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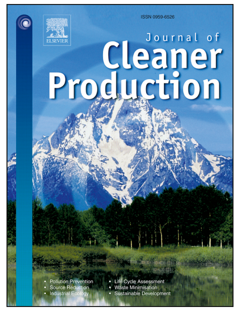

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PII: S0959-6526(20)33380-1

DOI: https://doi.org/10.1016/j.jclepro.2020.123335

Reference: JCLP 123335

To appear in: *Journal of Cleaner Production*

Received Date: 27 February 2020

Revised Date: 9 July 2020

Accepted Date: 16 July 2020

Please cite this article as: Zhang S, Xie Y, Sander R, Yue H, Shu Y, Potentials of energy efficiency improvement and energy–emission–health nexus in Jing-Jin-Ji's cement industry, *Journal of Cleaner Production*, https://doi.org/10.1016/j.jclepro.2020.123335.

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Potentials of energy efficiency improvement and energy–emission–health nexus in Jing-Jin-Ji's cement industry

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Abstract

China produces 52% of the global cement supply, and cement production accounts for 8% of China's total energy consumption. Moreover, 4% of China's total cement share is contributed by Jing-Jin-Ji (JJJ). In this study, we developed and used an integrated nexus framework that involves multiple tools to quantify the potential for energy efficiency improvements, for CO_2 and air pollutant emission reduction, and for public health benefits in relation to air pollution of the JJJ's cement industry at different scales from 2010 to 2030. Results show that the overall cost-effective energy efficiency measure implemented for energy efficiency improvement under the economic potential scenario could result in 21% energy savings, 8% reduction in CO_2 emissions, 13% reduction in air pollution, 0.5 μg/m^3 reduction in average annual $PM_{2.5}$ concentration, and in avoidance of morbidity in 17,000 individuals in the JJJ region. Under the technical potential scenario, the implementation of all the best available technologies for energy efficiency improvement would result in 23% energy savings and in reduction in CO_2 emission by 5%, in air pollution by 16%, in $PM_{2.5}$ by 0.2 μg/m^3, and in morbidity by 58%. At the prefecture level, the cities of Tangshan, Xingtai, and Shijiazhuang were the top three contributors to the potential for energy saving and to the mitigation of CO_2 emissions and air pollution, whereas Beijing and Tianjin demonstrated a limited potential. Overall, the direct energy-saving benefits could be 15–47% lower than the cost of the energy efficiency measures in both scenarios, but the full benefits (i.e., energy savings benefit, CO_2 reduction benefits, and health benefits) would be 1.3–3.6 times higher than the total costs during the study period. We recommend the design and implementation of an integrated policy (integrating carbon, air quality, and health elements into energy efficiency), which would create more opportunities to address multiple challenges in a cost-effective manner, for instance by increasing energy efficiency, cleaning the air, and extending human life.

Keywords: Energy efficiency; emissions; health effects; Nexus assessment; cement industry; Jing-Jin-Ji

Highlights

1. An integrated nexus assessment tool was developed to enhance the energy efficiency policy analysis

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2. Energy efficiency measures would save energy by 44% and would reduce CO_2 emission by 13% and pollution by 29%
3. The distribution of energy saving and energy–emission–health nexus differs widely
4. The benefits of the energy–emission–health nexus would be 1.3–3.6 times higher than the costs of the energy efficiency measures

Nomenclature	
Abbreviations	
IAMs	Integrated assessment models
BL	Baseline scenario
CCS	Carbon capture and storage
CDR	Carbon dioxide removal
DC	Derived coal
ECSC	Energy conservation supply curves
EEC	Energy efficiency improvement with economic potential scenario
EET	Energy efficiency improvement with the technical potential scenario
ELE	Electricity
GAINS	Greenhouse Gas and Air Pollution Interactions and Synergies
GAS	Natural gas
GHG	Greenhouse gas
GSL	Gasoline and other light fractions of oil
HC3	Hard coal
HEL	Health Impact Assessment
HF	Heavy fuel oil
HT	Heat
IAMGE	Integrated Model to Assess the Global Environment
IIASA	International Institute for Applied Systems Analysis
IMED|CGE	Integrated Model of Energy, Environment and Economy for Sustainable Development/Computable General Equilibrium
IU	Intensity use
JJJ	Jing-Jin-Ji
LPG	Liquefied petroleum gas
MD	Medium distillates
MIIT	Ministry of Industry and Information Technology
MRIO	Multi-region input-output model
SDS	Sustainable Development Scenario
TM5	the global chemistry transport model version 5
VSL	Value of statistical life
WEM	World Energy Model
WHO	World Health Organization
Symbols	
P	Cement production
p_i	Cement production in city i
NFS	New floor space in city i
BCI	Cement consumption for one-unit floor space of Building sector in city i
HCI	Cement consumption for one-unit of highway in city i
NLH	New length of highways in city i
RCI	Cement consumption for one-unit length of railway in city i

NLR	New length of railways in city i
Ini	Industrial investment in city i
ICI	Cement consumption per unit investment in industrial sector in city i
Im	Net import of cement in province i
CCE	costs of conserved energy for an energy efficiency measure
I	Investment
A	Annuity factor
$O\ \&\ M^{Fix}$	Annual change in operation and maintenance fixed costs
$O\ \&\ M^{Var}$	Annual change in operation and maintenance variable costs
ESP	Annual energy-saving potential
PE	Energy price
r	Discount rate
l	Lifetime of an energy efficiency measure

1. Overview

Modern integrated assessment models (IAMs) have been widely used to provide alternative development pathways in energy production and consumption, investment, technological advances, and strategies to meet certain climate and environmental targets (Paltsev, 2017). Several studies employing IAMs that involve scenario-based analysis have highlighted various mitigation pathways to cost-effectively limit global warming to 1.5–2 °C above the pre-industrial levels (Fuss et al., 2018; Xie et al., 2020). Many researchers have found that actions that aim to limit the temperature increase to 1.5 °C would require large-scale application of negative emission technologies (e.g., bioenergy with carbon capture and storage (CCS)) across the globe (Heck et al., 2018; Lemoine et al., 2012; Peters, 2016; Walsh et al., 2017). The pathways developed in previous studies differ widely even if they deal with the same climate target. For example, the Integrated Model of Energy, Environment and Economy for Sustainable Development/Computable General Equilibrium (IMED/CGE) was developed and used to assess the possible solutions that China could employ to achieve the 2 °C target, and it was found that increasing the renewable share of the energy system, accelerating the adoption of CCS, and limiting the new capacity expansion and improving the efficiency of most energy-intensive industry sectors are warranted (Xie et al., 2020). The Integrated Model to Assess the Global Environment (IMAGE), which is also an IAM, was employed to assess the pathway toward the 1.5 °C target, and it was found that the net carbon dioxide removal (CDR), lifestyle change, and electrification of the end-use sectors not only dominated the greenhouse gas (GHG) mitigation, but also the other benefits (Vuuren et al., 2018). Luderer et al. used seven global IAMs to explore the 1.5–2 °C climate pathways and pointed out that a cross-sectoral assessment is urgently needed (Luderer et al., 2018).

Efforts to decrease GHG emissions could reduce environmental pollution, resulting in essential short-term health benefits (Shindell et al., 2018). Integrated system and nexus approaches are increasingly being used to indicate the status of climate change as well as to present critical trends in order to tackle multiple challenges across regions and scales (Dierauer et al., 2018; Hülsmann and Ardakanian, 2018; Jianguo Liu et al., 2018; Liu et al., 2017). Sometimes, the words *nexus*, *interlinkages*, *co-benefits*, *multiple benefits*, *trade-off*, and *synergies* are used interchangeably, but they all have some nuances in their meaning (Irvine et al., 2014; Dooley et al., 2018; Peng et al., 2018; Rao et al., 2013; Zhang, 2016). The integrated system and the nexus approaches play an important role in modelling the linkages among multiple distinct entities, particularly in understanding connections, co-benefits, synergies, and trade-offs (Liu et al., 2018). The nexus concept, which consists of horizontal and vertical nexuses, has been widely used to explore solutions to meet the incremental demand for energy and resources and related multiple environmental pressures, such as air pollution and climate change (Hoff, 2018). The World Energy Model (WEM) combined with the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model were used to assess alternative pathways related to accessing clean energy and reducing GHG and environment pollution simultaneously. Rafaj et al. found that efforts to access clean energy in Sustainable Development Scenario (SDS) scenario not only reduced CO_2 emissions by 58%, but also decreased air pollution by 60–80% compared with the present levels; they thus recommended that systemic measure assessment is required to maximize the benefits and avoid trade-offs (Rafaj et al., 2018). Fang et al. employed the multi-region input–output (MRIO) model and an atmospheric chemical transport model to simulate the air quality improvement and the related synergies among air quality, CO_2 mitigation, and water use reduction in China (Fang et al., 2019). Yang et al. estimated the health effects related to pollution reduction in 28 prefectures in JJJ (Beijing-Tianjin-Hebei) and in the surrounding region of China; they found that synergistic effects positively contributed to $PM_{2.5}$ reduction, and 0.5% of gross domestic product (GDP) would be saved if the $PM_{2.5}$ concentration is reduced to the national air quality standard of China (Yang et al., 2019). An environmentally extended MRIO combined with the nexus approach was developed and used to assess the water–$PM_{2.5}$ nexus in the JJJ region. The results highlighted that 70% of $PM_{2.5}$ and 20% of water are related to the industrial sectors in Hebei (Gao et al., 2020).

A model-projected analysis does not always provide a sufficient basis for policymaking and investment decisions because models can only provide quantitative analysis of future directions and general options, and they fail to adequately examine policy efficiency and how a policy is designed and implemented in target sectors and regions (Kermeli et al., 2016; Zhang et al., 2018a). In addressing this challenge, many bottom-up sectoral analyses based on a technic-economic approach have been used to assess demand-side solutions for single and multiple challenges (e.g., energy and resource security, climate change, environmental pollution, and health effects), providing more useful insights for policymakers, industry experts, and end-use managers (Creutzig et al., 2018; Zhang et al., 2016). For example, Zhang et al. developed and used a GIS-based energy model to estimate the potential for energy efficiency improvement and the associated air quality co-benefits of the Jiangsu's cement industry at the prefecture level, and they found that 35% of energy and 30–56% of pollution would decline by 2030 due to the implementation of energy efficiency measures (Zhang et al., 2018b). Worrell and Carreon concluded that if all the current best practices were applied, a 20–35% improvement in energy efficiency and a 2.5 ± 0.8 Gt of $CO_{2\text{-eq}}$ mitigation would be potentially achieved by the energy-intensive manufacturing sectors (e.g., cement, steel, chemicals, and aluminum) worldwide. Worrell and Carreon recommend that integrated policies that combine energy and resource efficiency with energy transition will be one of the most efficient ways to decrease CO_2 emissions (Worrell and Carreon, 2017). Zhang et al. (2016a) developed an integrated framework that included energy conservation supply curves (ECSC), GAINS, ArcGIS, the global chemistry transport model version 5 (TM5), and health impact assessments and then used it to assess the energy saving potential and the associated energy efficiency co-benefits of China's cement industry. They found that the achieved social-economic energy efficiency co-benefits are more than twice as much the energy efficiency investments.

This study aims to overcome such a gap by developing an integrated nexus framework with horizontal and vertical components. We focus on the cement industry in JJJ in China for several reasons. First, the JJJ region, located in northern China and consists of Beijing, Tianjin, and 11 cities of Hebei (see Figure 1 in Appendix), is one of the most important regions in China owing to its status in terms of economic development. In 2018, 8% of the Chinese population lived in JJJ and made a 9.5% contribution to the total GDP (National Bureau of Statistics, 2019). In the last decade, many projects announced by the Chinese central government urgently required the JJJ to achieve a sustainable and coordinated development (e.g., equity of cement production and consumption). Second, cement is the fundamental material used to build infrastructure, and cement products are consumed to support the infrastructure construction also within JJJ. Third, the cement industry in the JJJ contributes significantly to CO_2 emissions and demands high amounts of limestone and energy (Zhang et al., 2015a). In 2015, the JJJ produced 104 million tons of cement, and around 95% of which was consumed within the JJJ region. The clinker capacity per production line ranges from 1,000 tons to 12,500 tons per day (National Bureau of Statistics, 2016). Fourth, energy security, climate change, and environmental pollution are the top three urgent issues facing JJJ. For example, the annual mean $PM_{2.5}$ concentration in JJJ was 106 μg/m^3, three times higher than the World Health Organization (WHO) interim target of 1 (Qi et al., 2017). The key features of the nexus framework developed in this study is that it consists of four highly detailed models that quantitatively model (1) the end-users' local cement demand for the construction of infrastructure and new buildings for instance, (2) the potential for energy efficiency improvements and for reduction of CO_2 emissions and air pollutants at the provincial and prefecture levels, and (3) the provincial air quality improvements and the health effects associated with $PM_{2.5}$.

2. Methods

This study develops and uses an integrated nexus framework that consists of intensity use (IU) curves along with a GIS-based energy model, the GAINS model, and the IMED|CGE and Health Impact Assessment (HEL) in order to quantify the energy saving potential of the JJJ's cement industry at different scales as well as to model the associated energy efficiency nexus, which includes clean air and public health benefits, and these factors' response to GDP gains. Specifically, first, we introduce the horizontal (which represents the relationships between cement and related consumers (e.g., building and infrastructure sectors)) and the vertical (which represents the dynamic relationship across the JJJ region in various scales) nexus approaches to forecast the outputs for cement and clinker based on the future activity of cement consumers. Then, a soft-linked approach is used to develop the linkages among the GIS-based energy model, the GAINS model, and the IMED|CGE & HEL models. Finally, the nexus framework is employed to explore the energy saving potential of the cement industry, the emission mitigation of CO_2 and air pollutants, and the air quality improvements and the associated public health benefits as well as the effects on GDP gains. During this step, the vertical (cross-scale) nexus will be modeled at the provincial and prefecture scales. The framework is depicted in Figure 1, and the working steps are as follows:

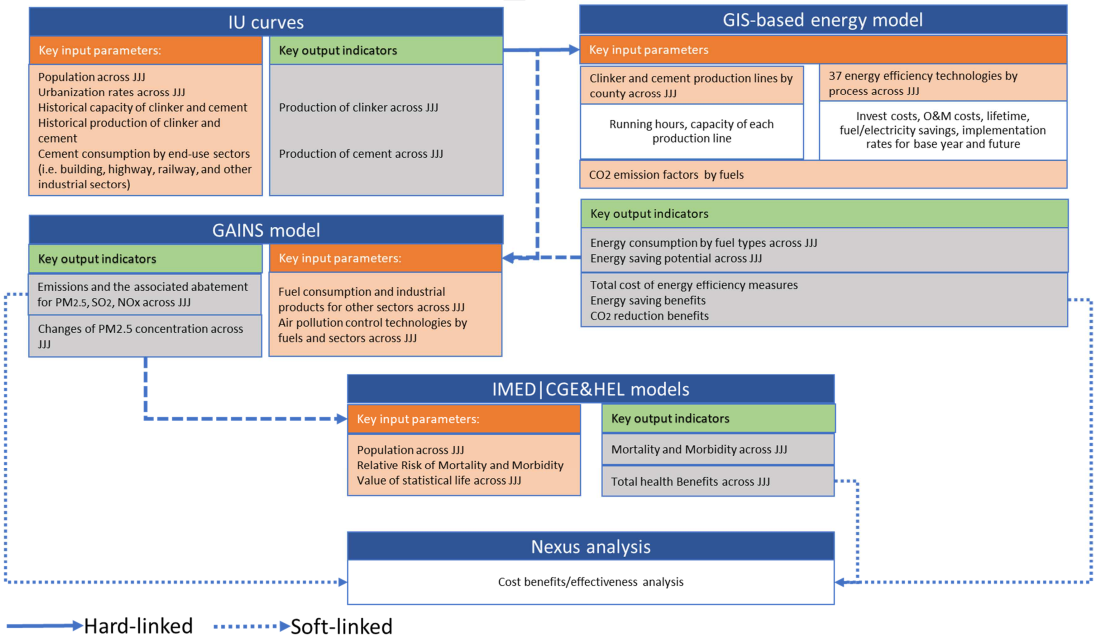


Figure 1: Workflow of integrated nexus framework that includes energy efficiency, climate change, air quality, and health.

1) Predict the production of cement until 2030 based on the IU curves of cement users and their activities. Clinker production is calculated based on the regional clinker-to-cement ratio.
2) Integrate cement and clinker outputs into the GIS-based energy model, which includes the regional ECSC and an ArcGIS-based distribution assessment platform (Zhang et al., 2018b).

3) Use the soft-linked approach to build the linkages between the GIS-based energy model and the GAINS-JJJ to assess the emission reduction of CO_2 mitigation and air pollutants due to the application of energy efficiency measures.
4) Import the changes in $PM_{2.5}$ concentration under the alternative scenarios into the IMED/CGE and HEL models to quantify the public health benefits (including the avoidance of mortality and morbidity) and the avoidance of GDP loss through air quality improvement.
5) Use the integrated nexus framework involving cost–benefit analysis to estimate the energy–emission–health nexus from the horizontal and vertical perspectives. In this step, the cost covered the investment costs, the operating and maintenance fixed costs, and the operating and maintenance variable costs of the energy efficiency measures. The benefits included energy saving benefits, CO_2 mitigation benefits, and health benefits.

2.1 IU Curves

In most IAMs, IU curves (including economic and physical-based IU curves) are used to quantify the relationships between the supply and demand sectors and to model a future product activity worldwide under different assumptions (Zhang et al., 2019). The economic IU curve is usually used to calculate a future product activity from an economic perspective (e.g., based on product consumption in relation to the value added), whereas the physical IU curve focuses on the physical perspective, which depends on the quality of sectoral information and on the associated data (Oshiro et al., 2017; Zhang et al., 2018b).

In this paper, the physical and economic IU curves are developed and used to forecast cement production in the JJJ region until 2030. The formula for the project cement production is shown in Equation 1 (Zhang et al., 2018b):

$$P = \sum_i p_i = \sum_i (NFS * BCI + HCI * NLH + RCI * NLR + Ini * ICI) + Im \qquad Equation\ 1$$

Where:
P = Cement production
p_i = Cement production in city *i*
NFS = New floor space in city *i*
BCI = Cement consumption for one-unit floor space of the building sector in city *i*
HCI = Cement consumption for one-unit of highway in city *i*
NLH = New length of highways in city *i*
RCI = Cement consumption for one-unit length of railway in city *i*
NLR = New length of railways in city *i*
Ini = Industrial investment in city *i*
ICI = Cement consumption per unit investment in the industrial sector in city *i*
Im = Net import of cement in province *i*

Note that the net import share of total cement production at the provincial level is assumed to not change during the study period because around 95% of cement produced in the JJJ region is consumed within the region (National Bureau of Statistics, 2016). The dynamic distribution of future cement production in JJJ is depicted in Appendix A: Table 1. The regional clinker-to-cement ratio in 2015 is used to estimate the future clinker output until 2030 at the prefecture level.

2.2 GIS-based energy model

A GIS-based energy model consisting of ArcGIS and ECSCs for the JJJ region is developed in this study. The regional ECSCs were employed to estimate the potential for energy saving and the associated CO_2 mitigation through the implementation of the best available energy efficiency technologies at the prefecture level, whereas ArcGIS was employed to quantify the dynamic distribution of the potential for energy saving from the economic and technical perspectives and the associated CO_2 emission reductions (Zhang et al., 2018b).

The method of calculating the costs of conserved energy (CCE) for an energy efficiency measure is presented in Equation 2. More information on the methodology for the development of ECSCs are presented by Hasanbeigi et al. (2013a, 2013b, 2010).

$$CCE = \frac{I \times A + O\ \&\ M^{Fix} + O\ \&\ M^{Var} - ESP \times PE}{ESP} \qquad Equation\ 2$$

Where:

CCE = costs of conserved energy for an energy efficiency measure ($/GJ)

I = Investment ($)

A = Annuity factor

$O\ \&\ M^{Fix}$ = Annual change in operation and maintenance fixed costs ($)

$O\ \&\ M^{Var}$ = Annual change in operation and maintenance variable costs ($)

ESP = Annual energy-saving potential (GJ)

PE = Energy price ($/GJ).

In this paper, a discount rate of 10% is used to calculate the annuity factor, which is calculated using Equation 3:

$$A = \frac{r}{(1 - (1 + r)^{-l})} \qquad Equation\ 3$$

Where:

r = Discount rate (%)

l = Lifetime of an energy efficiency measure (years)

2.3 GAINS model

GAINS, an IAM, has been widely used for multiple-policy assessment worldwide, particularly in Europe, China, JJJ, G20, Asia, France, Netherlands, Sweden, Italy, and Hebei of China. GAINS, which developed by the International Institute for Applied Systems Analysis, GAINS brings together data on population and economic development, activity of energy use by fuel types and industrial production, sectoral structure, agricultural livestock, control options and the costs of air pollution control technologies, pollutant formation and their dispersion in the atmosphere, and environmental impacts related to pollution (Amann et al., 2011; Amann et al., 2008; Wagner et al., 2018). The key advantage of GAINS is that it describes the interactions between pollutants (e.g., SO_2, NOx, PM, and NH_3) and GHG across sectors and regions. A large number of institutions employ the GAINS to explore the cost-effective mitigation potential for air pollutants and GHG in the context of multiple objectives (e.g., reduction of environmental impacts and achievement of climate targets; Amann et al., 2008; Woo, 2015, 2015; Zhang et al., 2015c). In this study, the GAINS-JJJ model was used to quantify the pollutants SO_2, NOx, and $PM_{2.5}$ (Zhang et al., 2014) across JJJ and to model the potential abatement of air pollution, including the associated annual $PM_{2.5}$ concentration reductions, as well as the associated energy–emissions synergies under different scenarios.

2.4 IMED|CGE and HEL

The IMED|CGE model is a recursive, dynamic CGE model that covers 22 commodities consumed by different sectors in 30 provinces in China and is modeled yearly (Dai et al. 2012, 2017; Dong et al. 2017; Xie et al.2018). The IMED|HEL model is widely used to assess the health endpoints and economic gains related to environmental pollution (Liu et al. 2019; Xie et al. 2016, 2017, 2018, 2019; Wu et al. 2017,2019; Zhang et al. 2019; Tian et al., 2018, 2019; Kim et al. 2020). For this model, a nonlinear approach was employed to estimate the relationship between pollution concentration and the relative risk of health endpoints (including mortality and morbidity) based on the latest studies (Apte et al., 2015; Turner et al., 2015). The IMED|HEL model monetizes the lost non-market value of statistical life (VSL) to represent the additional impacts of environment pollution abatement. Currently, the VSL differs widely across developed countries, ranging from 8 million to 31 million USD (Matus et al., 2012).

In this study, the benefits transfer approach was used to calculate the JJJ's VSL in the base year and future years based on the average VSL in China (0.26 million USD) and on the regional GDP per capita. Note that in this study, 0.5 of personal income elasticity was used, in line with recent studies (Viscusi and Aldy, 2003; Zhang et al., 2016). The outputs for the annual total medical expenditure and per capita work loss obtained from the IMED|HEL model was applied to the IMED|CGE model to estimate macroeconomic impacts. More details on the IMED|CGE and HEL model are available at http://scholar.pku.edu.cn/hanchengdai/imed_general.

2.4 Data sources and scenario assumptions

2.4.1 Data sources

Information on the historical production of cement and clinker in JJJ were obtained from the China Cement Almanac (China Cement Association, 2010), China Statistical Yearbook (National Bureau of Statistics of China, 2014, 2013, 2011), and Hebei Economic Yearbook (Hebei Statistical Bureau, 2019) as well as from recent studies (Tian et al., 2014). Information on the historical energy consumption by fuel types by the JJJ's cement industry were obtained from the China Energy Statistical Yearbook (National Bureau of Statistics of China, 2013) and then calibrated based on the current literature (Cai et al., 2016; Wen et al., 2015; Xi et al., 2013). Data on population and urbanization of each city in JJJ were obtained from the China Statistical Yearbook (National Bureau of Statistics, 2015). The future population of each city was calculated based on the World Energy Outlook 2018 Current Policy Scenario in the GAINS. The specific cement consumption per unit of production (e.g., floor area in square meter in the building sector and length of highway and railway in kilometer in the transportation sector) were obtained from state-of-the-art studies (Hasanbeigi et al., 2017; Liu, 2017). Note that the intensity of cement consumption and the net import share of total cement production remained the same during the study period.

Recent studies indicate that a large number of the best available energy efficiency measures has already been applied in the JJJ's cement industry (Hasanbeigi et al., 2013c; Tian et al., 2014; Wang et al., 2018). However, there is still a high potential for energy efficiency improvement and for emission reductions via the use of different technologies (Wang et al., 2018). This study considers 37 of the best available commercial energy efficiency measures in four main processes: fuel and raw material preparation, clinker making, finish grinding, and general measures. The parameters (i.e., energy savings by fuel types, investment costs, operating and maintenance fixed costs, operating and maintenance variable costs, lifetime, current implementation rate in base year) for such energy efficiency technologies were obtained from our recent studies (Zhang et al., 2018b, 2016) as well as from other recent studies, such as those conducted by the Lawrence Berkeley National Laboratory (Hasanbeigi et al., 2013b; Zhou et al., 2011), the Energy Research Institute of China (Dai and Hu, 2013; Dai and Xiong, 2013), the Ministry of Industry and Information Technology of China (Ministry of Industry and Information Technology (MIIT) of China, 2014, 2012), the Tsinghua University (Tsinghua University, 2008; Wang et al., 2014; Wen et al., 2015) and other institutions (Wang et al., 2014; Xi et al., 2013). Based on the current implementation rates, the future implementation rates of the selected energy efficiency measures were estimated by a linear deployment approach and with the assumption of their full implementation by 2030. Since the wet process technologies employed in the JJJ's cement industry were phased out in 2015 (Tian et al., 2014; Zhang et al., 2015c), this study does not consider energy efficiency measures for wet processes. The costs (i.e., investment costs, operating and maintenance fixed costs, and operating and maintenance variable costs) of energy efficiency measures are priced in 2005 in USD, and the energy prices by fuel types were obtained from the China Cement Almanac (China Cement Association, 2010). The energy-based CO_2 emission factor in the JJJ's cement industry was obtained from our recent studies (Zhang et al., 2016, 2015c), and the CO_2 emission factor caused by electricity consumption was obtained from Yi et al. (Yi et al., 2020). The pollution abatement potential (i.e., $PM_{2.5}$, SO_2, and NOx) related to energy consumption and processes were also assessed. The emission factors of $PM_{2.5}$, SO_2, and NOx were modeled using the GAINS-JJJ module. Moreover, 3.22 USD per GJ of energy and 10 USD per ton of CO_2 were used to quantify the benefits of energy saving and CO_2 reductions due to the application of selected energy efficiency technologies (Zhang et al., 2015c).

2.4.2 Scenario assumption

This study mainly focuses on the cement production process in JJJ, including fuel and raw material preparation, clinker making, and finish grinding, based on the guidebook for the GHG emissions of cement manufacturing enterprises (National Development and Reform Commission of China, 2013). We developed three scenarios: the baseline (BL) scenario, the energy efficiency improvement with economic potential (EEC) scenario, and the energy efficiency improvement with the technical potential (EET) scenario. For all of these scenarios, the study period is 2010–2030 with a five-year step, and 2010 is the base year. Note that the 2015 data are related to the distribution of clinker and grinding features (e.g., clinker capacity of each production line by county, cement capacity of each production line by county, and the associate number of production lines) are integrated into the GIS-based energy model. Further, the 2015 regional clinker and cement productions are used to verify the consistency between reality and forecast. The three scenarios are described in detail in Zhang et al. (2015c, 2015a). They were used as a basis to estimate the energy–emission–health nexus and the related response to GDP gains in the JJJ's cement industry at different scales. The discount rate, regional fuel prices, clinker and cement distribution, and energy structure remain consistent in all scenarios. The autonomous energy efficiency improvement in the BL scenario was 0.2% per year for the efficient cement plants, and the inefficient cement plants would be phased out because of the anticipated decline in their cement production, consistent with our recent findings (Zhang et al., 2016, 2015a). In the EEC and EET scenarios, we assumed that the inefficient cement plants would be phased out when the future dynamic distribution of clinker and cement for each prefecture is modeled and that the future implementation rate of each energy efficiency measure would decline. In the EEC scenario, the negative value of CCE of energy efficiency technologies with future implementation rates will be implemented in the cement industry to represent the potential energy savings from an economic perspective. All of the best available energy efficiency technologies are assumed to be fully implemented in the EET scenario to quantify the maximum energy saving potential and the associated synergies. The prefecture distribution of energy consumption and the emissions of GHG and air pollutants under the different scenarios were calculated to determine which region had the most significant potential for energy savings, emission reductions, and health benefits with the lowest costs. Moreover, the energy–emission–health nexus was calculated to assess how the nexus would affect the potential for a cost-effective saving of energy.

Table 1 CCE of energy efficiency measures by process in JJJ's cement industry

Number	Energy efficiency measures	Beijing	Tianjin	Hebei
	Fuel and raw material preparation			
1	New efficient coal separator	-22.12	-25.03	-27.00
2	VFD in raw mill vent fan	-20.39	-23.30	-25.27
3	Bucket elevators for raw meal transport	-20.26	-23.18	-25.15

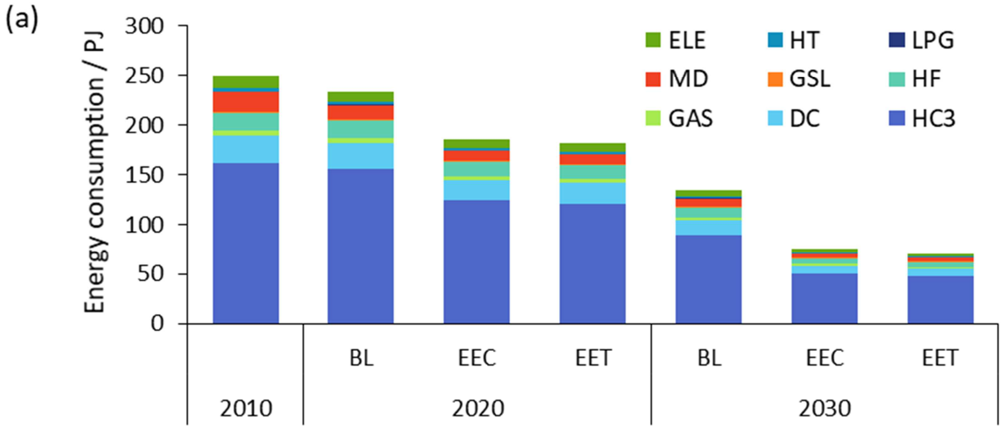
4	High efficiency fan for raw mill vent fan with inverter	-18.32	-21.24	-23.21
5	Efficient Transport System for mine	-15.35	-18.26	-20.23
6	Installation of variable frequency drive & replacement of coal mill bag dust collector's fan	-13.24	-16.15	-18.12
7	Raw mill process control for roller mill	-10.98	-13.89	-15.86
8	Optimize mine exploitation	-9.85	-5.96	-6.06
9	High efficiency drying for slag	-7.88	-3.99	-4.09
10	Slag powder production	-3.16	0.73	0.63
11	High Efficiency Classifiers	0.74	-2.17	-4.14
12	High Efficiency Roller Mills	6.82	3.91	1.94
13	High-Efficiency Roller Mill for raw mill and coal grinding	15.77	12.86	10.89
14	Raw mill process control for vertical mill	38.31	35.40	33.43
15	Raw mill Blending (homogenizing) systems	54.96	52.05	50.08
	Clinker making			
16	VFD in cooler fan of Grate Cooler	-18.68	-21.59	-23.56
17	Heat recovery for power generation	-16.02	-18.94	-20.90
18	Adjustable speed drive for kiln fan	-9.67	-12.58	-14.55
19	Kiln Shell Heat Loss Reduction (Improved refractories)	-8.32	-4.43	-4.53
20	Conversion to Grate Cooler	-8.29	-4.40	-4.50
21	combustion system improvements	-7.41	-3.52	-3.62
22	Optimize Grate Cooler	-6.62	-2.73	-2.83
23	Upgrade clinker cooler	-6.42	-2.05	-2.02
24	Energy management & process control	-6.36	-2.83	-3.03
25	Low temperature heat recovery for power generation	-5.39	-8.30	-10.27
26	Replacing Vertical Shaft Kilns with New Suspension	-6.12	-2.22	-2.32
27	Upgrading to a preheater & precalciner kiln	-5.09	-1.20	-1.30
28	Increasing Number of Preheater Stages (from 5 to 6) in Rotary Kilns	-4.87	-0.71	-0.73
29	Older dry kiln upgrade to multi-stage preheater kiln	38.43	42.59	42.57
30	Low pressure drop cyclones for suspension preheater	43.62	40.71	38.74
	Finish Grinding			
31	High Pressure Roller Press for ball mill pregrinding	-14.50	-17.42	-19.39
32	High-Efficiency Classifiers	5.38	2.47	0.50
	General measures			

33	High Efficiency Motors	-19.13	-22.04	-24.01
34	Adjustable Speed Drives	-18.17	-21.08	-23.05
35	Energy Management & Process Control	-8.55	-4.66	-4.76
	Product and feed stock change			
36	Blended Cement	-8.31	-4.32	-4.39
	Alternative Fuels			
37	Biomass and Waste	-8.30	-4.41	-4.51

3. Results and discussion

3.1 Energy consumption and energy saving potential

Figure 2 shows the total fuel consumption and savings that can be realized in the JJJ's cement industry up to 2030 under different scenarios. As depicted in Figure 2(a), in all scenarios, the total energy consumption gradually decreases until 2030. In the BL scenario, the total energy consumption in 2020 and 2030 significantly decreases by 6% and 46%, respectively, compared with that in 2010. During the study period, hard coal 3 (HC3) plays a dominant role in total energy consumption, accounting for 65% of the energy consumption, followed by derived coal (DC) (11%) and medium distillates (MD) (8%). The main reason behind this trend is that fossil fuels (e.g., HC3, DC, and MD) are used to crush, grind, and heat raw materials (limestone, chalk, and clay) to 1,400–1,500 °C to form a clinker (Liu et al., 2018). By implementing 30 cost-effective energy efficiency technologies in the EEC scenario during the study period, we can achieve 21% and 44% energy savings in 2020 and 2030, respectively, compared with that in the BL scenario. The most considerable additional saving potential (3%) was observed in the EET scenario owing to the application of seven non-cost-effective technologies. To better understand which city contributes most to the total energy saving potential, we assessed the dynamic distribution of energy savings at the city scale. Figure 2(b) shows the distribution of energy saving potential of the JJJ's cement industry under the EEC and EET scenarios until 2030. As shown in Figure 2(b), energy saving potential differs widely between cities. In both EEC and EET scenarios, Tangshan has the largest total energy saving potential, accounting for 32%, followed by Xingtai and Shijiazhuang, which together account for 25%. The cities of Langfang, Cangzhou, and Hengshui have the least amount of energy saving potential because they do not have sufficient financial support to implement advanced energy efficiency measures.



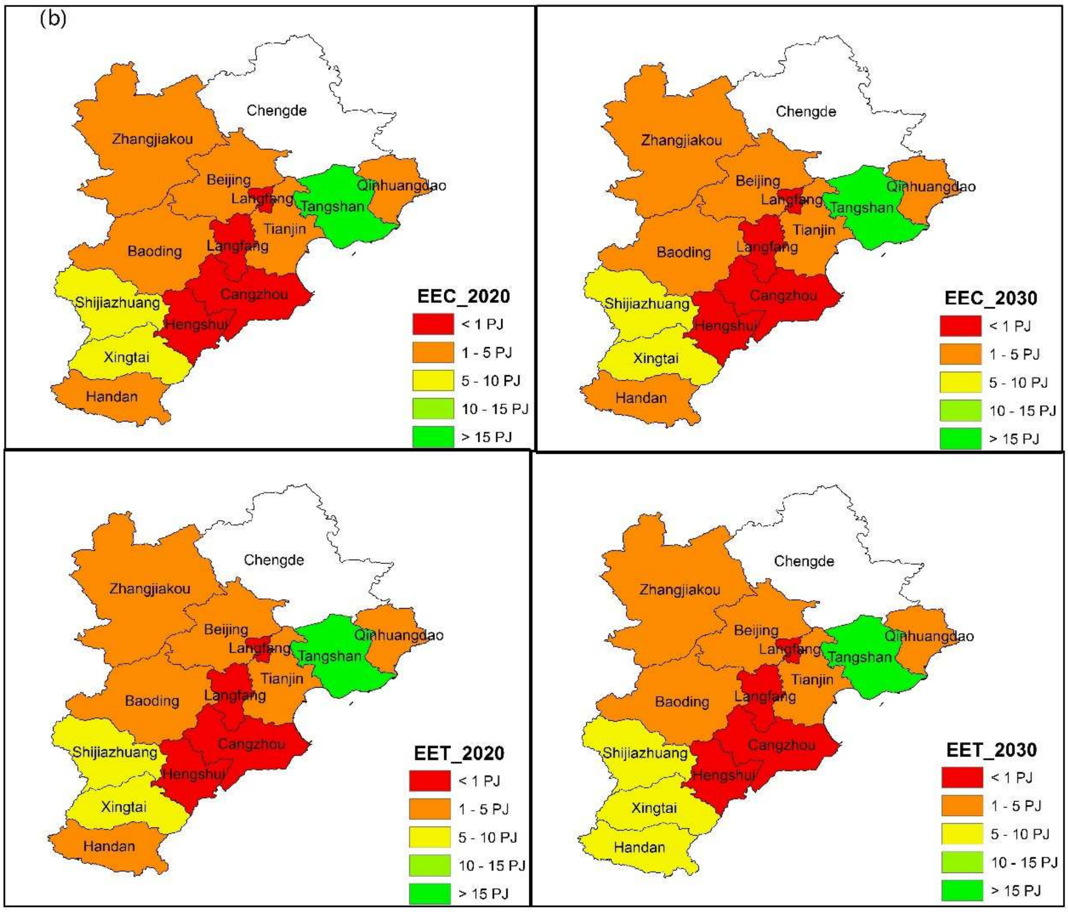


Figure 2. Energy consumption (a) and associated energy-savings potential (b) in the JJJ region

3.2 CO_2 emissions and mitigation

Figure 3 shows the total CO_2 emissions and the mitigation of energy-related CO_2 emissions by the JJJ's cement industry until 2030 at various scales. In general, the CO_2 emissions in different scenarios slightly fluctuated prior to 2020, but after 2020, CO_2 emissions will be significantly reduced. As expected, the application of 30 cost-effective energy efficiency technologies in the EEC scenario decreases CO_2 emissions by 4 Mt (equal to 7% of the total emissions) by 2030, and CO_2 emissions further decrease by 5% in the EET scenario. Compared with energy-savings potential, energy efficiency measures contribute less to CO_2 mitigation. Emissions from raw material calcination account for 44% of the total emissions. However, the opportunities related to the mitigation of processes that generate emissions are beyond the scope of this study. Regarding the distribution of CO_2 reduction potential at the city scale, in the EEC and EET scenarios, CO_2 mitigation varies significantly between cities depending on the cement output and penetration of selected energy efficiency measures (see Figure 3(lower)). In the EEC scenario, the cities of Tangshan, Shijiazhuang, and Xingtai are the top three contributors to CO_2 reduction, accounting for 56% of the total reduction potential throughout the studied period. In the EET scenario, the CO_2 reduction potential in the cities of Beijing, Tianjin, Handan, and Baoding is higher than that in the EEC scenario by 69–92% due to the application of seven non-cost-effective energy efficiency measures, including the use of high-efficiency classifiers and roller mills, multi-stage preheater kiln, and raw mill blending (homogenizing) systems.

(top)

(down)

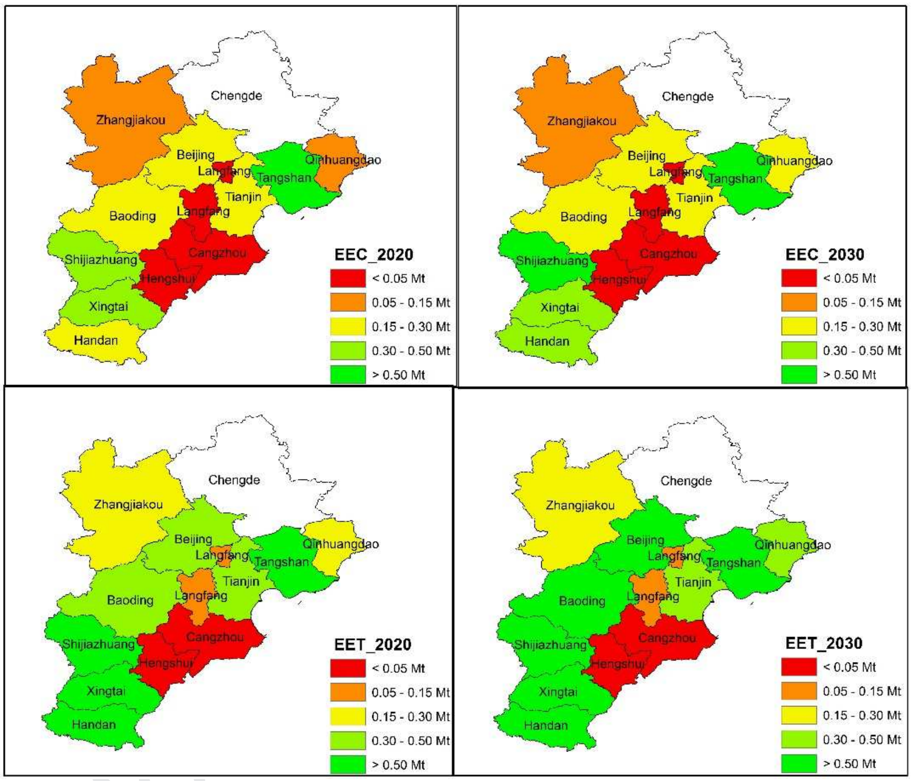


Figure 3. CO_2 emissions (top) and energy-related CO_2 mitigation (down) in the JJJ region.

3.4 Air pollutant emissions and abatement

The emission of air pollutants in the cement industry depends on the progress of development, on the self-sufficiency of limestone, on the scale of production, on the quality of fuel, and on the type of kiln. Figure 4 shows the regional trends in air pollution and pollution abatement based on the adoption of selected energy efficiency technologies in the JJJ's cement industry until 2030. As shown in Figure 4(a–c), between 2010 and 2030 and across regions, air pollution emissions range from 1,000 kt to 25,000 kt per year. Within the JJJ region, most air pollution emissions in the cement sector originate in Hebei, which contributes 93% of the emissions, followed by Tianjin and Beijing. During the study period, the total air pollution emissions in Beijing declines by 20–48% compared with that in the BL scenario. In all scenarios, each pollutant's (i.e., $PM_{2.5,}$ SO_2, and NOx) contribution to the total air pollution varies widely in different regions. For example, SO_2 contributes to 17–34% of the total pollution in Tianjin and Hebei but contributes only 4% of the pollution in Beijing between 2020 and 2030. Further, the share of $PM_{2.5}$ to the total air pollution in Beijing in the EET scenario increases by 16% from 2010 to 2030. The main reason is that the selected energy efficiency measures have higher co-benefits for NOx reduction than for $PM_{2.5}$ reduction. We also modeled the energy efficiency for clean air at the city scale in the EEC and EET scenarios by using the GAINS-JJJ model (see Figure 4 (d)). Overall, the highest air pollution abatement was unsurprisingly observed in Tangshan, Shijiazhuang, and

Xingtai of Heibei, and fewer $PM_{2.5}$ emissions by small-scale cement plants were observed in the megacities of Beijing and Tianjin. In the top three cities, the application of cost-effective energy efficiency technologies in the EEC scenario may decrease the total air pollution by 9–25%, and the application of the seven non-cost-effective energy efficiency technologies in the EET scenario will further reduce the pollution by 6–20%.

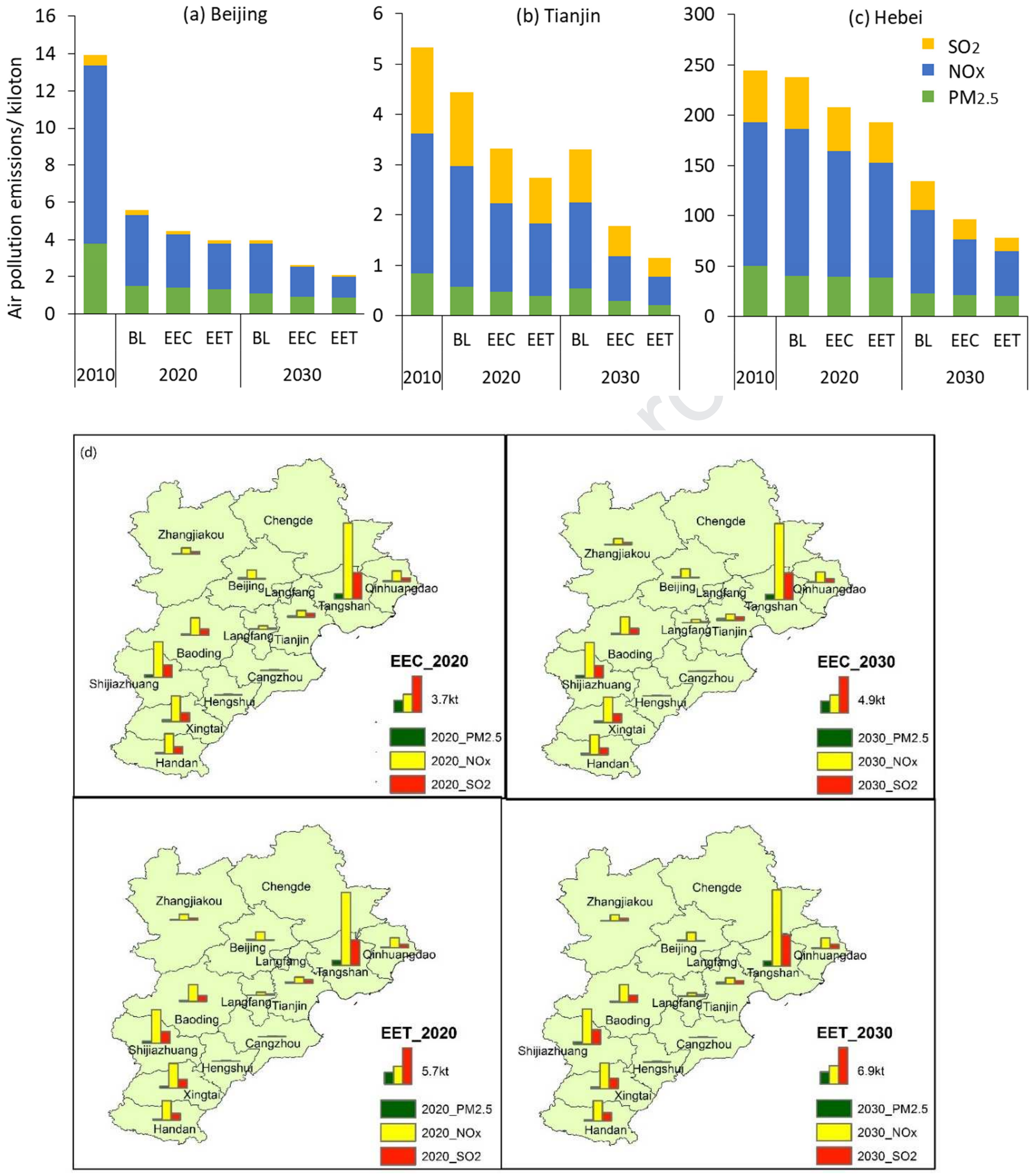


Figure 4. Regional air pollution emissions (a–c) and dynamic abatement (d) in the JJJ region.
Note: the legend scale represents the emission of air pollutant.

3.5 Health effects and economic impacts

The potential contribution of cement production to the decrease in $PM_{2.5}$ concentration is not significant for two reasons: (1) The share of $PM_{2.5}$ emissions caused by cement production in Hebei accounts for 16% of the total emissions. By contrast, the share of both Beijing and Tianjin is less than 1% of the total emissions (Zhang et al., 2016). (2) The best available air pollution control options in the cement industry have already been implemented in Beijing (Tian et al., 2014).

We assessed the contribution of energy efficiency in reducing the average annual $PM_{2.5}$ concentration under different scenarios. Overall, by making assumptions on the projected implementation rates for cost-effective energy efficiency technologies in the EEC scenario, we found that by 2030, the average annual $PM_{2.5}$ concentration decreases by less than 0.5 μg/m^3 in the JJJ region. For the EET scenario, wherein all of the best available energy efficiency measures will be fully applied, the average annual $PM_{2.5}$ concentration decreases by around 0.7 μg/m^3. The distribution of primary $PM_{2.5}$ emissions is similar to the distribution of $PM_{2.5}$ concentration abatement at the prefecture scale. Typically, Tianjin has the most significant potential for reduction, whereas Beijing has the lowest actual reduction.

In terms of health effects related to $PM_{2.5}$, in the EEC scenario, morbidity decreases by 2,600, 2,800, and 12,400 in Beijing, Tianjin, and Hebei, respectively. With the application of all selected energy efficiency technologies in the EET scenario, morbidity is further reduced by 5,200, 5,600, and 31,100 in Beijing, Tianjin, and Hebei, respectively. Although health improvement due to the implementation of energy efficiency technologies in the JJJ's cement industry is not significant, the willingness-to-pay method shows that the economic benefit remains substantial in the two alternative scenarios. For example, the VSL savings due to the avoidance of premature death are around 70 million USD in Beijing, 60 million USD in Tianjin, and 19 million USD in Hebei in 2030 under the EEC scenario. In the EET scenario, VSL savings are considerably increased (200 million USD, 190 million USD, and 670 million USD in Beijing, Tianjin, and Hebei, respectively).

Finally, we estimate the overall cost of energy efficiency measures and the benefit of energy–emission–health under different scenarios until 2030 at the JJJ aggregated level. As shown in Figure 5, the direct energy-saving benefits may be 15–30% lower than the cost of energy efficiency measures in the EEC scenario, whereas the total cost in EET scenario will further increase such that it becomes 47% higher than the benefits. However, if the energy–emission–health nexus is considered, the full benefits (i.e., energy-saving benefit, CO_2 reduction benefits, and the health benefits) will be 1.3–3.6 times higher than the total costs of energy efficiency measures during the study period. This finding means that it is essential to assess the energy–emission–health effects when designing and implementing an energy efficiency policy.

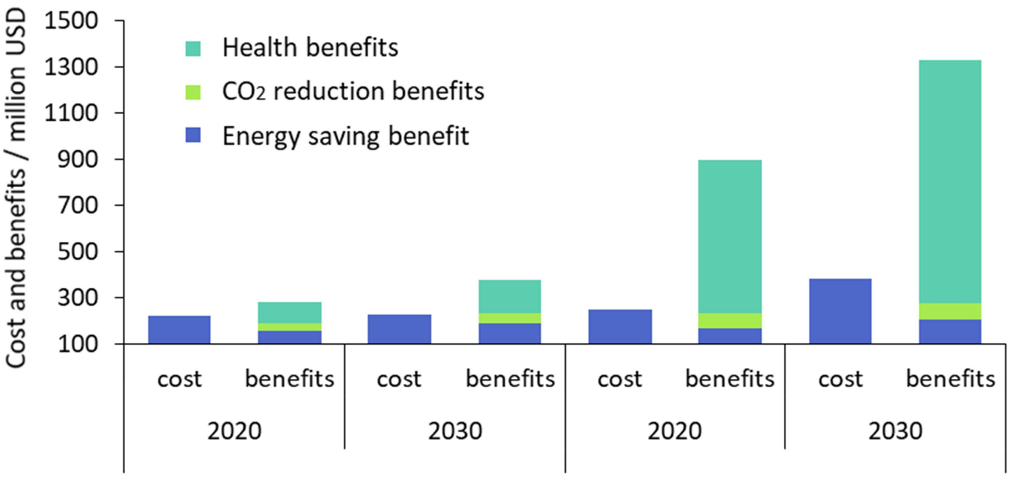


Figure 5. Cost and benefits under different scenarios

4. Conclusions

We assessed the potential for energy efficiency improvement and the associated energy–emission–health–economic nexus of the JJJ's cement industry at different scales until 2030.

An integrated nexus framework was used; this framework consisted of a GIS-based energy model involving the IU curves to model future cement production, the GAINS model to estimate air pollution abatement and the changes in pollutant concentration, and the IMED|CGE and HEL models that were developed and used to quantify the associated health effects and their effect on GDP gains at the regional and prefecture levels from 2011 to 2030. For all scenarios, energy consumption in the JJJ's cement industry shows a drastic decline after 2020. In the baseline scenario, by 2030, the energy consumption by the JJJ's cement industry is projected to be 134 PJ, which is 47% lower than that in 2010. In the EEC scenario, 21–44% energy savings, 8–13% CO_2 reduction, and 13–29% air pollution abatement are achieved when the selected cost-effective energy efficiency technologies were assumed to have been implemented. As regards potential distribution, heterogeneity in terms of energy savings, reductions in CO_2 emissions and air pollution, and associated health benefits for the next two decades is observed across the cities (except Chengde). Typically, the cities of Tangshan, Xingtai, and Shijiazhuang are the top three contributors to energy saving potential and potential for reduction of CO_2 and air pollutant emissions; together, these cities account for 57%, 56%, and 45% of energy saving and CO_2 and air pollutant mitigations, respectively.

Unsurprisingly, energy efficiency improvement in the JJJ's cement industry has less contribution to pollution concentration and to the associated public health effects because its $PM_{2.5}$ emissions has contributed less (4%) to total emissions compared with the other sectors, such as the steel, power, and transportation industries. In the two alternative scenarios, by 2030, the potential reduction of the average annual $PM_{2.5}$ concentration is 0.5–0.7 $\mu g/m^3$, which would avoid morbidity in 17,800–41,900 individuals and save 149–1060 million USD. However, direct energy-saving benefits could be 15–47% lower than the cost of energy efficiency measures in both scenarios, but the full benefits (i.e., energy saving benefit, CO_2 reduction benefits, and the health benefits) will be 1.3–3.6 times higher than the total costs during the study period. Hence, this study clearly indicates that policies that integrate design can create more possibilities for increasing energy efficiency, for cleaning the air, and for extending human life. Also, it is helpful to use a nexus approach to assess the possible solutions to multi-faceted challenges, such as energy and resource security, climate change mitigation, and environmental pollution and health.

Acknowledgments

The work was supported by the National Natural Science Foundation of China under Grant No. 71904007, 71903010, 71690245, the postdoctoral fellowships at the International Institute for Applied Systems Analysis (IIASA), Austria, and the special fund of State Key Joint Laboratory of Environment Simulation and Pollution Control (18K01ESPCP), Peking University, China. We extend our gratitude to the valuable comments of the anonymous reviewers. All remaining errors remain the sole responsibility of the authors.

References

Amann, M., Bertok, I., Borken, J., Cofala, J., Heyes, C., Höglund, L., Klimont, Z., Purohit, P., Rafaj, P., Schoepp, W., Toth, G., Wagner, F., Winiwarter, W., 2008. GAINS - Potentials and costs for greenhouse gas mitigation in Annex I countries. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Amann, M., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Höglund-Isaksson, L., Klimont, Z., Nguyen, B., Posch, M., Rafaj, P., Sandler, R., Schöpp, W., Wagner, F., Winiwarter, W., 2011. Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications. Environmental Modelling & Software 26, 1489–1501. https://doi.org/10.1016/j.envsoft.2011.07.012

Amann, M., Kejun, J., Hao, J., Wang, S., Wei, W., Xing, J., Zhang, Ch., Bertok, I., Borken, J., Cofala, J., Heyes, Ch., Hoglund, L., Klimont, Z., Purohit, P., Rafaj, P., Schöpp, W., Toth, G., Wagner, F., Winiwarter, W., 2008. GAINS-Asia: Scenarios for cost-effective control of air pollution and greenhouse gases in China. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Apte, J.S., Marshall, J.D., Cohen, A.J., Brauer, M., 2015. Addressing Global Mortality from Ambient PM2.5. Environ. Sci. Technol. 49, 8057–8066. https://doi.org/10.1021/acs.est.5b01236

Cai, B., Wang, J., He, J., Geng, Y., 2016. Evaluating CO2 emission performance in China's cement industry: An enterprise perspective. Applied Energy 166, 191–200. https://doi.org/10.1016/j.apenergy.2015.11.006
China Cement Association, 2010. China Cement Almanac 2011-2014.
Creutzig, F., Roy, J., Lamb, W.F., Azevedo, I.M.L., Bruin, W.B. de, Dalkmann, H., Edelenbosch, O.Y., Geels, F.W., Grubler, A., Hepburn, C., Hertwich, E.G., Khosla, R., Mattauch, L., Minx, J.C., Ramakrishnan, A., Rao, N.D., Steinberger, J.K., Tavoni, M., Ürge-Vorsatz, D., Weber, E.U., 2018. Towards demand-side solutions for mitigating climate change. Nature Climate Change 8, 268–271. https://doi.org/10.1038/s41558-018-0121-1
Dai, Y., Hu, X., 2013. Potential and cost study on China's carbon mitigation technologies. China Environmental Press.
Dai, Y., Xiong, H., 2013. Roadmap study on achieving technical energy conservation potential in China*s industrial sector by 2020. China Science and Technology Press.
Dierauer, J.R., Allen, D.M., Whitfield, P.H., 2018. Exploring Future Water Demand and Climate Change Impacts on Water Availability in the Peace Region of British Columbia, Canada, in: Endo, A., Oh, T. (Eds.), The Water-Energy-Food Nexus: Human-Environmental Security in the Asia-Pacific Ring of Fire, Global Environmental Studies. Springer Singapore, Singapore, pp. 45–54. https://doi.org/10.1007/978-981-10-7383-0_4
Dooley, K., Christoff, P., Nicholas, K.A., 2018. Co-producing climate policy and negative emissions: trade-offs for sustainable land-use. Global Sustainability 1. https://doi.org/10.1017/sus.2018.6
Fang, D., Chen, B., Hubacek, K., Ni, R., Chen, L., Feng, K., Lin, J., 2019. Clean air for some: Unintended spillover effects of regional air pollution policies. Science Advances 5, eaav4707. https://doi.org/10.1126/sciadv.aav4707
Fuss, S., Lamb, W.F., Callaghan, M.W., Hilaire, J., Creutzig, F., Amann, T., Tim Beringer, Garcia, W. de O., Hartmann, J., Khanna, T., Luderer, G., Nemet, G.F., Joeri Rogelj, Smith, P., Vicente, J.L.V., Wilcox, J., Dominguez, M. del M.Z., Minx, J.C., 2018. Negative emissions—Part 2: Costs, potentials and side effects. Environ. Res. Lett. 13, 063002. https://doi.org/10.1088/1748-9326/aabf9f
Gao, T., Fang, D., Chen, B., 2020. Multi-regional input-output and linkage analysis for water-PM2.5 nexus. Applied Energy 268, 115018. https://doi.org/10.1016/j.apenergy.2020.115018
Hasanbeigi, A., Khanna, N., Price, L., 2017. Air Pollutant Emissions Projection for the Cement and Steel Industry in China and the Impact of Emissions Control Technologies.
Hasanbeigi, A., Lobscheid, A., Lu, H., Price, L., 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 458–460, 624–636. https://doi.org/10.1016/j.scitotenv.2013.04.031
Hasanbeigi, A., Menke, C., Therdyothin, A., 2010. The use of conservation supply curves in energy policy and economic analysis: The case study of Thai cement industry. Energy Policy 38, 392–405. https://doi.org/10.1016/j.enpol.2009.09.030
Hasanbeigi, A., Morrow, W., Masanet, E., Sathaye, J., Xu, T., 2013b. Energy efficiency improvement and CO2 emission reduction opportunities in the cement industry in China. Energy Policy 57, 287–297. https://doi.org/10.1016/j.enpol.2013.01.053
Hasanbeigi, A., Morrow, W., Masanet, E., Sathaye, J., Xu, T., 2013c. Assessment of Energy Efficiency Improvement and CO2 Emission Reduction Potentials in the Cement Industry in China.
Hebei Statistical Bureau, 2019. Hebei Economic Yearbook 2016. URL http://tjj.hebei.gov.cn/res/nj2018/indexch.htm (accessed 9.16.19).
Heck, V., Gerten, D., Lucht, W., Popp, A., 2018. Biomass-based negative emissions difficult to reconcile with planetary boundaries. Nature Climate Change 1. https://doi.org/10.1038/s41558-017-0064-y
Hoff, H., 2018. Integrated SDG Implementation—How a Cross-Scale (Vertical) and Cross-Regional Nexus Approach Can Complement Cross-Sectoral (Horizontal) Integration, in: Hülsmann, S., Ardakanian, R. (Eds.), Managing Water, Soil and Waste Resources to Achieve Sustainable Development Goals: Monitoring and Implementation of Integrated Resources Management. Springer International Publishing, Cham, pp. 149–163. https://doi.org/10.1007/978-3-319-75163-4_7
Hülsmann, S., Ardakanian, R., 2018. The Nexus Approach as Tool for Achieving SDGs: Trends and Needs, in: Hülsmann, S., Ardakanian, R. (Eds.), Managing Water, Soil and Waste Resources to Achieve Sustainable Development Goals: Monitoring and Implementation of Integrated Resources Management. Springer International Publishing, Cham, pp. 1–9. https://doi.org/10.1007/978-3-319-75163-4_1
Irvine, E., J Hoskins, B., P Shine, K., 2014. A simple framework for assessing the trade-off between the climate impact of aviation carbon dioxide emissions and contrails for a single flight. Environmental Research Letters 9, 064021. https://doi.org/10.1088/1748-9326/9/6/064021
Kermeli, K., Worrell, E., Crijns-Graus, W.H.J., 2016. Modeling the cement industry in integrated assessment models: key factors for further improvement, in: ECEEE Industrial Summer Study Proceedings. ECEEE, pp. 207–221.

Lemoine, D.M., Fuss, S., Szolgayova, J., Obersteiner, M., Kammen, D.M., 2012. The influence of negative emission technologies and technology policies on the optimal climate mitigation portfolio. Climatic Change 113, 141–162.

Liu, J., Hull, V., Godfray, H.C.J., Tilman, D., Gleick, P., Hoff, H., Pahl-Wostl, C., Xu, Z., Chung, M.G., Sun, J., Li, S., 2018. Nexus approaches to global sustainable development. Nature Sustainability 1, 466–476. https://doi.org/10.1038/s41893-018-0135-8

Liu, J., Zhang, S., Wagner, F., 2018. Exploring the driving forces of energy consumption and environmental pollution in China's cement industry at the provincial level. Journal of Cleaner Production 184, 274–285. https://doi.org/10.1016/j.jclepro.2018.02.277

Liu, M., Huang, Y., Jin, Z., Ma, Z., Liu, X., Zhang, B., Liu, Y., Yu, Y., Wang, J., Bi, J., Kinney, P.L., 2017. The nexus between urbanization and PM2.5 related mortality in China. Environmental Pollution 227, 15–23. https://doi.org/10.1016/j.envpol.2017.04.049

Liu, Z., 2017. Promote building industrilization and energy and land saving buildings [WWW Document]. China House. URL http://www.chinahouse.gov.cn/ldjh/ld0066.htm

Luderer, G., Vrontisi, Z., Bertram, C., Edelenbosch, O.Y., Pietzcker, R.C., Rogelj, J., De Boer, H.S., Drouet, L., Emmerling, J., Fricko, O., Fujimori, S., Havlík, P., Iyer, G., Keramidas, K., Kitous, A., Pehl, M., Krey, V., Riahi, K., Saveyn, B., Tavoni, M., Van Vuuren, D.P., Kriegler, E., 2018. Residual fossil CO2 emissions in 1.5–2 °C pathways. Nature Climate Change 8, 626–633. https://doi.org/10.1038/s41558-018-0198-6

Matus, K., Nam, K.-M., Selin, N.E., Lamsal, L.N., Reilly, J.M., Paltsev, S., 2012. Health damages from air pollution in China. Global Environmental Change 22, 55–66. https://doi.org/10.1016/j.gloenvcha.2011.08.006

Ministry of Industry and Information Technology (MIIT) of China, 2014. the Guidebook of industrial energy efficiency in China.

Ministry of Industry and Information Technology (MIIT) of China, 2012. The guidebook of Chinese best energy saving measures and end-of-pipe options in cement industry.

National Bureau of Statistics, 2019. China Statistical Yearbook 2019. China Statistics Press, Beijing.

National Bureau of Statistics, 2016. China statistical Yearbook 2002-2016. China Statistics Press, Beijing.

National Bureau of Statistics, 2015. China Statistical Yearbook. China Statistics Press, Beijing.

National Bureau of Statistics of China, 2014. China Statistical Yearbook 2014. China Statistics Press, Beijing.

National Bureau of Statistics of China, 2013. China Energy Statistical Yearbook 2013. National Bureau of Statistics of China. http://www.stats.gov.cn/tjsj/ndsj/2011/indexeh.htm

National Bureau of Statistics of China, 2011. China Energy Statistical Yearbook 2011. National Bureau of Statistics of China. http://www.stats.gov.cn/tjsj/ndsj/2011/indexeh.htm

National Development and Reform Commission of China, 2013. Guidebook for greenhouse gas emissions of cement manufacturing enterprises in China.

Oshiro, K., Kainuma, M., Masui, T., 2017. Implications of Japan's 2030 target for long-term low emission pathways. Energy Policy 110, 581–587. https://doi.org/10.1016/j.enpol.2017.09.003

Paltsev, S., 2017. Energy scenarios: the value and limits of scenario analysis: The value and limits of energy scenario analysis. Wiley Interdisciplinary Reviews: Energy and Environment 6, e242. https://doi.org/10.1002/wene.242

Peng, W., Yang, J., Lu, X., Mauzerall, D.L., 2018. Potential co-benefits of electrification for air quality, health, and CO2 mitigation in 2030 China. Applied Energy 218, 511–519. https://doi.org/10.1016/j.apenergy.2018.02.048

Peters, G.P., 2016. The "best available science" to inform 1.5 °C policy choices. Nature Clim. Change 6, 646–649. https://doi.org/10.1038/nclimate3000

Qi, J., Zheng, B., Li, M., Yu, F., Chen, C., Liu, F., Zhou, X., Yuan, J., Zhang, Q., He, K., 2017. A high-resolution air pollutants emission inventory in 2013 for the Beijing-Tianjin-Hebei region, China. Atmospheric Environment 170, 156–168. https://doi.org/10.1016/j.atmosenv.2017.09.039

Rafaj, P., Kiesewetter, G., Gül, T., Schöpp, W., Cofala, J., Klimont, Z., Purohit, P., Heyes, C., Amann, M., Borken-Kleefeld, J., Cozzi, L., 2018. Outlook for clean air in the context of sustainable development goals. Global Environmental Change 53, 1–11. https://doi.org/10.1016/j.gloenvcha.2018.08.008

Rao, S., Pachauri, S., Dentener, F., Kinney, P., Klimont, Z., Riahi, K., Schoepp, W., 2013. Better air for better health: Forging synergies in policies for energy access, climate change and air pollution. Global Environmental Change 23, 1122–1130. https://doi.org/10.1016/j.gloenvcha.2013.05.003

Shindell, D., Faluvegi, G., Seltzer, K., Shindell, C., 2018. Quantified, localized health benefits of accelerated carbon dioxide emissions reductions. Nature Climate Change 1. https://doi.org/10.1038/s41558-018-0108-y

Tian, G., Wang, F., Shu, Y., Wang, H., Liu, Y., Zhang, F., 2014. Assessing air pollution control in Jing-Jin-Ji's cement industry. China Cement 68–70.

Tian, X., Dai, H., Geng, Y., Wilson, J., Wu, R., Xie, Y., Hao, H., 2018. Economic impacts from PM2.5 pollution-related health effects in China's road transport sector: A provincial-level analysis. Environment International 115, 220–229. https://doi.org/10.1016/j.envint.2018.03.030

Tsinghua University, 2008. Assisting Developing Country Climate Negotiators through Analysis and Dialogue : Report of Energy Saving and CO 2 Emission Reduction Analysis in China Cement Industry.

Turner, M.C., Jerrett, M., Pope, C.A., Krewski, D., Gapstur, S.M., Diver, W.R., Beckerman, B.S., Marshall, J.D., Su, J., Crouse, D.L., Burnett, R.T., 2015. Long-Term Ozone Exposure and Mortality in a Large Prospective Study. Am J Respir Crit Care Med 193, 1134–1142. https://doi.org/10.1164/rccm.201508-1633OC

Viscusi, W.K., Aldy, J.E., 2003. The Value of a Statistical Life: A Critical Review of Market Estimates Throughout the World. Journal of Risk and Uncertainty 27, 5–76. https://doi.org/10.1023/A:1025598106257

Vuuren, D.P. van, Stehfest, E., Gernaat, D.E.H.J., Berg, M. van den, Bijl, D.L., Boer, H.S. de, Daioglou, V., Doelman, J.C., Edelenbosch, O.Y., Harmsen, M., Hof, A.F., Sluisveld, M.A.E. van, 2018. Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. Nature Climate Change 8, 391. https://doi.org/10.1038/s41558-018-0119-8

Wagner, F., Borken-Kleefeld, J., Kiesewetter, G., Klimont, Z., Nguyen, B., Rafaj, P., Schöpp, W., 2018. The GAINS PMEH-Methodology -Version 2.0. URL http://pure.iiasa.ac.at/id/eprint/15695/ (accessed 1.30.19).

Walsh, B., Ciais, P., Janssens, I.A., Peñuelas, J., Riahi, K., Rydzak, F., Vuuren, D.P. van, Obersteiner, M., 2017. Pathways for balancing CO2 emissions and sinks. Nature Communications 8, 14856. https://doi.org/10.1038/ncomms14856

Wang, Y., Höller, S., Viebahn, P., Hao, Z., 2014. Integrated assessment of CO2 reduction technologies in China's cement industry. International Journal of Greenhouse Gas Control 20, 27–36. https://doi.org/10.1016/j.ijggc.2013.10.004

Wang, Y., Jiang, C., He, J., Zhong, Y., Song, X., 2018. Analysis of air pollutants control in cement industry in and around Beijing-Tianjin-Hebei region. China Environmental Science 38, 3683–3688.

Wen, Z., Chen, M., 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. https://doi.org/10.1016/j.enpol.2014.11.030

Worrell, E., Carreon, J.R., 2017. Energy demand for materials in an international context. Phil. Trans. R. Soc. A 375, 20160377. https://doi.org/10.1098/rsta.2016.0377

Woo, J., 2015. Gains-Korea Modeling Result and PM2.5 Monitoring Data.

Xi, Y., Fei, T., 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. https://doi.org/10.1016/j.jclepro.2013.07.020

Xie, Y., Liu, X., Chen, Q., Zhang, S., 2020. An integrated assessment for achieving the 2°C target pathway in China by 2030. Journal of Cleaner Production 122238. https://doi.org/10.1016/j.jclepro.2020.122238

Yang, S., Fang, D., Chen, B., 2019. Human health impact and economic effect for PM2.5 exposure in typical cities. Applied Energy 249, 316–325. https://doi.org/10.1016/j.apenergy.2019.04.173

Yi, B.-W., Zhang, S., Wang, Y., 2020. Estimating air pollution and health loss embodied in electricity transfers: An inter-provincial analysis in China. Science of The Total Environment 702, 134705. https://doi.org/10.1016/j.scitotenv.2019.134705

Zhang, S., 2016. Energy Efficiency for Clean Air: Capturing the multiple benefits for climate, air quality, and public health in China (Dissertation). Utrecht University, Utrecht.

Zhang, S., Fricko, O., Krey, V., Wagner, F., Guo, F., Worrell, E., Crijns-Graus, W.H.J., 2018a. International Association for Energy Economics: Online Proceedings, in: Transforming Energy Markets. Presented at the The 41st International Association for Energy Economics (IAEE) international conference, IAEE, Groningen, the Netherlands, pp. 1–8.

Zhang, S., Ren, H., Zhou, W., Yu, Y., Chen, C., 2018b. Assessing air pollution abatement co-benefits of energy efficiency improvement in cement industry: A city level analysis. Journal of Cleaner Production 185, 761–771. https://doi.org/10.1016/j.jclepro.2018.02.293

Zhang, S., Worrell, E., Crijns-Graus, W., 2015a. 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. https://doi.org/10.1016/j.apenergy.2015.05.104

Zhang, S., Worrell, E., Crijns-Graus, W., 2015b. Synergy of air pollutants and greenhouse gas emissions of Chinese industries: A critical assessment of energy models. Energy 93, 2436–2450. https://doi.org/10.1016/j.energy.2015.10.088

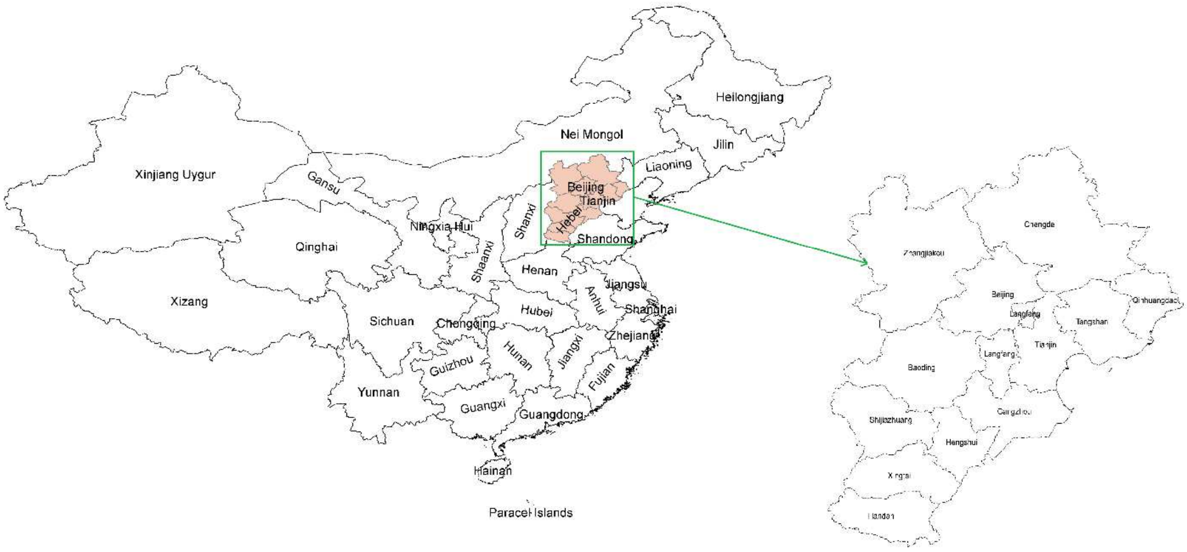
Zhang, S., Worrell, E., Crijns-Graus, W., 2015c. Evaluating co-benefits of energy efficiency and air pollution abatement in China's cement industry. Applied Energy 147, 192–213. https://doi.org/10.1016/j.apenergy.2015.02.081

Zhang, S., Worrell, E., Crijns-Graus, W., Krol, M., de Bruine, M., Geng, G., Wagner, F., Cofala, J., 2016. Modeling energy efficiency to improve air quality and health effects of China's cement industry. Applied Energy 184, 574–593. https://doi.org/10.1016/j.apenergy.2016.10.030

Zhang, S., Worrell, E., Crijns-Graus, W., Wagner, F., Cofala, J., 2014. Co-benefits of energy efficiency improvement and air pollution abatement in the Chinese iron and steel industry. Energy 78, 333–345. https://doi.org/10.1016/j.energy.2014.10.018

Zhang, S., Yi, B.-W., Worrell, E., Wagner, F., Crijns-Graus, W., Purohit, P., Wada, Y., Varis, O., 2019. Integrated assessment of resource-energy-environment nexus in China's iron and steel industry. Journal of Cleaner Production 232, 235–249. https://doi.org/10.1016/j.jclepro.2019.05.392

Zhou, N., Price, L., Zheng, N., Ke, J., 2011. National Level Co-Control Study of the Targets for Energy Intensity and Sulfur Dioxide in China.



Appendix A – Figure 1: the study area of Jing-Jin-Ji and the associated prefectures

Appendix A: Table 1 Cement production in JJJ Unit:[Mt]

Region	Year	cement production
Beijing	2010	10.49
Beijing	2015	11.53
Beijing	2020	4.25
Beijing	2025	3.65
Beijing	2030	3.09
Hebei	2010	127.72
Hebei	2015	90.73
Hebei	2020	87.35
Hebei	2025	71.36
Hebei	2030	50.38
Tianjin	2010	8.32
Tianjin	2015	7.78
Tianjin	2020	6.12
Tianjin	2025	5.69
Tianjin	2030	5.24

Appendix A: Table 2 Key parameter of energy efficiency measures in JJJ's cement industry

Number	energy efficiency measures	Raw material reduction (t/t-clinker)	fuel saving (GJ/t-clinker)	electricity saving(GJ/t-clinker)	emission reduction (Kg CO2/t-clinker)	capital cost($/t-clinker)	annual O&M cost ($/t-clinker)	Life time
	fuel and raw material preparation							
1	New efficient coal separator			0.00	0.27	0.01	0.00	20
2	VFD in raw mill vent fan			0.00	0.34	0.02	0.00	10
3	Bucket elevators for raw meal transport			0.01	2.42	0.19	0.00	20
4	High efficiency fan for raw mill vent fan with inverter			0.00	0.37	0.04	0.00	10
5	Efficient Transport System for mine			0.00	1.08	0.16	0.00	25
6	Installation of variable frequency drive & replacement of coal mill bag dust collector's fan			0.00	0.16	0.03	0.00	10
7	Raw mill process control for roller mill			0.04	13.22	2.42	0.08	20
8	Optimize mine exploitation	0.13	-0.01	0.00	1.65	0.02	0.01	40
9	High efficiency drying for slag		0.29	0.00	25.32	1.27		20
10	Slag powder production		0.06	0.00	0.36	2.06		20
11	High Efficiency Classifiers			0.02	5.23	2.85	0.00	20
12	High Efficiency Roller Mills			0.04	10.45	7.12	0.00	20
13	High-Efficiency Roller Mill for raw mill and coal grinding			0.01	1.51	1.33	0.00	20
14	Raw mill process control for vertical mill			0.01	1.45	1.49	0.08	20
15	Raw mill Blending (homogenizing)			0.01	2.73	4.79	0.00	20

	systems							
	clinker making	Raw material reduction (t/t-clinker)	fuel saving (GJ/t-clinker)	electricity saving(GJ/t-clinker)	emission reduction (Kg CO2/t-clinker)	capital cost($/t-clinker)	Change in annual O&M cost ($/t-clinker)	Life time
16	VFD in cooler fan of Grate Cooler			0.00	0.11	0.01	0.00	10
17	Heat recovery for power generation			0.08	5.10	3.40	0.08	20
18	Adjustable speed drive for kiln fan			0.01	2.05	0.40	0.04	10
19	Kiln Shell Heat Loss Reduction (Improved refractories)		0.26	0.00	24.60	0.21	0.00	5
20	Conversion to Grate Cooler		0.60	0.00	16.37	0.45	0.10	30
21	combustion system improvements		0.03	0.00	0.72	0.17	0.01	30
22	Optimize Grate Cooler		0.09	0.00	2.16	0.45	0.10	30
23	Upgrade clinker cooler		0.11	-0.01	8.35	0.21	0.08	30
24	Energy management & process control		0.15	0.01	16.61	2.36	0.00	10
25	Low temperature heat recovery for power generation			0.13	31.66	9.08	0.89	20
26	Replacing Vertical Shaft Kilns with New Suspension		2.00	0.00	62.00	34.50		40
27	Upgrading to a preheater/precalciner kiln		0.43	0.00	40.68	18.80	-1.18	40
28	Increasing Number of Preheater Stages (from 5 to 6) in Rotary Kilns		0.11	0.00	9.30	2.10	0.02	30
29	Older dry kiln upgrade to multi-stage preheater kiln		0.11	0.00	23.00	34.50		40
30	Low pressure drop cyclones for suspension preheater			0.01	2.67	4.32	0.00	30
	Finish Grinding	Raw material reduction (t/t-cement)	fuel saving (GJ/t-cement)	electricity saving(GJ/t-cement)	emission reduction (Kg CO2/t-cement)	capital cost($/t-cement)	Change in annual O&M cost ($/t-cement)	Life time
31	High Pressure Roller			0.04	8.53	1.61	0.08	20

	Press for ball mill pregrinding							
32	High-Efficiency Classifiers			0.02	6.27	4.07	0.00	20
	general measures	Raw material reduction (t/t-clinker)	fuel saving (GJ/t-clinker)	electricity saving(GJ/t-clinker)	emission reduction (Kg CO2/t-clinker)	capital cost($/t-clinker)	Change in annual O&M cost ($/t-clinker)	Life time
33	High Efficiency Motors			0.02	4.70	0.38	0.00	10
34	Adjustable Speed Drives			0.01	2.43	0.25	0.00	10
35	Energy Management & Process Control		0.40	0.00	9.91	0.04	0.00	10
	product and feed stock change	Raw material reduction (t/t-cement)	fuel saving (GJ/t-cem)		emission reduction (Kg CO2/t-cem)	capital cost($/t-cem)	Change in annual O&M cost ($/t-cem)	Lifetime
36	Blended Cement		1.77	-0.03	160.02	0.60	-0.03	30
	Alternative Fuels	Raw material reduction (t/t-cement)	fuel saving (GJ/t-cem)		emission reduction (Kg CO2/t-cem)	capital cost($/t-cem)	Change in annual O&M cost ($/t-cem)	Lifetime
37	Biomass and Waste		0.60	0.00	56.76	1.10	0.00	30

Appendix A: Table 3 Cement plants data in Jing-Jin-Ji (JJJ) region

Region	City	County	Unit	Category	Total production capacity for clinker	Total production capacity for grinding plants
Beijing	Beijing	Fangshan	Mt/year	clinker	12.40	0.00
		Shunyi	Mt/year	clinker	0.34	0.00
		Huairou	Mt/year	clinker	0.34	0.00
		Changping	Mt/year	clinker	6.23	0.00
Tianjin	Tianjin	Ji	Mt/year	grinding	0.00	4.00
		Hangu	Mt/year	grinding	0.00	0.60
		Tianjin	Mt/year	grinding	0.00	21.00
		Jinghai	Mt/year	grinding	0.00	2.00
		Xiqing	Mt/year	grinding	0.00	1.60
		Wuqing	Mt/year	grinding	0.00	0.60
		Ninghe	Mt/year	grinding	0.00	4.00
		Beichen	Mt/year	clinker	3.10	0.00
Hebei	Baoding	Laishui	Mt/year	grinding	0.60	0.60
		Xushui	Mt/year	grinding	0.00	0.60
		Baoding county	Mt/year	grinding	0.00	1.00
		Yi	Mt/year	clinker	3.10	0.00
		Tang	Mt/year	clinker	1.55	0.00
		Quyang	Mt/year	clinker	1.24	0.00
	Cangzhou	Cangzhou county	Mt/year	grinding	0.00	2.00
		Dongguang	Mt/year	grinding	0.00	0.60
	Chengde	Xinglong	Mt/year	clinker	2.98	0.00
		Kuancheng Manchu	Mt/year	clinker	1.40	0.00
		Pingquan	Mt/year	clinker	0.99	0.00
		Longhua	Mt/year	clinker	0.78	0.00

		Chengde county	Mt/year	clinker	0.99	0.00
		Luanping	Mt/year	grinding	0.00	0.25
	Handan	She	Mt/year	clinker	0.43	1.00
		Wu'an	Mt/year	grinding	1.80	2.80
		Handan county	Mt/year	grinding	0.00	1.00
		Fengfengkuang	Mt/year	clinker	2.33	0.00
	Hengshui	Hengshui county	Mt/year	grinding	0.00	3.60
		Gucheng	Mt/year	grinding	0.00	1.50
	Langfang	Sanhe	Mt/year	grinding	54.88	0.80
	Qinhuangdao	Changli	Mt/year	grinding	186.00	3.60
		Lulong	Mt/year	clinker	0.62	0.00
		Funing	Mt/year	clinker	3.72	0.00
	Shijiazhuang	lingshou	Mt/year	grinding	0.03	0.20
		Huelu	Mt/year	grinding	1.22	1.00
		Zhengding	Mt/year	grinding	0.00	0.60
		Jingjing	Mt/year	clinker	1.24	0.00
		Shijiazhuang county	Mt/year	grinding	1.00	1.00
		Zanhuang	Mt/year	clinker	1.55	0.00
	Tangshan	Yutian	Mt/year	grinding	1.29	8.00
		Fengrun	Mt/year	grinding	9.99	65.60
		Fengnan	Mt/year	grinding	0.00	0.07
		Luan	Mt/year	grinding	9.60	1.20
		Luannan	Mt/year	clinker	2.48	0.00
		Tangshan county	Mt/year	grinding	0.00	4.80
		Zunhua	Mt/year	grinding	1.20	1.20
		Qian'an	Mt/year	clinker	0.62	0.00
	Xingtai	Shahe	Mt/year	clinker	15.50	0.00

		Xingtai county	Mt/year	clinker	0.78	0.00
		Neiqiu	Mt/year	clinker	4.65	0.00
		Lincheng	Mt/year	clinker	4.65	0.00
		Longyao	Mt/year	clinker	0.78	0.00
	Zhangjiakou	Zhangjiakou county	Mt/year	grinding	2.00	1.00
		Xuanhua	Mt/year	grinding	0.00	1.00
		Chicheng	Mt/year	grinding	0.00	1.00
		Zhuolu	Mt/year	clinker	1.24	0.00

Declaration of interest statement

Dear Editors:

We would like to submit the enclosed manuscript entitled "Potentials of energy efficiency improvement and energy–emission–health nexus in Jing-Jin-Ji's cement industry", which we wish to be considered for publication in "Journal of Cleaner Production". No conflict of interest exits in the submission of this manuscript, and manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed.

The work was supported by the National Natural Science Foundation of China under Grant No. 71904007, 71903010, 71690245, the postdoctoral fellowships at the International Institute for Applied Systems Analysis (IIASA), Austria, and the special fund of State Key Joint Laboratory of Environment Simulation and Pollution Control (18K01ESPCP), Peking University, China.

Thank you and best regards.

Yours sincerely,
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Credit Author Statement

Shaohui Zhang and Yang Xie designed the research, analyzed the results, and drafted the paper. Robert Sander ran the GAINS model. Hui Yue and Yun Shu provided comments on the results and discussion. All the authors contributed to the discussion and interpretation of the results.