.00
Asphat	石油沥青	80.67	0.98
Petroleum coke	石油焦	100.83	0.98
LPG	液化石油气	63.10	0.98
Refinery gas	炼厂干气	66.73	0.98
Other petroleum products	其他石油制品	73.30	0.98
Natural gas	天然气	56.10	0.99
LNG	液化天然气	56.10	0.98

Supplementary Table 3. 2. Emission factors and Oxidation factors for different energy sources in Taiwan

Item	Emission factor	Oxidation factor (1.0 = 100%)
煙煤-煉焦煤(Bituminous Coal-Coking Coal)	94,600	1
煙煤-燃料煤(Bituminous Steam Coal)	94,600	1
無煙煤(Anthracite)	98,300	1
亞煙煤(Sub-bituminous Coal)	96,100	1
褐煤(Lignite)	101,000	1
泥煤(Peat)	106,000	1
焦炭(Coke Oven Coke)	107,000	1
煤球(Patent Fuel)	97,500	1
焦爐氣(Coke Oven Gas)	44,400	1
高爐氣(Blast Furnace Gas)	260,000	1
轉爐氣*(Oxygen Steel Furnace Gas)	182,000	1
原油(Crude Oil)	73,300	1
煉油廠進料(Refinery Feed stocks)	73,300	1
添加劑/含氧化合物 (Additives/Oxygenates)	73,300	1
煉油氣(Refinery Gas)	57,600	1
液化石油氣(LPG)	63,100	1
天然汽油(Natural Gasoline)	63,100	1
石油腦(Naphthas)	73,300	1
車用汽油(Motor Gasoline)	69,300	1
航空汽油(Aviation Gasoline)	70,000	1
航空燃油-汽油(Jet Fuel-Gasoline Type)	70,000	1
航空燃油-煤油(Jet Fuel-Kerosene Type)	71,500	1
煤油(Kerosene)	71,900	1

Supplementary Table 3. 2. (Continued)		
柴油(Diesel Oil)	74,100	1
燃料油(Fuel Oil)	77,400	1
白精油(White Spirits)	73,300	1
潤滑油(Lubricants)	73,300	1
柏油(Asphalts)	80,700	1
溶劑油(Solvents)	73,300	1
石蠟(Paraffin Waxes)	73,300	1
石油焦(Petroleum Coke)	97,500	1
其他石油產品(Other Petroleum Products)	73,300	1
(自產)天然氣(Indigenous-Natural Gas)	56,100	1
(進口)液化天然氣(Imported- LNG)	56,100	1
事業廢棄物之廢輪胎(Industry waste-scrape tyre)	81,480	1
一般廢棄物(Muncipal Wastes non-biomass fraction)	91,700	1

Reference

1. IPCC(2006), Guidelines for National Greenhouse Gas Inventories Volume 2: Energy, Table 2.4。
2. 廢輪胎：美國環保署(2013), Greenhouse Gas Inventory Protocol Core Module Guidance， US EPA Greenhouse Gas Reporting Rule and Regulation, Table C-2 to Subpart C。

3.8.2 Appendix 2 Sectoral classification in China and Taiwan

Industry	Taiwan[1]	China[2]
Primary	A 農、林、漁、牧業 B 礦業及土石採取業	1.农、林、牧、渔业
Secondary	C 製造業 D 電力及燃氣供應業 E 用水供應及污染整治業 F 營造業	2.工业 #用作原料、材料
Tertiary	G 批發及零售業 H 運輸及倉儲業 I 住宿及餐飲業 J 資訊及通訊傳播業 K 金融及保險業 L 不動產及住宅服務業 M 專業、科學及技術服務業 N 支援服務業 O 公共行政及國防；強制性社會安全 P 教育服務業 Q 醫療保健及社會工作服務業 R 藝術、娛樂及休閒服務業 S 其他服務業	3.建筑业 4.交通运输、仓储和邮政业 5.批发、零售业和住宿、餐饮业
Residential consumption	住宅部門	7.生活消费 城 镇 乡 村

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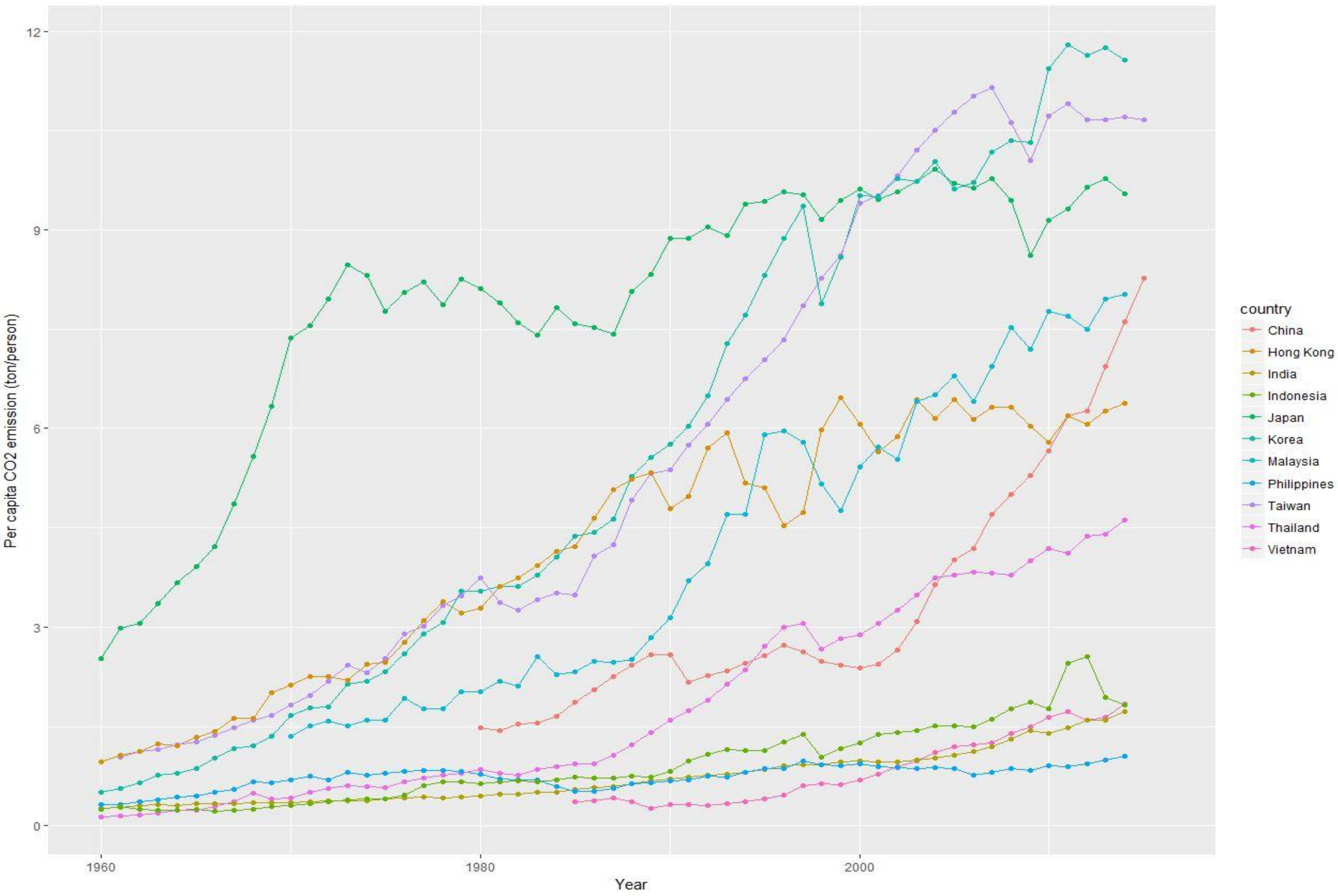

Supplementary figure 3.1 CO_2 emission per capita in East Asia flying geese group countries, 1960~2015

Supplementary figure 3.2. Per capita CO2 vs. per capita nominal GDP among 6 selected countries

Summary and Conclusion

We demonstrated an association between lung cancer incidence and coal-fired power plants via a novel approach that measures per capita coal capacity rather than PM. With a 1 KW increase of coal capacity per person in a country, the relative risk of lung cancer increases by a factor of 58.5% among males and 85.1 % among females. The study may be helpful in addressing a key policy question about the externality cost of coal power plants and estimates of the global disease burden from preventable lung cancer attributable to coal-fired power plants.

In chapter two, we provide scientific evidence that improving SO_x controls in coal-fired power plants has a marked association with lower incidence of CVD and IHD. Although the causality and biological mechanisms need further exploration, SO_x emission is a pervasive public health issue with major cardiovascular and healthcare economic consequences. Our study demonstrated that for 10% reduction in SOx emission, CVD incidence rates could decrease by 0.28% for males and 1.69% for females. Up to 1.43% and 8.06% of incident CVD cases are attributable to sub-optimal SOx control.

In Chapter three, we bridged a well-known FG paradigm in macroeconomics to Climate change study and proposes "flying S" hypothesis to predict and explain GHG emissions of the same FG countries in Asia. The "flying S" hypothesis provides a framework to describe and understand GHG emissions trajectories of developing countries under Asian development context, such as China and India.

Further studies might focus on the effectiveness of pollutant controls on health outcomes, quality of coal, synergistic effects between tobacco smoking and environmental exposure, and the financial burden of coal on healthcare expenditures. Policy maker might also focus on the geographic discrepancy on where the exposure to climate change is highest, while adaption capacity is lowest. Cost-effectiveness analysis is necessary to evaluate the economic benefit to remove coal-fired power plants and/or retrofitting the pollutant controls within the plants. Since current research already represented the relative risks of coal-fired power plants, multiplying a $ sign on the health loss in contrast to the potential loss from economic growth might further demonstrates the economic ground to reframe the energy matrix. With such strong evidence provided in the dissertation, we offer a clear scientific data to support public health implication of changing climate. International bodies should take immediate steps to curb GHG emission globally.