Applied Energy 155 (2015) 35–58

Contents lists available at ScienceDirect

Applied Energy

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

Mapping and modeling multiple benefits of energy efficiency and emission mitigation in China's cement industry at the provincial level

Shaohui Zhang *, Ernst Worrell, Wina Crijns-Graus

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

HIGHLIGHTS

- Provincial disparities in energy use and emissions are quantified for China's cement industry.
- We describe emission mitigation impacts on EEMs with integrated assessment model.
- We quantify the multiple benefits potential in China's cement industry on provincial level.
- Energy efficiency would lead to huge reductions in air pollution in all provinces.
- We discuss uncertainty in relation to distribution of energy saving and emission reduction.

ARTICLE INFO

Article history:
Received 8 April 2015
Received in revised form 12 May 2015
Accepted 29 May 2015
Available online 14 June 2015

Keywords:
China's cement industry
Energy efficiency
Multiple benefits
Integrated model
Provincial disparities

ABSTRACT

China's cement industry is the second largest energy consumer and key emitter of CO_2 and air pollutants. It accounts for 7% of total energy consumption in China and 15% of CO_2, 21% of PM, 4% SO_2 and 10% of NOx of total emissions, respectively. Provincial disparities in energy consumption and emissions of CO_2 and air pollutants in China's cement industry are rarely quantified. In this study, an integrated assessment model including provincial energy conservation supply curves (ECSC) (which can shows the cost-effective and technical energy saving potential per province), the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model (which can be used to calculate air pollutant emissions), and ArcGIS (a geographical information system (GIS) with elaborated spatial functions) is developed and used to assess the potential of energy savings in terms of emission mitigation of CO_2 and air pollutants and multiple benefits of energy efficiency measures at the provincial level during the period 2011–2030. The results show significant heterogeneity across provinces in terms of potential of energy saving as well as emission mitigation of CO_2 and air pollutants (i.e. PM, SO_2, and NOx) in the next two decades. Seven provinces (i.e. Shandong, Sichuan, Jiangsu, Guangdong, Zhejiang, Henan, Hebei), six of which are located in the central- and east-China, account for 47% of the total energy saving potential, equivalent to 26% of baseline energy use in 2030. The energy efficiency measures can help decrease 38% of CO_2, 23% of SO_2, 33% of NOx, and 26% of PM emissions in these seven provinces by 2030. This indicates that the multiple benefits should be considered when local policy makers or end users make decisions whether to use energy efficiency measures to solve environmental issues.

1. Introduction

China's cement industry is the second largest energy consumer and CO_2 emitter (after the iron and steel industry), accounting for 7% of total Chinese energy use and 15% of total CO_2 emissions [1,2]. In China, the cement industry has been identified as a key emitter of air pollutants and environmental impacts, such as the share in emissions of PM, SO_2 and NOx, which account for 15–27%, 3–4%, and 8–12%, respectively of the country's total emissions [3,4]. Therefore, the estimation of the trends of future energy use and emissions of both CO_2 and local air pollutants from China's cement industry has attracted worldwide attention.

Several approaches have been used to assess the possibilities of potentials for energy savings and emission mitigation, and to trace the impacts for key characteristics of China's cement industry, such as the future outputs of cement and clinker [5,6], rates of efficiency

---

* 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.2015.05.104
0306-2619/

Nomenclature

ECSC	energy conservation supply curves
GAINS	greenhouse gas and air pollution interactions and synergies
BL scenario	baseline scenario
EEPCP	energy efficiency policy with cost effective energy saving potential scenario
EEPTP	energy efficiency policy with technical energy saving potential scenario
SO_2	sulfur dioxide
NOx	nitrogen oxides
PM	particulate matter
WHR	waste heat recovery
Mt	million tons
kt	k tonne
NSP kilns	new suspension preheater/precalciner kilns
AEEI	annual autonomous energy efficiency improvement
IP	international price
NP	national price
PP	provincial price
CCPC	cement consumption per capita
OECD	the organisation for economic co-operation and development
WEO	world energy outlook
IEA	international energy agency
LBNL	Lawrence Berkeley national laboratory
ERI	energy research institute of China
MIIT	ministry of industry and information technology of China
CSI	cement sustainability initiative

Symbols

$POP_{i,n}$	future population in province i in year n (i = 2015, 2020, 2025, and 2030)
$POP_{i,2010}$	population in province i in 2010 from China statistical yearbook
$POP_{n}^{NL\_GAINS}$	future population in China in year n from GAINS database
$POP_{2010}^{NL\_CHN}$	China's population in 2010 from China statistical yearbook
$CC_{i,n}$	future cement consumption in province i in year n
I_b	the building cement material intensity, 0.2215 t_cement per square meter of building units
$U_{i,n}$	urbanization in province i in year n
$U_{i,2010}$	urbanization in province i in 2010
$FP_{i,n}$	average floor area per capita in province i in year n
$FP_{i,2010}$	average floor area per capita in province i in 2010
CP_{n}^{NL}	future cement production on national level in year n
$CP_{i,n}$	future cement production in province i in year n
EC_{n}^{NL}	exports cement on national level in year n
CP_{2010}^{NL}	cement production on national level in 2010
EC_{2010}^{NL}	exports cement on national level in 2010
IC_{2010}^{NL}	imports cement on national level in 2010
IC_{n}^{NL}	imports cement on national level in year n
$CLP_{i,n}$	future clinker production in province i in year n
$CLP_{i,2010}$	clinker production in province i in 2010
$CP_{i,2010}$	cement production in province i in 2010

Subscript

i, n	province, year, respectively

improvement [1,7], cost of energy efficiency measures [6], substitution of fuels and clinker [8]. Energy Conservation Supply Curves (ECSC) has been widely accepted as a standard tool in policy analysis to capture the cost effectiveness and technical potential for energy saving and CO_2 emission reduction in cement industry at both national and local levels [9–11]. Furthermore, several studies conducted on air pollutant emissions in China's cement industry found that it is urgently necessary to quantify the pollutants generated by cement production, assess their impacts, and the cost effectiveness potential for air quality improvement [2,3,12].

Efforts to quantify co-benefit or multiple benefits (non-energy benefits) of energy efficiency measures and emission mitigation have been fewer than those attempted to analyze them separately. In principle, multiple benefits analysis integrates energy saving with emission reduction of CO_2 and local air pollutants (i.e. PM, SO_2 and NOx) on other benefits [13–15]. A variety of co-benefits of energy efficiency measures in terms of reducing air pollution have been analyzed in-depth for all sectors on an inter/national level and with a main focus on the iron and steel and cement sector in developed countries [14,16–18]. Only few studies are based on ECSC or/and combined with other models to assess co-benefits in China's cement industry on a national level [19,20]. However, the distribution of multiple benefits potentials in China's cement industry on a local level is still missing. Only several studies are available which consider the impacts of energy efficiency [21,22], the impacts of carbon tax and financial incentives on CO_2 reduction [23,24], the environmental efficiency of energy utilization, CO_2 emissions and environmental regulation [25], air pollution control and performance [26], the key for energy conservation across regions in China [27]. However, within above studies the multiple benefits issue in the cement sector at a regional level has not yet been assessed. Considering the regional heterogeneity across China, the studies mentioned above can be ambiguous when policy makers and programme managers want to understand potentials on a provincial level. The purpose of this paper is to fill this gap by assessing the multiple benefits of energy efficiency measures in terms of emission reduction of CO_2 and local air pollutants on a regional level in China's cement industry.

First, historical trends of the cement industry are presented on a regional level. Next, we give a deeper assessment of the base year's (2010) distribution of outputs of cement and clinker, energy consumption and emissions of CO_2 and air pollutants, as well as of intensities of energy use, CO_2, and air pollutant emissions on a provincial level. They provides a detailed background for quantifying the cost effective potentials of energy saving and emission mitigation with and without co-benefits. The methodology includes approach, data sources, key assumptions, and scenario design in Section 3. Section 4 discusses the results for energy savings potential and emission mitigation of CO_2 and air pollutants for different scenarios on a provincial level. In Section 5, a sensitivity & uncertainty analysis is done for key drivers. Finally, conclusions and recommendations are given in Section 6.

2. Historical trends of cement industry in each region of China: production, energy consumption and emissions

In this section, the provincial distribution dynamics of the outputs of cement and clinker and fixed assets investment are first

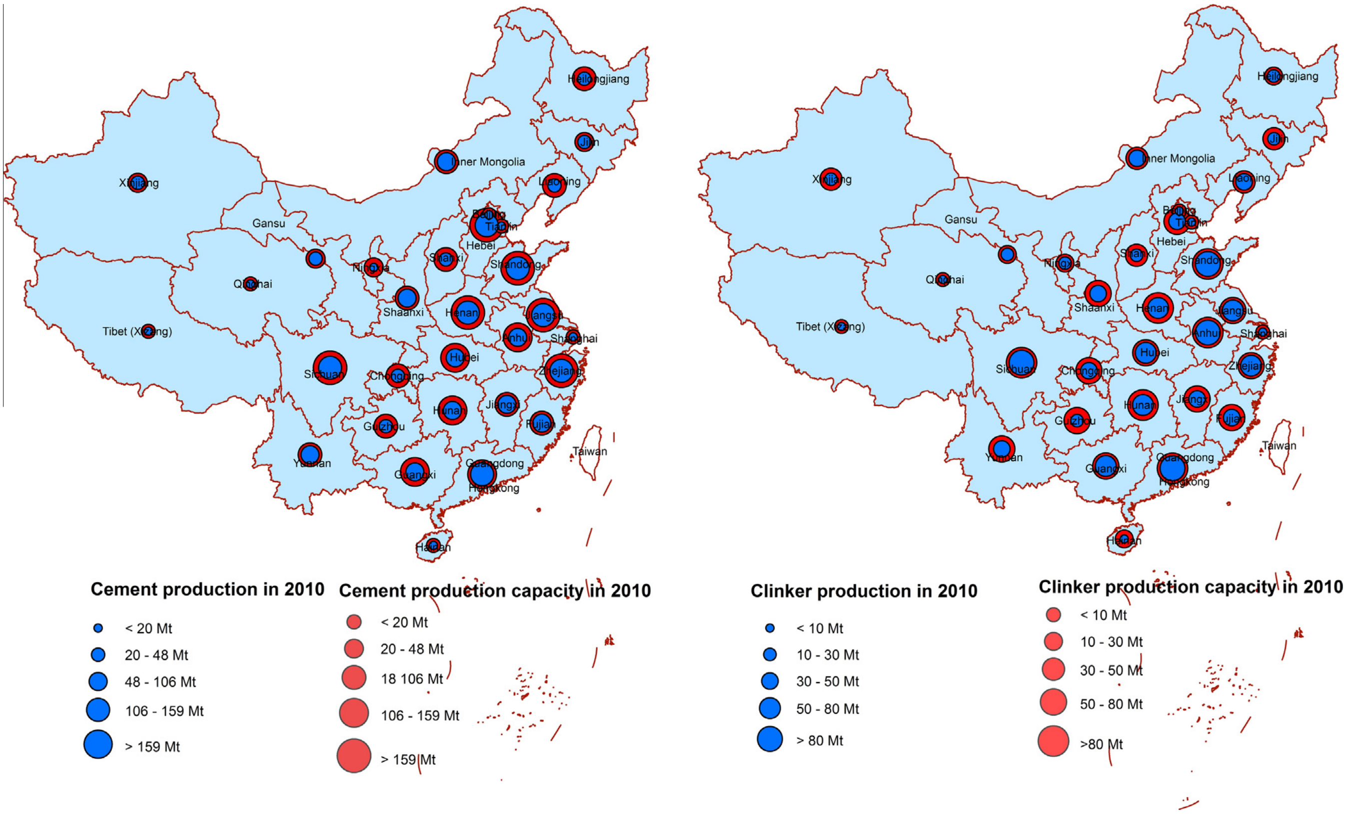

Fig. 1. The distribution of cement and clinker production (left) and its production capacity (right) in 2010.

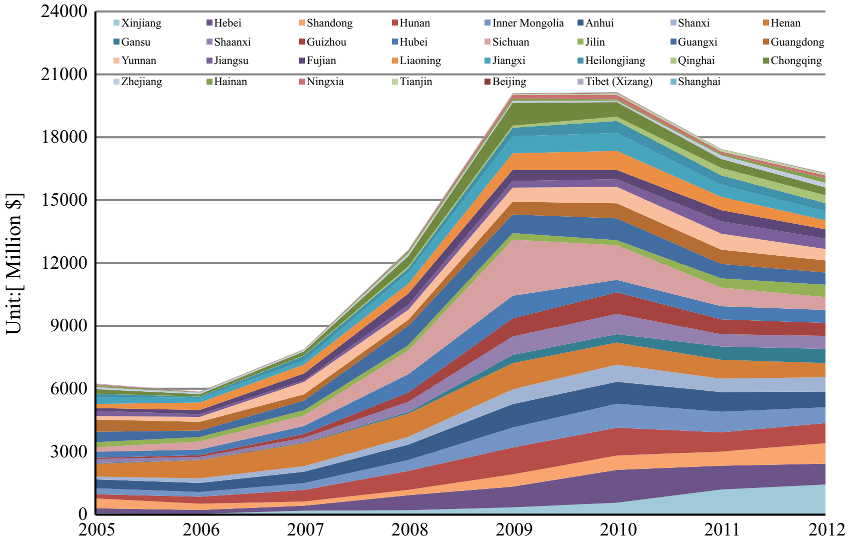

Fig. 2. Capital investment in cement industry between 2005 and 2012. *Source:* Primary data from [28,34] calculations by authors.

presented. Second, the trends of historical energy use among different provinces are investigated. Finally, the emission trends of CO_2 and air pollutants are evaluated.

2.1. Historical output of cement and clinker in cement industry in each region

The distribution trends of cement and clinker production in each province are presented in Fig. 1 and Appendix A-1. Nationally, the cement output increased drastically from 1069 Mt in 2005 to 2213 Mt in 2012, at an average rate of 11% per year [28]. The provinces of Shandong, Zhejiang, Jiangsu, Guangdong, Henan, and Hebei contributed up to 52% of the total national cement production in 2005 and 41% in 2010, and are mainly located in the east and southeast of China. The main reason of this decrease is that some local authorities like Zhejiang and Guangdong began to control the blind expansion of the cement industry and closed some of the obsolete vertical shaft kilns while the developing provinces showed faster development [29]. The cement production in two megacities (Beijing, Shanghai) also declined during the period, due to natural resource limitations and urbanization. Provinces located in western regions, such as

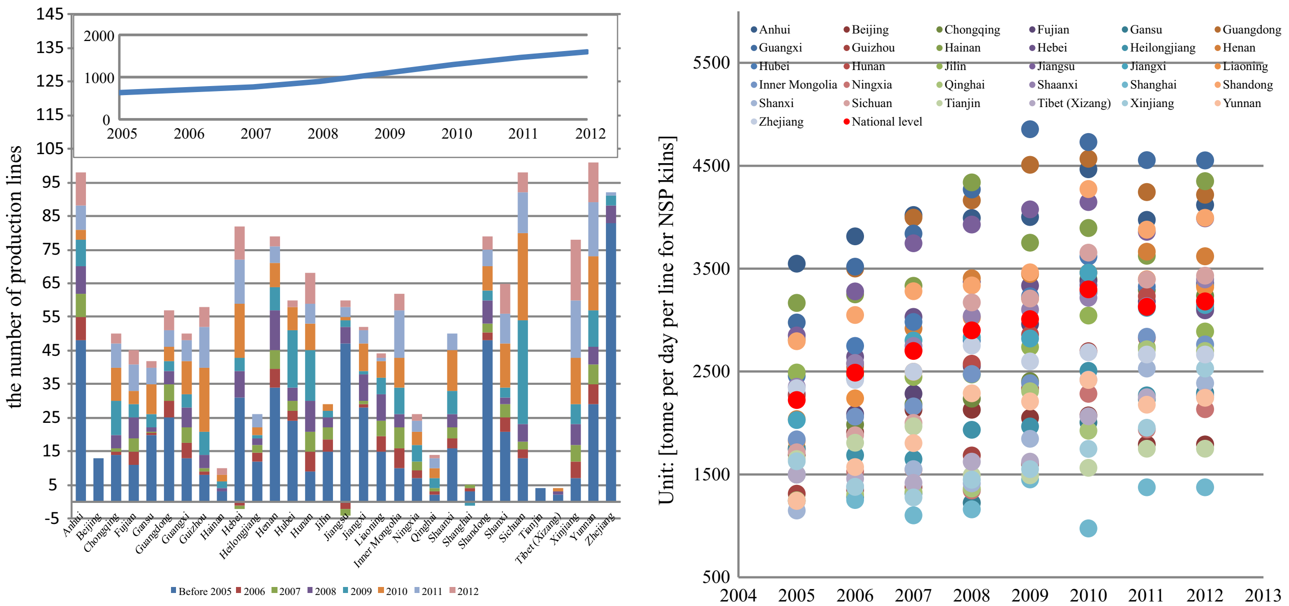

Fig. 3. The number of production line for NSP kilns (left) and the average clinker production capacity of NSP kilns. *Source:* 1. Primary data from [28] calculations by authors. 2. The negative data for some provinces represent the production line for NSP kilns were closed by government.

Xinjiang, Xizang, Qinghai, Ningxia, and Guizhou, typically have lower cement production which might be due to the fact that these regions have lower GDP per capita and resource endowments. The growth rates of different provinces vary strongly. The average annual growth rate of cement production in dominant cement production provinces (i.e. Zhejiang, Shandong, Guangdong) is half compared to the national level (11%) (see Appendix A-1). The cement production in lower income provinces, such as Anhui, Inner Mongolia, Fujian, Shaanxi, Shanxi, Sichuan, Gansu, Guangxi, Xinjiang, Xizang, Qinghai, Ningxia, and Guizhou shows a higher growth rate than the national level. Overall, developed areas (i.e. Beijing, Shanghai, Tianjin, Zhejiang, and Guangdong) are more inclined to import cement from near developing regions (i.e. Hebei and Jiangsu). Both local governments and cement enterprises in developing regions still prefer supporting investments in energy intensive projects (including the expansion of the cement industry) to stimulate local economy development.

The trends are similar for clinker production in the provinces. The clinker production increased rapidly from 765 Mt in 2005 to 1342 Mt in 2012, with an average annual growth rate of 11% in the whole country. Six provinces (i.e. Anhui, Shandong, Guangdong, Jiangsu, Zhejiang, and Sichuan) accounted for 48% of the country's clinker production in 2005 and 40% in 2010. Five of these provinces are located in the southeast coastal regions of China. The share of clinker production from Shandong, Guangdong, Zhejiang provinces declined half during that period.

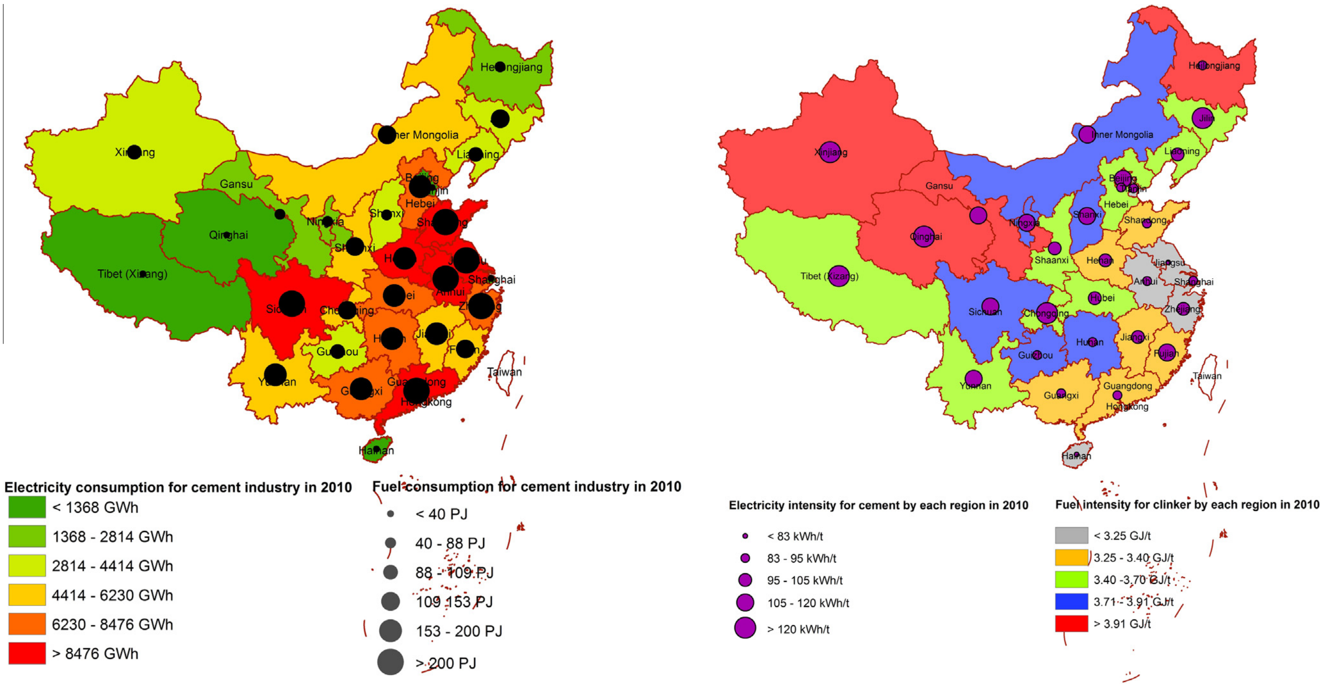

Fig. 4. The distribution of energy consumption and energy intensity for cement industry in 2010.

The central regions of China (Hebei, Henan, Hubei, Hunan, and Guangxi) contributed to 23% of clinker production while the developed regions like Beijing, Shanghai, Tianjin and the tourist-heavy Hainan had a lower contribution than western regions. Note that the share of clinker production in developed regions was lower than the contribution of cement production during the same period which might be due to that these regions imported clinker from nearby developing regions. For example, Jiangsu province, as the largest cement producing region imported 50 Mt clinker per year from Shandong and Anhui provinces in the last three years, while Anhui exported around 60 Mt clinker per year to e.g. Jiangsu, Zhejiang and Shanghai [30].

Cement production capacity utilization rate is usually above 80% worldwide [31]. In China, Previous massive capacity expansion has resulted in the average production capacity utilization rate of cement and clinker being 77% and 71% in 2010, respectively. As shown in Fig. 1, the average production capacity utilization rates were unequal among different provinces. Liaoning has the lowest cement production capacity utilization rate of 57%, followed by Shanxi (58%) and Henan (62%) versus 99% and 84% in Hainan and Beijing. Shanghai's cement production capacity utilization rate was 74% in 2010, although the clinker production capacity utilization rate was only 37% at the same time because 91% clinker was imported from other provinces.

The capital investment in cement industry in the provinces between 2005 and 2012 is plotted in Fig. 2. The capital investment increased steadily from 6 Billion $ in 2005 to 20 Billion $ in 2010 and then decreased to 16 Billion $ in 2012. Note that the rapid growth of capital investment of all provinces from 2008 to 2009 was accelerated by Chinese government's economic stimulus plan

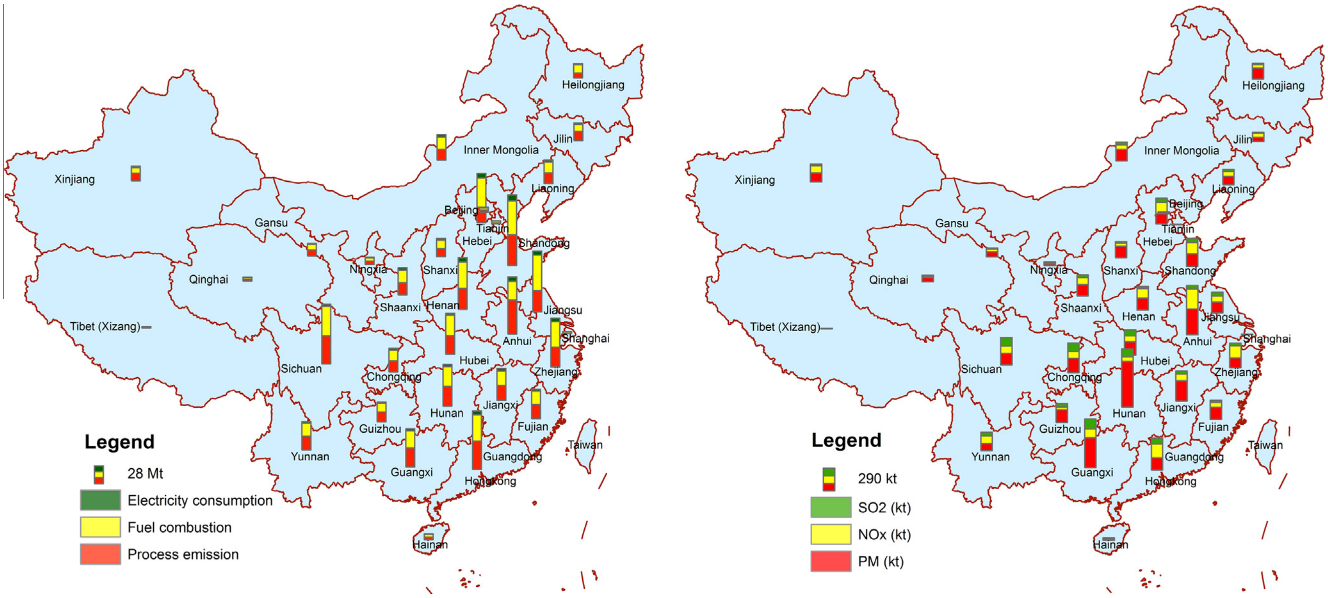

Fig. 5. The distribution of emissions of CO_2 (left) and air pollutants (right) in 2010.

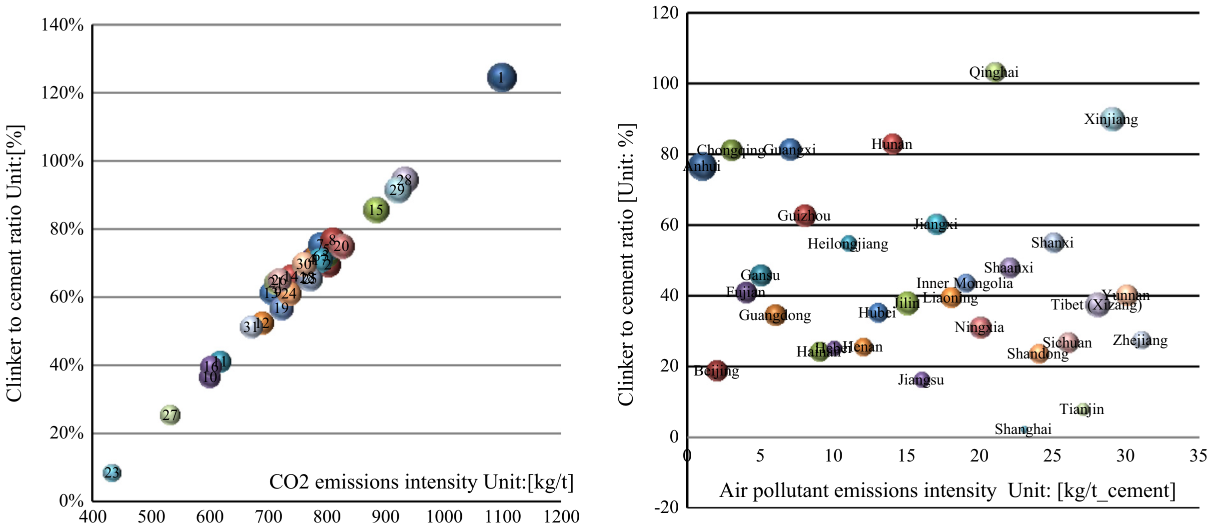

Fig. 6. The relations between clinker to cement ratio and emissions intensity of CO_2 (left) and air pollutants in 2010. Note: 1 – Anhui; 2 – Beijing; 3 – Chongqing; 4 – Fujian; 5 – Gansu; 6 – Guangdong; 7 – Guangxi; 8 – Guizhou; 9 – Hainan; 10 – Hebei; 11 – Heilongjiang; 12 – Henan; 13 – Hubei; 14 – Hunan; 15 – Jilin; 16 – Jiangsu; 17 – Jiangxi; 18 – Liaoning; 19 – Inner Mongolia; 20 – Ningxia; 21 – Qinghai; 22 – Shaanxi; 23 – Shanghai; 24 – Shandong; 25 – Shanxi; 26 – Sichuan; 27 – Tianjin; 28 – Tibet (Xizang); 29 – Xinjiang; 30 – Yunnan; 31 – Zhejiang.

for 2008–2010 [32,33]. Although the spatial distribution of capital investment varied, provinces have exhibited the same trends with different growth rates. In 2005, Henan has the highest share of total capital investment of 10%, followed by Guangdong, Guangxi, Shandong, and Anhui with 7–9%, respectively. However, the share of capital investment of these provinces together has decreased from 41% in 2005 to 22% in 2012. Developed regions (i.e. Beijing, Shanghai, Tianjin, and Guangdong) and the lowest income regions like Qinghai, Ningxia, and Heilongjiang have the lowest share in total capital investment. This indicates that the capital investment was used to retrofit existing plant in developed regions and to build new small and medium-sized (2500–4000 t/d) cement plants in developing regions. In spite of the slight increase of capital investment, the cement outputs have gradually declined in Beijing and Shanghai, and increased sharply in developing regions, especially in western areas.

Parallel to the rapid growth of fixed asset investment, the number of production lines for NSP kilns (an efficient type of cement kilns) and the average production capacity of NSP kilns increased significantly (see Fig. 3). As shown in Fig. 3 (blue line of left Fig. 3), the number of NSP production lines surged from 615 in 2005 to 1599 in 2012, which resulted in the average clinker production capacity from NSP kilns increasing from 2223 t/d per line in 2005 to 3182 in 2012. However, there are differences among the provinces. Before 2005, Zhejiang ranked among the highest share of the number of NSP kilns, estimated to have 13% of the total number of NSP kilns, followed by eastern regions (i.e. Shandong, Jiangsu, and Anhui) with 8%, respectively. At the same time, the

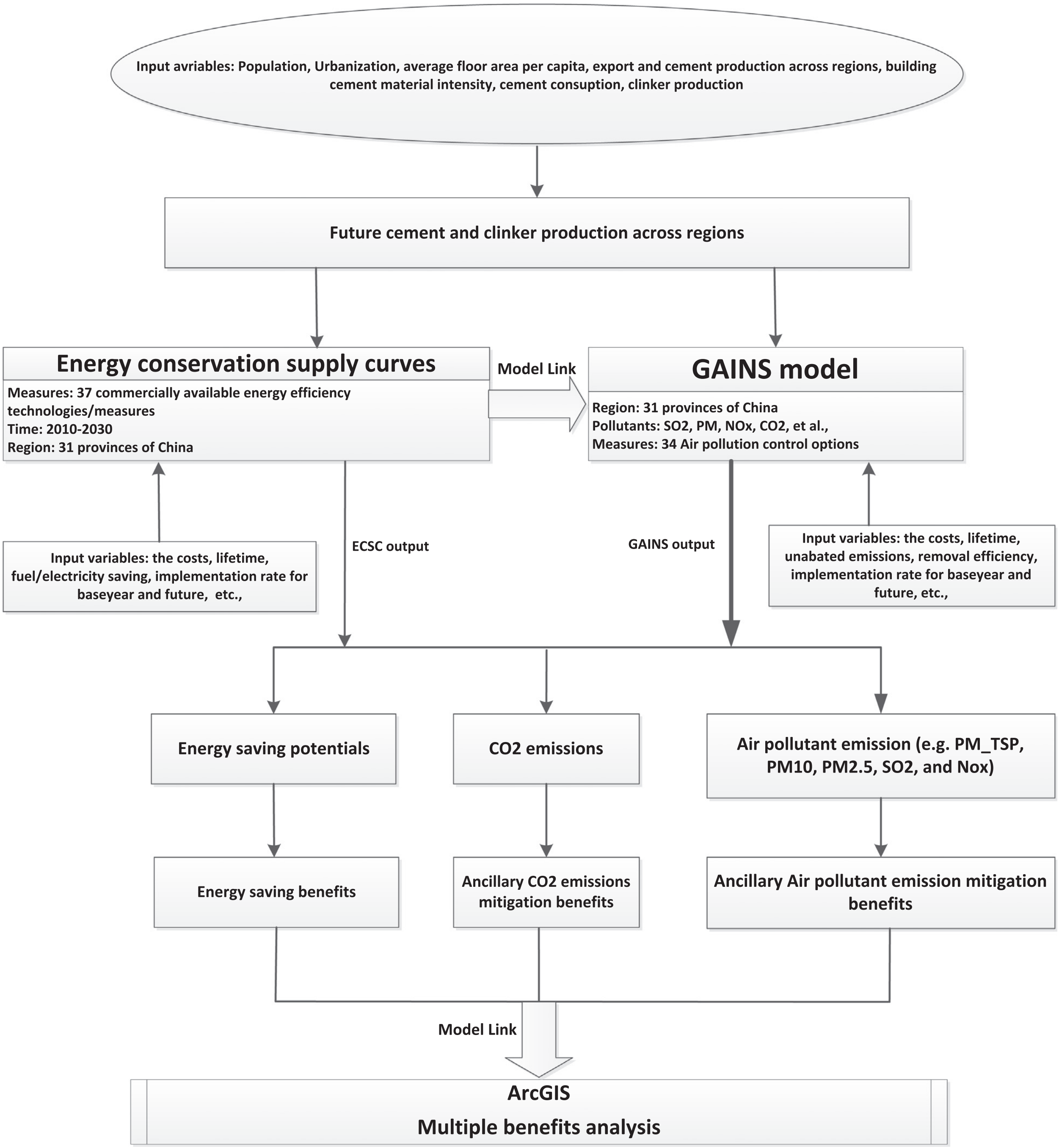

Fig. 7. The multiple benefits assessment by combing ECSC, GAINS model and ArcGIS.

Table 1
Cement and clinker production by each region between 2005 and 2030. Unit: [Mt].

Region	Cement production						Clinker production					
	2005	2010	2015	2020	2025	2030	2005	2010	2015	2020	2025	2030
Anhui	34	81	94	90	73	52	51	101	117	112	92	64
Beijing	12	10	12	12	10	7	8	7	8	8	7	5
Chongqing	22	46	54	52	42	30	18	33	39	37	30	21
Fujian	28	59	69	66	54	38	23	42	49	47	38	27
Gansu	14	24	28	27	22	16	12	18	21	20	16	12
Guangdong	82	116	135	130	106	74	64	84	97	94	76	54
Guangxi	33	75	87	84	68	48	27	57	66	63	52	36
Guizhou	17	38	44	43	35	24	14	29	34	33	27	19
Hainan	4	13	15	14	12	8	3	8	9	9	7	5
Hebei	77	128	148	142	116	82	42	47	54	52	43	30
Heilongjiang	12	36	42	40	33	23	9	15	17	16	13	9
Henan	65	117	135	130	106	75	44	61	71	68	56	39
Hubei	45	90	104	100	82	58	24	55	64	62	50	35
Hunan	37	88	102	98	80	57	27	58	68	65	53	37
Jilin	17	31	36	34	28	20	15	26	31	29	24	17
Jiangsu	97	157	182	175	143	101	55	62	72	69	57	40
Jiangxi	37	63	73	70	57	40	25	44	51	50	40	28
Liaoning	27	48	55	53	44	31	17	32	37	35	29	20
Inner Mongolia	16	55	63	61	50	35	12	31	36	35	28	20
Ningxia	6	14	16	16	13	9	5	11	12	12	10	7
Qinghai	4	8	9	9	7	5	2	5	6	6	5	3
Shaanxi	22	55	64	61	50	35	17	36	42	40	33	23
Shanghai	10	7	8	7	6	4	4	1	1	1	1	0
Shandong	144	149	173	166	136	96	98	91	106	102	83	58
Shanxi	23	37	43	41	33	24	15	24	28	27	22	15
Sichuan	45	129	149	144	117	83	33	84	97	94	76	54
Tianjin	5	8	10	9	8	5	2	2	2	2	2	1
Tibet (Xizang)	1	2	3	2	2	1	1	2	2	2	2	1
Xinjiang	12	25	29	28	22	16	9	23	26	25	21	15
Yunnan	28	58	67	65	53	37	22	40	47	45	37	26
Zhejiang	91	113	131	126	103	73	66	58	67	65	53	37
Nation level	1069	1879	2178	2096	1711	1205	765	1188	1377	1325	1082	762

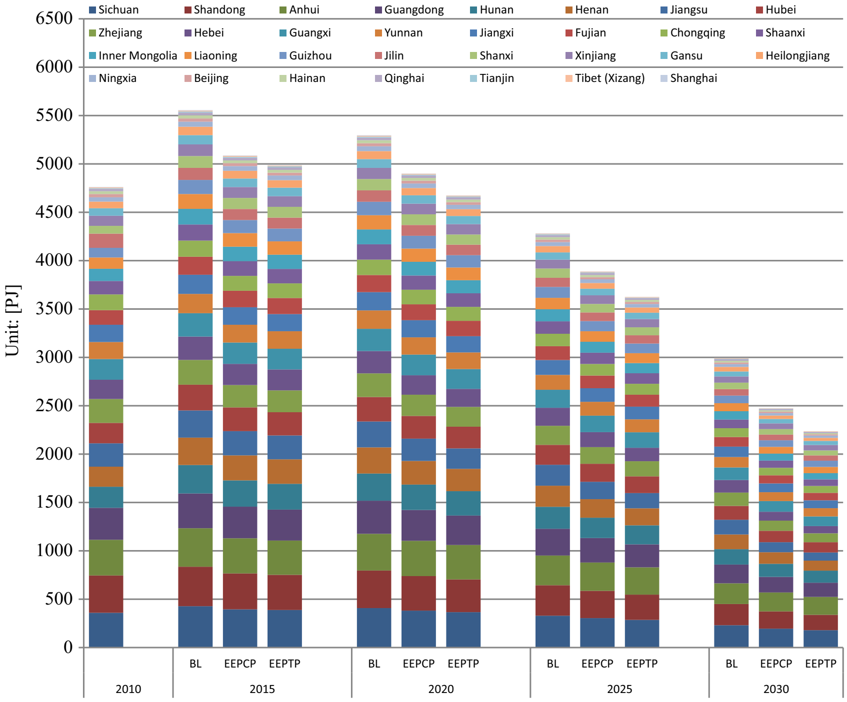

Fig. 8. Energy consumption for cement industry for different scenarios in 2010–2030.

average clinker production capacity per production line of these regions was higher than that the national average. Between 2005 and 2012, the newly NSP kilns widely expanded in all provinces except Megacities (i.e. Beijing, Shanghai, Tianjin), and resulted in the average clinker production capacity in east and central regions being higher than Megacities, north and western regions (i.e. Inner

Mongolia, Heilongjiang, Xinjiang, and Yunnan). The main reason is that the east and central regions prefer to build larger scale production lines (above 6000 t/d) and the other provinces construct small and medium-sized (2500–4000 t/d) cement plants.

2.2. Historical energy use of the cement industry

The energy consumption of China's cement industry has grown rapidly. The total energy consumption of China's cement industry increased by 50%, from 3433 PJ in 2005 to 5299 PJ in 2011 and 5195 PJ in 2012 (see Appendix A-2) [28,35]. This was mainly caused by the closure of 370 Mt cement production capacity during 2011–2012 [31]. Between 2005 and 2012, the energy consumption from megacities and southeastern regions of Guangdong, Zhejiang, Shandong remained unchanged, while the four provinces of Hebei, Henan, Hubei, and Jiangsu increased slowly. In contrast, energy consumption doubled in Anhui and Sichuan, from 201 PJ and 156 PJ in 2005 to 417 PJ and 322 PJ in 2012, respectively. 11 lower income provinces (i.e. Gansu, Guangxi, Guizhou, Xinjiang, and Qinghai) also increased more doubled and might continue to grow. As shown in Fig. 4, the energy consumption and energy intensity diffuse widely among different provinces, related to the production of clinker and cement output and energy intensity. Shandong, Anhui and Sichuan ranked among the highest contributors to total energy consumption of China's cement industry, estimated to be 8% per province, followed by Guangdong with 7%. The fuel intensity for clinker production was lower than 3.25 GJ/t in the five coastal regions (Tianjin, Jiangsu, Anhui, Zhejiang, Shanghai), followed by Shandong, Henan, Guangdong, with 3.25–3.40 GJ/t. In 2010, energy efficiency of over 85% of installed capacity lags behind international best practice [36].

2.3. Historical CO_2 emission of the cement industry

CO_2 emissions from China's cement industry have increased by 72% over the past 7 years, from 930 Mt in 2005 to 1386 Mt in 2010 and 1597 Mt in 2012. The key factors were rapid growth of cement production and changes in fuel combustion and electricity

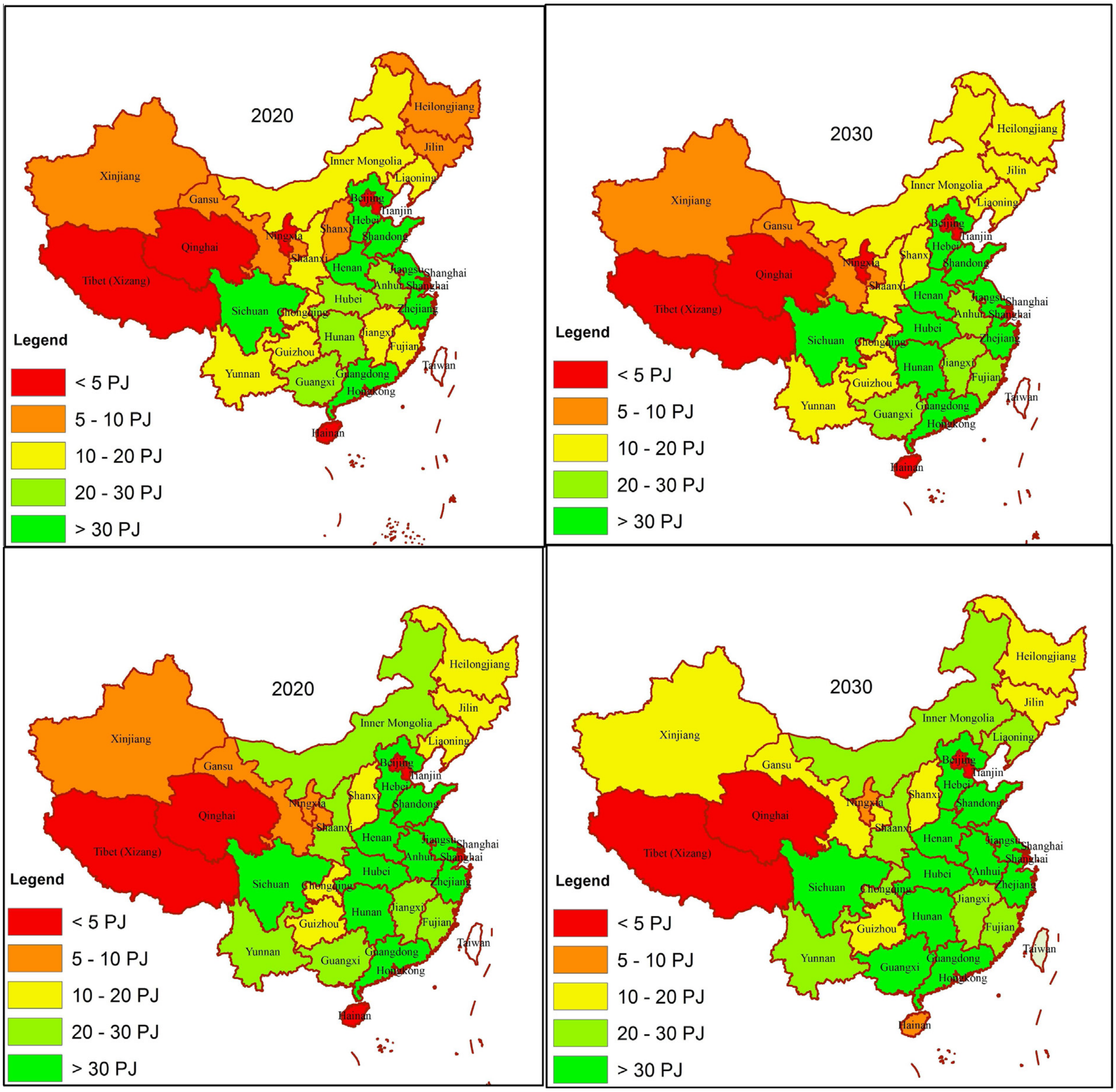

Fig. 9. Energy saving potential in cement industry in 2020 and 2030. Note: The top two figures represent cost-effective energy saving potential under EEPCP scenario, and the down two figures represent technical energy saving potential in EEPTP scenario.

consumption (see Appendix A-3) [28,35]. As shown in Fig. 5 (left), CO_2 emissions in the cement industry differ widely per province. Similar to the distribution of energy consumption, Shandong province, as the largest CO_2 emitter, accounts for 8% of total emissions in China's cement industry, followed by Sichuan, Guangdong, Jiangsu with 7%, respectively. Both megacities and western regions had a lower contribution to CO_2 emissions compared to middle regions. Because Anhui is the main clinker-exporting province, the contribution to total emissions from process (8%) was higher than that from fuel combustion (4%) and electricity consumption (7%). In contrast, the contribution to total emissions from electricity consumption was relatively low because the electricity generation in this province was dominated by hydropower.

In 2010, the clinker to cement ratio was 60% while the CO_2 intensity in cement production was 740 kg CO_2/t cement. Fig. 6 (left) illustrates the relations between clinker to cement ratio and CO_2 intensity for the provinces. Most of the bubbles have a good linear relationship, while the sizes of the bubbles show the gains of the reduction of regional CO_2 intensity. CO_2 intensity of 21 provinces varied in the range of 700–800 kg/t_cement. The process emission contributed more to the total emissions than energy consumption did in most regions. For example, for Anhui, as the largest clinker exporter, the CO_2 intensity (1097 kg/t_cement) was 49% higher than the national level, while Shanghai and Tianjin had a lower CO_2 intensity because these two Megacities had a lower clinker to cement ratio.

2.4. Historical air pollutant emissions of the cement industry

The trend of air pollutant emissions has been influenced by the output of cement and clinker, energy consumption, and end-of-pipe. China's cement industry contributed up to 15–30% of PM emission, 3–4% of SO_2 emission, and 8–10% of NOx emission throughout the country [4,37]. Nationally, the overall air pollutant emissions in China's cement industry decreased sharply before 2009 but rose rapidly during 2009–2010 (see Appendix A-4) [35]. The main reason was that the air pollution standards (2004) for cement were fully implemented for all cement plants at first but then offset by the fast growth of cement production. As shown in Fig. 5 (right), air pollutant emissions in the cement industry show large variations among provinces. Regions located in east and south of China contributed most to the air pollutant emissions. Hunan, Guangxi, and Anhui were the top three emitters of air pollutants, each of which had above 6000 kt and together contributed 25% to total emissions. The next four largest contributors were Guangdong, Jiangxi, Chongqing, and Shandong, accounting for 5%, respectively. Fig. 6 (right) shows the relations between clinker to cement ratio and air pollutant emissions intensity across provinces. The size of the bubbles represents the gains of the reduction of regional air pollution emissions intensity. Unlike the CO_2 trend, most of the bubbles have irregular relations, mainly due to different emission standards being used in the provinces. The air pollutant emissions intensity of 18 provinces varied in the range of 25 and 60 kg/t_cement, while four western provinces had the highest emission intensity over 80 kg/t_cement.

3. Methodology

This section explains the methodology to assess the potential of multiple benefits between energy saving and emission mitigation of CO_2 and air pollutants through implementation of commercially available energy efficiency measures for China's cement industry. We first introduce the multiple benefits approach and then explain in detail the data sources used and key assumptions made to construct several scenarios.

3.1. The multiple benefits approach

The term "multiple benefits" or "co-benefits" has been increasingly addressed in several issues such as energy efficiency, climate change, air pollution, and human health [16–18]. The multiple benefits can significantly change the outcomes of direct cost-benefit

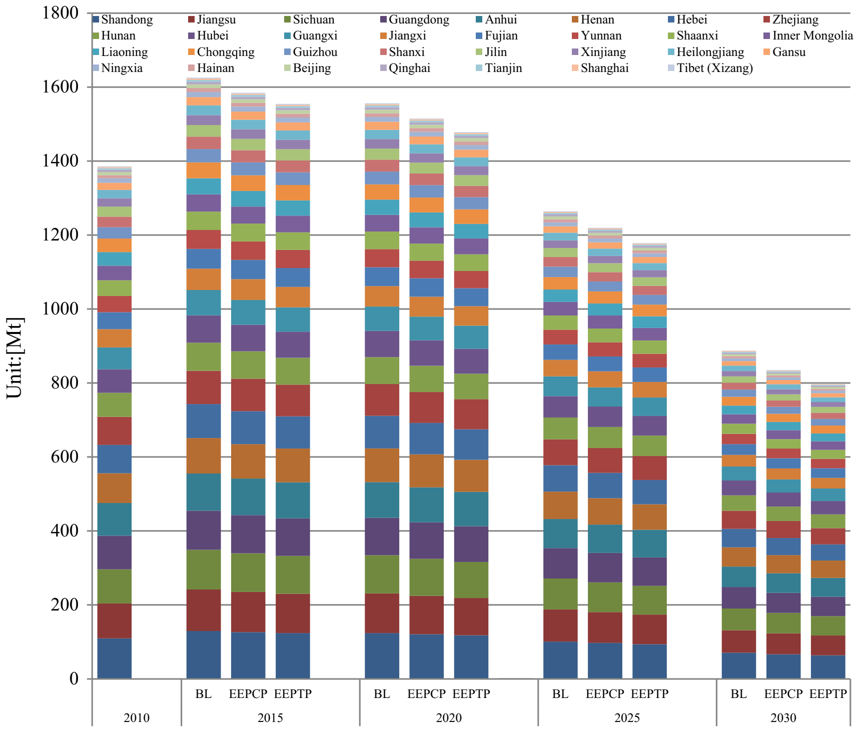

Fig. 10. CO_2 emissions for cement industry between 2015 and 2030 for different scenarios.

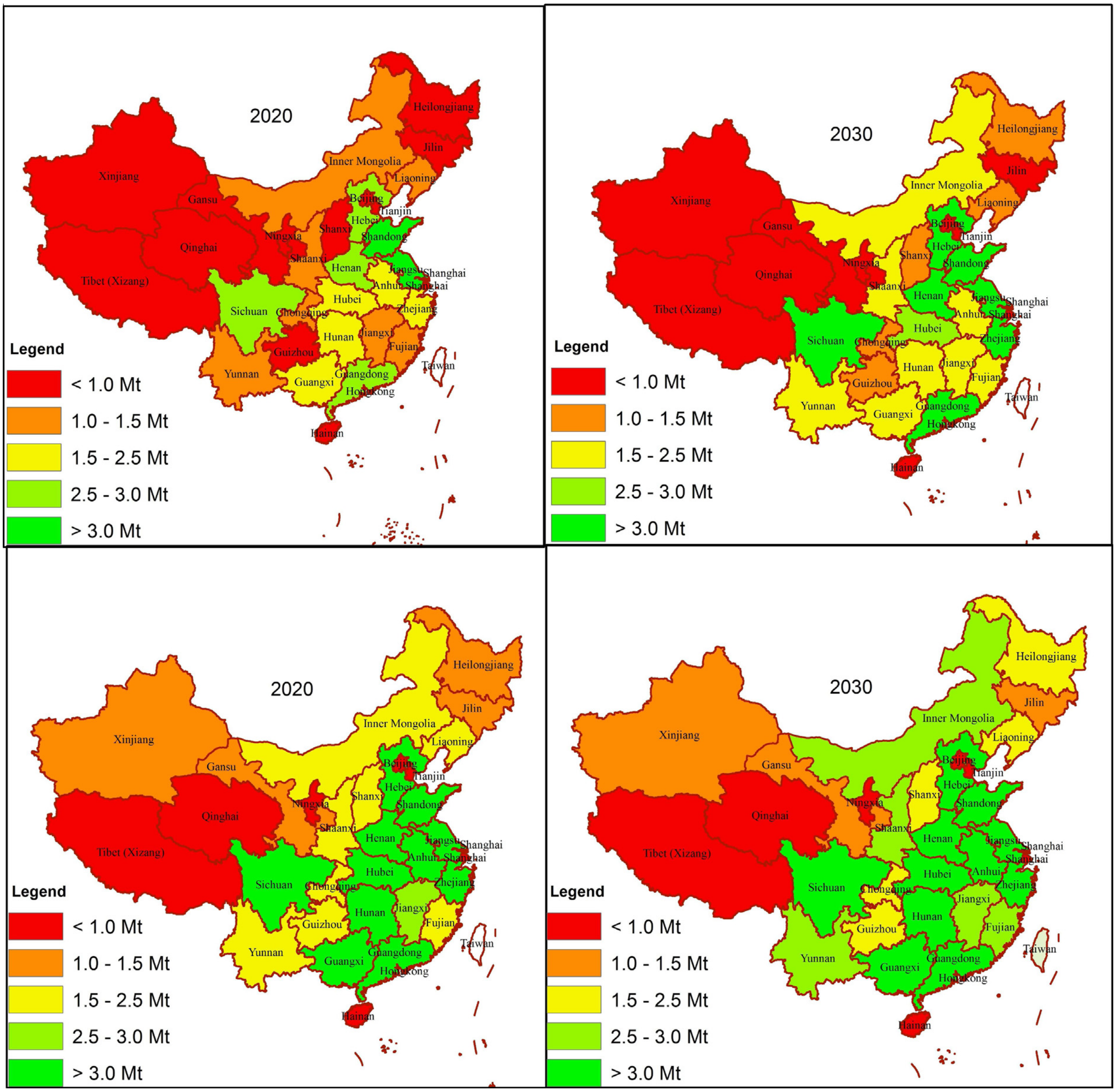

Fig. 11. CO_2 emission reduction potential in cement industry in 2020 and 2030. Note: the top two figures represent cost-effective CO_2 emission reduction potential under EEPCP scenario, and the down two figures represent technical CO_2 emission reduction potential in EEPTP scenario.

evaluation that can increase the attention paid to energy efficiency investment opportunities by policy makers and plant managers [15,38]. Several approaches have been employed to discuss the multiple benefits of energy efficiency and emission mitigation at national [13,16,17,39], industrial [19,20,40], and facility levels [41]. The cost curves approach (i.e., Energy Conservation Supply Curves and Marginal Abatement Cost Curves) was either used independently or incorporated in other models to estimate the multiple benefits in China's cement industry [10,19,20]. However, most of these studies focused on the national level and ignored the regional character. In this paper, we quantify, at the provincial level, the multiple benefits of energy saving, CO_2 emissions mitigation and air pollutants resulting from the implementation of energy efficiency measures. According to our knowledge, this paper would be the first study to assess the multiple benefits of energy efficiency measures for China's cement industry at the provincial level.

In this study, we integrate ECSCs, which can calculate cost-effectiveness and technical energy saving potential among different provinces, the GAINS model, which can calculate the multiple benefits, and ArcGIS, a geographical information system (GIS) with elaborated spatial function. The multiple benefits framework is given in Fig. 7. This research can be summarized into the following steps:

1. Establishment of 2010 as the base year for tracking the distribution of energy use and emissions of CO_2 and air pollutants (i.e. PM, SO_2 and NOx).
2. Compilation of a list of 37 commercially available energy efficiency technologies/measures. The costs, lifetime, fuel/electricity saving, current implementation in base year and potential implementation rates up to 2030 used in this paper are based on our recent study, which provides a detailed analysis of

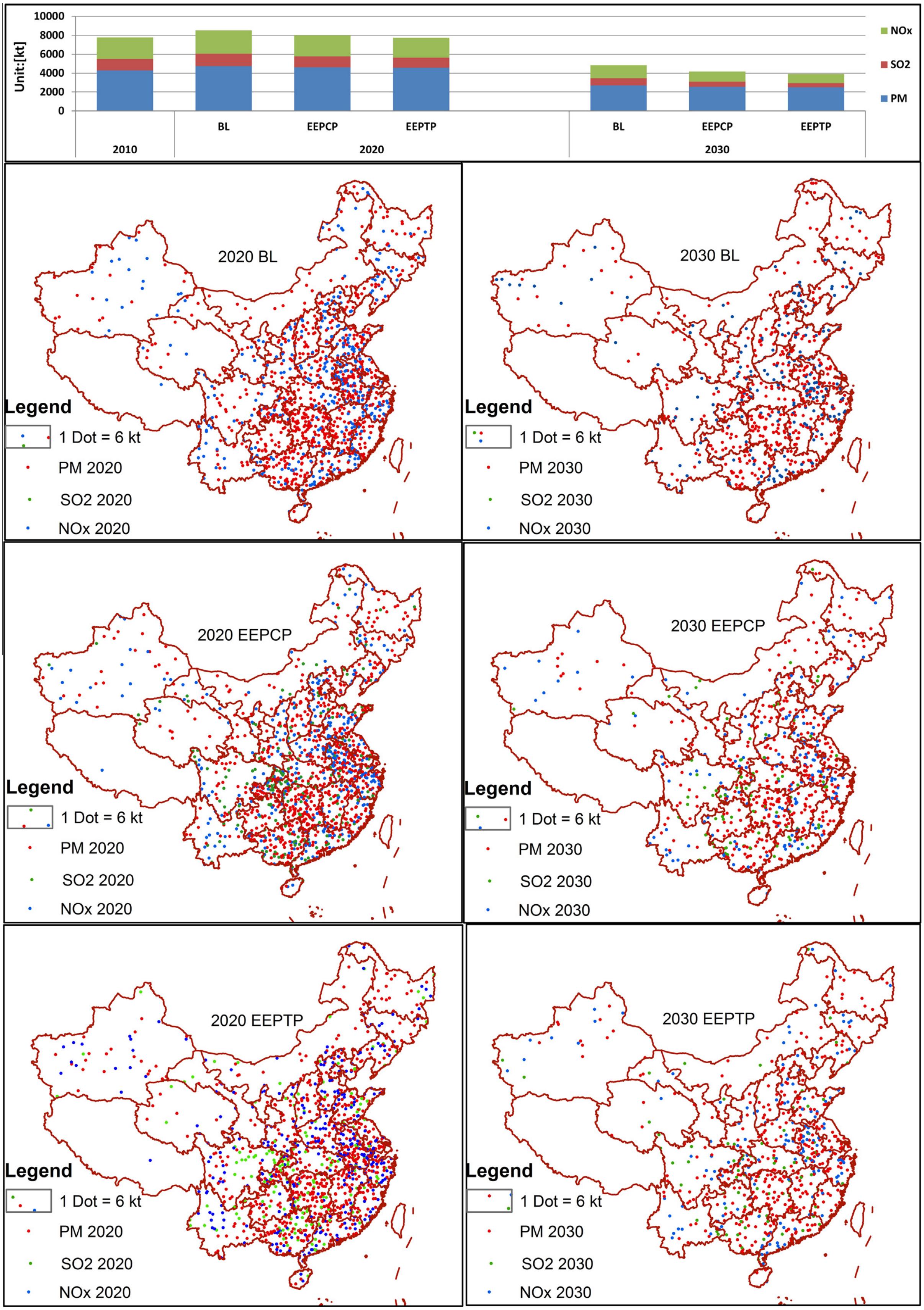

Fig. 12. Air pollutant emissions in cement industry in 2020 and 2030.

co-benefit potentials in China's cement industry [33]. The steps used to construct the provincial ECSC have been described by Hasanbeigi et al. [9,10].

3. Calculation of energy saving potentials under different scenarios in the Chinese cement industry at the provincial level and importation of these data into ArcGIS via a spreadsheet interface that creates extra function to assess the dynamic distribution of the future energy saving potential of China's cement industry.
4. Calculation of the future emissions and potential emissions reduction of CO_2 and air pollutants through using the results of ECSC and the GAINS output parameters, which include 34 end-of-pipe options from the GAINS database [33].
5. Importing of the results of future emissions and emission reduction potentials of CO_2 and air pollutants into ArcGIS to display the dynamic distribution among different provinces.

3.2. Data sources and key assumptions

3.2.1. Data sources

The historical outputs of cement and clinker production of each province used in this study are from the China statistical year book [42,43], China cement almanac [35], and China Cement Association [29]. The historical fuel combustion and electricity consumption data in cement industry of each province are from China energy statistical yearbook [42,43], China cement almanac [28,35], and relevant literature surveys [10,11,44]. The historical cement consumption per capita of each province are from [45–47]. Note that the population of each province, to project future cement output, from the GAINS database is in conflict with the Almanac of China's population. Hence, the future population of each province is calculated based on both the GAINS database and the Almanac of China's population [48] (see more detailed information in Section 3.2.2).

The parameters of 37 commercially available energy efficiency measures (i.e. fuel and electricity savings, fixed investment cost, operation and maintenance cost, lifetime, current implementation rate in base year and potential implementation rate up to 2030 and so on) are obtained from our recent study [33], as well as other sources such as LBNL [9,10,49], ERI of China [50,51], MIIT of China [52], and other institutes [8,19,44,53]. The costs of each energy efficiency measure are priced at 2005 $, with currency conversion factors derived from OECD Stat Extracts [34]. Energy prices are taken from GAINS, based on the 2012 World Energy Outlook (WEO) baseline scenario of the International Energy Agency (IEA). A discount rate of 10% is used.

The CO_2 emission factors for grid electricity by each province are from regional grid baseline emission factors of China [54]. The CO_2 emission factors for fuels are from LBNL [9,32]. The CO_2 emission factors for processes are from 2011 Cement Sustainability Initiative (CSI) on CO_2 and Energy Accounting and Reporting Standard for the Cement Industry [55]. The emission

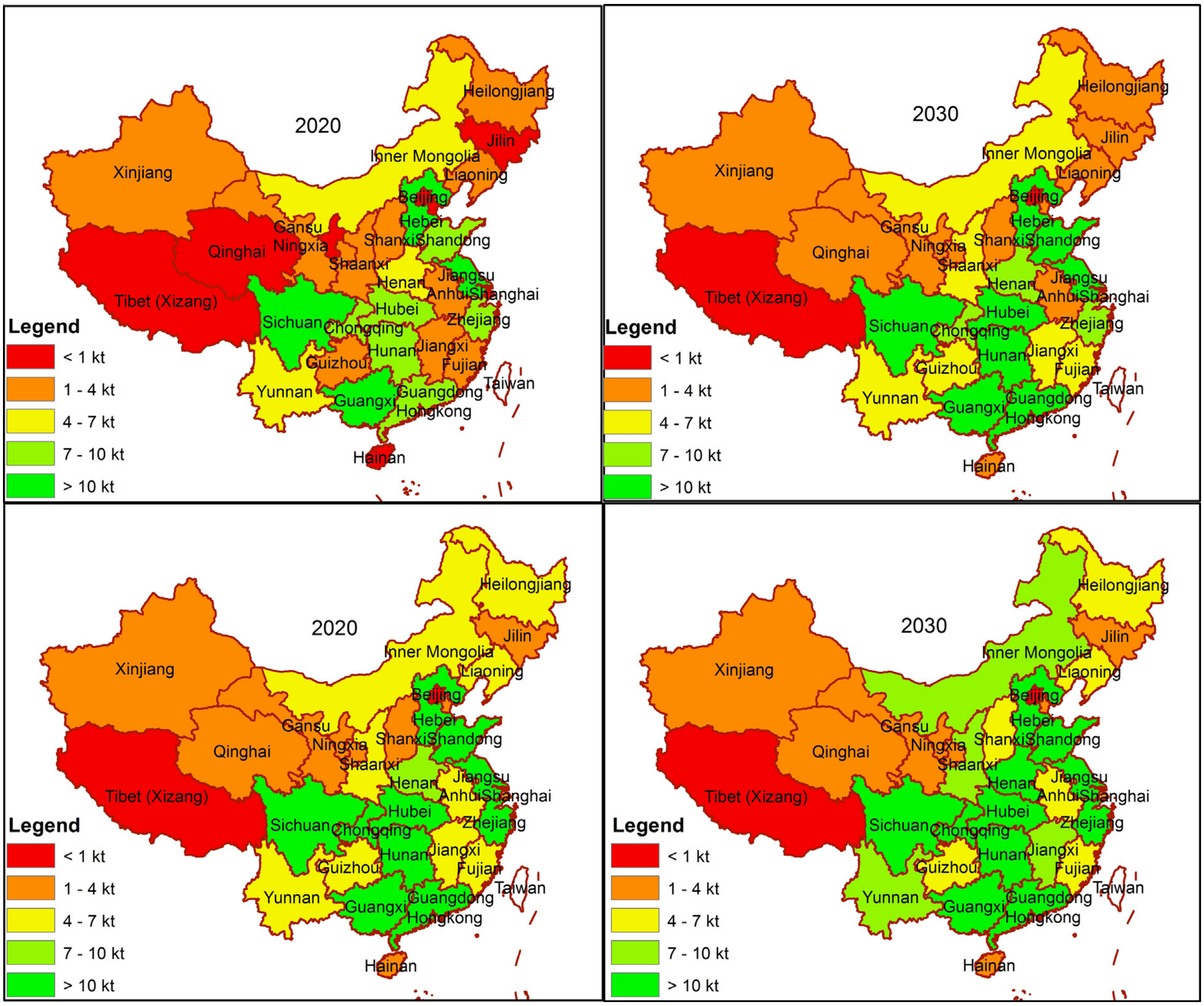

Fig. 13. SO_2 emissions abatement in cement industry in 2020 and 2030. Note: the top two figures represent cost-effective SO_2 emission reduction potential under EEPCP scenario, and the down two figures represent technical SO_2 emission reduction potential in EEPTP scenario.

factors of SO_2, NOx and PM are heavily dependent on two characteristics: (1) unabated emissions from raw materials, fuel combustion, electricity consumption, and (2) abatement efficiency of end-of-pipe options. Hence, The emission factors of SO_2, NOx and PM are obtained by running GAINS, which includes 34 end-of-pipe options (13 PM control technologies, 11 SO_2 control technologies, and 10 NOx control technologies), and calibrations based on related studies [3,56]. The above emission factors are assumed constant during the whole period.

3.2.2. key assumptions

Projection of China's provincial cement and clinker output up to 2030. Estimating future outputs of cement and clinker is needed when assessing multiple benefits of energy efficiency measures for the cement industry at the provincial level in the future. There are three types of forecasting methods including peak consumption per capita based method, fixed asset investment based method, and building and infrastructure construction based method [7,32]. Although adopting above different forecasting methods, several studies have indicated a similar trend for future cement production in China. Cement production is expected to continue to rise with a moderate growth rate until saturation occurs in 2015–2020 and decreases afterwards [1,7,8,32]. In our study, we forecast the future outputs of cement and clinker at provincial level between 2010 and 2030 using the peak consumption per capita method. The detailed projections are explained as follows:

1. Population projection: The future population of each province is based on GAINS (which uses the 2012 World Energy Outlook (WEO) baseline scenario of IEA). Because the population of each province in 2010 is in conflict with other sources, the future population is calibrated based on the Almanac of China's population by Eq. (1) [43].

$$POP_{i,n} = POP_{i,2010} \times \frac{POP_{n}^{NL\_GAINS}}{POP_{2010}^{NL\_CHN}} \qquad (1)$$

where

$POP_{i,n}$ = Future population in province i in year n (i = 2015, 2020, 2025, and 2030).

$POP_{i,2010}$ = Population in province i in 2010 from China statistical yearbook.

$POP_{n}^{NL\_GAINS}$ = Future population in China in year n from GAINS database.

$POP_{2010}^{NL\_CHN}$ = China's population in 2010 from China statistical yearbook.

2. Projection of cement consumption per capita for each province: Cement demand is closely linked to urbanization, housing and road development, especially highways development [32,45,46]. In this study, the urbanization rate of each province in 2010 is taken from China statistical yearbook [43] and the future urbanization rate of each province will reach 70% up to 2030 [57].

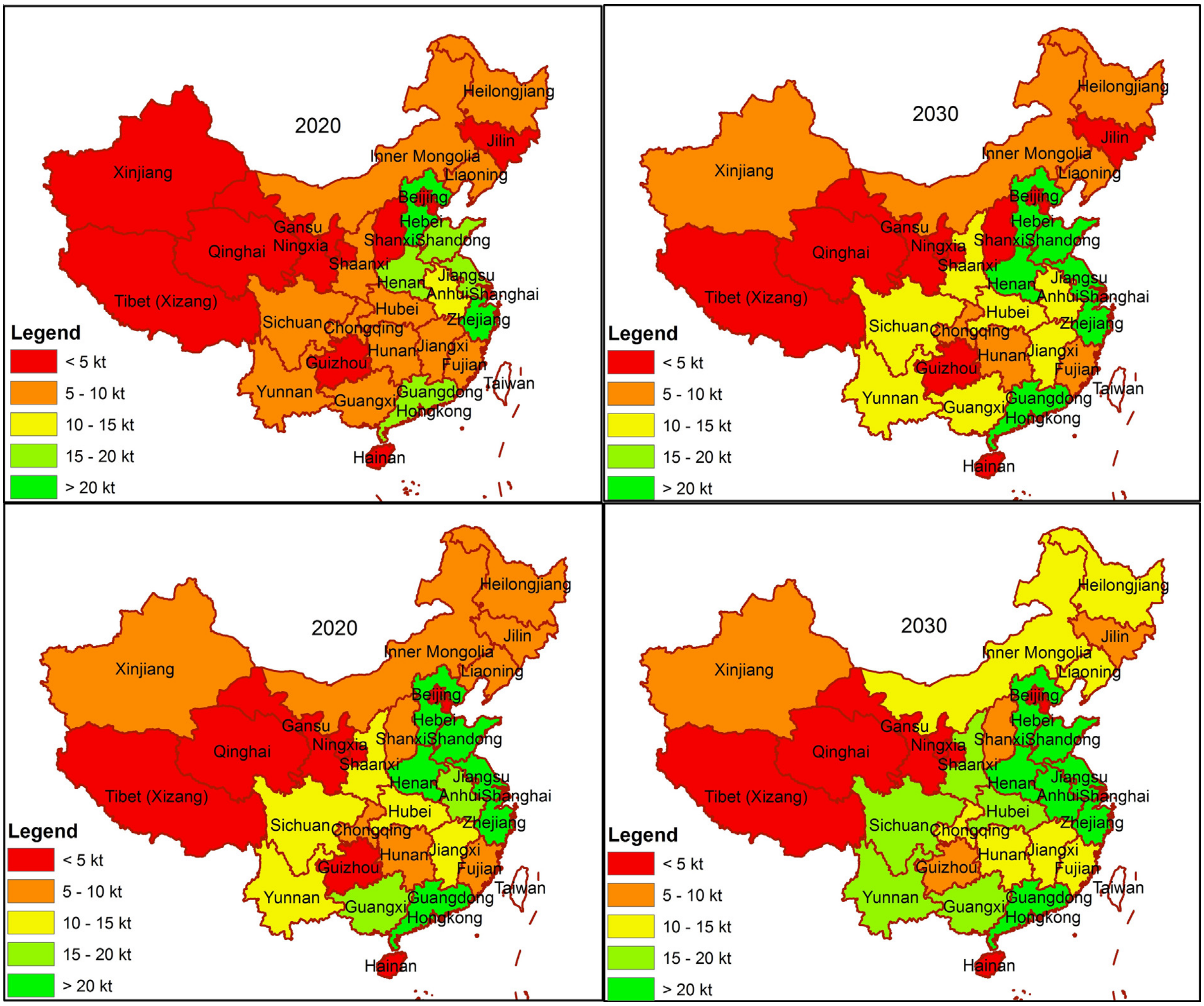

Fig. 14. NOx emissions abatement in cement industry in 2020 and 2030. Note: the top two figures represent cost-effective NOx emission reduction potential under EEPCP scenario, and the down two figures represent technical NOx emission reduction potential in EEPTP scenario.

The average floor area per capita of each province in 2010 is from Wei's study [46,47]. The future cement consumption per capita (CCPC) is calculated using Eq. (2). The peak point of cement consumption per capita at all provinces (except Guizhou and Heilongjiang) will occur between 2015 and 2020, at the range of 870–1980 kg per capita per year (see Appendix B).

$$CCPC_{i,n} = \frac{CC_{i,n}}{POP_{i,n}} = \frac{I_b \times [POP_{i,n} \times (U_{i,n} - U_{i,2010}) \times (FP_{i,n} - FP_{i,2010}) + (POP_{i,n} - POP_{i,2010}) \times U_{i,n}]}{POP_{i,n}} \qquad (2)$$

where

$CC_{i,n}$ = Future cement consumption in province *i* in year *n*.

I_b = The building cement material intensity, 0.2215 t_cement per square meter of building units.

$U_{i,n}$ = Urbanization in province *i* in year *n*.

$U_{i,2010}$ = Urbanization in province *i* in 2010.

$FP_{i,n}$ = Average floor area per capita in province *i* in year *n*.

$FP_{i,2010}$ = Average floor area per capita in province *i* in 2010.

3. Projection of future output of cement and clinker at the provincial level: Because of cement characteristics (e.g., short-haul trade, low production costs) and construction demand, China exported 9.8 million tons of cement in 2010, which was equivalent to 0.5% of the total production, and imported 0.82 million tons [35,58]. The ratio of cement export/import in percentage of total cement production in 2010 is used to estimate the future cement production during the whole period at the national level (see Eq. (3)). The future production of cement of each province is calculated by Eq. (4). The provincial ratio of clinker and cement production in 2010 is used to estimate the future clinker output up to 2030 at the provincial level (see Eq. (5)). The resulting outputs of cement and clinker and their spatial distribution in each region between 2005 and 2030 are listed in Table 1. From the Table 1, we determined that the saturation point of cement and clinker consumption per capita of each province will appear in 2015 and then decline gradually.

$$\begin{aligned} CP_n^{NL} = \sum_{i=1}^{31} CP_{i,n} &= EC_n^{NL} \times \frac{EC_{2010}^{NL}}{\left(CP_{2010}^{NL} - EC_{2010}^{NL} - IC_{2010}^{NL}\right)} \\ &- IC_n^{NL} \times \frac{IC_{2010}^{NL}}{\left(CP_{2010}^{NL} - EC_{2010}^{NL} - IC_{2010}^{NL}\right)} + \sum_{k=0}^{n} CCPC_{i,n} \times POP_{i,n} \qquad (3) \end{aligned}$$

$$CP_{i,n} = CP_n^{NL} \times \frac{CC_{i,n}}{\sum_{i=1}^{31} CC_{i,n}} \qquad (4)$$

$$CLP_{i,n} = CP_{i,n} \times \frac{CLP_{i,2010}}{CP_{i,2010}} \qquad (5)$$

where

CP_n^{NL} = Future cement production on national level in year *n*.

$CP_{i,n}$ = Future cement production in province *i* in year *n*.

EC_n^{NL} = Exports cement on national level in year *n*.

CP_{2010}^{NL} = Cement production on national level in 2010.

EC_{2010}^{NL} = Exports cement on national level in 2010.

IC_{2010}^{NL} = Imports cement on national level in 2010.

IC_n^{NL} = Imports cement on national level in year *n*.

$CLP_{i,n}$ = Future clinker production in province *i* in year *n*.

$CLP_{i,2010}$ = Clinker production in province *i* in 2010.

$CP_{i,2010}$ = Cement production in province *i* in 2010.

3.3. Scenario design

To compare and analyze the multiple benefits of energy saving and emission mitigation of CO_2 and air pollutants, three scenarios are constructed: Baseline scenario (BL), Energy Efficiency Policy with cost effective energy saving potential (EEPCP) scenario, and Energy Efficiency Policy with technical energy saving potential (EEPTP) scenario. The GAINS input parameters: energy price, discount rate, fuel structure, output of cement and clinker of each province are assumed unchanged under different scenarios during the study period.

The Baseline scenario is constructed based on GAINS WEO baseline scenario of IEA 2102 and future output of cement and clinker at all provinces. In this scenario, the annual autonomous energy efficiency improvement (AEEI) is 0.2% in all provinces.

The Energy Efficiency Policy with cost effective energy saving potential scenario is constructed based on 24 cost effective energy efficiency measures with projected implementation rates. This scenario represents the cost-effective energy saving potential of energy efficiency improvement and related emission mitigation level of China's cement industry in each province. As to Energy Efficiency Policy with technical energy saving potential scenario, we assume that 37 energy efficiency measures with projected implementation rates would be fully implemented during the study period. This scenario reflects the maximum potential of energy saving and energy-related emission mitigation of China's cement industry in all provinces. More information about which technologies are planned to be implemented and how the future performances are planned to be obtained to improve energy efficiency and reduce emissions of CO_2 and air pollutants under EEPCP and EEPTP scenarios can be found in our pervious study [33]. Note that the application of energy efficiency measures is assumed the same across all provinces.

4. Results and discussion

4.1. Energy consumption and energy saving potential by region between 2015 and 2030

Fig. 8 shows the future energy consumption from 2015 to 2030 under different scenarios in the cement industry at provincial level. On the whole, the peak of energy consumption of China's cement industry is expected to occur in 2015. The total baseline energy consumption will increase to 5297 PJ in 2020 and then decrease to 2994 PJ in 2030, 9% higher and 40% lower than 2010, respectively. There are large energy saving potentials in EEPCP and EEPTP scenarios when advanced energy efficiency measures are adopted compared to the corresponding BL scenario. The energy use in EEPCP scenario will decline by 8% in 2020 and 18% in 2030 compared to the baseline scenario. The energy use in EEPTP scenario would further decrease by 4% in 2020 and 8% in 2030, respectively. The activity level of cement and clinker production plays an important role in the rise or decline of energy consumption in all scenarios. Between 2015 and 2030, the contribution to energy consumption varies across different provinces. In EEPCP scenario, six provinces of Sichuan, Shandong, Anhui, Guangdong, Hunan, and Henan have a large share in energy consumption, combing 36–33% of the total energy consumption during 2020–2030, followed by Jiangsu, Hubei, Zhejiang, Hebei, Guangxi, Yunnan with 3–4% respectively per province.

To better understand which province has the greatest impact on the total energy saving potential and which province has more opportunities for the improvement of energy efficiency. Fig. 9 depicts the distribution of the energy saving potential of cement industry for different scenarios up to 2030. As shown in Fig. 8, the energy saving potential is diverse in different provinces. Provinces (i.e. Sichuan, Henan, Hebei, Shandong, Jiangsu, Zhejiang, and Guangdong) with dominant cement production and consumption show higher reduction of energy use than other provinces. Over 48% of total cost-effective energy saving potential is contributed by these provinces. Shandong, Jiangsu, Zhejiang, and Guangdong are located in eastern coastal regions. The cost-effective energy saving potential (EEPCP scenario) in Hunan, Hubei, Fujian, and Jiangxi provinces will increase from 16–24 PJ in 2020 to 20–31 PJ in 2030, which account for 7% in 2020 and 16% in 2030 respectively, compared to the baseline. It means that the developing provinces with large cement production indicate higher energy saving potential in the long term period than short term. Note that three megacities (Beijing, Shanghai, Tianjin) have the lowest share in the total energy saving potential. However, they have more opportunities to improve energy efficiency than other regions because these three megacities have strong economic ability to encourage implementation of advanced energy efficiency measures, which might result in higher energy savings than our estimates [59].

4.2. Ancillary CO_2 emissions mitigation benefits of energy efficiency measures

The CO_2 emissions per tonne of cement in China's cement industry are heavily influenced by the raw material calcination and clinker content in cement (44%), specific fuel combustion (48%) and electricity consumption (8%) [33,55,60,61]. In this study, only energy efficiency measures are considered. Additionally, due to data limitation we assume that the indirect CO_2 emissions from the production of clinker bought from other provinces are attributed to exporting provinces. The future CO_2 emissions in 2015 and 2030 for the different scenarios per province are summarized in Fig. 10. Nationally, CO_2 emissions will peak around 2015, but with variations among different provinces. Between 2015 and 2030, the CO_2 emissions will slightly increase to 1562 Mt in 2020 and then decrease sharply to 408 Mt in 2030 due to the rapid decline of cement production. Compared with 2010, the total CO_2 emissions will be cut by 1062 Mt and 1099 Mt in 2030 respectively under EEPCP and EEPTP scenarios. The provincial contribution to CO_2 emissions varies across provinces during the whole period. In 2020, the provinces of Shandong, Jiangsu, and Sichuan have large amount of CO_2 emissions, combines accounting for 22% of total emissions, followed by Guangdong, Anhui, Henan, Hebei, and Zhejiang with 6% each, respectively, under EEPCP scenario. However, the share of CO_2 emissions from Anhui province will increase from 6% in 2020 to 15% in 2030 under the EEPCP scenario.

Fig. 11 shows the dynamic distribution of CO_2 emission reduction potential per province under EEPCP and EEPTP scenarios in 2020 and 2030. Between 2020 and 2030, the number of provinces that can mitigate over 3 Mt CO_2 emissions per year increased from 2 (Shandong, and Jiangsu) to 6 (Shandong, Jiangsu, Sichuan, Hebei, Henan, and Guangdong) provinces through the implementation of cost-effective energy efficiency measures (EEPCP scenario), which account for 6% in 2020 and 38% in 2030 of the projected CO_2 emissions in BL scenario respectively. Assuming a full implementation of all currently available energy efficiency measures with projected implementation rates as in EEPTP scenario, it is found that other eight provinces (Sichuan, Hebei, Henan, Hubei, Hunan, Guangxi, Guangdong, and Anhui) will be able to decline each by over 3 Mt CO_2 emissions per year. For all alternative scenarios, the CO_2 emissions mitigation potential at the developing regions (Inner Mongolia, Shaanxi, Shanxi, Jiangxi, Fujian, and Yunnan) in long term period (2020–2030) indicate higher than in short term period (2015–2020), while other provinces have constant trends. The share of total CO_2 emissions in Anhui province amounts to 15% in 2030, but the share of CO2 emissions reduction potential in this province only reach 4%, due to that the CO_2 emissions from clinker export have more contribution than energy-related CO_2 emissions.

4.3. Ancillary air pollutant emission abatement benefits of energy efficiency measures

Fig. 12 shows air pollutant emissions and their dynamic distribution in China's cement industry under the different scenarios up to 2030. It is obvious that as a consequence of the changing fuel combustion and electricity consumption in China's cement industry, air pollutant emissions will reach a peak in 2015–2020 and then decrease sharply with the rapid decline of energy consumption in all scenarios. Nationally, the air pollutant emissions of PM, SO_2, and NOx in BL scenario will increase from 4290 kt, 1204 kt, 2287 kt in 2010 to 4743 kt, 1303 kt, and 2487 kt in 2020 and sharply decrease to 2713 kt, 730 kt, and 1400 kt in 2030 respectively. If the cost-effective energy efficiency measures were adopted (EEPCP scenario), the air pollutant emissions of PM, SO_2, and NOx amounts to 4587 kt, 1150 kt, and 2239 kt in 2020 and eventually drop to 2518 kt, 538 kt, and 1089 kt in 2030 respectively. Assuming a full implementation of all currently available energy efficiency measures with projected implementation rates as in EEPTP scenario, the air pollutant emission will further decline by around 2% of PM, 6–8 % of SO_2, and 5–10% of NOx respectively, compared to the baseline. The distribution of air pollutant (i.e. PM, SO_2 and NOx) emission in different provinces is extremely uneven depending on energy consumption and cement production. In EEPCP scenario, total air pollutants of each province are ranging from 1 kt in Shanghai to 756 kt in Hunan by 2020 and from 1 kt to 395 kt by 2030, respectively. Provinces with the largest share of total air pollutant emissions are mainly located in the southeast and central regions during the study period. In EEPCP scenario, the provinces of Hunan, Anhui, and Guangxi rank among the highest contributors to air pollutant emissions, accounting for one quarter, followed by Sichuan, Shandong, Jiangxi, Guangdong, and Chongqing, with 5% each, respectively. Considering that the air quality in developed provinces is significantly affected by emissions from their surrounding areas [62], energy efficiency measures could be a rapid way to cost-effectively reduce air pollution in surrounding developed areas.

4.3.1. Ancillary SO_2 emissions abatement benefits of energy efficiency measures

SO_2 emissions in cement industry are heavily influenced by fuel quality, kiln types, desulfurization measures, water content and residence time [63,64]. We evaluate the contribution of energy efficiency measures to total SO_2 emission abatement and its distribution in different provinces under different scenarios (see Fig. 13). Total SO_2 emission reductions in the EEPCP scenario are projected to be 142 kt in 2020 and 192 kt in 2030. Under EEPTP scenario, in which all available energy efficiency measure are fully implemented, SO_2 emissions will further decrease by 6–8% compared to the baseline. SO_2 emission reductions differ greatly across provinces during the whole period. For the large cement producing provinces (e.g. Henan, Anhui, Shandong, and Guangdong), the SO_2 reduction potentials in the long-term are higher than in the short-term in all scenarios. The main reason is that the end users have to adopt best available technology (e.g., advanced energy efficiency measures or end-of-control options) to improve energy efficiency and reduce emissions due to cement demand saturation. The share of SO_2 emission reduction in Jiangsu and Hebei provinces account for 18%, followed by Guangxi (8%) and Sichuan (7%). Note that the share of SO_2 emission reduction potential in clinker-producing provinces, such as Shandong and Anhui, is lower than clinker-importing provinces (Tianjin, Shanghai, and Guangdong) when comparing with their own total SO_2 emissions. The main reason is that process SO_2 emissions that mainly determined by kiln types have a higher contribution than energy-related SO_2 emissions. For example, the share of total SO_2 emission reductions from Anhui only accounts for 2%, while the contribution in total energy saving was estimated to be 4%.

4.3.2. Ancillary NOx emissions abatement benefits of energy efficiency measures

NOx emissions in cement industry are affected strongly by temperature and oxygen availability, nitrogen content of fuel used and the implementation of energy and emissions mitigation measures, which are controlled by resource endowments and development processes [3]. Fig. 14 displays the spatial distribution of NOx emission reductions of energy efficiency measures in 2020 and 2030 for different scenarios. The future NOx emission reductions are significantly affected by cement output. In the EEPCP scenario, the total NOx emission reductions are estimated at 248 kt in 2020 and 311 kt in 2030, which contribute to 25% of the total NOx emission reduction target [4]. When increasing the implementation of non-cost-effective energy efficiency measures as in EEPTP scenario, NOx emissions will be further decreased by 53% in 2020 and 44% in 2030 respectively, compared to the EEPCP scenario. Similar to the trend for SO_2 emissions, the NOx emission reductions from developing provinces (Sichuan, Yunnan, Hubei, Guangxi, and Jiangxi) in the long-term would be higher than in the short-term in all scenarios. Along with the first standard for nitrogen oxide (NOx) emissions from cement plants being issued by Chinese government in 2013, the NOx emissions for cement production in developed regions will decrease higher than in low income provinces [65]. This is because of the joint regional air pollution control program, where the less developed provinces (e.g. Hebei and Zhejiang) that surround developed regions (e.g. Beijing, Tianjin, and Shanghai) will become the top NOx emission reduction provinces, combines accounting for 18% of total NOx emission reduction, followed by Shandong, Henan, Jiangsu, and Guangdong with 6% each respectively [62].

4.3.3. Ancillary PM emission abatement benefits of energy efficiency measures

The emission abatement of PM$_{\text{TSP}}$ (Total Suspended Particles), PM_{10} (Particles with size less than 10 μm), and $PM_{2.5}$ (Fine

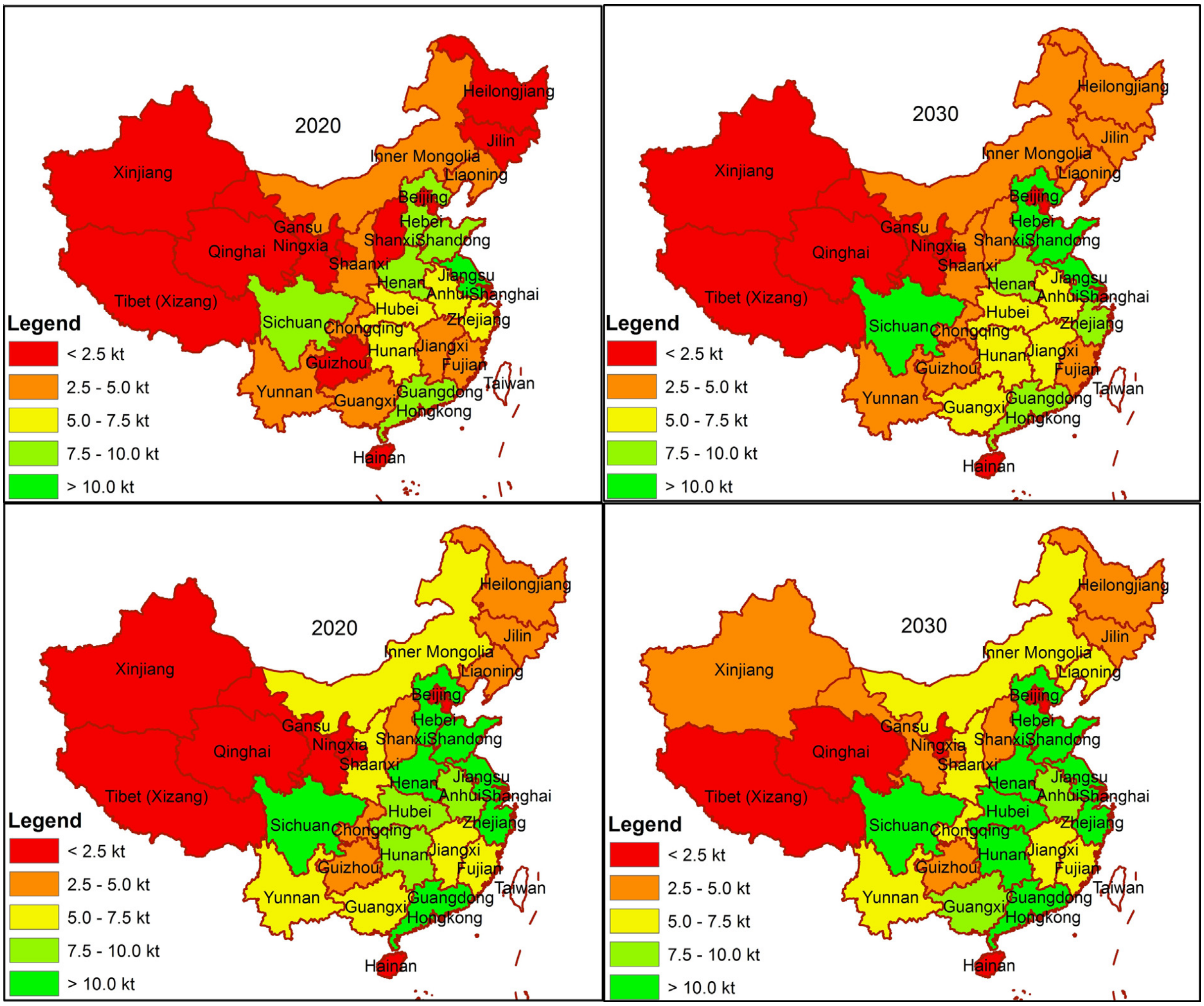

Fig. 15. PM$_{\text{TSP}}$ emissions abatement in cement industry in 2020 and 2030. Note: the top two figures represent cost-effective PM$_{\text{TSP}}$ emission reduction potential under EEPCP scenario, and the down two figures represent technical PM$_{\text{TSP}}$ emission reduction potential in EEPTP scenario.

Particles) of China's cement industry are investigated up to 2030 under different scenarios (see Figs. 15–17). As shown in Figs. 15–17, the spatial distributions of the emissions abatement of PM_{-TSP}, PM_{10}, and $PM_{2.5}$ are similar. Unsurprisingly, the potential emission reductions of PM_{-TSP}, PM_{10}, and $PM_{2.5}$ are significantly affected by the changes in cement output. The efforts applied to adopt the cost-effective energy efficiency measures in EEPCP scenario contribute to a 16% of PM_{-TSP} emission reduction, compared to the efforts implementation of end-of-pipe options to reach the new emission standard for cement plants [4]. In the EEPCP scenario, the ancillary benefits of energy efficiency measures may decrease by 3–6%, 2–5%, and 1–3% of PM_{-TSP}, PM_{10}, and $PM_{2.5}$, respectively. With the implementation of non-cost-effective energy measures in EEPTP scenario, a further decrease of 2% of PM_{-TSP}, 1.7% of PM_{10}, and 1% of $PM_{2.5}$ could be realized respectively, compared to EEPCP scenario. Between 2020 and 2030, of the total emission of PM_{-TSP}, PM_{10}, and $PM_{2.5}$, 30% would be from less developed provinces, with major contributions from Jiangsu (8%), Shandong (8%), Hebei (7%), and Sichuan (7%). Of the relative contribution of PM_{-TSP}, PM_{10}, and $PM_{2.5}$, 31% ranged between 4% and 6% in central- and east-China, like Anhui, Guangdong, Zhejiang, Hunan, and Hubei. Because $PM_{2.5}$ has larger influence on human health than other air pollutants, the emission reduction of $PM_{2.5}$ from megacities (e.g. Beijing, Tianjin, and Shanghai) in short term is expected to be higher than that in long term [13].

Summarizing the results of the multiple benefits assessment for different scenarios, there are large multiple benefits of improving energy efficiency and reducing CO_2 and air pollutants through implementation of energy efficiency measures in China's cement industry in different provinces. Generally, provinces with a large share in cement production have a large contribution to future energy savings and emission mitigation. Additionally, the multiple benefits of energy efficiency measures in clinker-producing provinces would be higher than those in clinker-exporting provinces. The developing provinces (Hebei and Jiangsu) located surrounding developed cities will have more opportunities than other developing provinces (Hunan, Hubei, Sichuan) to implement of energy efficiency measures as well as reducing emissions of CO_2 and air pollutants.

5. Sensitivity and uncertainty analysis

A detailed sensitivity and uncertainty analysis is conducted by combing uncertainties in the balance of cement and clinker production in different provinces, prices of fossil fuel and electricity, discount rates, and implementation rates.

5.1. The balance of cement and clinker outputs in each region

Cement and clinker production plays a key role when assessing potentials of energy saving and associated emission reductions.

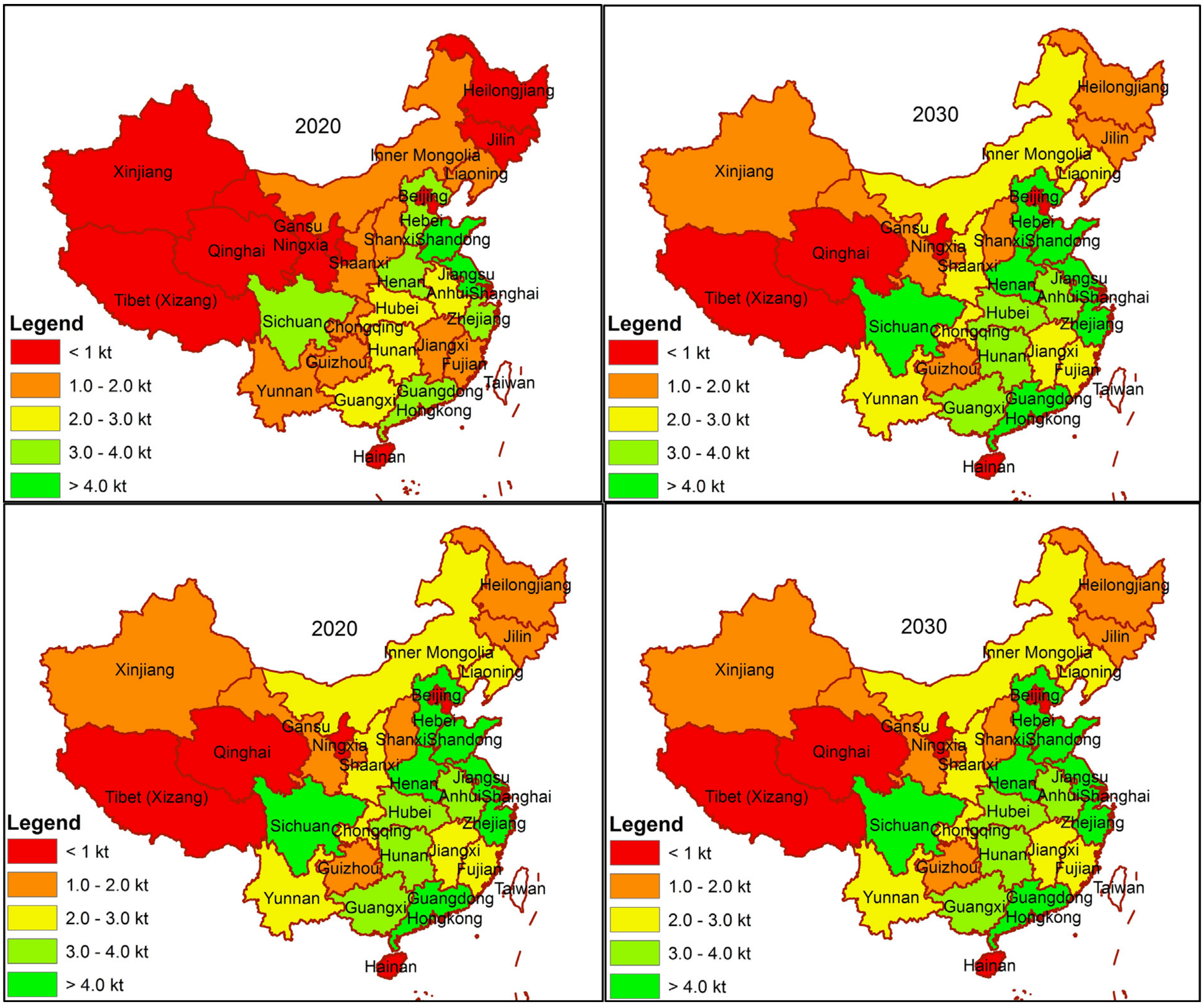

Fig. 16. PM_{10} emissions in cement industry in 2020 and 2030. Note: the top two figures represent cost-effective PM_{10} emission reduction potential under EEPCP scenario, and the down two figures represent technical PM_{10} emission reduction potential in EEPTP scenario.

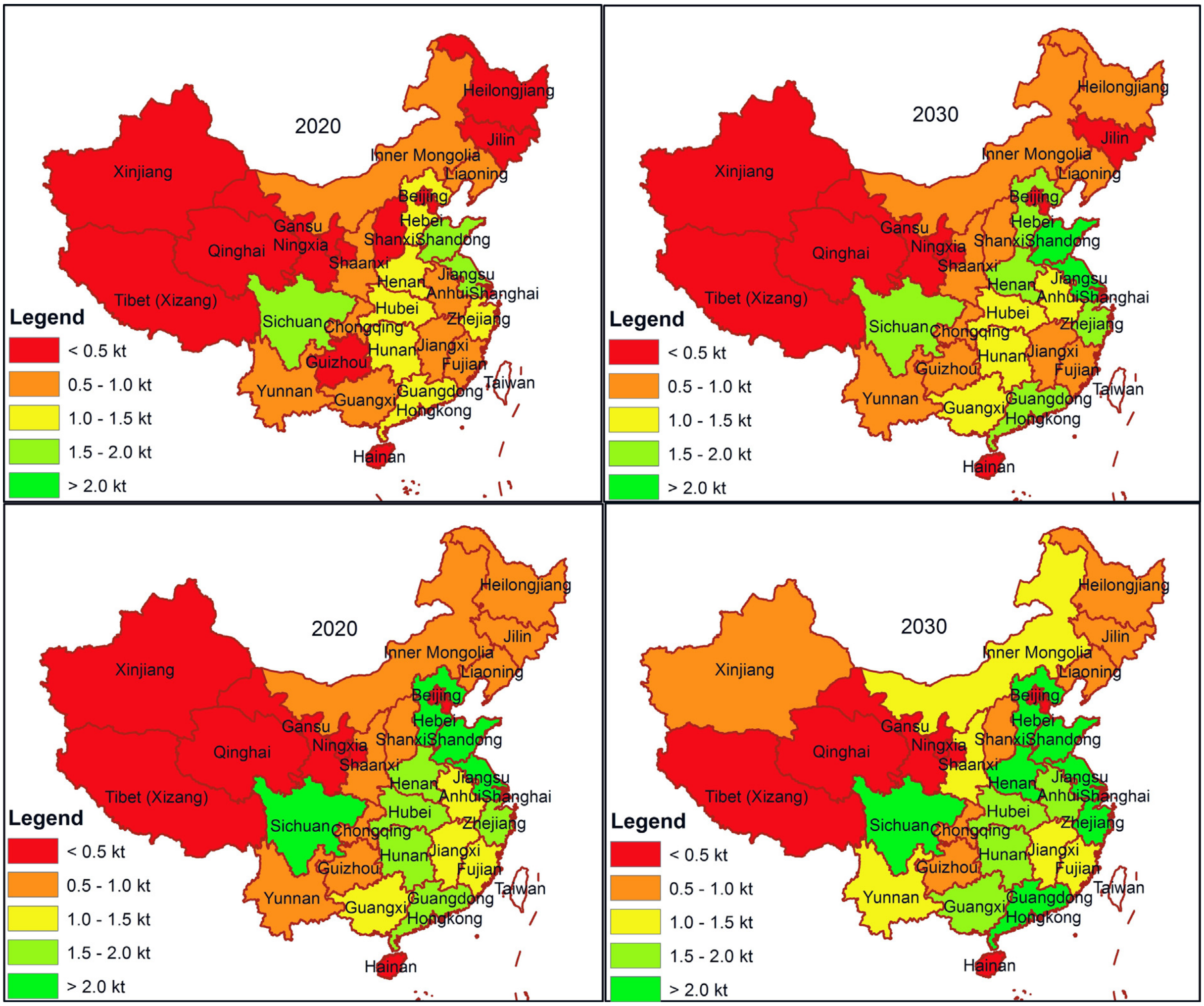

Fig. 17. $PM_{2.5}$ emissions abatement in cement industry in 2020 and 2030. Note: the top two figures represent cost-effective $PM_{2.5}$ emission reduction potential under EEPCP scenario, and the down two figures represent technical $PM_{2.5}$ emission reduction potential in EEPTP scenario.

The balance of clinker and cement output in each province largely depends on the clinker-to-cement ratio and the clinker trade between different provinces. The national average clinker-to-cement ratio in China's cement industry is much lower than the international average, which is heavily influenced by the chemical composition of waste and by-product materials (e.g., sludge, fly ash, and foundry sand) and their compatibility with the materials they replace in the content raw mix [61,66]. We use the national average clinker-to-cement ratio in 2010 to project future activity level of clinker and cement for the provinces (more information can be found in Section 3.2). Additionally, there exists significant clinker trade in China's cement industry among different provinces. The main reason is that some plants only produce clinker, selling it to grinding plants and to other plants that produce both cement and clinker. As a new feature in China's cement industry, grinding plants have expanded rapidly in the past decades. The cement production capacity of grinding plants increased from 156 Mt in 2005 to 1440 Mt in 2013. Those grinding plants are mainly located in three megacities and developed provinces [28,67]. For example, Jiangsu imported around 50 Mt clinker from Anhui and Shandong in 2013. Anhui exported a total of 60 Mt clinker at the same time [67]. The development of grinding plants has large impacts on production efficiency and energy use as well as on emissions of CO_2 and air pollutants of China's cement industry. The clinker trade in 2010 among different provinces is employed and assumed to remain unchanged in the future, which may underestimate multiple benefits potential in clinker-exporting provinces, like Anhui and Shandong.

5.2. Future price of fossil fuel and electricity

The rise of energy prices would lead to higher benefits from reducing energy use, which can increase the size of cost-effective potential for energy efficiency measures. The national average purchasing prices of coal and electricity in China's cement industry increased from 2.8 \$/GJ and 0.9 \$/kW h in 2005 to 4.7 \$/GJ and 1.0 \$/kW h in 2010 respectively. The provincial purchasing prices of coal and electricity varied across different provinces between 2005 and 2010. Policy makers and end users are normally ignore implement energy efficiency measures due to the lower final energy prices are decided by local government by implementation of taxes and subsidies [68]. As mentioned in Section 3, the energy prices in this study are from GAINS and assumed unchanged in the study period, which is likely to be an under-estimate. Therefore, it is necessary to assess how changes in the prices of fossil fuel and electricity will influence the cost-effective energy saving potential and associated emission mitigation of CO_2 and air pollutants at the provincial level. Three different price levels of coal and electricity are used to evaluate the sensitivity of economic potentials in different provinces. More specifically, the international energy price (IP) is from GAINS data base, while the national energy price (NP) and the Provincial energy Price (PP) are from China Cement

Table 2
Cost-effective energy saving potential in cement industry among different regions. Unit: [PJ].

Region	2020			2030			Region	2020			2030		
	IP	NP	PP	IP	NP	PP		IP	NP	PP	IP	NP	PP
Anhui	22	29	29	28	35	36	Jiangxi	17	23	23	21	28	28
Beijing	3	4	4	4	5	5	Liaoning	13	17	17	16	21	21
Chongqing	12	17	17	16	20	21	Inner Mongolia	15	20	16	19	24	20
Fujian	16	21	21	20	26	26	Ningxia	4	5	4	5	6	5
Gansu	6	9	7	8	11	9	Qinghai	2	3	3	3	4	3
Guangdong	31	42	42	40	51	51	Shaanxi	15	20	20	19	24	24
Guangxi	20	27	27	26	33	33	Shanghai	2	2	2	2	3	3
Guizhou	10	14	14	13	17	17	Shandong	40	54	54	51	66	66
Hainan	3	5	5	4	6	6	Shanxi	10	13	13	13	16	16
Hebei	34	46	46	44	56	56	Sichuan	34	46	46	44	57	57
Heilongjiang	10	13	11	12	16	13	Tianjin	2	3	3	3	4	4
Henan	31	42	42	40	51	51	Tibet (Xizang)	1	1	1	1	1	1
Hubei	24	32	33	31	40	40	Xinjiang	7	9	6	8	11	7
Hunan	24	32	32	30	39	39	Yunnan	15	21	21	20	25	25
Jilin	8	11	11	11	14	13	Zhejiang	30	41	41	39	50	50
Jiangsu	42	56	58	54	69	71							

Note: IP represent international energy price from GAINS model; NP represent Chinese energy price on national level; PP represent Chinese energy price at the provinces level.

Table 3
Cost-effective CO_2 emission reductions potential in cement industry among different regions. Unit: [Mt].

Region	2020			2030			Region	2020			2030		
	IP	NP	PP	IP	NP	PP		IP	NP	PP	IP	NP	PP
Anhui	1.77	2.79	2.89	2.26	3.27	3.39	Jiangxi	1.37	2.16	2.16	1.76	2.53	2.53
Beijing	0.23	0.36	0.35	0.29	0.42	0.42	Liaoning	1.05	1.65	1.65	1.34	1.94	1.94
Chongqing	1.01	1.60	1.66	1.30	1.87	1.94	Inner Mongolia	1.20	1.89	1.49	1.54	2.21	1.78
Fujian	1.30	2.05	2.05	1.66	2.40	2.40	Ningxia	0.31	0.49	0.32	0.40	0.58	0.40
Gansu	0.53	0.84	0.66	0.68	0.98	0.79	Qinghai	0.18	0.28	0.22	0.23	0.33	0.28
Guangdong	2.54	4.01	4.01	3.26	4.70	4.70	Shaanxi	1.21	1.91	1.91	1.55	2.23	2.23
Guangxi	1.65	2.60	2.69	2.11	3.04	3.16	Shanghai	0.15	0.23	0.23	0.19	0.27	0.27
Guizhou	0.83	1.32	1.32	1.07	1.54	1.54	Shandong	3.26	5.15	5.15	4.18	6.03	6.03
Hainan	0.28	0.44	0.47	0.35	0.51	0.55	Shanxi	0.80	1.27	1.23	1.03	1.49	1.46
Hebei	2.80	4.41	4.41	3.58	5.17	5.17	Sichuan	2.82	4.45	4.45	3.62	5.21	5.21
Heilongjiang	0.79	1.24	1.02	1.01	1.45	1.19	Tianjin	0.18	0.29	0.29	0.23	0.34	0.34
Henan	2.55	4.03	4.03	3.27	4.72	4.72	Tibet (Xizang)	0.05	0.08	0.08	0.06	0.09	0.09
Hubei	1.97	3.74	3.23	2.53	4.29	3.78	Xinjiang	0.54	0.85	0.61	0.69	1.00	0.74
Hunan	1.93	3.05	3.05	2.48	3.57	3.57	Yunnan	1.27	2.00	2.00	1.62	2.34	2.34
Jilin	0.67	1.06	1.09	0.86	1.25	1.29	Zhejiang	2.48	3.92	3.92	3.18	4.58	4.59
Jiangsu	3.43	5.42	5.83	4.40	6.35	6.83							

Note: IP represent international energy price from GAINS model; NP represent Chinese energy price on national level; PP represent Chinese energy price at the provinces level.

Almanac. The future three different energy prices are assumed to be unchanged during the whole period (more information about NP and PP can be found in Appendix C) [35]. The other parameters are kept the same. The cost-effective potential of energy saving and associated emission mitigation of CO_2 under different energy price levels among different provinces are listed in Tables 2 and 3 respectively. As shown in Table 2, the cost-effective energy saving potential with NP and PP would be higher than that with IP in all provinces. Compared to the international energy price, cost-effective energy saving potential will increase by 29% with NP, and will increase in a range between −5% in Xinjiang and 32% in Jiangsu with the Provincial energy price. The cost-effective energy saving potential with PP in 24 provinces would be 29% higher than that with IP. The main reason is that the international energy price is higher than that in developing regions, but lower than that in developed provinces. The energy prices have larger impacts on the future potential of CO_2 emission mitigation than on the energy saving potential. The cost-effective CO_2 emission reduction potential with NP would be 44% higher than that with IP, while the levels of CO_2 emission reduction potential with PP vary in different provinces. The cost-effective potential of CO_2 emission reductions with PP would be higher in the range between 1% in Ningxia and 55% in Jiangsu compared to IP.

Unlike the changes in cost-effective potentials of energy saving and CO_2 emission mitigation, the ancillary benefits of air pollutants emission mitigation of energy efficiency measures can be influenced significantly by different energy price levels across provinces. As shown in Fig. 18, the total cost-effective potentials of air pollutant emission reduction will increase by 33% and 47% under NP and PP, compared to with IP. The cost-effective potentials of air pollutants reduction with NP will decrease by 7% in Xinjiang, but will increase in other provinces, with a range between 1% in Ningxia and 45% in Anhui, compared to with IP. The economic potentials of air pollutants reductions under the Provincial energy price could be affected more than under IP, which can further increase by 6–60%, depending on the status quo of energy price in different provinces. For example, provinces of Anhui, Hunan, Guangxi, and Hebei will reduce 47–55% of air pollutants reductions together, compared to that with IP. Overall, the energy prices have greater impacts on economic potentials of air pollution reductions than on cost-effective energy saving and CO_2 emission mitigation in all provinces, especially for developing provinces, such as Anhui and Hunan.

Note: IP represent international energy price from GAINS model; NP represent Chinese energy price on national level; PP represent Chinese energy price at the provinces level.

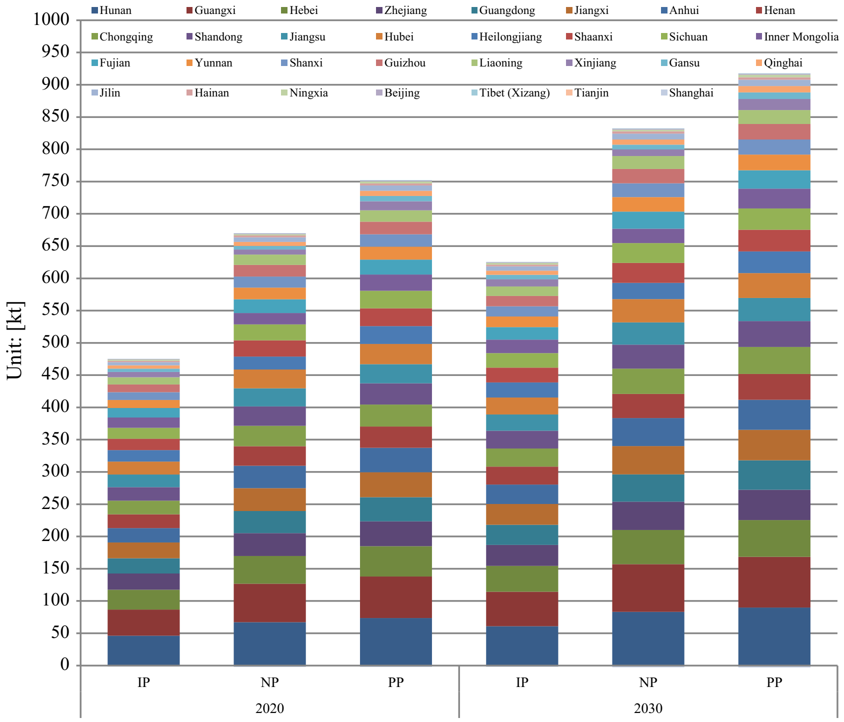

Fig. 18. Cost effective air pollutant emissions reduction potential in cement industry among different regions. Unit: [kt].

5.3. Discount rate

Discount rate is another factor in the economic assessment of potentials. Various discount rates are used to reflect different aims of the research to model the cost-benefits analysis. For public perspective, lower discount rate (4%) are used to evaluate long term issues, but end users often use higher discount rate (30%) to reflect common barriers for assessing the feasibility of programmes. A discount rate of 10% is widely used by researchers for assessing cost-effective energy conservation potentials in the industry sector [9,40,69,70]. The impacts of discount rates on the changes of potential between energy saving and emission mitigation in China's cement industry have been described before [33] and are not in the scope of this paper.

5.4. Future implementation rate of energy efficiency measures

As mentioned in Section 3.3, the potential implementation rates of each energy efficiency measure by each province are assumed the same as we could not obtain current implementation rates of each energy efficiency measure by each province. Generally, the developed regions have higher current implementation rate of commercially available energy efficiency measures and less room for adoption of these measures to improve the energy efficiency than developing regions, especially western provinces. The main reason is that most of the advanced energy efficiency measures are already implemented in developed regions, but the developing regions are still building small and medium scale plants [35]. In addition, different standards are adopted in different regions when new cement plants are built at the same time, which also can lead to different current implementation rates. For example, since 2006, all new cement plants must be equipped with WHR (waste heat recovery) and energy management system [71], however, the cement plants including WHR facility are mainly located in Shandong, Hebei, Jiangsu, Liaoning, Shanxi, and Henan [72,73]. All in all, this simplified assumption have effects on the economic potential of energy saving in terms of emission reductions of CO_2 and air pollutants for each region. However, the impact of this uncertainty on the main conclusions is small.

6. Conclusion

we assessed the multiple benefits of energy efficiency measures for improving energy efficiency, reducing emission of CO_2, and local air pollutants at a regional level in China's cement industry up to the year 2030.

We found that above half of cement production occurs at the coast in the south and east of China (except Fujian and Hainan). The energy consumption and associated emissions of CO_2 and air pollutants show large variations across provinces, depending on the of clinker and cement production, fuel structure, energy intensity, and applied end-of-pipe pollution abatement options. Between 2005 and 2012, the intensities of energy, CO_2, and air pollutants for cement production dropped in the range of 12–33%, 3–31%, and 6–72% per province, respectively. The main reason for the differences is that the clinker to cement ratio and CO_2 intensity have a good linear relationship, while the clinker to cement ratio and local air pollution emissions intensity have an irregular relationship, due to different emission standards being used among different provinces in the same time period.

We used provincial energy conservation supply curves (ECSC) to identify the cost-effective and technical energy saving potential per province, the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model was used to calculate air pollutant emissions, and ArcGIS to quantify the potential of energy savings in terms of emission mitigation of CO_2 and air pollutants of energy efficiency measures at the provincial level during the period 2011–2030. Over 48% of the total cost-effective energy savings potential is found in provinces with large amounts of cement production (i.e. Shandong, Jiangsu, Zhejiang, Anhui, and Guangdong etc.) during the study period. The cost-effective energy saving potential (EEPCP scenario) in Hunan, Hubei, Fujian, and Jiangxi provinces will take up to 7% in 2020 and 16% in 2030 of the predicted energy consumption (BL scenario) in 2020 and 2030 respectively. Although three megacities (Beijing, Shanghai, Tianjin) have the lowest share in the total energy saving potential, they have more driving force to improve energy efficiency than other regions.

The ancillary emission mitigation of CO_2, SO_2, PM, and NOx benefits of the implementation of energy efficiency measures and its dynamic distribution would vary in different provinces up to 2030. Over 3 Mt CO_2 emissions per year can be avoided in the two largest cement producer provinces (Shandong, and Jiangsu) in 2020 under EEPCP scenario, while another 3 Mt CO_2 emissions in four provinces (Sichuan, Hebei, Henan, and Guangdong) can be reduced in 2030. The economic potential of SO_2 emission reduction in Jiangsu and Hebei are expected to amount to 12–25 kt per year, which accounts for 18% of the total SO_2 emission reduction potential, followed by Guangxi (8%) and Sichuan (7%). The ancillary emission reduction potential of NOx and PM from clinker-importing provinces (i.e. Shanghai and Zhejiang) will have a higher contribution than that of clinker-exporting provinces (Shandong and Anhui) during the whole study period. For all alternative scenarios, the multiple benefits of energy efficiency measure in clinker-importing provinces would be higher than those of clinker-exporting provinces. The developing provinces (Hebei and Jiangsu) located surrounding developed cities show more incentives than other developing provinces (Hunan, Hubei, Sichuan) for implementing energy efficiency measures for both improving energy efficiency as well as reducing emissions of CO_2 and air pollutants. Hence, the end users and China's policy makers at local level (especially for the clinker-importing areas) should consider the multiple benefits of energy efficiency measures when developing and implementing programmes/policies to meet the targets of energy saving and emission reduction of CO_2 and air pollution.

Acknowledgments

This work was supported by the China Scholarship Council under Grant Number: 201207040022. The authors gratefully acknowledge Hongyou Lu from Lawrence Berkeley National Laboratory for her help on data input 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

See Figs. 19–22.

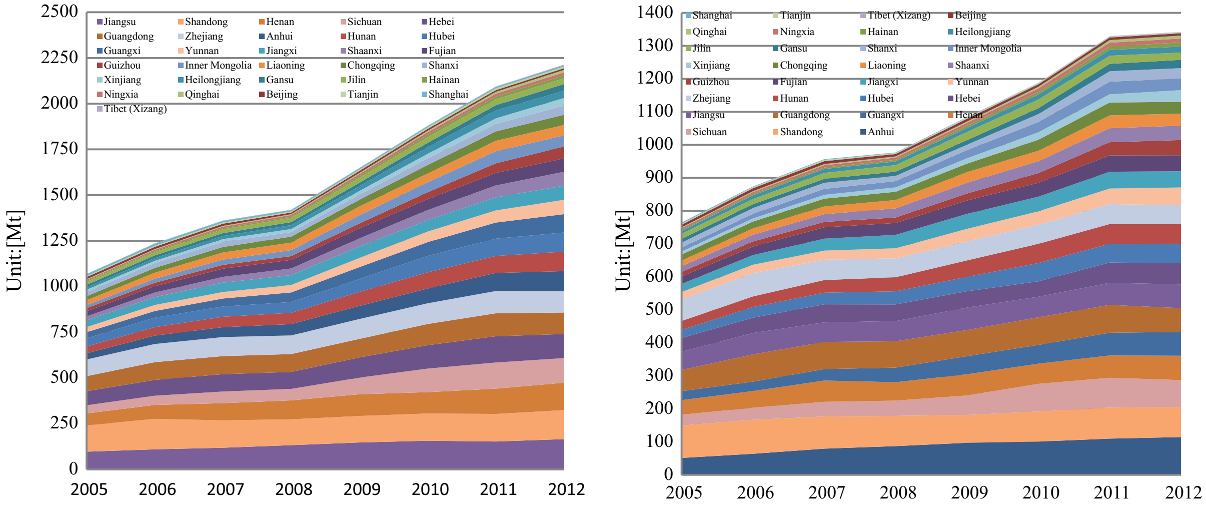

Fig. 19. Historical outputs of cement (left) and clinker (right) in cement industry between 2005 and 2012. *Source:* Primary data from [28] calculations by authors.

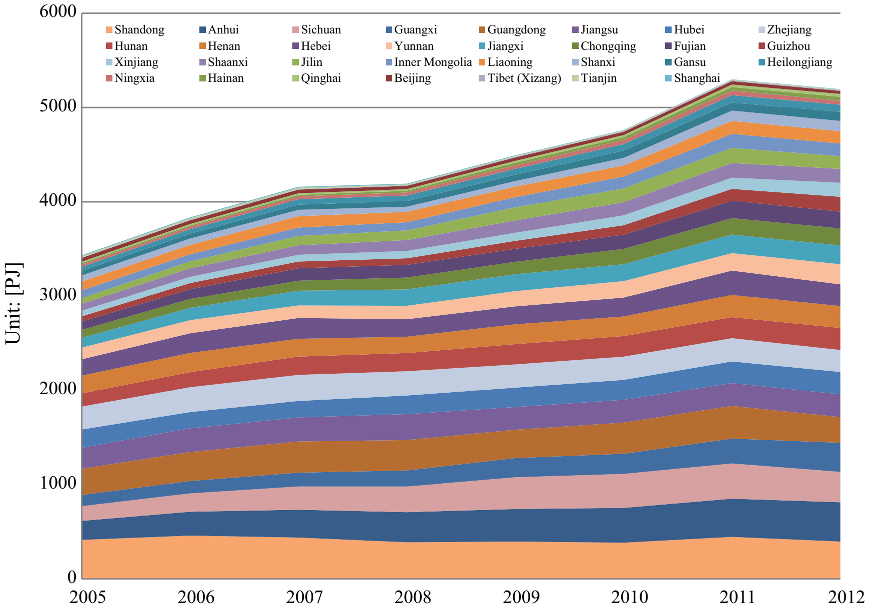

Fig. 20. Historical energy consumption for cement industry between 2005 and 2012. *Source:* Primary data from [28] calculations by authors.

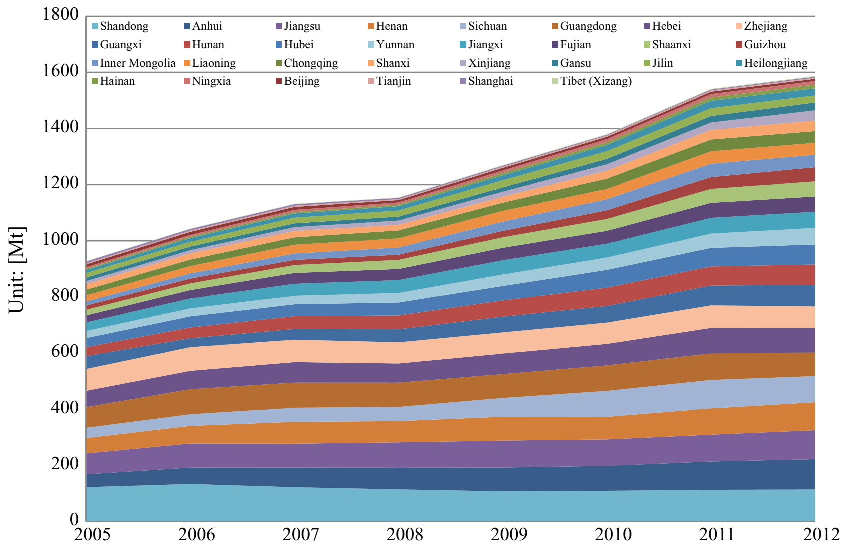

Fig. 21. Historical CO_2 emissions for cement industry between 2005 and 2012. *Source:* Primary data from [28] calculations by authors.

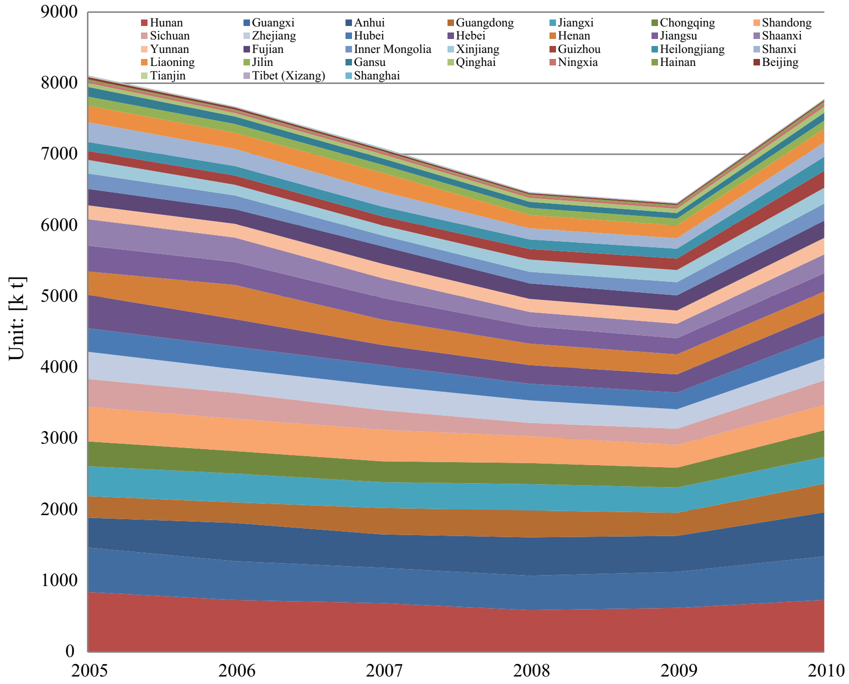

Fig. 22. Historical air pollutant emissions in cement industry by each region. *Source:* Primary data from [28] calculations by authors.

Appendix B

Cement consumption per capita per year between 2005 and 2030. Unit: [kg per capita per year].

Region	2005	2010	2015	2020	2025	2030
Anhui	538	1028	1290	1350	1060	710
Beijing	1756	1223	1550	1370	1080	730
Chongqing	802	1513	1730	1440	1090	740
Fujian	795	1641	1860	1660	1270	870
Gansu	541	681	897	1182	1150	830
Guangdong	926	1245	1370	1210	960	710
Guangxi	682	1056	1295	1250	1000	750
Guizhou	399	645	873	1180	1380	980
Hainan	539	1091	1546	1730	1480	980
Hebei	1119	1736	1695	1540	1260	790
Heilongjiang	318	491	592	714	865	870
Henan	668	1227	1592	1440	1100	750
Hubei	744	1174	1549	1400	1060	710
Hunan	607	1304	1850	1650	1260	860
Jilin	588	1321	1634	1480	1140	790
Jiangsu	1303	1830	1680	1380	1080	780
Jiangxi	878	1551	1980	1780	1360	910

Appendix B (*continued*)

Region	2005	2010	2015	2020	2025	2030
Liaoning	634	1014	1080	1000	810	610
Inner Mongolia	684	1517	1962	1750	1250	830
Ningxia	944	1878	1900	1500	1100	700
Qinghai	683	1101	1619	1650	1300	850
Shaanxi	864	1017	1311	1390	1100	750
Shanghai	1433,1	1020	1550	1370	1080	730
Shandong	1554	1700	1560	1300	1000	700
Shanxi	693	809	994	1040	910	710
Sichuan	512	1452	1185	1470	1270	880
Tianjin	1630	1925	1550	1370	1080	730
Tibet (Xizang)	903	997	1315	1330	1060	760
Xinjiang	634	975	1315	1330	1060	760
Yunnan	642	1004	1350	1460	1170	820
Zhejiang	1934	2190	1900	1600	1200	800

Appendix C

Fuel price and electricity price by each region in 2005 and 2010 (2010 $).

Region	2005		2010	
	Coal ($/GJ)	Electricity ($/kW h)	Coal ($/GJ)	Electricity ($/kW h)
Anhui	3.62	0.11	5.63	0.11
Beijing	3.70	0.09	8.57	0.09
Chongqing	2.32	0.10	4.45	0.11
Fujian	3.97	0.09	4.71	0.10
Gansu	1.75	0.08	3.21	0.08
Guangdong	3.69	0.10	5.23	0.10
Guangxi	3.79	0.10	5.06	0.11
Guizhou	2.59	0.07	5.38	0.09
Hainan	3.56	0.10	5.91	0.11
Hebei	2.89	0.09	4.78	0.10
Heilongjiang	2.39	0.09	2.97	0.11
Henan	3.10	0.09	5.68	0.09
Hubei	2.94	0.10	4.97	0.11
Hunan	3.36	0.10	5.31	0.10
Jilin	2.33	0.12	3.60	0.12
Jiangsu	4.42	0.10	5.72	0.12
Jiangxi	3.35	0.11	5.51	0.10
Liaoning	2.74	0.10	4.12	0.10
Inner Mongolia	1.99	0.09	2.89	0.08
Ningxia	1.65	0.07	3.12	0.08
Qinghai	1.96	0.07	3.55	0.07
Shaanxi	2.15	0.09	4.15	0.09
Shanghai	3.73	0.10	6.54	0.10
Shandong	3.75	0.10	5.43	0.10
Shanxi	2.07	0.08	4.13	0.09
Sichuan	2.25	0.09	4.22	0.09
Tianjin	2.92	0.08	4.68	0.10
Tibet (Xizang)	2.80	0.09	4.68	0.10
Xinjiang	1.29	0.09	1.45	0.07
Yunnan	2.57	0.07	3.86	0.09
Zhejiang	4.12	0.10	6.43	0.10
National average	2.80	0.09	4.68	0.10

References

[1] Wen Z, Chen M, Meng F. Evaluation of energy saving potential in China's cement industry using the Asian-Pacific Integrated Model and the technology promotion policy analysis. Energy Policy 2014:1–11.

[2] Chen W, Hong J, Xu C. Pollutants generated by cement production in China, their impacts, and the potential for environmental improvement. J Clean Prod 2014:1–9.

[3] 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.

[4] MEP of China. MEP announces new emission standards for major industries – efforts to implement the ten major measures against air pollution; 2014. <http://english.mep.gov.cn/News_service/news_release/201401/t20140115_266434.htm>.

[5] 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.

[6] Liu F, Ross M. Energy efficiency of China's cement industry. Energy 1995:20.

[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] 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.

[9] 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.

[10] 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.

[11] 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.

[12] Fujii H, Managi S, Kaneko S. Decomposition analysis of air pollution abatement in China: empirical study for ten industrial sectors from 1998 to 2009. J Clean Prod 2013;59:22–31.

[13] Shih Y-H, Tseng C-H. Cost-benefit analysis of sustainable energy development using life-cycle co-benefits assessment and the system dynamics approach. Appl Energy 2014;119:57–66.

[14] Worrell E, Laitner Ja, Ruth M, Finman H. Productivity benefits of industrial energy efficiency measures. Energy 2003;28:1081–98.

[15] International Energy Agency. Capturing the Multiple Benefits of Energy Efficiency Capturing the Multiple Benefits of Energy Efficiency; 2014.

[16] Nam K-M, Waugh CJ, Paltsev S, Reilly JM, Karplus VJ. Synergy between pollution and carbon emissions control: Comparing China and the United States. Energy Econ 2014;46:186–201.

[17] Nam K-M, Waugh CJ, Paltsev S, Reilly JM, Karplus VJ. Carbon co-benefits of tighter SO_2 and NOx regulations in China. Glob Environ Chang 2013;23:1648–61.

[18] Jiang P, Chen Y, Geng Y, Dong W, Xue B, Xu B, et al. Analysis of the co-benefits of climate change mitigation and air pollution reduction in China. J Clean Prod 2013;58:130–7.

[19] 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.

[20] 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.

[21] Pan H, Zhang H, Zhang X. China's provincial industrial energy efficiency and its determinants. Math Comput Model 2013;58:1032–9.

[22] Xiaoli Z, Rui Y, Qian M. China's total factor energy efficiency of provincial industrial sectors. Energy 2014;65:52–61.

[23] Yang M, Fan Y, Yang F, Hu H. Regional disparities in carbon dioxide reduction from China's uniform carbon tax: a perspective on interfactor/interfuel substitution. Energy 2014;74:131–9.

[24] Song Y, Zhang M, Dai S. Study on China's energy-related CO_2 emission at provincial level. Nat Hazards 2015;77:89–100.

[25] Yang L, Wang KL. Regional differences of environmental efficiency of China's energy utilization and environmental regulation cost based on provincial panel data and DEA method. Math Comput Model 2013;58:1074–83.

[26] Wei J, Jia R, Marinova D, Zhao D. Modeling pollution control and performance in China's provinces. J Environ Manage 2012;113:263–70.

[27] Liao H, Du J, Wei YM. Energy conservation in China: key provincial sectors at two-digit level. Appl Energy 2013;104:457–65.

[28] China Cement Association. China Cement Almanac; 2010. p. 435–531. <http://tongji.cnki.net/kns55/navi/HomePage.aspx?id=N2012070092&name=YZZSN&floor=1>.

[29] China Cement Association. The mid-term evaluation of "Twelfth Five Year Plan" for Chinese cement industry; 2012. <http://www.dcement.com/UploadFiles/Article_UploadFiles/201308/2013082117085674.pdf>.

[30] China Building Materials Daily. The status of China's cement grinding enterprises. China Build Mater Daily; 2014. <www.cbmd.cn:85/content/2014.../content_20540.htm>.

[31] Center for industrial energy efficiency and Energy Foundation China. China's industrial energy saving progress report 2013; 2014. <http://www.efchina.org/Attachments/Report/reports-20140701-zh>.
[32] 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.
[33] Zhang S, Ernst W, Crijns-Graus W. Evaluating the cobenefits of energy efficiency and emission mitigation for China's cement industry. Appl Energy 2015;147:192–213.
[34] OECD Stat Extracts. OECD Stat Extracts; 2014. <http://stats.oecd.org/>.
[35] China Cement Association. China Cement Almanac; 2011–2013. p. 421–41. <http://tongji.cnki.net/kns55/navi/HomePage.aspx?id=N2012070092&name=YZZSN&floor=1>.
[36] China Building Materials Daily. China's cement industry development has entered new era. China Build Mater Daily; 2014. <http://data.cementren.com/2014/Readings_1014/242.html>.
[37] Lei Y, Zhang Q, He KB, Streets DG. Primary anthropogenic aerosol emission trends for China, 1990–2005. Atmos Chem Phys 2011;11:931–54.
[38] Ürge-Vorsatz D, Herrero ST, Dubash NK, Lecocq F. Measuring the co-benefits of climate change mitigation. Annu Rev Environ Resour 2014;39:549–82.
[39] Saari RK, Selin NE, Rausch S, Thompson TM. A self-consistent method to assess air quality co-benefits from US climate policies. J Air Waste Manag Assoc 2015;65:74–89.
[40] Zhang S, Worrell E, Crijns-Graus W, Wagner F, Cofala J. Co-benefits of energy efficiency improvement and air pollution abatement in the Chinese iron and steel industry. Energy 2014;78:333–45.
[41] Russell C. Multiple benefits of business-sector energy efficiency: a survey of existing and potential measures; 2015.01.07 [35p]. <http://aceee.org/sites/default/files/publications/researchreports/ie1501.pdf>.
[42] National Bureau of Statistics of China. China Energy Statistical Yearbook 2013. National Bureau of Statistics of China; 2013 [Chapter 4]. <http://tongji.cnki.net/kns55/Navi/HomePage.aspx?id=N2010080088&name=YCXME>.
[43] National Bureau of Statistics of China. China Energy Statistical Yearbook 2011. National Bureau of Statistics of China; 2011 [Chapter 4]. <http://tongji.cnki.net/kns55/Navi/HomePage.aspx?id=N2010080088&name=YCXME>.
[44] China Building Materials Academy, Energy saving center of Sichuan Province. Energy saving potential on technical and economical aspecs in cement industry, Si Chuan Province; 2010 [internal report].
[45] Wei S, Wang Dong. The forecasting for China's cement output between 2009 and 2050. China Cem Technol Conf; 2009. p. 9–26.
[46] Wei S, Wang Dong. The forecasting for China's cement output between 2008 and 2050. China Cem Technol Conf; 2008. p. 96.
[47] Wei S, Wang Dong. The forecasting for China's cement output between 2011 and 2050. China Cem Technol Conf; 2011. p. 10.
[48] National Bureau of Statistics of China. Almanac of China's population 2011; 2011.
[49] Zhou N, Price L, Zheng N, Ke J. National level co-control study of the targets for energy intensity and sulfur dioxide in China; 2011.
[50] 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.
[51] Yande Dai, Hu X. Roadmap study on achieving technical energy conservation potential in China's industrial sector by 2020. China Environmental Press; 2013.
[52] MIIT of China. The assessment of energy saving and emissions reduction in key industries in China [n.d].
[53] 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.
[54] NCSC of China. The average carbon dioxide emission factor of power grid in China's regional and provincial level in 2010; 2010.
[55] CSI. CO_2 and energy accounting and reporting standard for the cement industry: the cement CO_2 and energy protocol; 2011.
[56] CSI. Guidelines for emissions monitoring and reporting in the cement industry; 2012.
[57] United Nations Development Program, Chinese Academy of Social Sciences. China national human development report 2013: sustainable and liveable cities: toward ecological urbanisation; 2013.
[58] Keith Bradsher. China's dominance in cement has little effect on European suppliers; 2014.
[59] Zhang LX, Feng YY, Zhao BH. Disaggregation of energy-saving targets for China's provinces: modeling results and real choices. J Clean Prod 2014:1–10.
[60] Matthes FC. Pilot on Benchmarking in the EU ETS Report prepared for the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety; 2008.
[61] IPCC. Chapter 10 industry. vol. 10; 2014.
[62] Wu D, Xu Y, Zhang S. Will joint regional air pollution control be more cost-effective? An empirical study of China's Beijing–Tianjin–Hebei region. J Environ Manage 2015;149:27–36.
[63] Miller FM, Young GL, Seebach M Von. Formation and techniques for control of sulfur dioxide and other sulfur compounds in Portland cement kiln systems; 2001.
[64] Xing J, Wang SX, Chatani S, Zhang CY, Wei W, Hao JM, et al. Projections of air pollutant emissions and its impacts on regional air quality in China in 2020. Atmos Chem Phys 2011;11:3119–36.
[65] Global Cement. China to cut nitrogen oxide emissions to 450 mg. Glob Cem 2013:1.
[66] Portland Cement Association. Innovations in Portland cement manufacturing; 2004.
[67] China Building Materials Daily. The status of grinding plant in China. China Build Mater Dly; 2014.
[68] Wang C, Cai W, Liao H, Lin J. China's carbon mitigation strategies: enough? Energy Policy 2014;73:47–56.
[69] 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.
[70] Hasanbeigi A, Morrow W, Sathaye J, Masanet E, Xu T. A bottom-up model to estimate the energy efficiency improvement and CO_2 emission reduction potentials in the Chinese iron and steel industry. Energy 2013;50:315–25.
[71] Institute for Industrial Productivity, International Finance Corporation. Waste heat recovery for the cement sector: market and supplier analysis; 2014.
[72] Peter Edwards. China: first in cement. Glob Cem Mag 2013.
[73] Huawen X. Policies for utilization of industrial waste heat and its current situation and potential in China. Natl Energy Conserv Cent 2014.