



Modeling the multiple benefits of electricity savings for emissions reduction on power grid level: A case study of China's chemical industry

Hui Yue*, Ernst Worrell, Wina Crijns-Graus

Copernicus Institute of Sustainable Development, Utrecht University, Princetonlaan 8a, 3584 CB Utrecht, The Netherlands

HIGHLIGHTS

- Parameters of 60 electricity-saving measures and 16 abatement measures are compiled.
- Synergies of electricity use in China's chemical sector at grid level are assessed.
- Efficient use of power can cut 154 Mt CO_{2eq}, 295 kt SO₂, 322 kt NO_x and 64 kt PM_{2.5}.
- North and Northwest grids have the largest economic benefits on emissions reduction.
- Grid with high electricity price is more sensitive to price change than other grids.

ARTICLE INFO

Keywords:

Multiple benefits
Chemical industry
Electricity efficiency
Power grid
Air pollutant
GHG emission

ABSTRACT

Industry is a large electricity user. China's chemical industry (globally the largest based on sales) contributes 7% to China's GDP, while it consumes 11% of the total electricity consumption in industry and is responsible for 40% of total CO_{2eq}, 40% of SO₂, 59% of NO_x and 18% of PM-emissions of the chemical industry emissions. The heterogeneity of GHG and air pollutant emissions across electricity grids (within a country) is rarely included in analyses. In this paper, electricity conservation supply curves are developed (distinguishing the grids) to estimate the cost-effective and technical potentials of electricity conservation in China's chemical industry. The emission factors per grid for GHG (i.e. CO₂, CH₄ and N₂O) and air pollutants (i.e. SO₂, NO_x and PM_{2.5}) are calculated and used to quantify the emissions mitigation achieved by electricity saving technologies in the chemical industry for the period 2012–2035. Results show that significant multiple benefits can be obtained by implementing electricity efficiency measures. There are large differences among the six grids in terms electricity savings and emissions abatement of GHG and air pollutants. 83% of the total electricity saving potential is contributed by the North, Northwest and Central grids, equal to 32% of baseline electricity consumption in 2035. In 2035, 129 Mt of CO₂, 33 kt CO_{2eq} of CH₄, 571 kt CO_{2eq} of N₂O, 235 kt of SO₂, 275 kt of NO_x and 52 kt of PM_{2.5} in these three grids can be avoided as a result of electricity savings (a reduction of 31–33% compared to baseline emissions). When decision-makers set targets for energy saving and emission reduction, the multiple benefits and grid heterogeneity should not be ignored.

1. Introduction

From 2010 to 2014, global electricity demand increased by 56% from 13,199 TWh to 20,557 TWh, accounting for 18% of total final energy demand [1,2]. This huge demand for electricity exacerbates emissions of air pollutants and GHGs worldwide. Electricity generation contributes to 42% of CO₂ emissions around the world, as well as 33% of SO₂ emissions, 14% of NO_x emissions, 5% of PM_{2.5} emissions [2,3]. As a major emission source of GHGs, the global power sector needs to convert to net zero emissions by 2050 [4,5]. Besides concerns for GHG

emissions and climate change, fossil fuel related air pollutant emissions are of high concern for public health [6]. The efficient use of electricity in end-user sectors would therefore generate synergies, by reducing both types of emissions, as well as reduce investments in new power plants [7–9]. Electricity savings are hence an integral part of air quality and climate policy. However, these synergies do not get the full attention they deserve and impacts are often not quantified.

The paper describes a method to quantify the synergies of electricity efficiency improvement on emissions reduction of GHG and air pollutants, and is applied to a case study of China's chemical industry.

* Corresponding author.

E-mail addresses: h.yue@uu.nl (H. Yue), E.Worrell@uu.nl (E. Worrell), W.H.J.Graus@uu.nl (W. Crijns-Graus).

<https://doi.org/10.1016/j.apenergy.2018.09.078>

Received 6 February 2018; Received in revised form 6 September 2018; Accepted 7 September 2018

0306-2619/© 2018 Elsevier Ltd. All rights reserved.

Nomenclature**Abbreviations**

GHG	greenhouse gas
CO _{2eq}	carbon dioxide equivalent
CH ₄	methane
N ₂ O	nitrous oxide
SO ₂	sulfur dioxide
NO _x	nitrogen oxides
PM _{2.5}	particular matter with aerodynamic diameters less than 2.5 μm
Mt	million tons
kt	kiloton
Mtce	million tons standard coal equivalent
LNG	liquefied natural gas
PVC	polyvinyl chloride
ECSCs	electricity conservation supply curves
MACCs	marginal abatement cost curves
NDRC	National Development and Reform Commission of China
WRI	World Resources Institute
IPCC	Intergovernmental Panel on Climate Change
LBNL	Lawrence Berkeley National Laboratory
CP	current energy prices
SP	energy prices of sensitivity analysis
LG	lime-gypsum
LIF	limestone injection into furnace
LNB	low nitrogen burning
SCR	selective catalytic reduction
SNCR	selective non-catalytic reduction
ESP	electrostatic precipitator

Symbols

$CCE_{grid,i}$	costs of conserved electricity for an electricity efficiency technology in a grid i
AI	annualized investment
$O \& M^{fix}$	annual change in operation and maintenance fixed cost
$O \& M^{var}$	annual change in operation and maintenance variable cost
ES	annual electricity saving for a technology
$P_{grid,i}$	electricity price in a grid i
FS	annual fuel saving for a technology
P_{fuel}	fuel price

$PES_{grid,i}$	annual primary energy saving in a grid i
I	investment
d	discount rate
l	lifetime of the electricity efficiency measures
$GE_{grid,i}$	generation efficiency of power grid i
$EF_{grid,i,G,y}$	emission factors of GHG G (i.e. CO ₂ , CH ₄ and N ₂ O) for grid i in year y
$EG_{imp,j,i,y}$	net import electricity of grid i from grid j in year y
$E_{grid,i,G,y}$	emissions of GHG G of grid i in year y
$EG_{grid,i,y}$	power generation from all technologies for grid i in year y
$EF_{grid,j,G,y}$	emission factors of GHG G for grid j in year y
$FC_{r,f,y}$	amount of fuel f consumed by province r in year y
LCV_f	lower calorific value of fuel f
$EF_{f,G}$	GHG G emission factors of fuel f
CC_f	carbon content per unit calorific value of fuel f
OR_f	oxidation rate of fuel f
$EF_{grid,i,p,y}$	emission factors of pollutant p (i.e. SO ₂ , NO _x and PM _{2.5}) for grid i in year y
$E_{grid,i,p,y}$	emissions of pollutant p for grid i in year y
$EF_{grid,j,p,y}$	emission factors of pollutant p for grid j in year y
$EF_{r,f,p}$	uncontrolled emission factor of pollutant p of fuel f in province r
$\gamma_{p,n}$	removal efficiency of abatement measure n for pollutant p
$S_{p,n,r,y}$	share of installed capacity of abatement measure n for pollutant p in province r in year y
$o_{p,n,r,y}$	operation rate of abatement measure n for pollutant p in province r in year y
$S_{f,r}$	sulfur content of fuel f in province r
$SCR_{f,r}$	SO ₂ conversion rate of fuel f in province r
$A_{f,r}$	ash content of fuel f in province r
$BA_{f,r}$	ratio of bottom ash of fuel f in province r
$\beta_{PM2.5,f,r}$	PM _{2.5} mass fraction of fuel f in province r
$ERS_{grid,i,y}$	emissions reduction synergies for a technology for grid i in year r

Subscripts

i, j	power grid type (e.g. Central grid and East grid)
$fuel$	fuel type (e.g. coal, oil, gas)
G, y	GHG and year
imp	net import electricity
r, p, n	province, pollutant, abatement measure

China's chemical industry is the world's largest, contributes to 7% of China's GDP. China makes a great case because of the poor air quality, massive use of coal-fired power generation, and new policies to clean up the air, coupled to a growing pressure to reduce GHG emissions [10–12]. Furthermore, China's chemical industry is one of the largest electricity consumers in the country, accounting for 11% of industrial electricity consumption in 2014 (with about 475 TWh). The indirect emissions of SO₂, NO_x and PM caused by electricity use in China's chemical industry account for 40%, 59% and 18% of total emissions in the chemical industry, respectively in 2014 [13–15]. For GHG emissions, this share is 40%, with 464 Mt CO_{2eq} in 2014 [14,16,17]. The high level of electricity use and emissions means that China's chemical industry should play a significant role in realizing electricity savings and emission reductions. In addition, considering substantial differences across China's six electricity grids (North, Northeast, Northwest, Central, East, Southern) in terms of electricity prices, fuel use, efficiency, and emissions performance, the potentials of electricity efficiency improvement and emission cuts in the chemical industry vary significantly depending on location. Therefore, it is important to evaluate the synergies for chemical industry in China at the grid level.

Multiple benefits of energy efficiency and emission mitigation for different sectors have been discussed by various researchers, especially focusing on the iron & steel industry and cement industry (e.g. global [18], national [19–23] and regional [24,25]). For example, Liu et al. [19] estimated the synergies of energy efficiency technologies to reduce CO₂ and air pollutant emissions in China's cement industry at the national level during the period of 2011–2030, and found significant cost-effective potentials of energy-savings and emission mitigation in China's cement sector. Karali et al. [23] used the industry sector energy efficiency model (ISEEM) to evaluate the impacts of 24 energy efficiency measures on energy-savings and CO₂ emission reduction in U.S. iron & steel industry between 2010 and 2050, and indicated 180 PJ energy use and 14.9 billion tons of CO₂ emissions would be saved by 2050. Unlike the single-product industries (iron & steel, cement and power [26]), few studies have separately estimated the potentials of CO₂ emission mitigation and energy conservation in the chemical industry [17,27,28]. Zhu et al. [17] studied the CO₂ emissions through emission factor-based methods and two-level method from the whole chemical industry and sub chemical sectors level respectively, and suggested large amounts of CO₂ can be saved in China's chemical

industry. Saygin et al. [27] assessed the energy conservation potential by implementing Best Practice Technology in global (petro)chemical industry at a country level, and found approximately 16% of energy efficiency improvement potential (excluding savings in electricity use) worldwide, varying by country. However, no study has focused on the synergies between electricity use and emissions of GHG and air pollutants characterized by regional grid heterogeneity for the chemical industry with multi-products. To fill this gap, a bottom-up approach is developed based on key characteristics of energy saving technologies and GHG and air pollutants emission factors for the six regional electricity grids. These are used to assess the multiple benefits of electricity efficiency improvement on energy use savings and emission mitigation (i.e. CO₂, CH₄, N₂O, SO₂, NO_x and PM_{2.5}) per grid in China's chemical industry for the period 2012–2035.

The paper is organized as follows: an overview of the chemical industry and its sub-sectors is given in Section 2. The methodology and data sources used to estimate the multiple benefits and costs of electricity saving measures are provided in Section 3, while the results of electricity savings and emission reductions of CO₂, CH₄, N₂O, SO₂, NO_x and PM_{2.5} in different scenarios and grids are presented in Section 4. A sensitivity analysis for important factors that affect the results is given in Section 5; and finally, conclusions and policy implications are drawn in Section 6.

2. Overview of China's chemical industry

China's chemical industry is a complicated system, producing many different chemical products. In this study, China's chemical industry is defined as the manufacture of raw chemical materials and chemical products based on the industrial classification for national economic activities (ICNEA) [29], i.e. classification code 26, which consists of 8 sub-categories (including basic chemicals manufacturing, fertilizers manufacturing, pesticides manufacturing, coatings, inks, paints and similar products manufacturing, synthetic materials manufacturing, special chemical products manufacturing, explosives, pyrotechnics and fireworks manufacturing, and daily chemical products manufacturing) [29]. China's chemical industry has grown dramatically since 2000, accounting for 14–35% of total industrial output value, with an annual growth rate of 23% [30,31]. As the largest chemical market worldwide,

China represents around 1/3 of the global chemicals demand. The production of main chemicals grew at an annual rate of 9% between 2000 and 2014, i.e. from 144 Mt to 484 Mt. Strong growth in chemical production has been primarily driven by fast growth of downstream industries such as construction, food and packaging sectors. In particular, China is the largest producer and consumer of ammonia [32], caustic soda [33], polyvinyl chloride (PVC) [34] and calcium carbide [35]. The total production of ammonia, caustic soda, PVC and calcium carbide accounts for 27% of main chemicals production, reaching 57 Mt, 32Mt, 16Mt and 25Mt, respectively, at the end of 2014 (see Fig. 1) [31,36].

Energy consumption of China's chemical industry increased with the growth of chemicals output. At present, China's chemical industry has become the second largest energy consumer after the iron & steel industry. Energy consumption in the chemical industry increased from 4.1 EJ in 2000 to 14.4 EJ in 2015, accounting for 11% of China's total energy demand [14]. The final energy consumption mix of China's chemical industry shows that electricity has increasingly become the dominant energy source, amounting to 30% in 2015 (see Fig. 2). Electricity use of China's chemical industry increased with an annual rate of 10% during 2000 to 2015, higher than the annual growth rate of total energy use of China's chemical industry (9% for the same period). With the implementation of a large number of energy efficiency measures and related policies (e.g. phasing out backward production capacities and promoting best practice technologies), the energy and electricity efficiency of the chemical industry has significantly improved. The energy intensity and electricity intensity of the chemical industry dropped by 82% and 73% respectively in 2013 compared to 1995 [14,31].

Despite the improvement in energy efficiency, the growing energy consumption of the chemical industry has resulted in enormous emissions of air pollutants and GHGs. As shown in Fig. 3, the energy-related CO₂ of China's chemical industry accounts for 3.7% of global total in 2015, with 1220 Mt CO₂, which nearly doubled since 2005 [37]. The share of electricity-related CO₂ emissions is approximately 39% of total emissions, while coal contributes to approximately 34%, coke to 10%, LNG to 1%, coal gas and nature gas together contribute to about 4%, and oil to 12%. Since 2011, the share of electricity based emissions has outgrown the direct coal emissions. The CO₂ emission intensity of key chemicals dropped at an annual rate of 1%, declining from 2.6 to 2.4 t

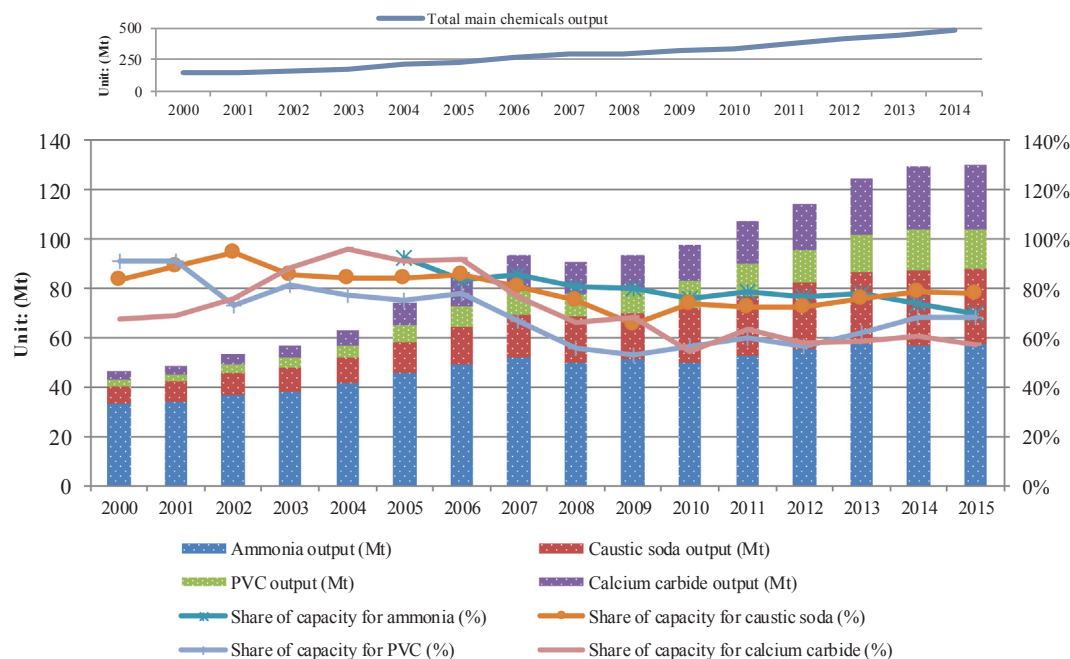


Fig. 1. Historical output of different chemicals (Mt) and share of capacity (%). Source: primary data from [30,31,36,64]. Calculated by authors. Note: data for ammonia capacity during 2000–2004 are not available.

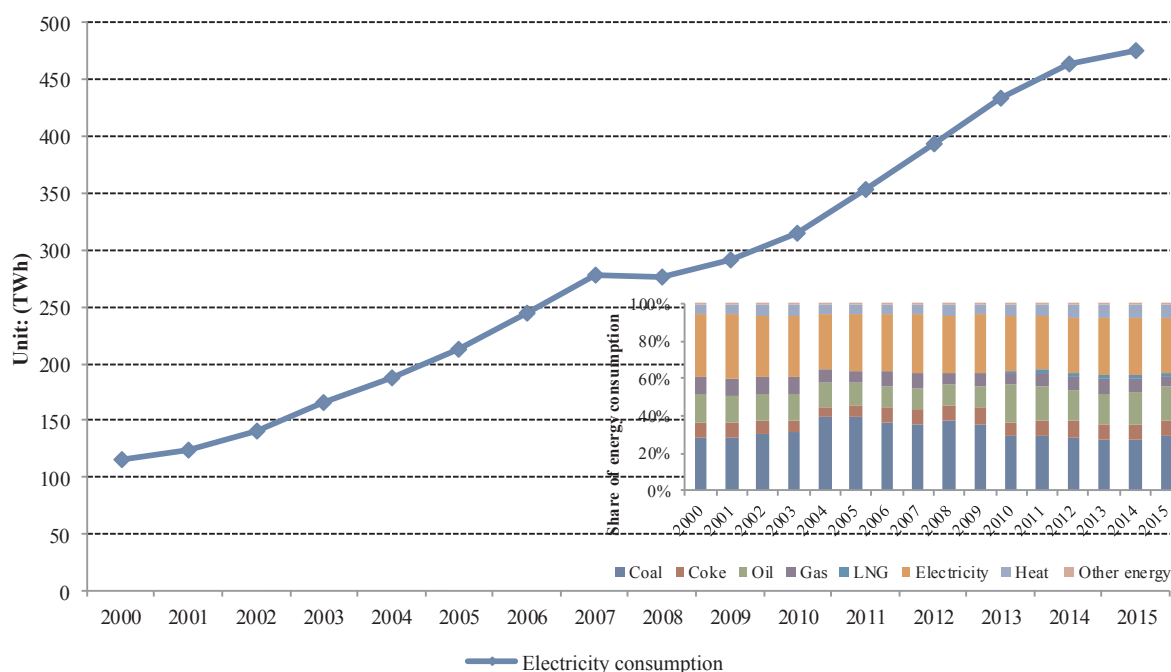


Fig. 2. Electricity consumption in China's chemical industry during 2000–2015. Source: [14]. Calculated by authors.

CO₂/t chemicals between 2005 and 2014. Despite the decline, it is still higher than that of the cement and iron & steel industries [38]. Fig. 4 shows the historical emissions of air pollutants and the emission intensity. As a key emitter of air pollutants, China's chemical industry emitted 2254 kt of SO₂, 1512 kt of NO_x and 808 kt of PM in 2015, contributing 12%, 8% and 5% to the national emissions, respectively [13,15]. In line with the energy consumption trend, total emissions of air pollutants increased at an average rate of 3.6% per year between 2005 and 2015, from 3250 kt to 4574 kt [15,39]. Declining air quality forced the government to introduce stricter emission standards, and

promote desulfurization and denitrification of combustion installations [40,41]. As a result of these initiatives, the emission intensities of SO₂, NO_x and PM declined by 32%, 22% and 50% respectively by 2015, compared to 2005 (see Fig. 5). In the 13th Five-Year Plan (2016–2020), more measures will be implemented to reduce NO_x and SO₂ emissions by an expected 15% in 2020, compared to 2015 levels.

While China's chemical industry produces thousands of chemicals, only a few chemicals are relevant for electricity use, GHG and air pollutant emissions [27]. The electricity use in three sub-sectors (ammonia, chlor-alkali and calcium carbide) accounts for 54% of total

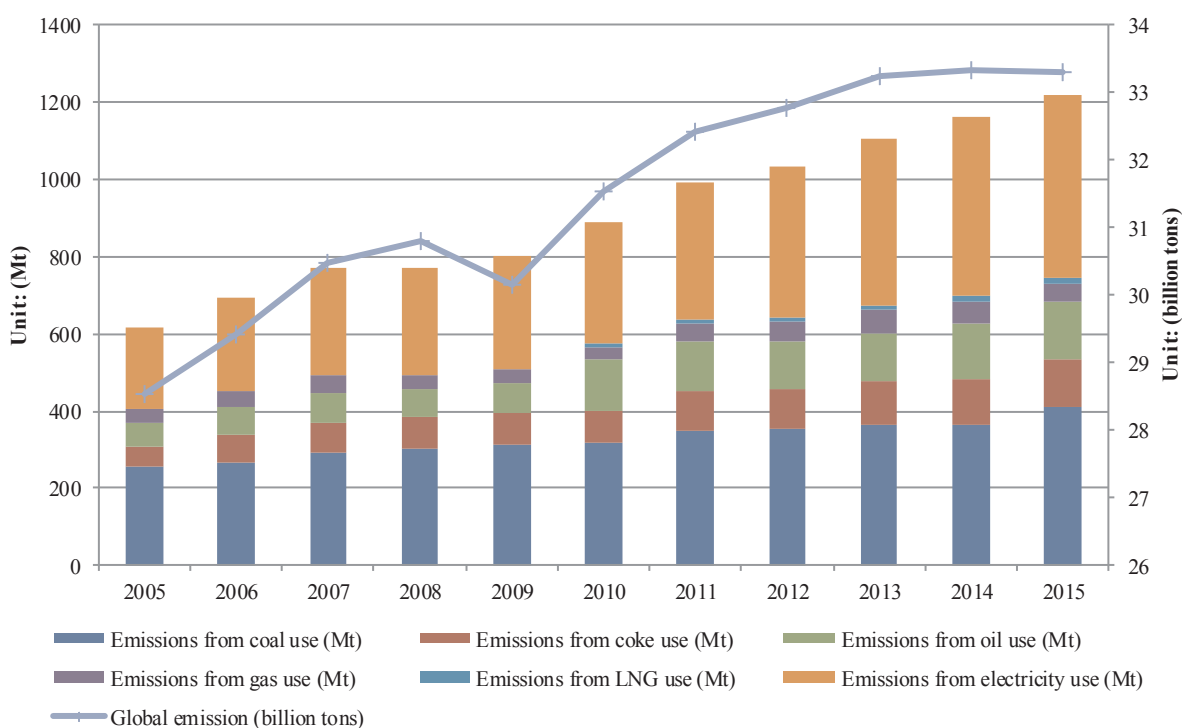


Fig. 3. CO₂ emissions of China's chemical industry (Mt) and global (billion tons) during 2005–2015. Source: primary data from [14,16,17,37,54,56,58,91–93]. Calculated by authors (see Supplementary material).

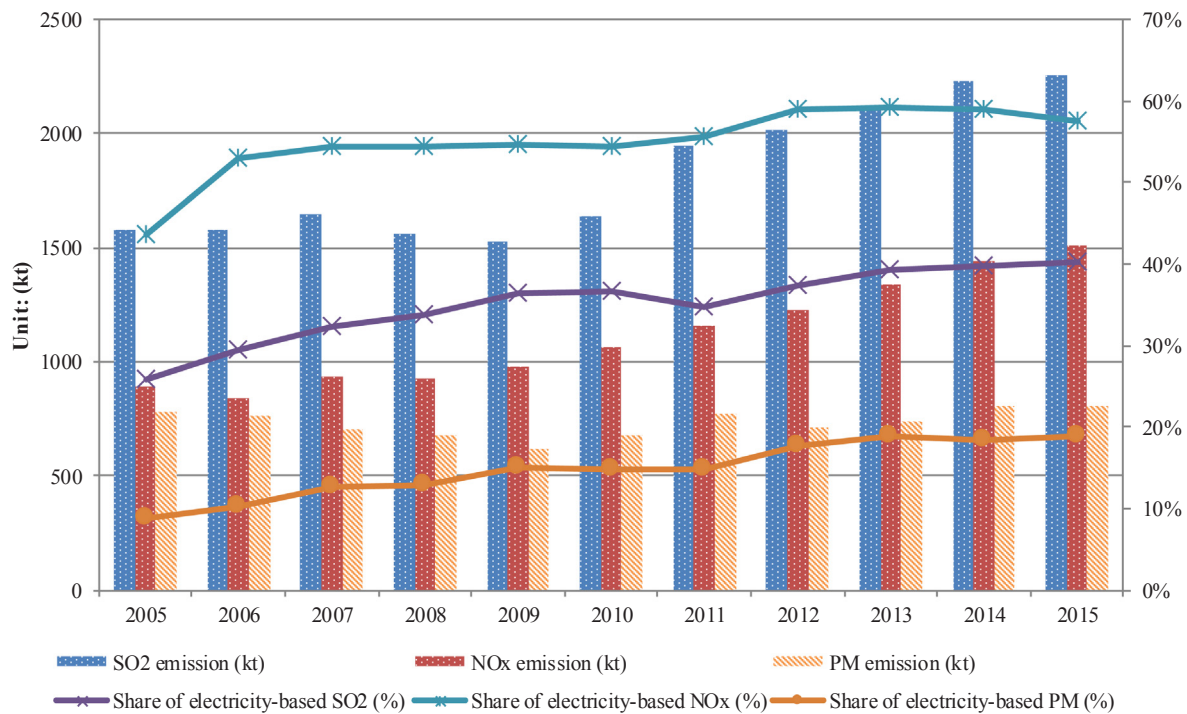


Fig. 4. Total air pollutants emission (kt) and share of electricity-based air pollutants emission (%) in China's chemical industry during 2005–2015. Source: primary data from [13–15,39,42,56,57,59,60,79,88]. Calculated by authors.

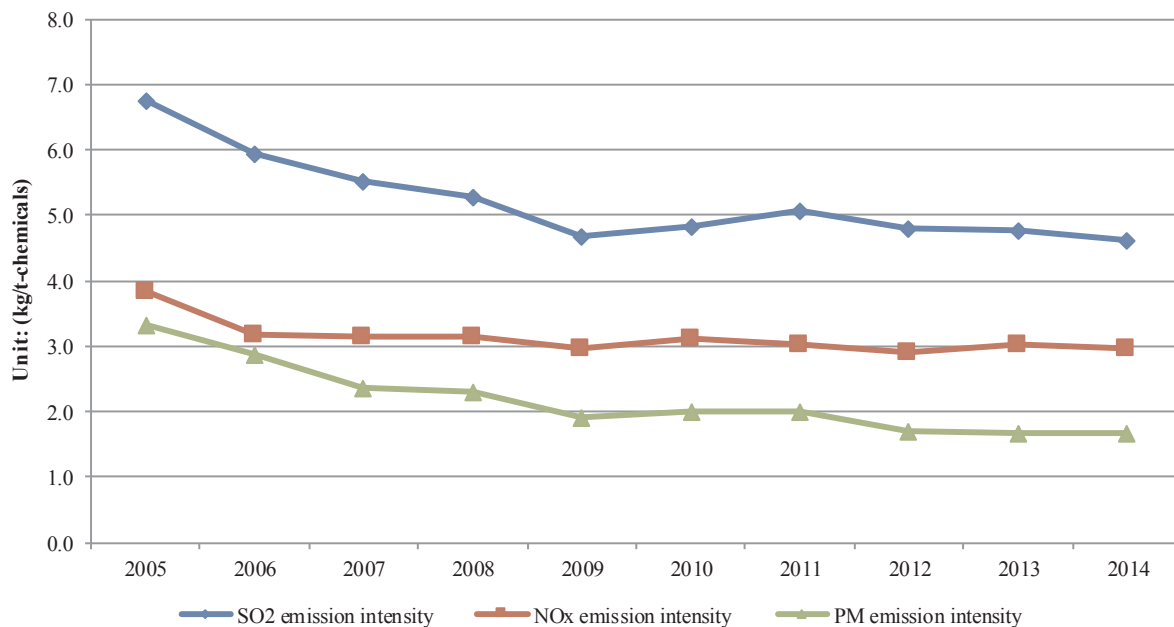


Fig. 5. Air pollutants emission intensity of China's chemical industry during 2005–2014. Source: [15,31,36,39,60,79]. Calculated by authors.

electricity consumption of China's chemical industry in 2015, which is equal to 15% of total energy consumption of the chemical industry [42]. Emission reduction in these three sub-sectors plays a crucial role for the chemical industry to achieve the 18% CO₂ emission reduction target and 15% reduction targets of SO₂ and NO_x in 2020. In addition, energy and environmental policy focus mainly on these three sub-sectors. Therefore, these three key electricity-intensive sub-sectors were selected to assess the multiple benefits of electricity savings and emissions reduction by implementing electricity efficiency technologies. Detailed description on the levels of production, electricity consumption and emissions of GHG and air pollutants for these sub-sectors is presented in the [Supplementary material](#).

3. Methodology and data sources

First, electricity conservation supply curves (ECSCs) (or marginal abatement cost curves; MACCs) are developed to analyze the cost associated with each energy efficiency technology and electricity saving potential for the six electricity grids in China (Section 3.1). Second, the emission factors of GHG, SO₂, NO_x and PM_{2.5} in each grid were calculated accounting for emission abatement measures applied in power generation (Section 3.2). Electricity prices, power generation efficiencies and emission factors per grid reflect the spatial variability of power generation. Finally, the results of the ECSC are combined with the emission factors to estimate the co-benefits of electricity conservation for

climate change mitigation and air quality improvement at grid level in China's chemical industry (Section 3.3). Data sources and electricity efficiency technologies are described in Section 3.4.

3.1. Electricity conservation supply curves

ECSCs are constructed per grid to quantify the cost effectiveness and technical potential of electricity conservation accumulated for the available technologies in the chemical industry from 2012 to 2035. Cost curves, including ECSCs and MACCs, have been used to evaluate costs and potentials of technologies for various industrial sectors [20–22,25,43–45]. For example, Kong et al. [43] employed the conservation supply curves to estimate the co-benefits of energy-savings and CO₂ emission mitigation by implementing 23 energy efficiency measures in China's pulp and paper industry. The results show that 180–254 PJ and 2316 GWh can be saved in 2010, and the corresponding CO₂ emission reduction potential is estimated to be 19–26 Mt. Similarly, Yang et al. [45] evaluated the multiple benefits of 18 mitigation technologies on CO₂ and air pollutants in the cement industry through MACCs approach. They found that the monetized co-benefits varied from 0.4 \$/t CO₂ to 39 \$/t CO₂ during 2011–2015 on the national level. Previous co-benefits studies have only estimated the impacts on CO₂ emissions alone (or on CO₂ and air pollutant emissions) in single-product industries at national level, like cement [19,21,45,46], iron & steel [20,22,23] and paper [43,47]. However, a study on the multiple benefits of electricity savings on emissions mitigation of GHG and air pollutants for the chemical industry is still lacking, as are studies that consider the heterogeneity of electricity grids. In this study, three electricity-intensive sectors representing China's chemical industry are selected to evaluate the multiple benefits of 60 electricity efficiency measures on electricity savings and emissions mitigation for six grids. These sectors account for more than 50% of the electricity consumption in the chemical industry in China.

In this study, electricity prices and power generation efficiencies for the six different grids in China are included in the costs calculations. The costs of each technology is converted to 2010 constant prices in \$ (2010 \$) using deflators and currency conversion factors, which are derived from the China statistical yearbook [30] and OECD data [48]. The CCE of each electricity efficiency technology at a grid level is calculated by Eqs. (1)–(3) [46].

$$CCE_{grid,i} = \frac{AI + O \& M^{fix} + O \& M^{var} - (ES \cdot P_{grid,i} + FS \cdot P_{fuel})}{PES_{grid,i}} \quad (1)$$

where $CCE_{grid,i}$ represents the cost of conserved electricity for an electricity efficiency technology (\$/GJ) in a grid i ; AI represents the annualized investment (\$); $O \& M^{fix}$ and $O \& M^{var}$ represent the annual change in operation and maintenance fixed and variable cost (\$), respectively; ES is the annual electricity saving for a technology (kWh); $P_{grid,i}$ represents the electricity price in a grid i (\$/kWh). FS is the annual fuel saving for a technology (GJ); P_{fuel} is the fuel price (\$/GJ) and $PES_{grid,i}$ is the annual primary energy saving in a grid i (GJ).

AI and $PES_{grid,i}$ can be obtained from Eqs. (2) and (3). A real discount rate of 10% is used in this research to reflect barriers [25,46,49]. The electricity prices per grid are based on the provincial electricity pricing policies released by State Grid Corporation of China [50].

$$AI = I \cdot \frac{d}{(1 - (1 + d)^{-l})} \quad (2)$$

$$PES_{grid,i} = ES \cdot GE_{grid,i} + FS \quad (3)$$

where I is the investment; d is the discount rate and l represents the lifetime of the electricity efficiency measures. $GE_{grid,i}$ is the generation efficiency of power grid i (GJ/kWh), including the transmission and distribution losses and auxiliary power use.

3.2. Emission factors of GHG and air pollutants for different grids

Power generation (primarily from coal) has resulted in massive emissions of GHG and air pollutants in China [51,52]. Hence, improving demand-side electricity efficiency contributes to emission reductions of GHG and air pollutants through reduced power generation. To quantify the potential of emissions mitigation achieved by electricity savings in China's chemical industry at grid level, GHG (CO₂, CH₄ and N₂O) intensity (ton/MWh) and air pollutants (SO₂, NO_x and PM) intensity (ton/MWh) of power generation for six grids are calculated in this study. Several approaches are used to measure the CO₂ intensity of power generation at different scopes (e.g. national, global and regional level), such as exergy method [53], consumer responsibility method [54] and power & heat method [55]. In this study, an approach to determine emission factors of purchased electricity for end-user sectors at the grid level (including 30 provinces) is developed, based on studies of NDRC [56], WRI [16], and Tsinghua University [13,52,57]. This approach includes electricity generated per technology, the exchange of electricity between grids and the emission allocation between power and heat from cogeneration plants.¹

3.2.1. GHG emission factors per grid

If electricity exchange between grids is present, emission factors of GHG for grid i in year y can be calculated by Eq. (4).

$$EF_{grid,i,G,y} = \frac{E_{grid,i,G,y} + \sum_j (EF_{grid,j,G,y} \cdot EG_{imp,j,i,y})}{EG_{grid,i,y} + \sum_j EG_{imp,j,i,y}} \quad (4)$$

If the net import electricity of grid i from grid j in year y is 0, the emission factors of GHG for grid i in year y can be obtained by Eq. (5).

$$EF_{grid,i,G,y} = E_{grid,i,G,y} / EG_{grid,i,y} \quad (5)$$

where i, j, G, y represents the grid i , grid j , GHG and year y ; $EF_{grid,i,G,y}$ is the emission factors of GHG G (e.g. CO₂, CH₄, N₂O) of grid i in year y (ton/MWh); $E_{grid,i,G,y}$ is the emissions of GHG G of grid i in year y (ton); $EF_{grid,j,G,y}$ is the emission factors of GHG G of grid j in year y (ton/MWh); $EG_{imp,j,i,y}$ is the net import electricity of grid i from grid j (MWh); $EG_{grid,i,y}$ is the power generation from all technologies for grid i in year y (MWh). The $E_{grid,i,G,y}$ can be calculated from Eq. (6).

$$E_{grid,i,G,y} = \sum_{r \in i} \sum_f \frac{FC_{r,f,y} \cdot LCV_f \cdot EF_{f,G}}{10^6} \quad (6)$$

where $r \in i$ represents province r belonging to grid i ; f represents the fuel type (e.g. raw coal, coke, crude oil, gasoline, etc); $FC_{r,f,y}$ represents the amount of fuel f consumed by province r in year y (ton or m³), LCV_f represents the lower calorific value of fuel f (MJ/ton or MJ/m³); $EF_{f,G}$ is the GHG emission factors of fuel f (g/MJ). In this study, the emission factors of CH₄ and N₂O of fuel f are derived from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (g/MJ) [58]. The emission factor of CO₂ of fuel f can be obtained by Eq. (7).

$$EF_{f,CO_2} = CC_f \cdot OR_f \cdot \frac{44}{12} \quad (7)$$

where CC_f is carbon content per unit calorific value of fuel f (g/MJ); OR_f is the oxidation rate of fuel f (%).

3.2.2. Air pollutant emission factors per grid

The grid-based emission factors of air pollutants after application of abatement measures for each grid can be calculated by Eq. (8).

¹ The fuel of cogeneration plants has been allocated to the emission factor of power generation although also heat is generated. The impacted is however expected to be small since cogeneration plants represent a small share of total power generation (IEA's 2016 World Energy Balances).

$$EF_{grid,i,p,y} = \frac{E_{grid,i,p,y} + \sum_j (EF_{grid,j,p,y} * EG_{imp,j,i,y})}{EG_{grid,i,y} + \sum_j EG_{imp,j,i,y}} \quad (8)$$

where $EF_{grid,i,p,y}$ represents the abated emission factors of pollutant p (e.g. SO_2 , NO_x , $PM_{2.5}$) for grid i in year y (ton/MWh); $E_{grid,i,p,y}$ is emissions of pollutant p for grid i in year y (ton); $EF_{grid,j,p,y}$ is the abated emission factors of pollutant p for grid j in year y (ton/MWh). The $E_{grid,i,p,y}$ can be calculated from Eq. (9).

$$E_{grid,i,p,y} = \sum_{r \in i} \sum_f \sum_n FC_{r,f,y} * EF_{r,f,p} * [(1 - \gamma_{p,n}) * s_{p,n,r,y} * o_{p,n,r,y} + s_{p,n,r,y} * (1 - o_{p,n,r,y}) + (1 - s_{p,n,r,y})] \quad (9)$$

where n identifies the individual abatement measure; $EF_{r,f,p}$ is the uncontrolled emission factors of pollutant p of fuel f in province r (g/g or g/m³); $\gamma_{p,n}$ is the removal efficiency of abatement measure n for pollutant p (%); $s_{p,n,r,y}$ is the share of installed capacity of abatement measure n for pollutant p in province r in year y (%); $o_{p,n,r,y}$ is the operation rate of abatement measure n for pollutant p in province r in year y (%).

In this study, EF_{r,f,NO_x} which is the uncontrolled emission factor of NO_x of fuel f in province r can be obtained from the manual of pollutants production and emission coefficients for coal-fired power plants [59], and literatures [13,60]. The uncontrolled emission factor of SO_2 and $PM_{2.5}$ can be calculated with Eqs. (10) and (11), respectively [13,57].

$$EF_{r,f,SO_2} = S_{f,r} * SCR_{f,r} * \frac{64}{32} \quad (10)$$

$$EF_{r,f,PM_{2.5}} = A_{f,r} * (1 - BA_{f,r}) * \beta_{PM_{2.5},f,r} \quad (11)$$

where EF_{r,f,SO_2} is the uncontrolled emission factor of SO_2 of fuel f in province r ; $S_{f,r}$ is sulfur content of fuel f in province r ; $SCR_{f,r}$ is SO_2 conversion rate of fuel f in province r . $EF_{r,f,PM_{2.5}}$ is the uncontrolled emission factor of $PM_{2.5}$ of fuel f in province r ; $A_{f,r}$ is ash content of fuel f in province r ; $BA_{f,r}$ is the ratio of bottom ash of fuel f in province r ; $\beta_{PM_{2.5},f,r}$ is the $PM_{2.5}$ mass fraction of fuel f in province r .

3.3. Multiple benefits on emissions reduction per grid

Technologies to improve electricity efficiency can generate synergies for climate change and air quality, by reducing both types of emissions. The multiple benefits of electricity saving on emissions reduction for an electricity efficiency technology at a grid level can be calculated by Eq. (12).

$$ERS_{grid,i,y} = ES * IR_y * EF_{grid,i} \quad (12)$$

where $ERS_{grid,i}$ represents the synergies of electricity saving in terms of emissions reduction for a technology at grid i in year y ; IR_y is the implementation rate for a technology in year y . $EF_{grid,i}$ is the emission factor (for CO_2 , CH_4 , N_2O , SO_2 , NO_x and $PM_{2.5}$) for grid i . The calculation of emission factors for the six grids was presented in Section 3.2.

3.4. Data sources

3.4.1. Future demand for chemical products

Future production levels for ammonia, caustic soda, PVC and calcium carbide are required to evaluate the benefits of electricity efficiency measures in the chemical industry. Material flow analysis (MFA) is widely used to predict steel and cement demand at national level via evaluating the product flow in downstream industries [20,22]. For example, steel demand can be divided into five steel-intensive industries reflecting the steel flow in construction, vehicle, machinery, appliances and other industries, of which 73% of total steel demand consumed by the former three in China [20]. Chemical industry products are extensively applied in various downstream industries such as agriculture, construction, food and packaging. However, few studies have done systematic analysis of the chemical products flow because of

Table 1

Average share of provincial production of national production during 12th Five-Year Plan (%).

Grid	Region	Ammonia	Caustic soda	PVC	Calcium carbide
North	Beijing	0.0	0.1	0.0	0.0
	Hebei	5.2	3.6	4.2	0.0
	Inner Mongolia	2.4	7.4	16.2	31.3
	Shanxi	9.1	1.8	3.3	1.7
	Shandong	13.3	22.2	6.9	0.2
	Tianjin	0.3	4.0	9.5	0.0
Northeast	Heilongjiang	1.4	0.5	0.4	0.0
	Jilin	0.9	0.6	0.8	0.0
	Liaoning	1.7	2.1	1.0	0.5
East	Anhui	5.8	1.7	0.6	0.1
	Fujian	1.6	0.9	0.1	0.1
	Jiangsu	6.3	13.4	1.3	0.0
	Shanghai	0.0	2.5	1.3	0.0
	Zhejiang	1.1	5.1	2.6	0.2
Central	Chongqing	3.4	1.1	0.0	0.1
	Henan	9.1	6.0	7.4	5.2
	Hubei	8.2	3.3	3.4	3.6
	Hunan	2.6	2.4	1.6	0.9
	Jiangxi	0.3	1.4	0.0	0.2
	Sichuan	6.9	4.0	6.5	3.5
Northwest	Gansu	1.2	0.8	0.6	5.7
	Ningxia	1.7	1.4	3.1	14.4
	Qinghai	0	0.8	1.6	1.3
	Shannxi	2.7	2.4	5.9	8.0
	Xinjiang	3.5	6.8	18.3	18.7
Southern	Hainan	1.5	0.0	0.0	0.0
	Guangdong	0.1	1.1	0.8	0.0
	Guangxi	1.9	1.5	0.7	0.5
	Guizhou	3.6	0.3	0.4	1.2
	Yunnan	4.2	0.8	1.5	2.6
Nation		100.0	100.0	100.0	100.0

Sources: [30,31,36].

its complexity. Based on the concept of MFA, the correlation between chemical products and downstream industries were firstly analyzed in this study. Based on the correlation analysis, the average annual growth rates of the chemicals during 2015–2035 are obtained from national plans and related studies. Finally, the average proportion of provincial production and future average annual growth rates of chemicals are used to forecast chemicals output at grid level between 2016 and 2035. Table 1 shows the share of provincial production of national production during 12th Five-Year Plan (2011–2015), and it is assumed that this remains unchanged during the study period. A sensitivity analysis was conducted to explore the impact of chemicals output (see Section 5.1).

Ammonia demand can be divided into two downstream industries: fertilizer and other, of which the former is the key market [32,61,62]. About 90% of ammonia production is used as a nitrogen source for the manufacture of fertilizers in China [63,64]. The remaining 10% of ammonia production is used for producing various industrial products, such as plastics, acrylonitrile, caprolactam, and other organic nitrogen compounds [62,63]. Driven by fertilizer demand, ammonia production is likely to show slower growth in the future and will peak by 2030 [65–67]. After 2030, ammonia production is expected to show a declining trend due to demand saturation and overcapacity (see Fig. 1) [36,66]. Therefore, the annual growth rate will be set at 1% during 2015–2020 based on the national plan [64,66,68,69]. Between 2020 and 2030, the annual growth rate will slow down to 0.5% and peak by 2030 [67]. After 2030, LBNL indicates that ammonia production will decline by 0.3% per year [66]. Ammonia production at a regional level in China between 2015 and 2035 is presented in Appendix A-1. Ammonia production in this study is similar to the new policy scenario of IEA's 2018 Word Energy Outlook (unpublished).

Caustic soda and PVC are the main products in the chlor-alkali industry and widely applied in various industries and have large market demand. Caustic soda demand in China is driven by 7 industries: paper (25%), chemical (23%), textile (19%), alumina (9%), medicines (5%), iron & steel (4%) and other industries (15%) [36,70,71]. PVC is mainly used to produce plastic products and applied in building, automobile, electrical parts, packaging and other industries [36,70]. As shown in Fig. 1 and Fig. 6, the output of caustic soda and PVC increased sharply with a growth rate of 13% per year during 11th Five-Year Plan (2006–2010). By phasing out inefficient production capacity, the annual growth rate of caustic soda and PVC output slowed and stabilized after 2010 (see Fig. 6) [72,73,90]. Industrialization and urbanization will further fuel caustic soda and PVC demand [30,34,72]. In addition, “The Belt and Road Initiative” and “Made in China 2025” will likely drive future market demand for caustic soda and PVC [74–76]. As a result of the current low capacity utilization rate, the future annual growth rate of caustic soda and PVC production are assumed to be lower than those of 12th Five-Year Plan (where were 6% and 7%, respectively). Annual growth rates of 4.5% and 4.6% are used for the total output of caustic soda and PVC, respectively, based on the national plans [72,73]. The output of caustic soda and PVC at regional level in China between 2015 and 2035 are presented in Appendix A-2.

The development of calcium carbide industry in China is highly correlated with that of the chlor-alkali industry, as 80% of the calcium carbide output is used to produce PVC [35,72]. The remaining 20% of calcium carbide is used to produce acetylene (9%) and other products (11%) [36]. As shown in Fig. 6, the historical trend of calcium carbide production maintain with that of PVC. The annual growth rate of calcium carbide output shows a gradual decline and tends to stabilize after 2010. Driven by PVC demand, the future trend of calcium carbide output is expected to be in line with the PVC growth rate [35,36,77,78]. Specifically, the total output of calcium carbide is assumed to grow at an average rate of 4.6% per year between 2015 and 2035 [73]. The future calcium carbide output at a regional level in China is presented in Appendix A-3.

3.4.2. Energy, emission and technical parameters

The historic production volumes and capacities of ammonia, caustic soda, PVC and calcium carbide in each province used to forecast future output are derived from the China statistical yearbook [30], China industrial statistical yearbook [31], China Petroleum and Chemical

Industry Federation (CPCIF), and China chemical industry yearbook [36]. Final energy consumption and electricity consumption of the chemical industry between 2000 and 2015 are from China energy statistical yearbook [14], and China electric power yearbook [42]. Air pollutants emissions are from the China environmental statistics yearbook [15], annual statistic report on environment in China [39], and studies from Zhang [60] and Shi [79].

Sixty electricity efficiency technologies (21 technologies for ammonia production, 17 technologies for calcium carbide production and 22 technologies for caustic soda and PVC production) are included in our study. The technology characteristics (e.g. investment, operation and maintenance cost and electricity saving) are derived from NDRC [80], Ministry of Industry and Information Technology of China [81–83], LBNL [64], Energy Research Institute of China [84,85], China Chemical Energy Efficiency Technology Association [86,87], and other studies (detailed information can be found in Appendix B-1) [34,35,61,69]. The transmission and distribution losses and auxiliary power use for the calculation of the generation efficiency for six grids are taken from the power industry statistical compilation [16,88]. The study period is 2012 to 2035, while 2012 is taken as the base year because that is the latest year for which the implementation rates are available. Based on new capacity and withdrawal of capacity for the selected sub-sector, potential implementation rates up to 2035 are determined for each technology assuming linear deployment (see Appendix B-1) [16,89]. The diaphragm caustic soda process will be withdrawn from the Chinese market due to its high electricity cost and high pollution [90]. Therefore, the implementation rates of electricity efficiency measures (e.g. three-phase flow evaporation technology and modified diaphragm and expanded metal anode technology) used for diaphragm caustic soda are assumed to be 0 after 2025 in this study. Electricity prices (\$/kWh) of the chemical industry in each grid can be obtained from the provincial electricity pricing policies released by State Grid Corporation of China [50]. In addition, 3.22 \$/GJ is used as the fuel price in this study [25,46]. The prices of electricity and fuel are assumed to remain unchanged during the study period 2012–2035. Appendix B-2 shows the CCE of each energy efficiency technology.

Electricity exchange between grids is derived from power industry statistical compilation [89], and NDRC [56]. Power generation per grid is from China electric power yearbook [42]. Fuel consumption for power generation in each province is obtained from the China energy statistical

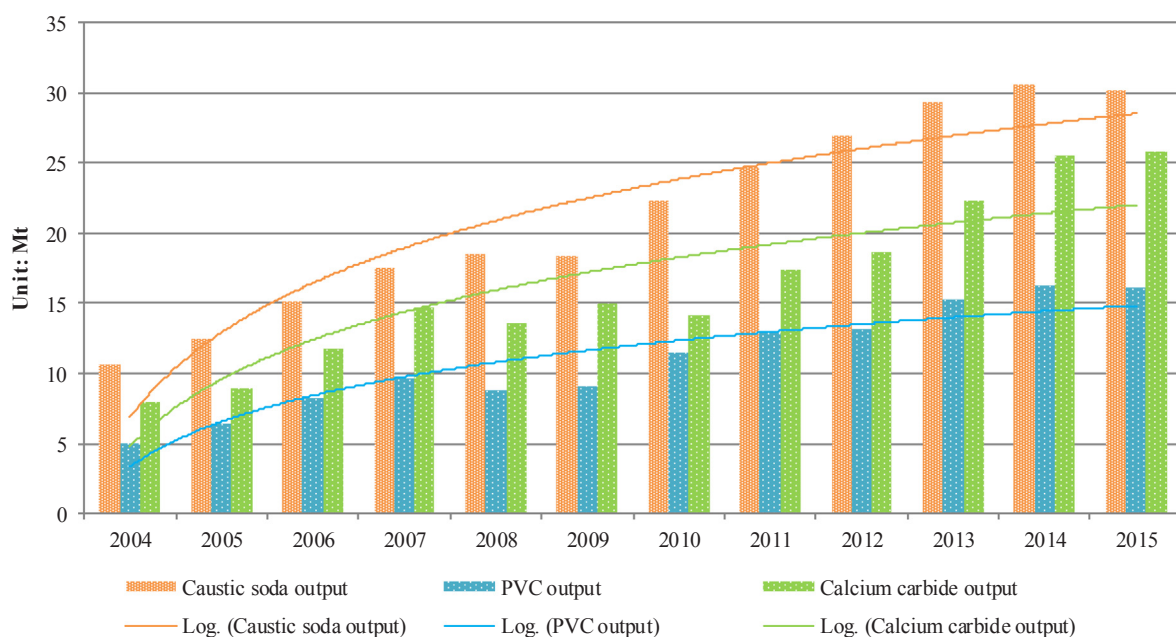


Fig. 6. Output trend of caustic soda, PVC and calcium carbide in China. Source: [30,31,36]. Calculated by authors.

yearbook [14]. The lower calorific value, carbon content and oxidation rate for each fuel are from NDRC [56,91,92], National Government Offices Administration [93], IPCC [58], and WRI [16]. 16 air pollutant control technologies (including 10 desulfurization technologies, 4 denitrification technologies and 2 PM_{2.5} removal technologies) are selected (see Appendix B-3) [59,94,95]. The share of each SO₂/NO_x abatement technology at provincial level is calculated from the list of desulfurization and denitrification facilities for China's coal-fired power units. The share of PM_{2.5} removal technologies at the provincial level are from Tsinghua University's study [13]. More than 50 abatement technologies in 4467 generator units in operation for removing SO₂ in China's power sector, 10 desulfurization technologies are selected because they have the largest shares in total installed capacity, and together account for more than 95% [94]. The remaining desulfurization technologies (e.g. dry process, NaOH + microbial reduction, and activated coke) are classified as remaining desulfurization technology. The removal efficiencies for each technology are derived from recent studies (including the sulfur content, SO₂ conservation rate, PM_{2.5} emission factors and NO_x emission factors for each fuel) [13,57,59,96]. Additionally, 95%, 100% and 100% operation rate are assumed for desulfurization, denitrification and PM_{2.5} removal technologies respectively, and remain unchanged for each grid [13,97]. The emission factors of air pollutants are assumed to remain constant over the studied period.

4. Results and discussion

The ECSCs per grid are developed to capture the cost effectiveness and technical potential of 60 electricity efficiency technologies in the chemical industry till 2035. A CCE of 0 \$/GJ (at a discount rate of 10%) is chosen as the threshold to determine the cost-effective potential, representing economically feasible opportunities. Moreover, the environmental benefits of the electricity savings in China's chemical industry are identified at grid level.

4.1. Electricity saving potential by grid in China's chemical industry

Fig. 7 shows the electricity consumption in three chemical sub-sectors between 2012 and 2035 under two scenarios (without and with

electricity efficiency measures called frozen scenario and technical scenario, respectively). Total electricity consumption for these sub-sectors under the frozen scenario will increase to 475 TWh in 2035, 1.4 times higher than in 2012. The potential technical electricity efficiency improvement is different for the six grids. North grid and Northwest grid have the greatest electricity saving potentials, together accounting for 60–63% of total electricity savings during 2015–2035, followed by the Central grid with around 20%. The East and Southern grids, which are clustered by coastal regions (e.g. Zhejiang, Guangdong and Shanghai) account for 16–15% of total electricity savings. The chemical industry is mainly concentrated in regions with abundant resources, showing the resource-oriented development pattern [74]. The Northeast grid, including Liaoning, Shenyang and Heilongjiang, with low shares of chemicals output, only accounts for around 2% of total electricity consumption and savings. The total cost-effective electricity savings potential (< 0 \$/GJ) accounts for more than 79% of the technical electricity savings potential, equal to 23 TWh in 2020, 49 TWh in 2025, 88 TWh in 2030 and 146 TWh in 2035, respectively (see Fig. 8). The cost-effective potential of electricity efficiency improvement for these chemical sectors in the North grid, Northwest grid and Central grid amounts to 121 TWh in 2035, or 83% of the total cost-effective electricity savings. Southern grid and Northeast grid have the lowest share of the cost-effective electricity savings, accounting for around 6% and 2% respectively in 2035.

4.1.1. Electricity saving potential by grid in China's ammonia industry

The ECSCs of each sub-sector per grid are constructed to identify which sub-sector has the largest contribution. Table 2 shows the annual electricity saving potentials in the ammonia industry, which vary from 11 TWh in 2020 to 50 TWh in 2035, equaling 38–27% of total electricity savings. The cost-effective measures are about 90% of the total electricity savings in ammonia industry (equal to 10 TWh in 2020, 19 TWh in 2025, 31 TWh in 2030 and 46 TWh in 2035; see Appendix C-1). Ammonia production capacity is concentrated in grain and cotton producing regions (e.g. Shanxi, Shandong, Henan, Sichuan) [36]. These regions are mainly located in the Central grid and North grid. Therefore, the North and Central grids show larger electricity saving potential than other grids, accounting for 61% of the total electricity saving

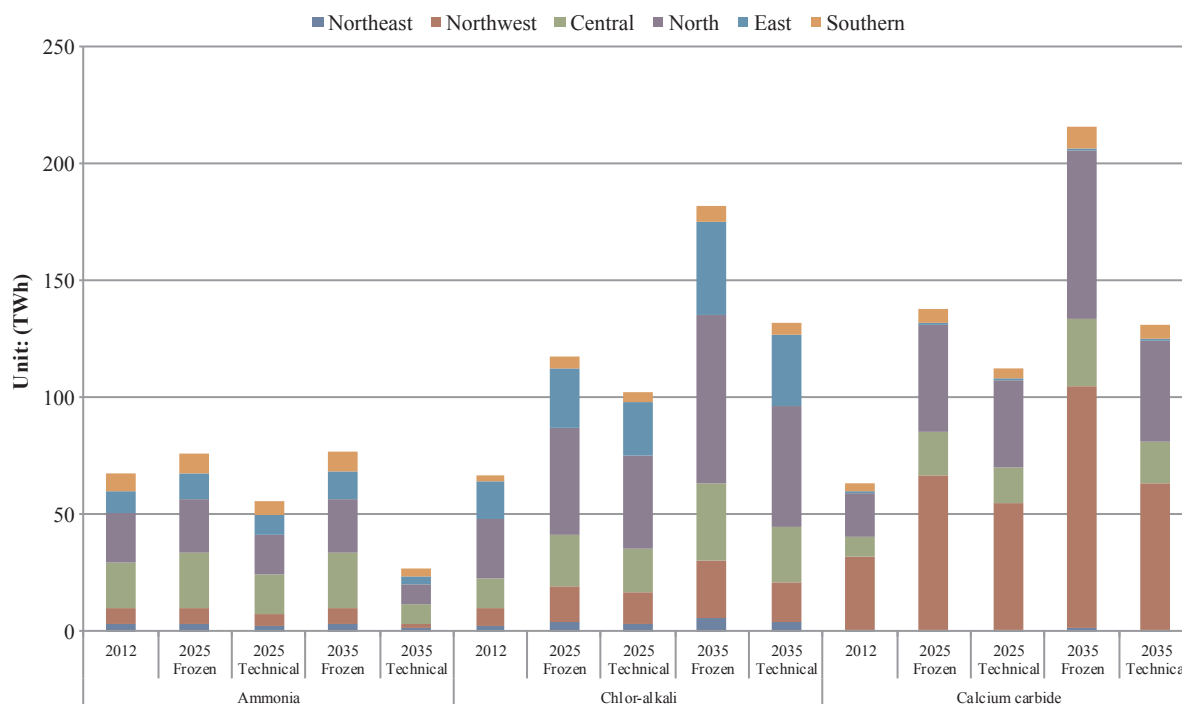


Fig. 7. Electricity consumption in sub-sectors at grid level during 2012–2035 under two scenarios.

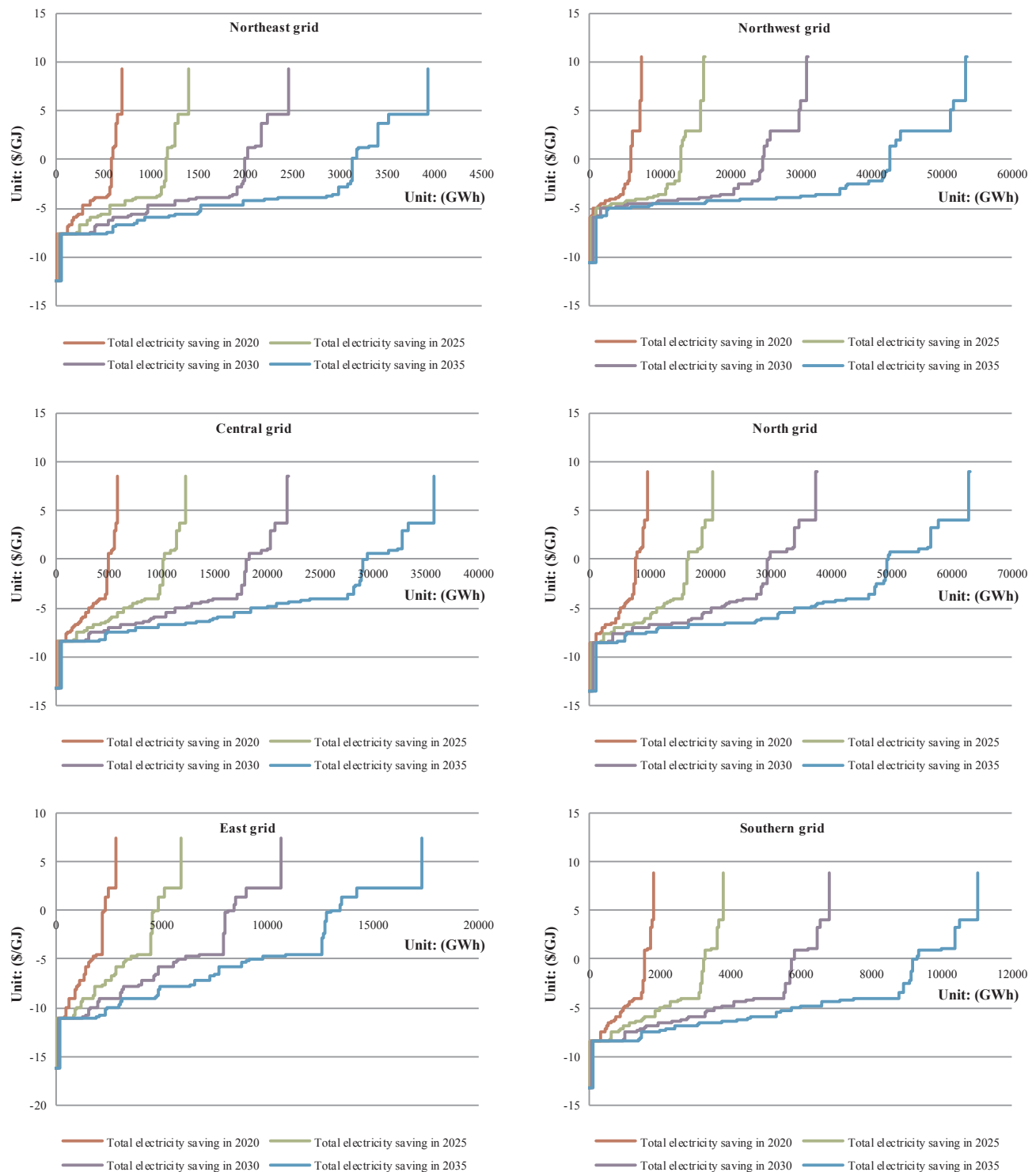


Fig. 8. Total electricity saving potentials for chemical sectors in each grid during 2020–2035.

potential in ammonia industry between 2020 and 2035. Liaoning, Jilin, Heilongjiang, Qinghai, Gansu, Ningxia located in Northeast grid and Northwest grid are ammonia importing provinces. Low shares of ammonia production cause lower electricity efficiency improvement potentials in the Northeast grid (0.5–2 TWh) and Northwest grid (1–5 TWh) during 2020–2035. Around 26% of electricity saving potential is contributed by the East grid and Southern grid in the same period.

4.1.2. Electricity saving potential by grid in China's chlor-alkali industry

The total (technical) electricity savings in the chlor-alkali industry

increase from 7 TWh in 2020 to 50 TWh in 2035, and account for 24–27% of the improvement potential (see Table 3). The cost-effective electricity saving potential in the chlor-alkali industry equals 5 TWh in 2020, 10 TWh in 2025, 19 TWh in 2030 and 33 TWh in 2035, which is a bit lower than that of the ammonia industry (see Appendix C-2). Shandong, Tianjin, Jiangsu, Zhejiang and Inner Mongolia, with the advantages of salt and power resources, have a large share in caustic soda and PVC production (accounted 54% of total caustic soda output and 39% of total PVC output in 2015). As a result, North grid and East grid hold the largest potential in electricity efficiency improvement,

Table 2
Electricity saving potentials in the ammonia industry at grid level. Unit: (GWh).

Grid	2020		2025		2030		2035	
	Cost-effective	Technical	Cost-effective	Technical	Cost-effective	Technical	Cost-effective	Technical
Northeast	424	460	785	854	1276	1390	1882	2049
Northwest	886	971	1704	1865	2819	3081	4195	4578
Central	2989	3275	5711	6251	9424	10,299	14,002	15,282
North	2886	3162	5579	6106	9252	10,111	13,782	15,040
East	1465	1565	2825	3007	4681	4970	6970	7385
Southern	1087	1191	2084	2281	3443	3762	5119	5586
Total	9737	10,624	18,688	20,364	30,895	33,613	45,950	49,920

Table 3
Electricity saving potentials in the chlor-alkali industry at grid level. Unit: (GWh).

Grid	2020		2025		2030		2035	
	Cost-effective	Technical	Cost-effective	Technical	Cost-effective	Technical	Cost-effective	Technical
Northeast	124	188	284	439	539	847	930	1479
Northwest	928	1234	1954	2651	3575	4924	6045	8409
Central	807	1177	1840	2744	3482	5282	6002	9204
North	1869	2714	4081	6070	7597	11,503	12,991	19,901
East	753	1202	1727	2819	3284	5461	5692	9576
Southern	152	227	356	540	681	1048	1179	1834
Total	4633	6742	10,242	15,263	19,158	29,065	32,839	50,403

accounting for 58% of electricity savings in the chlor-alkali industry. Affected by the circular economy project for integrated coal-electricity-salt production [73], the Northwest and Central grids also show higher reduction of electricity use, compared to 7% of improvement potential in the Northeast and Southern grid between 2020 and 2035.

4.1.3. Electricity saving potential by grid in China's calcium carbide industry

Calcium carbide production is the largest electricity consumer, and has the greatest impact on electricity efficiency improvement for the chemical industry. As shown in Table 4, the electricity saving potential in calcium carbide industry grows from 11 TWh to 85 TWh between 2020 and 2035. 85 TWh electricity savings in 2035 is nearly 43% electricity use of these chemical sectors in 2012. Around 79% of the technical electricity saving potential is contributed by the cost-effective measures in the calcium carbide industry (equaling 9 TWh in 2020, 20 TWh in 2025, 38 TWh in 2030 and 68 TWh in 2035; see Appendix C-3. Most of the calcium carbide enterprises are concentrated in the Northwest and North regions (i.e. Inner Mongolia, Shannxi, Gansu, Ningxia and Xinjiang) [78]. Therefore the Northwest grid has the largest electricity saving potential accounting for 48% of the improvement potential for calcium carbide industry in 2035, followed by the North and Central grid with 33% and 13% respectively. Only 4% of

improvement potential is found in the East, Northeast and Southern grid as a result of relatively small calcium carbide production capacity.

4.2. Multiple benefits on climate change and air quality

4.2.1. GHG emissions reduction by grid

Fig. 9 shows the GHG emissions caused by electricity use in the chemical sectors by grid between 2012 and 2035 under different scenarios. In the frozen scenario, GHG emissions increase rapidly from 168 Mt CO_{2eq} in 2012 to 397 Mt CO_{2eq} in 2035 with an average rate of 3.8% per year. Electricity efficiency measures play a key role in reducing CO₂ emissions. By adopting all 60 electricity efficiency measures, emissions can be reduced by 23 Mt CO_{2eq} in 2020, 50 Mt in 2025, 92 Mt in 2030 and 154 Mt in 2035 (equivalent to 39% reduction compared to the frozen scenario in 2035). More than 79% of the GHG emissions reduction potential can be achieved cost effectively. The reduction potential varies for the different grids. In 2035, the absolute savings potential is highest in North grid (42% of total savings), followed by Northwest grid (28%), Central grid (14%), East grid (9%), Southern grid (4%) and lastly Northeast grid (3%).

Detailed emissions of CO₂, CH₄ and N₂O for two scenarios per grid are shown in Fig. 10. Between 2020 and 2035, the North grid with the greatest CO₂ emissions has the largest potential for CO₂ emission

Table 4
Electricity saving potentials in the calcium carbide industry at grid level. Unit: (GWh).

Grid	2020		2025		2030		2035	
	Cost-effective	Technical	Cost-effective	Technical	Cost-effective	Technical	Cost-effective	Technical
Northeast	36	45	89	113	179	226	322	404
Northwest	4091	5229	9394	11,913	18,336	23,110	32,414	40,693
Central	1093	1391	2590	3272	5106	6423	9068	11,371
North	2954	3778	6612	8388	12,778	16,110	22,487	28,236
East	37	38	98	101	200	206	361	370
Southern	317	404	799	1012	1613	2031	2894	3631
Total	8528	10,885	19,582	24,799	38,212	48,106	67,546	84,705

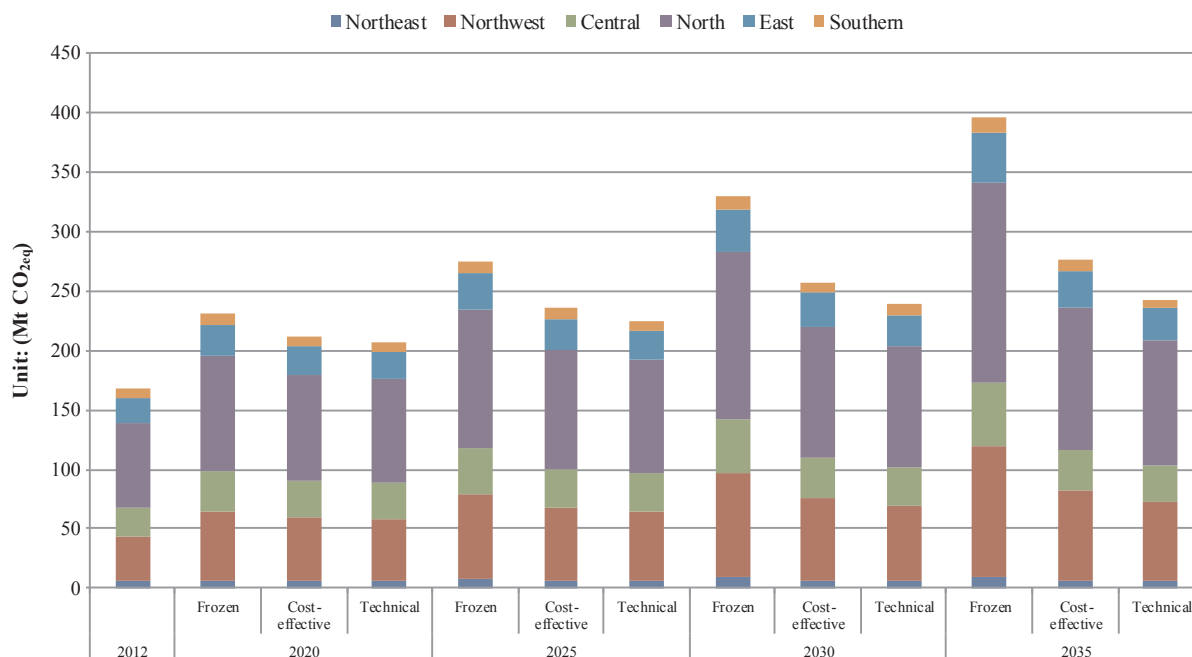


Fig. 9. GHG emissions in chemical sectors between 2012 and 2035 under different scenarios.

reduction though implementing cost-effective measures, which accounted for around 42% of total reduction potential. In 2020, the Northwest and Central grids together accounted for 40% of total grid emissions, and show a 41% CO₂ reduction potential under cost-effective scenario. The Northeast grid with the smallest share of chemical production emits 7 Mt CO₂ emissions under cost-effective scenario (equal to 3% of total emissions). Compared with 2012, in the technical scenario total CH₄ and N₂O emissions will increase by 19 kt CO_{2eq} and 321 kt CO_{2eq} in 2035 respectively.

4.2.2. Air pollutant emissions reduction by grid

SO₂ emissions caused by electricity consumption in the chemical industry are influenced by the generation efficiency, sulfur content of fuels and degree of flue gas desulfurization. SO₂ emissions in different grids under different scenarios between 2012 and 2035 are shown in Fig. 11. The total SO₂ emissions will increase from 320 kt in 2012 to 762 kt in 2035 under frozen scenario. If the cost-effective electricity saving measures were adopted, 8% and 31% of SO₂ emissions can be avoided in 2020 and 2035 respectively. If all electricity saving measures were implemented (technical scenario), SO₂ emissions will drop further by 2% and 8% in 2020 and 2035. In the frozen and cost-effective scenarios, SO₂ emissions in all grids show steady growth during 2012–2035. In the technical scenario, SO₂ emissions from the Northeast, Central and Southern grids will peak around 2030, and then decline slightly (see Fig. 12). As shown in Figs. 11 and 12, in the technical scenario SO₂ emissions would still grow at an average rate of 1.2%, 1.6% and 1.2% per year in the North, Northwest and East grid respectively, from 149 kt, 90 kt and 60 kt in 2020 to 178 kt, 114 kt and 71 kt in 2035. The contribution to SO₂ emission reductions varies among different grids, dependent on the electrical output and chemical production during 2020–2035. Regions with the largest share of SO₂ emissions are mainly located in the North and Northwest grids. North grid and Northwest grid account for 37% and 22% of total SO₂ emission reductions under cost-effective scenario in 2020, followed by Central grid and East grid with 19% and 13%, respectively (see Fig. 11). In cost-effective scenario, the share of reduction potential in Northwest grid will increase by 3% in 2035 because of the implementation of coal-electricity-salt projects for the chlor-alkali sector [73].

Fig. 13 shows the NO_x emissions (per grid) in the chemical industry for various scenarios between 2012 and 2035. Compared to the frozen

scenario, the cost-effective measures contribute to 105 kt and 322 kt of NO_x emission reductions in 2025 and 2035, respectively. If all the electricity efficiency measures implemented with expected adoption rates, the NO_x emissions

will further decrease by 21 kt in 2025 and 68 kt in 2035. NO_x emission reductions in the North and Northwest grids are higher than other grids during the studied period in all scenarios, together accounting for around 70% of total NO_x emission reductions (see Fig. 14). This is because more than 60% of total electricity savings in the chemical industry are from the North and Northwest grids. Additionally, the share of NO_x emission reductions from the Northwest grid in 2035 will be 2–3% higher than in 2020. Central grid and East grid with large share of ammonia, caustic soda and PVC production also have a high potential for NO_x emission reductions, accounting for 14% and 8% of total NO_x emission reductions in 2035 respectively. This is followed by the Southern grid and Northeast grid with 4% and 3%.

The co-benefit of electricity efficiency measures on PM_{2.5} emission reductions for chemical industry at grid level are shown in Fig. 15. The total PM_{2.5} emissions increase to 167 kt, or 2.4 times during 2012–2035 equal to an increase of 3.8%/year. Compared to the frozen scenario, in the cost-effective scenario, the average growth per year will decrease to 2.2%. Reductions of 17 kt and 51 kt PM_{2.5} emissions are feasible by adopting the cost-effective measures in 2025 and 2035 (equal to 15% and 31% of total PM_{2.5} emissions, respectively). If all the electricity saving measures were applied to the chemical sectors, the total PM_{2.5} emissions would further reduce by 3–8% during 2025–2035. Similar to the emissions of SO₂ and NO_x under the technical scenario, PM_{2.5} emissions from the Northeast, Central and Southern grids will reach a peak of 3.6 kt, 1.5 kt and 4.7 kt in 2030, and then decline to 3.5 kt, 1.4 kt and 4.3 kt in 2035 (see Fig. 16). In the North, Northwest and East grids, the trends of PM_{2.5} emission will continue to grow at an annual rate of 1%, 2% and 1% during 2020–2035, respectively. Provinces (e.g. Shandong, Inner Mongolia, Hebei, Shanxi and Xinjiang) with a large share of chemicals production and electricity consumption are mainly located in the North and Northwest. Therefore, the North grid and Northwest grid have the greatest PM_{2.5} emission reduction potential, together accounting for 64% of total PM_{2.5} emission reduction, followed by Central grid with 16%, and East grid with 11%. The Northeast and Southern grids with 8% of total electricity saving in chemical sectors, only account for 9% of total PM_{2.5} emission reduction in 2035.

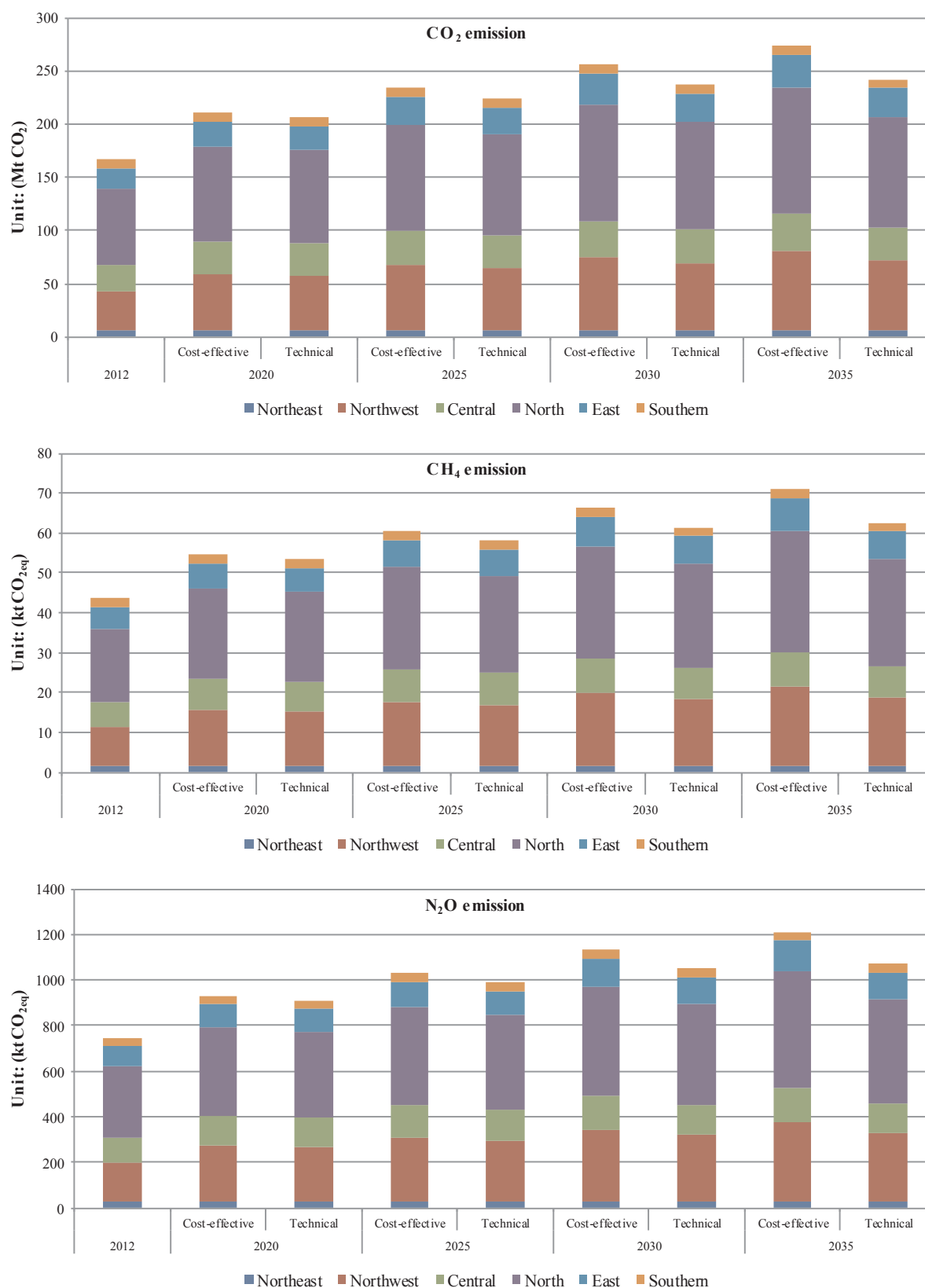


Fig. 10. Emissions per grid of CO₂, CH₄ and N₂O under two scenarios between 2020 and 2035.

5. Sensitivity analysis

The impact of key factors affecting the results of electricity saving potential and related emission reductions, like chemical output, discount rate, and electricity prices in different grids, are analyzed.

5.1. Chemicals output

The future output of chemical products plays a crucial role in estimating the benefits of electricity savings and emissions reduction. Few studies have analyzed future chemicals production on a national or

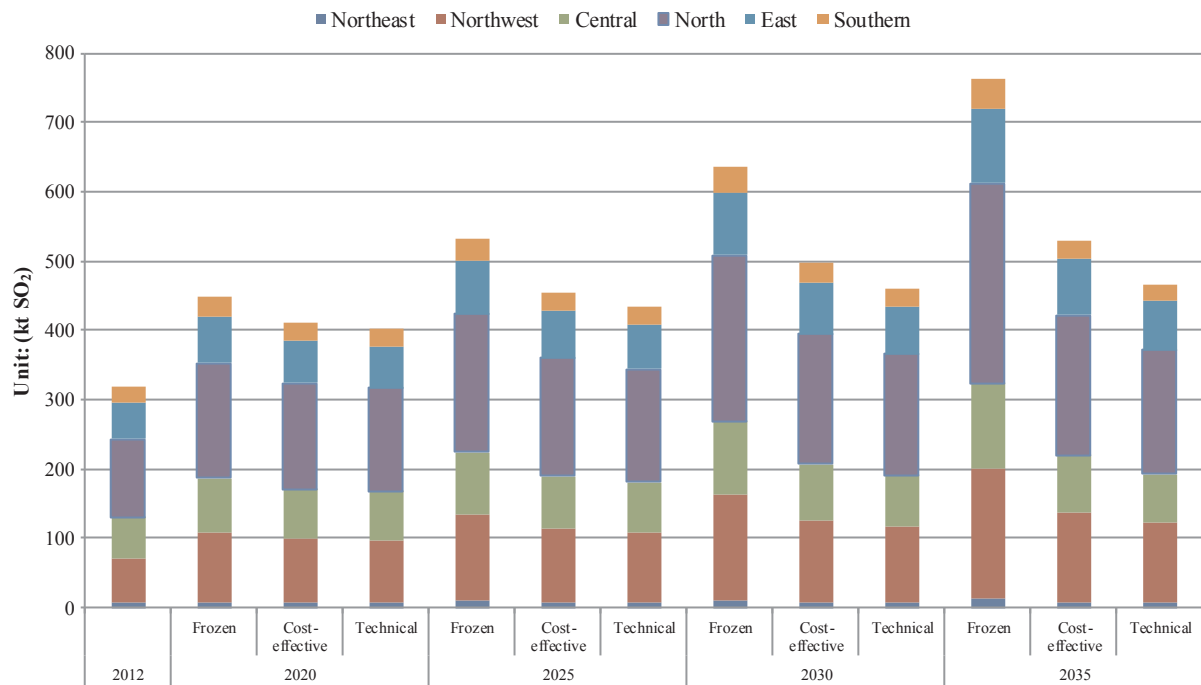


Fig. 11. SO₂ emissions at grid level between 2012 and 2035 under different scenarios.

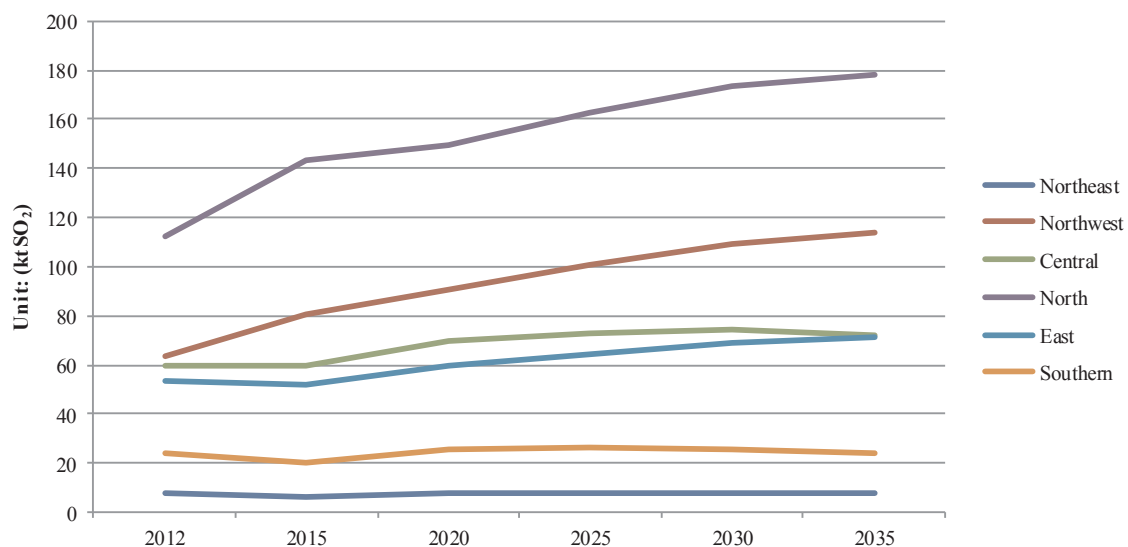


Fig. 12. Trend of SO₂ emissions at grid level in technical scenario during 2012–2035.

regional level due to its diversity and heterogeneity [27,98]. Based on the analysis of chemical products flow in downstream industries, the national plans and historical regional output for key chemicals are used to project the future output at grid level in this study (see Section 3.4.1 and Supplementary material). Chemical plants characterized by energy intensive products are mainly located in regions with abundant raw materials and energy (coal and electricity), that are mainly concentrated in the North and Northwest grids (e.g. Inner Mongolia, Xinjiang and Shandong). In general, the growth rate of chemicals output in these grids is higher than the national average rate during 12th Five-Year Plan. For example, the output of caustic soda and calcium carbide in Northwest grid increased from 2.7 Mt and 8.1 Mt in 2011 to 4.1 Mt and 12.4 Mt in 2015, with 10% and 11% of annual growth rate higher than 5% and 10% of national average rate. However, the annual growth of caustic soda and calcium carbide production in the Southern grid area is lower than the

national average, with -3.6% and -14.7% respectively. Under the guidance of industrial policy, the capacities of calcium carbide and chlor-alkali will be further concentrated in regions with large environmental capacity and rich resources [73,78]. Hence, electricity savings and emissions reduction in the North grid and Northwest grid may be underestimated as a result of the assumed average growth rate used to predict the chemicals output for each region.

5.2. Energy prices

The cost effectiveness of multiple benefits on electricity savings and emissions reduction is affected by the electricity prices among different grids. The electricity price in China is influenced by the coal price, which is expected to continue to rise in the future [99]. Increasing energy prices will increase cost-effective potentials of electricity savings

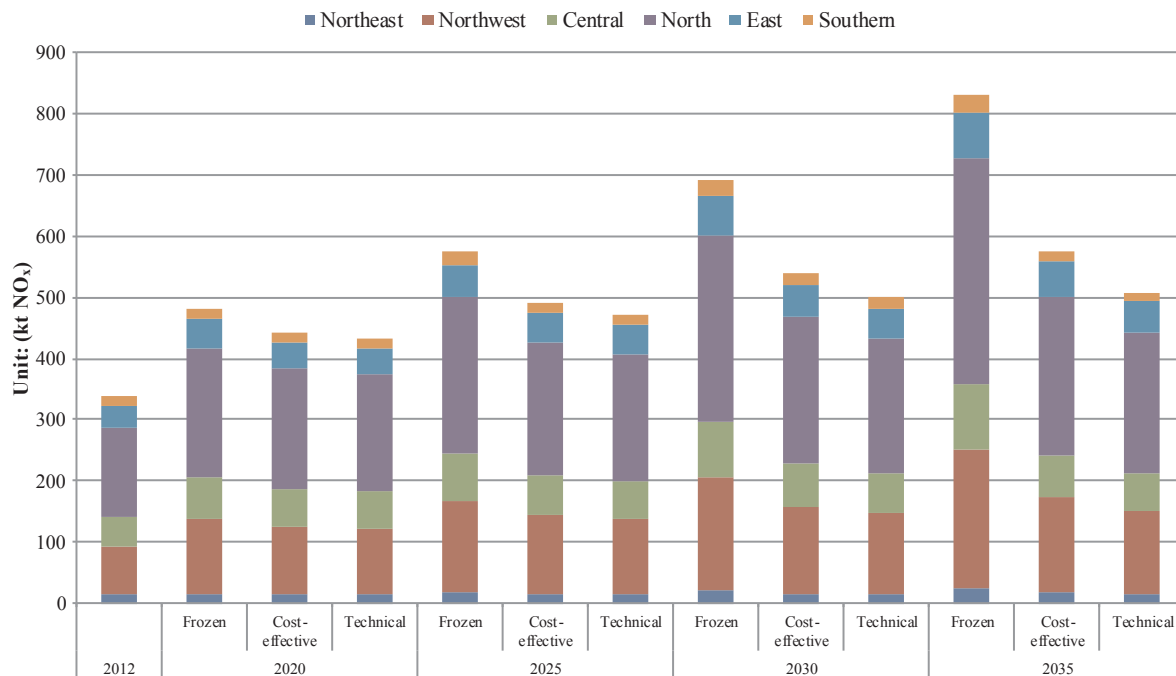


Fig. 13. NO_x emissions at grid level between 2012 and 2035 under different scenarios.

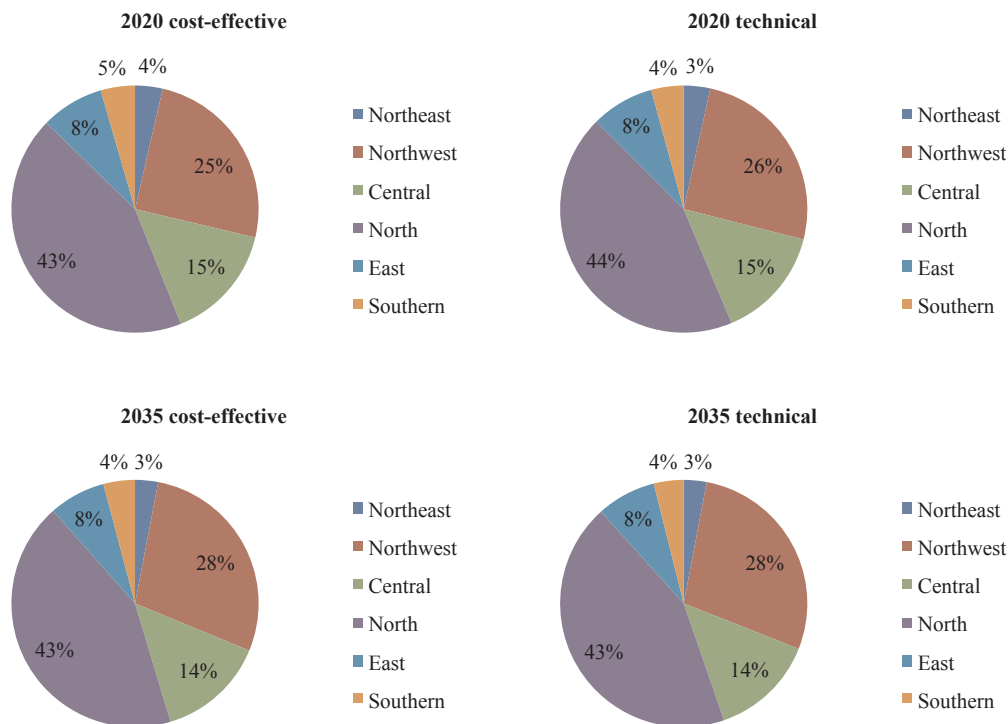


Fig. 14. Share of NO_x emission reduction potential per grid under different scenarios in 2020 and 2035.

and emissions reductions of GHG and air pollutants. Therefore, changing energy prices will affect the cost-effective potentials on a grid level. Based on the studies by LBNL, the annual price escalation rates of electricity and fuel are used to estimate the economic sensitivity of multiple benefits for each grid between 2020 and 2035, while the other factors remain constant (see Table 5) [89,99]. Table 6 and Fig. 17 show the sensitivity analysis results of energy prices on cost-effective potentials of electricity saving and related emission reduction of GHG and air pollutants in each grid during 2020–2035. Changes in energy prices have a great impact on cost-effective potentials, especially in the long-

term. 86% and 98% of the total electricity saving potentials can be achieved cost effectively with SP prices in 2020 and 2035 respectively, which increased by 5% and 19% compared to that with CP price. The East grid with high electricity prices is more sensitive to price changes than the other grids. Cost-effective electricity savings with SP price in East grid will rise by 33% in 2035 compared to that with CP price. Total cost-effective emission reductions of CO₂, CH₄ and N₂O with SP prices will future increase by 30 Mt CO₂, 8 kt CO_{2eq} and 132 kt CO_{2eq} in 2035 respectively. Similar to changes in electricity saving potentials, the cost-effective emission reduction potentials are affected by varying degrees

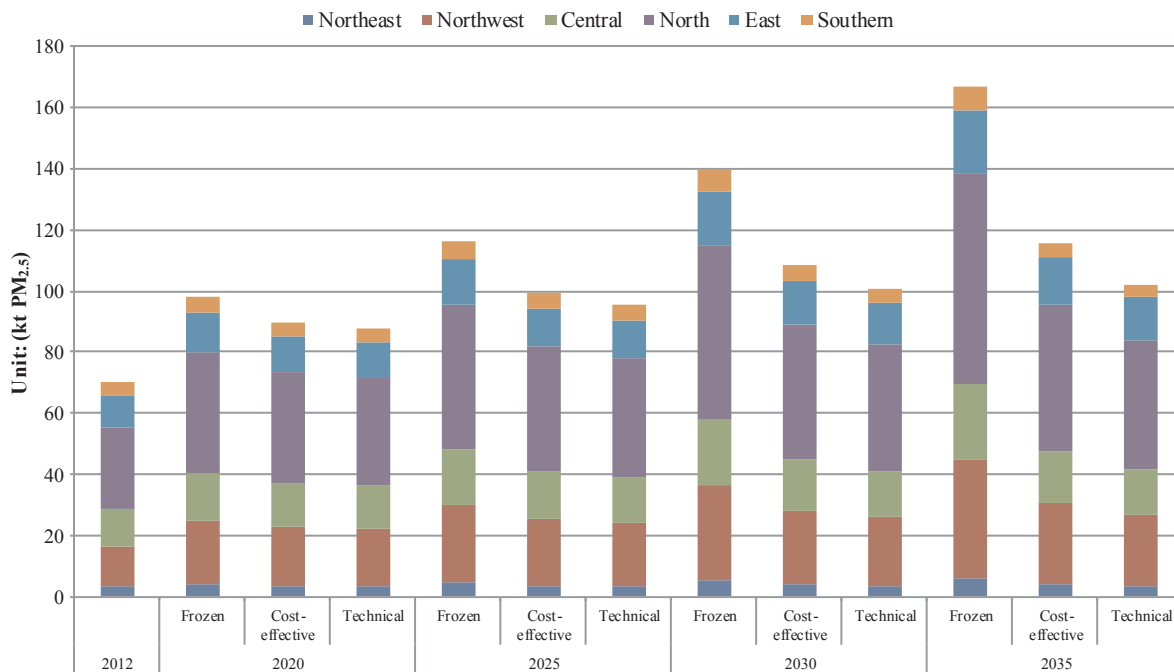


Fig. 15. PM_{2.5} emissions at grid level between 2012 and 2035 under different scenarios.

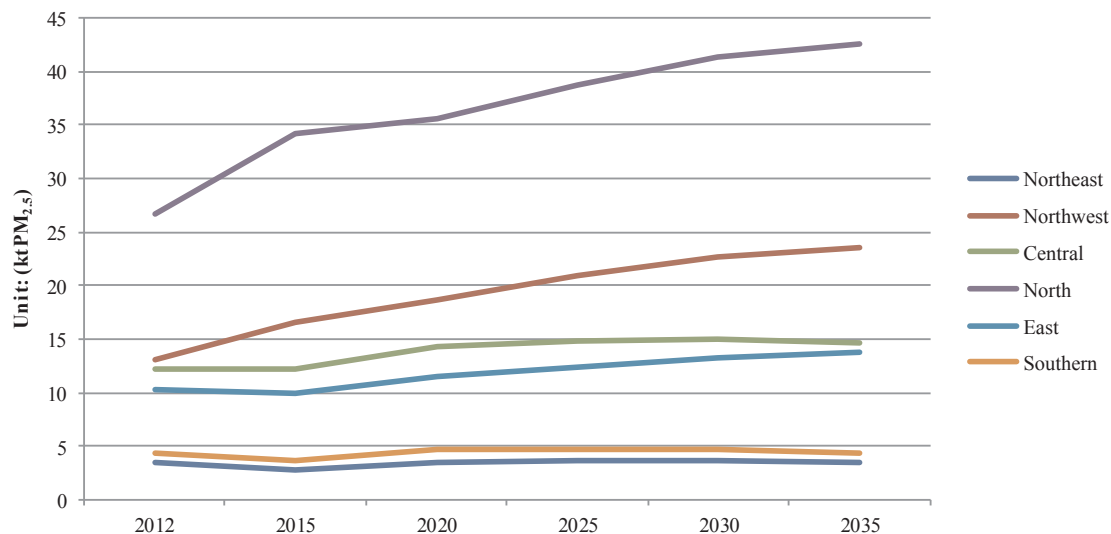


Fig. 16. Trend of PM_{2.5} emissions at grid level in technical scenario during 2012 – 2035.

among different grids. In 2035, nearly 100% of the CO₂ emission reduction potential will be cost-effective with SP price in North grid. Fig. 17 shows the impacts of different prices on the economic potentials of SO₂, NO_x and PM_{2.5} in the short-term lower than that in the long-term. The total economic potentials of SO₂, NO_x and PM_{2.5} reductions in 2035 will shift from 233 kt, 254 kt and 51 kt to 291 kt, 316 kt and 63 kt when using different energy prices. The cost-effective potentials of SO₂, NO_x and PM_{2.5} with SP prices in the North and Northwest grids would increase dramatically in the long-term.

5.3. Discount rate

A discount rate of 10% was assumed in this study. Dependent on the perspectives, various discount rates are used to estimate the economic benefits of energy efficiency improvement and emission reduction [89]. From the perspectives of policy making and market investment, discount rates of 4% to 30% are used to assess the sensitivity of cost-

effective potentials in different grids [26]. Table 7 and Fig. 18 show the effect of various discount rates on the economic potentials of electricity saving and associated emission reduction at a grid level (while other parameters remain constant). With a discount rate of 4%, 54 electricity efficiency technologies will be cost-effective in the North grid, corresponding to cost-effective electricity savings reached 87% of total electricity savings. However, the number of cost-effective measures would decrease to 46 when the discount rate is 30%, and the cost-effective electricity saving reduced to 74% of total electricity savings. A lower discount rate would result in more cost-effective potentials of electricity saving and emission reduction in the chemical industry. Compared to the used discount rate of 10%, the total cost-effective electricity saving would increase by 11% for a 4% discount rate and decrease by 5% for 30% discount rate in 2035 (see Table 7). The economic potentials would increase from 112 Mt, 215 kt, 235 kt and 48 kt to 130 Mt, 253 kt, 276 kt and 55 kt in 2035 when the discount rate decreases from 30% to 4%. Generally, the effect of the discount rate on

Table 5
Different energy prices assumed for each grid.

Grid	CP		2020 SP		2025 SP		2030 SP		2035 SP	
	Electricity (\$/KWh)	Fuel (\$/GJ)	Electricity (\$/KWh)	Fuel (\$/GJ)	Electricity (\$/KWh)	Fuel (\$/GJ)	Electricity (\$/KWh)	Fuel (\$/GJ)	Electricity (\$/KWh)	Fuel (\$/GJ)
Northeast	0.08	3.22	0.09	3.54	0.10	3.91	0.11	4.32	0.12	4.77
Northwest	0.07	3.22	0.07	3.54	0.08	3.91	0.09	4.32	0.10	4.77
Central	0.09	3.22	0.10	3.54	0.11	3.91	0.12	4.32	0.13	4.77
North	0.09	3.22	0.10	3.54	0.11	3.91	0.12	4.32	0.13	4.77
East	0.11	3.22	0.12	3.54	0.13	3.91	0.14	4.32	0.16	4.77
Southern	0.09	3.22	0.10	3.54	0.11	3.91	0.12	4.32	0.13	4.77

Note: CP is the current energy prices assumed to remain unchanged during the study period (see Section 3.4); SP is the energy prices of sensitivity analysis assumed to be dynamic between 2020 and 2035.

Table 6
Cost-effective electricity savings in the chemical industry on a grid level between 2020 and 2035. Unit: GWh.

Grid	2020		2025		2030		2035	
	CP	SP	CP	SP	CP	SP	CP	SP
Northeast	584	594	1158	1201	1994	2172	3134	3515
Northwest	5905	5928	13,052	13,100	24,730	24,813	42,654	51,429
Central	4889	5231	10,141	11,290	18,013	20,678	29,073	35,785
North	7709	8517	16,272	18,385	29,628	34,048	49,260	62,998
East	2256	2366	4650	5924	8165	10,635	13,023	17,329
Southern	1556	1662	3239	3626	5737	6488	9192	11,029
Total	22,899	24,298	48,512	53,526	88,267	98,834	146,336	182,085

Note: CP is the current energy prices assumed to remain unchanged during the study period (see Section 3.4); SP is the energy prices of sensitivity analysis assumed to be dynamic between 2020 and 2035.

the cost-effective potentials is lower than that of energy prices in China's chemical industry.

6. Conclusions and policy implications

6.1. Conclusions

The chemical industry is one of the most electricity-intensive sectors, subsequently resulting in high emissions of GHGs and air pollutants. In this study, the multiple benefits of electricity efficiency measures on electricity efficiency improvement, and emissions reduction of GHG (CO₂, CH₄ and N₂O) and air pollutants (SO₂, NO_x and PM_{2.5}) in China's chemical industry up to 2035 are quantified. Due to the spatial distribution of the chemical industry and variety in emission intensities of power generation in the power grids in China, the study discerns six regions. This results in large differences among the six grids in terms electricity savings and emissions reduction of GHG and air pollutants due to concentration of power generation/use and specific emissions. The following conclusions are drawn from the study:

- Electricity has become the dominant energy source equivalent to 30% of final energy use in China's chemical industry. Electricity use of China's chemical industry increased fourfold from 115 TWh in 2000 to 475 TWh in 2015. 54% of total electricity consumption of China's chemical industry consumed by three sub-sectors (ammonia, chlor-alkali and calcium carbide). These sub-sectors together indirectly emitted 254 Mt of CO₂, 447 kt of SO₂, 428 kt of NO_x and 75 kt of PM in 2015, contributing to 21%, 20%, 28% and 9% of total emissions of the chemical industry respectively.
- Electricity conservation supply curves are constructed per grid to quantify the cost-effective and technical potentials of electricity savings at the grid level up to 2035. The total cost-effective electricity savings account for more than 80% of total electricity savings in the chemical industry, reaching 147 TWh in 2035. Due to the

- heterogeneity of the regional grids, the contribution to electricity savings among the six grids is different. Most of the chemical plants are located in the regions with abundant resources (e.g. Inner Mongolia, Shandong, Shannxi, Gansu and Xinjiang). Therefore the Northwest grid and North grid have the largest electricity saving potential, accounting for 34% and 29% of the total economic potential in 2035 respectively, followed by the Central grid with 20%.
- The emission factors of GHG and air pollutants in each grid were calculated to quantify the emissions mitigation benefits achieved by electricity savings in China's chemical industry during 2012 to 2035, resulting in an economic emission reduction of 121 Mt CO₂, 233 kt SO₂, 254 kt NO_x and 51 kt PM_{2.5}. 70% of the economic potential for CO₂ emission reduction is contributed in the North and Northwest grids. Similar to GHG emissions, the North grid and Northwest grid have the high emission reduction potentials of SO₂, NO_x and PM_{2.5} due to the large chemicals production and electrical output. In 2035, 184 kt SO₂ emissions can be avoided in the North and Northwest grids, while 79% emission reduction is cost-effective. The economic electricity saving measures can cut 254 kt NO_x and 51 kt PM_{2.5} in 2035. Therefore, multiple economic and environmental benefits can be achieved by focusing on improving the efficiency with which electricity is consumed in end-use sectors, warranting to include electricity efficiency in air quality policy.
- The sensitivity analysis indicates that changes of energy price and discount rate have great influences on the cost-effective potentials in China's chemical industry. Increasing energy prices (or decreasing the discount rate) will increase cost-effective potentials of electricity savings and emissions reduction. Grids with a high electricity price are more sensitive to price changes than other grids.

6.2. Policy implications and future research direction

This study shows that multiple benefits of electricity savings are important for both policy as well as investment in electricity generation

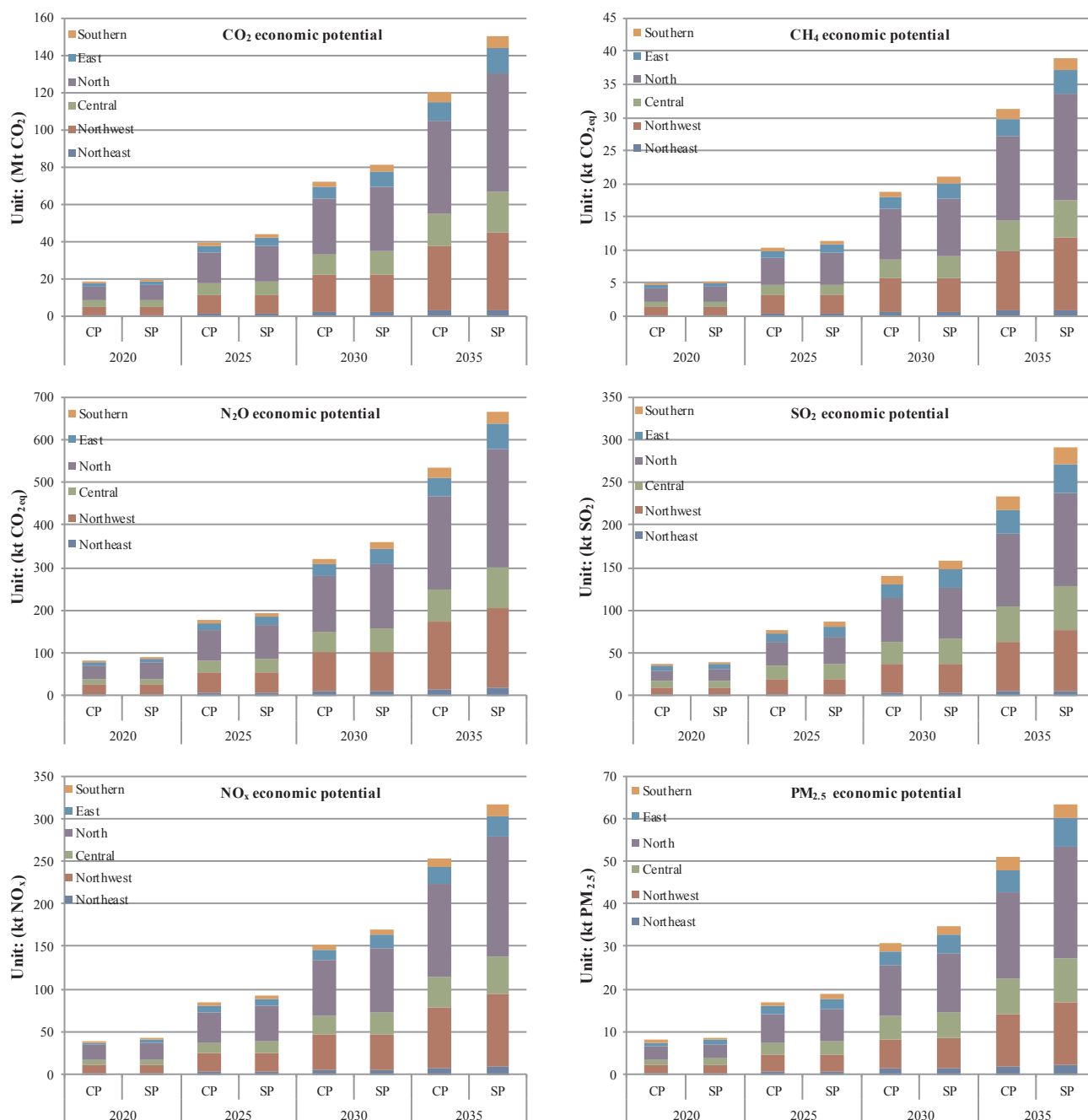


Fig. 17. Sensitivity analysis of energy prices on emissions mitigation in the chemical industry during 2020–2035.

Table 7

Cost-effective electricity savings and emissions reduction under various discount rates in the chemical industry on a grid level in 2035.

Grid	Electricity saving (GWh)			CO ₂ reduction (Mt)			SO ₂ reduction (kt)			NO _x reduction (kt)			PM _{2.5} reduction (kt)		
	4%	10%	30%	4%	10%	30%	4%	10%	30%	4%	10%	30%	4%	10%	30%
Northeast	3265	3134	2884	3	3	3	4	4	4	8	8	7	2	2	2
Northwest	42,686	42,654	37,571	34	34	30	59	59	52	72	72	63	12	12	11
Central	31,527	29,073	27,538	19	18	17	45	42	39	39	36	34	9	8	8
North	54,745	49,260	46,967	55	50	48	95	85	81	122	109	104	23	20	19
East	16,487	13,023	12,022	13	10	9	33	26	24	24	19	17	6	5	5
Southern	9994	9192	8724	6	5	5	17	16	15	11	10	10	3	3	3
Total	158,704	146,336	135,706	130	120	112	253	232	215	276	254	235	55	50	48

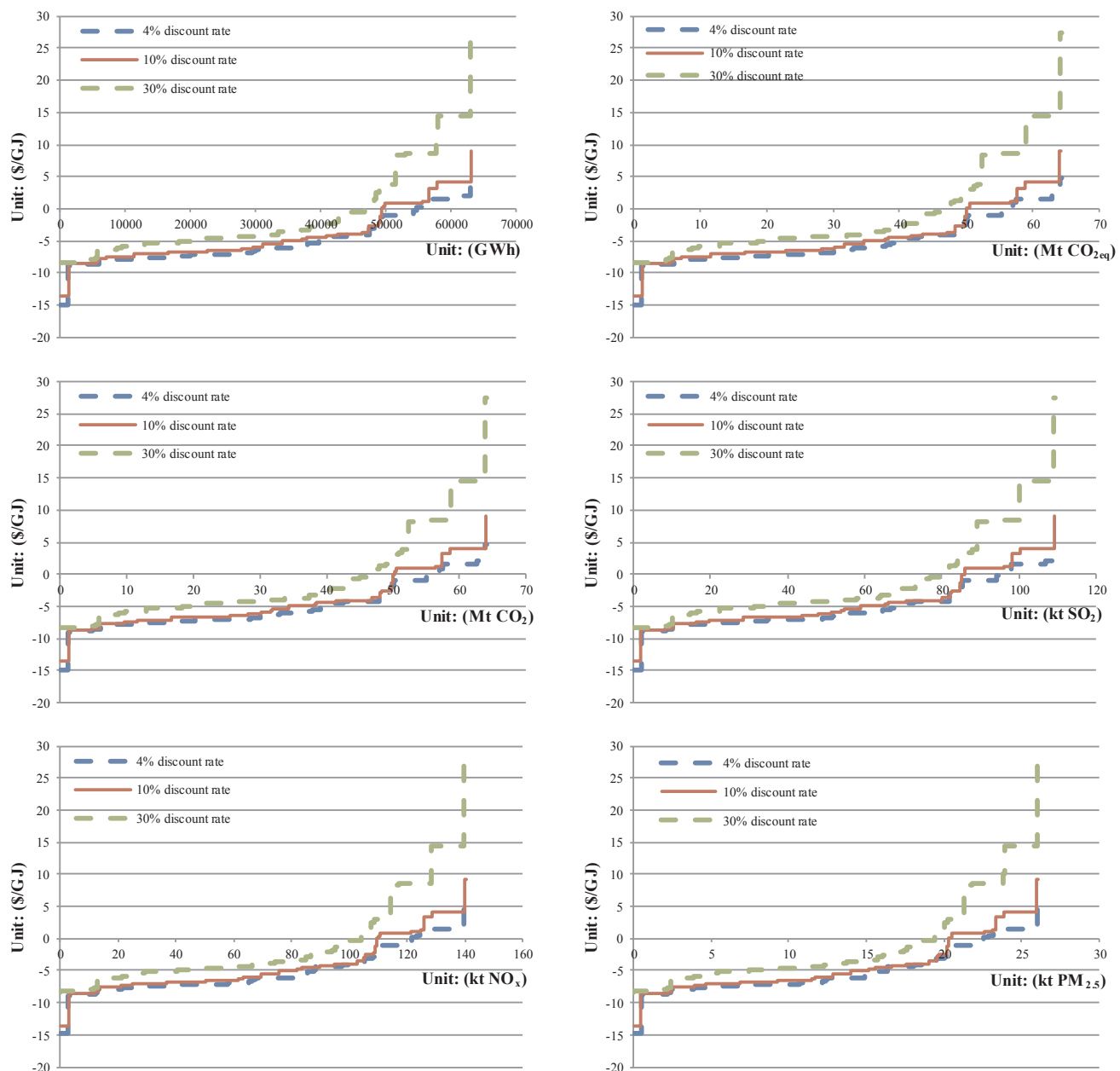


Fig. 18. Potentials of electricity saving and emission reduction in North grid under various discount rates.

and air pollution control options. This study highlights the policy implications for national and regional grid levels, and future research:

- Nationally, the results suggest that policies integrating end-use electricity efficiency would increase the efficiency and effectiveness of air quality policies and climate. It was shown that up to 80% of the emission reductions resulting from electricity efficiency can be achieved cost-effectively. Thus, policies promoting cost-effective efficiency technologies should be designed and implemented. To achieve greater benefits, policymakers should consider providing subsidies to specific currently non-economic but highly efficient technologies (e.g. high-temperature and high-pressure chlorine liquefying technology and new conductive copper contact shoe for closed furnaces), as the co-benefits may outweigh the investments (when evaluated based on energy cost-reductions alone).
- The synergies between electricity savings and emissions reduction vary for the regional grids due to the concentration of power generation (and consumption) and specific emission factors. The

understanding of grid-specific synergies is crucial for the regional allocation of emission reduction targets. Based on the principle of “common but differentiated responsibilities”, the results suggest that different regions should shoulder different abatement goals. In the case of the chemical industry, the largest responsibility should be shouldered by regions in grids with high potentials of electricity savings and emissions reduction, such as North and Northwest grids. The minimum burden should be allocated to regions in Northeast and Southern grids, which have low multiple benefits. Moreover, determining savings on grid level helps to identify options to optimize investments in new power generation capacity and grid capacity, resulting in additional economic benefits. This would warrant further research.

- For other countries these results are expected to be similar, depending on the energy sources and related emission factors associated with the electricity grids, as is shown in this study. Further research should focus on valuing all benefits to allow a full cost-benefit analysis. Furthermore, expanding the analysis to other sectors

will help to fully quantify the contribution of electricity savings to air quality, public health, climate change mitigation, and economics.

Acknowledgments

This study was supported by the China Scholarship Council under

Grant No. 201607040082. We extend our gratitude to the valuable comments of the anonymous reviewers. We thank Jing Hu (Copernicus Institute of Sustainable Development) for useful comments to this study.

Appendix A. Appendix A

See [Tables A.1–A.3](#).

Table A1

Ammonia production by each grid during the period of 2015–2035 (10^4 t).

Grid	Region	Coal-based					Gas-based				
		2015	2020	2025	2030	2035	2015	2020	2025	2030	2035
North	Beijing	0	0	0	0	0	0	0	0	0	0
	Hebei	214	258	268	281	283	60	60	59	54	46
	Inner Mongolia	97	116	120	126	127	27	27	26	24	21
	Shanxi	418	449	466	489	493	118	105	102	93	80
	Shandong	581	655	679	713	720	164	154	149	136	117
	Tianjin	16	14	14	15	15	4	3	3	3	2
Northeast	Heilongjiang	49	68	71	75	75	14	16	16	14	12
	Jilin	39	46	47	50	50	11	11	10	9	8
	Liaoning	72	85	88	93	94	20	20	19	18	15
East	Anhui	269	283	294	309	311	76	66	65	59	51
	Fujian	68	80	83	88	88	19	19	18	17	14
	Jiangsu	272	312	324	340	343	77	73	71	65	56
	Shanghai	0	0	0	0	0	0	0	0	0	0
	Zhejiang	59	55	57	60	60	17	13	12	11	10
Central	Chongqing	169	169	176	185	186	48	40	39	35	30
	Henan	492	448	465	488	493	139	105	102	93	80
	Hubei	381	406	421	442	446	107	95	92	84	73
	Hunan	83	128	133	140	141	23	30	29	27	23
	Jiangxi	7	13	14	15	15	2	3	3	3	2
	Sichuan	303	342	355	372	376	85	80	78	71	61
Northwest	Gansu	45	60	63	66	66	13	14	14	13	11
	Ningxia	50	86	89	94	95	14	20	20	18	15
	Qinghai	1	0	0	0	0	0	0	0	0	0
	Shannxi	148	134	139	146	147	42	31	31	28	24
	Xinjiang	170	172	178	187	189	48	40	39	36	31
Southern	Hainan	62	71	73	77	78	17	17	16	15	13
	Guangdong	0	4	4	4	4	0	1	1	1	1
	Guangxi	80	93	97	102	103	23	22	21	19	17
	Guizhou	188	176	183	192	194	53	41	40	37	32
	Yunnan	185	207	215	226	228	52	49	47	43	37
Nation		4518	4930	5116	5375	5420	1273	1155	1122	1026	882

Sources: historical outputs of ammonia are from [14,30,31,36]; the future outputs of ammonia are forecasted based on [32,36,61–69].

Table A2

Caustic soda and PVC production by each grid during the period of 2015–2035 (10^4 t).

Grid	Region	Caustic soda					PVC				
		2015	2020	2025	2030	2035	2015	2020	2025	2030	2035
North	Beijing	0	3	4	5	6	0	0	0	0	0
	Hebei	119	135	169	210	262	56	85	107	134	168
	Inner Mongolia	265	280	349	435	542	341	327	410	513	643
	Shanxi	45	68	84	105	131	64	67	84	105	132
	Shandong	741	836	1042	1298	1618	100	139	174	218	273
	Tianjin	97	149	186	232	289	125	191	239	300	375
Northeast	Heilongjiang	16	17	21	26	33	10	9	11	14	17
	Jilin	9	23	29	36	45	3	15	19	24	30
	Liaoning	65	80	99	124	154	13	21	26	33	41
East	Anhui	72	66	82	102	127	2	12	15	18	23
	Fujian	32	33	41	51	64	0	2	2	3	4
	Jiangsu	361	503	627	781	973	16	25	32	40	50

(continued on next page)

Table A2 (continued)

Grid	Region	Caustic soda					PVC				
		2015	2020	2025	2030	2035	2015	2020	2025	2030	2035
Central	Shanghai	69	93	116	144	179	10	26	33	41	52
	Zhejiang	153	190	237	296	368	38	53	66	82	103
	Chongqing	33	42	52	65	80	1	1	1	1	1
	Henan	154	227	282	352	439	80	149	186	233	292
	Hubei	107	126	157	196	244	60	68	85	106	133
	Hunan	48	89	111	138	172	13	31	39	49	61
	Jiangxi	31	54	67	84	104	0	0	0	0	0
Northwest	Sichuan	97	150	187	233	290	83	131	164	205	257
	Gansu	19	30	37	46	57	10	12	15	19	24
	Ningxia	35	54	67	83	104	47	62	78	97	122
	Qinghai	18	30	38	47	59	25	32	40	51	63
	Shannxi	94	92	115	143	178	131	118	148	185	232
	Xinjiang	242	254	317	395	492	353	369	462	579	725
	Hainan	0	0	0	0	0	0	0	0	0	0
Southern	Guangdong	31	43	53	66	83	7	16	20	25	31
	Guangxi	44	58	72	90	112	0	14	17	21	27
	Guizhou	2	11	14	17	21	0	8	10	13	16
	Yunnan	21	30	37	47	58	18	31	39	49	61
Nation		3020	3766	4692	5847	7284	1606	2014	2522	3158	3956

Sources: historical outputs of caustic soda and PVC are from [30,31,36]; the future outputs are forecasted based on [30,34,36,70–76,90].

Table A3

Calcium carbide production by each grid during the period of 2015–2035 (10^4 t).

Grid	Region	2015	2020	2025	2030	2035
North	Beijing	0	0	0	0	0
	Hebei	0	0	0	0	0
	Inner Mongolia	957	1011	1265	1584	1984
	Shanxi	34	55	69	87	109
	Shandong	0	6	7	9	12
	Tianjin	0	0	0	0	0
Northeast	Heilongjiang	0	0	0	0	0
	Jilin	0	0	1	1	1
	Liaoning	7	15	19	24	30
East	Anhui	0	3	4	5	7
	Fujian	3	4	5	7	8
	Jiangsu	0	0	0	1	1
	Shanghai	0	0	0	0	0
	Zhejiang	0	7	8	10	13
Central	Chongqing	7	4	5	6	8
	Henan	128	168	210	263	329
	Hubei	59	117	146	183	229
	Hunan	19	30	38	48	60
	Jiangxi	6	7	8	10	13
	Sichuan	67	112	140	175	219
Northwest	Gansu	114	185	232	290	364
	Ningxia	312	464	581	728	911
	Qinghai	26	42	53	67	83
	Shannxi	252	258	323	405	507
	Xinjiang	537	604	756	947	1185
Southern	Hainan	0	0	0	0	0
	Guangdong	0	0	0	0	0
	Guangxi	0	16	20	25	32
	Guizhou	6	40	50	63	79
	Yunnan	51	85	106	133	167
Nation		2585	3233	4046	5071	6351

Sources: historical outputs of calcium carbide are from [30,31,36]; the future outputs of calcium carbide are forecasted based on [35,36,72,73,77,78].

Appendix B. Appendix B

See Tables B.1–B.3.

Table B1
Electricity efficiency measures applied to China's chemical industry.

Sector	Electricity-efficiency measures	Electricity savings (kWh/t-product)	Fuel savings (GJ/t-product)	Annualized investment (\$/t-product)	Life time	Annual change in O&M cost (\$/t-product)	Current adoption rate in 2012 (%)	Potential adoption rate in 2035 (%)
Ammonia	<i>Gas generation</i>							
	Adiabatic pre-reformer	58.10		9.03	20	0.00	5	4
	Aeration intermittent gasification	4.30	1.11	8.40	20	0.00	5	6
	High-pressure coal-gasification	27.80		8.00	25	0.00	15	26
	Three-waste fluidized-mix combustion furnace	200.00	7.47	21.68	20	0.00	45	38
	<i>Shift conversion</i>							
	Full low temperature shift conversion	45.00	0.45	13.34	25	4.34	60	30
	<i>Gas purification</i>							
	Methanolization hydrocarbylation purification	50.00	0.88	18.67	20	−2.53	30	25
	Full autothermic non-constant pressure methanolizing-methanation process	21.40	1.13	33.35	20	−6.27	20	25
	Recovering waste heat from reformer flue gas	13.90	0.05	1.13	20	0.00	70	22
	NHD (Polyethylene glycol dimethyl ether) for CO ₂ and sulphide removal	70.00	5.79	41.35	20	18.67	45	13
	Pressure swing adsorption for removing CO ₂	60.00	1.64	28.01	25	−4.40	10	18
Ammonia	Low heat energy absorption refrigeration by lithium bromide chiller	110.00		2.00	25	0.00	5	60
	<i>Ammonia synthesis</i>							
	Axial-radial ammonia synthesis tower (GC synthesis tower)	20.00	3.22	30.01	25	0.00	10	13
	Automatic control and optimization of ammonia synthesis reactor temperature	40.00	0.37	0.67	20	0.00	13	60
	JR type ammonia synthesis tower internals with multi-stage adiabatic heat-exchange system	73.30		22.01	25	0.00	10	14
	Energy-efficient ammonia synthesis technology (IILJD ammonia synthesis system)	100.00		22.23	25	0.00	10	7
	Recovering energy from rich solution by turbine unit in CO ₂ removal	23.50		0.40	20	0.00	5	7
	Unpowered ammonia-recovery	27.17	0.84	1.07	25	0.00	15	49
	<i>General measures</i>							
	Evaporative condenser cooling	25.00		2.00	20	0.00	30	60
	High-efficiency copper rotor	1.22		0.27	20	0.00	14	50
	Power saving technology of power grid system	10.00		0.67	15	0.00	1	35
	High-voltage frequency conversion speed regulation	10.00		2.00	15	0.00	5	50
Caustic soda	<i>Power rectifying</i>							
	High efficiency silicon rectifier	52.00		9.34	20	0.29	45	65
	<i>Brine electrolysis</i>							
	High-efficiency diaphragm electrolyzer with modified diaphragm and expanded metal anode	105.00		1.33	10	0.00	4	0
	Zero electrode-distance membrane electrolyzer	100.00		10.67	10	0.00	10	36
	Perfluorinated ion membrane made by China	55.00		7.07	10	−1.20	0	4
	Oxygen depolarized cathodes membrane electrolyzer	600.00	0.45	383.22	10	0.00	1	14
	<i>Chlorine + hydrogen disposition</i>							
	New efficient hydrogen compressor	14.52		0.51	25	0.00	10	45
	Freon refrigeration machine	28.16		6.14	20	0.00	50	0
	High-temperature and high-pressure chlorine liquefying	70.00		20.01	15	5.03	10	25
	Turbine compressor for chlorine transport	30.40		10.67	25	0.00	35	55
	<i>Evaporation process</i>							
	Ultrasonic scale cleaning	0.46	1.47	1.75	10	0.80	5	56
	Three-phase flow evaporation	25.00		3.74	20	0.00	1	0
	<i>General measures</i>							

(continued on next page)

Table B1 (continued)

Sector	Electricity-efficiency measures	Electricity savings (kWh/t-product)	Fuel savings (GJ/t-product)	Annualized investment (\$/t-product)	Life time	Annual change in O&M cost (\$/t-product)	Current adoption rate in 2012 (%)	Potential adoption rate in 2035 (%)
PVC	High - voltage frequency converter for pumps, fans	1.71		0.93	15	0.00	15	55
	Energy management system for caustic soda production	62.16	2.08	4.16	10	0.00	3	46
	<i>Acetylene making</i>							
	Dry-process acetylene	45		13.34	20	−4.20	15	63
	<i>HCl synthesis</i>							
	Synthetic furnace of by-product medium pressure steam	14	2.77	13.34	20	0.00	1	27
	<i>Vinyl chloride monomer (VCM) synthesis</i>							
	Heat of hot water recovery	84.65	2.05	3.33	20	0.73	10	50
	High pressure distillation	48.25		1.33	25	0.00	15	28
	<i>PVC synthesis</i>							
PVC	New efficient fluid bed dryer	43.58	0.82	8.90	20	6.63	20	26
	Optimize polymerizer top condenser	147.42		11.01	15	0.00	10	15
	Energy-saving combined high-elasticity cyclone drier	28	0.38	4.00	20	0.00	10	8
	<i>General measures</i>							
	Variable-frequency drives for induced draft fans	9.55		1.33	15	0.00	20	30
	Dynamic reactive power compensation and harmonic suppression	20.76		2.13	15	0.00	1	13
	<i>Feedstock preparation</i>							
	Advanced kilns such as vocarse shaft kiln, double shell shaft kiln and maerz PFR shaft kiln	50.00	4.40	60.47	25	15.01	30	24
	Power supply for quasi stable DC dust collector	18.40		19.21	15	0.00	1	20
	<i>Calcium carbide manufacturing</i>							
Calcium carbide	Transforming semi-covered furnace to closed furnace (exclude the utilization of tail gas)	180.00		44.40	20	15.01	40	24
	Direct current electric arc furnace	330.00		57.72	25	0.00	0	5
	New conductive copper contact shoe for closed furnace	124.00		59.24	10		1	80
	40.5 MVA closed furnace	100.00	6.09	68.45	25	0.00	25	25
	63 MVA closed furnace	50.00	8.61	137.39	25	0.00	4	11
	Low-voltage dynamic reactive power compensation	153.14		16.06	15	0.00	5	70
	Combination electrodes	185.62		16.01	15	0.00	20	20
	Hollow electrode	50.00		8	15	0.00	5	50
	Comprehensive compensation of short-supply network	277.71	1.47	37.04	15	0.00	5	19
	Electricity saving expert system for electric arc furnace	102.86		7.85	15	0.00	3	30
Calcium carbide	Automatic control system for materials feeding and batching	131.43		16.26	15	0.00	20	52
	Waste heat of flue gas for power generation	384.00		45.62	10	0.00	0	13
	Isothermal transformation based on phase change heat transfer	34.76		20.01	20	0.00	6	0
	<i>General measures</i>							
	Energy management center of calcium carbide enterprise	2.78	0.31	1.33	10	0.00	10	30
	Variable frequency speed control	6.00		0.68	15	0.00	20	24

Source: the detailed information of these 60 measures can be found at [34,35,61,63,69,80–87]. Note: we have only collected energy conservation measures with electricity saving, and measures that only save fuels not included in this paper.

Table B2
CCE of electricity efficiency measures in different grids.

Sector	Number	Electricity saving measures	Northeast grid (\$/GJ)	Northwest grid (\$/GJ)	Central grid (\$/GJ)	North grid (\$/GJ)	East grid (\$/GJ)	Southern grid (\$/GJ)
Ammonia	1	Recovering energy from rich solution by turbine unit in CO ₂ removal	-7.69	-5.91	-8.46	-8.63	-11.02	-8.41
	2	Low heat energy absorption refrigeration by lithium	-7.68	-5.91	-8.46	-8.62	-11.01	-8.40
	3	Power saving technology of power grid system	-6.84	-5.09	-7.62	-7.75	-10.10	-7.55
	4	Evaporative condenser cooling	-6.73	-4.98	-7.51	-7.63	-9.98	-7.43
	5	Recovering waste heat from reformer flue gas	-5.80	-4.52	-6.39	-6.44	-8.11	-6.31
	6	Automatic control and optimization of ammonia synthesis reactor temperature	-5.58	-4.67	-6.00	-6.03	-7.19	-5.94
	7	Adiabatic pre-reformer	-5.58	-3.87	-6.37	-6.44	-8.74	-6.27
	8	Full autothermic non-constant pressure methanolizing-methanation process	-4.75	-4.46	-4.88	-4.88	-5.22	-4.86
	9	Energy-efficient ammonia synthesis technology (IIUD ammonia synthesis system)	-4.72	-3.03	-5.51	-5.54	-7.80	-5.39
	10	Methanolization hydrocarbylation purification	-4.68	-4.04	-4.97	-4.98	-5.76	-4.92
	11	High-voltage frequency conversion speed regulation	-4.63	-2.94	-5.42	-5.45	-7.71	-5.30
	12	High-efficiency copper rotor	-4.62	-2.93	-5.41	-5.44	-7.69	-5.29
	13	Pressure swing adsorption for removing CO ₂	-4.60	-4.13	-4.82	-4.82	-5.40	-4.78
	14	Unpowered ammonia-recovery	-4.26	-3.83	-4.46	-4.46	-4.98	-4.42
	15	Three-waste fluidized-mix combustion furnace	-3.89	-3.52	-4.06	-4.05	-4.50	-4.03
	16	High-pressure coal-gasification	-3.76	-2.11	-4.57	-4.55	-6.77	-4.42
	17	JR type ammonia synthesis tower internals with multi-stage adiabatic heat-exchange system	-3.58	-1.93	-4.39	-4.37	-6.58	-4.24
Chlor-alkali	18	Aeration intermittent gasification	-2.25	-2.19	-2.28	-2.28	-2.36	-2.28
	19	Axial-radial ammonia synthesis tower (GC synthesis tower)	-2.19	-2.09	-2.24	-2.23	-2.35	-2.23
	20	NHD (Polyethylene glycol dimethyl ether) for CO ₂ and sulphide removal	0.12	0.30	0.03	0.05	-0.16	0.06
	21	Full low temperature shift conversion	1.30	2.07	0.87	1.00	0.03	1.00
	22	Dry-process acetylene	-12.46	-10.54	-13.21	-13.58	-16.19	-13.25
Chlor-alkali	23	High-efficiency diaphragm electrolyzer with modified diaphragm and expanded metal anode	-7.70	-5.92	-8.47	-8.64	-11.03	-8.42
	24	High pressure distillation	-7.54	-5.77	-8.32	-8.48	-10.86	-8.26
	25	Perfluorinated ion membrane made by China	-7.54	-5.77	-8.31	-8.47	-10.86	-8.25
	26	New efficient hydrogen compressor	-7.44	-5.67	-8.22	-8.37	-10.75	-8.15
	27	Optimize polymerizer top condenser	-6.71	-4.96	-7.49	-7.61	-9.96	-7.41
	28	Dynamic reactive power compensation and harmonic suppression	-6.24	-4.51	-7.03	-7.12	-9.45	-6.94
	29	Zero electrode-distance membrane electrolyzer	-5.85	-4.13	-6.64	-6.72	-9.03	-6.54
	30	Three-phase flow evaporation	-5.67	-3.96	-6.46	-6.53	-8.84	-6.36
	31	Variable-frequency drives for induced draft fans	-5.63	-3.92	-6.42	-6.49	-8.79	-6.32
	32	High efficiency silicon rectifier	-4.66	-2.98	-5.46	-5.49	-7.75	-5.34
Calcium carbide	33	Freon refrigeration machine	-4.63	-2.94	-5.42	-5.45	-7.71	-5.30
	34	Energy-saving combined high-elasticity cyclone drier	-4.33	-3.59	-4.68	-4.68	-5.60	-4.62
	35	Heat of hot water recovery	-4.20	-3.69	-4.44	-4.44	-5.06	-4.40
	36	Energy management system for caustic soda production	-4.03	-3.62	-4.22	-4.21	-4.70	-4.18
	37	Turbine compressor for chlorine transport	-2.85	-1.22	-3.65	-3.60	-5.78	-3.49
	38	Synthetic furnace of by-product medium pressure steam	-2.73	-2.65	-2.77	-2.77	-2.87	-2.77
	39	Ultrasonic scale cleaning	-2.45	-2.44	-2.45	-2.45	-2.46	-2.45
	40	High-voltage frequency converter for pumps, fans	1.10	2.62	0.27	0.50	-1.50	0.52
	41	New efficient fluid bed dryer	1.44	1.98	1.14	1.23	0.57	1.24
	42	High-temperature and high-pressure chlorine liquefying	3.74	5.17	2.90	3.24	1.36	3.20
	43	Oxygen depolarized cathodes membrane electrolyzer	4.58	5.98	3.73	4.11	2.26	4.05
	44	Electricity saving expert system for electric arc furnace	-6.68	-4.94	-7.46	-7.58	-9.93	-7.38
	45	Combination electrodes	-6.52	-4.78	-7.30	-7.41	-9.75	-7.22
	46	Low-voltage dynamic reactive power compensation	-6.21	-4.48	-6.99	-7.09	-9.42	-6.90
	47	Variable frequency speed control	-6.06	-4.34	-6.85	-6.94	-9.26	-6.76
	48	Automatic control system for materials feeding and batching	-5.89	-4.17	-6.68	-6.76	-9.08	-6.59

(continued on next page)

Table B2 (continued)

Sector	Number	Electricity saving measures	Northeast grid (\$/GJ)	Northwest grid (\$/GJ)	Central grid (\$/GJ)	North grid (\$/GJ)	East grid (\$/GJ)	Southern grid (\$/GJ)
	49	Comprehensive compensation of short-supply network	–5.73	–4.02	–6.52	–6.60	–8.90	–6.42
	50	Waste heat of flue gas for power generation	–5.62	–3.90	–6.41	–6.48	–8.78	–6.30
	51	Direct current electric arc furnace	–5.40	–3.70	–6.20	–6.26	–8.55	–6.09
	52	Hollow electrode	–5.29	–3.59	–6.08	–6.14	–8.42	–5.97
	53	Transforming semi-covered furnace to closed furnace (exclude the utilization of tail gas)	–4.19	–2.52	–4.99	–4.99	–7.23	–4.85
	54	Energy management center of calcium carbide enterprise	–2.82	–2.68	–2.89	–2.88	–3.05	–2.87
	55	40.5 MVA closed furnace	–2.46	–2.22	–2.58	–2.57	–2.86	–2.55
	56	63 MVA closed furnace	–1.23	–1.14	–1.27	–1.27	–1.37	–1.26
	57	Isothermal transformation based on phase change heat transfer	0.82	2.34	–0.01	0.21	–1.81	0.23
	58	Advanced kilns such as vocarse shaft kiln, double shell shaft kiln and maerz PFR shaft kiln	1.18	1.34	1.09	1.12	0.93	1.12
	59	New conductive copper contact shoe for closed furnace	1.42	2.92	0.59	0.83	–1.15	0.84
	60	Power supply for quasi stable DC dust collector	9.36	10.63	8.48	9.08	7.45	8.91

Sources: the CCE of each grid is calculated based on [14,16,50,56,88]; the detailed descriptions of formula and data sources can be found at Sections 3.1 and 3.4.

Table B3
Air pollutant abatement measures applied to China's power sector.

Air pollutants	Number	Abatement measures	Removal efficiency (%)	Operation rate (%)	Share of total installation (%)
SO ₂	1	Wet limestone/lime-gypsum (LG)	95	95	83.1
	2	Limestone injection into furnace (LIF)	70	95	6.1
	3	Seawater	90	95	2.9
	4	Circulating fluidized bed	85	95	2.0
	5	Dual alkali process	95	95	1.0
	6	Ammonia process	95	95	0.8
	7	Carbide slag slurry/White mud	95	95	0.8
	8	LIF + LG	90	95	0.5
	9	Semi-dry process	85	95	0.5
	10	Magnesium oxide	95	95	0.5
	11	Remaining desulfurization technology (including dry process and NaOH + Microbial reduction)	90	95	1.8
NO _x	12	Low nitrogen burning (LNB)	33	100	50.3
	13	LNB + Selective catalytic reduction (LNB + SCR)	80	100	47.4
	14	LNB + Selective non-catalytic reduction (LNB + SNCR)	40	100	1.6
	15	LNB + SNCR + SCR	80	100	0.7
PM _{2.5}	16	Electrostatic precipitator (ESP)	93	100	16
	17	ESP + LG	97	100	79

Sources: the detailed information for 17 abatement measures can be found at [13,59,94–97]; the share of total installation is calculated by authors.

Appendix C. Appendix C

See Figs. C.1–C.3.

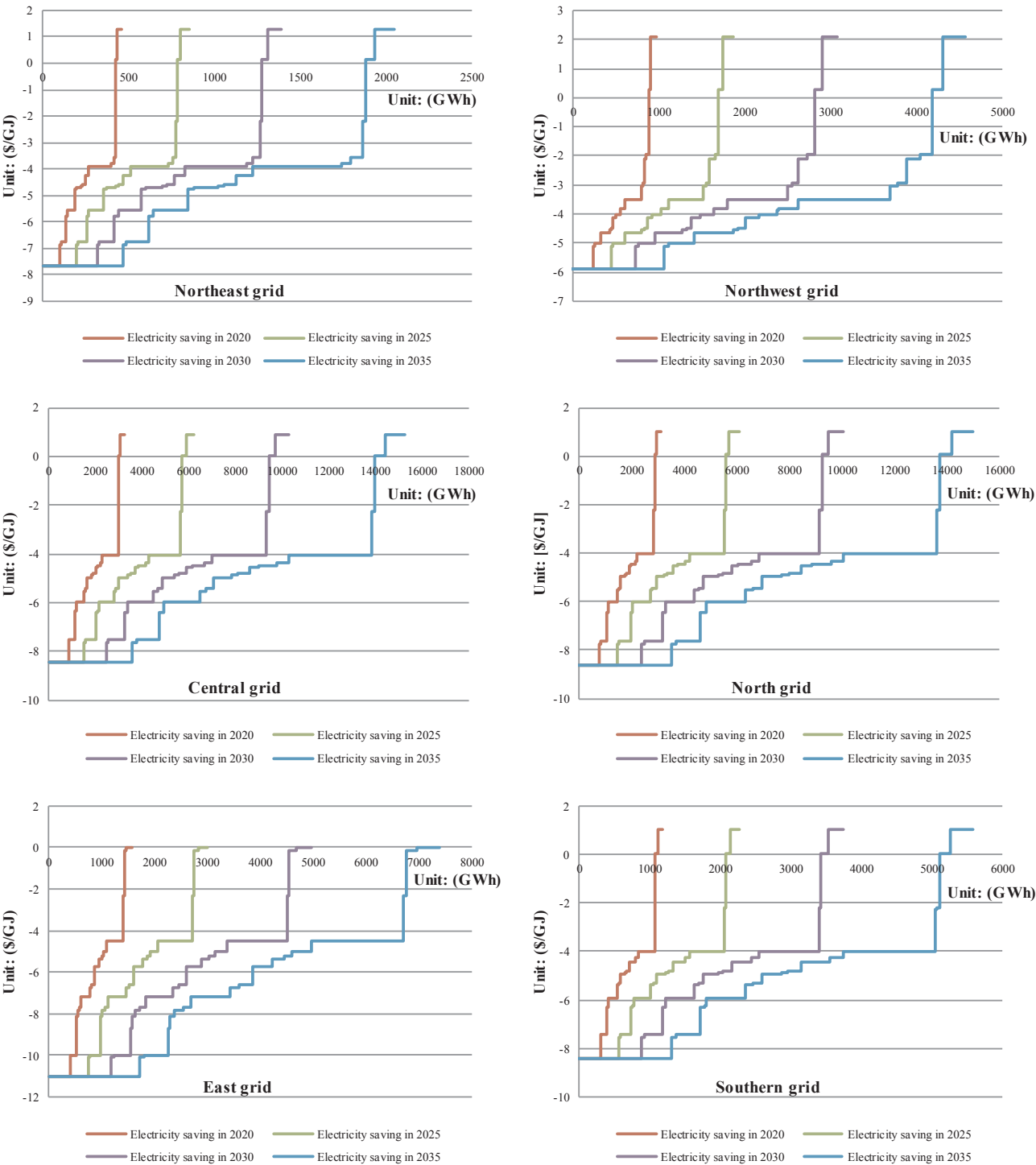


Fig. C1. ECSC per grid for ammonia industry between 2020 and 2035.

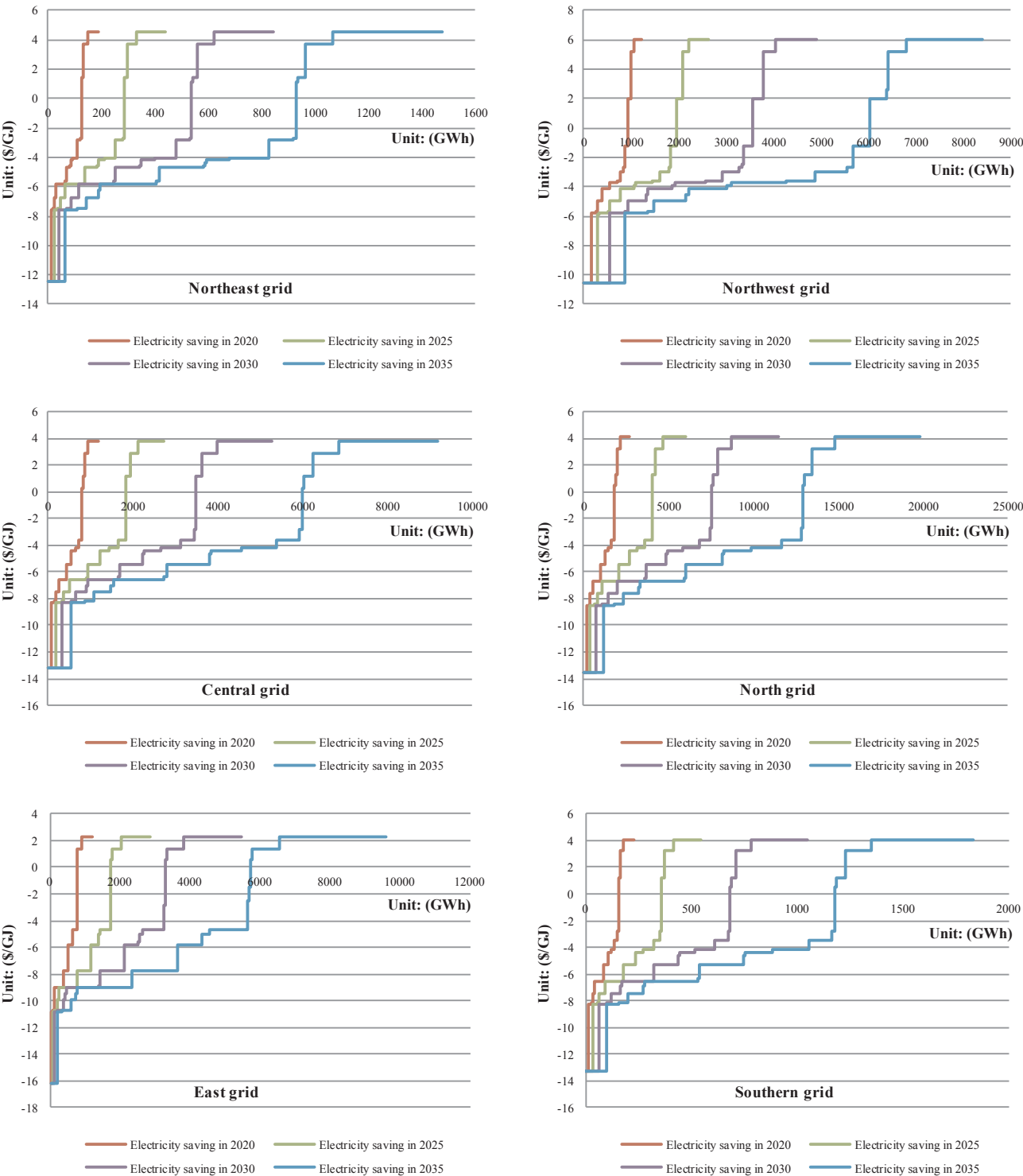


Fig. C2. ECSC per grid for chlor-alkali industry between 2020 and 2035.

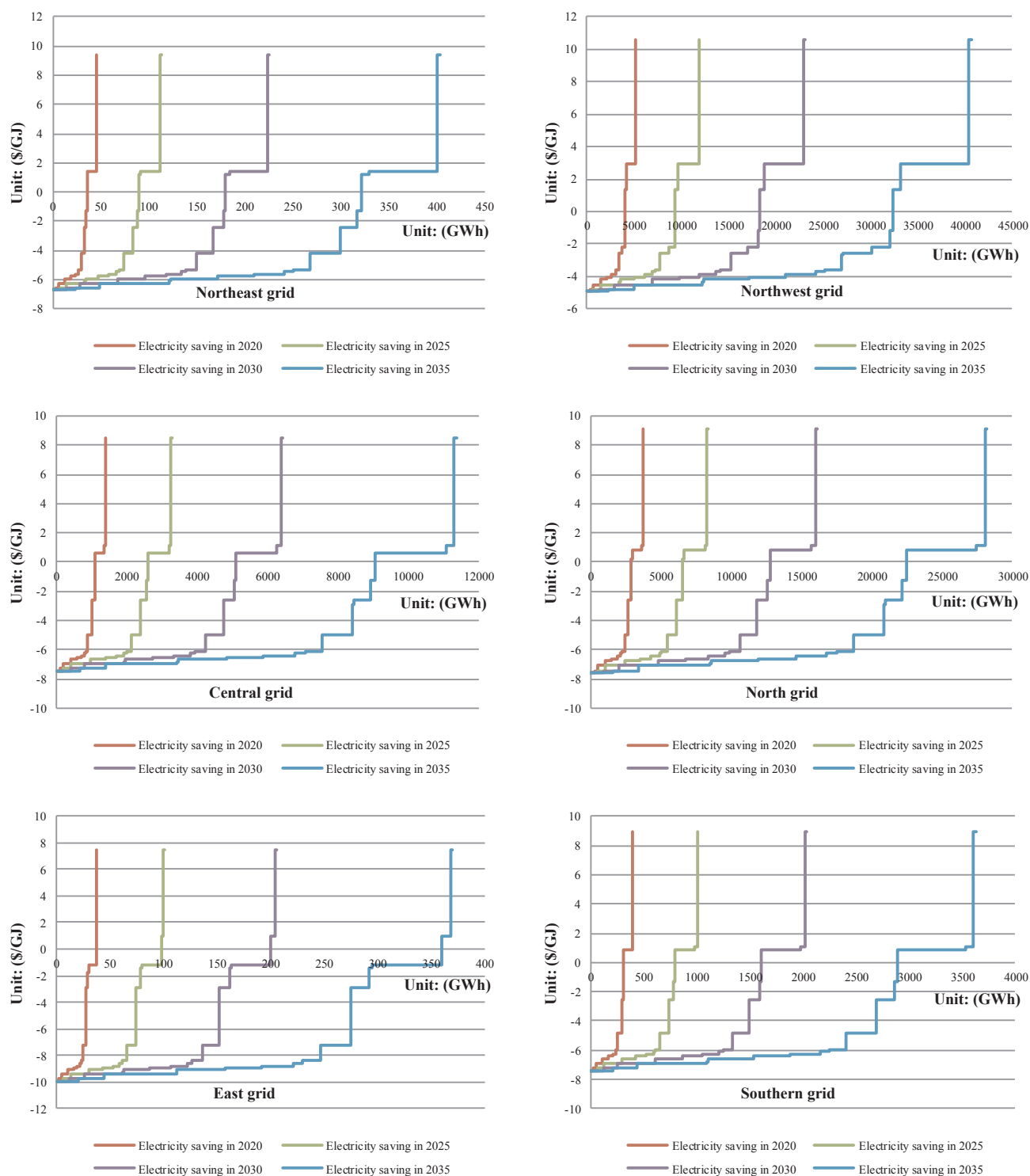


Fig. C3. ECSC per grid for calcium carbide industry between 2020 and 2035.

Appendix D. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.apenergy.2018.09.078>.

References

- [1] IEA. Energy technology perspectives 2017: catalysing energy technology transformation. Paris (France): International Energy Agency; 2017.
- [2] IEA. World energy outlook 2016. Paris (France): International Energy Agency; 2016.
- [3] IEA. World energy outlook special report 2016: energy and air pollution. Paris (France): International Energy Agency; 2016.
- [4] IPCC. Climate change 2014: Mitigation of climate change. Working Group III contribution to the fifth assessment report of the intergovernmental panel on climate change. Cambridge (UK): Cambridge University Press; 2014.

- [5] Audoly R, Vogt-Schilb A, Guivarch C, Pfeiffer A. Pathways toward zero-carbon electricity required for climate stabilization. *Appl Energy* 2018;225:884–901.
- [6] WHO. Health effects of particulate matter, Policy implications for countries in Eastern Europe, Caucasus and central Asia. Copenhagen (Denmark): World Health Organization Regional Office for Europe; 2013.
- [7] Summerbell DL, Khripko D, Barlow C, Hesselbach J. Cost and carbon reductions from industrial demand-side management: study of potential savings at a cement plant. *Appl Energy* 2017;197:100–13.
- [8] Peng W, Yang J, Lu X, Mauzerall DL. Potential co-benefits of electrification for air quality, health, and CO₂ mitigation in 2030 China. *Appl Energy* 2018;218:511–9.
- [9] Helin K, Käki A, Zakeri B, Lahdelma R, Syri S. Economic potential of industrial demand side management in pulp and paper industry. *Energy* 2017;141:1681–94.
- [10] State Council of China. Air pollution prevention and control action plan (English version). Beijing (China): Clean Air Alliance of China; 2013. <http://en.cleanairchina.org/product/6346.html>.
- [11] State Council of China. Work plan on controlling greenhouse gas emissions in 13th Five-Year Plan; 2016. http://www.gov.cn/zhengce/content/2016-11/04/content_5128619.htm.
- [12] Zhang Q, He K, Huo H. Policy: cleaning China's air. *Nature* 2012;484:161–2.
- [13] Cai W, Wang C, Jin Z, Chen J. Quantifying baseline emission factors of air pollutants in China's regional power grids. *Environ Sci Technol* 2013;47:3590–7.
- [14] National Bureau of Statistics of China. China energy statistical yearbook (2014–2016). Beijing (China): China Statistics Press; 2015–2017.
- [15] NBS, MEP. China statistical yearbook on environment (2006–2016). Beijing (China): China Statistics Press; 2006–2016.
- [16] Song R, Zhu J, Hou P, Wang H. Getting every ton of emissions right: an analysis of emission factors for purchased electricity in China. Wash DC (USA): World Resources Institute; 2013.
- [17] Zhu B, Zhou W, Hu S, Li Q, Griffy-Brown C, Jin Y. CO₂ emissions and reduction potential in China's chemical industry. *Energy* 2010;35:4663–70.
- [18] Van Ruijven BJ, Van Vuuren DP, Boskaij W, Neelis ML, Saygin D, Patel MK. Long-term model-based projections of energy use and CO₂ emissions from the global steel and cement industries. *Resour Conserv Recycl* 2016;112:15–36.
- [19] Liu X, Yuan Z, Xu Y, Jiang S. Greening cement in China: a cost-effective roadmap. *Appl Energy* 2017;189:233–44.
- [20] Zhang Q, Xu J, Wang Y, Hasanbeigi A, Zhang W, Lu H, et al. Comprehensive assessment of energy conservation and CO₂ emissions mitigation in China's iron and steel industry based on dynamic material flows. *Appl Energy* 2018;209:251–65.
- [21] Zuberi MJS, Patel MK. Bottom-up analysis of energy efficiency improvement and CO₂ emission reduction potentials in the Swiss cement industry. *J Clean Prod* 2017;142:4294–309.
- [22] Ma D, Chen W, Yin X, Wang L. Quantifying the co-benefits of decarbonisation in China's steel sector: an integrated assessment approach. *Appl Energy* 2016;162:1225–37.
- [23] Karali N, Park WY, McNeil M. Modeling technological change and its impact on energy savings in the US iron and steel sector. *Appl Energy* 2017;202:447–58.
- [24] Zhang S, Ren H, Zhou W, Yu Y, Chen C. Assessing air pollution abatement co-benefits of energy efficiency improvement in cement industry: A city level analysis. *J Clean Prod* 2018;185:761–71.
- [25] Zhang S, Worrell E, Crijns-Graus W, Krol M, de Bruine M, Geng G, et al. Modeling energy efficiency to improve air quality and health effects of China's cement industry. *Appl Energy* 2016;184:574–93.
- [26] Wang K, Wang S, Liu L, Yue H, Zhang R, Tang X. Environmental co-benefits of energy efficiency improvement in coal-fired power sector: a case study of Henan Province China. *Appl Energy* 2016;184:810–9.
- [27] Saygin D, Patel MK, Worrell E, Tam C, Gielen DJ. Potential of best practice technology to improve energy efficiency in the global chemical and petrochemical sector. *Energy* 2011;36:5779–90.
- [28] Lin B, Long H. Emissions reduction in China's chemical industry - Based on LMDI. *Renew Sustain Energy Rev* 2015;53:1348–55.
- [29] AQSIQ, SAC. Industrial classification for national economic activities (GB/T 4754-2017); 2017.
- [30] National Bureau of Statistics of China. China statistical yearbook (2014–2017). Beijing (China): China Statistics Press; 2014–2017.
- [31] National Bureau of Statistics of China. China industry (economy) statistical yearbook (2006–2017). Beijing (China): China Statistics Press; 2006–2017.
- [32] Zhou W, Zhu B, Li Q, Ma T, Hu S, Griffy-Brown C. CO₂ emissions and mitigation potential in China's ammonia industry. *Energy Policy* 2010;38:3701–9.
- [33] Hong J, Chen W, Wang Y, Xu C, Xu X. Life cycle assessment of caustic soda production: a case study in China. *J Clean Prod* 2014;66:113–20.
- [34] Li C, Zhu L, Fleiter T. Energy efficiency potentials in the chlor-alkali sector – a case study of Shandong province in China. *Energy Environ* 2014;25:661–86.
- [35] Liu X, Zhu B, Zhou W, Hu S, Chen D, Griffy-Brown C. CO₂ emissions in calcium carbide industry: an analysis of China's mitigation potential. *Int J Greenh Gas Control* 2011;5:1240–9.
- [36] China Petroleum and Chemical Industry Federation. China chemical industry yearbook (2001–2015). Beijing (China): China National Chemical Information Center; 2002–2016.
- [37] BP. Statistical review of world energy. London (UK): British Petroleum; 2017.
- [38] Cai B, Wang J, He J, Geng Y. Evaluating CO₂ emission performance in China's cement industry: an enterprise perspective. *Appl Energy* 2016;166:191–200.
- [39] Ministry of Environmental Protection of China. Annual statistic report on environment in China (2005–2015); 2009–2017.
- [40] MEP, AQSIQ. Emission standard of pollutants for petroleum chemistry industry (GB 31571-2015); 2015.
- [41] State Council of China. Comprehensive work plan for energy conservation and emission reduction in the 13th Five-Year Plan; 2017. http://www.gov.cn/zhengce/content/2017-01/05/content_5156789.htm.
- [42] China Electric Power Yearbook Editorial Committee. China electric power yearbook (2013–2016). Beijing (China): China Electric Power Press; 2013–2017.
- [43] Kong L, Hasanbeigi A, Price L, Liu H. Energy conservation and CO₂ mitigation potentials in the Chinese pulp and paper industry. *Resour Conserv Recycl* 2015;117:74–84.
- [44] Zhang Q, Zhao X, Lu H, Ni T, Li Y. Waste energy recovery and energy efficiency improvement in China's iron and steel industry. *Appl Energy* 2017;191:502–20.
- [45] Yang X, Teng F, Wang G. Quantifying co-benefit potentials in the Chinese cement sector during 12th Five Year Plan: an analysis based on marginal abatement cost with monetized environmental effect. *J Clean Prod* 2013;58:102–11.
- [46] Zhang S, Worrell E, Crijns-Graus W. Evaluating co-benefits of energy efficiency and air pollution abatement in China's cement industry. *Appl Energy* 2015;147:192–213.
- [47] Wen Z, Xu C, Zhang X. Integrated control of emission reductions, energy-saving, and cost-benefit using a multi-objective optimization technique in the pulp and paper Industry. *Environ Sci Technol* 2015;49:3636–43.
- [48] Organization for Economic Co-operation and Development. OECD statistics; n.d. <http://stats.oecd.org>.
- [49] Worrell E, Price L, Martin N. Energy efficiency and carbon dioxide emissions reduction opportunities in the US iron and steel sector. *Energy* 2001;26:513–36.
- [50] State Grid Corporation of China. Electricity pricing policy per province; 2014.
- [51] Ma X, Wang Y, Wang C. Low-carbon development of China's thermal power industry based on an international comparison: review, analysis and forecast. *Renew Sustain Energy Rev* 2017;80:942–70.
- [52] Zhao Y, Wang S, Duan L, Lei Y, Cao P, Hao J. Primary air pollutant emissions of coal-fired power plants in China: current status and future prediction. *Atmos Environ* 2008;42:8442–52.
- [53] Graus W, Worrell E. Methods for calculating CO₂ intensity of power generation and consumption: a global perspective. *Energy Policy* 2011;39:613–27.
- [54] Ma C, Ge Q. Method for calculating CO₂ emissions from the power sector at the provincial level in China. *Adv Clim Change Res* 2014;5:92–9.
- [55] Harmens R, Graus W. How much CO₂ emissions do we reduce by saving electricity? A focus on methods. *Energy Policy* 2013;60:803–12.
- [56] National Development and Reform Commission of China. Baseline emission factors in China's regional grids (2006–2015); 2006–2017.
- [57] Zhao Y, Wang S, Nielsen CP, Li X, Hao J. Establishment of a database of emission factors for atmospheric pollutants from Chinese coal-fired power plants. *Atmos Environ* 2010;44:1515–23.
- [58] IPCC. IPCC guidelines for national greenhouse gas inventories. Intergovernmental Panel on Climate Change; 2006.
- [59] Chinese Research Academy of Environmental Sciences. First China pollution source census: manual of industrial pollutants production and discharge coefficients; 2010 [Chapter 10].
- [60] Zhang C. Studies on present and future emissions of PM, SO₂, NO_x. MS thesis. Beijing: Tsinghua University; 2008. 147 pp.
- [61] Zhang C, Chen J, Wen Z. Assessment of policy alternatives and key technologies for energy conservation and water pollution reduction in China's synthetic ammonia industry. *J Clean Prod* 2012;25:96–105.
- [62] Kermeli K, Corsten M, Worrell E, Crijns-Graus W. Ammonia production: Energy efficiency technology, practices, organizations and programs. Utrecht (the Netherlands): Institute for Industrial Productivity and Utrecht University; 2013.
- [63] Ma D, Hasanbeigi A, Chen W. Energy-efficiency and air-pollutant emissions-reduction opportunities for the ammonia industry in China. Lawrence Berkeley National Laboratory; 2015.
- [64] Wen Q. Development analysis of China's ammonia industry. *Chem Ind* 2012;30:16–9.
- [65] Zhou N, Fridley D, Khanna NZ, Ke J, McNeil M, Levine M. China's energy and emissions outlook to 2050: perspectives from bottom-up energy end-use model. *Energy Policy* 2013;53:51–62.
- [66] Ren Y. Study on the potential of carbon reduction in China's synthetic ammonia industry. MS thesis. Beijing: Beijing University of Chemical Technology; 2015. 67 pp.
- [67] Zhang W, Dou Z, He P, Ju X, Powlson D, Chadwick D, et al. New technologies reduce greenhouse gas emissions from nitrogenous fertilizer in China. *Proc Natl Acad Sci* 2013;110:8375–80.
- [68] Ministry of Agriculture of China. Zero growth programme in fertilizer use by 2020; 2015. http://jiuban.moa.gov.cn/zwllm/tzgg/tz/201503/t20150318_4444765.htm.
- [69] Zhu B, Chen X, Zhang W, Hu S, Jin Y. Potential assessment of cleaner production in China's ammonia industry. *J Tsinghua Univ Sci Technol* 2015;54:309–13.
- [70] Zhang Y. Present situation analysis and prospect forecast of chlor-alkali industry of China. *China Chlor-Alkali* 2017;8:1–6.
- [71] Zhang P. Analysis of economic operation in 2017 of China chlor-alkali industry. *China Chlor-Alkali* 2018;2:1–3.
- [72] China Chlor-Alkali Online. 13th Five-Year Plan of China's chlor-alkali industry; 2016.
- [73] Ministry of Industry and Information Technology of China. The development plan of petrochemical and chemical industry 2016–2020; 2016.
- [74] Kearney AT, CPCIF. Global opportunities for the Chinese chemical industry; 2017.
- [75] Ascensão F, Fahrig L, Clevenger AP, Corlett RT, Jaeger JAG, Laurance WF, et al. Environmental challenges for the belt and road initiative. *Nat Sustain* 2018;1:206–9.
- [76] Li L. China's manufacturing locus in 2025: with a comparison of “Made-in-China 2025” and “Industry 4.0”. *Technol Forecast Soc Change* 2017.
- [77] China Chlor-Alkali Online. Research report on China's calcium carbide industry;

- 2016.
- [78] China Carbide Industry Association. 12th Five-Year Plan of China's calcium carbide industry; 2013.
- [79] Shi Y, Xia Y, Lu B, Liu N, Zhang L, Li S, et al. Emission inventory and trends of NO_x for China, 2000–2020. *J Zhejiang Univ Sci A* 2014;15:454–64.
- [80] National Development and Reform Commission of China. National key energy conservation and low carbon technologies promotion catalogue; n.d.
- [81] Ministry of Industry and Information Technology of China. Advanced technologies guideline for energy conservation and emission reduction in China's petroleum and chemical industry.
- [82] Ministry of Industry and Information Technology of China. Implementation plan of cleaner production technologies in 17 key sectors.
- [83] Ministry of Industry and Information Technology of China. Guidance catalogue of electronic information application technologies of energy conservation and emission reduction in industry.
- [84] Dai Y, Xiong H, Jiao J. Roadmap study on achieving technical energy conservation potential in China's industrial sector by 2020. Beijing (China): China Science and Technology Press; 2013.
- [85] Dai Y, Hu X. Potential and cost study on China's carbon mitigation technologies. Beijing (China): China Environmental Press; 2013.
- [86] China Chemical Energy Efficiency Technology Association. Handbook of energy saving technology in chemical industry. Beijing (China): Chemical Industry Press; 2006.
- [87] China Chemical Energy Efficiency Technology Association. 100 energy conservation technologies for China's petroleum and chemical industry.
- [88] China Electricity Council. Power industry statistical compilation 2014; 2015.
- [89] Hasanbeigi A, Morrow W, Masanet E, Sathaye J, Xu T. Energy efficiency improvement and CO₂ emission reduction opportunities in the cement industry in China. *Energy Policy* 2013;57:287–97.
- [90] State Council of China. Development strategy of circular economy and recent action plan; 2013. http://www.gov.cn/zhengce/content/2013-02/06/content_1631.htm.
- [91] National Development and Reform Commission of China. Guideline for provincial greenhouse gas inventories; 2011.
- [92] National Development and Reform Commission of China. Implementation plan of energy efficiency report of key energy-consuming enterprises; 2008.
- [93] National Government Offices Administration. Public institutional energy resource consumption statistics system; 2011.
- [94] Ministry of Environmental Protection of China. List of desulfurization facilities for China's coal-fired power units (2008–2013); 2009–2014.
- [95] Ministry of Environmental Protection of China. List of denitrification facilities for China's coal-fired power units (2010–2013); 2011–2014.
- [96] Ministry of Environmental Protection of China. Technical specifications of desulfurization and denitrification project for thermal power plant; n.d. <http://kjs.mep.gov.cn/hjbhzb/bzwb/other/hjbhgc/index.shtml>.
- [97] National Development and Reform Commission of China. Measures for operation and management of desulfurization price and facilities of China's coal-fired units; 2007.
- [98] IEA. Technology roadmap: Energy and GHG reductions in the chemical industry via catalytic processes. Paris (France): International Energy Agency; 2013.
- [99] Chun C. China energy primer. Lawrence Berkeley National Laboratory; 2009.