Evaluation of Potential Co-benefits of Air Pollution Control and Climate Mitigation Policies for China's Electricity Sector

1. Introduction

China's economy has grown rapidly over the past decade with an annual growth rate of 4.4% of its primary energy consumption from 2006 to 2016 (BP, 2018). In 2010 China's total energy consumption has also surpassed that of the US and became the world's largest energy consumer. Given that almost half of China's electricity is generated by coal-fired power plants (Qi et al., 2016), China is also the one that emitts the most greenhouse gases (GHG) and suffers from severe regional air pollution. In 2017, coal-fired power plants accounted for 4,565 million tonnes (Mt) of CO_2 emissions, 1.2 Mt of SO_2 emissions, 1.14 Mt of nitrogen oxides emissions, and 0.26 Mt of $PM_{2.5}$ emissions (IEA, 2019). As the main cause of air pollution in China, coal combustion is estimated to contribute 40% to the total $PM_{2.5}$ concentration at its national level (Ma et al., 2017).

The Chinese government has made substantial efforts to reduce regional and global air pollutants by, for example, promoting renewable energy generation and introducing air pollution standards and regulations. As a result, the overall air quality in the country has improved significantly and China has made substantial progress to mitigate air emissions, such as decreasing SO_2 from burning coal and has reached comparable levels to the US with 0.5 g SO_2/kWh (IEA, 2018). However, it is still far away from clean air and SO_2, NO_x, smoke and dust, as well as VOCs, remain at a high level with more than 10 million tons/year (Ministry of Environmental Protection, 2018) and surpass often Chinese standards according to the Pollution Map Database[1]. This can be explained by strong economic growth driving further industrial expansion and household consumption, and the time it takes to achieve changes in energy infrastructure.

[1] http://wwwen.ipe.org.cn/MapPollution/Pollution.aspx?q=3&type=1

Given the high coal use in the Chinese electricity industry this sector has also a prime obligation in contributing to both regional air pollution and GHG emissions reductions. It is, however, a complex and challenging sector to reform given its vital economic role and capital-intensive infrastructure. Clearly, also, policies intended to address either regional air pollution or GHG emissions may well impact on the other. There are certainly potential co-benefits given that both regional air pollution and GHG emissions are invariably co-generated when fossil fuels, most particularly coal, are burnt. Additionally, the electricity industry, in particular thermal power, is not only the major source for direct $PM_{2.5}$ emissions but also makes the biggest contribution to SO_2 and NO_x emissions, which are precursors for additional $PM_{2.5}$. As such, the growth of SO_2 and NO_x emissions is the biggest threat to the $PM_{2.5}$ governance and thermal power generation is the largest sectoral source of $PM_{2.5}$ emissions (Mo and Zhu, 2013; Mo et al., 2013).

Which policy or policy mix for the electricity sector can achieve both global climate change as well as regional air pollution targets most efficiently is therefore a question of vital importance to policy makers, and will be the focus of this study. Since policies that target regional air quality provide direct national benefits and address a problem of growing public concern, this study particularly focuses on the potential co-benefits of regional air pollution control in the electricity sector on GHG emissions. Since the stringency of these policies in China has significantly tightened in recent years and associated pollution taxes have reached much higher levels than before, there is great interest in their effect on future electricity generation investment. On the other hand, pressures on China to address its world-leading GHG emissions seem likely only to grow, so there is also value in assessing the impact of climate policy approaches for the electricity sector on associated regional pollutant emissions. Finally, there are the potential impacts of mixes of both types of policy efforts.

This paper assesses the potential impacts of the policy or policy mix on future generation investment in China's electricity sector in 2030 using a previously developed decision-support tool for modeling generation portfolios. This tool incorporates load duration curve techniques with Monte Carlo Simulation and Mean Variance Portfolio Theory and it has been applied to a range of electricity industries around the world (Vithayasrichareon and MacGill, 2012a).[2] By taking different policy efforts into account, the model can analyze the potential trade-offs between different future generation portfolios in terms of expected electricity generation costs and their associated uncertainties as well as their environmental impacts based on the calculated expected emissions of CO_2 and air pollutants. The main contribution of this method is the way in which uncertainties are incorporated in long-term planning through the application of Monte Carlo simulation techniques.

The data for electricity demand, technical and economic parameters of each generation technologies, fuel prices, carbon price, air pollution control costs and air pollutant taxes which are used in the modeling are derived from Chinese sources. This study goes beyond existing work by: (i) comparing single versus combined climate and air pollution policy scenarios, (ii) including $PM_{2.5}$ in addition to NO_x and SO_2, which other co-benefit studies have generally focused upon, (iii) using a portfolio assessment model, which allows incorporation of key uncertainties and (iv) taking the revenues generated from a carbon price and environmental taxes into account when assessing overall generation costs. The latter allows estimation of the 'net' generation costs of different generation portfolios.

The result shows that while both carbon price and air pollution control policies can deliver co-benefits, the co-benefit from a sufficient carbon pricing policy to air pollutant emissions reductions is much stronger than that from stringent air pollutant policies to carbon mitigation. In particular, regulatory measures that require air pollution reductions from the coal-fired plant through the use of scrubber and other clean-up technologies can effectively control regional air pollutant emissions but will, alone, have only limited impact on reducing carbon emissions. The impact of taxes on regional air pollutants as an alternative to regulation depends, of course, on the level of these taxes. Low taxes do not provide assurance that coal generation will

[2] The code and data for the model CEEM MC-ELECT (Monte Carlo Electricity Generation Portfolio Assessment Tool) is available here: http://ceem.unsw.edu.au/open-source-tools

implement air pollution clean-up, rather than just paying the tax and this poses a risk to effective action. Another consideration, evident in the Chinese experience to date with both these measures, is the ability of regulators to actually enforce such regulations or taxes. In a somewhat analogous manner, carbon pricing alone will reduce the amount of coal-fired generation and hence air pollution but, alone, won't incentivize the remaining coal plants in the generation mix to clean up its air pollutant emissions. Therefore, in order to achieve the goal of effective and efficient control of carbon and pollutant emissions, both air pollution control and climate change policies are almost certain to be required in combination.

The paper is structured as follows: First, the challenges facing China with regard to electricity demand and environmental impacts are described. Second, the literature on co-benefits is reviewed. Third, the modeling approaches and policy scenarios are presented. Fourth, the methodology namely the portfolio assessment model, as well as the data which are applied in the modelling, are further explained. Finally, the results are presented and discussed in section 5, while section 6 draws conclusions.

2. Co-benefits between air pollution control and climate change policies

Emissions of SO_2, NO_x and CO_2 are inherent outcomes of fossil fuel burning. This provides potential synergies of controlling emissions of GHG and air pollutants simultaneously (Nam et al., 2013). Therefore, one policy (for example, climate policy) can have a positive side effect on another policy (for example, air pollution control). Such interactions are termed co-benefits in the literature. Including co-benefits in policy assessment can lead to a more accurate evaluation of the 'net costs' of different mitigation policies (Burtraw et al., 2003; Dudek et al., 2003) and thus be beneficial for policy makers to select the most efficient policy instrument or mix in order to achieve multiple objectives (He et al., 2010). The plethora of terminologies being used to describe the phenomena of co-benefits (Edenhofer et al., 2013; Schwanitz et al., 2015) ranges from ancillary benefits (Burtraw et al., 2003), non-separable pollution control

(Ageea et al., 2012) to synergies (Nam et al., 2014), reflecting a growing interest in this research area.

Research on co-benefits have already demonstrated that climate policies can generate additional environmental, health, social and economic benefits. These studies mainly focus on the US and China, the world's most emitting countries. Environmental co-benefits can be identified as the improvement of the quality of soil, water and air (Rive, 2010; Winiwarter and Klimont, 2011; Thambiran and Diab, 2011). Researchers found that GHG reductions significantly mitigated air pollutant emissions (Bollen, 2015) and such environmental co-benefits can lead to beneficial effects on public health (Mayrhofer and Gupta, 2016). In many high-income countries, higher air quality standards have improved public health (Harlan and Ruddell, 2011). But the achieved co-benefits can also be high in developing countries, such as China (Dong et al., 2015), and they depend mainly on the stringency of the standard applied (Driscoll et al., 2015). Air quality and health co-benefits, especially as they are mainly local and near-term, provide strong additional motivation for transitioning to a low-carbon future (West et al., 2013). In addition, co-benefits of social and economic impacts are also identified from carbon mitigation (Zhang et al., 2013). These co-benefits include energy independence or energy security by reducing the dependence on imported fossil fuels (Mondal et al., 2010), generating so-called green jobs (Cai et al., 2011) as well as technology transfer in developing countries promoting economic development (Barker et al., 2010). Besides, Parry et al. (2014) indicated that the nationally efficient carbon price for China would be \$63 t/CO_2 in 2010, considering high benefits from air pollution mitigation from coal use. Further studies also demonstrated that a carbon mitigation policy would be less expensive when considering the unintended air quality improvements (Nemet et al., 2010). Co-benefits from improved air quality can partially or fully compensate for the costs of CO_2 reduction (Saari et al., 2015; Li et al., 2018) and sometimes can even exceed policy costs (Thompson et al., 2016). However, potential co-benefits decrease rapidly with more stringent carbon policies. (Thompson et al., 2014).

In comparison, the literature on the synergy from the other perspective - that is, the co-benefits on carbon reduction from air pollution control - is relatively sparse; but of great importance for developing countries (Nam et al., 2013). In reality, the benefits which directly originate from air pollution control tend to be more obvious and are more likely to accrue within the short-term, while the benefits from carbon mitigation mostly accrue over a long period of time (Burtraw et al., 2003). Furthermore, developing countries are confronted with more urgent needs for regional air pollution control rather than carbon reduction and there is much stronger incentive and priority for the government to develop and implement air pollutant related environmental policies (Gielen and Chen, 2001; Morgenstern et al., 2004).

Nam et al. (2013) used a CGE model and incorporated air pollutant reductions based on a comprehensive assessment of abatement technology and related costs. They found that the emissions control targets for SO_2 and NO_x in China would also have considerable effects on its CO_2 emissions. Nam et al. (2014) expanded this study on the synergy between air pollution and carbon emissions control by a comparative analysis between China and the US. In both countries, they found co-benefits of carbon reductions originating from SO_2 and NO_x control would rise with more stringent pollution control targets. However, co-effects of carbon mitigation from air pollutant control in China were higher than that in the US due to China's energy structure relying on coal. Peng et al. (2018) examined the co-benefits of air quality and GHG emission of different industrial policies in China and they found that energy efficiency and air pollution control technology improvements had significant co-benefits for climate, air quality and health benefits. Yang et al. (2018) estimated the co-benefits of carbon policy in local air pollutant control by using a partial equilibrium model. They found that the nationally determined contribution of China to peak its CO_2 emission by 2030 was consistent with its domestic benefit to reduce local air pollution.

In conclusion, co-benefits between regional air pollution and climate policy efforts can be potentially significant and there are growing research efforts to better understand and quantify such interactions. There has already been some investigation of such co-benefits in the Chinese context and these have highlighted its potential. This study aims to extend existing studies to the electricity sector in China by using a more detailed electricity generation modeling tool across a wider range of possible air pollution and GHG emission policy scenarios.

3. Policy Scenarios

In order to explore the implications of different policies on air pollution and co-benefits of carbon emissions, six policy scenarios are considered as shown in Table 1. These policy scenarios with different environmental costs are put into the optimization process as data inputs. The **Base** scenario includes no carbon or regional air pollution policy efforts to provide a basis for comparison with the various policy interventions considered. Three scenarios involve the use of a single policy measure - air pollution regulation, air pollution pricing or carbon pricing. Two scenarios consider combined air pollution regulation and carbon pricing, and combined air pollution pricing and carbon pricing.

Scenario **Reg**, a regulation policy on air pollutant emissions is applied. For this scenario, emission factors of air pollutants after treatment are applied and related control costs are included as operating costs. The emission factors for this scenario are considered to meet the *Emission Standard of Air Pollutants for Thermal Power Plants*, which was established by the Ministry of Environmental Protection of China and came into effect on 1st of January 2012 (Jinan Environmental Protection Bureau, 2011). It is viewed as the most stringent air pollution control policy in history. For the other scenarios, the emission factors of air pollutants are before treatment, which measure the original emissions of each generation technology. These emission factors together with the emission factor of CO_2 are determined from various studies reported in the literature - Liu (2008), Zhang et al. (2012), Shi (2013) and National Energy Administration (2013).

Table 1 Policy scenarios

No.	Scenario	Brief description	Emission factors for air pollutant emissions
1	Base	No air pollution control policy or carbon mitigation policy.	Before treatment
2	Regulation (Reg)	The policy regulates air pollutant emissions with a specific emission standard. Control costs for clean coal generation are included.	After treatment
3	Air Pollution Tax (PTaxL, PTaxH)	Policy levies air pollution taxes on the air pollutant emissions of thermal power plants and a low (L) and high (H) scenario of tax rates are simulated. If plants choose to treat air emissions, control costs for clean coal generation are included.	Before treatment or after treatment
4	Carbon Price (CTax)	The policy aims to reduce carbon emissions by setting a carbon price.	Before treatment
5	Carbon price & regulation (CTaxReg)	The policy combines scenario 2 and scenario 4 implementing regulation on air pollutants and carbon mitigation policies simultaneously.	After treatment
6	Carbon price & Air pollutant tax (CTaxPTaxL, CTaxPTaxH)	The policy combines scenario 3 and scenario 4 implementing air pollutant taxes and carbon mitigation policies simultaneously.	Before treatment or after treatment

For scenario **Reg**, the control costs are based on the current standard subsidies for the coal power plants to invest in and operate the treatment facilities controlling air pollution emissions (National Energy Administration, 2014) as well as the surveys of the power plant operators such as Li et al. (2014). Moreover, in order to put the control costs into the model, they are divided into capital costs, fixed O&M costs and variable O&M costs. Capital costs and fixed O&M costs of SO_2 and NO_x treatment facilities are obtained through an interview.[3] Variable costs for SO_2 and NO_x treatment are obtained by subtracting capital costs and fixed O&M costs from the total costs. As the capital costs for $PM_{2.5}$ treatment are very difficult to obtain and they are relatively low compared with those for SO_2 and NO_x, the total costs for $PM_{2.5}$ treatment are used. An overview on the costs applied by this paper is shown in Table 2.

[3] The data is from a coal-fired power plant in China. As required, the interviewee is kept as anonymous.

Table 2 Control costs of air pollutants for coal generation

Treatment	Capital costs ($/MW)	Fixed O&M ($/MWh)	Variable O&M ($/MWh)	Total costs ($/MWh)
Desulfurization (SO_2)	22,400	0.44	2.49	3.25
Denitration (NO_x)	13,400	0.22	1.81	2.22
Dedusting ($PM_{2.5}$)	N/A	N/A	N/A	0.44

Notes: N/A means not applicable and all monetary values are expressed in US$ by the exchange rate 1 US$ = 6.77 RMB Yuan.

In scenario **PTax** air pollution taxes are adopted. In order to explore the effects of different tax levels, two different sub-scenarios are distinguished: a 'High Scenario' and a 'Low Scenario'. As different cities and provinces have established their own local air pollution tax rates, this study uses local price signals in China. For the high scenario of the air pollution taxes **PTaxH**, the latest tax rates of Beijing and Hebei are referenced. With the implementation of the new *Environmental Protection Tax Law*, these local rates have entered into force since January 2018 (Beijing Municipal Congress, 2017; Hebei Provincial Department of Finance, 2017). Specifically, 10,000 Yuan RMB/Tonne (1480$/Tonne) for SO_2 and NO_x emissions are applied in this paper. These tax levels are not only the highest rates in China due to severe local air pollution and smog weather in Beijing and Hebei, but they are also comparable with one of the highest levels of environmental taxes in Europe, that of Denmark which has charges of 1500 $/tonne for SO_2, 794 $/tonne for NO_x (Paraschiv, et al., 2011; Braathen, 2012; State Administration of Taxation, 2017). For the low scenario of the air pollution taxes **PTaxL**, the benchmark prices of pollution permit auction in Chongqing are selected (Chongqing Municipal Environmental Protection Bureau, 2012). They are 4,890 Yuan RMB/Tonne (721 $/Tonne) for SO_2 and 6,000 Yuan RMB/Tonne (886.32 $/Tonne) for NO_x and they are determined mainly based on the average costs of the treatment of pollutants. As the current emissions taxes only include general particulate matter emissions, the tax rate for $PM_{2.5}$ is derived from the control cost of de-dusting which is shown in Table 2. We use this rate for both scenarios of air pollution taxes. With additional pollution costs for the air pollutants in this scenario, coal-fired plants might choose to control the air emissions, or they might well just pay the taxes. In the first case, the air pollution outcomes will be the same as for the **Reg** scenario. In the latter, air pollution will remain far higher. Much will depend, of course, on future costs for emission control versus the level of taxes, as well as the effectiveness of their associated governance arrangements including penalties. Therefore, both dirty coal (without treatment) and clean coal (with treatment) are considered as generation technology in this scenario in order to obtain efficient investment portfolios.

In scenario **CTax** the focus is on climate mitigation policy only and involves the introduction of a carbon price. This is consistent with China's latest climate policy, which is to introduce a price of carbon with a national cap-and-trade system, which was announced at the end of 2017 and which would start with the electricity sector given its high level of emissions and emission reduction potential. For this scenario, the 2030 carbon price is based on an equilibrium price of the carbon market of 29.4 \$/tonnes CO_2 taken from Wu (2012). The actual level of tax up to 2030 is of course potentially very wide - an advantage of the chosen modeling tool which explicitly models carbon price uncertainty around this chosen central price.

In order to explore which policy in the electricity sector can achieve both global climate change and regional air pollution targets most efficiently, these three scenarios consider the case of a single policy measure ranging from emissions regulation, taxes for regional air pollution to a carbon tax. However, in practice, most energy and climate policy frameworks involve a mix of carbon and air pollution policies. According to the announcement of the Chinese government a national wide emission trading schemes and an environmental tax are both likely to be implemented. Hence, two scenarios that combine air pollution control and carbon mitigation policies are considered. Scenario **CTaxReg** combines the air pollution regulation policy of scenario **Reg** with the climate change policy of scenario **CTax**. Scenario **CTaxPTax** combines the air pollution taxes of scenario **PTax** with climate change policy of scenario **CTax**.

4. Modeling Methods and Data Inputs

4.1. Modeling approaches

In order to better address the problem of uncertainties in the process of electricity investment planning, Vithayasrichareon and MacGill (2012a) present a new method that combines Monte Carlo Simulation (MCS) with Mean Variance Portfolio (MVP) Theory. By using MCS, the key uncertain factors are treated as random variables and they are given a specific probability distribution, which can be derived from historical data or scientific prediction. Further, by using the MVP, the mean (expected generation costs and emissions) and corresponding variance (the risks) for a very wide range of potential future generation mixes (portfolios) can be modeled based on the simulation of uncertainties. Trade-offs between different possible portfolios in terms of expected cost uncertainties and risks as well as environmental emissions can be assessed through the use of efficient frontier techniques as illustrated in Figure 1. As a result, this unique model determines optimal generation portfolios with specific generation mix by considering these outcomes. This model has been used for case studies in different regions and countries to explore a range of electricity sector planning and renewable energy development issues (Vithayasrichareon and MacGill, 2012b; Vithayasrichareon et al., 2015; Vithayasrichareon et al., 2017).

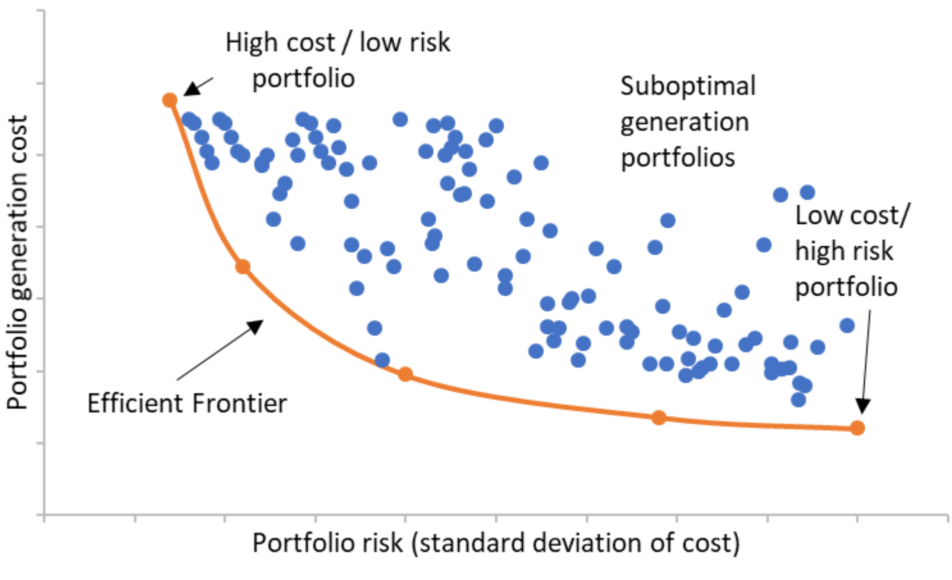


Figure 1 Efficient frontier for electricity generation portfolios showing cost-risk trade-off.

With this approach, generation portfolios that are not on the efficient frontier are considered sub-optimal, either because their expected generation costs are too high relative to the cost risks or the cost risks are too high relative to the expected cost. From a societal perspective, the most desirable generation portfolio is the one that results in the lowest expected cost within some level of acceptable risk.

The modeling tool used for this study contributes to existing efforts by addressing some of the key limitations in the typical least-cost optimization models such as Wien Automatic System Planning Program (WASP-IV) and MARKAL/TIMES since these models do not fully account for multiple and potentially interacting uncertainties associated with electricity industry investment (Vithayasrichareon and MacGill, 2012a).

This study adopts and extends this model to the Chinese electricity sector and applies it to GHG emissions and regional air pollutants. By incorporating different policy scenarios into generation costs, this model can explore the effects and potential co-benefits of these policies on the electricity generation investment in China. The year 2030 is selected given that it is a target year for international climate policy commitments, and it provides a sufficient period for major generation investment and hence structural change in the sector.

In total, seven electricity generation technologies are considered: conventional pulverized coal, Combined Cycle Gas Turbines (CCGT), nuclear, coal integrated gasification combined cycle (IGCC), wind and solar power and hydro generation. And for each policy scenario, different PV and wind penetrations for 2030 ranging from 10% to 70% are considered in the modeling, which are shown in Table 3. The renewable penetration rate is decided in an exogenous way.

Table 3 Different renewable energy penetration rate for each policy scenario in 2030

RE penetration	Percentage by Energy		
	PV	Wind	All other
1	5%	5%	90%
2	5%	10%	85%

3	10%	20%	70%
4	20%	30%	50%
5	30%	40%	30%

Total annual generation costs of each generation portfolio consist of annual fixed costs and variable costs of all generation technologies in the portfolio.

$$Total\ Generation\ Cost = \sum_{i=1}^{n} FixedCost_i + VariableCost_i \quad (1)$$

where $FixedCost_i$ is the annual fixed cost for the generation technology i and $VariableCost_i$ is the annual variable cost for the same generation technology i. The annual fixed cost is:

$$FixedCost_i = (AnnualisedCapitalCost_i + FixedO\&MCost_i) \times InstalledCapacity_i \quad (2)$$

where $AnnualisedCapitalCost_i$ is the annualized capital cost ($/MW) and $FixedO\&MCost_i$ is the annual fixed O&M cost ($/MW) and $Installed\ Capacity_i$ is the installed capacity (MW) of technology i in the portfolio. The annual variable cost of generation portfolio is calculated based on annual energy (MWh) generated by each technology in the portfolio. The variable cost comprises variable O&M, fuel costs, carbon costs and other air pollution costs.

$$VariableCost_i = (VariableO\&MCost_i + FuelCost_i + CarbonCost_i + AirCost_i) \times Energy_i \quad (3)$$

where $Energy_i$ is the annual energy (MWh) generated by each technology i in the portfolio and the unit of $VariableO\&MCost_i$ is $/MWh. $FuelCost_i$ are the fuel costs for technology i. For the scenarios with emission standards such as Reg the air pollution costs $AirCost_i$ are the control costs from the end-of-pipe option or the taxed paid for air emissions, while for the scenarios CTax the respective tax level is included as a cost e.g. $CarbonCost_i$. For the policies, which do not include any carbon price or air pollution control costs/emission costs, the related costs are equal to zero. Annualized capital costs are computed from the capital cost of each generation technology i by using the capital recovery factor (CRF)[2] which are depicted in the following equations.

$$AnnualisedCapitalCost_i = CapitalCost_i \times CRF_i \tag{4}$$

$$CRF_i = \frac{j(1+j)^m}{j(1+j)^m - 1} \tag{5}$$

The CRF is used to determine the equivalent value of a future annuity given the present value of money. Generation output of each technology in the portfolio in each period of the Residual Load Duration Curve (RLDC) is identified by using partial economic dispatch with an objective function which minimizes operating costs subjected to demand and supply constraints.

$$Minimise\ \sum_{i=1}^{n}(VariableO\&MCost_i + FuelCost_i + CarbonCost_i + AirCost_i) \times Power_i \tag{6}$$

$$Subject\ to\ \sum_{i=1}^{n} Power_i = Demand \tag{7}$$

$$InstalledCapacity_i \leq Power_i \tag{8}$$

where $Power_i$ (MW) is the generation output from technology i. *Demand* is the electricity demand (MW) in each interval of the RLDC. Total annual emissions of CO_2 and air pollutants of each portfolio are determined as follows:

$$CO_2\ emissions = \sum_{i=1}^{n} CO_2EmissionFactor_i \times Energy_i \tag{9}$$

$$SO_2\ emissions = \sum_{i=1}^{n} SO_2EmissionFactor_i \times Energy_i \tag{10}$$

$$NO_x\ emissions = \sum_{i=1}^{n} NO_xEmissionFactor_i \times Energy_i \tag{11}$$

$$PM_{2.5}\ emissions = \sum_{i=1}^{n} PM_{2.5}EmissionFactor_i \times Energy_i \tag{12}$$

For the scenarios with air pollution regulation, including Reg and CTaxReg, the emission factors of air pollutants are based on the emissions after treatment, which satisfies the regulated emission standard. For the scenarios of Base and CTax, the emission factors of air pollutants are based on the original emissions of each generation technology before treatment. For scenarios of PTax and CTaxPTax, the emission factors of air pollutants can be either before or after treatment, which depends on thermal plants' choices between treatment and paying taxes.

4.2. Data and model input

An hourly electricity demand profile in 2030 is simulated based on the actual demand pattern in 2012. Specifically, eight days of actual hourly demand are adopted and they are categorized into weekdays and weekends for four seasons. Hourly wind generation is simulated based on normalized hourly wind generation data for the whole year from Hebei Province. It is assumed that Hebei provides a reasonable representation of the average wind generation across China. Hourly PV generation data is simulated using System Advisor Model (SAM) across 30 locations in China and then scaled to match actual annual PV energy. Hourly hydro generation for 2030 is simulated based on the actual hydro generation pattern obtained for 2012 and the projected installed hydro capacity in 2030.

For each possible energy penetration of PV and wind penetration shown in Table 3, possible thermal generation portfolio mixes (coal, CCGT, nuclear and IGCC) are simulated by varying each technology in 10% intervals. Given the significant existing coal capacity (676 GW) the existing coal capacity is allowed to vary in order to consider different retirement plans of existing coal plants. In order to compute the generation costs, the model also incorporates the economic and operating parameters of each generation technology. The investment costs of the existing capacity in 2030 are considered 'sunk' and are not included in the calculation of generation costs. Other model assumptions can be referred to (Vithayasrichareon and MacGill, 2012a; Vithayasrichareon and MacGill, 2012b). The parameters of each generation technology applied by this paper are presented in Table 4.

For the key uncertainties included in the modeling, lognormal distributions are applied to model future fuel prices, carbon prices and plant capital costs, while electricity demand uncertainty is modeled by assuming a normal distribution of residual demand for each generation portfolio of renewable penetration. For each of the policy scenarios under consideration, the output of the model is a probability distribution of expected total electricity generation costs and emissions for each possible generation portfolio of different PV, wind, nuclear, CCGT, coal and IGCC capacities.

Table 4 Generator parameters[4]

Generator parameters	New entry plants				Existing plants			Hydro	PV	Wind
	Nuclear	Coal	CCGT	IGCC	Nuclear	Coal	CCGT			
Plant life (years)	40	40	30	20	N/A	N/A	N/A	40	20	20
Overnight capital cost ($Million/MW) - year 2030	1.7 - 3.2	0.51	0.39	1.21	N/A	N/A	N/A	0.98	0.83	0.53
Fixed O&M cost ($/MW/yr)	153600	20700	41040	78370	153600	21750	43010	49100	9600	23820
Variable O&M cost ($/MWh)	2.22	2.07	1.48	2.95	2.22	2.18	1.48	8.86	7.39	7.39
Average thermal efficiency (%)	37	42	60	46	37	42	56	N/A	N/A	N/A
Heat Rate (GJ/MWh)	9.73	8.57	6.00	7.83	9.73	8.57	6.43	N/A	N/A	N/A
CO_2 emission factor (tCO_2/MWh)	N/A	0.92	0.38	0.90	N/A	0.98	0.41	N/A	N/A	N/A
NO_x before treatment (g/MWh)	N/A	2390	439	182	N/A	2391	439	N/A	N/A	N/A
NO_x after treatment (g/MWh)	N/A	478	439	182	N/A	478	439	N/A	N/A	N/A
SO_2 before treatment (g/MWh)	N/A	6490	49	4.09 - 13.17	N/A	6493	49	N/A	N/A	N/A
SO_2 after treatment (g/MWh)	N/A	649	49	4.09 - 13.17	N/A	649	49	N/A	N/A	N/A
$PM_{2.5}$ before treatment (g/MWh)	N/A	1790	N/A	22.7	N/A	1787	N/A	N/A	N/A	N/A
$PM_{2.5}$ after treatment (g/MWh)	N/A	53	N/A	22.7	N/A	53	N/A	N/A	N/A	N/A
Expected fuel price ($/GJ)	0.7	4.52	8.94	8.41	0.7	4.52	8.94	N/A	N/A	N/A

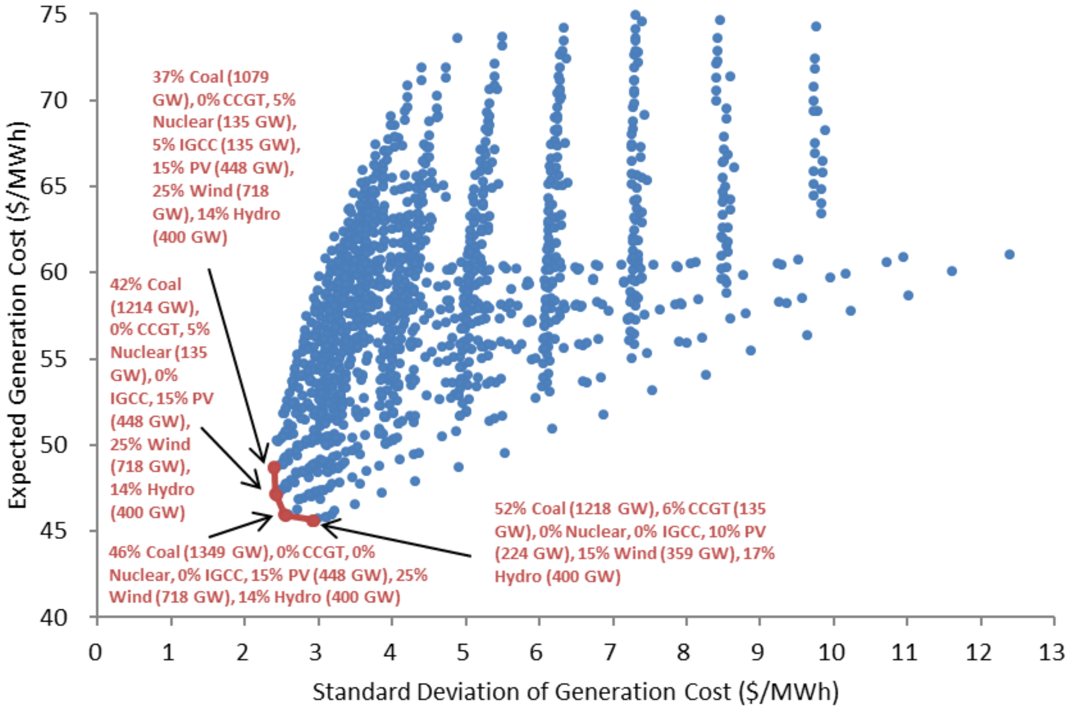
[4] N/A means not applicable, and all monetary values are expressed in US$ with the exchange rate 1 US$ = 6.7695 RMB Yuan.

5. Results

5.1. Efficient Frontier Analysis and Scenario Base

For the *Base scenario* in which power plants are free to emit CO_2 and air pollutants without any constraint or costs for externalities, a plot of expected costs and cost risks for each possible generation portfolio is shown in Figure 2. The efficient frontier for costs versus cost risks is also depicted in the graph. The generation portfolios on the efficient frontier represent the 'first best' portfolios in terms of cost and cost risks.

Figure 2 Efficient frontier of scenario Base (no carbon and air pollution control). The labels show the % share of generation capacity.



For each of these policy scenarios, the lowest expected cost generation portfolio on the efficient frontier is selected for comparative analysis. This choice was made since the difference in cost uncertainty between the lowest risk portfolio and the lowest cost portfolio is not as large compared to their difference in expected costs. The efficient frontier also shows that renewable penetration is robust and the main differences between the scenarios are related to the coal-nuclear-gas-mix.

Figure 3 Generation mix for different policy scenarios in 2030

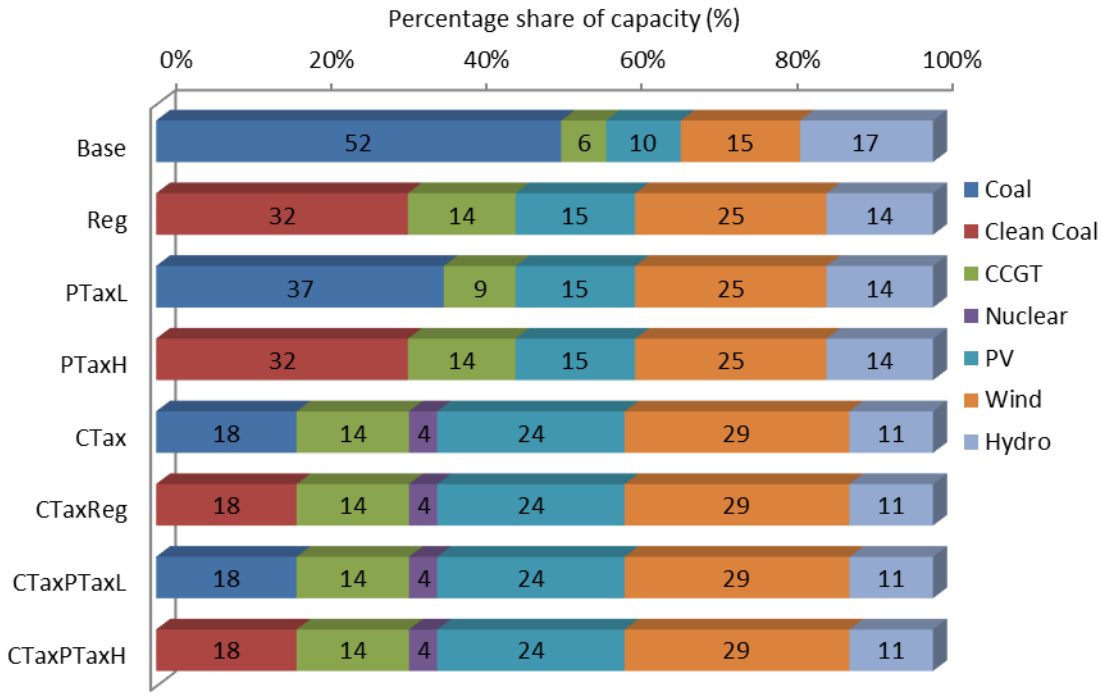


Figure 4 Annual CO_2 emissions for different policy scenarios in 2030

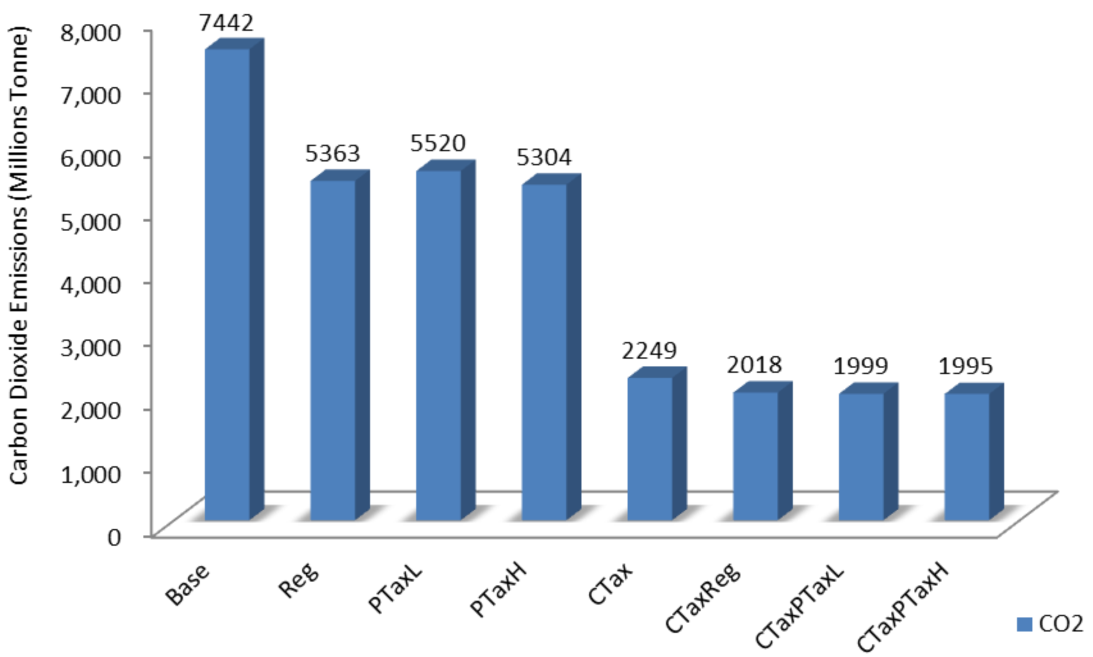


Figure 5 Air pollutant emissions for different policy scenarios in 2030

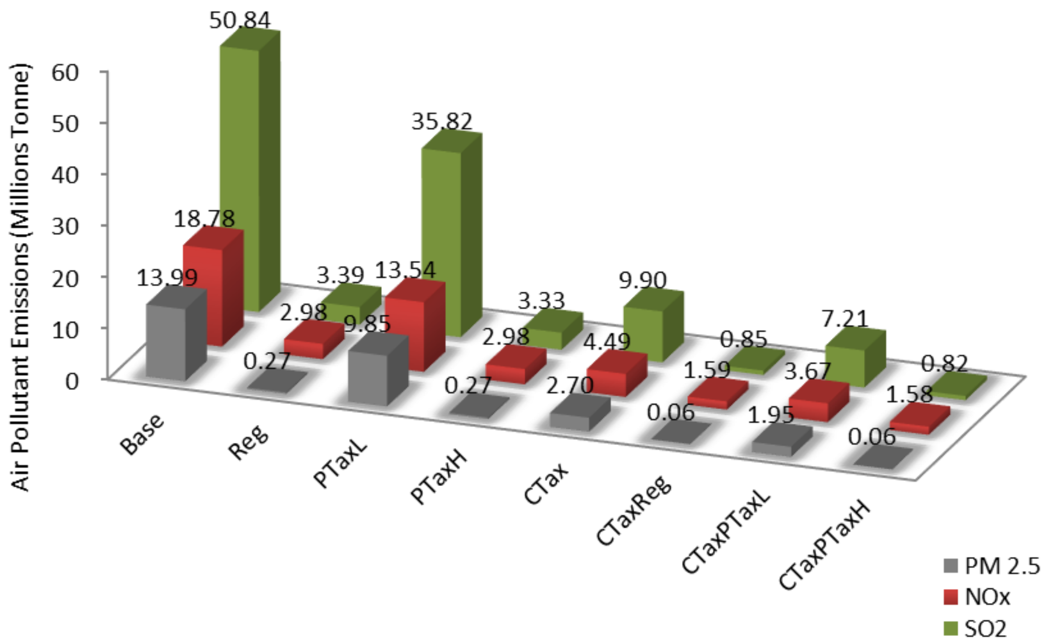
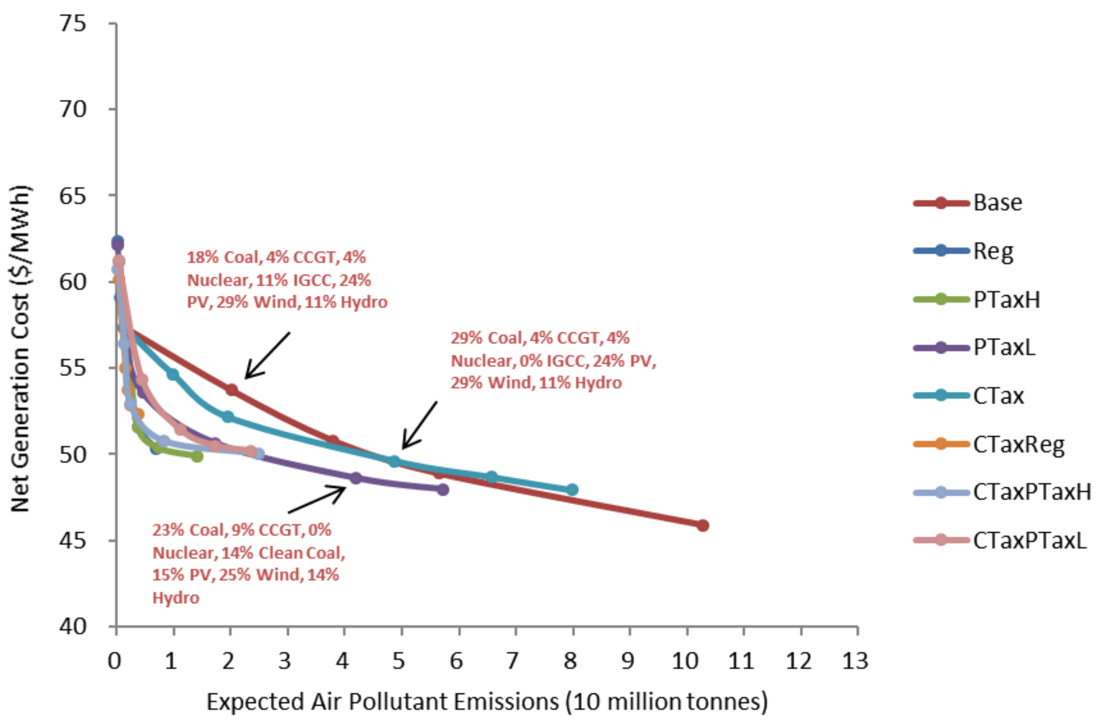
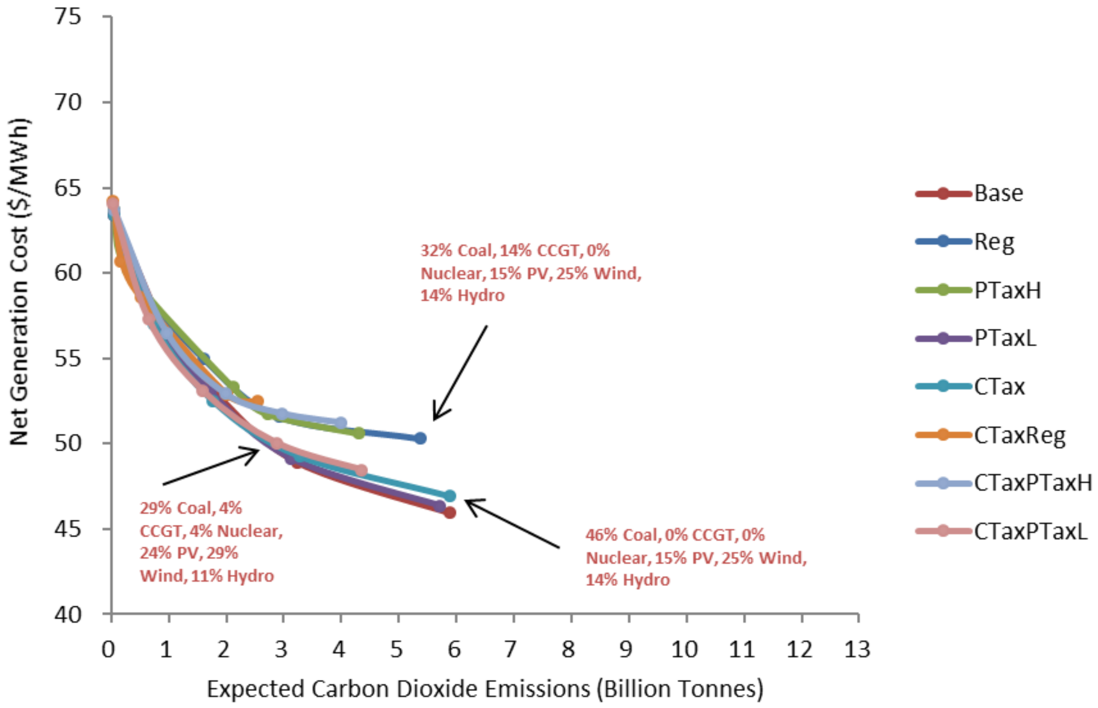


Figure 6 Efficient frontiers of Costs VS Air Pollutant Emissions



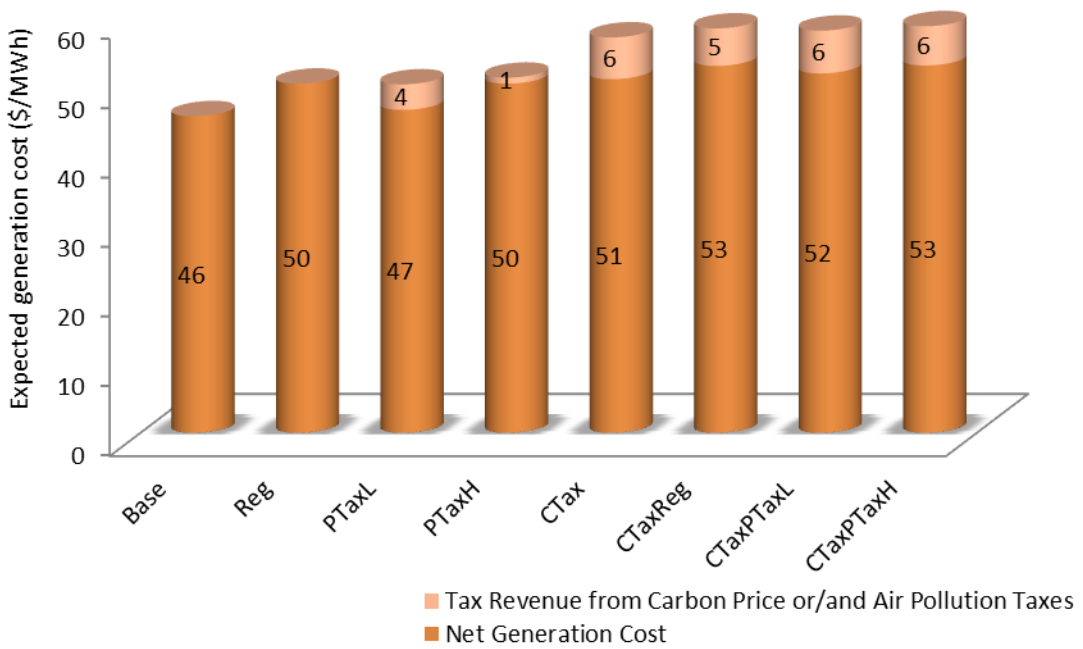
Notes: different policy scenarios are presented.

Figure 7 Efficient frontiers of Costs VS Carbon Emissions



Notes: different policy scenarios are presented.

Figure 8 Expected generation costs for different policy scenarios in 2030



As shown in Figure 3, the portfolio of *scenario Base* consists of 52% coal, 6% CCGT, 10% PV, 15% wind and 17% hydro in terms of generation capacity because of the low generation costs of coal-fired plants and no constraints on carbon or air emissions. As shown in Figure 4, the expected CO_2 emissions in 2030 reach 7,442 million tonnes, which are higher than the current coal-fired CO_2 emissions of 4,565 million tonnes (IEA, 2019). However, as the power generation is assumed to be 71.4% higher in 2030 compared to 6417.1 TWh in 2017, the carbon intensity (CO_2 per generation unit) is decreasing. Hence, even without any climate or pollution control policy in 2030, the assumed estimates for the costs of different generation technologies in China would see the lowest cost generation mix feature a lower proportion of coal than at present, with significantly more PV and wind as well as CCGT.

With respect to the air pollutant emissions shown in Figure 5, 50.84, 18.78 and 13.99 million tonnes of SO_2, NO_x and $PM_{2.5}$ are generated respectively. Those values are much higher than the historical emissions from coal-fired plants in 2017, which are 1.2, 1.14 and 0.26 million tonnes respectively. This result is expected because no constraints are applied and while the proportion of coal generation has fallen, the total generation is greater and none of the plants undertakes emission control. Also, these historical emissions suggest that the existing coal-fired plants are undertaking pollutant emissions control.

5.2. Single policy scenarios

5.2.1. Scenario Reg

The situation is greatly changed when regulation on air pollutants is applied (*Scenario Reg*). The emission requirements applied are based on the new version of the *Emission Standard of Air Pollutants for Thermal Power Plants*, and the modeling assumes that regulations are actually enforced. The least-cost generation mix has been changed with a proportion of coal-fired capacity reduced by 20%, while PV and wind increased by 5% and 10% respectively (see

Fig. 2). This effect is due to the increase in the generation costs of coal power plants, as an outcome of the need to invest in, and operate, end-of-pipe clean-up facilities.

As all coal-fired generation in this scenario is clean coal, the emissions of air pollutants are drastically reduced and the expected emissions of SO_2, NO_x and $PM_{2.5}$ of this scenario are 3.39, 2.98 and 0.27 million tonnes respectively (see Fig. 4), which are only 6%, 16% and 2% compared to the *Base scenario*. This highlights that regulation of air pollutants can be a very effective policy instrument for controlling air pollution, however, they do need to be actually adhered to. Moreover, air emissions in this scenario are higher than the emission levels from coal-fired plants in 2017, given that the power generation in 2017 was 6,417 TWh, which represents 58% of the power generation in 2030. This result also assumes that the new version of the *Emission Standard of Air Pollutants for Thermal Power Plants* has been properly enforced. As expected, the policy on air pollution control has co-benefits also in terms of carbon emission mitigation. With expected CO_2 emissions of 5,363 million tonnes, the *Reg scenario* achieves 28% CO_2 reduction compared to the *Base scenario* (see Fig. 3). The emissions are higher than the level in 2017, but note that the industry is supplying 133% more generation.

5.2.2. Scenario PTax

Scenario PTaxL and *PTaxH* present possible generation portfolios by considering two levels of air pollution taxes on air pollutant emissions. As noted earlier, it is assumed that coal plants can either choose to pay taxes on their air emissions or take up emission control. With respect to the low-level pollution tax scenario, its generation mix is very similar to the *Scenario Reg*. This seems reasonable because the low-level tax rates are determined based on the average costs of pollutant treatments and the treatment costs and emission costs increase the generation costs for coal-fired power plants at a similar level.

However, coal-fired plants in *Scenario PTaxL* choose to pay the pollutant taxes rather than controlling their air emissions as the control costs are slightly higher than the low-level taxes.

The emissions of SO_2, NO_x and $PM_{2.5}$ for this scenario are 35.82, 13.54, and 9.85 million tonnes (see Fig. 4), which represent 28% to 30% air pollution emission reductions compared to the *Base scenario*. However, given coal plant clean-up is not undertaken, air pollutant emissions are much higher compared to those in *scenario Reg*. Moreover, pollution taxes lead to climate co-benefits by emitting around 5,520 million tonnes of CO_2. This is comparable to the level in *scenario Reg* which has similar air emissions costs.

As to the high-level pollution tax scenario, the generation mix keeps the same with that in *scenario Reg*. Thus, as long as the tax rates are higher than the control costs, there will be incentives for all coal-fired plants to treat air emissions rather than paying the taxes for emitting them. The emissions of SO_2, NO_x and $PM_{2.5}$ for this scenario are 3.33, 2.98, and 0.27 million tonnes, which are reduced significantly and are comparable with those in the *Scenario Reg*. Hence, sufficient high environmental taxes and air emissions regulation can both achieve the same effect in terms of air pollution control. The major difference is with regard to the revenue, which will be assessed in 5.4. With regard to the co-benefits, high taxes reduce carbon emissions by 29% compared to *scenario Base*, which is close to *scenarios Reg* and *PTaxL*.

5.2.3. Scenario CTax

For the single policy *scenario CTax* the carbon price of 29.4 \$/tonne of CO_2 leads to the least-cost generation portfolio consisting of 18% coal-fired generation, 14% CCGT, 4% nuclear, 24% PV, 29% wind and 11% hydro (see Fig. 2). This portfolio has, unsurprisingly perhaps given its explicit policy objective, the lowest share of coal-fired generation of any of the single policy scenarios. This is due to the increase in generation costs for coal-fired power plants from directly pricing carbon emissions.[5] Correspondingly, the carbon emissions of this scenario are the lowest among all the scenarios presented so far and it achieves 66% and 49% million tonnes of CO_2 mitigation compared to the *Base scenario* and the emission level of coal plants in 2017.

[5] Specifically, the carbon price applied in this scenario increases the generation costs of the portfolio by 4.74 \$/MWh, which is the highest among the single policies.

The carbon intensity of this scenario is about one-quarter of the carbon intensity of China's electricity sector in 2017, which represents a considerable reduction.

Additionally, the co-benefits on the air pollution emissions are also significant, with 9.90, 4.49 and 2.70 million tonnes of SO_2, NO_x and $PM_{2.5}$ emissions, representing 19%, 24% and 19% of the emissions in the *scenario Base* respectively. As shown, co-benefits are achieved with both policies. However, the co-benefits derived from sufficient carbon pricing on air emissions are higher than those from stringent air pollutant control on carbon emissions. This can be explained by the fact that the carbon price leads to substantial extra generation costs for coal-fired power plants compared to the air pollutant taxes due to the much higher volume of CO_2 emissions compared to air pollutant emissions.

5.3. Policy mix: interaction effects

This sub-section studies the policy interactions of combining air pollution control and carbon mitigation policies. *Scenario CTaxReg* applies a carbon price plus regulation on air pollution emissions, which can be treated as a combination of *scenario Reg* and *scenario CTax*. *Scenarios CTaxPTaxL* and *CTaxPTaxH* apply a carbon price plus air pollution taxes of two different levels. Thus, these are combinations of *scenario PTaxL* or *PTaxH* with *scenario CTax*.

In contrast to the comparison from *scenario Base* to *CTax*, where different policy instruments have different impacts on the portfolio generation mix, the portfolio generation mix stays unchanged from *scenario CTaxReg* to *scenario CTaxPTax*. Interestingly the generation mix is consistent with that in *scenario CTax* (see Fig. 2), where the carbon price is employed as the only policy instrument. This indicates that the carbon price dominates the effect on the composition of portfolio mix and stringent air pollutant control policies are not as strong to significantly change the capacity share in the portfolio if there is already a sufficient carbon price. Again, this is potentially due to the large volumes of CO_2 emissions from thermal power plants compared to air pollutant emissions. Therefore, a carbon tax may have a much broader and deeper impact on coal-fired generation.

However, even if the generation mix is proved to be fixed for combined scenarios, the air pollutant control policies can influence air pollution and carbon emissions by adjusting dispatch. As shown in Figure 5, the *scenarios CTaxReg* and *CTaxPTaxH* have the same low air pollutant emissions because all coal-fired plants control their air pollutant emissions. With regards to *Scenarios CTaxPTaxL*, it has relatively higher pollutant emissions as its tax rates are not high enough to make plants treat their emissions.

In addition, all policy mix scenarios have different degrees of CO_2 emissions reductions compared to *scenario CTax (*see Fig. 3). This again shows the co-benefits of carbon mitigation derived from air pollution control policies. Compared to *scenarios CTaxPTax*, *scenario CTaxReg* has relatively higher CO_2 emissions. However, comparing their carbon reductions to the CO_2 emission levels of *scenario CTax* it shows that they are not particularly strong. This again indicates that the co-benefits from air pollution control policies to carbon mitigation are not as significant when there has already been an influential carbon price, at least for the relatively low air pollution tax levels modeled. In contrast, the co-benefits from a sufficient carbon price to air pollution control are still significant when comparing the combined scenarios with the single air pollution policy scenarios (see Fig. 4). For example, the regional air pollution emissions of SO_2, NO_x and $PM_{2.5}$ of *scenario CTaxReg* are only 25%, 53% and 22% of corresponding emissions in *scenario Reg.*

Wang (2014) stated that coal-fired generation is the key factor to address the air pollution problems in China and this can be solved by developing 'green' coal-fired generation rather than limiting its development. At first glance this argument seems to be supported by the results of this paper given that the air pollution emissions of *scenario Reg* are greatly reduced. However, it neglects the important issue of carbon emissions from the electricity sector. The *scenario Reg* highlights that proper enforcement of the new emission standard can lead to low air pollution levels, however the CO_2 emissions from this scenario are still relatively high compared to scenarios with a sufficient carbon price. Therefore, although the implementation of air pollution regulation can avoid air pollution problems, it will not address the issue of global climate change. Consequently, in order to achieve sustainable development, restricting investment in additional coal-fired plants is necessary. As shown in Figures 4 and 5, China can achieve great emissions reductions for both air pollutants and CO_2 on the basis of historical emissions levels by jointly implementing air control and carbon mitigation policies, which depends on large-scale capacity reductions in coal-fired generation.

In order to compare the possible trade-offs between generation costs and emissions this study has also compared the costs of portfolios which achieve the lowest emissions of air pollutants and CO_2. In order to aggregate the regional air pollution emissions to a single measure, they are scaled according to their damage costs compared to SO_2. This allows the derivation of an efficient frontier of cost versus air pollutants. These damage costs are taken from AEA Technology Environment (2005). In order to allow a clearer picture of generation costs under different scenarios, net generation costs are presented.

As shown in Figure 6, the general trend is that the net generation costs decrease as the pollutant emissions increase. Another finding is compared to the other policy scenarios, *scenarios Reg*, *PTaxH*, *CTaxReg* and *CTaxPTaxH* have significantly lower air pollutant emissions, especially when the total amount is below 10 million tonnes. This is because all coal-fired plants choose to implement air pollution control policies in these scenarios. Comparing the efficient frontier of costs versus CO_2 emissions (see Figure 7) shows that the portfolio mixes which achieve comparable level of emissions are similar to each other. *Scenarios Reg, PTaxH, CTaxReg and CTaxPTaxH* have relatively higher net generation costs as they incur extra costs from treatment. This highlights that there is great potential for a range of policies to deliver significant air pollution and emission reductions at only fairly modest net cost increases.

5.4. Tax revenue aspects of the electricity sector costs

In order to provide a comprehensive view of the policy evaluation this sub-section includes estimation of the tax revenues generated by the policies. Both air pollution taxes and carbon price revenues may be used to provide subsidies for consumers' electricity bills and raise funds for investment in clean and renewable technologies. In addition to comparing the tax revenues generated by each policy scenario, they can then be excluded from overall generation costs to show the net costs of each generation portfolio.

As shown in Figure 8, *scenario Base* and *Reg* do not generate any revenues because no carbon price or air pollution taxes are applied and treatment costs originating from regulation are, instead, included in operating costs. Even if the total generation costs of *scenarios PTaxL* and *PTaxH* are higher than *scenario Reg*, the taxes applied in *scenarios PTaxL* and *PTaxH* generate overall 4 \$/MWh and 1 \$/MWh revenues. The lower tax revenue in the higher Tax scenarios is due to the fact, that all coal plants will invest in control facilities and not pay the tax for their emissions. By subtracting the revenues from the generation costs, the 'net' generation costs of *scenarios PTaxL* and *PTaxH* are 47 \$/MWh and 50 \$/MWh. While the net costs of scenario PTaxL are lower than that in *scenario Reg* due to no control costs incurred, the net costs of *scenarios Reg* and *PTaxH* are the same because of the same generation mix.

With regard to the *scenario CTax*, the carbon price shifts the generation cost to 57 \$/MWh, which is the highest among the single policy scenarios. However, this scenario also generates the highest tax revenue. The 'net' generation cost is 51 \$/MWh if the 6 \$/MWh revenue is subtracted. The increase in the 'net' generation costs is possibly due to the increase in nuclear and PV capacity which have higher capital investment costs and in return, this scenario achieves the greatest carbon emissions reductions among these single policy scenarios by fuel switch.

Looking at the combined *scenarios CTaxReg*, *CTaxPTaxL* and *CTaxPTaxH*, the generation costs are shifted upwards on the basis of *scenario CTax* by adding air pollution regulation or related taxes on top of the carbon price (see Fig. 7). However, since the air pollution emissions in *scenario CTax* have already been constrained to relatively low levels by pricing carbon emissions, the additional air pollution control instruments have only increased the generation costs by $1/MWh for *CTaxPTaxL* and $2/MWh for *CTaxPTaxH*. For these combined scenarios, the revenues generated by carbon or/and air pollution taxes are 5, 6 and 6 $/MWh respectively. In total these carbon or/and air pollution taxes of these scenarios accumulate 59,322, 67,712 and 62,225 million dollars tax revenue respectively for the country. While these huge amounts of tax revenues can be used for reducing potential distorting of the tax system, the 'net' generation costs of these combined scenarios are between 52 and 53 $/MWh. Again, this similarity may come from the same generation mix.

6. Conclusions

Many countries have implemented a mix of policies to reduce local and global emissions but co-benefits are often not taken into account in the policy planning processes. Which policy or policy mix can achieve the local and global pollution targets most efficiently remains therefore largely unknown. This paper compares different single and combined policy scenarios for the Chinese electricity sector and evaluates the effect on global and local air pollution applying a portfolio assessment model. This model simulates the efficient frontier of possible generation portfolios in 2030. Despite some limitations of the applied model, e.g. assuming effective and efficient electricity industry investments and operation although the electricity sector in China is not yet liberalized, our findings may provide interesting insights for policy makers introducing or amending climate and local air pollution policies in a cost-efficient way.

The results suggest that while both carbon price and air pollution control policies have presented co-benefits, the co-benefit from a sufficient carbon pricing policy to air pollutant reductions is much stronger than that from stringent air pollutant policies to carbon mitigation. This can be shown by the fact that while the single air pollution control policy *scenarios Reg* and *PTaxH*, reduce 28% and 29% CO_2 emissions respectively compared to the *Base scenario,* the single climate change policy *CTax* achieves wit around 66% of CO_2 mitigation. In addition, the *CTax* scenario can achieve also low emissions of SO_2, NO_x and $PM_{2.5}$ with 10, 4, 3 million tonnes, respectively. If policy makers want to achieve even higher local air pollutant reduction targets a combined policy scenario such as *CTaxReg* needs to be applied, which can achieve very low emissions of SO_2, NO_x and $PM_{2.5}$ with 1, 2, 0.06 million tonnes. If a single air pollution control policy is chosen such as *a local air pollution tax* nationwide tax rates this would need tax rates to be as high as those of Beijing and Hebei. In addition, it would require improved enforcement in order to have comparable effects to such as combined policies. However, the CO_2 emissions will be high since the share of coal in the production mix in the *local air regulation policy or high environmental local air pollution tax* is 32% whereas it is only 18% in the *CTax* scenario. Although the combined scenarios have the highest power generation costs, the 'net' cost of these scenarios after excluding tax revenues is not much different from the *Scenario Reg*. In order to implement the combined policies the government needs to explain the fairly modest net cost increases and the distributional effects of these taxes to the public.

As mentioned, the single climate policy or combined policy approaches will achieve substantial CO_2 emissions mitigation compared to the *Base* scenario. However, those scenarios require a portfolio with a very low share of fossil fuels such as 18% clean coal, 14% CCGT and very high shares of renewables such as 24% PV, 29% Wind and 11% Hydro in case of the *CTaxReg*. Thus, renewables need to be increased substantially compared to the *Base* scenario which only has 10% PV and 15% Wind in its portfolio. This result is in line with the modeling results of the IEA. In its latest *China Power System Transformation* report, it provided two possible scenarios of achieving a transformed electricity sector in China by 2035, with 60% and 74% of install capacity for non-fossil technologies including hydropower - the New Policies Scenario (NPS) and the Sustainable Development Scenario (SDS) (IEA, 2019).[6] Thus, cleaning up the

[6] The IEA modelling was more sophisticated than the modelling approach employed in this paper due the different research objectives. The main objective of the modelling used in this paper is to explore the trade-offs between costs, cost uncertainly and emissions under different policy scenarios. However, the main purpose of the IEA study was to explore the value of reform goals and innovative system flexibility measures without considering the emission implications.

In the IEA modelling, hourly production cost modelling was employed, which capture the detail of the generation mix, electricity demand, interregional transmission networks, market rules and operation flexibility options such as demand side response and storage. For each of the key scenarios, China was disaggregated into eight regions via a detailed bottom-up electricity sector by reducing coal production capacity seems therefore the best way forward which will provide a high contribution to the global effort to combat climate change but at the same time also improve China's air quality substantially.

Comparing the portfolio results of our study with the *13th FYP Development Plan for Renewable Energy*, which foresees a share of 20% of primary energy consumption in 2030 by non-fossil energy, our results - covering only the electricity sector - seem much more ambitious especially with low levels of coal and much higher levels of renewables. Such a transition would not be unique for China. A transition away from coal to more renewables is happening around the world and countries like Germany had established a Structural Reform Commission (informally known as the "Coal Commission"), which recommended the German government to close 12.5GW of coal power capacity by 2022 and another 25.6GW by 2030 and which is now in the process of beeing implemented (Bundesregierung, 2020). Other countries like Canada, Austria, France, the UK plan to completely phase-out coal by 2030 (Sartor 2018). Even in the US, where President Trump has ordered a rescue plan of the nation's struggling coal power plants, utilities still plan to take 11.4 GW of coal-fired capacity offline in 2018. This is because renewable generation technologies are getting less and less expensive compared to traditional thermal power plants (Buchsbaum, 2018). A study for China shows that the Chinese NDC requires coal consumption to be peaked in 2020 which will allow CO_2 peaking around 2030. They also conclude that an earlier peaking of CO_2 emissions in 2025 would lead to an almost complete phase-out of coal from the power sector by 2050. In order to achieve such a target the current policy of a coal cap is insufficient and further policies need to be introduced such as a national carbon market – which was already announced and planned to be implemented by 2020 (Temple, 2018) – or placing coal plants in a strategic reserve or providing ancillary services. Those instruments are helping coal plant investors to generate some revenue as it is expected that many new but also existing coal plants are risking being stranded assets (Teng, 2018). Our modeling results also show that in order to increase the generation costs of

analysis. Hourly load profiles and generation capacity were projected for each region to capture regional differences. Key factors of the projections include regional trends, geographical shifts of industry and planned generation capacity.

coal-fired power plants and affect investment decision making, a sufficient carbon price is needed. A carbon price floor for China's carbon market may be an effective design choice as the UK experience has shown (Abrell, 2019).

The Chinese government has formulated a series of key strategies for the medium and long-term development of the Chinese economy and hence also for the electricity sector (IEA, 2019). In order to achieve the goal of "Ecological Civilisation" by the year 2035 - and ultimately a "Beautiful China" concept in 2050, efficient and cost-effective climate change policy and environmental pollution control policies are essential. In sum, single local air pollution policy instruments are found to have limited capacities to reduce CO_2 emissions therefore climate policies are superior and will lead to a phase-out of coal-fired power plants rather than cleaning them up. The tendency is also in line with the *13th FYP Development Plan for Energy,* where the Chinese government has indicated to shut down 20 million kilowatts old coal plants by the end of 2020 (NDRC, 2016), although the absolute numbers will need to increase. In order to limit the risk of an electricity supply shortage market reforms of the electricity sector are needed in China to incentivize the construction of power grids from regions where wind farms and photovoltaic power stations are built to the major demand centers at the coast.

Further research may test different renewable scenarios, expand – as done by the IEA 2019 study – the resolution and detail the variable renewable dispatch as well including the trade-off of an increase of energy and CO_2 emissions due to the installation of pollution control technologies such as scrubbers. But the general finding, that cleaning up the electricity sector by reducing coal generation and increasing renewable generation in China as the best way forward to reduce GHG and air pollution, seems secure and supported by other studies.

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