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Clean production pathways for regional power-generation system under emission constraints: A case study of Shanghai, China

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A B S T R A C T

China is now facing pressures of emission reduction both from greenhouse gases (GHGs) and local air pollutants (LAPs). Considering power generation system contributes a great share of CO_2 and $PM_{2.5}$ emissions, a regional power generation system modelling and optimization framework using Long-range Energy Alternatives Planning System (LEAP) is conducted in order to explore the cost-effective cleaner capacity expansion pathways under various emissions constraints. A case study of Shanghai follows, focusing on analysis of capacity additions for different power generation technologies, as well as energy inputs, reduction co-benefits and system costs. The results indicate that: i) the clean production pathways differentiate along with stricter CO_2 constraints; ii) Ultra-supercritical coal-fired units have significant advantage under no emission constraint, which are substitute by cleaner power generation units such as wind power, solar power and Integrated Gasification Combined Cycle (IGCC) under the CO_2 constrained scenario and the combined CO_2-$PM_{2.5}$ constrained scenario; iii) CO_2 constraint displays stronger reduction co-benefits than that of $PM_{2.5}$; iv) Emission constraints are conductive to energy savings that will increase system cost. Finally, policy recommendations are made through sensitivity analysis that only when the price of natural gas declines sharply can natural gas units become one of the alternatives that reduce coal consumption and the related CO_2 emissions.

1. Introduction

As a global environmental influential greenhouse gases (GHGs), CO_2 emissions in China are continuously increasing to 10.3 billion tons by 2013, almost twice as much as the U.S. (CDIAC, 2016). Meanwhile, frequently occurred smog crisis has become a key consideration along with the accelerating industrialization process and the awakening environmental consciousness, the appeal for enhancing air quality from domestic residents is increasingly pressing. Considering the severe impact on human health, the control of fine particulate matter ($PM_{2.5}$) emissions is regarded as one of the efficient method to solve smog crisis and improve regional air quality. The Chinese government has made a great deal of effort to address the serious air pollution through better laws, policies, enforcement by monitoring of ambient $PM_{2.5}$ concentrations (Shi et al., 2016; Yao et al., 2016).

Power generation sector is the most important and fundamental energy industry, as well as the main consumer of coal that contributes approximately 55% of China's total consumption in 2014 (State Statistical Bureau, 2016; Pan et al., 2013). Notably, coal-fired power plants take the largest share of 73% in total installed capacity, generating 80% of total power production (Yan et al., 2012). Nevertheless, as the key source of multiple air emissions, power generation system contributes 40% and 20% of total emissions for CO_2 and $PM_{2.5}$ respectively (State Statistical Bureau, 2016). In the consideration that the formation mechanism of smog is comparatively complicated, coal-fired power plants should not take full responsibilities for smog problem (Xu and Lin, 2016). However, comparing with other sectors, power sector is characterized by centralized emissions, mature emission control technologies, great reduction potentials and multiple clean production methods. Therefore, it is meaningful for power generation system planning to

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explore cleaner capacity expansion pathways that could simultaneously realize CO_2 mitigation and $PM_{2.5}$ reduction targets. Studies with respect to Generation Expansion Planning (GEP) have constructed mixed-variable mathematical modelling in the consideration of CO_2 mitigation (Rajesh et al., 2016; Benidris et al., 2016; Koltsaklis et al., 2014; Mirzaesmaeeli et al., 2010). Multi-period and multi-region load-dispatch modelling and optimization approach to the planning of China's power sector with consideration of carbon dioxide mitigation have been developed (Zhang et al., 2012; Cheng et al., 2015; Guo et al., 2016a, 2016b). In Zhang et al.'s work, power generation technology and fuel type are considered to illustrate the main features of the evolution of the model. Guo et al. further develop the spatial characteristic and grid structures based on the previous work to better reflect real world situations and give robust insights into the development of China of the model through to 2035. This paper explores the clean production pathways for regional power generation system based on a modelling and optimizing framework built on Long-range Energy Alternatives Planning System (LEAP), a software tool for energy environment planning developed by the Stockholm Environment Institute (SEI, 2016). As an integrated modelling platform, LEAP can be used to simulate mid to long-term energy supply-demand, local air pollutants and GHG emissions originated from energy utilization, and has been widely used by researchers and organizations for national and regional energy demand forecast and scenario analysis. Many previous literature have applied LEAP to predict power demand in the field of power generation sector (Suhono and Sarjiya, 2015; Andrade Guerra et al., 2015; McPherson and Karney, 2014). More recent studies adopt LEAP to analyze energy savings, energy related GHGs and LAPs reduction potentials for power generation system (Cai et al., 2007; Perwez and Sohail, 2014; Hong et al., 2016; Dias et al., 2014; Zhou et al., 2016). The studies find that more emphasis and strength of energy-environment-ecomomy policy imposed on the economic and/or power sector would help to reduce the energy consumption and air emissions compared with the baseline scenario. Previous studies applying LEAP on electric power system have put much focuses on the forecast of power demand, energy savings and emission reductions under various alternative scenarios. However, few of the existing works allow for optimization objective in LEAP modelling construction. Thus, it is quite reasonable to assume that cost-effectiveness may be of great importance for power generation planning where capacity expansion should not only fulfill electric demand or reach emission reduction targets, but also should be economic feasible for power plants to build. Therefore, this paper develops a mathematical model of regional power generation system that embeds optimization targets, providing cost-effective solutions for capacity expansion under various CO_2 and $PM_{2.5}$ reduction targets. This model is then applied in a case study of Shanghai over the period between 2015 and 2030, simulating the optimal capacity expansions under different CO_2 and $PM_{2.5}$ constraints in order to sketch clean production pathways for Shanghai's power-generation planning. Results and analysis cover the amount and types of capacity additions, energy input, system cost and emission reduction co-benefits.

Previous studies of emission reduction co-benefits have mainly focused on developed countries (Bollen, 2015; Menikpura et al., 2014; Mrkajic et al., 2015), and yet, co-benefit studies begin to aim at China in recent years. The objectives of those studies shift to multiple air emissions reductions and the co-benefits including GHGs (mainly CO_2) and LAPs (He et al., 2010; Jiang et al., 2013; Chen et al., 2006). With regard to China's industry co-benefits assessing, several studies evaluated co-benefits of energy efficiency and air pollution abatement in China's cement industry (Zhang et al., 2015; Yang et al., 2013; Xi et al., 2013). Similar works are also conducted for transportation sector (Mao et al., 2012) and iron and steel industry (Ma et al., 2014). In terms of power sector, Ma et al. (2013) computed the co-benefits of CO_2, LAPs and water savings of wind industry for Xin-jiang province.

Along with the reduction and control targets allocated to industry and enterprise from national level, policymakers begin to focus on mitigation strategies and technologies that are suitable for the specific industry and region. Their concerns include reduction allocation, mitigation cost-benefits, technology selection and policy measurement choosing (e.g. energy subside and carbon tax). Nevertheless, as many existing studies focused on national level, there is still a gap between researchers and regional policymakers to translate academic achievement to policymaking.

In this paper, the methodology is constructed before the case study of Shanghai is presented. Five scenarios and sensitivity analysis are conducted. The results may benefit policymaking and for future studies.

2. Research methodology

2.1. Structure of the model

Regional Power-generation System Optimization (RPSO) is a multi-stage mixed integer linear power-generation planning model, which takes the minimization of accumulative system cost as optimizing objectives. Built on LEAP system, the model adopts ILOG CPLEX Optimization Studio 12.6.3 developed by IBM as the optimal solver. It can be used to evaluate existing power generation plan and to select appropriate technologies under air emission constraints in the mid to long-term. An illustrative model structure is demonstrated in Fig. 1. The model comprises four parts model constraints, exogenous variables, objective functions and endogenous variables. The framework in the middle of the figure is the power generation system operating diagram originated from energy supply module and power plants module to power demand module with fuels and power plants matched respectively.

2.1.1. Energy supply module

Energy supply for power generation system is classified into two categories, indigenous energy production and imported energy from outer regions. The energy types include coal, natural gas, residual fuel oil, hydro, nuclear, wind, solar, biomass and combustible solid municipal waste. Data input requires indigenous resource reserves, lower heating value, fuel price and emission factors.

2.1.2. Power plant module

For the regional power generation system, many technologies are involved for installed capacity and available for new power plants to be built. According to energy types, they are classified as: (1) pulverized coal-fired power plants, including ultra-supercritical coal-fired plants, supercritical coal-fired power plants, subcritical coal-fired power plants, other small coal-fired power plants and Integrated Gasification Combined Cycle power plants (IGCC); (2) oil power plants; (3) natural gas power plants, including Natural Gas Combined Cycle power plants (NGCC) and distributed natural gas power plants; (4) nuclear power plants; (4) renewable power plants (hydro, wind, solar, biomass) and (5) comprehensive utilization plants, including residual heat-pressure-gas power plants (HPG) and combustible solid municipal waste power plants.

Exogenous variables involved in power plant module include generating efficiency, exogenous capacity, maximum availability, costs (capital cost, variable O&M cost, fixed O&M cost and fuel cost), expected lifetime of power plant, planning reserve margin of the system, dispatch rule etc.

According to *Energy Saving Power Generation Dispatching Policy*

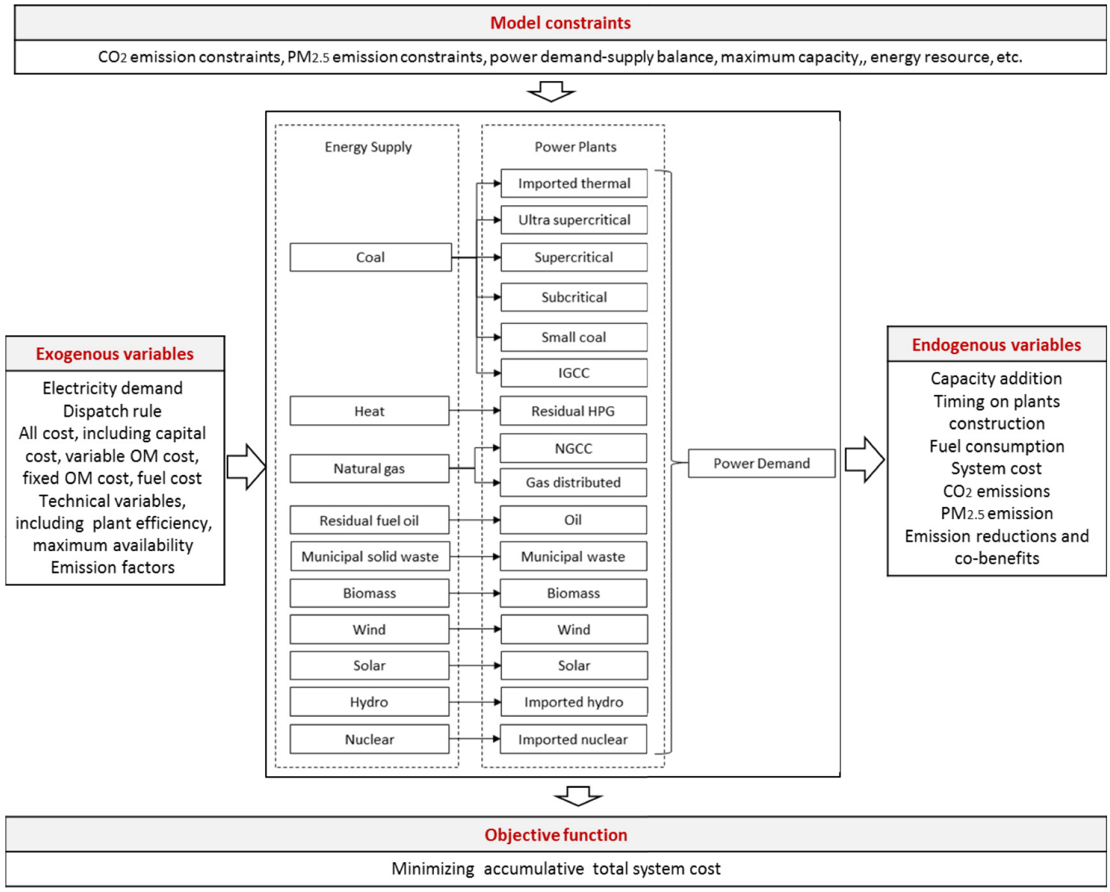

Fig. 1. An illustrative structure of the model.

(NDRC, 2007), dispatch rule for power generation technologies is set as follows: (1) renewable power plants without adjustment abilities, including wind, solar, hydro, for instance; (2) renewable power plants that have the adjustment abilities, including biomass power plants and combustible solid municipal waste power plants; (3) nuclear power plants; (4) Combined Heat and Power (CHP) coal-fired plants that generating power by heat, and residual HPG power plants; (5) natural gas power plants and IGCC power plants; (6) coal-fired power plants including CHP power plants that without heat load; (7) oil power plants.

2.2. Objective functions

The objective function of the model is to minimize the accumulated system total cost by regional power generation system over the planning period in Eq. (1). Accumulated system cost comprises of capital cost, fixed O&M cost, variable O&M cost and fuel cost over the planning time horizon for all categories of technologies.

$$cost = min\left\{ \sum_{t=1}^{T} \left[\sum_{n=1}^{N} \left(cap_{n,t} + fom_{n,t} + vom_{n,t} + fuel_{n,t} \right) \Big/ (1+i)^{t-1} \right] \right\}$$
$$= min\left\{ \sum_{t=1}^{T} \left[\sum_{n=1}^{N} \left(qcap_{n,t} \times icapc_{n,t} \times i \times \frac{(1+i)^{l(n)}}{(l+i)^{l(n)-1}} + qcap_{n,t} \times fomc_{n,t} + gelec_{n,t} \times vomc_{n,t} + gelec_{n,t}/EFFI_{n,t} \times fuelp_{m,t} \right) \Big/ (1+i)^{t-1} \right] \right\} \quad (1)$$

2.1.3. Power demand module

This paper deals with the drivers of power demand, such as the economic growth, electricity intensity, electricity trade, efficiency of electricity generation and fuel mix etc. (Karmellos et al., 2016; Lyu et al., 2016) as exogenous parameters.

To compare the economic performance of all technologies, capital cost of constructing a power plant is discounted equally into each year over its entire expected lifetime with the discount rate. In addition, annual change rate of capital cost, fixed O&M cost and variable O&M cost per unit capacity as well as fuel price are defined in Eqs. (2)–(5).

$$icap_{n,t} = ICAP_{n,0}(1 + ICAPR_{n,t})^t \quad (2)$$

$$fomc_{n,t} = FOMC_{n,0}(1 + FOMCR_{n,t})^t \quad (3)$$

$$vomc_{n,t} = VOMC_{n,0}(1 + VOMCR_{n,t})^t \quad (4)$$

$$fuelp_{m,t} = FUELP_{n,0}(1 + FUELPR_{m,t})^t \quad (5)$$

2.3. Emission calculation

Total emissions of CO_2 or $PM_{2.5}$ in year t can be descried by Eq. (6):

$$emis_{j,t} = \sum_{n=1}^{N} (gelec_{n,t} / EFFI_{n,t} \times EF_{j,m,t}) \quad (6)$$

2.4. Constraints

2.4.1. Electricity balance

The balance between electricity consumption and total electricity generation is expressed as follow:

$$CELEC_t \le \sum_{n=1}^{N} gelec_{n,t} \quad (7)$$

2.4.2. Maximum availability

A power plant can be out of production due to maintenance, repairs and weather conditions. Therefore, the maximum availability of a power generation technology is the share of time that is able to produce electricity in the whole year divided by the total amount of time in a year. In each year, the electricity generated by a power generation technology cannot exceed its maximum availability multiplied by its capacity:

$$gelec_{n,t} \le AMAX_n \times qcap_{n,t} \quad (8)$$

2.4.3. Total installed capacity

Regarding the factors that constrain the total installed capacity such as resource endowment and technology development, maximum total installed capacity and minimum total installed capacity are introduced to constrain installed capacity:

$$MinQCAP_{n,t} \le qcap_{n,t} \le MaxQCAP_{n,t} \quad (9)$$

2.4.4. Minimum capacity addition

The cap of minimum capacity addition is imposed, as for some types of technologies, ultra-supercritical, IGCC, NGCC for instance, the capacity of a unit is often 1000 MW, 60 MW or 30 MW. Thus, the capacity addition should be no less than one unit:

$$qcapa_n \ge MinQCAPA_{n,t} \quad (10)$$

2.4.5. Emission constraints

To control the amount of air emissions from power generation system, the cap of annual air emission released from all types of technologies is imposed by Eq. (11):

$$emis_{j,t} \le EMIS_0 \times (1 - REMIS_{j,t}) \quad (11)$$

3. Case study

3.1. General profile of Shanghai's power generation system

The proposed model has been applied on a case study of Shanghai power generation system over the period between 2015 and 2030. Located in China's central eastern coast of the Yangtze Delta, Shanghai is an international metropolitan covering 6340 square kilometers with more than 24 million populations. As the economic center of eastern China, it is responsible for one twelfth of China's industrial output, one tenth of cargo handling, a quarter of imports and exports and one eight of the tax revenue (Piao et al., 2015). Power generation system plays a supportive role in Shanghai's economic development and residents' daily life. There are 48 power plants included in Shanghai's power generation system which covering most of the power generation technologies with different fuel types such as coal, natural gas, oil, residual HPG, biomass, waste, wind, solar power plants, with a total installed capacity of 20,943 MW and electricity production of 80,800 GWh by the year of 2014. The installed capacity of imported electricity is equal to 15,690 MW, covering the technologies of coal, hydro and nuclear power plants. Imported electricity reached 56,089 GWh in 2014.

Shanghai has very limited primary energy resource endowment, while fossil fuel input for local power generation system is mainly imported from the outer regions such as Shanxi, Anhui province. Electricity production from local coal-fired power plants accounts for 83% of the total production, and that of natural gas, residual HPG, oil and other types of technologies amount to 8%, 5%, 1% and 3% respectively.

3.2. Design of scenarios

Taking 2014 as the base year, planning reserve margin of the case study is set to 15%. There are five scenarios to simulate the power generation system expansion pathways which are Business-as-usual scenario (BAU), Baseline scenario (BASE), CO_2 Constraint scenario (CO_2), $PM_{2.5}$ Constraint scenario ($PM_{2.5}$) and Combined Air Emission Constraint scenario (CAEC). Logistics and contents of the scenario setting are shown in Table 1.

3.2.1. Business-as-usual scenario (BAU)

In this scenario it is assumed that the development trends of power generation technologies in Shanghai in the future will follow the past and no capacity-added plan and air emission constraints will be imposed except the ones that suggested in the *Encourage Large Projects and Discourage Small Energy-inefficient Power Plants* (Office of the State Council, 2007). Under the BAU scenario, installed capacities will decommission on their expected lifetime. Capacity-added plan for IGCC and renewable plants is carried out according to the timetable. Installed capacity of ultra-supercritical coal-fired power plants and NGCC power plants will not decommission over the planning period. Two units of 600 MW supercritical coal-fired plants will retire in 2022, while subcritical coal-fired plants will decommission a certain number of capacity in almost every year over the planning period. All small coal plant will

Table 1
Alternative scenarios and their description.

Scenario	Optimization function	CO_2 constraint	$PM_{2.5}$ constraint	Content
BAU	No	No	No	Business-as-usual. Capacity is addition and retired as planned.
BASE	Yes	No	No	Based on BAU scenario, system cost minimization with no emission constraints.
CO_2	Yes	Yes	No	Based on the BASE scenario, system cost minimization with CO_2 emission constraint.
$PM_{2.5}$	Yes	No	Yes	Based on the BASE scenario, system cost minimization with $PM_{2.5}$ emission constraint.
CAEC	Yes	Yes	Yes	Based on the BASE scenario, system cost minimization with both CO_2 and $PM_{2.5}$ emission constraints.

be shutdown before lifetime expire, with the installed capacity of 741 MW in 2014 gradually decreasing to 400 MW in 2020 and all closed in 2030. Capacity of residual oil plants will decline year by year, with the shutdown of 2 units of 125 MW in 2015 and 4 units of 100 MW in 2027. Two units of 400 MW IGCC plants will commission in 2020. Accumulated wind power capacity will rise to 600 MW, and that amount of solar power will be 900 MW in 2030.

It should be noted that the BAU scenario does not have the function of optimization for future capacity expansion but merely designed for accounting and assessing existed planning (unmet electricity demand for instance).

3.2.2. Baseline scenario (BASE)

Built on the BAU scenario, the Baseline scenario takes the minimized accumulative system total cost as the objectives without any air emission constraints.

3.2.3. CO_2 constrained scenario (CO_2)

This scenario is added CO_2 constraint based on the BASE scenario. According to the climate mitigation commitment by the Chinese government to United Nations, CO_2 emissions will peak in around 2030, thus the case study of Shanghai set the emission peaking year at 2025, earlier than the national target, with emission reduced by 5% in 2030 than the peaking value.

3.2.4. $PM_{2.5}$ constrained scenario ($PM_{2.5}$)

$PM_{2.5}$ emission constraint is applied based on the BASE scenario. According to *Shanghai Clean Air Action Plan 2013–2017* (Shanghai Environmental Protection Bureau, 2013), heavily polluted days should reduced sharply, with atmospheric concentration of $PM_{2.5}$ decreased by 20% in 2017. Since concentration control cannot prevent the increase of total emission amount led by the growing volume of emission resources, it is possible that concentration at the power plant reaches emission standard but air quality may not get improved due to total emission amount increase within the region. Therefore, we adopt total amount of $PM_{2.5}$ emission constraints. It is assumed that the total emission amount of $PM_{2.5}$ is reduced by 20% in 2017 and by 35% in 2030 than the base year.

3.2.5. Combined air emission constraints scenario (CAEC)

To simulate the pathways that both CO_2 and $PM_{2.5}$ constraints simultaneously imposed on power generation system, this paper constructs the CAEC scenario based on the BASE scenario. The parameter settings of CO_2 and $PM_{2.5}$ constraints are same with the CO_2 scenario and the $PM_{2.5}$ scenario.

3.3. Data input

3.3.1. Technology parameters

As shown in Section 2.4, a series of parameters form the model which the accuracy of the results largely depend on. Installed capacity in the base year, minimum capacity addition and maximum capacity over the planning horizon are listed in Table 2. Technology characteristic parameters including unit efficiency in the base year and the end year, expected lifetime and maximum availability are referred from Zhang et al. (2012) and Han et al. (2012). Regarding to cost parameters, capital costs for all types of coal-fired units dropped in 2014, among which the 2 × 1000 MW capacity plant experiences the biggest drop. Capital cost of 2 × 300 MW (9FGrade) NGCC plant demonstrated a declining trend in 2014 as well. Capital cost of hydro power plant has displayed an increase trend in recent years since salvage value and the price keep rising. Easily-developing hydro resource becomes less, and the higher compensation which paid to immigrants also contributed to the increase of capital cost. The average capital cost of hydro power plant in 2014 was 11,193 RMB/KW which however varied between 8000 and 13,000 RMB/KW which is depend on the size of the unit capacity and geological conditions for instance. Capital cost of nuclear, wind and solar power also witnessed a drop in 2014. Data of cost and the change rate over the planning horizon that obtained from China Electricity Council (2015) is also seen in Table 2.

3.3.2. Energy price and emission factors

Energy types involved in the case study include coal, natural gas, residual fuel oil, biomass etc. In this study, emission factors for all types of energy are assumed to keep unchanged. Fuel price and emission factors for CO_2 and $PM_{2.5}$ by fuel type are listed in Table 3.

CO_2 emission factors mainly depend on fuel characters such as carbon content and heating value, as well as combustion equipment. Data of fuel content is referred to LEAP's built-in TED Database. Carbon oxidation rates during the combustion of fuel for coal-fired power plants of ultra-supercritical, supercritical, subcritical and small unit are 99%, 99%, 98%, 95% respectively (NDRC, 2014), and that of IGCC and imported coal plants are assumed the same with supercritical ones.

$PM_{2.5}$ emission factors of coal-fired power plants are referred from a survey carried out by Ding et al. (2015), which showed all installed and new built capacity in Shanghai power generation system has all been installed selective catalytic reduction (SCR), electrostatic precipitators (ESP) and flue gas desulfurization (FGD) devices. According to Huaneng GreenGen IGCC Demonstration (Hua-neng Group, 2014), $PM_{2.5}$ emission factors of IGCC plant is 10% of traditional pulverized coal-fired plants. *The Manual of First National Pollution Census for Industrial Pollution Source Emission Coefficient* (Office of the State Council Leading Group for the First National Survey of Pollution Sources, 2010) provides emission factors of NGCC and distributed natural gas power plants. The other $PM_{2.5}$ emission factors are referred to the study by Zhao et al. (2010).

3.3.3. Electricity demand

Highly related with economic development, Shanghai's power consumption had been linked up with GDP growth in the past two decades. Especially in the year between 2000 and 2010, electricity consumption increased rapidly with the strong economic growth. However, electricity consumption growth has weakened as the

Table 2
Existing installed capacity, technology characteristics and cost for different types of technology.

Technology	Dispatch order	Capacity			Technology characteristics				Cost				
		Installed capacity in 2014 (MW)	Minimum capacity addition (MW)	Maximum capacity (MW)	Efficiency in 2014 (%)	Efficiency in 2030 (%)	Expected lifetime (year)	Maximum availability (hours)	Initial capital cost (RMB/KW)	Annual decrease rate of capital cost and fixed OM cost (%)	Fixed OM cost (RMB/KW)	Variable OM cost (RMB/MWh)	Annual decrease rate of variable OM cost (%)
Ultra-supercritical coal	6	5320	1000	N/A	45.0	46.5	30	6300	3202	N/A	106.2	27.8	N/A
Supercritical coal	6	3000	N/A	3000	41.5	43.0	30	6100	3305	N/A	117.0	27.8	N/A
Subcritical coal	6	5430	N/A	5430	39.5	41.0	30	6000	4323	N/A	133.3	27.8	N/A
Small coal	6	101	N/A	101	34.0	34.0	30	6000	4410	N/A	132.3	34.7	N/A
Residual HPG	4	586	N/A	586	100.0	100.0	30	8000	8000	N/A	133.3	27.8	N/A
IGCC	4	0	300	N/A	50.5	53.0	30	6500	8981	0.90	269.3	30.6	0.75
NGCC	1	4224	300	N/A	52.0	53.5	25	6500	2762	0.50	100.8	31.0	N/A
Gas distributed	7	47	N/A	N/A	38.0	38.0	25	6500	8350	0.70	358.0	93.0	N/A
Oil	1	864	N/A	864	39.0	39.0	20	1900	3680	N/A	110.0	19.5	N/A
Wind	1	374	N/A	6500	100.0	100.0	20	2100	7551	1.10	310.0	14.0	0.50
Solar	1	207	N/A	5000	100.0	100.0	20	1384	8657	3.00	216.0	0.5	0.50
Municipal waste	1	136	N/A	200	40.5	40.5	30	6000	4443	N/A	133.0	27.8	N/A
Biomass	2	14	N/A	200	40.6	40.6	20	3000	9700	0.15	390.0	48.4	1.00
Imported thermal	6	4000	600	7000	41.5	43.0	30	5800	3590	N/A	117.0	27.8	N/A
Imported hydro	1	11,000	N/A	12,700	100.0	100.0	50	3385	11,193	N/A	105.0	7.0	N/A
Imported nuclear	3	690	N/A	1010	100.0	100.0	40	7000	8657	N/A	600.0	28.0	N/A

economic growth slowed down since 2010. With China's economy steps into a moderate growth period, as well as electricity demand will be further decoupled with economic growth, it can be predicted that electricity demand will keep in a relatively low growth speed. Therefore, this study assumes electricity demand growth rate is 3% in 2015–2020 and slows down to 2% in 2020–2030 (Chang and Pan, 2014).

4. Results and discussion

The gap between the power demand and supply for Shanghai grows from 340 GWh in 2018 to 31600 GWh in 2030, accounting for 0.2% and 15.9% of the total demand respectively. The growing trend of unmet electricity demand under the BAU scenario indicates that additional capacity should be planned for power generation system.

Based on the model presented in Section 2 and data input in Section 3, the optimal cleaner production pathways of Shanghai's power generation system are obtained under various emission constrained scenarios. The results include power generation capacity expansion planning, estimation of reduction co-benefits, and comparisons of accumulative total energy consumptions and cost changes.

4.1. CO_2 constraints promote renewable capacity increase

As shown in Fig. 2, during the period of 2015–2023, optimal capacity additions of ultra-supercritical, imported hydro, imported nuclear and biomass power plants keep almost the same under the four optimizing scenarios (BASE, CO_2, $PM_{2.5}$ and CAEC scenario). Ultra-supercritical coal-fired power plants added by one 1000-MW unit for each year between 2015 and 2021 and three units in 2022. Imported nuclear power reaches its maximum capacity of 320 MW at the very beginning of the planning period, and biomass power increases slightly in 2015. Imported hydro power increases by 910 MW in 2015 under the BASE scenario, while by 1023 MW in 2015 under the other three optimizing scenarios. It suggests that imposing CO_2 or $PM_{2.5}$ constraints on Shanghai's power generation system has no impacts on pathways variation in the short to mid-term due to the moderate constraints.

Capacity addition pathways vary along with the stricter emission constraints in the long-term. During the period between 2026 and 2030, all capacity additions come from ultra-supercritical units under the BASE scenario, with one 1000-MW unit in each year. While under the $PM_{2.5}$ scenario, hydro power are additionally installed 307 MW in 2024 and 370 MW in 2026, also one 600-MW unit of imported thermal capacity and 45 MW of wind power are installed in 2030. For the CO_2 scenario and the CAEC scenario, technologies and capacity additions are same, with the only difference is the time when the hydro power addition comes up. A 677 MW capacity addition of hydro power is one-time increased in 2026 under the CO_2 scenario, which the amount is split into 307 MW in 2024 and 370 MW in 2026 under the CAEC scenario.

Total installed power capacity for the four optimizing scenarios

Table 3
Fuel characteristics, price and emission factors for different types of technology.

Fuel type	Lower heating value	Price	Technology	CO_2 (t/TJ)	$PM_{2.5}$ (kg/t or g/m^3)
Coal	20.93 GJ/t	500 RMB/t	Ultra-supercritical	95.03	0.37
			Supercritical	95.03	0.37
			Imported	95.03	0.00
			Subcritical	94.06	0.37
			Small l	91.20	2.50
			IGCC	95.03	0.37
			CFB	95.03	0.37
Natural gas	34.20 MJ/m^3	2.72 RMB/m^3	NGCC	55.78	1.10
			Gas distributed	55.78	1.10
Residual fuel oil	40.19 GJ/t	2580 RMB/t	Oil	76.54	0.25
Municipal solid waste	7.59 GJ/t	N/A	Municipal waste	123.56	0.07
Biomass	13.99 GJ/t	700 RMB/t	Biogas	109.56	0.20

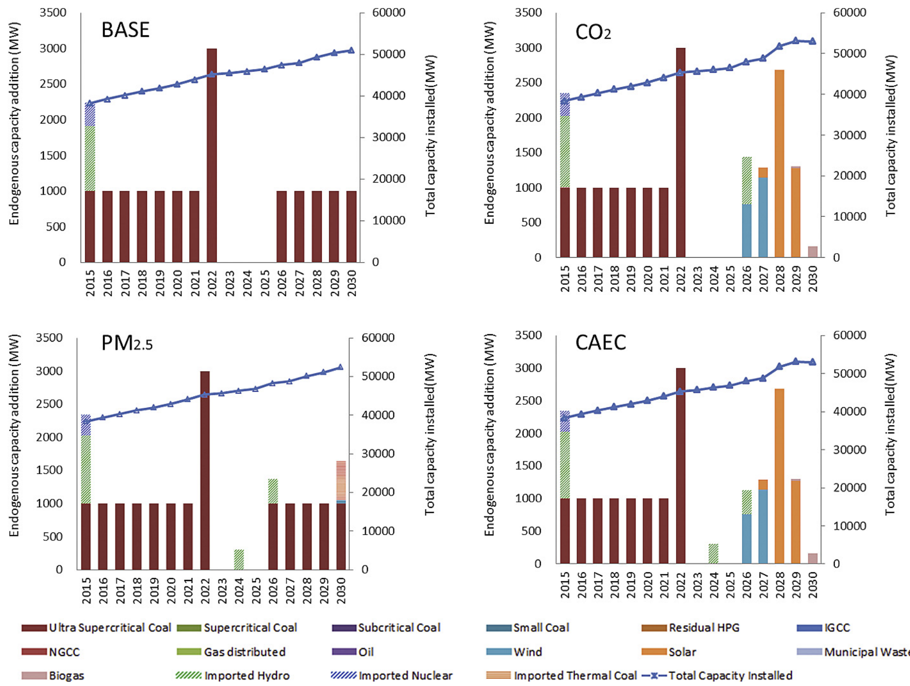

Fig. 2. Endogenous capacity addition and total capacity installed under the four optimizing scenarios between 2015 and 2030 (MW).

and the structures are seen in Fig. 3. By the year of 2030, the BASE scenario keeps the smallest size of 50,972 MW, and the other three optimizing scenarios are 52,407 MW in the $PM_{2.5}$ scenario, 52,946 MW in the CO_2 scenario and the CAEC scenario. The share of coal-fired power plants drops slightly from 54.0% under the BASE scenario to 53.3% under the $PM_{2.5}$ scenario, and further to 40.8% under the CO_2 and the CAEC scenario. The share of clean power generation technologies (natural gas, nuclear, wind, hydro, solar and biomass) witnesses a growth from 45.5% under the BASE scenario to 57.7% under the CO_2 and the CAEC scenario.

Since many studies of optimal planning for China's power sector still focus on national level, it is difficult to compare the results of Shanghai case study with others. We try to compare the main findings for East area (including provinces of Shanghai, Jinagsu, Zhejiang, Anhui and Fujian) by Guo et al. (2016b) with our study. In Guo et al.'s study, nuclear power will be deployed in large quantities through to 2035 to meet the growing power demand in East and Guangdong area due to higher fossil fuel cost and low quality of renewable resource. Ultra-supercritical power plants take the second biggest share of new built capacity. These findings are partially coincided with our study that nuclear power will develop to the maximum extend of potential capacity at the very beginning of the planning period and ultra-supercritcal coal is the only source of capacity addition other than nuclear and hydro. The difference is

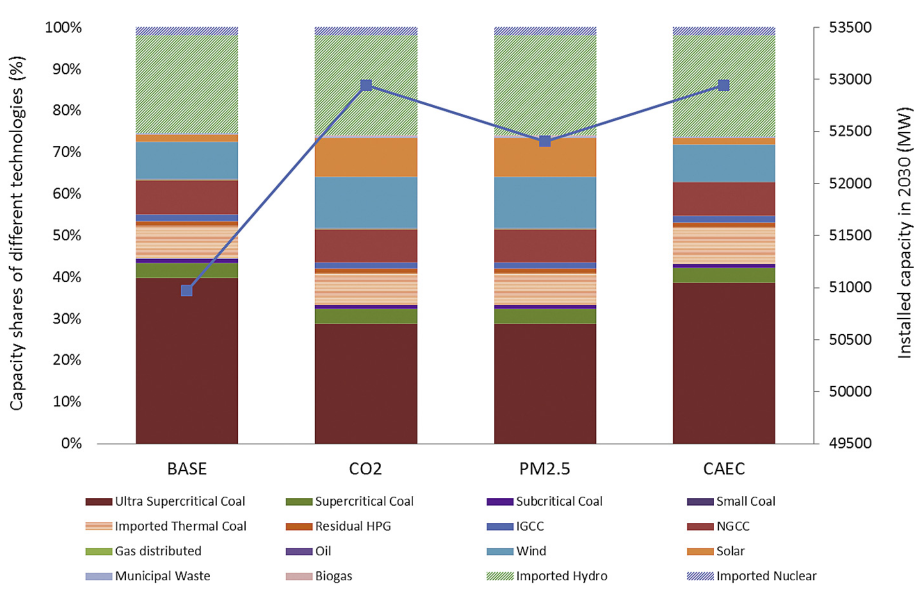

Fig. 3. Capacity shares of different technologies (%) and installed capacity (MW) under the four optimizing scenarios in 2030.

the expansion scale, which is largely depend on parameters exogenously defined by the study.

4.2. Stronger reduction co-benefits come from CO_2 constraints

Reduction co-benefits of CO_2 constraints on $PM_{2.5}$ emission are seen in Fig. 4. The $PM_{2.5}$ reduction amount is increased from 56 tons in 2015 to 2934 tons in 2030, accumulated 245,000 tons over the planning period. Regarding the contributors, power plants of municipal waste and biomass show negative effects compared with the BASE scenario. Co-benefits of subcritical power plants and NGCC power plants are not always positive in each year. In general, negative effects from municipal waste, biomass, subcritical and NGCC units are offset by positive effects from ultra-supercritical and supercritical coal-fired power plants. Another proof of stronger co-benefits of CO_2 constraint is observed from $PM_{2.5}$ emissions during the period of 2026–2030 under the four optimizing scenarios. $PM_{2.5}$ emissions under the CO_2 scenario is even less than that of the $PM_{2.5}$ scenario, which implies that along with the CO_2 constraints tightening in the long-term, more reduction co-benefits will be generated over $PM_{2.5}$ reduction.

Similarly, reduction co-benefits of $PM_{2.5}$ constraints over CO_2 emission are positive, growing from 370 thousand tons in 2015 to 1220 thousand tons in 2030 (Fig. 5). Compared with the BASE scenario, positive co-benefits from ultra-supercritical, supercritical, subcritical and NGCC units under the $PM_{2.5}$ scenario are almost offset by negative co-benefits from imported thermal power plants due to higher carbon emission factors. Accumulative CO_2 reduction co-benefits over the planning period sum up to 1.47 Gt. Further comparisons show that CO_2 emission curves of the period from 2015 to 2030 under the $PM_{2.5}$ scenario is in between of the BASE scenario and the CO_2 scenario as well as the CAEC scenario. Hence, it can be concluded that reduction co-benefits by $PM_{2.5}$ constraints are not stronger than that of CO_2.

4.3. No natural gas capacity appears under any scenario

Natural gas power plants including NGCC and natural gas distributed power plants perform no techno-economic and emission control advantages compared with the other technologies under existing conditions. A sensitivity analysis is taken in the next section to examine whether the drop of fuel price can benefit the development for these technologies. Installed capacity under the four optimizing scenarios for natural gas power plants makes no difference with each other, only the electricity production varies by year, which is less under the BASE and the $PM_{2.5}$ scenario than in the CO_2 scenario and the CAEC scenario.

4.4. Emission constraints generate energy savings

As emission constraints play a more important role in determining the pathways of Shanghai's power generation system under the CO_2 scenario, cleaner technologies that featured as lower carbon emission factors as well as less energy intensity are taken as the main sources of capacity additions in the mid to long-term planning horizon. As a result, energy consumption under the CO_2 scenario is also less than the BASE scenario, with the accumulative amount of 19.8 billion GJ over the planning period, a slightly drop of 0.9% than the BASE scenario. Besides, since $PM_{2.5}$ emission is not accounted into local account, capacity addition of imported thermal power plants is endogenously generated at the end of the planning period under the $PM_{2.5}$ scenario. Thus, accumulative energy consumption increases under the $PM_{2.5}$ scenario due to the lower energy efficiencies of imported thermal power plants compared with the ultra-supercritical ones added in the BASE scenario. However, energy savings from the capacity addition of hydro power, which energy intensity is even lower, are offset by the increase of energy consumption from the capacity addition of imported thermal power plants under the $PM_{2.5}$ scenario. Therefore, accumulative

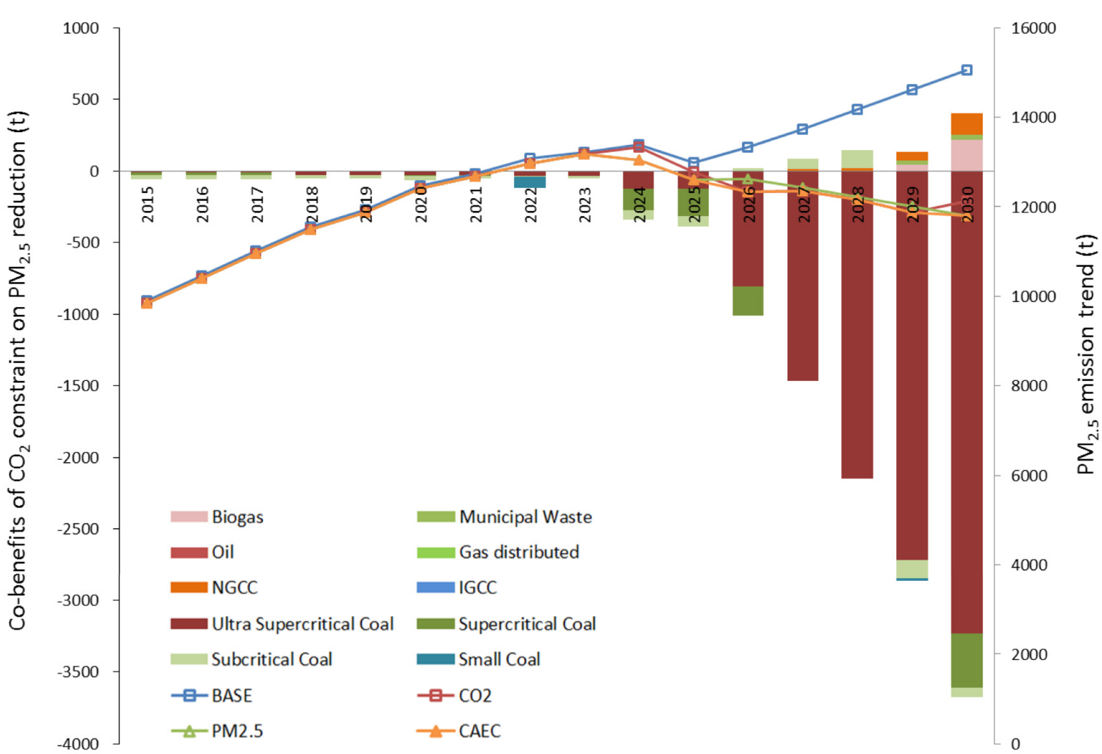

Fig. 4. Co-benefits of CO_2 constraint on $PM_{2.5}$ reduction and $PM_{2.5}$ emission trend between 2015 and 2030 (ton).

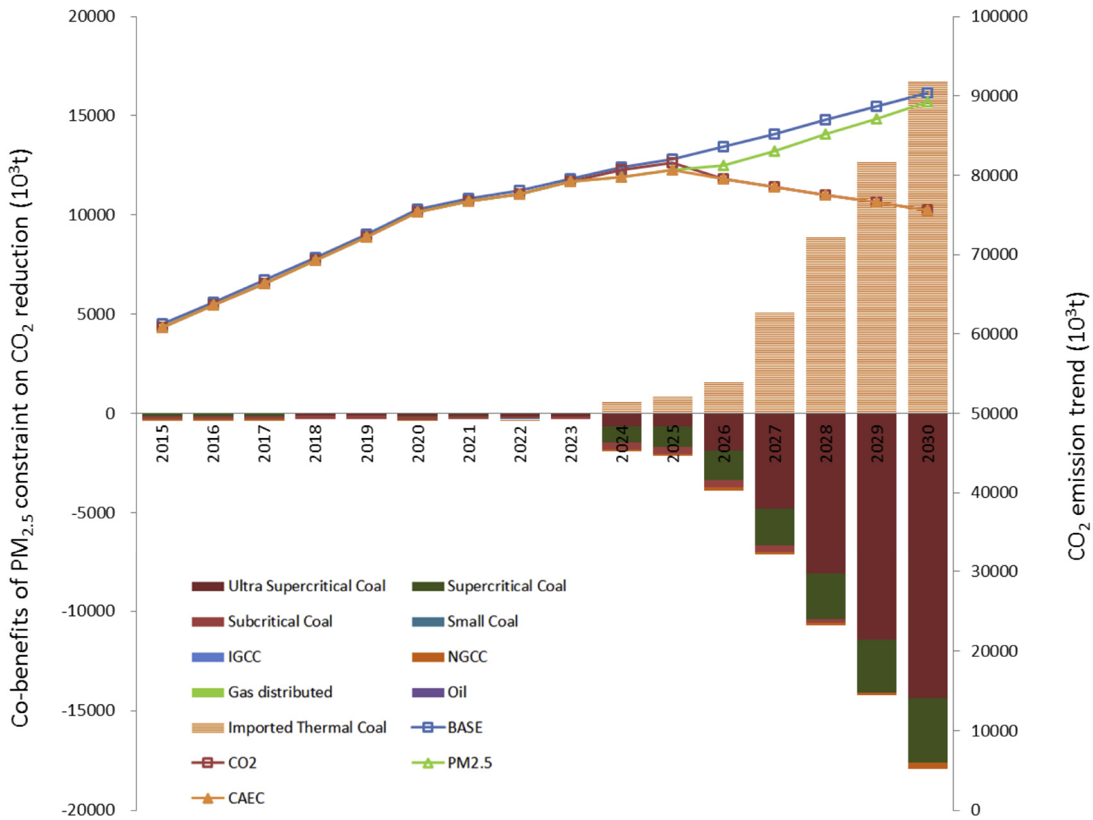

Fig. 5. Co-benefits of $PM_{2.5}$ constraint on CO_2 reduction and CO_2 emission trend between 2015 and 2030 (10^3t).

energy consumption under the $PM_{2.5}$ scenario sums up to 19.9 billion GJ, a drop of 0.8% than the BASE scenario. Hence, it can be concluded that both CO_2 and $PM_{2.5}$ emission constraints will generate energy savings.

4.5. Emission constraints raise accumulative system cost

Accumulative system cost under the $PM_{2.5}$ scenario, the CO_2 scenario and the CAEC scenario increase 0.1% and 1.5% respectively compared with the BASE scenario. As mentioned previously, emission constraints would lead to extra capacity addition which will raise the system cost. Moreover, the share of ultra-supercritical power plants which are the most cost-effective plants, drops as stricter emission constraints imposed on power generation system, and is substitute by higher cost power plants such as IGCC, wind power, solar power and biomass power.

4.6. Sensitivity analysis for key parameters of the model

To further analyze the impacts of different factors on pathways choosing for the power generation system, a sensitivity analysis is conducted for several key parameters of the model, including emission constraints, $PM_{2.5}$ emission apportion of imported thermal power plants, as well as natural gas price. Data input in Section 3 and 4 is served as the reference case for sensitivity analysis.

4.6.1. Impacts of emission constraints

4.6.1.1. Emission constraints. The changes of accumulative emissions, costs and capacity additions under stricter CO_2 emission constraints are shown in Table 4. Based on emission constraint settings in the reference case, emission peaking year is brought forward from 2025 to 2023. And the reduction rate in 2030 compared with the peaking level is enhanced, from 5% in the reference case to 8% in the sensitivity analysis. It is observed that accumulative system cost rises by 1.1%, yet CO_2 emission is reduced by 1.3%, as well as 1.2% for $PM_{2.5}$ emission. Given that no capacity added under reference case, for IGCC power plants, a capacity addition of 1200 MW is generated in sensitivity analysis where capacity additions of other technologies remain unchanged over the planning horizon.

Sensitivity analysis is executed for $PM_{2.5}$ emission constraints in a similar way. $PM_{2.5}$ emission is reduced by 30% in 2017 and 45% in 2030 compared with the year of 2012. The accumulative $PM_{2.5}$ emission declines 7.5% and CO_2 drops 3.2%, with the cost merely rising 0.3% compared with the reference scenario. Capacity addition are quite different with the results of CO_2 constraint changes. Strengthening $PM_{2.5}$ emission constraints benefits ultra-supercritical coal-fired power plants and imported thermal power plants as well as wind power, with the capacity addition of 2000 MW, 1800 MW and 642 MW respectively more than the reference scenario over the planning period.

4.6.1.2. $PM_{2.5}$ emission allocation of imported coal-fired power plants. Considering $PM_{2.5}$ emissions from imported thermal power plants will be allocated to the place where the electricity consumed when auditing regional emissions in China, sensitivity analysis evaluates the impacts on power generation cleaner production pathways. The accumulative emission of $PM_{2.5}$ rises by 6.5%, and system total cost increases 2.1% compared with the reference case. Capacity additions of ultra-supercritical power plants and imported

Table 4
Sensitivity analysis for emission constraints and $PM_{2.5}$ emission allocation from imported thermal power plants.

Changes compared with the reference case	CO_2 emission constraint	$PM_{2.5}$ emission constraint	$PM_{2.5}$ emission allocation
CO_2 emissions (%)	−1.3	−3.2	−4.0
$PM_{2.5}$ emissions (%)	−1.2	−7.5	6.5
System total cost (%)	1.1	0.3	2.1
Ultra-supercritical units capacity addition (MW)	0	2000	−1000
Imported thermal units capacity addition (MW)	0	1800	−600
IGCC units capacity addition (MW)	1200	0	4500
Wind power capacity addition (MW)	0	642	468

Table 5
Sensitivity analysis for natural gas prices.

	Natural gas price (RMB/m^3)	Price change rate (%)	Accumulative endogenous capacity addition	
			NGCC (MW)	Of total in 2030 (%)
Reference case	2.72	0	0	0.0
OECD countries	3.06	12.5	0	0.0
Japan LNG	2.97	9.3	0	0.0
Average German import price	1.66	−39.0	0	0.0
UK Heren NBP Index	1.50	−45.0	0	0.0
Price A	1.47	−46.0	600	3.4
US Henry Hub	0.79	−86.8	13,800	99.9
Canada Alberta	0.70	−88.3	13,800	99.9

thermal power plants endeavor a drop of 1000 MW and 600 MW than the reference case, while IGCC power plants are largely in favor of the policy change, with the capacity addition growing from zero to 4500 MW.

4.6.2. Impacts of natural gas price

As mentioned above, there is no natural gas power plant built over the planning horizon under reference case. Sensitivity analysis is executed to examine whether it is associated with high price of natural gas. We adopt the natural gas prices of global major markets. The results (Table 5) indicate that when the price keeps in a relatively high level (the prices of OECD countries, Japan LNG, average German import price and UK Heren NBP Index for example), no NGCC and gas distributed power plants appear over the planning period. However, 600 MW capacity additions emerge when the fuel price experiences a drop of about 46% (a virtual price A of 1.47 RMB/m^3). When the price further falls to the level of US Henry Hub (by 86.8%), NGCC power plants are becoming the only source of capacity addition. Nevertheless, gas distributed power plants do not make any progress even the energy price drops dramatically. Thus, it can be concluded that fuel price is a key factor that influences the expansion of NGCC power plants. The lower the price, the more capacity addition turns up. However, this principle does not work for gas distributed power plants which implies there may be other factors block its development.

5. Conclusions and policy recommendations

A regional power generation system model for cleaner production pathways under different emission constraints is presented in this paper. The results of the case study of Shanghai show that existing plan for power generation development cannot meet the growing electricity demand, thus new capacity should be built at the appropriate time. The differences of capacity additions under four optimizing scenarios are getting obvious along with stricter emission constraints imposed in the long-term.

Imposing air emission constraints over power generation system is helpful for energy savings, yet generates extra system cost for more capacity additions. Carbon emission constraints could promote cleaner production technologies development, as well as realize $PM_{2.5}$ reduction co-benefits. Thus, when policymakers face both carbon mitigation and $PM_{2.5}$ reduction targets, a workable practice is to design the strategy only directing at CO_2 reduction, as co-benefits of carbon constraints could cover $PM_{2.5}$ reduction targets, although a higher system cost will be engendered. However, with the $PM_{2.5}$ emission accounting method transform from the control of single region to multiple regions, ultra-supercritical power plants and imported thermal power plants would be largely alternated by IGCC power plants.

High energy price is the main barrier that obstacles the development of NGCC power plants. When the price falls more than approximately 50%, these types of technologies will make breakthrough at capacity additions. Besides, under the safety assurance, the capacity of hydro and nuclear power could be extended as large as possible since they are the first choices for power generation system in the consideration of cost-effectiveness and emission reductions.

It should be noted that other substantial components of smog such as SO_2, NOx and other PMs should be taken into account in future analysis. The factors that hinder the development of gas distributed power plants need to be explored in depth.

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Appendix. Nomenclatures

Table A1
Physical meaning of variables.

Symbol	Physical meaning
$cost$	Accumulative total system cost over the planning period
$cap_{n,t}$	Capital cost for construction power plants of type n in year t
$fom_{n,t}$	Fixed operation and maintenance cost for power plants of type n in year t
$vom_{n,t}$	Variable O&M cost for power plants of type n in year t
$fuel_{m,t}$	Cost for fuels of type m in year t
$qcap_{n,t}$	Installed capacity for power plants of type n in year t
i	Discount rate
$gelec_{n,t}$	Electricity generation for power plants of type n in year t
$icap_{n,t}$	Initial capital cost for construction of 1 kW of power plants of type n in year t
$l(n)$	Expected lifetime for power plants of type n
$fomc_{n,t}$	Fixed O&M cost for construction of 1 kW of power plants of type n in year t
$vomc_{n,t}$	Variable O&M cost for production of 1 MWh of power plants of type n in year t
$fuelp_{m,t}$	Price of fuels of type m in year t
$emis_{j,t}$	Emission of air types of j in year t
$qcapa_{n,t}$	Capacity addition for power plants of type n in year t
$emis_{j,0}$	Emissions of air types of j in the base year

Table A2
Physical meaning of parameters.

Symbol	Physical meaning
$EFFI_{n,t}$	Generation efficiency for power plants of type n in year t
$ICAP_{n,0}$	Initial capital cost for construction of 1 kW of power plants of type n in the base year
$ICAPR_{n,t}$	Anural change of initial capital cost for construction of 1 kW of power plants of type n in year t compared with the base year
$FOMC_{n,0}$	Fixed O&M cost for construction of 1 kW of power plants of type n in the base year
$FOMCR_{n,t}$	Anural change of fixed O&M cost for construction of 1 kW of power plants of type n in year t compared with the base year
$VOMC_{n,0}$	Variable O&M cost for production of 1 MWh of power plants of type n in the base year
$VOMCR_{n,t}$	Anural change rate of variable O&M cost for production of 1 MWh of power plants of type n in year t compared with the base year
$FUELPR_{m,0}$	Fuel price of type m in the base year
$FUELPR_{m,t}$	Anural change rate of fuel price of type m in year t compared with the base year
$EF_{j,m,t}$	Emission factor for air type of j by fuel types of m in year t
$CELEC_t$	Total electricity consumption in year t
$AMAX_n$	The maximum availability of power plants of type n
$MinQCAP_{n,t}$	Minimum installed capacity for power plants of type n in year t
$MaxQCAP_{n,t}$	Maximum installed capacity for power plants of type n in year t
$MinQCAPA_{n,t}$	Minimum capacity addition for power plants of type n in year t
$REMIS_{j,t}$	Reduction rate for emission types of j in year t compared with the base year

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