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Co-controlling CO_2 and NO_x emission in China's cement industry: An optimal development pathway study

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Abstract

It is of important practical significance to reduce NO_x emission and CO_2 emission in China's cement industry. This paper firstly identifies key factors that influence China's future cement demand, and then uses the Gompertz model to project China's future cement demand and production. Furthermore, the multi-pollutant abatement planning model (MAP) was developed based on the TIMES model to analyze the co-benefits of CO_2 and NO_x control in China's cement industry. During modeling analysis, three scenarios such as basic as usual scenario (BAU), moderately low carbon scenario (MLC), and radically low carbon scenario (RLC), were built according to different policy constraints and emission control goals. Moreover, the benefits of co-controlling NO_x and CO_2 emission in China's cement industry have been estimated. Finally, this paper proposes a cost-efficient, green, and low carbon development roadmap for the Chinese cement sector, and puts forwards countermeasures as follows: first, different ministries should enhance communication and coordination about how to promote the co-control of NO_x and CO_2 in cement industry. Second, co-control technology list should be issued timely for cement industry, and the R&D investment on new technologies and demonstration projects should be increased. Third, the phase-out of old cement capacity needs to be continued at policy level. Fourth, it is important to scientifically evaluate the relevant environmental impact and adverse motivation of ammonia production by NO_x removal requirement in cement industry.

Keywords: Cement industry; CO_2 abatement; NO_x reduction; Co-benefit analysis

1. Introduction

The cement industry forms an important emission source of GHGs and NO_x and is thus considered as one of the key industries for energy conservation and emission reduction in China. In 2015, China produced 2.35 Gt of cement, accounting for 55% of the world's total cement production. Based on relevant research, the cement industry contributes 13%−15% to China's total annual CO_2 emission (IEA, 2011; Xu and Fleiter, 2012). NO_x emissions from the cement industry of China present 10% of the country's total emissions (Li and Li, 2013). Therefore, it is necessary that China enhances both energy conservation and emission reduction in the cement industry.

As for cement production, CO_2 emission mainly originates from the decomposition of calcareous materials (such as limestone, calcite, marl, and chalk) in kilns, direct coal combustion, as well as indirect electricity consumption during the production process (WBCSD/IEA, 2009; Ke et al., 2012). NO_x is formed during the high temperature combustion process within the kilns. Thus, CO_2 and NO_x generated from cement production have the same emission sources, and this is also the fundamental physical reason why it is possible to integrate

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emission control of conventional air pollutants and CO_2 in the cement industry. In fact, many individual control practices of conventional air pollutants and CO_2 have proven that co-benefits exist. In recent years, more and more researchers have paid attention to the co-benefits of energy efficient measures together with fuel substitutes in cement sector (Jiang et al., 2012; Ke et al., 2012; Moya et al., 2011; Gu et al., 2012). However, there are several limitations of facilitating an integrated control of multiple air pollutants and CO_2 in China's cement industry. First, various stakeholders are lack of knowledge on co-controlling NO_x and CO_2 emission. It is difficult for policy makers to realize the benefit of co-control of carbon dioxide and conventional air pollutants. Second, current energy conservation and low-carbon policies and measures have not yet reflect the concept of cooperative control. Third, it is insufficient to support co-controlling technology commercialization, which results in the failure of companies to select the most suitable co-control technologies.

Therefore, this paper decides to conduct a co-benefit study by taking the cement industry as a case sector. First, it summarizes relevant research progress about energy conservation practices and technology trends for the domestic and international cement industry. Second, China's future cement demand peak will be projected based on key impact factors. Third, a bottom-up model named MAP-TIMES is used to explore co-benefits of CO_2 and NO_x control in China's cement industry. Fourth, on the basis of modeling analysis, we proposes a cost-efficient, green, and low carbon development roadmap for the Chinese cement sector. Finally, relevant countermeasures towards promoting the co-benefits in China's cement sector will be put forward.

2. Literature review

Since 2005, China has emphasized the importance of energy conservation and pollution control in the cement industry, and has consequently issued a number of policy measures, special planning, and technical guidance to promote pollutant reduction as well as low-carbon development in the cement industry. Especially in the “Twelfth Five-Year Plan of Energy Saving and Pollutant Reduction”, China added nitrogen oxide emission reduction targets, in which it planned to reduce nitrogen oxide emissions originating from the cement industry by 12% by 2015 compared to the 2010 level (ST, 2012).

The technological development is the key driving force for energy saving and emission reduction in China's cement industry. During the period 2006–2010, by applying many policy measures such as eliminating old capacities, promoting low temperature waste heat power generation, energy efficient grinding, frequency control, cement grinding aids, and waste utilization technologies, the comprehensive energy consumption per ton of cement clinker with NSP technology dropped by 12% in 2010 compared to 2005. The industry also utilized more than 400 Mt solid waste (MIIT, 2011).

To promote the reduction of pollutants and carbon emissions, it is a fundamental prerequisite to scientifically project the future cement demand. Many studies have been conducted to project the future cement demands, and major projection methodologies include the fixed assets investment method (Song, 2004; Liu and Sun, 2008), the economic development synchronization method (Wei, 2007), the cement consumption elasticity coefficient method (Yang, 2007), and the per capita consumption of saturated cement method (Ke et al., 2012). These methods can be categorized into two groups. The first one is a trend extrapolation prediction via econometric models. Such trend extrapolation methods are only useful for short-term forecasting; however, they cannot predict the saturation point of the cement demand. Another group of methods is via analogy. Studying the cement consumption in developed countries, suggests cement demand growth laws, and enables selection of relevant indicators to simulate China's future cement demand (Zeng, 2003; Zhou, 2005; Shi et al., 2011). Although these types of methods follow a quite reasonable argumentation, they are considered to lack the theoretical basis, thus often produce significant errors in the predicted results, while subjectively judging the time point of saturation point appearance.

With its intensive energy requirement in the production process, the cement industry is considered as one of the largest industrial energy consumers and carbon emitters, both directly and indirectly (Jiang et al., 2012). The studies are mostly focusing on China's future cement production and consumptions, and the projections are obtained from a top-down approach, which are more based on static links between cement industries in the future macroeconomic circumstances (Shi et al., 2012; Wei, 2006). However, bottom-up approaches started to be increasingly used to analyze China's energy and environmental studies. Zhou et al. (2013) propose a bottom-up energy end-use model towards China's energy and emission outlook until 2050. Via detailed assumptions of different energy use and carbon emission parameters, breaking the whole energy system into five major sectors (e.g. residential, commercial, industrial, transport, and power), the model projected various perspectives of China's future energy consumption and presented alternatives for long term pathways under two predesigned policy scenarios. Chen (2005) created the China MARKAL-MACRO modeling that merged the bottom-up and top-down macroeconomic approaches to study carbon emission abatement costs. The model was constructed to convert primary energy to end-use industries. More than 50 conversion technologies are included on the energy supply side and the demand sector has been divided into industry, agriculture, commercial, urban residential, rural residential, and transportation. By imposing progressively stricter constraints on the carbon emission cap, the carbon shadow prices were recorded and a marginal abatement cost curve has been generated for China.

Apart from studies on energy systems, bottom-up model analytic approaches were also used in industries other than cement production. Wen et al. (2013) used the AIM model to evaluate the energy conservation and carbon mitigation in the iron and steel industries. By setting up a detailed technologies description, it models system optimization, considering three policy scenarios. The bottom-up model developed by

Hasanbeigi et al. (2012) also estimated the carbon mitigation cost of the iron and steel industry. A service industry analysis by Zhang (2013) was also conducted via the bottom-up cohort-based model SERVE to estimate the energy conservation production of services, rather than of tangible goods, covering all sub-sectors in the service industry and dividing the whole of China into three regions for simplicity. The bottom-up model analysis of the cement industry that considers technology improvements is still limited in the current literature. Hasanbeigi et al. (2013a) described emerging energy-efficiency and CO_2 emission reduction technologies for cement production in their technical review. Based on a portfolio of technologies that should be developed and deployed to reduce energy use and carbon emissions of the cement industry, a bottom-up energy conservation supply curves model (CSC) was recently built by analyzing more than 23 energy efficiency technologies and measures in China's cement industry (Hasanbeigi et al., 2013b). Similar to the GHG abatement cost curve developed by McKinsey, it estimates the savings potential and cost of energy efficiency implementations under two scenarios that apply best international technology options and China's domestic best technologies, respectively. However, it does not discount the amount of energy conservation in the future since discounting physical values will be misleading. The benchmarking and energy saving tool BEST cement was jointly developed in 2008, which provides a bottom-up approach for the cement industry of China. It compares the current Chinese cement plant practice and best energy efficiency practice, to picture the energy saving potential of each individual cement plant in China (Galitsky et al., 2008). The process based modeling tool consists of eight main process steps during cement production, and includes all direct and indirect energy used for each process, using best domestic and international practices. The result of the modeling tool will provide an energy saving potential and cost for each tested cement plant. Ke et al. (2012) also concluded the existence of an enormous potential of carbon emission reduction and energy consumption reduction though energy efficiency measures in China's cement industry. By designing scenarios based on different energy intensities and cement demand, the authors used the long-range energy alternatives planning system (LEAP) modeling tool and developed three projections for China's future cement sector. In this paper, energy intensity has been analyzed through each process of the cement production chain. A similar decomposition study of China's cement industry (Xu et al., 2012) was also conducted to analyze the change of energy consumption and carbon emissions and its driving factors via the log-mean divisia index (LMDI) method.

Comparable international studies regarding the energy conservation and carbon emission reduction in cement industries can be found as well. Mikulcic et al. (2013) concluded that clinker substitution, alternative fuels, and efficiency improvement in the kiln process are economically viable measures that can decrease CO_2 emission of the cement industry in Croatia. Mandal and Madheswaran (2010) attempted to estimate the environmental efficiency of the Indian cement industry within a joint framework and emphasized that sufficient potential existed within the industry to improve its environmental efficiency if faced with environmental regulation in India. Hasanbeigi et al. (2010) projected a similar electricity conservation supply curve as mentioned above for the cement industry in Thailand. Pang et al. (2014) built up the MAP-TIMES model to analyze the abatement of both CO_2 emission and air pollutants facilitated by low-carbon cement standard in China's cement industry.

3. Demand projection

Based on above literature reviews about cement demand projection, we think that the cement demand in China will also follow the S-shaped growth curve. So this study decided to use the following three-phase prediction methods:

1) Growth phase: to apply a logical growth curve based the model by Gompertz, which involves both urbanization rate and GDP per capita to predict the cement demand per capita and the total cement production peak prior to arrival of the saturation point.
2) Saturation phase: to identify the most important influencing factors of cement demand, and to analyze the saturation lasting time based on the development of various drivers.
3) Declining phase: to use the method of reference scenario analysis, to predict the lasting time of different saturation points and the declining cement production in the subsequent periods.

This study proposes two cement demand scenarios, based on the conditions of economic development, resource and energy constraints, and environmental protection policy limitations. The first scenario is the high development scenario. It assumes that the annual GDP growth rate in China will be shown as follows (Table 1) and the development pattern barely changes. Without much consideration of either resource and energy constraints, or environmental protection policies, it suggests that China's economy will continue to grow rapidly, which drives a relatively high growth speed for cement demand, the cement demand peaks late, and the amount of peak demand is high. The second scenario is named the low development

Table 1
Prediction of annual GDP growth rate.

Period	Annual GDP growth rate (%)	
	High	Low
2014–2015	8.0	7.5
2016–2020	6.5	5.0
2021–2025	5.0	4.0
2026–2030	4.0	3.0
2031–2035	3.0	2.0
2036–2040	2.5	1.5
2041–2045	2.0	1.5
2046–2050	2.0	1.5
Average	3.2	2.5

scenario, which assumes a lower annual GDP growth rate during the same period. The whole society's development is assumed to follow the concept of "scientific development", with heavy attention to the constraint of resource, energy, and environment. It is predicted that under such a scenario, the GDP per capita grows least, and per person cement demand peaks early and at the lowest level.

The Gompertz model is introduced as follows:

$$C_t = (C_{\max} + \varphi\Delta U_t)\theta e^{\alpha e^{\beta GDP_t}} + (1-\theta)C_{t-1} \tag{1}$$

Among that:

C_t represents the per capita cement demand in year t and C_{max} represents the peak value of per capita cement demand. We assumed a per capita cement demand of 2200 kg per person in this study;

U_t represents the urbanization rate in year t and GDP_t represents the per capita GDP in year t. ΔU_t represents the urbanization rate gap between year t and the saturation time. We assumed that the urbanization rate will be 70% when cement demand peaks in China, and consequently, $\Delta U_t = U_t - 70$.

θ represents the adjusting factor of the time series, namely the influence of the former year's per capita cement demand to next year's per capita cement demand;

α, φ, and β and represent the influencing factors of the two independent variables (urbanization rate and GDP per capita) to per person cement demand.

Based on the STATA statistical software, this paper first used the existing data of per person cement production, urbanization rate, and as well GDP per capita in China from 1990 to 2014 as input variables, and then used the MLE maximum likelihood estimation method to estimate the values of the proposed parameters such as α, φ, β, and θ. Finally, the derived regression equation can be written as follows:

$$C_t = (2200 + 11.663(U_t - 75)) \times 0.457e^{-2.061e^{-0.0000748GDP_t}} + 0.543C_{t-1} \tag{2}$$

According to the forecasts for both future urbanization rate and GDP per capita, cement production per capita and total output can be calculated under two scenarios before cement production peaked. Prediction results are shown in Figs. 1 and 2.

The above prediction indicates that under the high development scenario, both China's total cement production and per capita cement demand will increase, and peak in 2030 for two indicators: per capita cement consumption will reach 2007 kg and the total cement production will reach 2.76 Gt. The projection value is of the same magnitude to other peer research results (Ke et al., 2012; Xu et al., 2012; Pang et al., 2014). However, there is a difference among proposed research results. Under the low development scenario, both China's total cement production and per capita cement demand will peak in 2015: per capita cement consumption will reach 1850 kg and the total cement production will reach 2.5 Gt. In both scenarios, the peak period will continue for almost five years

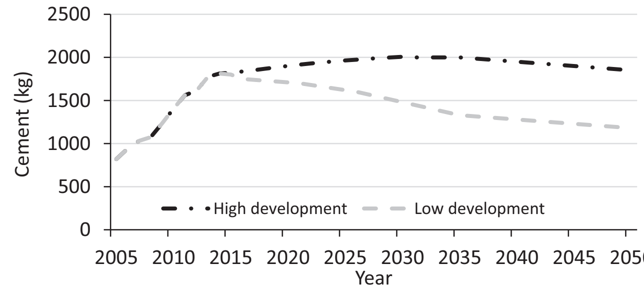

Fig. 1. China's per capita cement demand.

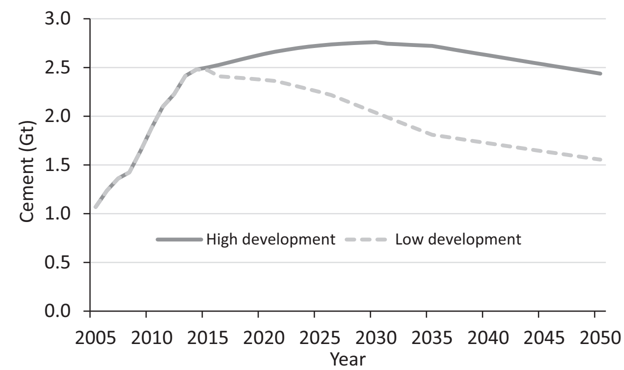

Fig. 2. Total cement demand in China.

before they start to decline; the per capita cement consumption will decrease to 1300–1400 kg and the total cement production will be around 1.7–1.8 Gt.

4. Model methodology

4.1. MAP-TIMES model

This study uses the MAP-TIMES model to explore a green and low carbon development roadmap for China's cement industry, based on comprehensive analysis of energy consumption, NO_x, and CO_2 co-control technology and the respective emission reduction costs under different scenarios. China's cement industry's reference system (RES) was developed based on the cement industry features of "two grinding processes and one combustion process". It considered that energy consumption and emission mainly occur during three processes: preparation of raw material, clinker combustion, and cement grinding. The analysis time range of this study ranged from 2005 to 2050, with 2005 being the base year and milestone years before 2030 were selected for analysis. In the model, coal and electricity were the major energy products consumed in the cement industry, and the environmental emissions to be analyzed were CO_2 and NO_x, among which, CO_2 emission not only included the direct emission from fuel combustion and raw material decomposition, but also indirect emission from electricity consumption. Based on the energy technology model, this study mainly considered three major groups of 27 technologies in total as mentioned above, namely 12 technologies of the energy efficiency improvement group, nine technologies of the alternative fuels and raw materials group, and six technologies of nitrogen oxides and dust emissions group. It is noteworthy that the cement demand forecast results under high development scenario will be imported as an exogenous variable into the TIMES model for analysis.

4.2. Scenario setting

Apart from the cement demand set as external variable, the scenario settings in the MAP-TIMES model mainly considered policy and technological variables. In this study, policy variables such as carbon tax, low carbon cement standards, NO_x emission standards update, NO_x emission cap, and phase-out scrap capacities were converted. Furthermore, it included technological variables, such as energy efficiency improvement, raw materials substitution, clinker substitution, CCS, and NO_x removal. Based on the combination of different policies and technological variables, as well as the research requirements of air pollutants and GHG co-control, this study built five emission scenarios as shown in Table 2.

The business as usual (BAUH) scenario did not consider any new policies. Under this scenario, the major drivers are population growth and economic development. The pattern of population growth follows the national demography plan, and economic growth was based on several key research institutes.

MLCH-NO_x scenario only considered NO_x control, namely the structurally reduction of NO_x emissions by phasing out scrap capacities of 430 Mt during the 11th Five-Year Plan (FYP), 250 Mt during the 12FYP, and 84 Mt during the 13FYP. In the meantime, the forced emission reduction started from the 12FYP, and reduced by 10% by 2015 compared to 2010. The entire cement industry started to implement new standards in 2013. Yet, no specific carbon policy has been implemented so far.

The MLCH-CO_2 scenario only consider CO_2 emission reduction, namely by introducing various policies in different time including energy saving measures, carbon tax, raw material substitution requirement, and CCS technologies. Yet, no specific NO_x control policy has been implemented so far.

The moderate low carbon (MLCH) scenario considers both air pollutants control and GHG emission reduction. At the same time, the cement demand peak was assumed to happen around the year 2022.

The radical low carbon (RLCH) scenario was based on the stricter global industrial emission pressure of China's cement industry and domestically enhanced air pollution control constraints. The cement demand peak was assumed to happen as early as 2020.

5. Results

5.1. Emissions trends

With regard to CO_2 emission, Fig. 3 shows that carbon emissions from the cement industry under scenario RLCH will peak in 2020, and CO_2 emission level will be at 1.765 Gt; under both BAUH and MLCH scenarios, such a carbon emissions peak will occur five years later than under the RLCH (namely in 2025), by which time, the peak levels will be 1.885 Gt and 1.769 Gt, respectively. With regard to the carbon emission reduction potential, under the RLCH scenario, the cement industry has the greatest potential, especially after 2020. Taking the year of 2030 as example, MLCH and RLCH scenarios will witness carbon emission reductions of 10.3% and 20.5% compared to BAUH scenario, respectively. The main reason for this is that prior to 2020, carbon emission reduction measures in the cement industry depend largely on the low temperature waste heat power generation technology, raw mill and cement mill, and other energy or energy efficiency technologies; after 2020, as the carbon reduction constraint of the cement industry enhances and the CCS technology starts to be applied and widely expanded, which enable a significant mitigation of CO_2 emissions.

With regard to NO_x emission, Fig. 4 shows that the RLCH scenario has the largest NO_x emission reduction potential. Under MLCH-NO_x, MLCH, and RLCH scenarios, the NO_x emissions start to reduce from 2010 onwards, because not only the NO_x emission cap starts to apply in 2010, but the NO_x emission standard for the cement industry became stricter after 2013. However, the results are different under BAUH and MLCH-CO_2 scenarios. Since no NO_x emission cap exists, NO_x emission did not decrease after 2010. NO_x emissions from the cement industry will peak between 2025 and 2030, in line with the cement demand development trend. However, thanks to the widespread implementations of energy efficiency measures, NO_x emissions under MLCH-CO_2 scenario start to decrease from 2020. Such change indicates that a co-benefit for NO_x control in the cement industry exists when carbon emission measures are implemented. Those energy efficiency technologies help to reduce energy consumption, while at the same time, reducing the NO_x emission level.

5.2. Energy consumption structure

Comparing various scenarios indicate that coal and electricity are the main energy sources for cement production. Coal has always occupied a dominant position for energy consumption, accounting for more than 90% of the total energy consumption of the cement industry. With promulgation and implementation of incentive policies of co-treatment of disposal of solid waste and resource comprehensive utilization improvement in the cement industry, the treatment of city solid waste and sewage sludge through cement kilns has become an important raw material and fuel substitution measure. Taking the year 2020 as an example: under the BAUH scenario, fuel substitution rate of city waste is 0.20%. While under both the MLCH and RLCH scenarios, these rates were 3.00% and 3.03%, respectively. Furthermore, under both the MLCH and RLCH scenarios, the shares of electricity consumption have no significantly changed. The underlying reasons are that in both emission scenarios, CCS technology in the cement industry will have been increasingly applied from 2020, and more electricity will be consumed through those CCS facilities that prevent the cement industry from reducing electricity consumption intensity. Consequently, the effective reduction

Table 2
Five scenarios setting compare.

Policy and measure/Scenario	BAUH	MLCH-NO_x	MLCH-CO_2	MLCH	RLCH
Carbon tax	No	No	2015 CN¥50 t^{-1}, 2020 CN¥75 t^{-1}, 2025 CN¥100 t^{-1}, similar after, CN¥25 increase every 5 years	2015 CN¥50 t^{-1}, 2020 CN¥75 t^{-1}, 2025 CN¥100 t^{-1}, similar after, CN¥25 increase every 5 years	2015 CN¥100 t^{-1}, 2020 CN¥150 t^{-1}, 2025 CN¥1200 t^{-1}, similar after, CN¥50 increase every 5 years
Scrap old capacity	2006–2010 phase out 430 Mt capacity (real situation), no more new phasing out policy	2006–2010 phase out 430 Mt capacity (real situation); 2011–2015, will phase out 250 Mt capacity; 2016–2020, will phase out 84 Mt capacity	2006–2010 phase out 430 Mt capacity (real situation), no more new phasing out policy	2006–2010 phase out 430 Mt capacity (real situation); 2011–2015, will phase out 250 Mt capacity; 2016–2020, will phase out 84 Mt capacity	2006–2010 phase out 430 Mt capacity (real situation); 2011–2015, will phase out 334 Mt capacity
Energy efficiency improvement	NSP for clinker production (2010, 81%), low temperature waste heat recovery electricity generation (2010, 55%)	NSP for clinker production (2010, 81%), low temperature waste heat recovery electricity generation (2010, 55%)	NSP for clinker production (2010, 81%; 2015, 90%; 2020, 100%), low temperature waste heat recovery electricity generation (2010, 55%; 2015, 90%; 2020, 100%)	NSP for clinker production (2010, 81%; 2015, 90%; 2020, 100%), low temperature waste heat recovery electricity generation (2010, 55%; 2015, 90%; 2020, 100%)	NSP for clinker production (2010, 81%; 2015, 100%), low temperature waste heat recovery electricity generation (2010, 55%; 2015, 100%)
Raw material substitute	Fly ash substitution rate (low) Carbide slag substitution rate (low)	Fly ash substitution rate (low) Carbide slag substitution rate (low)	Fly ash substitution rate (medium) Carbide slag substitution rate (medium)	Fly ash substitution rate (medium) Carbide slag substitution rate (medium)	Fly ash substitution rate (high) Carbide slag substitution rate (high)
Fuel switch	High-sulfur coal, waste tires (low apply rate) Co-treatment with urban waste (low apply rate)	High-sulfur coal, waste tires (low apply rate) Co-treatment with urban waste (low apply rate)	High-sulfur coal, waste tires (medium apply rate) Co-treatment with urban waste (medium apply rate)	High-sulfur coal, waste tires (medium apply rate) Co-treatment with urban waste (medium apply rate)	High-sulfur coal, waste tires (high apply rate) Co-treatment with urban waste (high apply rate)
Clinker substitute	Low mix rate of blast furnace slag, fly ash	Low mix rate of blast furnace slag, fly ash	Medium mix rate of blast furnace slag, fly ash	Medium mix rate of blast furnace slag, fly ash	High mix rate of blast furnace slag, fly ash
CCS	No	No	Starting to pilot from 2020	Starting to pilot from 2020	Starting earlier than 2020, and by 2030 widely applied
NO_x removing	No	The total amount of reduction starts from 2011; in 2011–2015 reduce 10%; the new emission standard for NO_x emission starts from 2013	No	The total amount reduction starts from 2011; in 2011–2015 reduce 10%; the new emission standard for NO_x emission starts from 2013	The total amount reduction starts from 2011; in 2011–2015 reduce 10%; the new emission standard for NO_x emission starts from 2013
Oxygen combustion	No	No	Starting to pilot from 2020	Starting to pilot from 2020	Starting earlier than 2020, and by 2030 widely applied
Low carbon cement product standard (carbon intensity)	No	No	Starting from 2012	Starting from 2012	Starting from 2012, and increase the standard from 2020
Carbon emission cap in cement sector	No	No	No	No	Starting from 2015

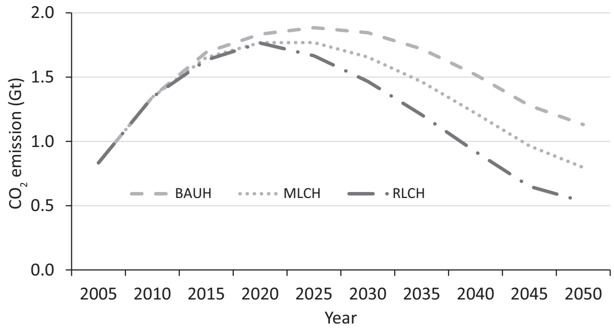

Fig. 3. CO_2 emissions in China's cement industry.

of indirect CO_2 emissions in the cement industry depends on the process of China's low-carbon power system.

5.3. Co-benefit analysis

Fig. 5 shown that carbon emission reduction measures have high co-beneficial effects for NO_x control. This is because carbon emission reduction technologies and policies are mostly for the improvement of energy efficiency in the cement industry, with the exception of CCS technology. Whereas, for NO_x emission reduction, technology options include low nitrogen combustion, staged combustion, and SNCR technology. SNCR technology, which has the highest NO_x removal efficiency, is considered as an end control technology. Its application increases electricity consumption and indirect CO_2 emissions. Moreover, since SNCR technology consumes ammonia, application of this technology in the cement industry will impose adverse incentives for high energy consumption, due to the high pollution ammonia industry. Based on a rough estimate, it will consume 5 kg of 20% ammonia solution (1 kg pure ammonia) to remove NO_x (NO_x removal efficiency is 50%) per tonne clinker production. For example, in 2012, China's cement plants produced a total of 1.279 Gt of clinkers, which (in theory) required 1.28 Mt of ammonia. The ammonia industry in China uses coal as its major material, and therefore, the production of such an amount of ammonia will require 1.984 Mt of standard coal. As a result, this would produce an additional 4.96 Mt CO_2 emission, 11.49 Mt industrial wastewater, 637 t COD, 434 t ammonia nitrogen, 480 t dust, and 2275 t SO_2. Such an indirect emission effect cannot be ignored.

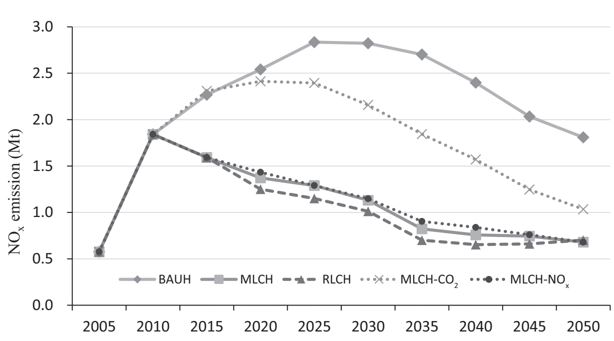

Fig. 4. NO_x emission from clinker production.

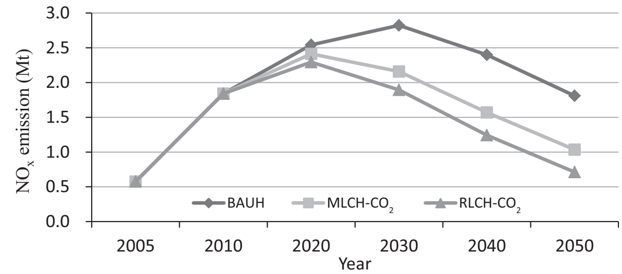

Fig. 5. Co-benefits of different pollutants in the cement industry.

5.4. Cost analysis

Table 3 provides estimates for total discounted costs of cement production by scenarios for the entire considered period of simulation. This includes calibration years (2005–2013), which were identical for all of the scenarios and did not change the results much. An annual discount factor of 7.5% was assumed. Table 4 describes the decomposition of total costs (TOT) by sources: annualized investment costs (INV), fuel costs (FUE), and operational and maintenance (O&M) costs. The costs were constant with 2013 prices and were calculated as annual average for the considered time period. Investment costs were annualized for the entire period of life for each capacity unit (plant).

As a result of the data presented in Table 4, the most expensive scenario is RLCH, where the total costs were about 8% higher than for BAUH. The radical emission control scenario requires about 7.6% higher investments due to SNCR and CCS technologies of emissions control. This also leads to 19.3% higher operational and maintenance costs to control NO_x and CO_2 emissions (including ammonia), causing additional electricity costs. However, emission control stimulates switching to technologies with higher energy efficiency, resulting in decreased overall fuel costs.

Scenarios that only control NO_x or CO_2 demonstrated co-benefits of multi-pollutants control when compared with BAUH. For example, NO_x control in the MLCH scenario added about 3.7% to the total costs (see MLCH-NO_x vs. BAUH in Table 4). Similarly, CO_2 control would add 3% to the costs (MLCH-CO_2 vs. BAUH in Table 4). However, both

Table 3
Total discounted costs of production in 2005–2050, at an annual discount of 7.5%.

Scenario	PV (billion CN¥)	Rate of BAUH (%)
BAUH	3366.9	100.0
MLCH	3534.8	105.0
MLCH-CO_2	3431.3	101.9
MLCH-NO_x	3489.0	103.6
RLCH	3649.3	108.4
RLCH-CO_2	3494.3	103.8
RLCH-NO_x	3544.7	105.3

Table 4
Aggregated annualized costs by scenarios for 2014–2030, assuming constant 2013 prices.

Scenario	Aggregated costs (CN¥)				Difference with BAUH (CN¥)				Percent comparing to BAUH (%)			
	INV	FUE	O&M	TOT	INV	FUE	O&M	TOT	INV	FUE	O&M	TOT
BAUH	3228.6	5810.1	6685.4	15,724.1	–	–	–	–	100.0	100.0	100.0	100.0
MLCH-CO_2	3309.5	5648.1	7230.9	16,188.5	80.9	(162.1)	545.58	464.4	102.5	97.2	108.2	103.0
MLCH-NO_x	3370.3	5541.1	7395.9	16,307.3	141.7	(269.1)	710.53	583.2	104.4	95.4	110.6	103.7
MLCH	3402.5	5586.5	7581.4	16,570.4	173.9	(223.6)	896.04	846.3	105.4	96.2	113.4	105.4
RLCH	3474.0	5553.3	7974.5	17,001.8	245.4	(256.8)	1289.12	1277.7	107.6	95.6	119.3	108.1

measures will add only 5.4% to the costs if controlled together (see MLCH vs. BAUH in Table 4). The sources of co-benefits were mostly higher energy efficiency, which resulted in lower overall emissions. The benefits increased when emissions control was stronger (see RLCH scenarios).

The total costs were still not drastically different among scenarios. The "cleanest" scenario increased overall costs below 10%, which seems feasible.

6. Conclusions

Co-benefits exist in the processes of NO_x reduction and CO_2 emission control in the cement industry. And carbon emission control has more outstanding co-benefits for NO_x control. From the perspective of co-control technologies, highly energy efficient technologies, such as waste heat generation and fuel substitution, have significant co-benefit effects on NO_x and CO_2 emission control. However, the SNCR technology with high NO_x removal efficiency consumes more electricity, which will indirectly lead to an increase of CO_2 emission. As far as reduction cost is concerned, most technologies have cost advantages. Instead CCS technologies have very high cost barrier under the absence of carbon emission cap. After 2020, due to the stricter carbon emission constraints, this technology will probably become a key carbon emission control measure, and its cost will also be projected to decrease as it commercializes.

We propose the policy suggestions from the following aspects:

At an institutional level, the Ministry of Environmental Protection needs to enhance communication and coordination with other ministries, such as National Development and Reform Commission and the Ministry of Industry and Informational Technology, and to promote the co-control of NO_x and CO_2 in the cement industry.

At the technological level, the government should recommend a co-control technology list for the cement industry at the right time, increase the R&D investment on new technologies and demonstration projects, and encourage companies to apply the currently available co-treatment technologies, including raw materials and fuel substitution, city waste co-treatment by cement kilns, waste heat collection and utilization, and low nitrogen combustion. For CCS carbon emission reduction technology, the government should enhance international communication and cooperation, improve the research and development and demonstration projects for such technologies in future.

At the policy level, the phase-out of old cement capacity needs to be continued. The cement industry should implement low carbon cement product standards, and start to study the carbon tax and cement industry carbon emission cap. Moreover, policies should direct companies to use cement kilns to co-control city waste, and solid disposals, to improve the raw material and fuel substitution rate in clinkers, thus promoting the green and low carbon development of the cement industry.

At the regulation level, current NO_x removal requirements in the cement industry have already become a solid environmental constraint. However, it cannot be ignored that NO_x removal requirements will increase company investment, energy consumption, operational cost, and clinker production cost, and will possibly encourage growth within the ammonia industry, which is associated with high energy consumption and high pollution. Therefore, it is important to scientifically evaluate the relevant environmental impacts and adverse motivations of ammonia production by NO_x removal requirement in the cement industry. At the same time, regulations need to be established well to require the enhancement of operational safety and management of NO_x removal equipment in companies.

It should be pointed out that there are still some limitations for our research due to some constraints, such as uncertainty of emission reduction technology development and relevant cost estimation. We will continue to improve our research by implementing more relevant projects.

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