Applied Energy 147 (2015) 192–213

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Evaluating co-benefits of energy efficiency and air pollution abatement in China's cement industry

Shaohui Zhang *, Ernst Worrell, Wina Crijns-Graus

Copernicus Institute of Sustainable Development, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands

HIGHLIGHTS

- Implementation rates of 37 EEMs are quantified for China's cement industry.
- Energy Supply Cost Curves were implemented in the GAINS model.
- The economic energy saving potential is 3.0 EJ and costs is $4.1 billion in 2030.
- Energy efficiency would lead to large reductions in air pollution.
- The co-benefits decrease average marginal costs of EEMs by 20%.

ARTICLE INFO

Article history:
Received 17 December 2014
Received in revised form 5 February 2015
Accepted 24 February 2015

Keywords:
Co-benefits
Energy efficiency
Air pollution
GAINS
Economics

ABSTRACT

China's cement industry is the world's largest and is one of the largest energy consuming, and GHG and air pollutant emitting industries. Actions to improve energy efficiency by best available technology can often bring co-benefits for climate change and air quality through reducing emissions of GHGs and air pollutants emission. 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 implementing 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 that there are large co-benefits of improving energy efficiency and reducing emissions of CO_2 and air pollutants for the China's cement industry during the study period. 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 amount to 4.2 EJ and 8.4 billion $ at the same time. Compared to the baseline scenario, energy efficiency measures can help decrease 5% of CO_2, 3% of PM, 15% of SO_2, and 12% of NOx emissions by 2030 in EEP1 scenario. If we do not consider costs (EEP2 scenario), energy efficiency measures can further reduce 3% of CO_2, 2% of PM, 10% of SO_2, and 8% of NOx 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. The plant managers and end users can consider using energy efficiency measures to reach new air pollutants emission standards in China's cement industry.

1. Introduction

The cement industry consumes around 2% of global primary energy use and produces 5–7% of anthropogenic CO_2 emissions worldwide, together with very high air pollutant emissions, including sulfur dioxide (SO_2), nitrogen oxides (NOx) and particulate matter (PM) [1–4]. Past studies estimate that the global potential of improved energy efficiency and reduced greenhouse gas emissions in the cement industry could save up to 50% of fuel use, and mitigate 18% of direct CO_2 emissions and almost 20% of process CO_2 emissions from current level by 2050, through adopting best available technology, shifting process from wet to dry, replacing fossil fuels with alternative fuels, and decreasing clinker to cement ratio [1,5,6].

China's cement industry has attracted attention worldwide. Despite several efforts, such as increasing the new dry process

* Corresponding author. Tel.: +31 30 253 7405; fax: +31 30 253 7601.
E-mail addresses: s.zhang@uu.nl (S. Zhang), e.worrell@uu.nl (E. Worrell), W.H.J.Graus@uu.nl (W. Crijns-Graus).

http://dx.doi.org/10.1016/j.apenergy.2015.02.081
0306-2619/

Nomenclature

Abbreviations

ECSC energy conservation supply curves
MACC marginal abatement cost curves
GAINS Greenhouse Gas and Air Pollution Interactions and Synergies
BL scenario baseline scenario
EEP1 energy efficiency policy scenario 1
EEP2 energy efficiency policy scenario 2
BLAP baseline scenario with air pollutants policy scenario
EEPAP1 energy efficiency policy with air pollutants policy scenario 1
EEPAP2 energy efficiency policy with air pollutants policy scenario 2
GHGs greenhouse gases
SO_2 sulfur dioxide
NOx nitrogen oxides
PM particulate matter
Mt million tons
NSP kilns new suspension preheater/precalciner kilns
WHR waste heat recovery
SEC specific energy consumption
ESP electrostatic precipitator
SNCR Selective Non-Catalytic Reduction
AEEI annual autonomous energy efficiency improvement
EEI energy efficiency investment
OECD The Organisation for Economic Co-operation and Development
WEO World Energy Outlook
IEA International Energy Agency
IIASA International Institute for Applied System Analysis
LBNL Lawrence Berkeley National Laboratory
ERI Energy Research Institute of China
MIIT Ministry of Industry and Information Technology of China
NCSC National center for Climate Change Strategy and International Cooperation of China
ITIBMI IT Institute of Building Materials Industry
CSIBM China Development Strategy Institute for Building Materials Industry
CAS The Chinese Academy of Sciences
EMEP/EEA European Monitoring and Evaluation Programme/European Environment Agency
CSI Cement Sustainability Initiative
IPCC Intergovernmental Panel on Climate Change

Symbols

CCE cost of conserved energy for an energy efficiency measures
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
PE future energy price ($/GJ)
d discount rate
n lifetime of the energy efficiency measures
E_p emissions of pollutant p (for e.g. SO_2, $PM_{2.5}$, CO_2, PM_{10}, PM_{TSP}, etc.)
cn unit cost of end-of-pipe measures
A_k energy consumption of each fuel (e.g., coal consumption) in iron and steel industry
$ef_{k,m,p}$ emission factor of pollutant p for activity k after application of control measure m
$x_{k,m,p}$ share of total activity of type k to which a control measure m for pollutant p is applied
A activity
ef uncontrolled emission factor
ef_m controlled emission factor under end-of-pipe measures

Subscript

k, m, p activity type, abatement measure, pollutant, respectively

application, closing obsolete plants, and using various best practice technologies, that have been made by Chinese government in the past two decades, recent studies indicate that there is still large opportunity to improve energy efficiency, reduce emissions of GHGs and air pollutants [7–10]. 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 [8,10]. 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 [7,11]. Lei 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 [12]. 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 [3,13,14]. For instance, Xi [15] 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 [15]. 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. Section 5 provides a discussion of sensitivities and comparison with other studies. Finally, the conclusion is given in Section 6.

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

In this section, we first give an analysis of historical production of clinker and cement and associated fixed investment in China. The Historical energy use, emissions of GHGs and air pollutants and intensity are presented in Sections 2.2 and 2.3, respectively.

2.1. Historical production of clinker and cement, and its investment trends

In the past 25 years, the cement production has expanded rapidly worldwide. The global production of cement has increased from 1000 Mt in 1990 to 3750 Mt in 2012, expanding 3.75 times [16] (see Fig. 1). 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 [17]. 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 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 closing of obsolete vertical shaft kilns, and the decrease of the clinker to cement ratio.

The capital investment in 2005-dollar constant value and cement production of China's cement industry in 1995–2012 are presented in Fig. 2. There are lots of similarities between the overall trends of cement production and those of capital investment between 1995 and 2012 [8]. Due to the market downturns, the capital investment gradual dips between 1995 and 2002, which lead to a slower cement output increase. Investments of the Chinese government of 0.59 trillion $ (equal to 4 trillion RMB), to stimulate economic development in 2009–2011, caused a sharp increase in capital investments in the Chinese cement industry, from 6935 million $ in 2007 to 18,571 million $ in 2009, and slight decline from 2010 to 2012 [18].

China's cement industry, especially for the new suspension preheater/precalciner (NSP) kilns, has seen rapid developments in the last decade due to fast economic growth and government policy. The number of total NSP kilns increased from 136 in 2000 to 1304 in 2010 (see Fig. 3). Since 2005, the annual growth rate of clinker production capacity above 4000 t/d of newly NSP kilns has grown more rapidly than total new NSP kilns. Between 2000 and 2010, the average clinker capacity from NSP kilns increased from 1627 t/d in 2000 to 3002 t/d in 2010, which was mainly due to the explosive growth of clinker produced with dry process and the phase out of obsolete cement production capacity of 370 Mt between 2006 and 2010. The central government plans to phase out another 250 Mt obsolete cement production capacity during the 12th Five Year Plan (FYP) (2011–2015) [19–21].

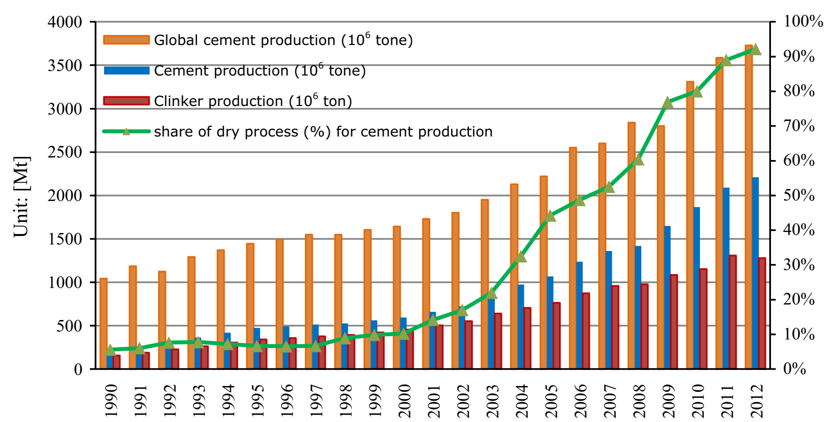

Fig. 1. Historical production of clinker and cement and capital investment in 1990–2012. *Source:* Primary data from [16–18]. Calculations by authors.

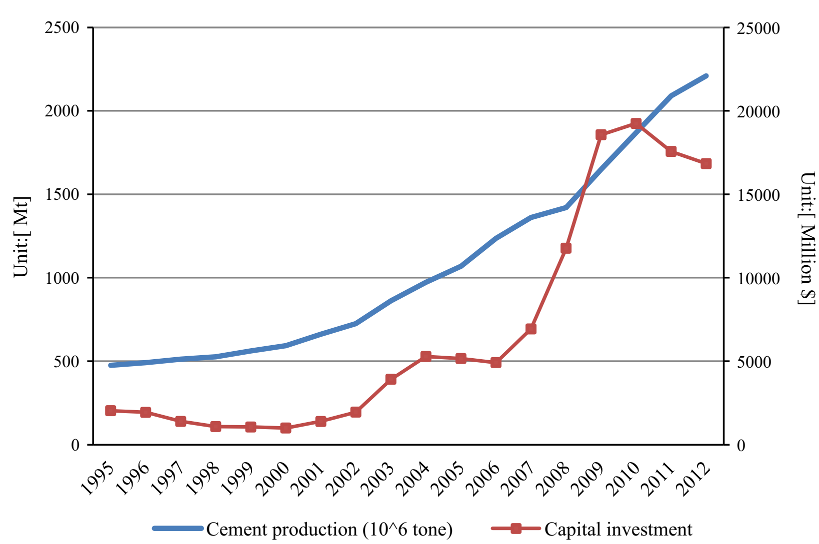

Fig. 2. Capital investment and cement output in China's cement industry in 1995–2012. *Source:* Ref. [18] The exchange rate of the CHN for the US dollar in 2005 is 8.19 Yuan per dollar. Calculation by authors.

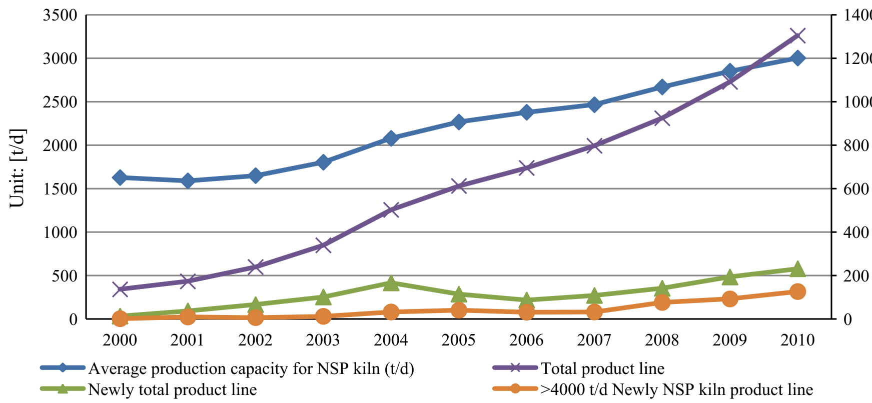

Fig. 3. The quantity and capacity of NSP kilns between 2000 and 2010. *Source:* The unit for the right *y*-axis is the number of production lines; Primary data from China Cement [18]. Calculations by authors.

The structure of the cement industry has different varieties in three regions of China (East area, Middle area, and West area). In 2010, the total number of clinker production lines of NSP kilns reached 383 in east, 387 in middle, and 473 in the west, respectively (see Fig. 4). Although the number of new NSP kilns (141 lines) in the west grew faster than in the middle (51 lines) and east of China (39 lines), the east and middle area have higher average income levels and prefer to invest in larger scale production lines than in the west of China. The east area of China has the largest clinker plant with 12,000 tonne/day (t/d) [17].

The structure of China's cement industry changed drastically between 2005 and 2012. The number of clinker production line with NSP kilns increased from 622 in 2005 to 1627 in 2012, while the clinker production capacity for NSP kilns increases at an average of 19.8% per year (from 447 tonne/day in 2005 to 1586 tonne/day in 2012) (see Fig. 5). China's cement industry was dominated by small and medium-sized enterprises before 2007. However, there has been a dramatic reversal due to the fast development of NSP kilns and the phasing out of a large amount of inefficient production capacity. It means that the contribution of over 4000 tonne/day NSP kilns grew rapidly from 38.5% in 2005 to 58.9% in 2012. Note that the small and medium-sized kilns are mainly concentrated in the west and middle of China, and might be phased out in the next decade as a result of higher energy costs than for larger scale plants.

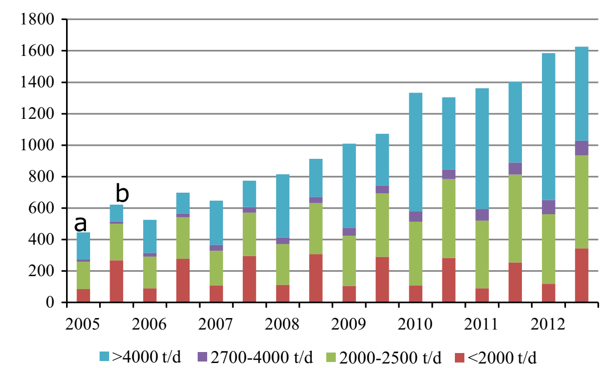

Fig. 5. Structural change of NSP kilns and its clinker production capacity in 2005–2012. Note: a is the average clinker production capacity for NSP kilns (unit: tonne/day); b is the number of clinker production lines for NSP kilns; 1 the primary data from Aq NDRC [17], Ar China Cement [18], calculation by authors; 2 the data of 2011 are not available.

2.2. Historical energy use and its energy intensity trends

The energy consumption of China's cement industry generally kept pace with the growth of China's cement output. As shown in Fig. 6, the total amount of energy consumption of China's

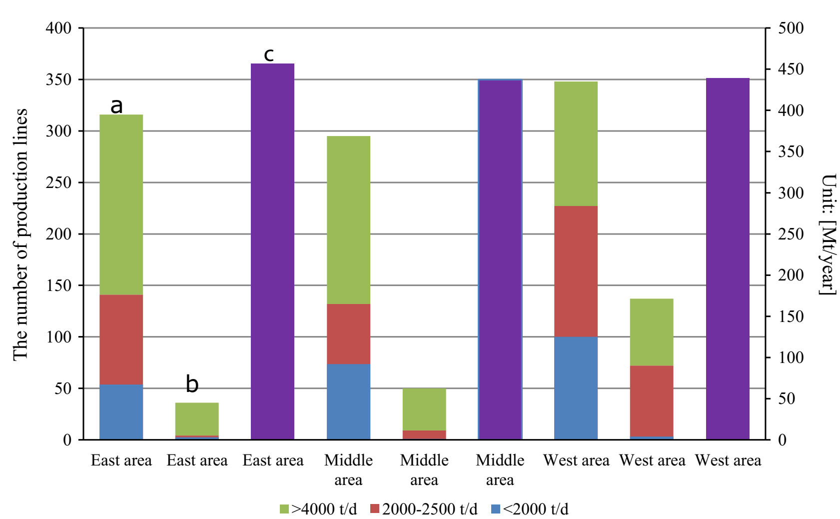

Fig. 4. The number of NSP kilns and clinker production capacity on 2010. Note: a is the number of clinker production lines for total NSP kilns; b is the number of clinker production lines for newly NSP kilns; c is the clinker production capacity. *Source:* Ref. [18]. Calculation by authors.

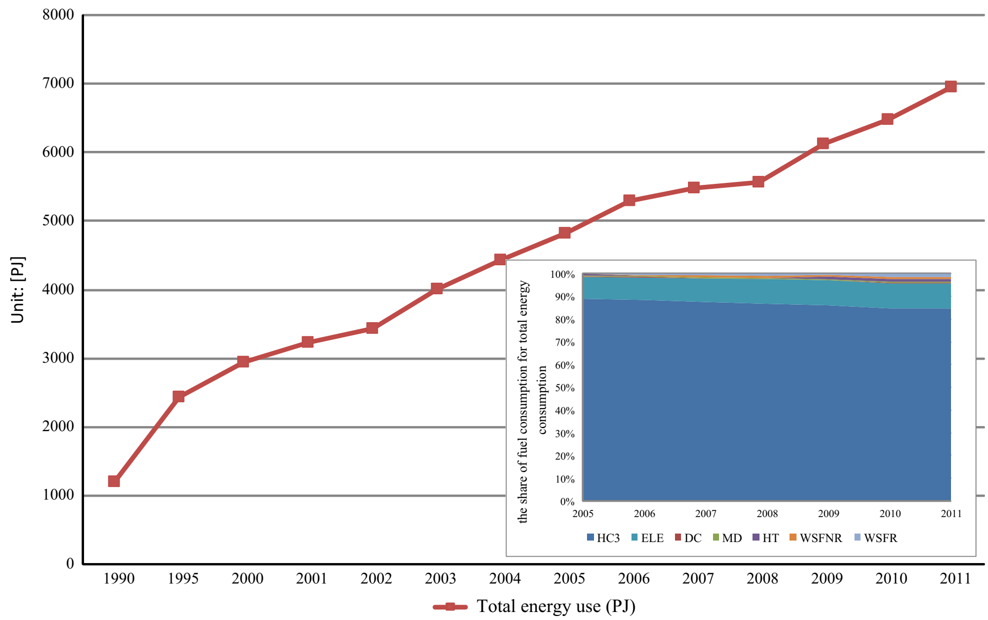

Fig. 6. Energy consumption in China's cement industry in 1990–2011. *Source:* the primary data from Ke et al. [8], Xi et al. [15], China Cement [18], Yande Dai [52], Dai and Hu [47]. Calculations by authors.

cement industry increased about 6 times from 1200 PJ to 6961 PJ in 2011, which equals 7% of Chinese total energy consumption [22]. 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 [8]. China's cement production relies heavily on coal, which amounted up to 85–89% of total fuel used, followed by electricity (9–11%). The share of alternative fuels (e.g., solid waste and biomass) increased from 0.05% in 2005 to 2.33% in 2010 [8,18].

The energy intensity of the Chinese cement industry improved significantly due to the wide range of technologies that were implemented (especially waste heat recovery (WHR) and NSP kilns) and due to the closing of inefficient kilns [23]. The intensities of fuels, electricity, and overall specific energy consumption (SEC) by different kilns are given in Table 1. In the past two decades, the final overall SEC per ton of cement dropped by 45.5%. The SEC for fuels of NSP kilns decreased at an average rate of 0.71% per year, from 3.89 GJ/ton of clinker in 1990 to 3.37 in 2010 [24]. With the strong increase of the more energy efficient dry process and the closing of many inefficient plants (smallest shaft kilns and wet-process with vertical shaft kilns), the overall SEC for fuels of clinker production decreased at an average of 2.28% per year, from 5.53 GJ/ton of clinker to 3.49 in 2010. Between 1990 and 2010, the SEC for electricity of NSP kilns declined at an average rate of 1% per year (from 114 in 1990 to 93 kW h per ton of cement in 2010), which is higher than the decrease in average electricity intensity of the total cement industry in China (0.87%).

2.3. Historical emissions of CO_2 and air pollutants and its intensity trends

CO_2 emissions in cement production come from calcination, fuel combustion, and indirect emissions of electricity consumption. As the second largest CO_2 emitter, China's cement industry accounts for 7% of total emissions in China [25]. As shown in Fig. 7, 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. The average CO_2 intensity of clinker dropped at an average rate of 3.5% per year, decreasing from 1.3 in 2000 to 1.2 t CO_2/t clinker in 2010, while the average CO_2 intensity in cement production declined at an average 13% per year, from 1.00 to 0.74 t CO_2/t cement during the same period. One main reason for the CO_2 intensity 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%) [5,26].

Table 1
Specific energy consumption by different kilns for China's cement sector.

Year	SEC for fuels (GJ/t clinker)				SEC for electricity (KW h/t cement)				Final overall SEC (GJ/t cement)
	NSP kilns	Shaft kilns	Other kilns	Overall	NSP kilns	Shaft kilns	Other kilns	Overall	
1990	3.89	4.72	5.85	5.53	114.00	105.00	120.00	106.00	5.74
1995	3.75	4.54	5.65	4.66	114.00	98.00	118.00	104.00	5.13
2000	3.66	4.39	5.50	4.44	112.00	95.00	116.00	102.00	4.75
2005	3.63	4.59	5.21	4.11	99.00	93.00	100.00	99.00	3.78
2008	3.40	4.42	5.07	3.77	95.00	91.00	108.00	93.90	3.25
2009	3.34	4.16	4.95	3.57	95.00	90.00	105.00	91.10	3.19
2010	3.37	4.01	4.89	3.49	93.00	90.00	102.00	89.00	3.13

Source: the primary data from [8,12,18,52,47,24,89,90,91,92,93]; SEC is specific energy consumption.

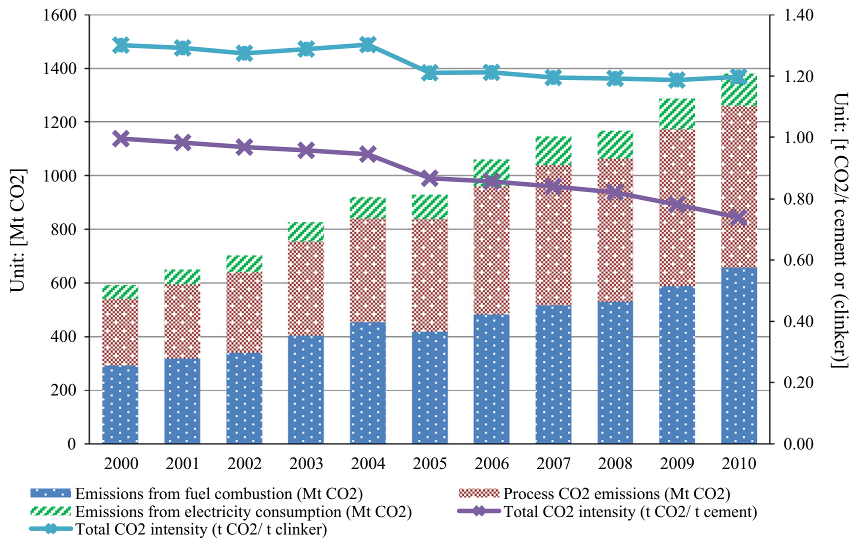

Fig. 7. CO_2 emissions by different types of China's cement industry. Note: the CO_2 emission factors are from Ke et al. [8], CSI [16], Dai and Hu [47], IPCC [76], CSI [83], CSI [77], Cui-mei et al. [84]. Calculations by authors.

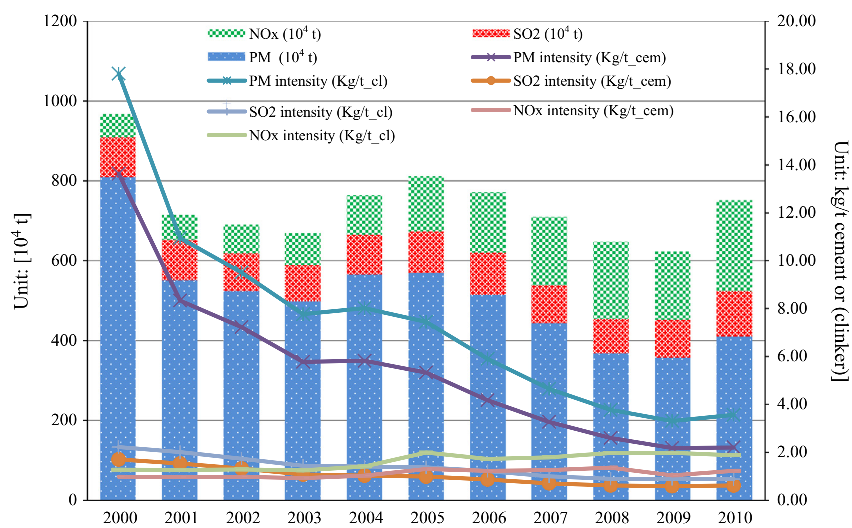

Fig. 8. Historical air pollutants emission trend and associated intensities of China's cement industry. *Source:* the primary data from Lei et al. [12], China Cement [18], Jian-mei and Guo-dong [29], Yu et al. [31], Wen-fu et al. [85], Xin-miao et al. [86], Chang-mi [87], Chen [88]. *Calculations by authors.

In spite of the government taking a series of policy measures (e.g. key projects for reducing air pollutant emissions and the top 10,000 programme for improving energy efficiency and phasing out inefficient cement production capacity), the rapid development of China's cement industry has resulted in massive air pollutant emissions [27]. As a major emitter of air pollutants, the Chinese cement industry contributed to around 15–27% of national PM emission, 3–4% of SO_2 emission, and 8–12% of NOx emission [12,28–30]. Unlike the trends of cement output and energy consumption, the total emissions of air pollutants (e.g. PM, SO_2, and NOx) show a declining trend from 2000 to 2010, with a slight increase over the past two years (see Fig. 8). 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 [17,31]. The PM emission intensities declined from 13.64 in 2000 to 2.20 kg per ton of cement over this period. Between 2000 and 2010, the removal efficiency increased slightly from 79% to 94%, at an average of 1.7% per year. Although cement output increased significantly, SO_2 emission remained relatively stable, due to the sharp decline of SO_2 emission intensities (from 1.69 in 2000 to 0.60 kg per ton cement in 2010). 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 [17]. To meet air pollutants emission targets as set in the 12th Five Year Plan[1] [27], the removal efficiency for NOx should reach 40% in 2014 and 60% in 2015 and the total emissions of PM and NOx should be reduced by 50% and 25% in 2015, compared to 2009 levels. Furthermore, according to the new standard of air pollutant emissions in the cement industry, the PM emission will be cut around 0.77 Mt (30.8–38.5%) and NOx emission will decrease about 0.98 Mt (44.5–51.6%) compared to 2010 level [28]. This means

[1] By 2015, the target is set to reduce the air pollutants emission of SO_2, NOx and PM of Chinese industry by 12%, 13% and 10%, respectively.

that if all cement enterprises reach these new emission standards, the future emission target would be realized smoothly.

3. Methodology

This section describes the approach used to estimate the potentials of energy efficiency improvement and emissions mitigation of GHGs and air pollutants for currently commercially available energy efficiency measures and end-of-pipe options. First, an overview of the energy conservation supply curves (ECSC) and the GAINS (Greenhouse Gas and Air pollution Interactions and Synergies) model are introduced. Second, the description of data sources is provided followed by a description of scenario assumptions for assessing the potentials of co-benefits. Due to the methodological challenges and data limitations, co-benefits, in our study, focus only on energy efficiency, greenhouse gas emissions and air pollutants, while other co-benefits such as societal welfare and health effects are not included.

3.1. Energy conservation supply curves

Cost curves (i.e. energy conservation supply curves or marginal abatement cost curves) are a standard policy tool to analyze potentials of energy efficiency, emissions mitigation of GHGs and air pollutants [32]. Mostly energy conservation supply curves are used to evaluate potentials of reducing energy use and CO_2 emission by implementing energy efficiency measures [10,33]. Similarly, marginal abatement cost curves (MACC) are used to assess the mitigation effects of abatement measures [34]. 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 [3,13–15,35]. For example, Yang et al. [13] employed marginal abatement cost curves (MACC) to analyzed the co-benefits on local air quality improvement for mitigation measures in the Chinese cement industry. The results shown that the co-benefits ranged from 3 \$/t CO_2 to 39 \$/t CO_2 at a national level. Similarly, Hasanbeigi et al. [3] quantified the co-benefits of PM_{10} and sulfur dioxide (SO_2) emission reductions and energy-saving in the cement industry in Shandong Province, using energy conservation supply curves and the AERSCREEN screening-level model. They found that 40% of PM and SO_2 emissions would be reduced through implementing energy saving measures. This illustrates that co-benefits from air pollutant emission reductions as a result of energy saving measures can reduce the CCE of those measures. 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. include 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 [36]. The costs of each energy efficiency measure is priced at 2005 dollars (\$), with currency conversion factors derived from OECD Stat Extracts [37]. The calculation of the costs of conserved energy for each energy efficiency measure is presented in Eq. (1) [3,10,38].

$$\mathrm{CCE} = \frac{I \times \mathrm{AF} + O\ \&\ M^{Fix} + O\ \&\ M^{Var} - \mathrm{ESP} \times \mathrm{PE}}{\mathrm{ESP}} \tag{1}$$

where CCE is the cost of conserved energy for an energy efficiency measures (\$/GJ); I is investment (\$); AF is annuity factor; $O\ \&\ M^{Fix}$ is annual change in operation and maintenance fixed cost (\$); $O\ \&\ M^{Var}$ is annual change in operation and maintenance variable cost (\$); ESP is annual energy saving potential (GJ) and PE is future energy price (\$/GJ).

In this study, a discount rate of 10% is assumed (see also in Section 5.3). 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 Eq. (2).

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

where d is the discount rate and n is 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, developed by the International Institute for Applied System Analysis (IIASA), is an integrated model to identify emission control strategies that estimates costs and potentials for air pollution control and greenhouse gas (GHG) mitigation [39,40]. Also, the GAINS model can be used to assesses the technical and economic interactions between mitigation measures for the considered air pollutants and greenhouse gases [41]. 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 [42,43]. 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 [44]. 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 CO_2 emission reduction on decreasing cost of conserved energy (CCE) for energy efficiency measures.

The emissions of air pollutants and greenhouse gases are calculated by Eq. (3), 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. [40].

$$E_p = \sum_k \sum_m A_k ef_{k,m,p} x_{k,m,p} \tag{3}$$

where k, m, p is the activity type, abatement measure, pollutant, respectively; E_p is emissions of pollutant p (for e.g. SO_2, $PM_{2.5}$, CO_2, PM_{10}, PM_{TSP}, etc.); A_k is energy consumption of each fuel (e.g., coal consumption) in iron and steel industry; $ef_{k,m,p}$ is emission factor of pollutant p for activity k after application of control measure m and $x_{k,m,p}$ is share of total activity of type k to which a control measure m for pollutant p is applied.

The unit cost of end-of-pipe measures (cn) is calculated through Eq. (4), using investment costs (I), annual change in operation and maintenance costs (includes fixed cost and variable cost), and one unit of activity (A).

$$cn = \left(\frac{I \times \mathrm{AF} + OM^{Fix}}{A} + OM^{Var}\right) / (ef - ef_m) \tag{4}$$

where *cn* is the unit cost of end-of-pipe measures ($/t); *A* is activity (*t*); *ef* is uncontrolled emission factor and ef_m is controlled emission factor under end-of-pipe measures.

3.3. Scenario description

3.3.1. Data source and key assumptions

The cement and clinker output data used in this study are from China statistical yearbook [45], China Cement Association [20], China cement almanac [18] and relevant literature surveys [7,46]. The historical energy consumption and associated fuel structure are from the China cement almanac [18], China energy statistical yearbook [45], and literature [8,47].

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 [7,8,11,48,49] (see section 5.1 for more detailed information). Here, we assume that cement and clinker output in China's cement industry will peak in 2020, based on Ze's latest research [48] (see Table 2).

Although many cost-effective energy efficiency measures and end-of-pipe options have been implemented in China's cement industry, there still is room for improving energy efficiency and reducing emissions of GHGs and air pollutants [10,14]. Our study includes 37 commercially available energy efficient technologies/measures (including international technologies and Chinese domestic technologies), costs, lifetime, fuel/electricity saving, current implementation in base year and possible and potential implementation rates up to 2030 (Appendix A provides a list of these options). 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 measure are mainly from recent studies, such as LBNL [3,10,50,51], ERI of China [52,47], MIIT of China [53], and other institutes [11,15,34,54]. In addition, 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 (detailed information for potential implementation rate of each measures see Appendix A). 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 energy efficiency and emission reduction technologies that are currently not commercially available are beyond the scope of our study, such as Fluidized bed kilns [55].

Because we could not obtain sufficient information of individual end-of-pipe options for pollution abatement in China's cement industry, 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 [56], historical air pollutant emissions [12,18,31], integrated emission standards of air pollutants (GB1627-1996) [57] and air pollution standards for cement (GB4915-1996) [58] and (GB4915-2004), for the respective period [59].

The conversion factors used for calculating CO_2 emissions and PM emissions are taken from the GAINS database and updated based on recent studies [60,61]. The emission factor for electricity from the grid are based on the NCSC of China, Ranping et al., Hasanbeigi et al., and Ke et al. [8,10,62,63]. Emission factors of fuels for CO_2, PM, SO_2 and NOx are from the GAINS database (for more information about GAINS emission factors, http://gains.iiasa.ac.at/models/index.html) and calibrated based on the EMEP/EEA air pollutant emission inventory guidebook 2013 [64], production of industrial pollution discharge coefficient [65] and related studies [66]. We also note that the GAINS model does not estimate how much of the emissions is captured within the process [67,68]. Therefore, in this paper, the control costs of air pollution abatement options based on the GAINS model were used to monetize the co-benefits of energy efficiency measures that reduce air pollutants emission. For example, the Chinese air pollution standards for cement industry requires air pollution abatement options (e.g. ESP (electrostatic precipitator) and SNCR (Selective Non-Catalytic Reduction)) to be installed on cement plants to limit air pollutant emissions. These abatement options would generate a value that represents the costs of air pollutant emissions from cement plants with abatement options installed and without. Similarly, the energy efficiency measures can be reduced air pollutant emissions to some extent, which means that the plant managers can invest less in pollution abatement to reach the same emission level. So the avoided investment costs in pollution abatement were used to calculate the co-benefits of energy efficiency measures.

3.3.2. Scenarios

The time period in this study covers 2010–2030, 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 co-impacts of energy efficiency measures and end-of-pipe options are quantified by a soft-linkage of ECSC with GAINS, where the output of ECSC is exogenously entered into GAINS to project emissions of GHGs and air pollutants with and without end-of-pipe options. 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 (see Table 3).

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 steps 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. In this scenario, 24 cost-effective energy efficiency measures will be implemented with the projected implementation rates (see Table 4). This scenario might be achieved by overcoming

Table 2
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	

Table 3
Key features of different scenarios.

Item	Sub stage	Scenario description
BL	–	The annual AEEI of each process are 0.2%
EEP	1	Energy efficiency measures below 0 $/GJ (represents economically feasible opportunities)
	2	All commercially available energy efficiency measures will be fully implemented
BLAP	–	The annual AEEI of each process are 0.2%. The current and potential implementation rates of end-of-pipe controls are from the GAINS database and defined based on WEO 2012 baseline in GAINS and literature
EEPAP	1	The activity level of energy efficiency measures keep consistent with EEP1 scenario and the future implementation rates of end-of-pipe controls remain constant with BLAP scenario
	2	The activity level of energy efficiency measures keep consistent with EEP2 scenario and the future implementation rates of end-of-pipe controls remain unchanged with scenarios of BLAP and EEPAP1

Table 4
Energy efficiency measures of different scenarios.

Number	Measures	CCE ($/GJ)	Number	Measures	CCE ($/GJ)
1	New efficient coal separator	−12.21	19	Combustion system improvements	−2.06
2	VFD in raw mill vent fan	−10.48	20	Upgrade clinker cooler	−1.39
3	Bucket elevators for raw meal transport	−10.35	21	Optimize grate cooler	−1.27
4	High efficiency motors	−9.22	22	Raw mill process control for roller mill	−1.07
5	VFD in cooler fan of grate cooler	−8.77	23	Replacing vertical shaft kilns with new suspension	−0.77
			24	Energy management and process control	−0.77
6	High efficiency fan for raw mill vent fan with inverter	−8.41	25	Adjustable speed drive for kiln fan	0.24
7	Adjustable speed drives	−8.26	26	Upgrading to a preheater/ precalciner kiln	0.26
8	Heat recovery for power generation	−6.11	27	Increasing number of preheater stages (from 5 to 6) in rotary kilns	0.30
9	Efficient transport system for mine	−5.44	28	Slag powder production	2.19
10	High pressure roller press for ball mill pregrinding	−4.59	29	Low temperature heat recovery for power generation	4.52
11	Optimize mine exploitation	−4.50	30	High efficiency classifiers	10.65
12	Installation of variable frequency drive and replacement of coal mill bag dust collector's fan	−3.33	31	High-efficiency classifiers	15.29
13	Energy management and process control	−3.20	32	High efficiency roller mills	16.73
14	Blended cement	−3.03	33	High-efficiency roller mill for raw mill and coal grinding	25.68
15	Kiln shell heat loss reduction (Improved refractories)	−2.97	34	Older dry kiln upgrade to multi-stage preheater kiln	43.60
16	Biomass and waste	−2.95	35	Raw mill process control for vertical mill	48.22
17	Conversion to grate cooler	−2.94	36	Low pressure drop cyclones for suspension preheater	53.53
18	High efficiency drying for slag	−2.53	37	Raw mill blending (homogenizing) systems	64.87

barriers to implementation of energy efficiency measures, such as strengthening awareness and improving professional skills of staff [69]. 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 is kept the same as in the BL scenario. 34 end-of-pipe options are used in the second category scenarios (see Appendix B), the current activity level and future implementation rates of these end-of-pipe options are projected based on the WEO 2012 baseline in GAINS and literature sources. 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

This section first discusses the cost-effective and technical potential for energy savings in China's cement industry up to 2030. Thereafter, the emission mitigation of CO_2 and air pollutants is assessed. Finally, the economics of energy efficiency measures and air pollutant control options are estimated.

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

Fig. 9 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 the 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.

To better understand which energy efficiency measures have the greatest impact on energy savings, energy conservation supply curves were constructed. As shown in Fig. 10, 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,

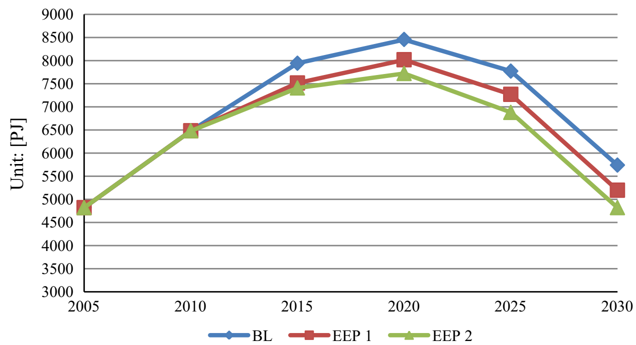

Fig. 9. The future potential of energy saving for China's cement industry in 2010–2030.

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 and process control as economically feasible energy efficiency measures, contributing to 23%, 11% and 10% of the total energy saving potentials, respectively. Note that energy management and 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 and 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 (see Fig. 11).

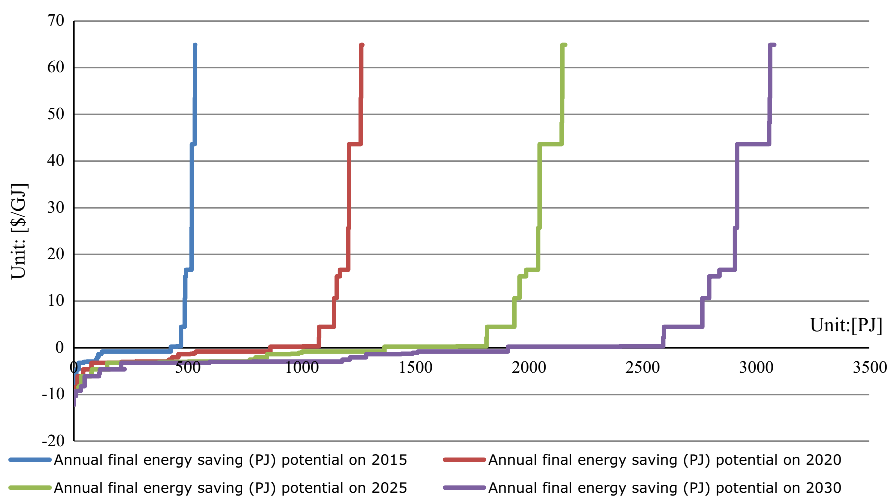

Fig. 10. The potential of annual final energy saving for China's cement industry in 2010–2030.

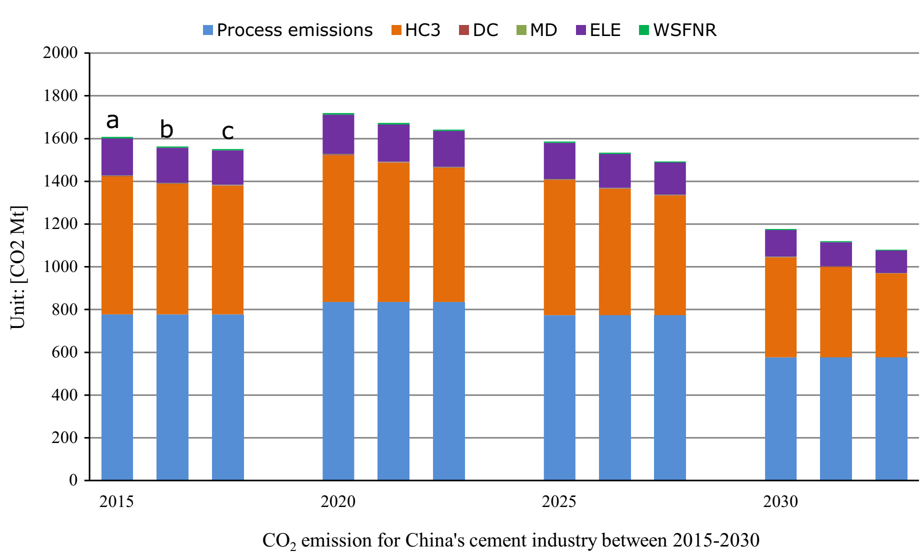

Fig. 11. CO_2 emissions for China's cement industry in 2015–2030. Note: a is BL scenario; b is EEP1 scenario; c is EEP2 scenario.

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

Fig. 12 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. Upgrading to a preheater/precalciner kiln, with specific cost close to zero, accounts for 14% of CO_2 emission reduction.

CO_2 is emitted by three different components in the cement production process; fuel combustion, electricity consumption and process emissions. 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.

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

SO_2 emissions in the cement industry mainly depend on the sulfur content of the fuels used [67]. Several factors affect the control SO_2 emissions, such as desulfurization used, water content and residence time [70]. Traditionally, there are three ways to control SO_2 emissions in a kiln system, i.e. inherent removal by the process, process alterations, and SO_2 scrubbing technologies. Future potential mitigation of SO_2 emissions in Chinese cement industry is shown in Fig. 12. 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% of SO_2 emission would be reduced through cost-effective 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 higher than implementing energy efficiency measures before 2020 (see Section 4.4). Note that the energy management and process control measures (e.g. adjusting the molecular ratio between sulfur and alkalines, oxidizing conditions in the burning zone in the kiln system and the temperature profile in the kiln system) can decrease SO_2 emission generation, but, may increase nitrogen oxides (NOx) emissions [67]. If 37 energy efficiency technologies and 11 end-of-pipe options are both adopted, 29% and 44% of SO_2 emission will be reduced by 2020 and 2030, respectively. In 2030, the emission levels of SO_2 will be lower than 2010 levels in all scenarios.

PM emissions are mainly generated in the grate cooler, kiln inlet, coal mill and cement mill, storage and handling of raw materials and fuel combustion [64,71]. Future emission reduction potentials of $PM_{\_TSP}$, PM_{10}, and $PM_{2.5}$ in the China's cement industry are shown in Figs. 13–15 respectively. Emissions of $PM_{\_TSP}$, PM_{10}, and $PM_{2.5}$ will increase by 40%, 43%, and 45% in the BL scenario from 2010 to 2020. Thereafter they will decrease in 2030 to around the same level as in base year 2010. Which depends heavily on the cement output. The emission reduction potentials of $PM_{\_TSP}$, PM_{10}, and $PM_{2.5}$ 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 a 3–5 times higher contribution to PM emission mitigation than implementing 37 energy efficiency measures from 2010 to 2030. Although PM control technologies have higher costs than energy efficiency measures, policy makers still prefer to choose more efficient PM control technologies (i.e. high efficiency deduster) and neglect energy efficiency measures

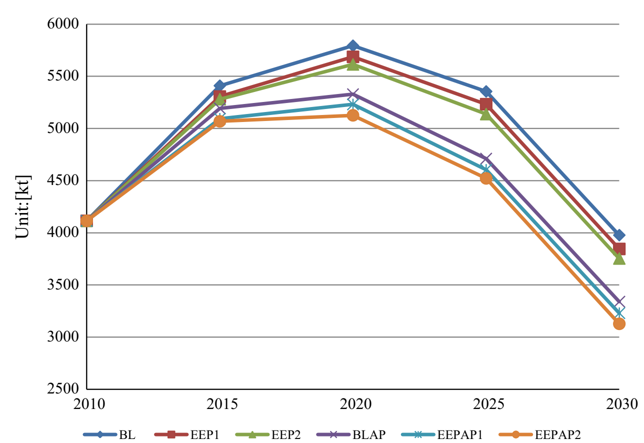

Fig. 13. The future potential of $PM_{\_TSP}$ emission reduction for China's cement industry in 2010–2030.

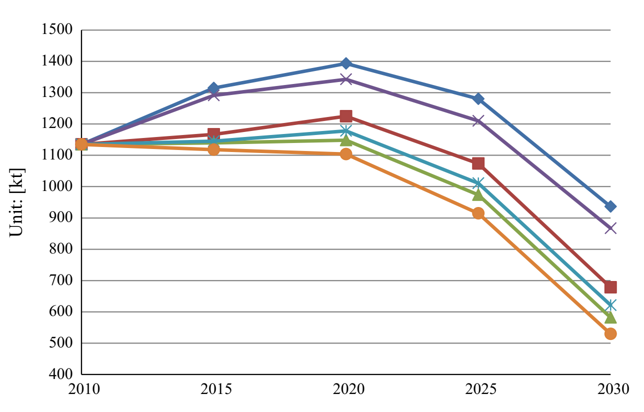

Fig. 12. The future potential of SO_2 emission reduction for China's cement industry in 2010–2030.

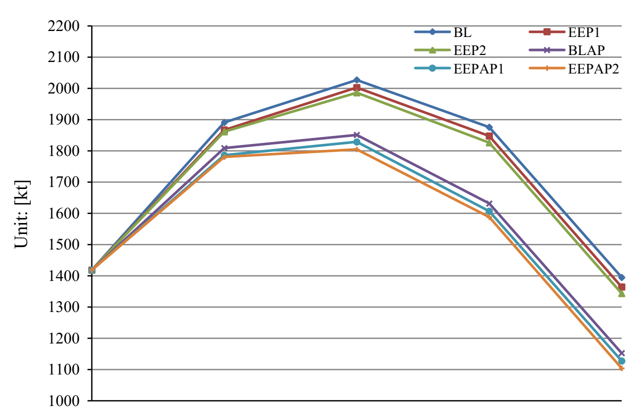

Fig. 14. The future potential of PM_{10} emission reduction for China's cement industry in 2010–2030.

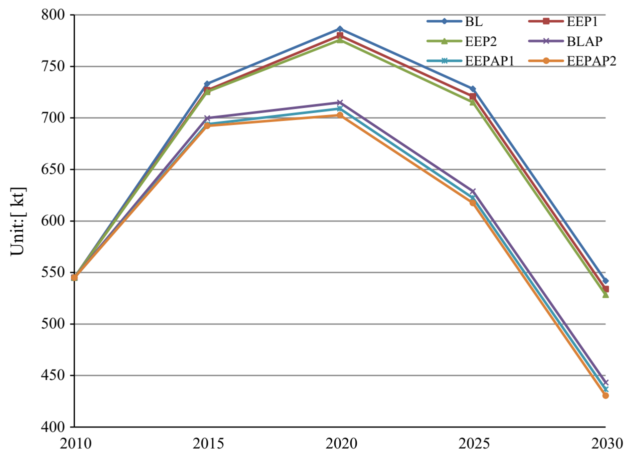

Fig. 15. The future potential of $PM_{2.5}$ emission reduction for China's cement industry in 2010–2030.

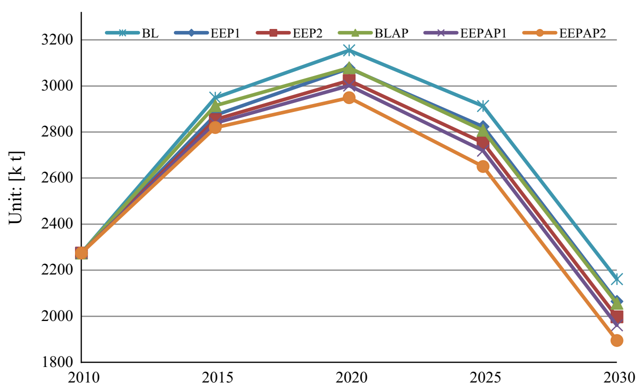

Fig. 16. The future potential of NOx emission reduction for China's cement industry in 2010–2030.

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 [27]. Furthermore, bag filters can reduce SO_2 emissions simultaneously.

NOx emissions result from process reactions and fuel combustion [29]. Fig. 16 presents the future emissions of NOx for China's cement industry up to 2030. Like for PM and SO_2, the quantity and future trend of NOx emissions depends heavily on the production of cement output. However, the contribution of energy efficiency measures to NOx emission reduction is higher than of end-of-pipe 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 economically feasible than 10 NOx control technologies during the whole period. However, the extra 13 non cost effective energy efficiency measures seem to have less economic feasibility than NOx control options after 2020, due to higher costs.

In summary, policy makers, as mentioned before, usually focus on implementing policies to solve energy efficiency, GHGs and air pollutants issue separately. They hardly consider the air pollutants emission reduction impacts through implementing energy efficiency measures and the additional electricity consumed from end-of-pipe options. In this study, several factors played a key role in reducing emissions of PM, SO_2 and NOx, such as cement output, conversion to grate cooler, energy management and process control, bag filter, ESP and SNCR. We also found that energy efficiency measures not only improve energy efficiency but also significantly reduce emissions of CO_2, SO_2 and NOx.

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

Fig. 17 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

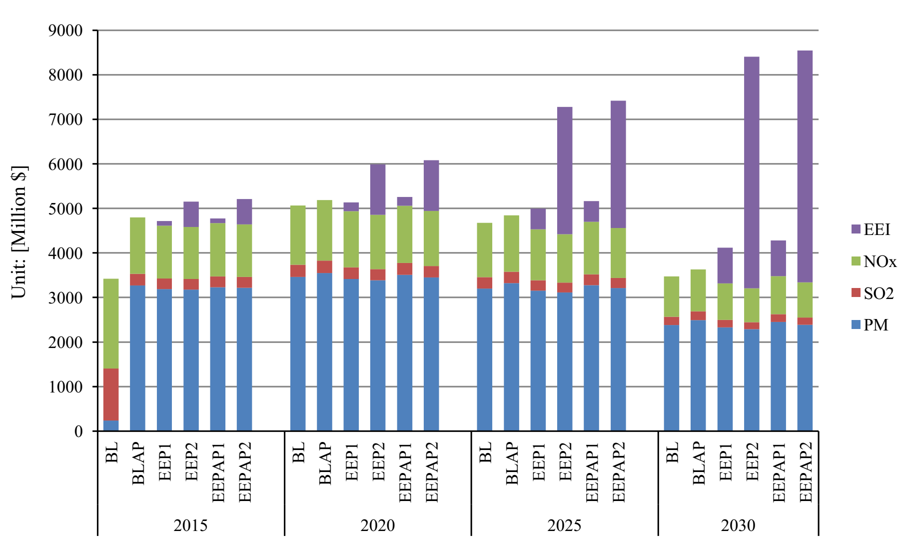

Fig. 17. Future investments for China's cement industry for different category in 2010–2030.

standards [28]. 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.

In summary, our results indicate that there are large potentials for improving energy efficiency and reducing emissions of CO_2 and air pollutants for China's cement industry. According to Fig. 10, most of energy efficiency measures are cost-effective even without considering co-benefits in terms of air pollutant emission reduction. Compared to the BL scenario, the co-effect from 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. The inclusion of co-benefit can decrease the marginal costs to some extent, which means that some not cost-effective measures become economically feasible. Specifically, combined with EEP1 and EEPAP1 scenarios, we found that the average marginal costs will decrease by 20%, from 1.48 \$/GJ to 1.19 \$/GJ[2]. In addition, all end-of-pipe options consume extra electricity, increasing the total costs.

5. Sensitivity and uncertainty analysis

In this section, we begin with discussing the future cement output up to 2030 based on available studies. After that, key factors affecting the results will be discussed, such as CO_2 emission factors, energy price, discount rate, fuel substitutions and different emission factors for air pollutants (includes SO_2 and NOx). Last but not least, the findings from our results will be compared to other studies.

5.1. Future cement activity level

A number of variables (e.g. economic development, urbanization, fixed assets investment, market demand and policy impacts) play a vital role for China's cement industry. The future production of cement and clinker was projected by several studies (LBNL [8], ERI [52,47], and ITIBMI [49] under different assumptions and with large differences in results. Between 2010 and 2030, the maximum cumulative cement output in CSIBM_Higher scenario (59,000 Mt) is 56% higher than the minimum cumulative cement output in LBNL_BIC scenario (26,000 Mt). The cumulative cement output, in our study, is based on the CSIBM_Middle scenario, reaching 49,000 Mt in the period 2010–2030. As an integrated scenario, the assumptions are mainly based on economic development, cumulative cement consumption per capita, and policy impacts. Therefore, the future cement (clinker) output could continue to increase until the urbanization process slows down. Once saturation occurs, the demand of cement would decrease drastically, which means that the production capacity will be higher than cement demand [8].

[2] The results are calculated based on Figs. 10 and 11, Figs. 12 and 13, and Figs. 16 and 17.

5.2. Energy price

The energy price is often determined by fuel type, region, market environment and policy impacts and plays a key role in the size of cost-effective potentials of energy saving and related CO_2 emission reduction. Between 2005 and 2010, the average coal 'purchasing price in China's cement industry increased by a factor of 2, with strong regional differences [18]. As mentioned in Section 3, the future energy price in this study, was assumed to be constant, which is likely to be an underestimate. Hence, three energy price levels of 2.42 \$/GJ, 3.22 \$/GJ, and 4.03 \$/GJ were used to evaluate the sensitivity of the economic potentials. The other drivers are kept the same. As shown in Fig. 21, the lower energy price (2.42 \$/GJ) a has larger impact on the future energy savings potential than a higher energy price (4.03 \$/GJ). Compared to the middle energy price (3.22 \$/GJ), cost-effective energy saving will decrease 50% with a lower energy price, but just increase 7% with the higher energy price. The main reason is that the CCE of replacing vertical shaft kiln with new suspension are close to zero, which means that its cost-effectiveness is very sensitive to the energy price. The energy price has a higher effect on the future cost-effective potential of CO_2 emission reduction than on the energy saving potential, which might be due to the options of blended cement and alternative fuels contribute more CO_2 emissions than energy savings (see Figs. 18 and 19). The cost-effective CO_2 emission reduction would shift from 213 Mt to 320 Mt by using different energy prices. Note that the ranking of energy efficiency measures remains unchanged and 10 additional energy efficiency measures will become cost-effective when the energy price increases. Last year, the central government amended the air pollutant emission reduction standard and drafted a series of policies to solve air pollution issues which could promote plants to use energy efficiency measures or end-of-pipe options to reach the standards [28]. If the co-benefits for emissions reduction of CO_2 and air pollutants are considered, the cost-effective energy saving potentials would increase.

5.3. Discount rate

Various discount rates are widely used to estimate costs and benefits of energy efficiency improvement and emissions reduction, depending upon the aims of the research (the perspective considered) and the methodology used. For example, end users typically prefer to use a high discount rate (i.e. 30%) when making investment decisions due to higher risk uncertainty. In contrast, policy makers and energy modelers often choose lower (social) discount rates (i.e. 4%) to evaluate long-term issues [72]. Considering barriers and risks of energy efficiency measures (e.g. lack of information and capital constraints), a sensitivity analysis is conducted for a discount rate of 4% which reflects the policy-makers perspectives to estimate how the cost-effective energy saving potentials and CO_2 emission reduction potentials would be influenced under a lower discount rate. A 30% discount rate is employed to depict the end user perspective. As shown in Figs. 20 and 21, the discount rate has a larger influence on the cost-effective potentials of energy saving and CO_2 emission reduction than the energy price does, 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. For example, the ordering of heat recovery for power generation, efficient transport system, high pressure roller press for ball mill pregrinding, and raw mill process control for vertical mill all change with different discount rates. The cost-effectiveness of CO_2 emission reduction would shift from 182 Mt to 320 Mt when employing different discount rates.

Fig. 18. Annual final energy saving potential for different energy prices between 2010 and 2030.

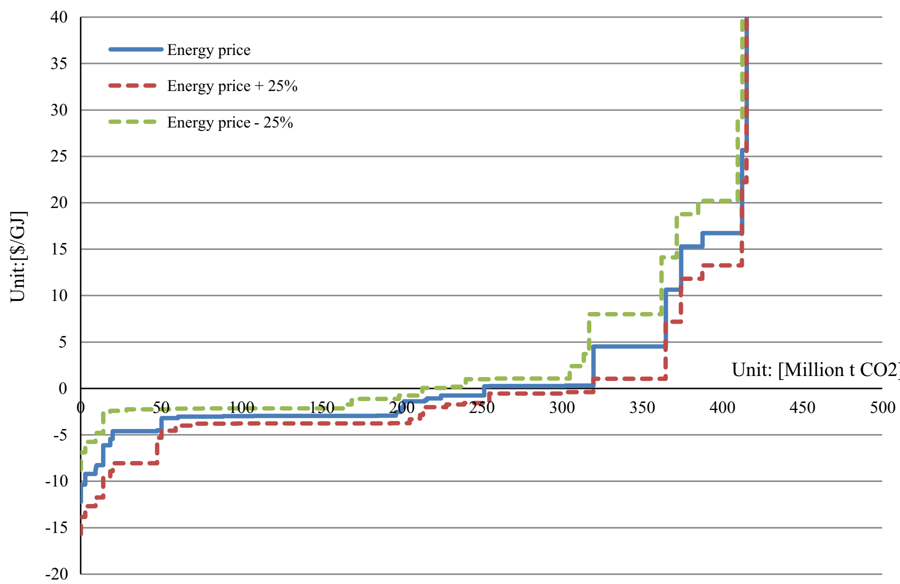

Fig. 19. The future CO_2 emission reduction potential under different energy prices in 2010–2030.

5.4. Fuel substitution

Utilization of alternative fuels (i.e. biomass, chemical waste, petroleum-based fuels, and miscellaneous fuels) to replace conventional fuels is widely used in the cement industry, which can often reduce greenhouse gas emissions. Note that if not handled appropriately, the chemical and hazardous waste might increase the emissions of dioxin and POPs depending on the characteristics of the alternative fuels [73]. Although China's cement industry has a rapid growth in the last decade, the share of alternatives fuels in total energy use is much lower compared to developed countries, due to barriers and limitations (the characteristics of alternative fuel vary, technical challenges) still existing [7]. Several studies indicate that the share of alternatives fuels (including biomass, tyres, chemical and hazardous) in total energy use would increase from 2.33% in 2010 to 20% by 2050. However, alternatives fuels would have lower impacts on CO_2 emission reduction in comparison to energy efficiency measures [11,7]. If we assume that the share of alternative fuels in total energy use could increase by 25% in 2030 [74], total emissions of CO_2 would only decrease by 9% in EEP1 scenario. Considering the complex characteristics of alternative fuels, especially for chemical and hazardous waste, they may or may not reduce air pollutants and could increase the concentration of volatile metals if the government/plant managers cannot handle it appropriately.

5.5. CO_2 emission factors

In general, CO_2 emissions originate not only from fuel combustion and electricity consumption but also depend on the raw material used in cement making. Therefore, the CO_2 emissions per tonne of cement are heavily influenced by various factors, such as characteristics of raw material, types of kiln systems used, clinker to cement ratio, fuel mix, and emission factors for electricity production [26,75]. Detailed estimation of the CO_2 emissions in the Chinese cement industry, from several studies, shows large differences, because each study has its own data sources (i.e. different emission factors) and methods [8,15]. According to our survey (see Table 5), Chinese researchers, LBNL and CSI often employed higher calcination CO_2 emission factors than IPCC, with an average

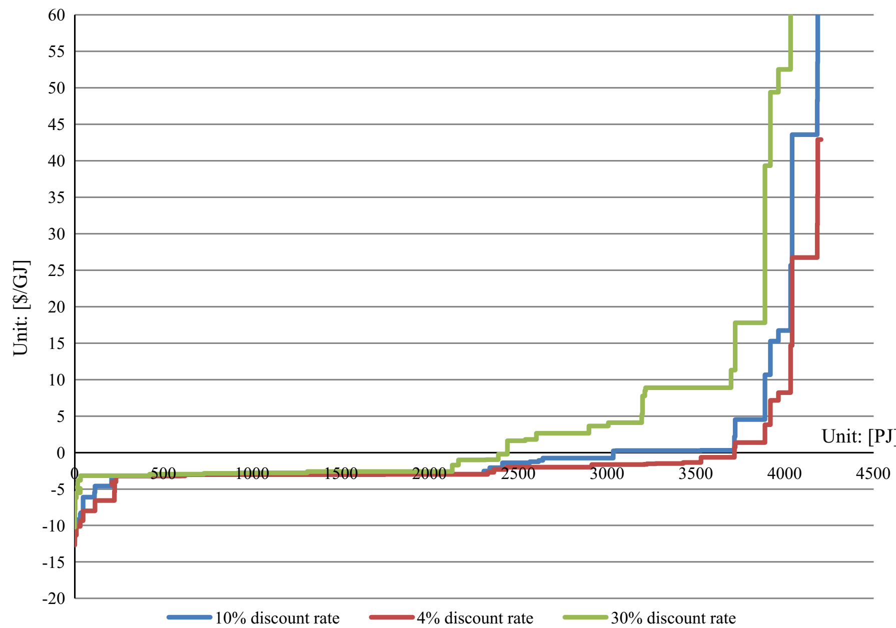

Fig. 20. Annual final energy saving potential for different discount rate between 2010 and 2030.

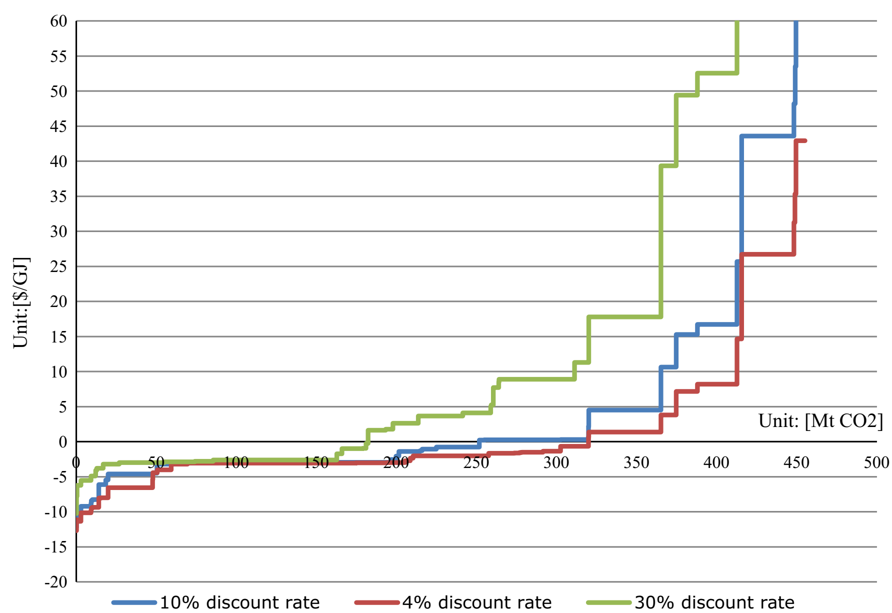

Fig. 21. The future CO_2 emission reduction potential under different discount rate in 2010–2030.

difference of 7% [76,77,71,7]. The main reason is that the emission factor from IPCC tier 2 could be underestimated because CO_2 emissions from decomposition of magnesium carbonates are neglected by IPCC. The highest CO_2 emissions based on Wang for cement-based, for example, would be 25% higher than that of the lowest, based on G. Habert for clinker-based [78,79]. However, total CO_2 emissions from domestic studies usually are lower than those from international studies, which might be due to the following reasons: (1) a higher clinker to cement ratio is used by global studies than domestic studies; (2) the domestic studies hardly consider indirect CO_2 emissions from electricity consumption [12]. In China, the indirect CO_2 emissions from electricity consumption are varying because of different local electricity mix. The average CO_2 emission factor in Shandong province (0.924 kg CO_2/kW h) would be more than 300% higher than Sichuan province (0.289 kg CO_2/kW h).

5.6. Emission factors for air pollutants

The emission of air pollutants (i.e., SO_2, PM, NOx) from the cement industry mainly comes from fuels and raw materials in the cement making process. This depends on operating temperatures, kiln system types, oxygen concentrations, and alkaline conditions [67,80]. The rotary kilns often lead to less air pollutant emissions than shaft kilns. It is also verified that the growth rate of air pollutant emissions in the Chinese cement industry was lower than that of cement output during the last decade. Taking into account the impacts of above factors on air pollutant emissions, several studies assume that it is impossible to split the process and combustion air pollutant emissions from cement production. Therefore, the EMEP/EEA emission inventory guidebook treats these pollutants as just from combustion and does

Table 5
Process CO_2 emission factors for cement.

		2005	2006	2007	2008	2009	2010	2011	Reference
IPCC tier 2	PR_emission factor (kg CO_2/t clinker)	520	520	520	–	–	–	510	[10]
CSI clinker based (our study)	PR_emission factor (kg CO_2/t clinker)	547	547	547	–	540	–	525	[83,77,61]
Yang clinker based	PR_emission factor (kg CO_2/t clinker)	528	–	–	–	–	–	531	[15]
Dai clinker based	PR_emission factor (kg CO_2/t clinker)	545	545	545	545	545	545	–	[52,47]
G. Habert clinker based	PR_emission factor (kg CO_2/t clinker)	–	–	–	–	–	478–398	–	[78]
Wang cement based	PR_emission factor (kg CO_2/t cement)	425	425	425	425	–	–	–	[94]
Xu clinker based	PR_emission factor (kg CO_2/t clinker)	–	547	–	–	–	547	–	[7]
Jing clinker based	PR_emission factor (kg CO_2/t clinker)	547	547	547	547	547	–	–	[8]
Li clinker based	PR_emission factor (kg CO_2/t clinker)							532.3	[71]

not consider process emissions [64]. In contrast, the GAINS assumes that the air pollutants in the cement industry are from the process and neglects the emissions that are produced by fuel use and electricity consumption [68], the main reason is that the GAINS model assumes that emissions of air pollutants are weekly related to fuel consumption, depending mostly on combustion temperature and add-on control equipment (De-NOx, De-SO_2, de-dusters)[3]. The process removal efficiency for SO_2 and NOx, in our study, would reach 50% (of the total processes emissions) [70]. Hence, three-process removal efficiency for SO_2 and NOx levels of 25%, 50% and 70% were used to evaluate their influence on emissions reduction of SO_2 and NOx. The results show that if the process removal efficiency for SO_2 and NOx shifts from 25% to 75%, the emissions of SO_2 and NOx would reduce to 50% and 26% respectively [4]. It means that the process impacts for reducing SO_2 are higher than for reducing NOx, that is why higher sulfur content in waste (e.g., used tyres) can be used as alternative fuels.

5.7. Comparison of our findings with existing studies

Several studies have been conducted in the past few years, to measure the potentials of energy efficiency improvement and emissions mitigation in the China's cement industry. Although these studies differ partly in their research questions and scope to ours, they act as useful comparisons anyway. The energy saving potential, in our study, is estimated to be 9.5 EJ and 15.4 EJ from an economic and technical perspective, respectively. Due to the following reasons, the results from our study is 50% higher than those of Hasanbeigi's but similar with those of Ke's in the CIS scenario [8,10]. First, different cement output is employed to estimate future energy saving potentials, which is the most direct factor leading to different results. Second, our study not only considers best commercial energy efficiency measures but also looks into more detail (e.g. possible implementation rate and potential implementation rate) at future assumptions than Hasanbeigi's study. Third, the other assumptions (e.g., discount rate and energy price) also have large impacts on results. Besides, others parameters, such as emission factors of fuel, electricity grid, and process, all heavily influence the future CO_2 emissions. We also note that our estimates for future CO_2 emissions are lower than international studies, due to some higher parameters (e.g. the higher clinker to cement ratio, CO_2 emission intensity from electricity consumption) often used in the international studies, which do not fit the real situation for China's cement industry [12]. Domestic studies often neglect indirect CO_2 emissions from electricity consumed in the making cement process, which lead to total CO_2 emissions higher than domestic studies. Because some parameters (e.g. clinker to cement ratio, CO_2 emission factors from fuel, raw material, and electricity) are calibrated in our study, the CO_2 emissions would be more reasonable in comparison to recent studies. Although several studies estimated co-benefits of energy efficiency measures or mitigation technologies through energy conservation supply curve (ECSC) or marginal abatement cost curve (MACC), there are still several sources of uncertainties in quantifying the co-benefits as monetized valuation, especially monetizing the health impacts from air pollution. Therefore, we use control costs to estimate these co-benefits rather than a monetary value of health impacts.

6. 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 calibrated historical data (e.g. emissions of CO_2 and air pollutants). We found that the cement output from China increased by 11.5 times, from 210 Mt in 1990 to 2420 Mt 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. Scenario analysis results clearly show that there are large co-benefits of improving energy efficiency and reducing GHGs and air pollutants in the Chinese cement industry. 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 4.2 EJ 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

[3] Personal communication with Janusz Cofala, Mitigation of Air Pollution and Greenhouse Gases (MAG), International Institute for Applied Systems Analysis (IIASA).

[4] The results are based on EEP1 scenario for our study.

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.

Acknowledgments

The work was supported by the China Scholarship Council under Grant Number: 201207040022. The authors gratefully acknowledge Janusz Cofala and Fabian Wagner from The International Institute for Applied Systems Analysis (IIASA) for their valuable inputs to this study. We extend our gratitude to the valuable comments of the anonymous reviewers. All remaining errors remain the sole responsibility of the authors.

Appendix A

Energy efficiency measures for China's cement industry

Energy efficiency measures	Fuel saving (GJ/t-cl)	Electricity saving (kW h/t-cl)	Emission reduction (kg CO_2/t-cl)	Capital cost ($/t-cl)	Change in annual O&M cost ($/t-cl)	Life time	Current implementation rate in 2010	Possible implementation rate in 2030	Potential implementation rate in 2030
Fuel and raw material preparation									
Raw mill process control for vertical mill		1.41	1.45	1.49	0.08	20	5%	20%	9%
Raw mill process control for roller mill		10.00	13.22	2.42	0.08	20	5%	20%	11%
High efficiency classifiers		5.08	5.23	2.85	0.00	20	35%	55%	24%
High efficiency roller mills		10.17	10.45	7.12	0.00	20	54%	40%	23%
Efficient transport system for mine		0.79	1.08	0.16	0,00	25	17%	40%	23%
Optimize mine exploitation	−0.01		1.65	0.02	0.01	40	2%	25%	25%
High-efficiency roller mill for raw mill and coal grinding		1.47	1.51	1.33	0.00	20	55%	45%	26%
Slag powder production	0.06		0.36	2.06		20	10%	40%	1%
High efficiency drying for slag	0.29		25.32	1.27		20	45%	55%	2%
Raw mill blending (homogenizing) systems		2.66	2.73	4.79	0.00	20	18%	37%	37%
New efficient coal separator		0.26	0.27	0.01	0.00	20	29%	22%	13%
Installation of variable frequency drive and replacement of coal mill bag dust collector's fan		0.16	0.16	0.03	0.00	10	33%	22%	22%
High efficiency fan for raw mill vent fan with inverter		0.36	0.37	0.04	0.00	10	69%	25%	25%

Appendix A (*continued*)

Energy efficiency measures	Fuel saving (GJ/t-cl)	Electricity saving (kW h/t-cl)	Emission reduction (kg CO_2/t-cl)	Capital cost ($/t-cl)	Change in annual O&M cost ($/t-cl)	Life time	Current implementation rate in 2010	Possible implementation rate in 2030	Potential implementation rate in 2030
VFD in raw mill vent fan		0.33	0.34	0.02	0.00	10	64%	25%	12%
Bucket elevators for raw meal transport		2.35	2.42	0.19	0.00	20	17%	40%	17%
Clinker making									
Adjustable speed drive for kiln fan		2.40	2.05	0.40	0.04	10	15%	25%	25%
Upgrading to a preheater/precalciner kiln	0.43		40.68	18.80	−1.18	40	19%	37%	21%
Upgrade clinker cooler	0.11	−2.00	8.35	0.21	0.08	30	9%	25%	25%
Low temperature heat recovery for power generation		35.00	31.66	9.08	0.89	20	65%	35%	20%
Increasing number of preheater stages (from 5 to 6) in rotary kilns	0.11	−1.17	9.30	2.10	0.02	30	13%	50%	29%
Heat recovery for power generation		22.00	5.10	3.40	0.08	20	70%	22%	13%
Combustion system improvements	0.03	0.00	0.72	0.17	0.01	30	5%	60%	34%
Low pressure drop cyclones for suspension preheater		2.60	2.67	4.32	0.00	30	1%	0%	0%
Energy management and process control	0.15	2.35	16.61	2.36	0.00	10	1%	20%	11%
VFD in cooler fan of grate cooler		0.11	0.11	0.01	0.00	10	5%	55%	25%
Kiln shell heat loss reduction (improved refractories)	0.26	0.00	24.60	0.21	0.00	5	15%	22%	13%
Conversion to grate cooler	0.60	−0.01	16.37	0.45	0.10	30	4%	20%	11%
Optimize grate cooler	0.09	0.00	2.16	0.45	0.10	30	63%	22%	10%
Older dry kiln upgrade to multi-stage preheater kiln	0.11	−1.17	23.00	34.50		40	13%	50%	22%
Replacing vertical shaft kilns with new suspension	2.00	0.00	62.00	34.50		40	90%	0%	0%
Finish grinding									
High-efficiency classifiers		6.10	6.27	4.07	0.00	20	33%	38%	38%

(*continued on next page*)

Appendix A (*continued*)

Energy efficiency measures	Fuel saving (GJ/t-cl)	Electricity saving (kW h/t-cl)	Emission reduction (kg CO_2/t-cl)	Capital cost ($/t-cl)	Change in annual O&M cost ($/t-cl)	Life time	Current implementation rate in 2010	Possible implementation rate in 2030	Potential implementation rate in 2030
High pressure roller press for ball mill pregrinding		10.00	8.53	1.61	0.08	20	20%	65%	46%
General measures									
Energy management and process control	0.40	0.02	9.91	0.04	0.00	10	47%	37%	21%
High efficiency motors		4.58	4.70	0.38	0.00	10	48%	22%	22%
Adjustable speed drives		2.50	2.43	0.25	0.00	10	22%	25%	25%
Product and feed stock change	Fuel saving (GJ/t-cem)	Electricity saving(KW h/t-cem)	Emission reduction (kg CO_2/t-cem)	Capital cost ($/t-cem)	Change in annual O&M cost ($/t-cem)	Lifetime			
Blended cement	1.77	−7.21	160.02	0.60	−0.03	30	38%	13%	7%
Alternative fuels	Fuel saving (GJ/t-cem)	Electricity saving (kW h/t-cem)	Emission reduction (kg CO_2/t-cem)	Capital cost ($/t-cem)	Change in annual O&M cost ($/t-cem)	Lifetime			
Biomass and waste	0.60	0.00	56.76	1.10	0.00	30	4%	22%	22%

Source: 1. The descriptions of these 37 measures can be found at [3,10,11,14,15,52,33,34,51,54,81,82]; the negative value for electricity saving indicates that although the application of this measure saves fuel, it will increase electricity consumption. However, it should be noted that the total primary energy savings of these measures is positive.

Appendix B

B.1. The activity level of PM control technologies

Activity	Sector	Technology	Unit	Abated emission factor	2005 (%)	2010 (%)	2015 (%)	2020 (%)	2025 (%)	2030 (%)
DC	IN_OC	IN_CYC	[kt PM/PJ]	0.08	30	16	6	1	0	0
DC	IN_OC	IN_ESP1	[kt PM/PJ]	0.01	70	84	84	84	84	79
DC	IN_OC	IN_ESP2	[kt PM/PJ]	0.00	0	0	10	15	16	21
DC	IN_OC	IN_HED	[kt PM/PJ]	0.00	0	0	0	0	0	0
HC3	IN_OC	IN_ESP1	[kt PM/PJ]	0.25	100	100	90	85	80	75
HC3	IN_OC	IN_ESP2	[kt PM/PJ]	0.03	0	0	10	15	20	25
HC3	IN_OC	IN_HED	[kt PM/PJ]	0.01	0	0	0	0	0	0
MD	IN_OC	GHIND	[kt PM/PJ]	0.01	100	100	100	100	100	100
NOF	PR_CEM	PR_CYC	[kt PM/Mt]	33.28	5	0	0	0	0	0
NOF	PR_CEM	PR_ESP1	[kt PM/Mt]	5.46	28	0	0	0	0	0
NOF	PR_CEM	PR_ESP2	[kt PM/Mt]	1.32	67	90	80	75	70	65
NOF	PR_CEM	PR_HED	[kt PM/Mt]	0.28	0	10	20	25	30	35
NOF	PR_CEM	PR_WSCRB	[kt PM/Mt]	17.08	0	0	0	0	0	0
Fugitive emission	PR_CEM	PR_FU	[kt PM/Mt]	0.14	100	100	100	100	100	100

Source: the end-of-pipe options are from the GAINS database and defined based on WEO 2012 baseline in GAINS; the detailed information for these measures can be found at http://gains.iiasa.ac.at/models/index.html.

B.2. The activity level of SO_2 control technologies

Activity	Sector	Technology	Unit	Abated emission factor	2005 (%)	2010 (%)	2015 (%)	2020 (%)	2025 (%)	2030 (%)
HC3	INOC	IWFGD	[kt SO_2/PJ]	0.01	43	47	47	48	48	49
HC3	INOC	LINJ	[kt SO_2/PJ]	0.02	18	19	19	19	19	19
HC3	INOC	LSCO	[kt SO_2/PJ]	0.02	4	4	4	4	4	4
HC3	INOC	NOC	[kt SO_2/PJ]	0.06	35	31	30	29	28	28
MD	INOC	LSMD1	[kt SO_2/PJ]	0.01	35	47	47	48	48	49
MD	INOC	LSMD2	[kt SO_2/PJ]	0.00	18	19	19	19	20	20
MD	INOC	NOC	[kt SO_2/PJ]	0.01	47	34	33	33	32	31
OS2	INOC	IWFGD	[kt SO_2/PJ]	0.00	35	47	47	48	48	49
OS2	INOC	LINJ	[kt SO_2/PJ]	0.01	18	19	19	19	20	20
OS2	INOC	NOC	[kt SO_2/PJ]	0.03	47	34	33	33	32	31
PR_CEM	NOF	SO2PR1	[kt SO_2/Mt]	0.00	0	0	0	0	0	0
PR_CEM	NOF	SO2PR2	[kt SO_2/Mt]	0.00	0	0	0	0	0	0
PR_CEM	NOF	SO2PR3	[kt SO_2/Mt]	0.00	0	0	0	0	0	0
PR_CEM	NOF	NOC	[kt SO_2/Mt]	−0.03	100	100	100	100	100	100

B.3. The activity level of NOx control technologies

Activity	Sector	Technology	Unit	Abated emission factor	2005 (%)	2010 (%)	2015 (%)	2020 (%)	2025 (%)	2030 (%)
DC	INOC	NOC	[Kt NOx/PJ]	0.19	100	100	100	100	100	100
HC3	INOC	ISFCM	[Kt NOx/PJ]	0.27	10	5	6	6	6	6
HC3	INOC	ISFCSC	[Kt NOx/PJ]	0.11	24	12	13	13	14	15
HC3	INOC	ISFCSN	[Kt NOx/PJ]	0.16	15	9	9	9	10	10
HC3	INOC	NOC	[Kt NOx/PJ]	0.53	51	74	73	72	70	69
MD	INOC	IOGCM	[Kt NOx/PJ]	0.09	45	26	27	28	30	31
MD	INOC	NOC	[Kt NOx/PJ]	0.17	55	74	73	72	70	69
OS2	INOC	ISFCM	[Kt NOx/PJ]	0.07	10	5	6	6	6	6
OS2	INOC	ISFCSC	[Kt NOx/PJ]	0.03	24	12	13	13	14	15
OS2	INOC	ISFCSN	[Kt NOx/PJ]	0.04	15	9	9	9	10	10
OS2	NOF	NOC	[Kt NOx/PJ]	0.13	51	74	73	72	70	69
PR_CEM	NOF	NOC	[kt NOx/Mt]	−0.27	100	100	100	100	100	100
PR_CEM	NOF	PRNOX1	[kt NOx/Mt]	−0.27	0	0	0	0	0	0
PR_CEM	NOF	PRNOX2	[kt NOx/Mt]	−0.27	0	0	0	0	0	0
PR_CEM	NOF	PRNOX3	[kt NOx/Mt]	−0.27	0	0	0	0	0	0

References

[1] WBCSD, IEA. Cement technology roadmap 2009-carbon emissions reductions up to 2050; 2010.

[2] Wang Y, Zhu Q, Geng Y. Trajectory and driving factors for GHG emissions in the Chinese cement industry. J Clean Prod 2013;53:252–60.

[3] Hasanbeigi A, Lobscheid A, Lu H, Price L, Dai Y. Quantifying the co-benefits of energy-efficiency policies: a case study of the cement industry in Shandong Province, China. Sci Total Environ 2013;458–460:624–36.

[4] Hendriks CA, Worrell E, De Jager D, Blok K, Riemer P. Emission reduction of greenhouse gases from the cement industry; n.d. p. 1–11.

[5] Benhelal E, Zahedi G, Shamsaei E, Bahadori A. Global strategies and potentials to curb CO_2 emissions in cement industry. J Clean Prod 2013;51:142–61.

[6] Worrell E, Price L, Martin N, Hendriks C, Meida LO. Carbon dioxide emissions from the global cement industry. Annu Rev Energy Environ 2001;26:303–29.

[7] Xu J-H, Fleiter T, Fan Y, Eichhammer W. CO_2 emissions reduction potential in China's cement industry compared to IEA's Cement Technology Roadmap up to 2050. Appl Energy 2014.

[8] Ke J, Zheng N, Fridley D, Price L, Zhou N. Potential energy savings and CO_2 emissions reduction of China's cement industry. Energy Policy 2012;45:739–51.
[9] Liu F, Ross M. Energy efficiency of China's cement industry. Energy 1995:20.
[10] Hasanbeigi A, Morrow W, Masanet E, Sathaye J, Xu T. Energy efficiency improvement and CO_2 emission reduction opportunities in the cement industry in China. Energy Policy 2013;57:287–97.
[11] Wang Y, Höller S, Viebahn P, Hao Z. Integrated assessment of CO_2 reduction technologies in China's cement industry. Int J Greenh Gas Control 2014;20:27–36.
[12] Lei Y, Zhang Q, Nielsen C, He K. An inventory of primary air pollutants and CO_2 emissions from cement production in China, 1990–2020. Atmos Environ 2011;45:147–54.
[13] Yang X, Teng F, Wang G. Incorporating environmental co-benefits into climate policies: a regional study of the cement industry in China. Appl Energy 2013;112:1446–53.
[14] Zhou N, Price L, Zheng N, Ke J. National level co-control study of the targets for energy intensity and sulfur dioxide in China. Lawrence Berkeley Nat Lab 2011. LBNL-5253E.
[15] Xi Y, Fei T, Gehua W. Quantifying co-benefit potentials in the Chinese cement sector during 12th Five Year Plan: an analysis based on marginal abatement cost with monetized environmental effect. J Clean Prod 2013;58:102–11.
[16] CSI. Global cement production 1970–2050; n.d.
[17] NDRC. The guidebook of PM2,5 emission accounting and monitoring in cement industry; 2013.
[18] China Cement Association. China Cement Almanac; n.d.
[19] State council of China. China's policies and actions for addressing climate change; 2011.
[20] China Cement Association. The mid-term evaluation of "Twelfth Five Year Plan" for Chinese cement industry. 2012.
[21] MIIT of China. 12th Five Year Plan for cement industry; 2011.
[22] National Bureau of Statistics of China. China Energy Statistical Yearbook 2011. National Bureau of Statistics of China; 2011.
[23] Soule MH, Logan JS, Stewart Todd A. Trends, challenges, and opportunities in china's cement industry. The World Bus Counc Sustainable Dev 2002.
[24] Xu J-H, Fleiter T, Eichhammer W, Fan Y. Energy consumption and CO_2 emissions in China's cement industry: a perspective from LMDI decomposition analysis. Energy Policy 2012;50:821–32.
[25] Shi Y, Chen L, Liu Z, Yan J, Hu J. Analysis on the carbon emission reduction potential in the cement industry in terms of technology diffusion and structural adjustment: a case study of Chongqing. Energy Proc 2012;16:121–30.
[26] Li-tao L, Yan Z, Lei S, Tian-ming G, Jing-jing X, Feng-nan C. A review of cement production carbon emission factors: progress and prospects. Resour Sci 2014;36:0110-9.
[27] State council of China. "Twelfth Five-Year Plan" on air pollutant prevention and control in key regions; 2012.
[28] MEP of China. MEP announces new emission standards for major industries-efforts to implement the ten major measures against air pollution; 2014.
[29] Jian-mei L, Guo-dong L. Present situation and countermeasures of nitrogen oxides emissions in Chinese cement industry. Appl Chem Ind 2013;42:1687–9.
[30] Qing Z, He Hong-tao. The impacts of technology for new air pollutant emissions standard. China Cem 2013;6:17–22.
[31] Yu L, Ke-bin H, Qiang Z, Zuo-yi L. Technology-based emission inventory of particulate matters from cement industry. Environ Sci 2008;29:2366–71.
[32] Kesicki F, Strachan N. Marginal abatement cost (MAC) curves: confronting theory and practice. Environ Sci Policy 2011;14:1195–204.
[33] Worrell E, Martin N, Price L. Potentials for energy efficiency improvement in the US cement industry. Energy 2000;25:1189–214.
[34] Tsinghua university. Assisting developing country climate negotiators through analysis and dialogue: report of energy saving and CO_2 emission reduction analysis in China cement industry; 2008.
[35] Vine El, Harris Jeffrey p. Evaluating energy and non-energy impacts of energy conservation programs: a supply curve framework of analysis. Energy 1990;15: 11–21.
[36] Kesicki F, Ekins P. Marginal abatement cost curves: a call for caution. Clim Policy 2012;12:219–36.
[37] OECD stat extracts. OECD stat extracts; 2014.
[38] Hasanbeigi A, Menke C, Therdyothin A. The use of conservation supply curves in energy policy and economic analysis: the case study of Thai cement industry. Energy policy 2010;38:392–405.
[39] Cofala J, Purohit P, Rafaj P, Zbigniew Klinmont. GAINS GHG mitigation potentials and costs from energy use and industrial sources in Annex I countries; 2009.
[40] Amann M, Bertok I, Borken-Kleefeld J, Cofala J, Heyes C, Höglund-Isaksson L, et al. Cost-effective control of air quality and greenhouse gases in Europe: modeling and policy applications. Environ Model Softw 2011;26:1489–501.
[41] Markus Amann. The GAINS integrated assessment model; 2012.
[42] Wagner F, Amann M, Borken-Kleefeld J, Cofala J, Höglund-Isaksson L, Purohit P, et al. Sectoral marginal abatement cost curves: implications for mitigation pledges and air pollution co-benefits for Annex I countries. Sustain Sci 2012;7:169–84.
[43] Liu F, Klimont Z, Zhang Q, Cofala J, Zhao L, Huo H, et al. Integrating mitigation of air pollutants and greenhouse gases in Chinese cities: development of GAINS-city model for Beijing. J Clean Prod 2013;58:25–33.
[44] Syri S, Amann M, Capros P, Mantzos L, Cofala J, Klimont Z. Low-CO_2 energy pathways and regional air pollution in Europe. Energy Policy 2001;29:871–84.
[45] National Bureau of Statistics of China. China Statistical Yearbook 2013. National Bureau of Statistics of China; 2013.
[46] Zeng X. Current situation and prospect of China cement industry; 2008.
[47] Dai Yande, Hu X. Potential and cost study on China's carbon mitigation technologies. China Environmental Press; 2013.
[48] Xiang-zhen Ze. The discussion of China's cement demand peak. China Cem 2013;8:17–21.
[49] Wei S, Dong Wang. The forecasting for China's cement output between 2009 and 2050. China Cem Technol Conf 2009:9–26.
[50] Ernst Worrell. Energy efficiency improvement and cost saving opportunities for cement making an ENERGY STAR® guide for energy and plant managers Ernst Worrell and Christina Galitsky Energy Analysis. Department University of California; 2008.
[51] Worrell E, Kermeli K, Christina Galitsky. Energy efficiency improvement and cost saving opportunities for cement making an ENERGY STAR® Guide for Energy and Plant Managers; 2013.
[52] Yande Dai, Huawen X. Roadmap study on achieving technical energy conservation potential in China's industrial sector by 2020. China Science and Technology Press; 2013.
[53] MIIT of China. The assessment of energy saving and emissions reduction in key industries in China; n.d.
[54] China building materials academy. Energy saving center of Sichuan Province. Energy saving potential on technical and economical aspects in cement industry, SiChuan Province; 2010.
[55] Hasanbeigi A, Price L, Lin E. Emerging energy-efficiency and CO_2 emission-reduction technologies for cement and concrete production: a technical review. Renew Sustain Energy Rev 2012;16:6220–38.
[56] Guo-ning Z, Xiang-zhong K, Xiao-qian L, Jiang Mei. Guideline on best available technologies of pollution prevention and control for cement industry. Ministry of Environ Prot China 2012.
[57] MEP of China. Integrated emission standard of air pollutants; 1996.
[58] Ministry of Environmental Protection of (MEP) China. Emission standard of air pollutants for cement; 1996.
[59] MEP of China. Emission standard of air pollutants for cement industry; 2004.
[60] WBSCD. Safety in the cement industry: guidelines for measuring and reporting; 2013.
[61] Pang Cuijuan. Analysis of influence factors and mathematical modeling for the cabron emisssion of cement industry. South China University of Technology; n.d.
[62] Ran-ping S, Jing-jing Z, Ping H, Hong-tao W. An analysis of emission factors for purchased electricity in China; 2013.
[63] NCSC of China. The average carbon dioxide emission factor of power grid in China's regional and provincial level in 2010; 2010.
[64] European Environment Agency. EMEP/EEA air pollutant emission inventory guidebook 2013; 2013.
[65] China Pollution Source Census. Production of industrial pollution discharge coefficient; 2011.
[66] Ya-ming W, Qing-jun H, Yuan Xiu-xia. The research and application of discharge coefficient in cement manufacturing. Annu Conf China Silic Acad 2009.
[67] Miller FM, Young GL, Von Seebach M. Formation and techniques for control of sulfur dioxide and other sulfur compounds in Portland cement kiln systems. Portland Cem Assoc 2001.
[68] Cofala J, Syri S. Sulfur emissions, abatement technologies and related costs for Europe in the RAINS model database; n.d.
[69] International energy agency. Energy efficiency governance handbook. International energy agency; 2010.
[70] Xiaoyan L, Zhijuan H, Xuchu Y, Yu Weimin, Tao Congxi. Removal of SO_2 from process and end of pipe technology in cement industry. Cement 2010:16–8.
[71] Li C, Nie Z, Cui S, Gong X, Wang Z, Meng X. The life cycle inventory study of cement manufacture in China. J Clean Prod 2014;72:204–11.
[72] Hasanbeigi A, Menke C, Price L. The CO_2 abatement cost curve for the Thailand cement industry. J Clean Prod 2010;18:1509–18.
[73] Murray A. Use of alternative fuels in cement manufacture: analysis of fuel characteristics and feasibility for use in the chinese cement sector. Lawrence Berkeley Nat Lab 2008. LBNL-525E.
[74] Wang Xinchun. Review of alternative Fuel in cement industry in some developed countries and suggestion for China's cement industry. Cem Ind 2010:151–4.
[75] Matthes FC. Pilot on benchmarking in the EU ETS report prepared for the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety and the 2008.
[76] IPCC. Chapter 10 industry; 2014, vol. 10.
[77] CSI. CO_2 and energy accounting and reporting standard for the cement industry: the cement CO_2 and energy protocol; 2011.
[78] Habert G, Billard C, Rossi P, Chen C, Roussel N. Cement production technology improvement compared to factor 4 objectives. Cem Concr Res 2010;40:820–6.
[79] Ke J, McNeil M, Price L, Khanna NZ, Zhou N. Estimation of CO_2 emissions from China's cement production: methodologies and uncertainties. Energy Policy 2013;57:172–81.
[80] Wesselink B, Melle T van, Klaus S, Smit A, Marc van Gent. The ETS paradox; 2010.
[81] Madlool Na, Saidur R, Rahim Na, Kamalisarvestani M. An overview of energy savings measures for cement industries. Renew Sustain Energy Rev 2013;19: 18–29.
[82] Madlool Na, Saidur R, Hossain MS, Rahim Na. A critical review on energy use and savings in the cement industries. Renew Sustain Energy Rev 2011;15: 2042–60.

[83] CSI. Development of state of the art-techniques in cement manufacturing: trying to look ahead; 2009.
[84] Cui-mei M, Shi-cheng L, Quan-sheng G. Greenhouse gas emission factors for grid electricity for Chinese Provinces. Resour Sci 2014:1005–12.
[85] Wen-fu D, De-qian F, Tai-peng W. Study on the situation of pollution emissions reduction of the cement in the 11th FYP of China. Environ Prot Sci 2009;3:1–3.
[86] Xin-miao D, Ya-ming W, Xue-fei Y, Qing-jun H, Xiu-xia Y, Ling-xiu W, et al. Emissions of atmospheric pollutants and treatment of China's cement industry. China Cem Forum Environ Resour 2011:73–6.
[87] Chang-ming G. Discussion of nitrogen oxides and denitrification efforts for China's cement industry emissions. Guideb Denitrif Cem Ind; n.d. p. 3–4.
[88] Chen Man-xiang. The target of NOx emission in cement industry. Resour Econ Environ Prot 2014:1.
[89] Hua-wen X, Zu-yu Z, Yao-xing X, Xian-zhi D. The impact of structural adjustment to reduce energy consumption in cement industry. China Build Mater 2004;8:23–7.
[90] Ke J, Zheng N, Fridley D, Price L, Zhou N. Potential energy savings and CO_2 emissions reduction of China's Cement Industry. Energy Policy 2012;45:739–51.
[91] Wang S. Improving energy efficiency. China Cem Ind 2010:2006–10.
[92] Yan-de D, Quan B. Overview of China's energy conservation progress (2006–2010). China economic publishing house; 2012.
[93] Zeng X, Wei-min Y, Zhi-juan H, Cong-xi T, Ji-kai L, Xing-teng C, et al. The overview of energy efficiency benchmarking in cement industry. Cement 2009;6:1–10.
[94] Hasanbeigi A, Price L, Lu H, Lan W. Analysis of energy-efficiency opportunities for the cement industry in Shandong Province, China: a case study of 16 cement plants. Energy 2010;35:3461–73.