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Cutting air pollution by improving energy efficiency of China's cement industry

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Abstract

In this study, the energy conservation supply curves (ECSC) combined with the GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies) was used to estimate the co-benefits of energy savings on CO_2 and air pollutants emission for implementation co-control options of energy efficiency measures and end-of-pipe options in the china's cement industry for the period 2011-2030. Results show the cost-effective energy saving potential (EEP1 scenario) and its costs is estimated to be 3.0 EJ and 4.1 Billion $ in 2030. The technical energy savings potential (EEP2 scenario) and its costs amounts to 4.2 EJ and 8.4 Billion $ at the same time. Energy efficiency measures can help decrease 5-8% of CO_2, 3-5% of PM, 15-25% of SO_2, and 12-20% of NOx emissions by 2030. Overall, the average marginal costs of energy efficiency measures will decrease by 20%, from 1.48 $/GJ to 1.19 $/GJ, when taking into account avoided investments in air pollution control measures. Therefore, implementation of energy efficiency measures is more cost-effective than a solely end-of-pipe based policy in China's cement industry. The plant managers and end users can consider using energy efficiency measures to reach new air pollutants emission standards in China's cement industry.

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Keywords: Co-benefits; energy efficiency; air pollution; GAINS; Cement industry

1. Introduction

China's cement industry has attracted attention worldwide. Despite several efforts, such as increasing the new dry process application, closing obsolete plants, and using various best practice technologies, that have been made by

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Chinese government in the past two decades, recent studies indicate that there is still a large opportunity to improve energy efficiency, reduce emissions of GHGs and air pollutants [1–3]. Comparing the disparity between the current energy efficiency level in China and best practice, indicates a cumulative energy savings potential of 5.0-37.5 EJ in the period 2011-2030, under different scenarios [2,3]. Likewise, if all Chinese cement plants adopted energy efficiency improvement measures, alternative fuels, and clinker substitution (to reduce the clinker-cement ratio), 2.5-4.7 Gt or 53% CO_2 would be saved up to 2050 [1,4]. Lei [5] evaluated local air pollutants, such as PM, SO_2, and NOx in China's cement industry using the proportion of different types of kilns to produce cement and air pollutant emission standards for the Chinese cement industry, and they found that PM and SO_2 emissions would decrease, by shifting from wet to dry process. NOx emissions would decrease because of the increase of precalciner kilns [5]. Furthermore, many studies have shown that the co-benefits (including direct co-benefits and indirect co-benefits) of health effects of energy efficiency improvement and CO_2 mitigation can be substantial [6,7]. For instance, Xi [8] estimated the interaction between carbon mitigation and air pollutant control measures in China's cement industry during the 12th Five Year Plan period, and found significant co-benefits of 18 energy saving technologies. However, most of these studies usually do not monetize the co-benefits when assessing the best available technologies and end-of-pipe options. Therefore, synergies between policies to address energy efficiency and air pollutant emissions mitigation have been neglected by policy makers. The aim of this paper is to address this gap by assessing the co-benefits of energy efficient technologies and air pollutant control in the China's cement industry and quantify how co-benefits would affect the cost effectiveness of energy efficiency technologies.

The structure of this paper is as follows, section 2 gives an overview of China's cement industry. The methodology, data collection, and scenarios construction is given in section 3. The results of energy saving potential and emission mitigations of GHGs and air pollutions and associated costs for different scenarios are discussed in section 4. Finally, the conclusion is given in section 5.

2. Overview of China's cement industry: production, energy consumption and emissions

As the largest cement market in the world, China's share in cement production has surged from 20% in 1990 to 59% by 2012. Although the annual growth rate of cement and clinker production fluctuated drastically between 1990 and 2012, the total production of cement and clinker increased rapidly from 210 Mt and 157 Mt in 1990 to 2210 Mt and 1278 Mt in 2012, respectively [9]. The annual growth rate of cement production was 18% from 1990 to 1996, and slowed down to 4% by 2000. Between 2001 and 2012 (except 2008), it resumed rapid growth at an average of 9% per year. The cement produced from dry process increased slightly from 6% share of total cement production in 1990 to 10% by 2000, however, it was increased at an average of 7.6% per year, from 14% in 2001 to 92% in 2012, which was caused not only by the expansion of dry process for cement production and retrofitting but also by the elimination of wet process, closing of obsolete vertical shaft kilns, and the decrease of the clinker to cement ratio.

The energy consumption of China's cement industry generally kept pace with the growth of China's cement output. The total amount of energy consumption of China's cement industry increased about 6 times from 1200 PJ to 6961 PJ in 2011, which equals 7% of Chinese total energy consumption [10]. The annual growth rate of energy consumption was 8.7% between 1990 and 2011, lower than the annual growth rate of cement production, which was 11.6% during this period. This may be due to the decrease of the clinker to cement ratio from 74.9% in 1990 to 62.5% in 2011 and 57.9% in 2012 and improved efficiency of new NSP kilns [2].

CO_2 emissions in cement production come from calcination, fuel combustion, and indirect emissions of electricity consumption. The overall CO_2 emissions increased at an average of 8.9% per year, from 591 Mt in 2000 to 1380 Mt in 2010. In 2010, approximately 43.8% was due to process emissions, 47.6% due to fuel combustion, and 8.6% due to electricity consumption. One main reason for the CO_2 emissions reduction is the lower ratio of clinker to cement (63%) that was adopted through utilizing alternative materials such as blast furnace slag, and fly ash, compared to the weighted average world level (76%) [11,12].

Unlike the trends of cement output and energy consumption, the total emissions of air pollutants (e.g. PM, SO2, and NOx) show a declining trend from 2000 to 2010, with a slight increase over the past two years. Because of the fast development of large scale NSP kilns, the PM emission decreased steadily from 809 Mt in 2000 to 410 Mt in 2010, at an average rate of 6.6% per year [9,13]. Although cement output increased significantly, SO2 emission remained relatively stable. The expansion of the cement industry during the last decades led to a corresponding increase in emissions of NOx from 0.57 Mt in 2000 to 2.27 Mt in 2010. The main reason was that less strict NOx emission standards were implemented than in the US and EU, due to which many cement plants hardly implemented NOx abatement measures.

3. Methodology

3.1. Energy conservation supply curves

Cost curves (i.e. energy conservation supply curves (ECSC) or marginal abatement cost curves (MACC)) are a standard policy tool to analyse potentials of energy efficiency, emissions mitigation of GHGs and air pollutants [14]. Mostly ECSC are used to evaluate potentials of reducing energy use and CO_2 emission by implementing energy efficiency measures [3,15]. Similarly, MACC are used to assess the mitigation effects of abatement measures [16]. Both of them typically ignore the benefits of reducing air pollutants. Several studies give attention to co-benefits of energy efficiency improvement and emissions mitigation of GHGs and air pollutants using ECSC and MACC combined with other models [7,8,6,17,18]. However, none of these studies quantify the co-benefits of energy efficiency improvement and emissions reduction of GHGs and air pollutants through combining energy efficiency measures with end-of-pipe technology. In this study we evaluated potentials of energy saving of 37 energy-saving technologies and quantified how co-benefits would affect the cost effectiveness of those measures.

In this study, the costs of energy conservation in China's cement industry are determined, i.e. including capital costs and changes in fixed and variable costs. The indirect costs (e.g., economy-wide costs, welfare costs, and non-financial costs) and transaction and policy implementation costs are not considered [19]. The costs of each energy efficiency measure is priced at 2005 dollars ($), with currency conversion factors derived from OECD Stat Extracts [20]. The calculation of the costs of conserved energy for each energy efficiency measure is presented in Equation 1 [3,6,21].

$$CCE = \frac{I \times AF + O\,\&\,M^{Fix} + O\,\&\,M^{Var} - ESP \times PE}{ESP} \qquad (1)$$

Where:

CCE= Cost of conserved energy for an energy efficiency measures ($/GJ); I= Investment ($); AF= Annuity factor; $O\,\&\,M^{Fix}$= Annual change in operation and maintenance fixed cost ($); $O\,\&\,M^{Var}$= Annual change in operation and maintenance variable cost ($); ESP= Annual energy saving potential (GJ); PE= Future energy price ($/GJ).

In this study, a discount rate of 10% is assumed. Energy prices are taken from the GAINS WEO (World Energy Outlook) baseline scenario of IEA (International Energy Agency) 2012 database. The annuity factor can be calculated from Equation 2.

$$AF = \frac{d}{(1-(1+d)^{-n})} \qquad (2)$$

Where:

d= Discount rate; n= Lifetime of the energy efficiency measures

3.2. Greenhouse Gas and Air pollution Interactions and Synergies

The Greenhouse Gas and Air pollution Interactions and Synergies (GAINS) model is an integrated model to identify emission control strategies that estimates costs and potentials for air pollution control and greenhouse gas (GHG) mitigation [22,23]. Several studies focused on a wider scale (national and regional level) to estimate future economic development, energy, emission control potentials and costs, atmospheric dispersion and environmental sensitivities of air pollution [24,25]. However, there are no studies focused on a sectorial level to estimate the co-benefits, especially for the cement industry. In addition, the advantage of GAINS is that it allows to link it to other tools or models [26]. The Baseline scenario and energy efficiency scenarios in China's cement industry, developed by ECSC, were implemented in GAINS. We conducted two analyses to:1) estimate potentials of emission reduction for GHGs and air pollutants under different scenarios; 2) calculate the influence of co-benefits of air pollutants and CO2 emission reduction on decreasing cost of conserved energy (CCE) for energy efficiency measures.

The emissions of air pollutants and greenhouse gases are calculated based on activity data, uncontrolled emission factors, removal efficiency of mitigation measures and the extent to which such measures are applied. More details have been described by Amann et al [23].

3.3. Data source and scenario description

The cement and clinker output data used in this study are from China statistical yearbook [27], China Cement Association [28], China cement almanac [29] and relevant literature surveys [1,30]. The historical energy consumption and associated fuel structure are from the China cement almanac [29], China energy statistical yearbook [27], and literature [2,31]. Several studies indicate that the future trend of cement and clinker activity level relies heavily on changes in urbanization progress, population growth and fixed asset investment [2,1,4,32,33]. Here, we assume that cement and clinker output in China's cement industry will peak in 2020, based on Ze's latest research [32] (see Table 1).

Table 1 Future projections of cement and clinker output in China's cement industry in 2015-2030

	2000	2010	2015	2020	2025	2030	Between 2011 and 2030	Clinker to cement ratio in 2030
Cement-[Mt]	593	1868	2560	2750	2550	1900	4923	58%
Clinker-[Mt]	454	1152	1481	1591	1475	1099	2848	

Our study includes 37 commercially available energy efficient technologies/measures, costs, lifetime, fuel/electricity saving, current implementation in base year and possible and potential implementation rates up to 2030. These technologies are classified for different processes (e.g., fuel and raw material preparation, clinker making, finish grinding, product change and general measures). These energy efficiency measures are mainly from recent studies, such as LBNL [3,6,34,35], ERI of China [31,36], MIIT of China [37], and other institutes [16,8,4,38]. The implementation rate of each energy efficiency measure in the base year was defined based on these studies and potential implementation rates of those measures were defined using a linear deployment approach. According to development progress of China's cement industry, there will be no wet process in cement production in China after 2015. Energy efficiency measures for wet process are therefore not considered in this study. The co-benefit analysis is based on 34 end-of-pipe options from GAINS (13 PM control technologies, 11 SO_2 control technologies, and 10 NOx control technologies). To improve the accuracy of future forecasts, the removal efficiency and historical activity level or current implementation rate of each end-of-pipe option are based on Chinese end-of-pipe options [39], historical air pollutant emissions [29,5,13], integrated emission standards of air pollutants (GB1627-1996) [40] and air pollution standards for cement (GB4915-1996) [41] and (GB4915-2004), for the respective period [42].

The time period in this study covers from 2010 to 2030, with 2010 as the base year. Costs will be treated as 2005 USD. In order to estimate the impacts of co-control options of energy efficiency measures and end-of-pipe technologies, 6 scenarios are designed, which have been divided into two categories. The first category includes the baseline scenario (BL), energy efficiency policy scenario 1 (EEP1) and energy efficiency policy scenario 2 (EEP2).

The second category includes the baseline scenario with air pollutants policy scenario (BLAP), Energy efficiency policy with air pollutants policy scenario 1 (EEPAP1), and Energy efficiency policy with air pollutants policy scenario 2 (EEPAP2). For all scenarios, we assume that the discount rate, energy prices, cement and clinker production level and fuel structures are the same.

The baseline scenario is constructed in GAINS based on the World Energy Outlook (WEO) 2012 baseline scenario of the International Energy Agency (IEA). In this scenario, overall annual autonomous energy efficiency improvement (AEEI) rate is 0.2%, for the cement industry. To build the alternative scenarios, the ECSCs were made in a 5-year step to evaluate energy efficiency improvement potentials. In this step, a future energy price of 3.22 $/GJ is used and no change is assumed over the study period to calculate the CCE of each energy efficiency measures. We include energy efficiency measures below 0 $/GJ in energy efficiency policy scenario 1 (EEP1), which represents the cost-effective potential for energy efficiency improvement in China's cement industry. This scenario might be achieved by overcoming barriers to implementation of energy efficiency measures, such as strengthening awareness and improving professional skills of staff [43]. For the energy efficiency policy scenario 2 (EEP2), we assume that all commercially available energy efficiency measures will be fully implemented using the projected implementation rates over the period. This scenario represents the technical potential of energy efficiency improvement in China's cement industry up to 2030.

The second category scenarios (e.g. BLAP, EEPAP1, and EEPAP2) are developed to quantify how much impacts air pollutants emission reduction could have on reducing the costs of conserved energy (CCE), and to assess co-benefits. In the BLAP scenario, to stay consistent with the BL scenario, the annual AEEI of each process are kept consistent with the BL scenario. the current activity level and future potential implementation rates of these end-of-pipe options are projected based on WEO 2012 baseline in GAINS and literature. In the EEPAP1 scenario, the activity level of energy efficiency measures is kept consistent with the EEP1 scenario and the future implementation rates of end-of-pipe controls remain the same as in the BLAP scenario. For EEPAP2 scenario, the activity level of energy efficiency measures is kept consistent with EEP2 and the future implementation rates of end-of-pipe controls remain unchanged in comparison to the BLAP and EEPAP1 scenarios.

4. Results and discussion

4.1. Future potential of energy saving for China's cement industry

Figure 1 shows the results of future energy consumption for China's cement industry from 2005 to 2030 for different scenarios. Energy use of China's cement industry increases until it peaks around 2020, and then, shows a sharp declining trend due to replacing vertical shaft kilns with NSP kilns, implementing energy efficiency measures, and output of clinker and cement will peak during that period. Compared to the energy use in the BL scenario in 2020, it declines by 5% in EEP1 and 9% in EEP2, respectively. In 2030, the EEP2 scenario indicates higher potential of reducing energy use, decrease by 7% when comparing to the EEP1 scenario. In addition, the discount rate has a large influence on the cost-effective potentials of energy saving, keeping all the other parameters constant. In 2030, the energy saving potential on cost-effective perspective will increase by 34% from 2436 PJ (30% discount rate) to 3715 PJ (4% discount rate), while the ranking of energy efficiency measures varies greatly with different discount rates.

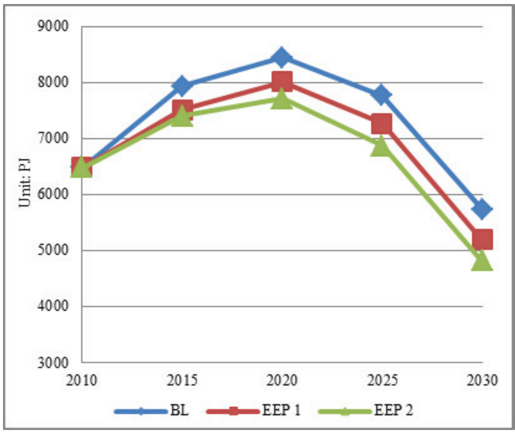


Figure 1 the future potential of energy saving between 2010-2030

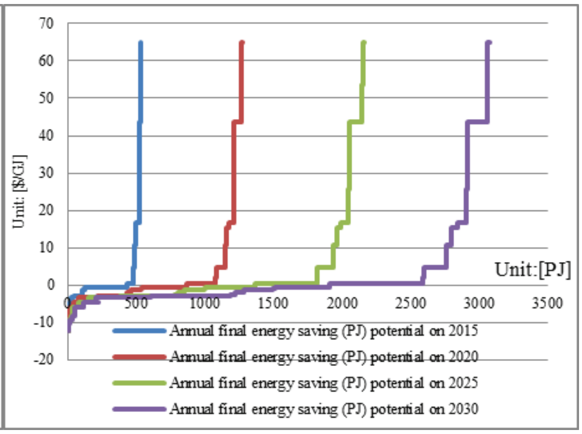


Figure 2 the potential of Annual final energy saving for China's cement industry in 2010-2030

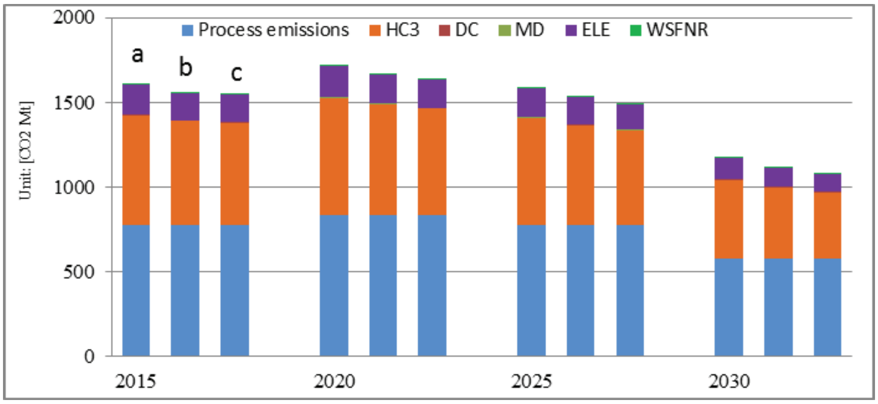
To better understand which energy efficiency measures have the greatest impact on energy savings, energy conservation supply curves were constructed. As shown in Figure 2, energy efficiency plays a key role in reducing future energy consumption in China's cement industry. The cost-effective energy saving potential amounts to 427 PJ in 2015, 865 PJ in 2020, 1367 PJ in 2025, and 1910 PJ in 2030, respectively. If the costs factor are not considered, around 20%-38% additional energy could be achieved over the same period.

If all energy efficiency measures will be implemented with projected implementation rates before 2020 (detailed information can be found in Appendix A), the largest potential to save energy are mainly from replacing vertical shaft kilns with new suspension, conversion to grate cooler, and energy management & process control as economically feasible energy efficiency measures, contributing 23%, 11% and 10% of the total energy saving potentials, respectively. Note that energy management & process control can not only reduce energy use but also decrease air pollutants. The upgrading to a preheater/precalciner kiln accounts for 11% of total energy savings. The CCE of this measure is close to zero and might become cost-effective when energy costs increase or through implementation of carbon emission trading.

Low temperature heat recovery for power generation and older dry kiln upgrade to multi-stage preheater kiln, contribute to 5% of total energy saving respectively. Compared to other energy efficiency measures (e.g., upgrade clinker cooler and kiln shell heat loss reduction) in the first decade (from 2010 to 2020), the contribution of replacing vertical shaft kilns with new suspension has less impacts on total energy saving from 2020 to 2030. Overall, three energy efficiency measures of energy management & process control, conversion to grate cooler, and upgrading to a preheater/precalciner kiln contribute to 10-13%, 11-13%, and 11-16% of total energy saving respectively from 2010 to 2030.

4.2. Emission mitigation for CO_2 in China's cement industry

Figure 3 shows the level of CO_2 emissions of the China's cement industry between 2015 and 2030 under different scenarios. For the BL scenario, the CO_2 emissions increase slightly and reach peak emissions around 2020, from 1607 Mt in 2015 to 1719 Mt in 2020, and then decrease steadily thereafter, from 1587 Mt in 2025 to 1117 Mt in 2030. Compared to the BL scenario, 46-57 Mt can be avoided by cost-effective energy efficiency measures in EEP1 scenario between 2015 and 2030; similarly, a range of 52-96 Mt would be saved by all energy efficiency measures in EEP2 scenario during the same period. High pressure roller press for ball mill pregrinding and kiln shell heat loss reduction contribute most to cost-effective CO_2 emission reduction with nearly 8% and 5%, respectively. The share of CO_2 emissions from fuel combustion dropped from 48% in 2010 to 37-41% in 2030, while the share for electricity consumption and process of total CO_2 emission increased slightly, from 8.6% and 43.8% in 2010 to 10-11% and 49-53% in 2030, respectively.



Note: a is BL scenario; b is EEP1 scenario; c is EEP2 scenario

Figure 3 CO_2 emissions for China's cement industry in 2015-2030

4.3. Emission mitigation for Air pollutants in China's cement industry

Future potential mitigation of SO_2 emissions in Chinese cement industry is shown in Figure 4. Like the trend of CO_2 emissions, SO_2 emissions increase slightly and reach peak emissions around 2020. After 2020, however, SO_2 emissions in all scenarios are reduced significantly, caused mainly by the production of cement and clinker output. Between 2020 and 2030, 12% and 28% SO_2 emission would be reduced through cost-effectiveness energy efficiency measures respectively, when comparing to the BL scenario. It means that applying 24 cost effective energy efficiency measures with projected implementation rates in China's cement industry can not only reduce energy use by 7%, but also decrease SO_2 emissions by 12-28%. 4-8% SO_2 emission reduction will be realized through applying 11 SO_2 end-of-pipe options, but its costs are more higher than implementing energy efficiency measures before 2020 (see section 4.4). If 37 energy efficiency technologies and 11 end-of-pipe options are both adopted, 29% and 44% of SO2 emission will be reduced by 2020 and 2030, respectively. In 2030, the emission levels of SO2 will be lower than 2010 levels in all scenarios.

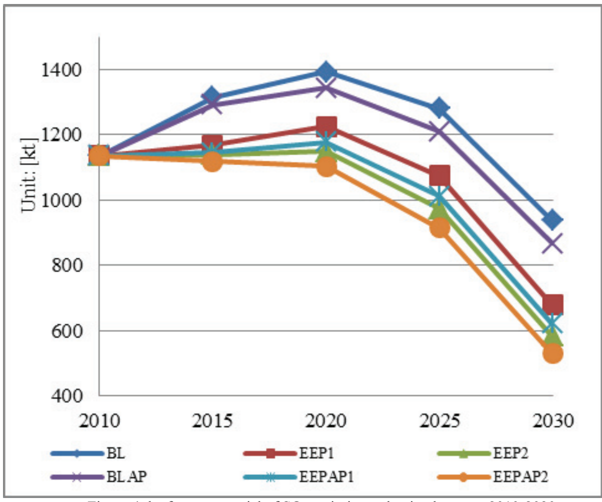


Figure 4 the future potential of SO_2 emission reduction between 2010-2030

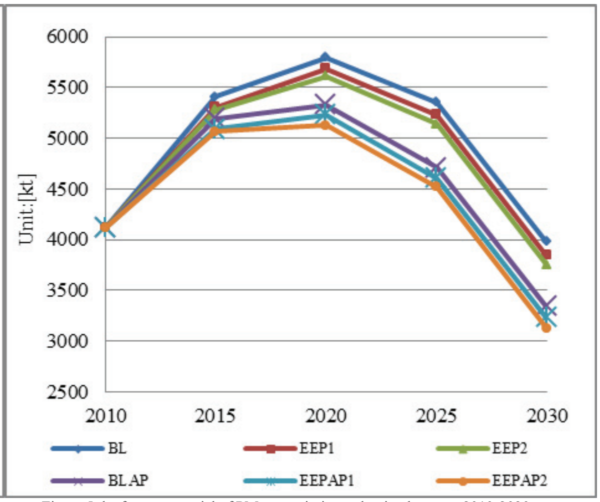


Figure 5 the future potential of $PM_{\_TSP}$ emission reduction between 2010-2030

Future emission reduction potentials of $PM_{\_TSP}$ in the China's cement industry are shown in Figure 5. Emissions of $PM_{\_TSP}$, will increase by 40% in the BL scenario from 2010 to 2020. Thereafter they will decrease in 2030 to around the same level as in base year 2010. The emission reduction potentials of $PM_{\_TSP}$ in EEP1 and EEP2 scenarios are about 2-6%, compared to baseline emissions. In EEPAP1 and EEPAP2 scenarios the reduction is about 10-16%. This illustrates that applying 13 PM control technologies have higher 3-5 times contribution of PM emission mitigation than implementing 37 energy efficiency measures from 2010 to 2030. In spite of PM control technologies have higher costs than energy efficiency measures, policy makers still prefer to choose more efficient PM control technologies and neglect energy efficiency measures to control PM emissions. For example, in line with the "Twelfth Five-Year Plan", bag filters will be implemented on key cement making facilities (crushers, mills, coal mills, drying mills, machines, packing machines, cooling machines, and cement bin) to reach the new air pollutants emission standards [44]. Furthermore, bag filters can reduce SO_2 emissions simultaneously.

Figure 6 presents the future emissions of NOx for China's cement industry up to 2030. Like the PM and SO_2, The quantity and future trend of NOx emissions depend heavily on the production of cement output. However, the contribution of NOx emission reduction of energy efficiency measures is higher than of NOx control options. Between 2010 and 2030, NOx emissions in the BL scenario would be 6-12% and 11-20% higher than in the EEP1 and EEP2 scenarios, respectively. Compared to EEP1 scenario, the air pollutant emissions would be further decrease around 1% in EEPAP1, due to implementation of end-of-pipe options. The EEPAP2 scenario has the largest potential for reduction of NOx emissions by 9-21% in the period 2010-2030. 24 cost effective energy efficiency measures are more economic feasibility than 10 NOx control technologies during whole period. However, the extra 13 non cost effective energy efficiency measures seems less economic feasibility than NOx control options after 2020, due to higher costs.

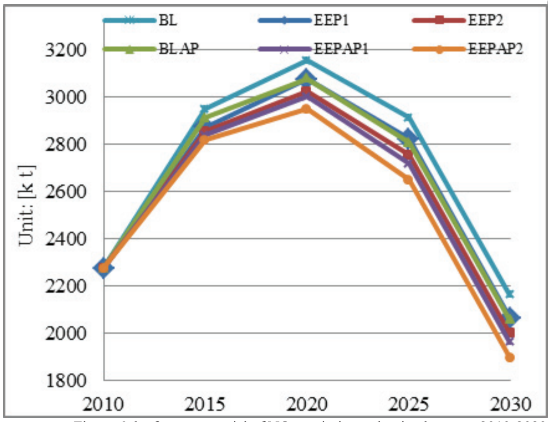


Figure 6 the future potential of NOx emission reduction between 2010-2030

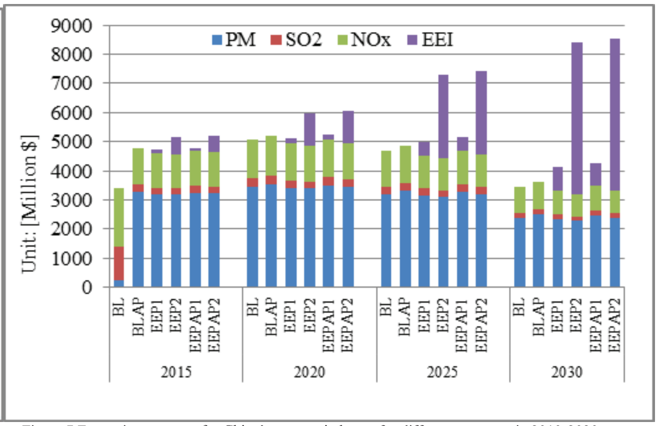


Figure 7 Future investments for China's cement industry for different category in 2010-2030

4.4. Future investments for China's cement industry under different scenarios

Figure 7 gives an indication of the investment costs for energy efficiency measures and end-of-pipe options is needed up to 2030, which is calculated in five year increments based on the ECSC and GAINS framework. Total investments for China's cement industry are classified into four types, i.e. energy efficiency investment (EEI), NOx investment, SO_2 investment, and PM investment. Before 2020, over half (57%) of the investments are for PM, followed by NOx investments (25%) and EEI (10%), which is consistent with the government's policy to tackle air pollution, especially to reduce PM emissions and reaching the new air pollutant emissions standards [45]. Between 2020 and 2030, EEI investments will increase at an average annual rate of 45%. The main reason is that cost-effective energy efficiency measures are adopted mainly before 2020, leaving the non-cost-effective measures after 2020. If non cost-effective energy efficiency measures are not considered (in EEP1 and EEPAP1 scenarios), total investments costs (includes EEI investment, NOx investment, SO_2 investment, and PM investment) will increase by 6% per year until it peaks in 2020, and then decrease by 9-8% per year from 2020 to 2030. In contrast, future investments in EEP2 and EEPAP2 scenarios increase drastically over the period 2015 throughout 2030 because some energy efficiency measures require high capital expenditure, such as low temperature heat recovery for power generation, high efficiency roller mill for raw mill and coal grinding, upgrading older dry kilns to multi-stage preheater kiln, high efficiency gassifiers, upgrading to a preheater/precalciner kiln, slag power production and raw mill blending (homogenizing) systems.

5. Conclusion

China's cement industry is one of the highest energy consuming and GHGs and air pollutants emitting industry. The aim of this study is to provide better a understanding of co-benefits of energy savings and the abatement of CO_2 and air pollutant emissions, through the implementation of best commercially available energy efficiency measures and end-of-pipe emission control options.

We first give a detailed discussion of historical trends of cement production, energy use and emissions in the Chinese cement industry and found that the cement output from China increased by 11.5 times, from 210 Mt in 1990 to 2420Mt in 2013. Between 2000 and 2010, intensities of energy, CO_2, PM, SO_2, and NOx for cement production dropped 34%, 26%, 84%, 64%, and 10%, respectively.

Next, the energy conservation supply curves (ECSC) combined with the GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies) model were employed to quantify the potentials of energy saving and emissions mitigation of CO_2 and air pollutants and co-benefits during the period 2011-2030. The results show that the cost-effective energy saving potential (EEP1 scenario) is estimated to be 3.0 EJ in 2030, and fuels-related emissions reduction is 252 Mt of CO_2, and 503 kt of air pollutants, which is equal to 9% of energy consumption and CO_2 emissions, and 14% of air pollutants in the BL scenario in 2030. The costs of cost-effective energy efficiency measures and end-of-pipe options are around 0.8 billion $ and 3.3 billion $, respectively. The technical energy saving potential (EEP2 scenario) is estimated to be 4.2 EJ in 2030, and fuels-related emissions reduction is 455 Mt of CO_2, and 864 kt of air pollutants. The costs of all energy efficiency measures and end-of-pipe options are around 5.2 billion $ and 3.2 billion $, respectively. When combining energy efficiency measures and end-of-pipe technologies the largest potentials of energy saving and emission reduction were found in the EEPAP2 scenario, with 4.2EJ energy savings by 2030 and 1183 kt of air pollutant emission reductions. Associated costs of this scenario are around 5.2 billion $ and 3.3 billion $, respectively.

When both types of scenarios are compared it becomes clear that through using energy efficiency measures investment to reduce air pollutant emissions can be avoided, especially for SO_2 and NOx emissions. Compared to the BL scenario, the co-effect of energy efficiency measures can result in decreasing 5% of CO_2, 3% of PM, 15% of SO_2, and 12% of NOx by 2030 in EEP1 scenario. If we cannot consider costs factor (in EEP2 scenario), the co-effect of energy efficiency measures can further reduce 3% of CO_2, 2% of PM, 10% of SO_2, and 8% of NOx by 2030. Due to the influence of co-benefits, the average marginal costs of energy efficiency measures will decrease 20%, from 1.48 $/GJ to 1.19 $/GJ. Therefore, implementation of energy efficiency measures is more cost-effective than a solely end-of-pipe based policy. Plant managers and end users can consider using energy efficiency measures to reach new air pollutants emission standards in China's cement industry.

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