

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 CO₂ 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 CO₂ emissions, 13% reduction in air pollution, 0.5 μg/m³ 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 CO₂ emission by 5%, in air pollution by 16%, in PM_{2.5} by 0.2 μg/m³, 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 CO₂ 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, CO₂ 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.

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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

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Nomenclature			
<i>Abbreviations</i>			
IAMs	Integrated assessment models	MRIO	Multi-region input-output model
BL	Baseline scenario	SDS	Sustainable Development Scenario
CCS	Carbon capture and storage	TM5	the global chemistry transport model version 5
CDR	Carbon dioxide removal	VSL	Value of statistical life
DC	Derived coal	WEM	World Energy Model
ECSC	Energy conservation supply curves	WHO	World Health Organization
EEC	Energy efficiency improvement with economic potential scenario		
EET	Energy efficiency improvement with the technical potential scenario	<i>Symbols</i>	
ELE	Electricity	P	Cement production
GAINS	Greenhouse Gas and Air Pollution Interactions and Synergies	p_i	Cement production in city i
GAS	Natural gas	NFS	New floor space in city i
GHG	Greenhouse gas	BCI	Cement consumption for one-unit floor space of Building sector in city i
GSL	Gasoline and other light fractions of oil	HCI	Cement consumption for one-unit of highway in city i
HC3	Hard coal	NLH	New length of highways in city i
HEL	Health Impact Assessment	RCI	Cement consumption for one-unit length of railway in city i
HF	Heavy fuel oil	NLR	New length of railways in city i
HT	Heat	Ini	Industrial investment in city i
IAMGE	Integrated Model to Assess the Global Environment	ICI	Cement consumption per unit investment in industrial sector in city i
IIASA	International Institute for Applied Systems Analysis	Im	Net import of cement in province i
IMED CGE	Integrated Model of Energy, Environment and Economy for Sustainable Development/Computable General Equilibrium	CCE	costs of conserved energy for an energy efficiency measure
IU	Intensity use	I	Investment
III	Jing-Jin-Ji	A	Annuity factor
LPG	Liquefied petroleum gas	$O \& M^{Fix}$	Annual change in operation and maintenance fixed costs
MD	Medium distillates	$O \& M^{Var}$	Annual change in operation and maintenance variable costs
MIIT	Ministry of Industry and Information Technology	ESP	Annual energy-saving potential
		PE	Energy price
		r	Discount rate
		l	Lifetime of an energy efficiency measure

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., 2018a,b; 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., 2018a,b). 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 CO₂ 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, CO₂ 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 III (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

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

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., 2018, 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., 2018). 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-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 CO₂ 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 Fig. 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

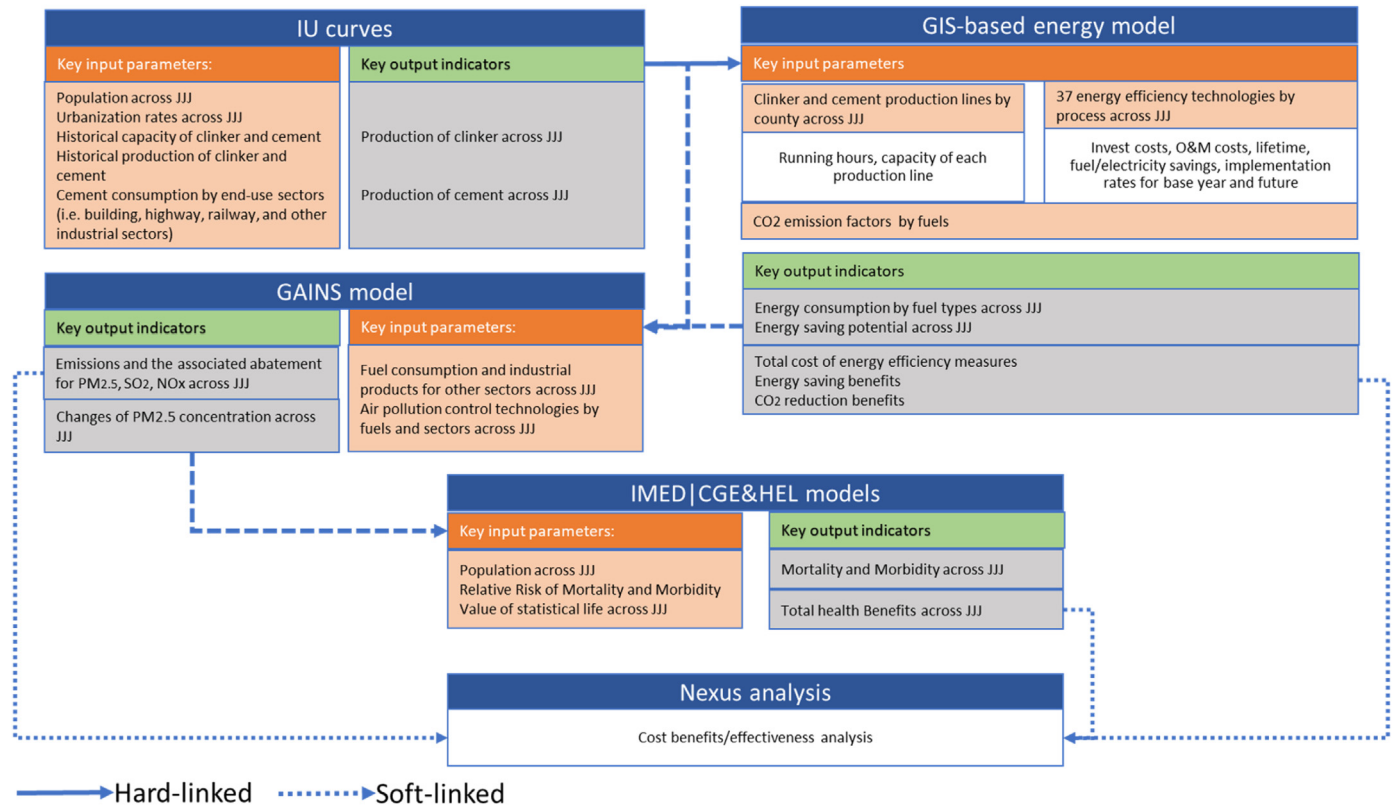


Fig. 1. Workflow of integrated nexus framework that includes energy efficiency, climate change, air quality, and health.

- 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., 2018).
- 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 CO₂ 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, CO₂ mitigation benefits, and health benefits.

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 CO₂ 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 1000 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/m³, 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 CO₂ 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 CO₂ 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 Fig. 1, and the working steps are as follows:

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., 2018).

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., 2018):

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

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 CO₂ 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 CO₂ emission reductions (Zhang et al., 2018).

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).

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

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):

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

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., 2008a, 2008b, 2011; Wagner et al., 2018). The key advantage of GAINS is that it describes the interactions between pollutants (e.g., SO₂, NO_x, PM, and NH₃) 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., 2008a, 2008b; Woo, 2015, 2015; Zhang et al., 2015b). In this study, the GAINS-JJJ model was used to quantify the pollutants SO₂, NO_x, 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.

2.5. Data sources and scenario assumptions

2.5.1. 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., 2018, 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., 2015b), 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 CO₂ emission factor in the JJJ's cement industry was obtained from our recent studies (Zhang et al., 2016, 2015b), and the CO₂ emission factor caused by electricity consumption was obtained from Yi et al. (2020). The pollution abatement potential (i.e., PM_{2.5}, SO₂, and NO_x) related to energy consumption and processes were also assessed. The emission factors of PM_{2.5}, SO₂, and NO_x were modeled using the GAINS-JJJ module. Moreover, 3.22 USD per GJ of energy and 10 USD per ton of CO₂ were used to quantify the benefits of energy saving and CO₂ reductions due to the application of selected energy efficiency technologies (Zhang et al., 2015b).

2.5.2. 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. (2015b, 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 (Table 1). 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.

3. Results and discussion

3.1. Energy consumption and energy saving potential

Fig. 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 Fig. 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 1400–1500 °C to form a clinker (Liu et al., 2018a,b). 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

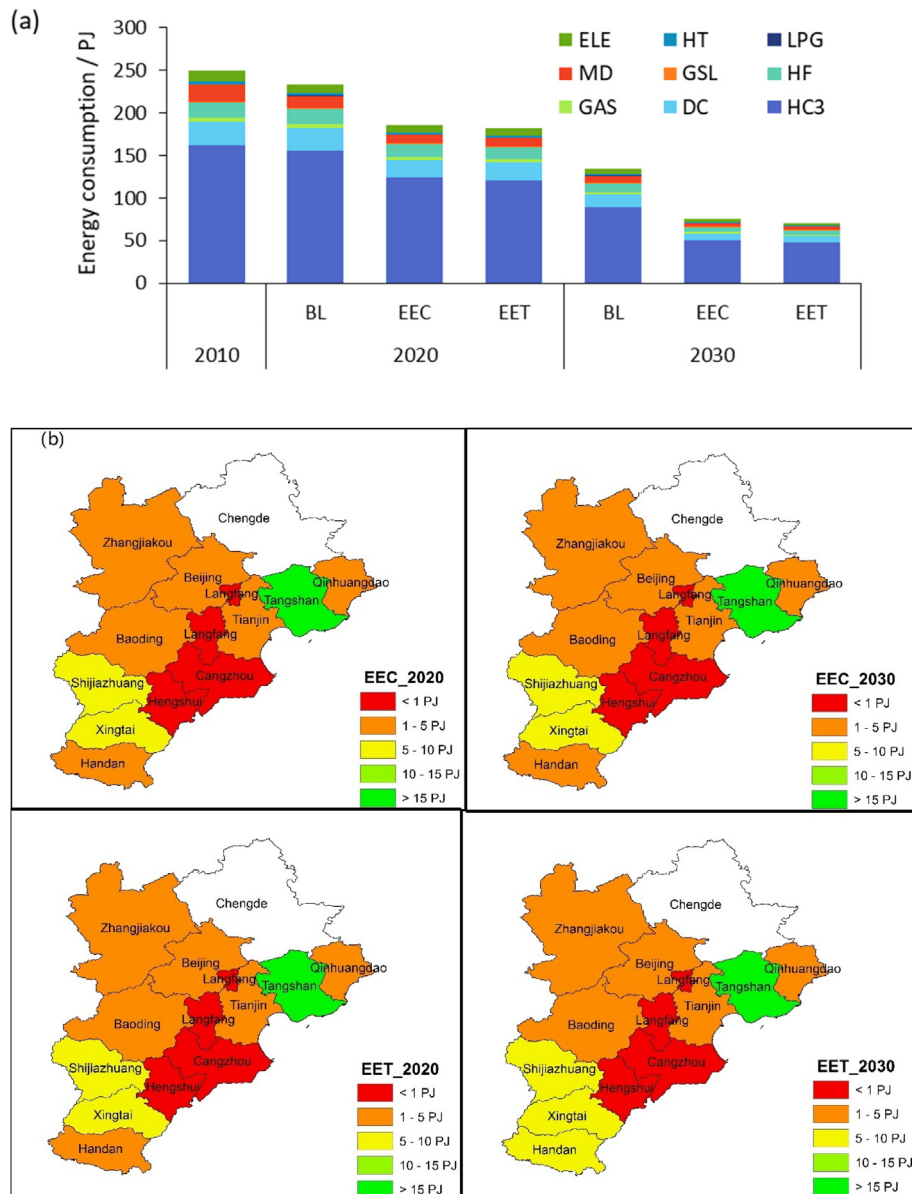


Fig. 2. Energy consumption (a) and associated energy-savings potential (b) in the JJJ region.

energy saving potential, we assessed the dynamic distribution of energy savings at the city scale. Fig. 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 Fig. 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.

3.2. CO₂ emissions and mitigation

Fig. 3 shows the total CO₂ emissions and the mitigation of energy-related CO₂ emissions by the JJJ's cement industry until 2030 at various scales. In general, the CO₂ emissions in different scenarios slightly fluctuated prior to 2020, but after 2020, CO₂ emissions will be significantly reduced. As expected, the application of 30 cost-effective energy efficiency technologies in the EEC

scenario decreases CO₂ emissions by 4 Mt (equal to 7% of the total emissions) by 2030, and CO₂ emissions further decrease by 5% in the EET scenario. Compared with energy-savings potential, energy efficiency measures contribute less to CO₂ 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 CO₂ reduction potential at the city scale, in the EEC and EET scenarios, CO₂ mitigation varies significantly between cities depending on the cement output and penetration of selected energy efficiency measures (see Fig. 3(lower)). In the EEC scenario, the cities of Tangshan, Shijiazhuang, and Xingtai are the top three contributors to CO₂ reduction, accounting for 56% of the total reduction potential throughout the studied period. In the EET scenario, the CO₂ 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

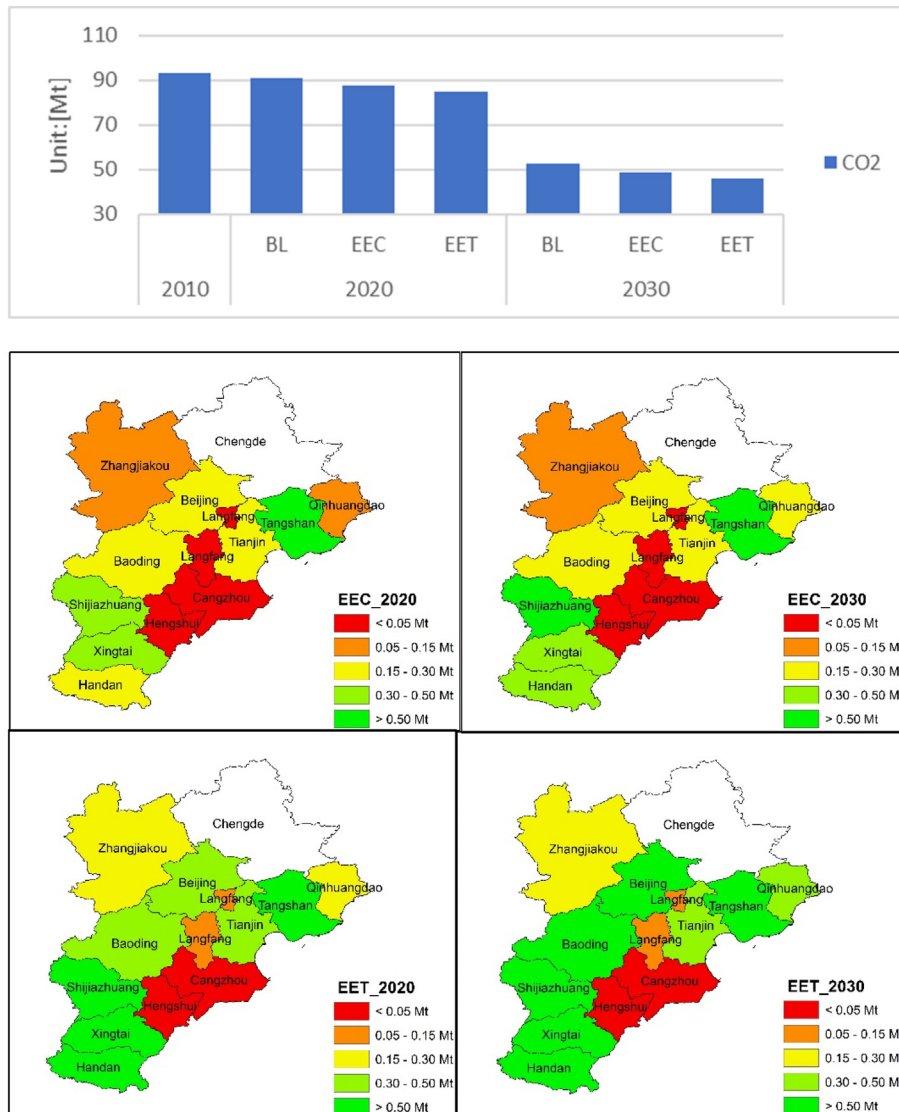


Fig. 3. CO₂ emissions (top) and energy-related CO₂ mitigation (down) in the JJJ region.

(homogenizing) systems.

3.3. 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. Fig. 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 Fig. 4(a–c), between 2010 and 2030 and across regions, air pollution emissions range from 1000 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}, SO₂, and NO_x) contribution to the total air pollution varies widely in different regions. For example, SO₂ 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 NO_x 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 Fig. 4 (d)). Overall, the highest air pollution abatement was unsurprisingly observed in

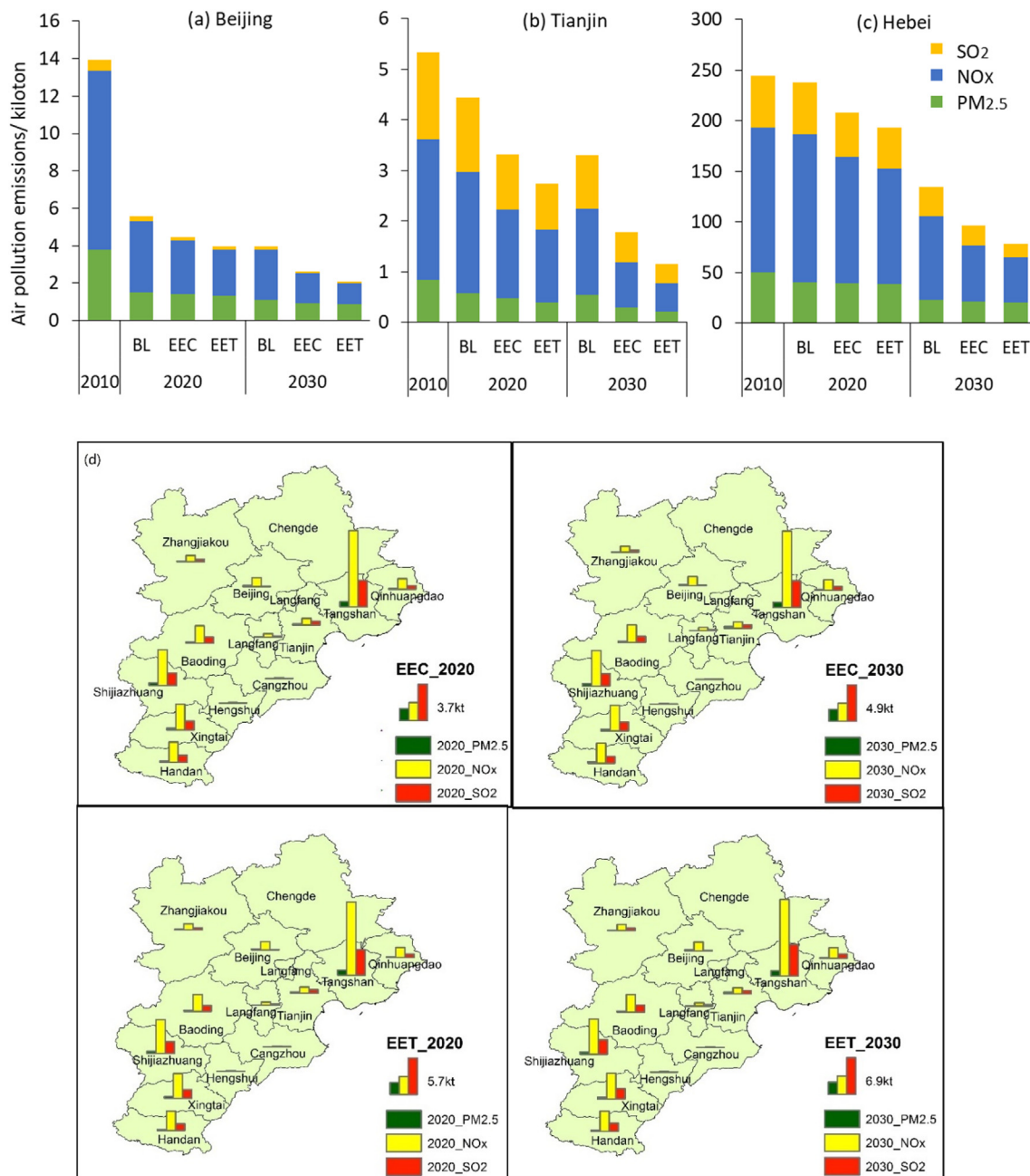


Fig. 4. Regional air pollution emissions (a–c) and dynamic abatement (d) in the JJJ region. Note: the legend scale represents the emission of air pollutant.

Tangshan, Shijiazhuang, and Xingtai of Hebei, 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%.

3.4. 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/m³ 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/m³. 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 Fig. 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, CO₂ 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.

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% CO₂ 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 CO₂ 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 CO₂ and air pollutant emissions; together, these cities account for 57%, 56%, and 45% of energy saving and CO₂ 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

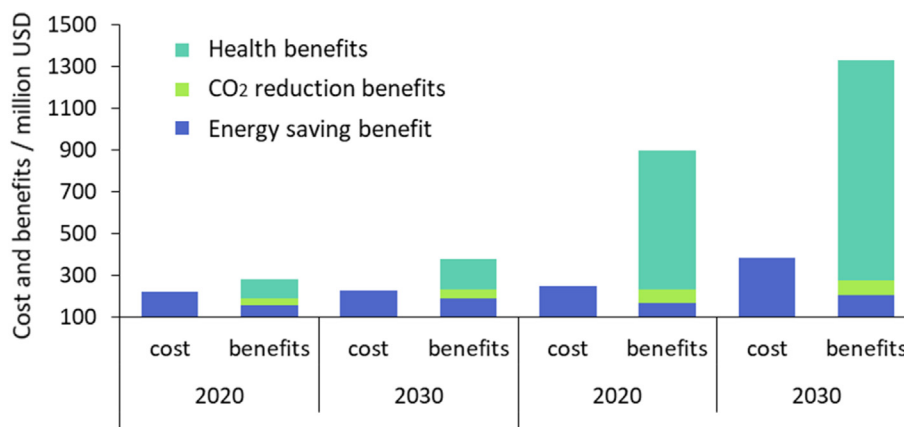


Fig. 5. Cost and benefits under different scenarios.

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 μg/m³, 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, CO₂ 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.

CRedit authorship contribution statement

Shaohui Zhang: Formal analysis, Writing - original draft. **Yang Xie:** Formal analysis, Writing - original draft.

Declaration of competing interest

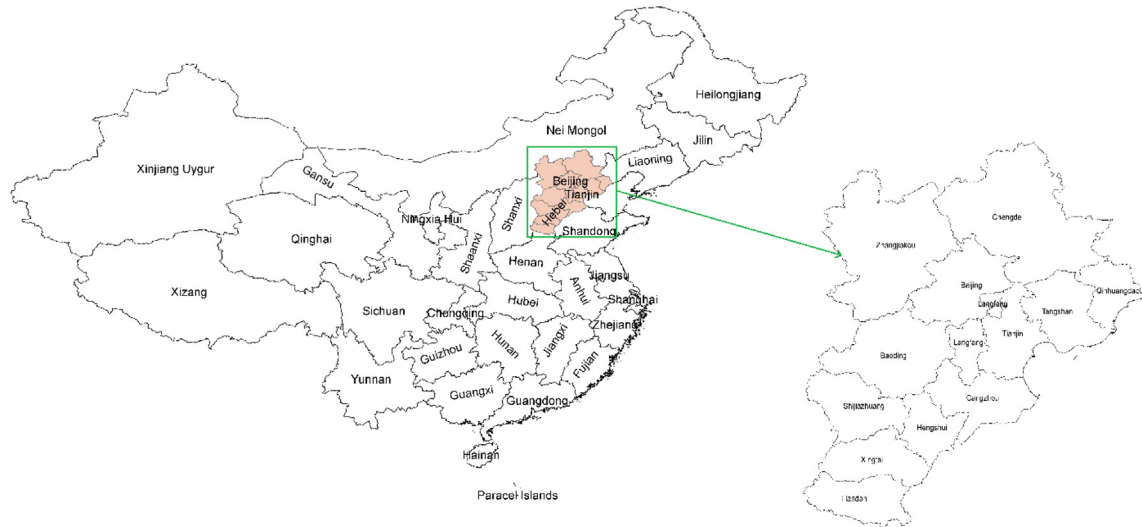
We would like to submit the enclosed manuscript entitled “Potentials of energy efficiency improvement and energy–emission–health nexus in Jing-Jin-Ji’s cement industry”, which

we wish to be considered for publication in “Journal of Cleaner Production”. No conflict of interest exists 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.

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Appendix A



Figs. 1. the study area of Jing-Jin-Ji and the associated prefectures.

Table 1
Cement production in 10^4 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

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 CO ₂ /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) systems			0.01	2.73	4.79	0.00	20
clinker making								
		Raw material reduction (t/t-clinker)	fuel saving (GJ/t-clinker)	electricity saving(GJ/t-clinker)	emission reduction (Kg CO ₂ /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 CO ₂ /t-cement)	capital cost(\$/t-cement)	Change in annual O&M cost (\$/t-cement)	Life time
31	High Pressure Roller Press for ball mill pregrinding			0.04	8.53	1.61	0.08	20
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 CO ₂ /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 CO ₂ /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 CO ₂ /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

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
Xushui	Mt/year	grinding		0.00	0.60		
Hebei	Baoding	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	
		Quyuan	Mt/year	clinker	1.24	0.00	
		Cangzhou	Cangzhou county	Mt/year	grinding	0.00	2.00
		Chengde	Dongguang	Mt/year	grinding	0.00	0.60
			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	
	Handan	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	
		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	
	Hengshui	Fengfengkuang	Mt/year	clinker	2.33	0.00	
		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		
Zhangjiakou	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 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			

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