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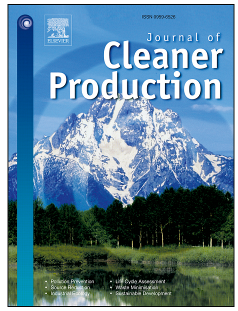

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Assessing air pollution abatement co-benefits of energy efficiency improvement in cement industry: a city level analysis

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Abstract

China is the world's largest cement producer, contributing to 60% of the global total. Jiangsu province takes the lead of cement production among China's provinces, contributing to 8.4% of the national total cement output. In this study, a geo-graphical information system-based energy model is developed to assess the potential of energy savings and associated mitigation of CO_2 and air pollutant emissions in Jiangsu's cement industry during 2015–2030. Results show that 1) compared to 2015, energy consumption in the baseline scenario will decrease by 54% at the provincial level. Economical energy saving potential for 2030 is around 50 PJ, which equals to 35% of energy use in the baseline in 2030. 2) At the city level, Changzhou, Wuxi, and Xuzhou are top three cities in terms of energy saving potential. 3) The economical CO_2 emission reductions will decrease by 4.4 Mt in 2030, while the emissions of PM and NOx would decline by 30% and 56%, respectively. This study will help policy makers develop integrated policies to support the coordinated development of Jiangsu and can also enhance the effectiveness of the implementation of joint prevention and control of atmospheric pollution to improve regional air quality.

Keywords: co-benefits; GIS-based energy model; energy efficiency; cement industry; emission reduction

Nomenclature

Abbreviations

ECSC Energy conservation supply curves
CSC Conservation Supply Curve
GHG Greenhouse gases
SO_2 Sulfur dioxide
NOx Nitrogen oxides

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PM Particulate matter
Mt Million tons
kt Thousand tons
EJ Exajoule
GAINS–ECSC Greenhouse Gas - Air Pollution Interactions and Synergies (GAINS)- Energy conservation supply curves
NSP New Suspension Preheater/Precalciner
t/d Tons per day
GIS A geo-graphical information system (GIS)
EECP Energy efficiency policy with cost effective energy saving potential scenario
EETP Energy efficiency policy with technical energy saving potential scenario
AEEI Annual autonomous energy efficiency improvement
BL Baseline scenario
NBS China National Bureau of Statistics
NDRC China National Development and Reform Commission

Symbols

CCE Cost of conserved energy for an energy efficiency measures
P Cement production
p_i Cement production in city i
NFS New floor space in city i
BCI Building cement material intensity
HCI Highway cement material intensity
NLH New length Highways in city i
RCI Railway cement material intensity
NLH New length Railways in city i
Ini Industrial Investment
ICI Industrial construction cement intensity
Ex Net export of cement
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 Energy price
d Discount rate;
n Lifetime of the energy efficiency measures

Subscript

i city

1. Introduction

Chinese government announced the target "to achieve a peak of CO_2 emissions around 2030 and to make the best efforts to peak early" for the Paris agreement (NDRC, 2015). Cement industry is one of the most energy intensive industrial sectors, and also one of the largest contributors to CO_2 emissions and air pollution (Morrow III et al., 2014; Worrell et al., 2013; Worrell et al., 2001). China is the largest cement producer and consumer in the world, accounting for 59% of the global total, consuming 6961 PJ of final energy, and emitting 1380 Mt CO_2, 410 Mt of PM, 1.3 Mt of SO_2, and 2.27 Mt of NOx, respectively, of the total sectors' emissions (Zhang et al., 2015b). Recent studies have shown that the future energy consumption of China's cement industry in a reference scenario could continue increase to 8,500 PJ by 2020, 84% higher than 2010. This would result in increased projected annual emissions of 1,719 Mt of CO_2, 5,700 kt of PM, 1,400 kt of SO_2, and 780 kt of NOx, respectively (Zhang et al., 2015b,c). Jiangsu is China's largest cement producer and responsible for 8.4% of total China's cement production. In 2015, Jiangsu's cement industry consumed around 261 PJ of final energy and emitted 98 Mt of CO_2, 9 kt of SO_2, 67 kt of PM, and 74 kt of NOx (Jiangsu Provincial Bureau of Statistics, 2016).

Various studies have shown that there is large potential to improve energy efficiency and reduce emissions in China's cement industry (Chen et al., 2015; Hasanbeigi et al., 2013a; Hasanbeigi et al., 2013b; Hasanbeigi et al., 2010b; Ke et al., 2012; Wen et al., 2015). Energy efficiency measures can not only enhance the sustainability of the energy system but also can reduce emissions of CO_2 and other air pollutants (IEA, 2014a; IEA, 2014b). In this way, a smart air quality policy that incorporates energy efficiency as a core approach can simultaneously reduce energy use and greenhouse gas emissions, while achieving air quality targets at lower costs. However, the current energy models only simulate the potentials of energy efficiency improvement and emissions' mitigation based on direct costs, which leads to an underestimation of the full benefits of energy efficiency. The GAINS–ECSC model, developed by Utrecht University, was used to assess the co-benefits of energy efficiency measures for reducing greenhouse gas (GHG) and air pollutant emissions, in addition to energy consumption in China's cement industry (Zhang et al., 2015a,b). These studies neglected the regional heterogeneity across China, especially for Jiangsu province. The co-benefits of energy efficiency have not yet been systematically assessed for Jiangsu's cement industry, owing to limited data and few mature methodologies to measure their scope and scale. As a result, there is lack of supporting tools for local policy makers to develop and implement effective policies of adopting energy efficiency technologies in cement industry. Understanding the co-benefit of energy efficiency for air pollution in Jiangsu's cement industry at city level is an urgent necessity. This knowledge gap is the starting point of this study, which aims to assess the potential of energy efficiency improvement in Jiangsu's cement industry to mitigate emissions of CO_2 and air pollutants. Combining geographic data as well as air quality data with energy modeling will allow a thorough analysis of the impacts of energy efficiency improvement. Furthermore, the geographic modeling will allow evaluation of the effects of different policies (including closure of outdated cement plants) on local air quality. This paper can support the development of effective air quality policy implemented by national and provincial authorities, and realizing the indirect climate benefits in the process.

2. Overview of the cement industry in Jiangsu Province

Cement production in Jiangsu province has increased 1.8-fold since 2005, reaching 180 Mt in 2015 (Fig. A-1 in Supplementary-A). However, the clinker production has only increased by 30%, from 55 Mt in 2005 to 72 Mt in 2012, since when there has been a slight decrease, at an average of 4% per year (China Cement Association, 2016; Jiangsu Provincial Bureau of Statistics, 2016). The outdated kiln systems were almost completely replaced by New Suspension Preheater/Precalciner (NSP) kilns before 2005 (Fig. A-2 in Supplementary-A). The total production capacity of NSP kilns increased from 6 Mt before 2000 to 60 Mt in 2015. Meanwhile, the average clinker production capacity increased from 2,450 t/d before 2000 to 3,432 t/d in 2015. Compared to the growth of cement output, energy consumed in this industry showed a mild increasing trend, from 216 PJ in 2005 to 286 PJ in 2013 (Fig. A-3 in Supplementary-A), due to fast development of dry process, phase-out of smaller scale cement plants, and import of clinker from surrounding regions. Coal plays a dominant role in energy consumption in Jiangsu's cement industry, accounting for 86% of the total, followed by electricity.

Total CO_2 emissions in Jiangsu's cement industry increased from 74 Mt in 2005 to 104 Mt in 2015, at an average annual growth rate of 4% (see Fig. 1.). The fuel combustion share of total CO_2 emissions ranges from 50–60%, followed by process emissions (30–40%). Interestingly, the contribution of process calcination to total CO_2 emissions in Jiangsu's cement industry is comparatively 5–10% lower than the national average level due to the ratio difference between clinker and cement.

Fig. 1. Emissions CO_2 and air pollutants from Jiangsu's cement production

Fig. 1 also shows that the historical trends of air pollutants emissions in Jiangsu's cement industry were completely different from those of energy-related CO_2 emissions. Air pollutant emissions decreased by two thirds from 2005 through 2011 and then declined modestly over the next four years. PM is the largest contributor to air pollution in the Jiangsu's cement industry; the PM share of total air pollution decreased from 70% in 2005 to 45% in 2015, due to accelerating the implementation of NSP kilns, energy efficiency improvement, and the phasing-out of small scale cement plants. Like the trend of PM emissions, the SO_2 emissions decreased by four fifths from 2005 to 2010 and then remained at a stable level. However, the NOx emissions showed an opposite trend compared to the PM and SO_2 emissions.

3. Methods and data

3.1 General description of model framework

To support the development of an appropriate air quality policy that builds on energy efficiency and assess the effect of changing regional productions of cement and clinker (by closing or concentrating production at specific sites), a GIS-based energy model is developed that can assess the impacts on air quality, energy use, and greenhouse gas emissions. Fig. 2 shows the simplified diagram of the model framework. This model can not only be used to formulate effective policy strategies for the provincial government, but also be extended to apply to other regions or industries.

Fig. 2. Simplified diagram of model framework

As the diagram shows, the framework comprises four parts, demand projection, GIS-based modeling, and cost-benefit analysis. The demand projection part provides the future's development of cement industry in Jiangsu Province as well as in all the cities over the period from 2015 to 2030. This serves the basic input for the overall scenario analysis. The second step is to set up a GIS-based energy model based on the combination of provincial energy conservation supply curves (ECSC) and the core model constructed with elaborated spatial functions by applying ArcGIS, a geo-graphical information system (GIS) software. By applying this model, the cost-benefit analysis can be conducted to assess the potential of energy savings and associated mitigation of emissions of CO_2 and air pollutants. More details are provided as follows.

3.2 Projection of the outputs of cement and clinker

Cement production is closely linked to new buildings, urbanization rates, and construction of roads, highways, and railways (Hasanbeigi et al., 2017; Ke et al., 2012). For a better projection of Jiangsu's cement output, the current economy growth rate, the urbanization process, future activities of new buildings, construction of roads, highways, and railways are estimated. Also, the phase-out rate of outdated production, and other policies that aim to control the overcapacity are considered. Set 2015 as the base year for analyzing the historical trends of energy use, production structure, emissions. This step can provide more evidence when estimating implementation rates of energy efficiency measures and the potential needs to be assessed based on existing production capacities and production structures. In the study, the urbanization rate of each city in 2015 is from the Jiangsu Statistical Yearbook (Jiangsu Provincial Bureau of Statistics, 2016). The average floor area per capita of each province in 2015 is from Wei's study (Wei and Dong, 2011). The formula for projecting the future cement production of each city is shown below (see Eq. (1)).

$$P = \sum_i p_i = \sum_i (NFS * BCI + HCI * NLH + RCI * NLR + Ini * ICI + Ex) \quad \text{Eq. (1)}$$

Where:
P= cement production;
p_i= cement production in city i;
NFS= New floor space in city i;
BCI= Building cement material intensity;
HCI= Highway cement material intensity;
NLH= New length Highways in city i;
RCI= Railway cement material intensity;
NLH= New length Railways in city i;
Ini = Industrial Investment;
ICI= Industrial construction cement intensity;
Ex= Net export of cement.

Note that the net export of cement in the base year is used to estimate the future cement production at provincial level during the whole period. The provincial ratio of clinker and cement production in 2015 is used to estimate the future clinker outputs up to 2030 at the city level. The results of cement and clinker production of each city between 2015 and 2030 are listed in Table A-1 of Supplementary-A, which shows the peak of cement and clinker production of each city appears in 2015 and then declines gradually. Detailed data containing production capacities, production scales and technology distributions etc. for all the cities of Jiangsu Province are provided in Supplementary-C.

3.3 GIS-based energy model

A GIS-based energy model is constructed by incorporating energy conservation supply curve into an ArcGIS-based distribution analysis platform. Energy Conservation Supply Curve is used to assess the energy saving potential function of the marginal cost of conserved energy. In this approach, the cost of conserved energy by dividing the net present value (NPV) of annual costs over the study period (2015–2030) by the simple sum of annual energy saving over the same period. Several studies illustrate that co-benefits from air pollutant emissions' reduction as a result of energy saving measures can reduce the CCE of those measures (Hasanbeigi et al., 2013a; Ma et al., 2015; Price et al., 2008; Tomaschek, 2015; Worrell et al., 2013; Xi et al., 2013; Zhang et al., 2014). However, none of these studies quantified the co-benefits of energy efficiency improvement and emissions' reduction of GHG and air pollutants through energy efficiency measures at a regional scale, especially at city level. The calculation of the costs of conserved energy for energy efficiency technology is presented in Eq. (2), more details on the methodology for the construction of ECSCs are presented in (Hasanbeigi et al., 2013a, 2013b, 2010b).

$$CCE = \frac{I \times AF + O\ \&\ M^{Fix} + O\ \&\ M^{Var} - ESP \times PE}{ESP} \qquad \text{Eq. (2)}$$

Where:

CCE= Cost of conserved energy (CCE) for an energy efficiency measures, in $/GJ;

I= Investment;

AF= Annuity factor;

$O\ \&\ M^{Fix}$= Annual change in operation and maintenance fixed cost;

$O\ \&\ M^{Var}$= Annual change in operation and maintenance variable cost;

ESP= Annual energy saving potential;

PE= Energy price ($/GJ).

In this study, a discount rate of 10% is assumed. The annuity factor can be calculated from Eq. (3).

$$AF = \frac{d}{(1-(1+d)^{-n})} \qquad \text{Eq. (3)}$$

Where:

d= Discount rate;

n= Lifetime of the energy efficiency measures.

To construct ECSCs, a database that includes all the detailed techno-economic parameters of energy efficiency measures (e.g., capital costs, operation and maintenance costs, lifetime, etc.) is built up. Note that cement and clinker production facilities are treated individually, characterizing them by production, energy use, and emissions. Integrating the outputs of energy saving and emission mitigation potentials into ArcGIS. The model is employed to simulate the dynamic potential of cost-effective energy savings and emission reductions of CO_2 and air pollutants (e.g. SO_2, NOx, and PM) in Jiangsu's cement industry both with and without multiple benefits.

3.4 Scenario design

In this study, we develop three scenarios in line with our previous research, to estimate the co-benefits of energy efficiency improvement and associated mitigation of emissions of CO_2 and air pollutants in Jiangsu's cement industry at the city level. The first one is the baseline scenario, the second one considers energy efficiency policies only adopting cost-effective energy saving potential (EEPCP scenario), and the third one considers energy efficiency policies that can realize full potential of technical energy savings (EEPTP scenario) (Zhang et al., 2015b). Fig. 3 defines the analysis scope of these three scenarios.

Fig. 3. Analysis scope of the three scenarios

One key innovation of this study is that eliminating older and small-scale cement plants is considered when forecasting the dynamic distribution of clinker and cement for each city. We assume that the discount rate, energy prices, the distribution of clinker and cement, and fuel structures are the same in all scenarios. The baseline scenario assumes that annual autonomous energy efficiency improvement (AEEI) is 0.2%, which is consistent with our previous studies (Zhang et al., 2015b; Zhang et al., 2016). For the EEPCP scenario, we assume that the cost-effective energy efficiency measures (the CCE of energy efficiency measures below 0 $/GJ) with projected implementation rates would be implemented across Jiangsu province. In this scenario, we calculate the cost-effective energy saving potential in Jiangsu's cement industry, based on 24 current commercially available energy efficiency measures. We show how cost-effective energy saving and associated emissions mitigation will be responsible for provincial targets. Additionally, we assume that all energy efficiency measures will be fully implemented in energy efficiency policy with an EEPTP scenario. The dynamic geographic distribution of energy consumption, GHG, and air pollution under different scenarios are simulated; this can be used to ensure the highest air quality and energy/GHG benefits with minimum costs. As a major advancement, the co-benefits of energy efficiency are modeled. This allows for the evaluation of the synergies between policies and of the resulting cost savings. The co-benefits of energy efficiency for emission mitigation are further calculated to model how co-benefits would affect the cost-effective potential of energy saving.

3.5 Data sources

The production data of cement and clinker in Jiangsu province are from the China Cement Almanac (China Cement Association, 2016), the China Statistical Yearbook (NBS, 2016), and the Jiangsu Statistical Yearbook (Jiangsu Provincial Bureau of Statistics, 2016). The historical coal combustion and electricity consumption data in Jiangsu's cement industry are obtained from the China Energy Statistical Yearbook (NBS, 2017) and the Jiangsu Statistical Yearbook (Jiangsu Provincial Bureau of Statistics, 2016) and are calibrated based on current literature (Cai et al., 2016; Dai and Hu, 2013; Hasanbeigi et al., 2013a; Hasanbeigi et al., 2013b; Wen et al., 2015; Xi et al., 2013; Xu et al., 2014; Zhang et al., 2015d). The historical data of the population and urbanization of each city in Jiangsu Province are collected from the Jiangsu Statistical Yearbook (Jiangsu Provincial Bureau of Statistics, 2016). The future population of each city is calculated based on the projection in the GAINS database.

The cement material intensity in the building industry is assumed to be 0.18 t/m^2 floor area (Liu, 2017). The cement material intensities for highway, railway, and construction industries are obtained from the current literature (Hasanbeigi et al., 2017). Note that the cement material intensity by end-users and the net export share of total cement production are assumed to be unchanged in the study period. Some key parameters including production capacities, production scales and technology distributions etc. in the cities of Jiangsu Province are provided in Supplementary Data.

Several studies indicate that many best energy efficiency technologies are already implemented in Jiangsu's cement industry. However, there is still room for improving energy efficiency and reducing emissions of GHG and air pollutants, due to the scales of NSP line have large difference in Jiangsu province. This study includes 37 best commercially available energy efficient measures that includes four different processes (see Supplementary-B): fuel and raw material preparation, clinker making, finish grinding, and general measures. The parameters (i.e., fuel saving, electricity saving, capital cost, operating and maintenance costs, lifetime, and current implementation rate in base year) of these energy efficiency measures are obtained from our recent study (Zhang et al., 2015b,c), in addition to other recent studies from (Tsinghua University, 2008; Hasanbeigi et al., 2013b; Wang et al., 2014; Wen et al., 2015; Worrell et al., 2013). In addition, the implementation rates of each energy efficiency measure are defined using a linear deployment approach and assumed to be fully implemented by 2030. Note that cement production from the wet process in Jiangsu was already phased out in 2015 (Economic and Information Commission of Jiangsu Province, 2016); therefore, energy efficiency measures for the wet process are not taken into account in this study. The costs of each energy efficiency measure are priced at $2015, and the prices of coal and electricity are taken from the China Cement Almanac (China Cement Association, 2016).

The CO_2 emission factors for electricity consumption in Jiangsu province are obtained from regional grid baseline emission factors of China (NDRC, 2011). The CO_2 emission factors for coal and process are from our recent studies (Zhang et al., 2015b; Zhang et al., 2016). The emission factors of SO_2, NOx, and PM are calculated according to recent studies (Lei et al., 2011), and calibrated through running the GAINS model (for more information about GAINS, http://gains.iiasa.ac.at/models/index.html). Note that the above emission factors are assumed constant during the whole period. The energy efficient technologies and the associated key techno-economic parameters are provided in Supplementary Data.

4. Results and discussion

4.1 Energy consumption under different scenarios

The results of energy consumption in Jiangsu's cement industry from 2015 to 2030 across the three scenarios are shown in Fig. 4. In the baseline scenario, energy consumption is expected to decline to 141 PJ in 2030, roughly 54% of the level in 2015. This reduction reflects the effect from shrinkage of the production size of the industry. In contrast, the results of EEPCP and EEPTP indicate remarkable energy saving potential through the adoption of energy efficiency technologies. Under the EEPCP scenario, in which all cost-effective energy efficiency measures (represent economically feasible opportunities to reduce energy consumption) are fully implemented, energy consumption will decrease by 35% compared to the baseline scenario. This potential is further enlarged in the more stringent scenario of EEPTP, in which almost half of the energy use in BL scenario can be reduced.

The regional distribution of energy saving potential, as measured by the gaps between the baseline scenario and the other two scenarios, is significantly uneven, as shown in Fig. 4. Apparently, this potential for each city is closely associated with their respective cement production sizes. For example, Changzhou, Wuxi, and Xuzhou, as the top three cement producing cities in Jiangsu, possess the most significant energy saving potential in the EEPCP results for 2020. On the contrary, by virtue of their size, small producers such as Lianyungang have much less potential. However, this relationship does not apply to all the cases, because other factors, such as urbanization rate and technology level, also matter with respect to reaching this potential. In particular, the results for 2030 in the EEPCP scenario reveal that Huai'an replaces Wuxi as the third largest city in terms of energy saving potential in cement production. An important reason for this is that Wuxi is currently more urbanized than is Xuzhou, and its cement need in the future is, therefore, much smaller. The results of Table A-1 show that cement output for Wuxi in 2030 will reduce to only 40% of its 2015 level in our prediction, whereas this ratio is 67% in Huai'an's case. Another noteworthy example is Suzhou. As one of the most affluent cities in China, Suzhou's urbanization rate reached as high as 75% in 2015, far higher than the national average level. As a result, its potential demand for infrastructure and construction in the future will be much smaller than will be the demands of less developed regions, which, in turn, affects the energy saving potential within its cement industry. Despite this, the EEPTP scenario demonstrates notable potential that is larger than 3 PJ for all the cities other than Lianyungang.

Fig. 4. Energy consumption and saving potential by city under different scenarios

4.2 CO_2 emissions for different scenarios

CO_2 emissions from Jiangsu's cement production in 2015 was roughly 104 Mt. Following the same reduction rate as energy consumption, CO_2 emissions in the baseline decrease to 57 Mt in 2030, or 54% of the level in 2015. Note that Fig. 5 shows that the reduction potential of carbon emissions in EEPCP and EEPTP are much smaller compared to energy saving. The main reason for this is that adopting energy efficient technologies reduces the energy-related emissions; however, it has little impact on process-related emissions, which account for roughly 40% of total emissions from cement production. Nevertheless, the absolute term is still large, cost-effective energy efficiency measures will contribute to decreasing emissions by 4.4 Mt in 2030 compared to the baseline, and all the technologies, in total, have a larger potential of 7.48 Mt, as shown in the EEPTP scenario.

Furthermore, this reduction potential is unevenly distributed across all the cities. Similar to the energy saving profile, Changzhou, Xuzhou, and Huai'an take larger shares among the cities, while Lianyungang has the smallest room for reduction. Not surprisingly, the results from EEPTP show much larger reduction potential relative to EEPCP from the very beginning to the end of this timespan. Apart from Lianyungang, all the cities can reduce emissions by more than 0.4 Mt in 2030 with the adoption of technically viable technologies. In particularly, Changzhou and Xuzhou show potential exceeding 1 Mt. Under the EEPCP scenario, which adds the restraint of the economic profitable condition, the potential will shrink to 60% of the EEPTP level.

Fig. 5. CO_2 emissions and their reduction potential by city under different scenarios

4.3 Abatement of air pollution under different scenarios

Fig. 6 illustrates that significant potential for air pollution reduction can also be realized. In 2015, SO_2, NOx, and PM emissions from Jiangsu's cement industry reached as high as 9.0, 74.2, and 67.1 thousand tons, respectively. In the baseline scenario, a decline of production scale will reduce the emissions of the three pollutants to 4.9, 39.3, and 36.4 kt, respectively, or 54%, 53%, and 54%, respectively, of the 2015 levels.

However, the reduction potential for the three pollutants varies remarkably in the EEPCP and EEPTP scenarios. For example, in the EEPCP scenario, PM emissions are roughly 25.8 thousand tons in 2030, or 70% of the baseline scenario, indicating that 30% of PM can be reduced through applying cost-effective technology. In contrast, NOx emissions can achieve 17.2 kt, just 44% of the baseline; in other words, 56% of NOx can be cut under the same scenario. Furthermore, in the EEPTP scenario, the emissions can be as low as 8.9 kt, implying that a reduction of 77% of the baseline emissions can be realized. The case of SO_2 falls in the middle of the range between NOx and PM. This notable difference indicates that the effect of adopting these technologies is more significant in terms of NOx reduction, compared to PM and SO_2, which provides a feasible solution, particularly considering that the rate of installation of NOx removal systems in China's cement industry is currently low.

Fig. 6. Air pollutant emissions by city under different scenarios

Marked regional disparities also exist within Jiangsu in terms of the reduction potential of the three pollutants, as shown in Fig. 7. A common characteristic across the profiles of the three pollutants is that Xuzhou and Changzhou always rank in the first tier, and, therefore, possess the largest potential for pollution alleviation, mainly because of their relatively larger production volumes. An interesting phenomenon is that, although Changzhou is producing more cement and clinker than Xuzhou at present, its reduction potential will be surpassed by that of Xuzhou in the near future. This can be attributed to the higher urbanization rate of Changzhou, a more developed city (with almost twice the GDP per capita of Xuzhou) that will, hence, need less cement production in the different scenarios. Other cities, such as Wuxi, Nanjing, Huai'an, and Zhenjiang, can also benefit a lot, in terms of reducing these pollutions, from applying energy efficient technologies. It is noteworthy that the more affluent cities concentrated in the south part of Jiangsu, e.g., Nanjing, Wuxi, Changzhou, and Zhenjiang, have severe problems of air pollutant emissions, while the implementation of energy efficiency technologies offers not only a technically viable but also cost-effective solution to address this issue in Jiangsu.

Fig. 7. Air pollution reduction potential under different scenarios

5. Sensitivity and uncertainty analysis

Sensitivity/uncertainty analysis remains an important part in the state-of-the-art energy models, because current models cannot project the future precisely. In this paper, the key factors of the future distribution of cement and clinker by cities, fuel prices, and discount rates are discussed below.

To meet the requirement of cement demand for each city in Jiangsu, around 50% of clinker is imported from surrounding regions (e.g., Anhui and Shandong), due to the availability of raw material resources. The limestone resources in Jiangsu province are mainly located in the northern cities, such as Xuzhou, and the southern cities, such as Nanjing, Suzhou, Wuxi, and Changzhou (Wang et al., 2006). Therefore, we assume that the future distribution of clinker production is mainly from these cities. Additionally, we use the average utilization rate in the base year to forecast future activity levels and assume that the small-scale cement/grinding plants will be phased out to address the problems arising from increased excessive production capacity; thus, our approach might overestimate the potential benefits in the cities with small scale plants. Additionally, increasing energy price is one of the most important strategies to improve energy efficiency and mitigate CO_2 emissions (Hasanbeigi et al., 2013a; Tian and Liu, 2010). The energy price in Jiangsu province depends heavily on the policy impacts from government and the relationship between supply and demand. Hence, we assume that the future prices of coal and electricity remain unchanged, which should result in underestimation of the cost-effective electricity saving potential. Discount rate is another key factor in the cost and effectiveness analysis. In general, plants prefer to choose a high discount rate (i.e., 30%) when making investment decisions, while policy makers prefer to use a lower (social) discount rate (i.e. 4%) when projecting future pathways (Hasanbeigi et al., 2010a). Considering the development progress in Jiangsu at a city scale, the measures with higher marginal costs (e.g., high efficiency classifiers, high efficiency roller millers, and low pressure drop cyclones for suspension preheater) would be installed firstly by the cities where the people have higher personal income, such as Nanjing and Suzhou. Furthermore, if the co-benefits for mitigation of CO_2 emissions and air pollution are considered, the cost-effective energy saving potentials would increase across the province. One should note that the adoption of other substitutive technologies including such as geopolymers or SCC (self-consolidating concrete) materials has also very important impacts on sustainable development of cement industry, and thus influences the energy consumption in this industry to some extent. Though beyond the scope of this study focusing on energy efficiency technologies, further investigation of these factors would need to be explored in the future.

6. Conclusion

Jiangsu is the largest cement producer and consumer in China, accounting for 7.5% of China's total output. However, the Jiangsu's cement industry only consumes 5% of the final energy in China's cement industry. The key feature for Jiangsu's cement industry is that approximately 50% of clinker is imported from surrounding regions, and uses grinding plants to produce cement. The purpose of this study is to model the co-benefit potentials of energy efficiency and emission reductions of CO_2 and air pollutants in Jiangsu's cement industry at city level, using a GIS-based energy model that considers implementation of best energy efficiency measures.

First, we present a comprehensive analysis of outputs of clinker and cement, production capacity of NSP kilns, capital investment, energy consumption by fuel types, and emissions of CO_2 and air pollutants across the province. We find that the cement and clinker production in Jiangsu province has increased 1.8-fold and 30% during 2005–2015, while energy consumption and CO_2 emissions only increased by 21% and 40%, respectively. However, total air pollution decreased by two thirds during the same period.

Second, we develop a GIS-based energy model that includes provincial energy conservation supply curves that show the cost-effective and technical energy saving potential and emissions' reduction potential through energy efficiency at city levels and ArcGIS, a GIS with elaborated spatial functions. The model is used to assess the potential of energy savings and associated emission mitigation of CO_2 and air pollutants in Jiangsu's cement industry during 2015–2030. The results clearly show that: 1) at the provincial level, energy consumption in the baseline scenario will decrease by 54%, compared to the 2015 level. Under energy efficient scenarios, energy consumption in Jiangsu's cement industry will decline by 35% and 50% in EEPCP and EEPTP scenarios, respectively. 2) At the city scale we find that Changzhou, Wuxi, and Xuzhou are the top three largest cities in terms of energy saving potential between 2020 and 2030 in both scenarios; however, in 2030, Huai'an replaces Wuxi as the city with the third largest energy saving potential. Additionally, energy efficiency measures can not only reduce energy consumption, but also lower emissions of CO_2 and air pollution. Hence, scenario analysis in this paper indicates that, compared to baseline, the CO_2 emissions in EEPCP and EEPTP scenarios will decrease by 4.4 Mt and 7.5 Mt, respectively, in 2030. Similarly, the emissions of PM and NOx would decline by 30% and 56%, respectively, in the EEPCP scenario. The main reason for this is that of the emissions from process has less contribution than are those of than fuel combustion and electricity consumption. Another key finding is that the distribution of co-benefits varies greatly among different cities and is significantly affected by clinker output. Therefore, the policy makers of Jiangsu province, and end users (especially for the less-developed cities), should consider the co-benefits of energy efficiency measures when designing strategies for tackling issues of climate change and air quality.

Finally, the findings of this study will help policy makers of Jiangsu province develop and adopt an integrated policy to support the coordinated development of the Yangtze River Delta Economic Region (which encompasses Shanghai, Jiangsu, Anhui, and Zhejiang province), and can also enhance the effectiveness of the implementation of joint prevention and control of atmospheric pollution to improve the region's air quality.

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Reference

Tsinghua University, 2008. Assisting developing country climate negotiators through analysis and dialogue : report on energy saving and CO_2 emission reduction analysis in China's cement industry.

NDRC, 2011. Average carbon dioxide emission factor of power grid in China's regional and provincial level in China.

IEA, 2014a. Capturing the multiple benefits of energy efficiency.

IEA, 2014b. Energy efficiency market report.

NDRC, 2015. Enhanced actions on climate change: China's intended nationally determined contributions.

Economic and Information Commission of Jiangsu Province, 2016. 13th Five Year Plan for building materials industry development in Jiangsu Province

China Cement Association, 2016. China Cement Almanac 2005-2015.

NBS, 2016. China Statistical Yearbook 2010-2016.

Jiangsu Provincial Bureau of Statistics, 2016. Jiangsu Statistical Yearbook 2011-2015.

NBS, 2017. China Energy Statistical Yearbook 2010-2016.

Cai, B., Wang, J., He, J. and Geng, Y., 2016. Evaluating CO_2 emission performance in China's cement industry: an enterprise perspective. Applied Energy 166: 191-200.

Chen, W., Hong, J. and Xu, C., 2015. Pollutants generated by cement production in China, their impacts, and the potential for environmental improvement. Journal of Cleaner Production 103: 61-69.

Dai, Y. and Hu, X., 2013. Potential and Cost Study on China's Carbon Mitigation Technologies.

Hasanbeigi, A., Khanna, N. and Price, L., 2017. Air Pollutant Emissions Projections for the Cement and Steel Industry in China and the Impact of Emissions Control Technologies.

Hasanbeigi, A., Lobscheid, A., Lu, H., Price, L. and Dai, Y., 2013a. Quantifying the co-benefits of energy-efficiency policies: a case study of the cement industry in Shandong Province, China. Science of the total environment 458: 624-636.

Hasanbeigi, A., Menke, C. and Therdyothin, A., 2010a. The use of conservation supply curves in energy policy and economic analysis: the case study of Thai cement industry. Energy Policy 38(1): 392-405.

Hasanbeigi, A., Morrow, W., Masanet, E., Sathaye, J. and Xu, T., 2013b. Energy efficiency improvement and CO_2 emission reduction opportunities in the cement industry in China. Energy Policy 57: 287-297.

Hasanbeigi, A., Price, L., Lu, H. and Lan, W., 2010b. Analysis of energy-efficiency opportunities for the cement industry in Shandong Province, China: A case study of 16 cement plants. Energy 35(8): 3461-3473.

Ke, J., Zheng, N., Fridley, D., Price, L. and Zhou, N., 2012. Potential energy savings and CO_2 emissions reduction of China's cement industry. Energy Policy 45: 739-751.

Lei, Y., Zhang, Q., Nielsen, C. and He, K., 2011. An inventory of primary air pollutants and CO_2 emissions from cement production in China, 1990–2020. Atmospheric Environment 45(1): 147-154.

Ma, D., Hasanbeigi, A., Price, L. and Chen, W., 2015. Assessment of energy-saving and emission reduction potentials in China's ammonia industry. Clean Technologies and Environmental Policy 17(6): 1633-1644.

Morrow III, W. R., Hasanbeigi, A., Sathaye, J. and Xu, T., 2014. Assessment of energy efficiency improvement and CO_2 emission reduction potentials in India's cement and iron & steel industries. Journal of Cleaner Production 65: 131-141.

Price, L., Worrell, E., Price, L. and Galitsky, C., 2008. Energy Efficiency Improvement Opportunities for the Cement Industry.

Tian, L. and Liu, J., 2010. Empirical analysis of energy prices in the research of the energy intensity. Journal of Natural Resources 25(9): 1-6.

Tomaschek, J., 2015. Marginal abatement cost curves for policy recommendation–A method for energy system analysis. Energy Policy 85: 376-385.

Wang, C. L., Jin-Zhong, L. I. and Shui-Quan, Y. E., 2006. Resources situation and its potential of limestone ore used for cement in Jiangsu province. Resources Survey & Environment.

Wang, Y., Höller, S., Viebahn, P. and Hao, Z., 2014. Integrated assessment of CO_2 reduction technologies in China's cement industry. International Journal of Greenhouse Gas Control 20: 27-36.

Wei, S. and Dong, W., 2011. Forecasting of China's cement output between 2011 and 2050

Wen, Z., Chen, M. and Meng, F., 2015. Evaluation of energy saving potential in China's cement industry using the Asian-Pacific Integrated Model and the technology promotion policy analysis. Energy Policy 77: 227-237.

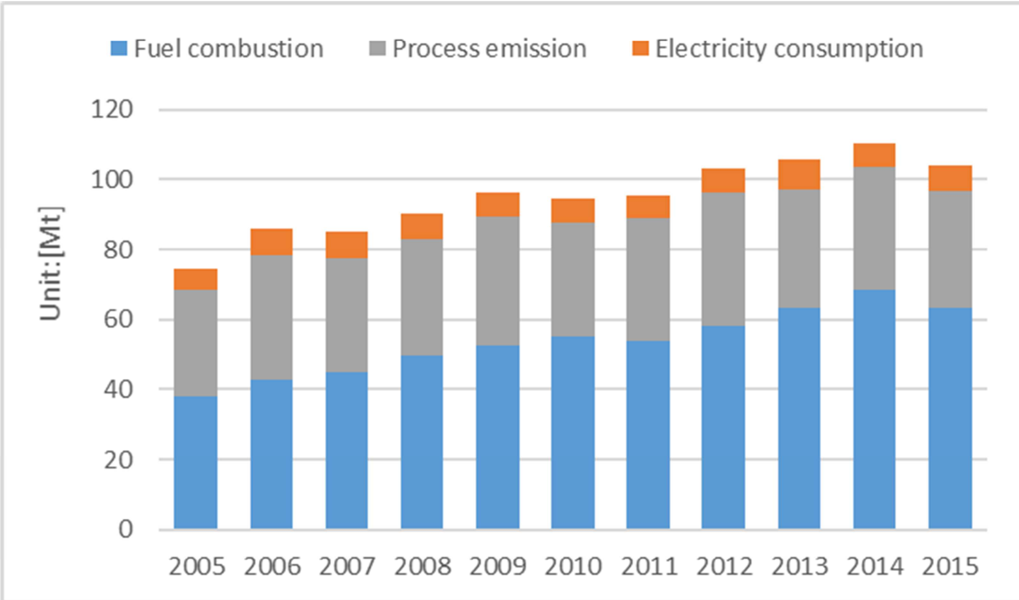
Worrell, E., Kermeli, K. and Galitsky, C., 2013. Energy Efficiency Improvement and Cost Saving Opportunities for Cement Making An ENERGY STAR® Guide for Energy and Plant Managers.

Worrell, E., Price, L., Martin, N., Hendriks, C. and Meida, L. O., 2001. Carbon dioxide emissions from the global cement industry. Annual review of energy and the environment 26(1): 303-329.

Xi, Y., Fei, T. and Gehua, W., 2013. 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. Journal of Cleaner Production 58: 102-111.

Xu, J.-H., Fleiter, T., Fan, Y. and Eichhammer, W., 2014. CO_2 emissions reduction potential in China's cement industry compared to IEA's Cement Technology Roadmap up to 2050. Applied Energy 130: 592-602.
Zhang, S., Worrell, E. and Crijns-Graus, W., 2015a. Cutting air Pollution by Improving Energy Efficiency of China's Cement Industry. Energy Procedia 83: 10-20.
Zhang, S., Worrell, E. and Crijns-Graus, W., 2015b. Evaluating co-benefits of energy efficiency and air pollution abatement in China's cement industry. Applied Energy 147: 192-213.
Zhang, S., Worrell, E. and Crijns-Graus, W., 2015c. Mapping and modeling multiple benefits of energy efficiency and emission mitigation in China's cement industry at the provincial level. Applied Energy 155: 35-58.
Zhang, S., Worrell, E. and Crijns-Graus, W., 2015d. Synergy of air pollutants and greenhouse gas emissions of Chinese industries: A critical assessment of energy models. Energy 93: 2436-2450.
Zhang, S., Worrell, E., Crijns-Graus, W., Krol, M., de Bruine, M., Geng, G., Wagner, F. and Cofala, J., 2016. Modeling energy efficiency to improve air quality and health effects of China's cement industry. Applied Energy 184: 574-593.
Zhang, S., Worrell, E., Crijns-Graus, W., Wagner, F. and Cofala, J., 2014. Co-benefits of energy efficiency improvement and air pollution abatement in the Chinese iron and steel industry. Energy 78: 333-345.

a. CO_2 emissions



b. air pollutants emissions

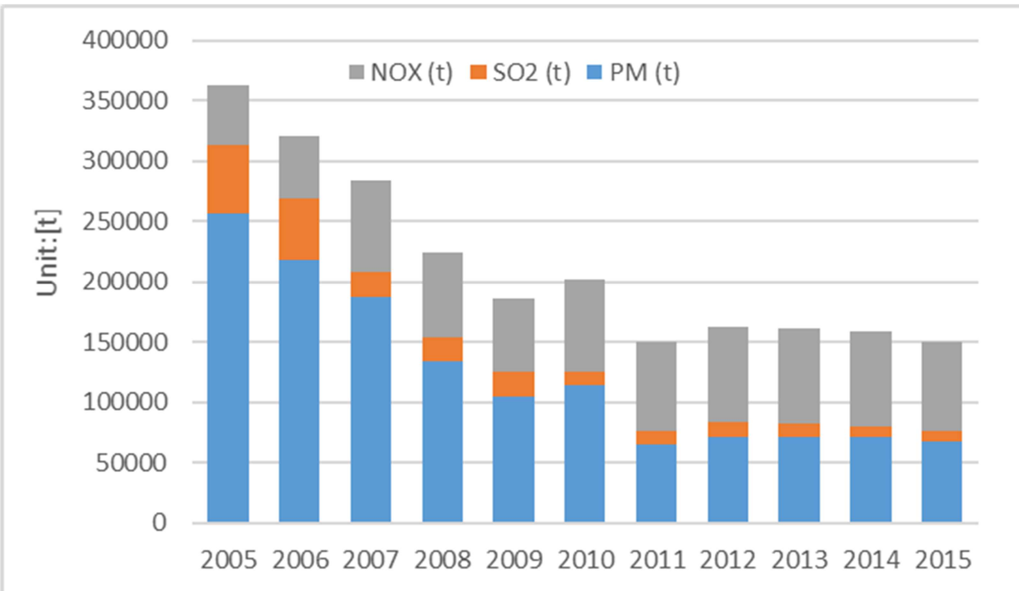


Fig. 1. Emissions of CO_2 and air pollutants from Jiangsu's cement production. (Panel a: CO_2 emissions, Panel b: emissions of SO_2, NOx, and PM)

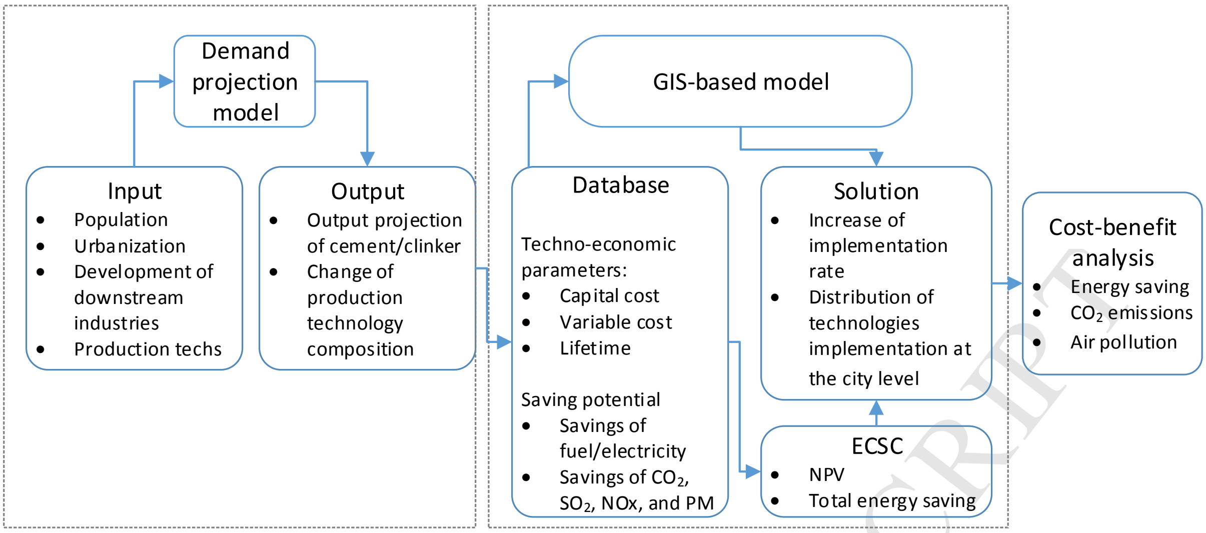


Fig. 2. Simplified diagram of model framework

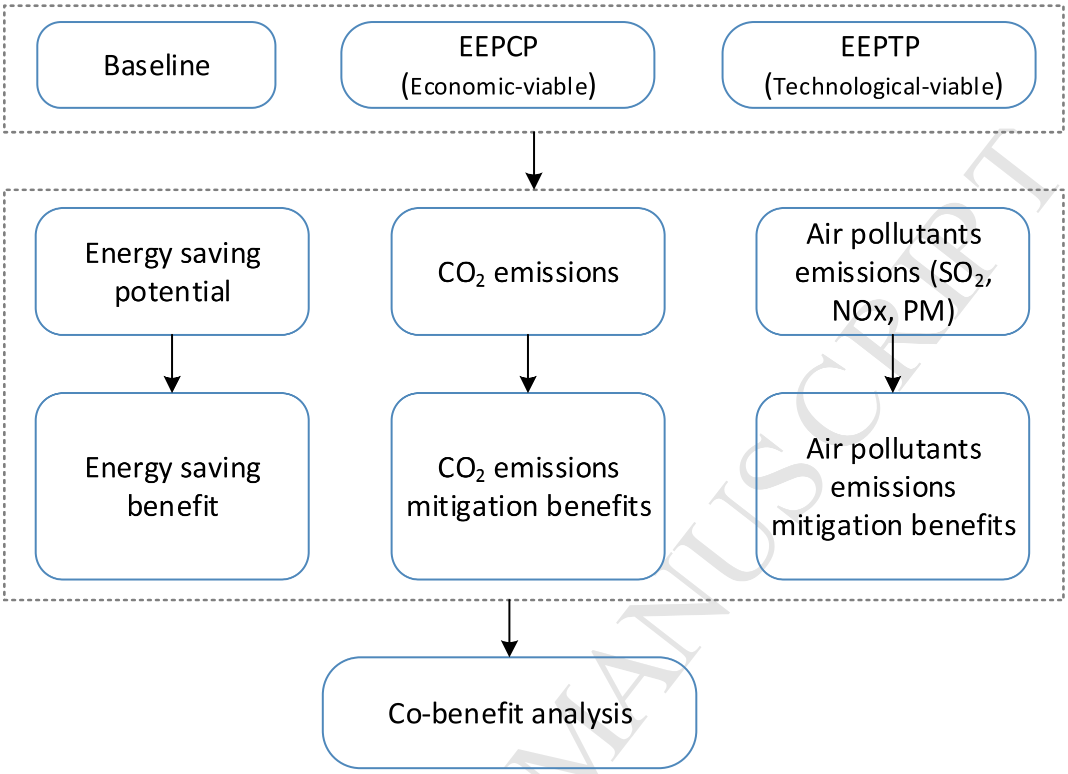


Fig. 3. Analysis scope of the three scenarios

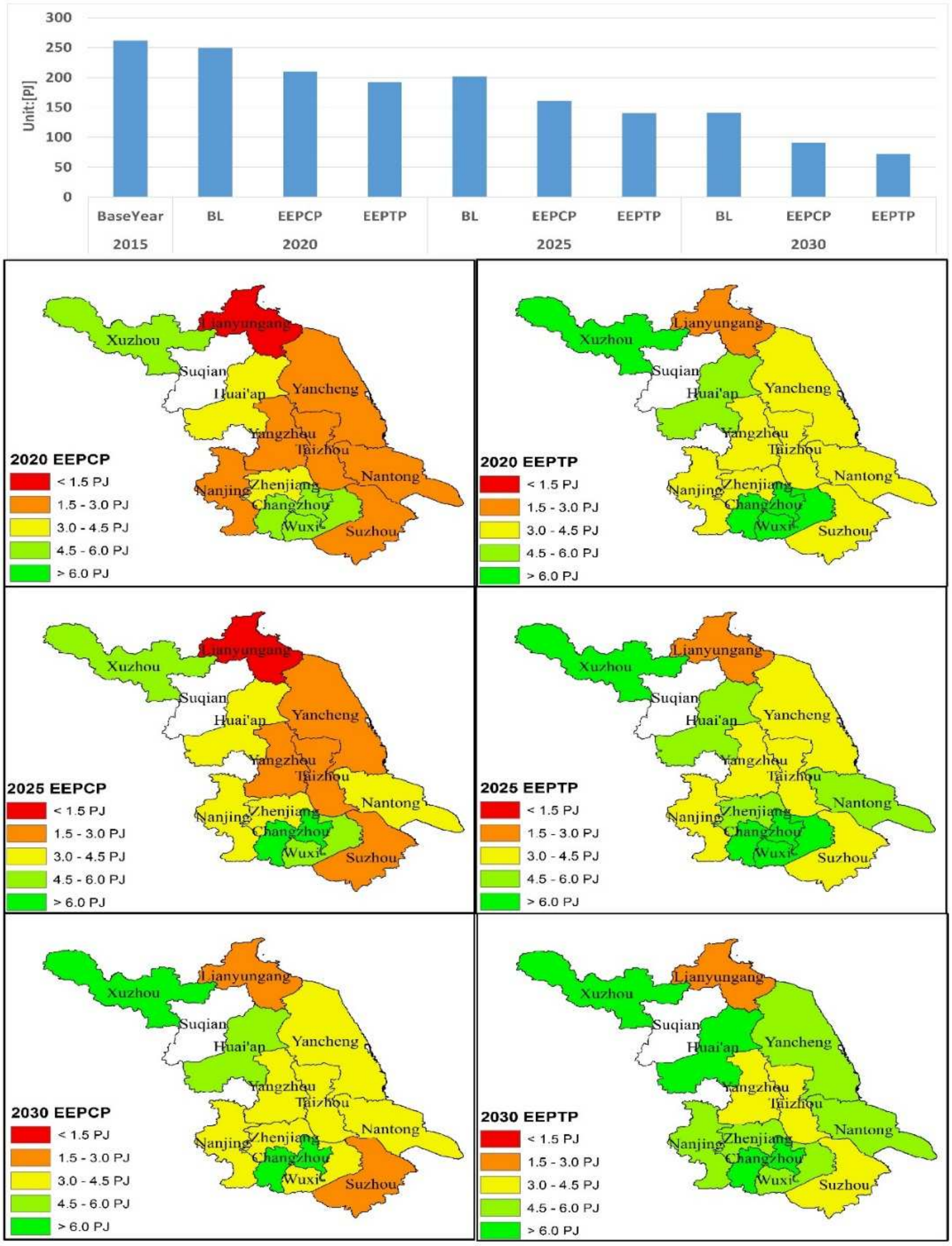


Fig. 4. Energy consumption and saving potential by city under different scenarios

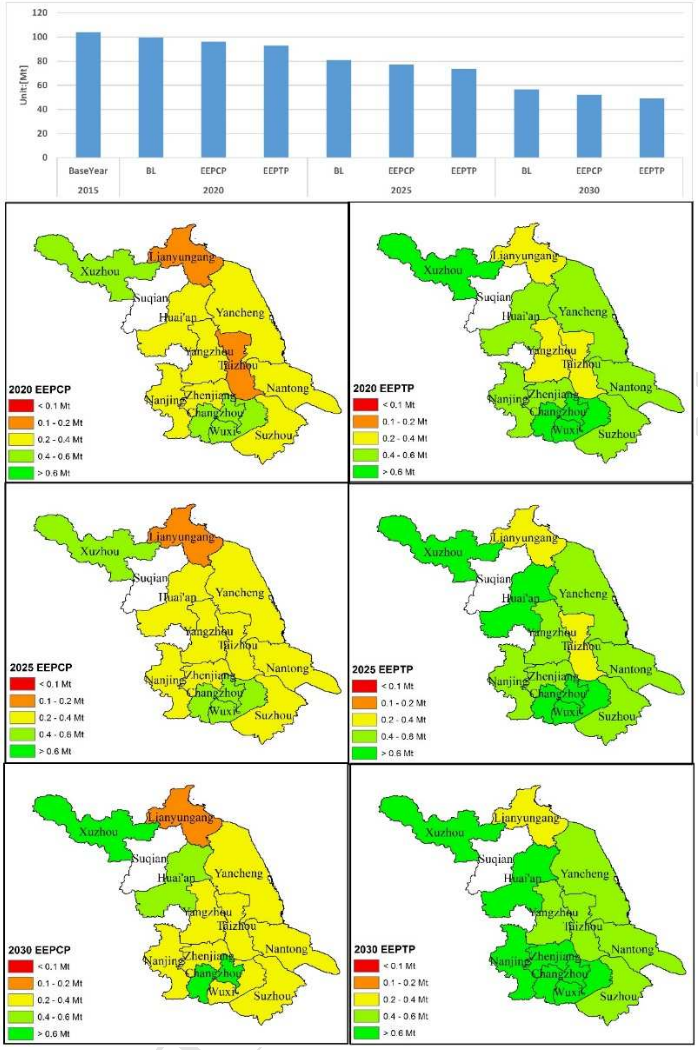


Fig. 5. CO_2 emissions and reduction potential by city under different scenarios

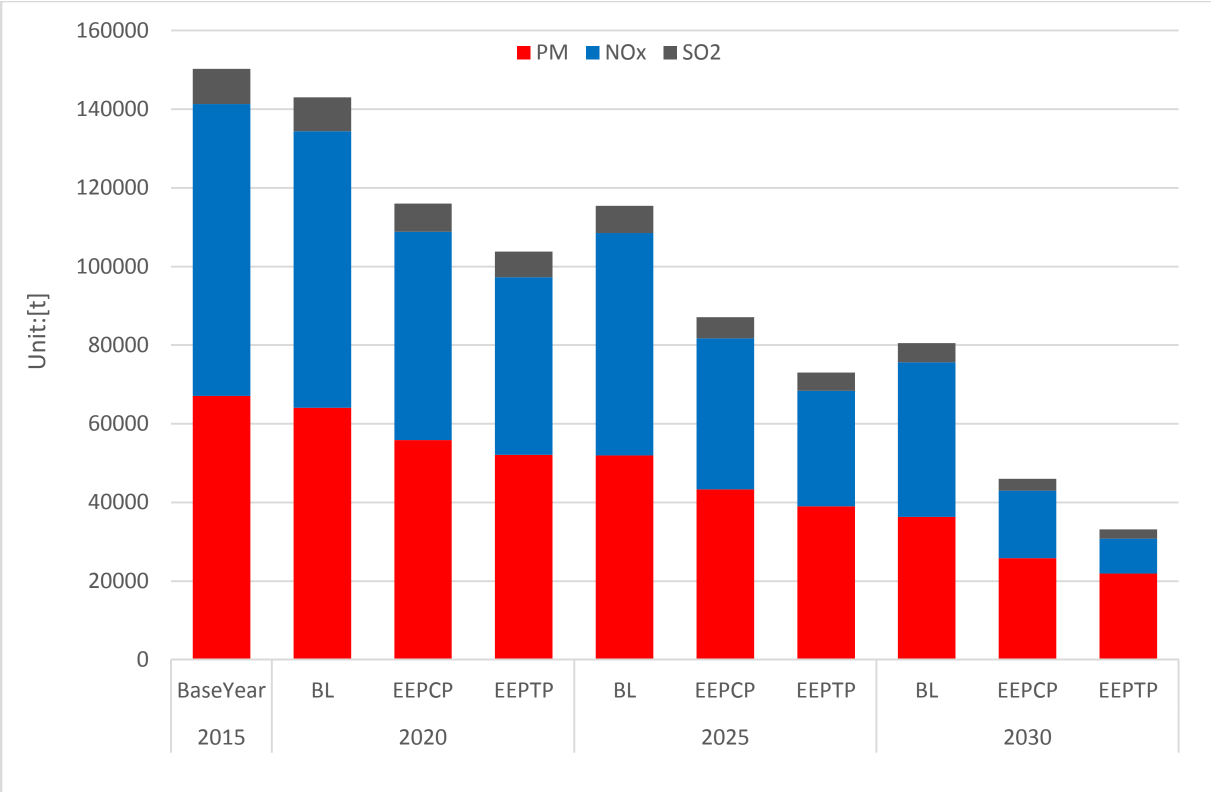


Fig. 6. Air pollutant emissions by city under different scenarios

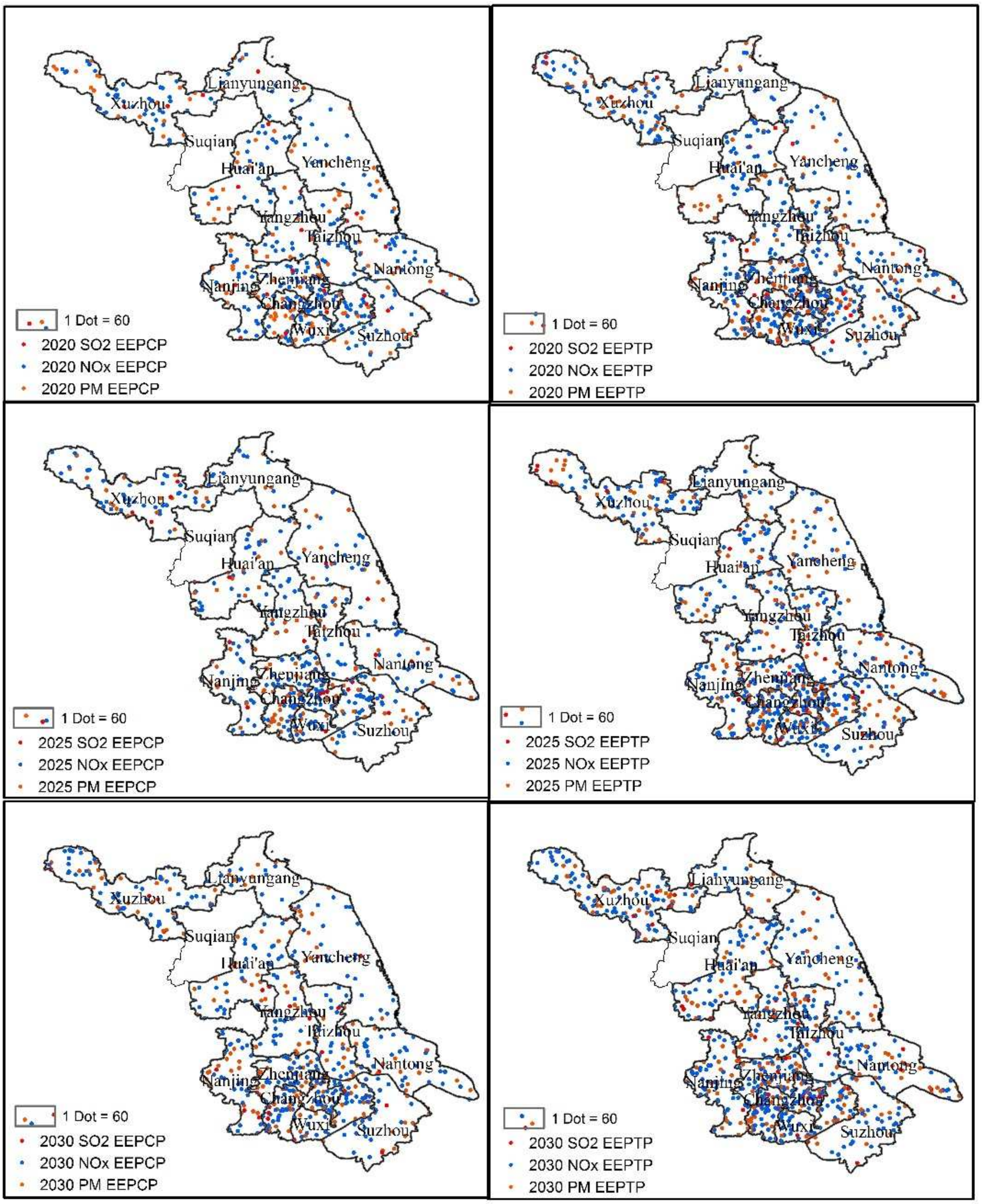


Fig. 7. Air pollution reduction potential under different scenarios

Highlights

1. Disparities in energy use and emissions are quantified for Jiangsu's cement industry
2. A GIS-based energy model developed to assess co-benefits of energy efficiency
3. Energy efficiency would lead to huge reductions in air pollution in all cities
4. Co-benefits of energy efficiency should be integrated into air quality policy