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Impacts of regional industrial electricity savings on the development of future coal capacity per electricity grid and related air pollution emissions – A case study for China

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ABSTRACT

Moving to a sustainable industry and weaning electricity supply off coal are critical to mitigate ambient air pollution and climate change. This is particularly true in China which is globally the largest manufacturer and relies heavily on coal-fired electricity. Research that explores the linkages between industrial electricity use and the electricity supply sector to curb air pollution is limited. In this study, an integrated modeling framework is developed that quantifies the impact of industrial electricity savings on the evolution of the coal power plant fleet in China, and on air pollutants for the different power grids in the period 2016–2040. The framework includes a rich set of efficiency technologies and detailed unit-level information (geo-coordinates, thermal efficiency, environmental performance). We find that the reduced electricity load due to the industrial efficiency improvements can effectively scale down the coal power fleet, and most importantly allows closing the most polluting units. The potentials for electricity savings vary amongst the industrial sectors and provinces, resulting in significant heterogeneity of coal plant phaseout per power grid. Because energy-intensive industrial plants are mostly found in the North, Central and Northwest grids, these three grids provide 66% of the total displaced coal capacity. The closing of coal units leads to a variation in annual emission reductions per power grid of 13–85 kt-SO_2, 19–129 kt-NO_x, 3–17 kt-PM and 21–167 Mt-CO_2, compared to business-as-usual emissions. The iron & steel, aluminium and chemical sectors, together contribute to 84% of the total electricity savings by 2040, and are thereby most important to target.

1. Introduction

Industry is responsible for 42% of global electricity consumption and even more than 60% of electricity consumption in China in 2018 [1], making it undoubtedly the globally largest electricity consumer. With an annual growth rate of 9%, electricity is the strongest driving force of China's growing industrial energy consumption from 2000 to 2018, contributing to 38% of growth in industrial end-use energy [1,2]. The share of electricity consumption in industrial final energy use has increased by 13 percentage points, from 19% in 2000 to 32% in 2018. Industrial electricity use is expected to further grow due to electrification [3] and the unabated use of inefficient industrial equipment [4]. Hence, electricity will gradually displace fossil-fuels as the dominant energy source of industry [5]. This displacement can substantially reduce direct industrial air emissions (i.e. air pollutants and greenhouse gases (GHGs)) but lead to increased indirect emissions from electricity generation processes [6,7]. These concerns are particularly prominent in China, where electricity generation is heavily dependent on a coal-intensive power generation fleet (corresponding to 70% of total generation). This dependence on coal is more serious than that in the European Union (20% from coal-fired plants) or the United States (30% from coal-fired plants) [1].

Coal-fired power plants have been massively deployed in China (more than 3,000 coal generation units in service in 2016), and are responsible for ~ 19%, ~21% and ~ 11% of China's total SO_2, NO_x and PM emissions, respectively [2,8], seriously impacting local air quality. At the same time, the deterioration of air quality has caused people to reflect on public health [9,10]. Gao et al. [11] estimated that annually 520 thousand premature deaths in China are attributed to ambient air pollutants emitted from power generation. According to the World

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Electric Power Plants (WEPP) Database [12], China still has around 200 GW new coal-fired power plants in the pipeline, which is more than the existing coal capacity in the European Union (170 GW). Although many countries plan to phase out coal-fired power plants [13–15] to help reduce emissions, China's growing appetite for new coal-fired power stations has outstripped plant closures (32 GW retirements) in the rest of the world in 2016 [12,16]. This is particularly important because of the growing electricity demand driven by booming industrialization [17,18]. Transitioning to a sustainable industry and shifting away from coal for electricity generation is urgent for the world and China. Promoting efficient electricity use by end-users to reduce the deployment of coal power plants should play a significant role to reduce multiple air emissions from coal generation fleet in a cost-effective way [4,19,20].

Here, we comprehensively evaluate the impacts of industrial electricity savings via energy efficiency improvements on the deployment of coal-fired power plants by 2040 targeting to reduce air pollutant emissions in China. We do so at a regional grid level to correctly evaluate the impacts on air pollutant emissions. Air pollutants can also be removed by flue gas control devices. However, traditional pollution control systems reduce power generation efficiency [21,22] and increase CO_2 emissions due to the consumed additional energy and resources (e.g. sorbents and catalyst) [23,24]. Economically, these technologies are usually expensive, with high capital costs plus considerable operation and maintenance costs. To identify the most economical way, a cost-performance analysis is carried out in this study to compare the investment and air quality benefits of electricity savings compared to end-of-pipe controls. Characterizing the complex relationship between the largest energy consumer (industry) and the largest energy infrastructure (power sector) is critical to cost-effectively pursue the four United Nations Sustainable Development Goals (SDGs): SDG 3 (good health), SDG 7 (energy access), SDG 9 (sustainable industry), and SDG 13 (climate action).

Various researchers have emphasized the pivotal role of energy efficiency improvements to offset additional energy supply [25] and capturing air emission reduction benefits across different locations [19,26–30]. Reyna et al. [29] projected the residential electricity use in Los Angeles County, U.S. during 2020–2060 under different scenarios, and found that energy efficiency can largely reduce net energy use, slowing the increase in electricity use by 13–59%. Zhou et al. [27] estimated the co-benefits of CO_2 emission reductions by 2050 in China's buildings sector, and suggested that efficiency technologies can effectively limit the growth of energy use and peak CO_2 emissions by 2030. Zhang et al. [30] evaluated the impacts of energy savings on air pollutant emissions in China's cement industry, and revealed that many efficiency measures are cost-effective clean air strategies, and as such, are often preferable to alternatives. A large body of this research focuses on a specific energy user and pay attention to single benefits (e.g. carbon or air pollutant emission reductions) at a national or a local level. Few authors explore the regional heterogeneity of potential multiple benefits attributable to energy efficiency in economic activities across a country [24,26,31]. Yue et al. [26] analyzed the multiple benefits of 60 energy efficiency technologies to reduce GHGs and air pollutant emissions in China's key chemical sectors across six power grids, up to 2035. Abel et al. [24] assumed 15% of annual energy efficiency improvements by states in the U.S. aiming to capture the health benefits of air pollutant abatement due to the reduced energy demands on a regional level.

However, none have quantified the role of electricity savings of industrial consumers in the evolution of electricity supply systems, particularly in regards to displacing coal generation capacity and associated changes of multiple air emissions. Although demand-side management (DSM) has stressed this impact [4,32], these high-value benefits still receive less attention. This study is the first to build an integrated modeling framework considering regional characteristics to quantify displaced coal-fired power units (prioritizing high-polluting and less-efficient units) by load reduction, and assess the contributions to air emission reductions (SO_2, NO_x, PM and CO_2) for six electricity grids (covering 31 provinces) across China. Our multi-sectoral and multi-regional perspective allows national and provincial decision-makers to prioritize efforts across sectors and regions on building an efficient industry and decreasing dependence on coal power, given the regional differences in electricity demand and installation of coal power plants, as well as the level of local air pollution.

This research addresses the knowledge gap of what is the potential impact of efficient electricity use in the industrial demand-side on the evolution of the coal-based electricity supply system and associated air quality benefits, for different power grids. Three key subgoals, i.e. electricity savings by industries, displaced coal-fired power capacity, and air emission reductions from electricity generation, are established and measured in this study to meet the main purpose. Besides, cost portfolios of air pollutant abatement measures between industrial efficiency improvements and retrofitting coal power plants with flue gas controls are compared to determine the highest cost performance strategy. By assessing the interconnections of the industry and the electricity supply system, this study provides a comprehensive understanding of the pivotal role of industrial energy efficiency improvements, which is critical not only for China but for the world to achieve a more sustainable industry and move towards a coal-free electricity supply system in an economically feasible way. The structure of this paper is presented as follows. Section 2 provides information on the storylines of scenario design, an integrated modeling framework and data sources (e.g. unit-level information of power plants, characteristics of energy efficiency technologies and parameters of end-of-pipe control measures). The key research output in terms of electricity savings by industries, displaced coal power capacity, air pollutant emission levels and cost comparison of abatement portfolios in different scenarios for the six power girds, are presented in Section 3, while the important factors that affect the results are discussed in Section 4. Section 5 concludes the research and draws policy implications.

2. Methods and materials

In this section, we develop an integrated analysis structure to model the impacts of reduced industrial electricity use on future power plant capacity developments, on a regional level in China. The resulting air pollutant emission abatement is compared to the alternative of installing flue gas control technologies in terms of costs for each region to achieve the same impact. The GAINS (Greenhouse Gas - Air Pollution Interactions and Synergies) model is used, in combination with two comprehensive databases, that are developed in this study. The first database consists of energy efficiency technologies in industry including energy savings potential and costs. The second database contains details about the current and future power generation fleet, on a power plant unit basis This database enables us to conduct a unit-by-unit assessment to identify which power plant units could be avoided because of electricity savings across the six electricity grids. The geographic location of coal-fired power units, emission levels, and potential electricity savings are mapped at a provincial and grid level using a geographic information system—ArcGIS. An overview of the research design for this study is briefly summarized below.

Section 2.1 describes the four scenarios that are modeled. Section 2.2 provides the method to quantify the electricity saving potential per energy efficiency technologies implemented in the industry. The GAINS model is introduced in Section 2.3, which is used to model the cost of per ton air pollutants removed by end-of-pipe controls. Section 2.4 proposes the methods to measure the emission inventory (SO_2, NO_x, PM and CO_2) from the coal power fleet at unit level. Data sources are described in Section 2.5.

2.1. Scenario design

Four scenarios are designed to examine the impacts of industrial electricity savings on the power plant fleet and air emission changes.

Our business-as-usual scenario (BAU) is constructed as a reference case based on the Current Policies (CPol) Scenario in the World Energy Outlook 2018 [2] developed by the International Energy Agency (IEA). The BAU scenario respects the effects of currently implemented policies on electricity demand, power generation, and installed capacity over the period of 2016–2040, providing a baseline to compare with alternative scenarios. In this scenario, incremental growth of the electricity demand would lead to an expansion of the fossil-fuel power fleet, particularly of coal power stations in China by 2040 [2].

The efficient electricity use management (EUM) scenario describes the transition to an efficient and sustainable industry (which represents the efficient use of electricity in industrial processes) by implementing high-efficiency technologies. This scenario measures the electricity savings and associated benefits by implementing hundreds of specific technologies in five energy-intensive industries (iron & steel, cement, chemicals, aluminium and pulp & paper). These five industries are the largest electricity consumers, and together account for about 50% of total electricity consumption [33] in China's industry, and are also emphasized by the IEA [18] and Chinese National Five-Year Plan [34]. This scenario examines the role of industrial electricity savings on the (earlier) retirement of the existing power plant fleet and curbing new proposed power projects, as well as the avoided air pollutants from the displaced power plants.

The air pollution control (APC) scenario aims to explore the cost portfolios of retrofitting coal-fired power plants with end-of-pipe treatment measures to cut emissions to the same level as those avoided in the EUM scenario. The APC scenario is designed with the GAINS model and has the same energy related parameters (e.g. installed capacity and electricity generation) as the BAU scenario. The deployment of end-of-pipe treatment devices at provincial level in the APC scenario is based on the ECLIPSE V5a database [35] developed by the International Institute for Applied Systems Analysis (IIASA). This scenario provides an alternative for air pollutant reductions to identify the most cost-effective scenario by comparing the costs of end-of-pipe to electricity savings.

Finally, the joint electricity savings and air pollution controls scenario (EUM + APC) includes both promoting energy efficiency technologies in industry and installing additional end-of-pipe controls in coal-fired power plants, to understand the combined impacts and costs on air pollutant reductions. This scenario uses the investments in end-of-pipe measures in the APC scenario as a starting point, while incorporating the same assumptions for electricity savings in China's industries as in the EUM scenario (so the costs of the joint scenario are the sum of the costs spending of the APC and the EUM scenarios).

2.2. Electricity conservation supply curve modeling

Here, we construct electricity conservation supply curves (CSCs) at a regional level to quantify the electricity savings per province from both cost performance and technical perspectives, in the five energy-intensive industries. The concept of CSC, which is introduced by Lawrence Berkeley National Laboratory [36] to identify the cost-effective portfolios for meeting energy service demands [37], is used to develop the electricity CSCs per province in this study. CSC is widely used as a quantitative analysis tool by energy researchers to model the potentials and costs of conserved energy in various demand-side energy systems (e.g. a group of plants and an independent economic activity). Zhang et al. [38] modeled the performance of 35 available energy efficiency technologies applied to China's iron & steel sector by CSC, and identified that 61% of energy savings can be achieved by 19 cost-effective technologies by 2050. Li et al. [39] introduced carbon price in the CSC to evaluate the CO_2 mitigation costs of 20 high-efficiency technologies in China's cement sector by 2050, and shown that improving energy efficiency is a cost-effective and powerful measure to decarbonize the cement industry. Prior CSCs typically focus on one sector (concentrating on iron & steel [38,40–42] and cement [30,39,43]). However, rarely studies developed a regional CSC to explore the co-benefits of efficiency improvements, in particular electricity savings, for multi-sectors on a power grid level [26].

Based on the previous studies of co-authors [26,31], the energy CSCs are modified and presented as equation (1) to assess the electricity saving potentials and associated costs per available technology implemented in the studied industries. This formula reflects the electricity conservation potential as a function of the marginal cost of conserved final energy. The parameters related to fossil fuels are also considered in equation (1). This is because some efficiency technologies do not only save electricity but also save fossil fuels, which should not be ignored when calculating the energy benefits. The electricity and fossil-fuel prices at provincial level (see Appendix) are introduced into the equation to represent the regional cost function heterogeneity.

$$CCE_{i,k,p} = \frac{\frac{d}{\left(1-(1+d)^{-l_{i,k,p}}\right)} \times CC_{i,k,p} + \Delta O\&M_{i,k,p} - ES_{i,k,p} \times EP_p - FS_{i,k,p} \times FP_p}{TES_{i,k,p}} \tag{1}$$

where i, k and p represent the technology type, industrial subsector and province, respectively; CCE is the cost of conserved energy in \$/GJ; d is the discount rate in %, i.e. 7%; l is the lifetime in years; CC is the capital cost per technology in \$; $\Delta O\&M$ is the change in annual operation and maintenance cost in \$; ES is the annual electricity saving in kWh; EP is the electricity price in \$/kWh; FS is annual fuel savings (if possible) per technology in GJ; FP is the fuel price in \$/GJ; and TES is the annual total energy saving including all energy saving types in GJ.

2.3. GAINS model

The GAINS model is an integrated assessment tool, developed by IIASA, with detailed information regarding macroeconomic drivers, energy activity, cost parameters per installed emission control measure and emission control strategies by primary air pollutants (e.g. SO_2, NO_x, PM, NH_3 and VOCs) on various scales (e.g. global, national and subregional levels) [44,45]. The GAINS model allows user to customize emission reduction scenarios using exogenous parameters [31,46,47] (e.g. energy use by fuel type, electricity supply and future assumptions) to examine the cost portfolios of control measures to tackle local air quality and mitigating climate change. Due to the rich information and flexibility, the GAINS model has been widely used to evaluate emission levels [48,49], emission reduction potentials [50,51], and control system costs [47,52] for air pollutants and GHGs. Moreover, the IEA adopted the GAINS model to project air pollutant emission levels across countries [2], and provides policy recommendations. Based on the ECLIPSE V5a database, we here use the GAINS-China module [53] (a regional part of the GAINS model) to measure the unit costs per ton air pollutant removed by end-of-pipe measures from China's coal power plants, at provincial level.

The calculation process of the unit cost per ton air pollutant removed UC in the GAINS model is presented by equation (2) [47]. The detailed description of the way GAINS models emission reduction and control costs can be found in the studies [54–56].

$$UC_{m,t,p,j} = \left(\frac{AF_{m,t,p} \times CC_{m,t,p} + OM^{fix}_{m,t,p}}{FC_{t,p}} + OM^{var}_{m,t,p}\right) \Big/ \left(ef_{t,p,j} \times \eta_{m,t,p,j} \times \gamma_{m,t,p,j}\right) \tag{2}$$

where m, t and j represent the emission control technology, fuel type and air pollutant (e.g. SO_2, NO_x and PM), respectively; AF is the annuity factor; CC is the capital cost in \$; OM^{fix} is the annual fixed expenditures of maintenance and operation in \$; OM^{var} is the variable operating costs in \$/PJ; FC is the annual fuel consumption in PJ; ef is the unabated emission factor for an air pollutant in ton/PJ; η is the removal efficiency of a control technology for an air pollutant in %; and γ is the capacities controlled factor in %.

Table 1
Energy and emission characteristics of China's coal-fired power units.

Technology	Unit size (MW)	Thermal efficiency (%)	Emission factors with controls (g/kWh)			Emission factors w/o controls (g/kWh)		
			SO_2	NOx	PM	SO_2	NOx	PM
Subcritical	< 100	35	0.67	0.64	0.16	13.34	2.56	56.79
	100–299	37	0.36	0.32	0.10	9.29	1.61	27.05
	300–599	39	0.26	0.25	0.05	8.52	1.56	26.02
	≥ 600	41	0.22	0.19	0.03	7.63	1.32	13.25
Supercritical	< 300	36	0.30	0.23	0.04	N/A	N/A	N/A
	300–599	40	0.18	0.19	0.04	5.04	1.18	30.56
	≥ 600	42	0.15	0.17	0.03	5.75	1.06	14.91
USC	≥ 600	45	0.08	0.12	0.02	3.58	0.68	9.74
IGCC		46	0.05	0.07	0.02	N/A	N/A	N/A

N/A, not applicable.

2.4. Emissions from coal generation fleet

In the scenarios we assume that industrial electricity savings are used to offset coal-fired power plants. The coal plant power fleet in 2040 consists of currently operating coal power units (in service of 2016) and new coal power plants (constructed in the period 2017–2040). Based on unit-level information, we use equation (3) to estimate air emission levels from coal-fired power plants at power grid level in the future.

$$E_{coal,a,g,y} = \sum_{p\in g}\left(\sum_{e\in p}^{exi}(EF_{e,a,y}\times S_{e,y}\times\beta\times CF_{p,y}) + \sum_{n\in p}^{new}(EF_{m,a,y}\times S_{m,y}\times\beta \times CF_{p,y})\right) \tag{3}$$

where *coal*, *a*, *g*, *e*, *n* and *y* indicate the coal generation fleet, air emission species, power grid, existing unit, newly installed unit and year, respectively; *E* is the air emission level in kg; *EF* is the emission factor for a unit in kg/MWh; *S* is the installed capacity size in MW; β is the full-load period per year, i.e. 8760 h; and *CF* is the capacity factor in %.

The emission factors of air pollutants (i.e. SO_2, NO_x and PM) for a generation unit are estimated using the following equation [8,57].

$$EF_{j,y} = \frac{\theta_{j,y}\times\nu_y\times A_y}{EG_y} \tag{4}$$

where θ represents the abated emission concentration from power station stacks in g/Nm^3; ν is the theoretical flue gas rate in Nm^3/ton-coal; *A* is the amount of coal consumption in ton; and *EG* is the electricity generation by a unit in kWh.

The CO_2 emission factors at unit-level are estimated based on coal generation efficiency and carbon content as follows.

$$EF_{CO_2,y} = \frac{\omega\times COF\times LHV}{\lambda_y}\times\frac{M_{CO_2}}{M_c} \tag{5}$$

where ω is the carbon content of coal in g/MJ; *COF* is the carbon oxidation factor of coal in %; *LHV* is the lower calorific value for electricity in MJ/kWh; λ is the unit generation efficiency in %; M_{CO_2} is the molar mass of CO_2, i.e. 44 g/mol; and M_c is the molar mass of carbon, i.e. 12 g/mol.

2.5. Data sources

2.5.1. Power plant fleet

Our data are based on unit-level assessments of existing and new coal power plants in China. Operational coal-fired power units in 2016 are taken from the Platts World Electric Power Plants (WEPP) database (September 2017 release) [12] (in total 3102 operational units). The information per unit includes capacity, commissioning year, fuel type, location and generation technology (i.e. subcritical, supercritical, USC and IGCC). Around 14 GW or 167 coal power units lack commissioning year in the database. Through cross-checking various global power plant databases [16,58,59], power company websites and environmental impact assessment report from reliable sources, the commissioning year information of 153 coal power units is found. For the remaining 14 units (a total installed capacity of 1.5 GW), we fill the data gap by adopting the mean commissioning year of the units who (1) are located in the same province, (2) use the same feedstock, (3) generate electricity by the same technology, and (4) have a similar capacity size (within three standard deviations) [60]. A retirement pathway is designed for the installed power plants by assuming a lifetime of 40 years. This lifetime of coal power plant is an average value, which is calculated from globally retired units before 2016 (in total 2968 retired units). The average lifetime matches with values found in literature sources [61,62].

Although the WEPP database includes the administrative-level information, the exact latitudes and longitudes per unit are missing. Thus, we collect the geocoordinates for each power plant unit, of which 85% of the units' coordinates (accounting for 97% of existing installed capacity) is obtained from the Global Energy Monitor [16], the Global Power Plant Database [58], the Global Energy Observatory [63], the Worldwide Industrial Information [59] and Enipedia Database [64]. The remaining 15% of units are generally small, with an average capacity of 70 MW. The geographical information of these small coal units is captured using the Google Maps on the basis of physical address information recorded in the WEPP (e.g. company, street, county and city). Google Earth is also used to accurately determine the coordinates of individual power plants through identifying power plant characteristics (e.g. on-site fuel storage, power houses and flue stacks) from the captured high-resolution satellite imagery.

The WEPP database does not provide unit operation and emission parameters, such as pollutant stack concentration, removal efficiency of end-of-pipe measures and thermal efficiency. We cross-checked unit-based parameters with CEC-China Electricity Council (unit greater than 100 MW), Tang et al. [8] (unit < 100 MW) and China Renewable Energy Outlook (unit < 100 MW), and collected the information of around 2,500 units in WEPP, equivalent to 65% of the operational coal capacity in 2016. From the collected emission factors and thermal efficiencies, general values are derived for technology categories (see Table 1). The results are cross-checked with data on coal-fired power plants in the Energy Technology Systems Analysis Program (IEA-ETSAP). The unit-based emission factors and thermal efficiencies are applied to fill the missing data for the remaining 35% of the capacity.

2.5.2. Energy efficiency technologies

A total of 175 commercially available electricity-saving measures is included in this study to pursue a sustainable industry in China. Specifically, 31 technologies for the iron & steel sector, 32 technologies for cement, 61 technologies for the chemical sector, 31 technologies for the aluminium sector and 20 technologies for the pulp & paper sector are compiled in the technology database (see Supplementary Information). The technologies are applied to different production processes per sector (e.g. alumina refining, aluminium smelting, anode making and general

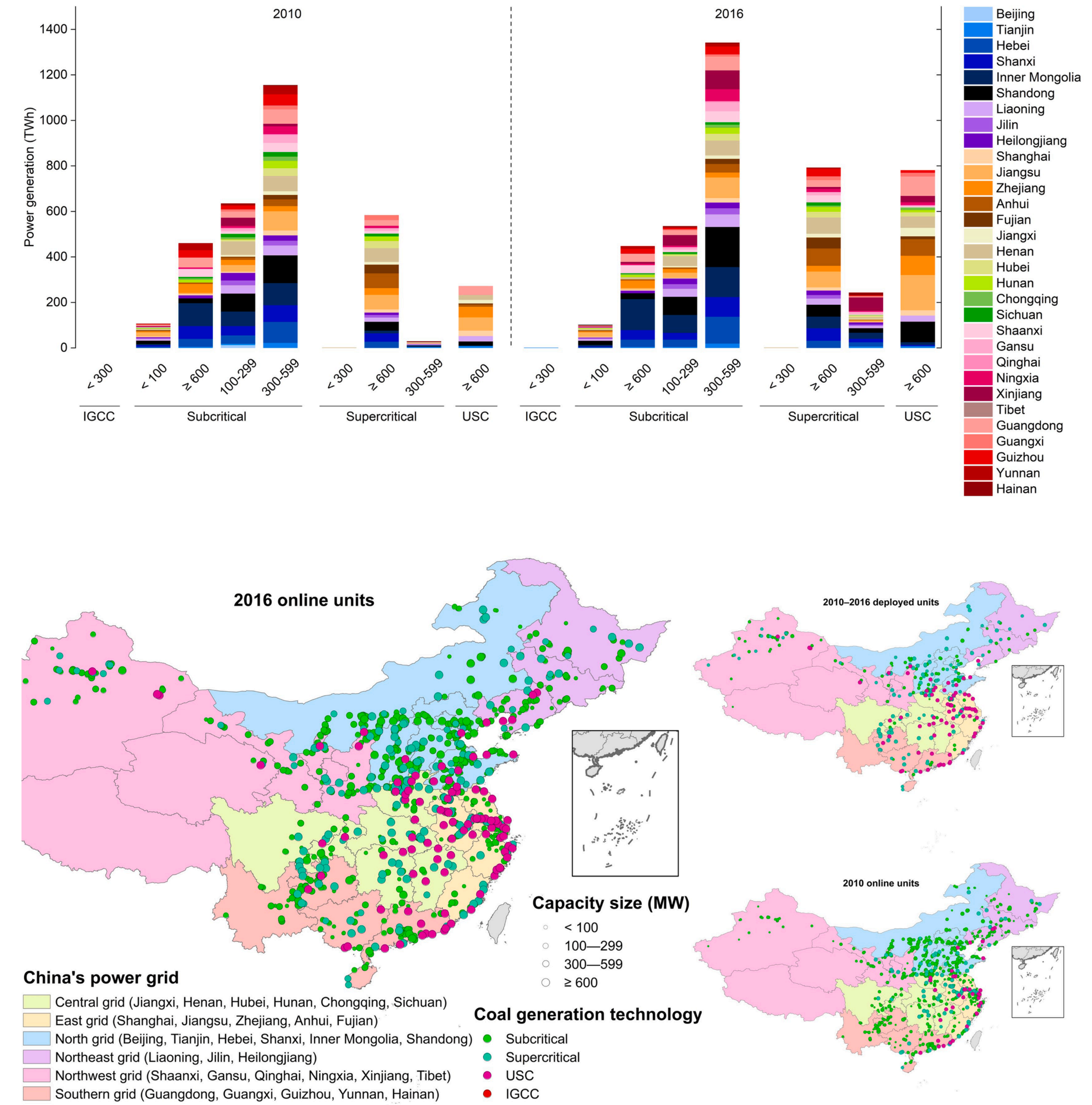

Fig. 1. (Top) Electricity generation from coal power fleet by technology and capacity size at provincial level in 2010 and 2016. (Bottom) the distribution of coal power units in China's six power grids during 2010–2016.

measures in aluminium sector). The detailed characteristics of each energy efficiency technology (e.g. electricity saving, installed cost, lifetime and market share) are derived from published research articles (e.g. refs. [26,31,38,65]), technical books (e.g. refs. [66,67]) and government official documents (e.g. refs. [68,69]), while taking into account their reliability. In this study, process structure changes are reflected by production yield adjustments. For example, caustic soda can be produced by both the diaphragm and ion-exchange membrane processes. As the diaphragm process is being phased out, the yields of diaphragm-based caustic soda production is assumed to be 0 after 2020 [26,70].

2.5.3. *Cost parameters of end-of-pipe measures*

The ECLIPSE V5a global emission fields [71], included in the GAINS model, is used to simulate the installation cost and operation cost of flue gas control measures for China's coal power plants at a provincial level. The ECLIPSE database considers 3,500 pollutant control measures, and provides detailed information (e.g. capital cost, catalyst cost, sorbent cost and capacity control rate) for air pollution control in power and industrial plants, at a regional level. The Electricity and fuel (coal, gas and oil) prices at provincial level are obtained from NDRC of China [72,73], CEC of China [74] and IEA-WEO [2] (see Appendix). Although the base year in our study is 2016, our data are all derived at the end of

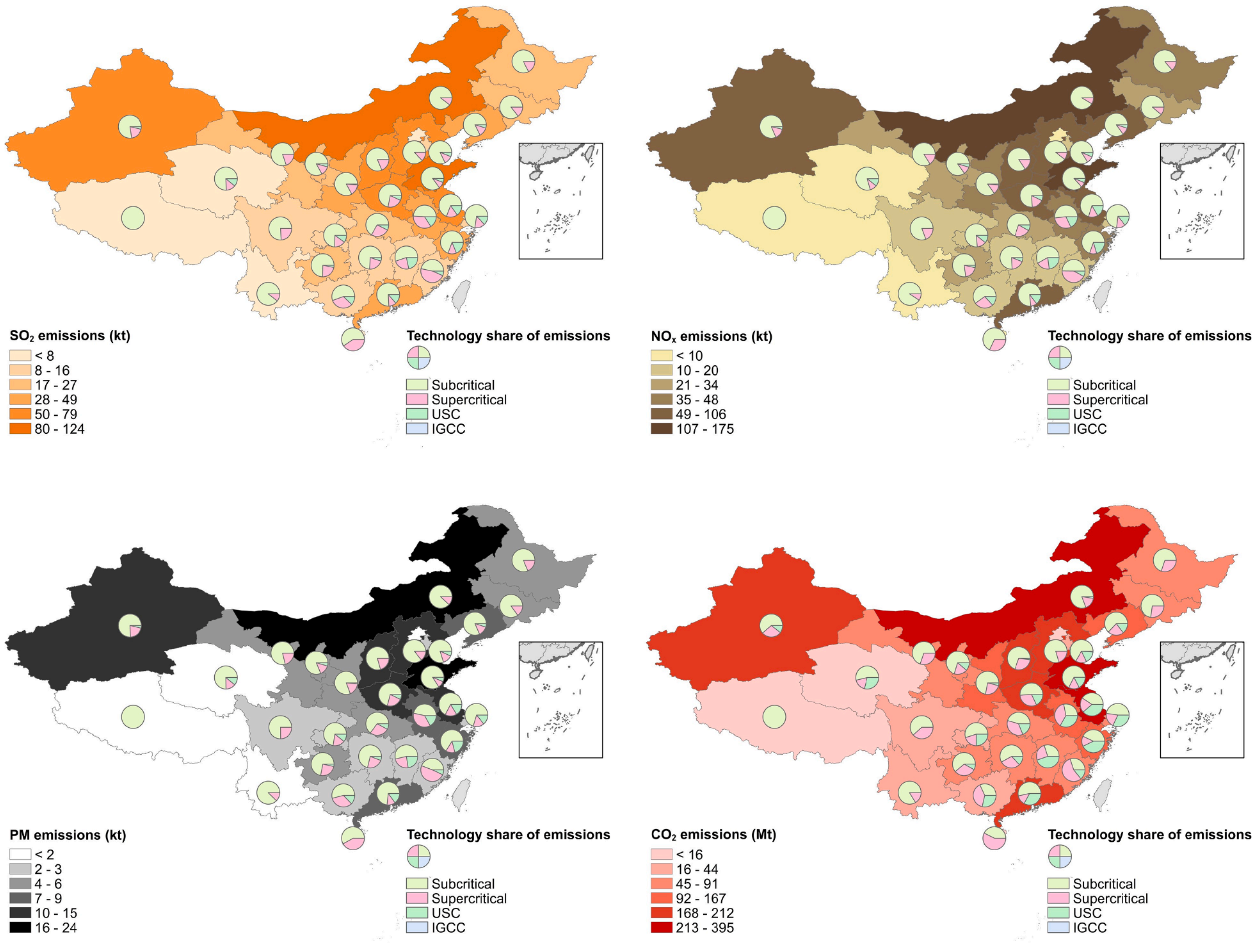

Fig. 2. The emissions of air pollutants and CO_2 in 2016 by generation technology at province level.

2016. The technology cost and energy prices are converted to 2017 constant prices in $ (2017 $).

3. Results

The research results are presented progressively in four ways, which address the proposed subgoals that answer the main purpose of assessing the multiple benefits of actions to reduce industrial electricity demand for removing coal-fired power capacity and thus improving air quality. The results begin with a unit-based overview of China's coal-fired power plant fleet in terms of geolocation, generation technology, installed capacity, electricity generation and air emission levels, across China's provinces. Subsequently, the technology-driven electricity savings by industries at regional level are presented in subchapter 3.2. The quantified impacts of industrial electricity savings on displacing coal-fired power capacity and reducing air pollutant emissions from electricity generation are given in subchapter 3.3; and finally, the cost analysis results of different emission control strategies are drawn in subchapter 3.4.

3.1. Commissioning coal power fleet in 2016

Fig. 1 shows the location of installed coal-fired power plants in 2010 and 2016 including capacity size categories, generation technology, and sum of electricity generation. With surged electricity requirements, the total installed coal-fired power capacity in China increased by 41%, from 671 GW in 2010 to 946 GW in 2016. Around 640 coal-fired units, with a total capacity 295 GW, came online after 2010, of which 40% consisted of ultra-supercritical capacity. Meanwhile, only 200 subcritical coal units, with a combined capacity of 20 GW, retired during 2010–2016, which is far less than the newly commissioned capacity. The subcritical steam generator operates at low pressure, resulting in a comparatively low thermal efficiency, particularly for unit sizes of<300 MW. Although the retired units are all subcritical coal units, the less-efficient coal fleet with a total installed capacity of 524 GW still is the backbone of the electricity supply in 2016. As shown in Fig. 1, China's electricity generation from the subcritical coal fleet accounts for 57% of total power generation in 2016, following by the supercritical fleet (25%). While the high efficiency low emissions (HELE) fleet consisting of ultra-supercritical (USC) and integrated gasification combined cycle (IGCC) units contribute to only 18% of the country's electricity.

Most of the coal-fired power plants were deployed in coal-rich inland provinces (e.g. Shanxi, Inner Mongolia and Shaanxi) and power-hungry coastal regions (e.g. Shanghai, Jiangsu, Zhenjiang and Guangdong). The uneven distribution of coal power plants shows resource and demand oriented deployment patterns. This means that the North and East grids are the two largest coal power bases, which together account for 50% of the total installed capacity in 2016 (see Fig. 1). It is worth noting that the Northwest grid has seen a rapid expansion of its coal power fleet. The new capacity in service after 2010 is equal to the total installed capacity in 2010, of which 76% of the new capacity installed in Xinjiang and Shaanxi Provinces. The main driving forces are coal-electricity vertical integration strategies and energy-intensive industry development plan proposed by the policy of *the Development of China's Western Region in 12th Five-Year Period (2011–2016)* [75]. The Central and Southern grids have both expanded their coal fleet with around 50% in the period 2010–2016. This is in line with the overall expansion, meaning that their share in total installed capacity remains at around 30%. This is below

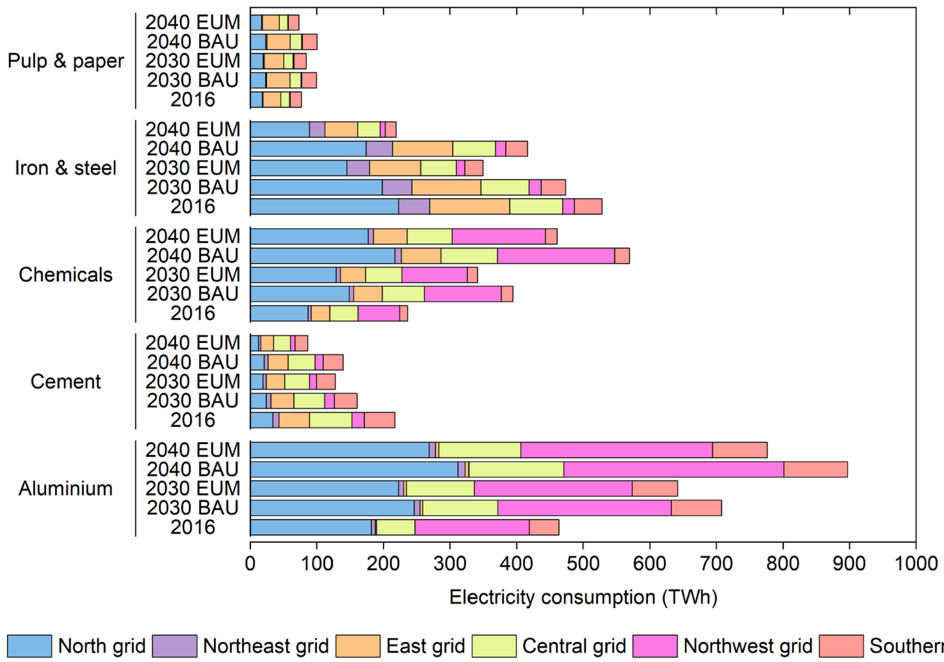

Fig. 3. Electricity demand per industrial sector for each power grid in 2030 and 2040 under the BAU and EUM scenario.

the share of the biggest grids North and East, which together account for 50% of capacity in 2016, coming down from 53% in 2010. The Northeast gird covers only three provinces; Liaoning, Jilin and Heilongjiang, and has the smallest coal power fleet (covering 8% of the installed coal power capacity in 2016). The regions in the Northeast grid are surrounded by traditional manufacturing industry, thus the demand for electricity is far less than that in the eastern coastal and central regions. Only 5% of the new coal power capacity (that came online in the period 2010 to 2016) is installed in the Northeast grid, meanwhile, without the newly commissioned HELE units. Most of the new HELE plants are built in the East, Central and Southern grids (accounting for 81% of the total newly-built HELE capacity), which directly improves the coal generation performance in these three power grids.

Fig. 2 shows the air pollutants and CO_2 emissions in 2016 for each province at technology level. The subcritical coal fleet generates the largest amount of electricity and emits the highest shares of power emissions (78%, 80%, 76% and 59% of SO_2, NO_x, PM and CO_2, respectively). Nevertheless, the small less-efficient units tend to be most polluting. The subcritical units with capacities below 300 MW account for only 14% of total installed capacity, but contribute disproportionately to air pollution (representing 33%, 38% and 36% of total SO_2, NO_x and PM emissions, respectively). Conversely, the HELE units, with large capacity size ($\geq$600 MW), with a share of 19% of total installed capacity, emits relatively few air pollutants (representing 6.0%, 6.4% and 6.5% of total SO_2, NO_x and PM emissions). These characteristics are reflected in the six power grids (see Fig. 2). The Northwest grid has a lower installed coal-fired capacity compared to the Central grid, but the air pollutant emissions in the Northwest gird (139 kt-SO_2, 191-kt NO_x and 27 kt-PM) are larger than in the Central grid (125 kt-SO_2, 172 kt-NO_x and 24 kt-PM). This is particularly the case because the deployment share of HELE units in the Central grid (representing 21% of the installed capacity in the Central grid) is much higher than that in the Northwest grid (9% of installed capacity in the Northwest capacity). A similar situation also appeared in the Northeast grid vs. the Southern grid. The higher share of HELE in the Central and Southern grids is a result of the increased new capacity installed after 2010, which accounts for 76% and 73% of total HELE installed capacity of the Central and Southern grids in 2016, respectively. Furthermore, the deployed coal capacity in the North grid is only 30% more than the East grid, while the North grid emits twice as much air pollutants as the East grid. The main reason is that around 25 GW of subcritical coal capacity came online between 2010 and 2016 in the North grid, while only 5 GW of subcritical capacity are installed in the East grid in the same period. Therefore, an accelerated phaseout of these less-efficient and high-polluting units in each grid is critical for China to achieve the ultra-low emission target [15] faster. Here, we identify the super-polluting power units that urgently need to be phased out (Table 1).

3.2. Electricity savings by industrial sectors at power grid level

The electricity consumption per energy-intensive industrial sector in 2040 is depicted in Fig. 3, per power grid, under the BAU and EUM scenarios. The electricity demand at the national level undergoes a significant increase in the BAU scenario, with an annual growth rate of 1.4% during the period 2016–2040. Only the iron & steel and cement sectors show a decreasing trend, by 21% and 36% in 2040, respectively, relative to 2016. This is mainly because the production demand of crude steel [38,76–78] and cement [31,39,65,79] is expected to peak around 2020, and decrease by 2040. Driven by the demand for primary aluminium and a vast array of chemicals [80], China's aluminium and chemical sectors are key drivers for the growing electricity requirements. These energy-intensive industrial plants are mostly distributed in the North and Northwest regions (e.g. Hebei, Shandong and Xinjiang) and bring a heavy electricity supply burden to the local power grid. The ever-growing electricity demand in these industries can be effectively curbed by implementing energy efficiency measures (see Fig. 3). In the EUM scenario, the total electricity demand in the industries drops by 16% and 24% in 2030 and 2040, respectively, compared to the BAU scenario. The annual curbed electricity demand by 2040 (506 TWh) is equivalent to the total electricity consumption by the industrial users in Northeast, Northwest and Southern grids in 2016. The iron & steel and aluminium sectors are the two largest contributors to the total electricity savings, which together provide 63% of the reduction by 2040, followed by the chemical (21%) and cement sector (11%). Although the pulp & paper sector has the smallest contribution (5%) to the electricity reduction, it holds a substantial potential to improve its own end-use efficiency (27% of unreleased potentials). The electricity saving potentials of each industrial subsector vary among the six power

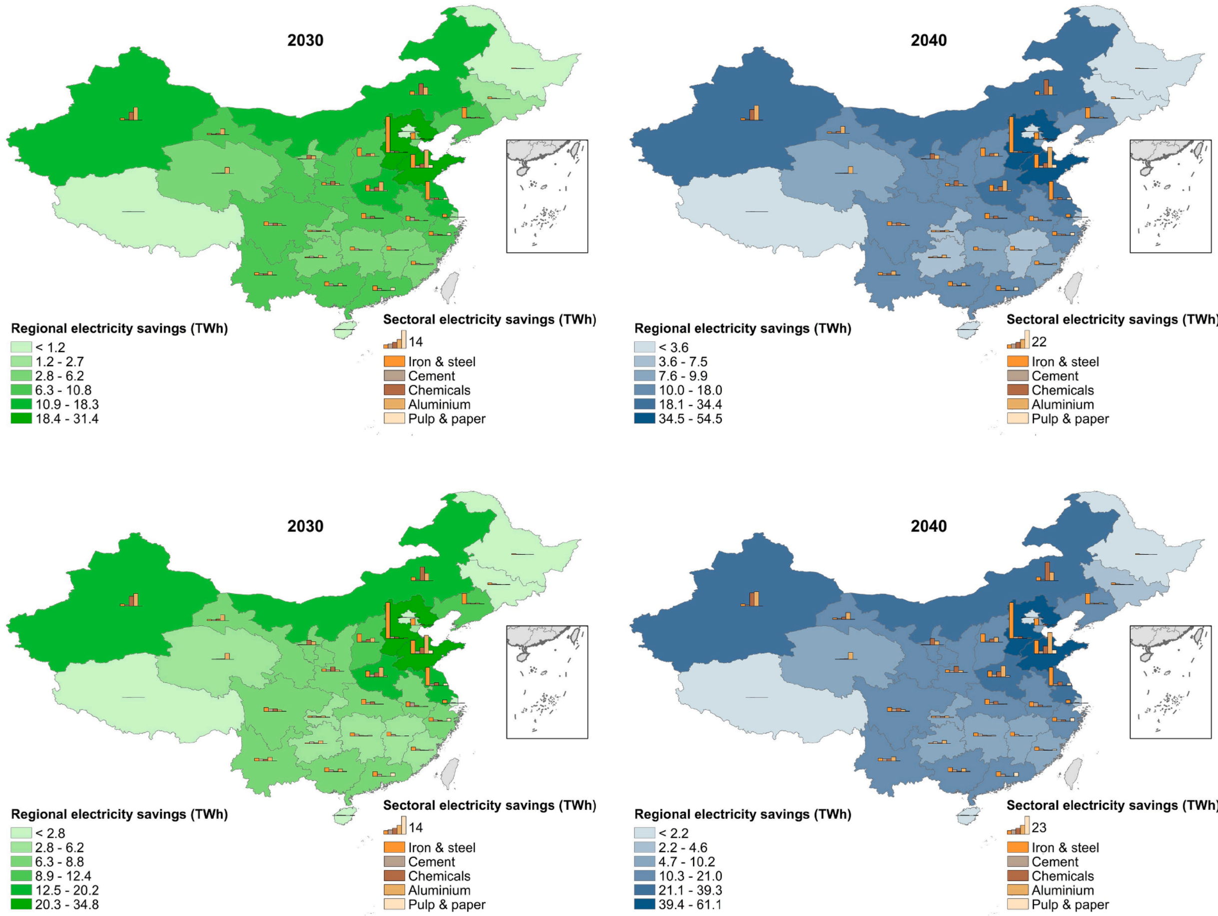

Fig. 4. Electricity savings by industrial sectors at a regional level in 2030 and 2040. The top two figures represent the cost-effective electricity savings, and the bottom two figures show the technical electricity savings in 2030 and 2040.

grids.

To compare the regional variations, as shown in Fig. 4, we explored the sectoral electricity savings from an economic perspective at a regional level in 2030 and 2040. Around 182 TWh of electricity use in 2040 can be reduced in the North grid, contributing to the largest share of national electricity savings (36%). While the iron & steel sector provides 47% of the electricity reductions in the North grid. As most of the emerging industries are based in Gansu, Ningxia and Xinjiang, the Northwest grid also provides considerable electricity reductions by 2040, accounting to 18% of total electricity savings. The chemical and aluminium sectors are the two largest contributors in the Northwest grid, which together represent 85% of electricity savings. Provinces (e.g. Henan, Hubei and Sichuan) in the Central grid, with dominant cement and chemicals production, show a significant reduction of electricity use (86 TWh), representing 17% of national electricity reductions. Developed coastal regions (e.g. Guangdong, Zhejiang and Shanghai) are located in the East and Southern grids, which have small scale energy-intensive industries. Therefore, the contributions of electricity savings provided by the East grid and Southern grids are relatively small, which together can decrease 123 TWh of electricity use. The Northeast grid

Table 2
Unit-based coal capacity built-up in 2040 under two scenarios.

Technology	Online year	Unit size (MW)	Capacity in 2040 w/o EUM (GW)						Avoided capacity in 2040 with EUM (GW)					
			N	NE	E	C	NW	S	N	NE	E	C	NW	S
Subcritical	≤ 2016	< 100	3.6	1.2	2.7	1.7	1.1	0.5	3.6	1.2	2.7	1.7	1.1	0.5
		100–299	24.9	5.6	6.8	9.6	10.4	5.7	17.1	2.9	6.8	9.6	9.3	5.7
		300–599	74.1	18.3	25.5	30.4	41.4	26.7	8.6	0.0	3.5	10.0	5.8	8.1
		≥ 600	42.4	1.3	5.7	7.9	10.0	18.1	0.0	0.0	0.0	1.3	0.0	1.3
	2017–2040	N/A	2.9	1.0	2.1	1.4	1.1	1.2	1.0	0.4	2.1	1.1	0.6	0.7
Supercritical	≤ 2016	< 300	0.0	0.0	0.0	0.27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		300–599	14.4	4.9	2.2	5.8	14.8	5.0	0.0	0.0	0.0	0.0	0.6	0.4
		≥ 600	35.6	12.2	51.5	44.6	14.3	25.1	0.0	0.0	0.0	0.0	0.0	0.0
	2017–2040	N/A	16.1	5.3	11.9	7.8	5.9	6.9	0.0	0.0	0.0	0.0	0.2	0.0
USC	≤ 2016	≥ 600	18.5	5.2	78.7	34.6	9.7	30.7	0.0	0.0	0.0	0.0	0.0	0.0
	2017–2040	N/A	101.6	35.6	81.8	56.3	35.6	46.5	0.0	0.0	0.0	0.0	0.0	0.0
IGCC	≤ 2016	< 300	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	2017–2040	N/A	4.9	1.8	4.1	2.9	1.6	2.3	0.0	0.0	0.0	0.0	0.0	0.0
Total			339.2	92.4	273.0	203.3	145.9	168.7	30.3	4.5	15.1	23.7	17.6	16.7

Note: N, NE, E, C, NW and S means the North, Northeast, East, Central, Northwest and Southern grid.

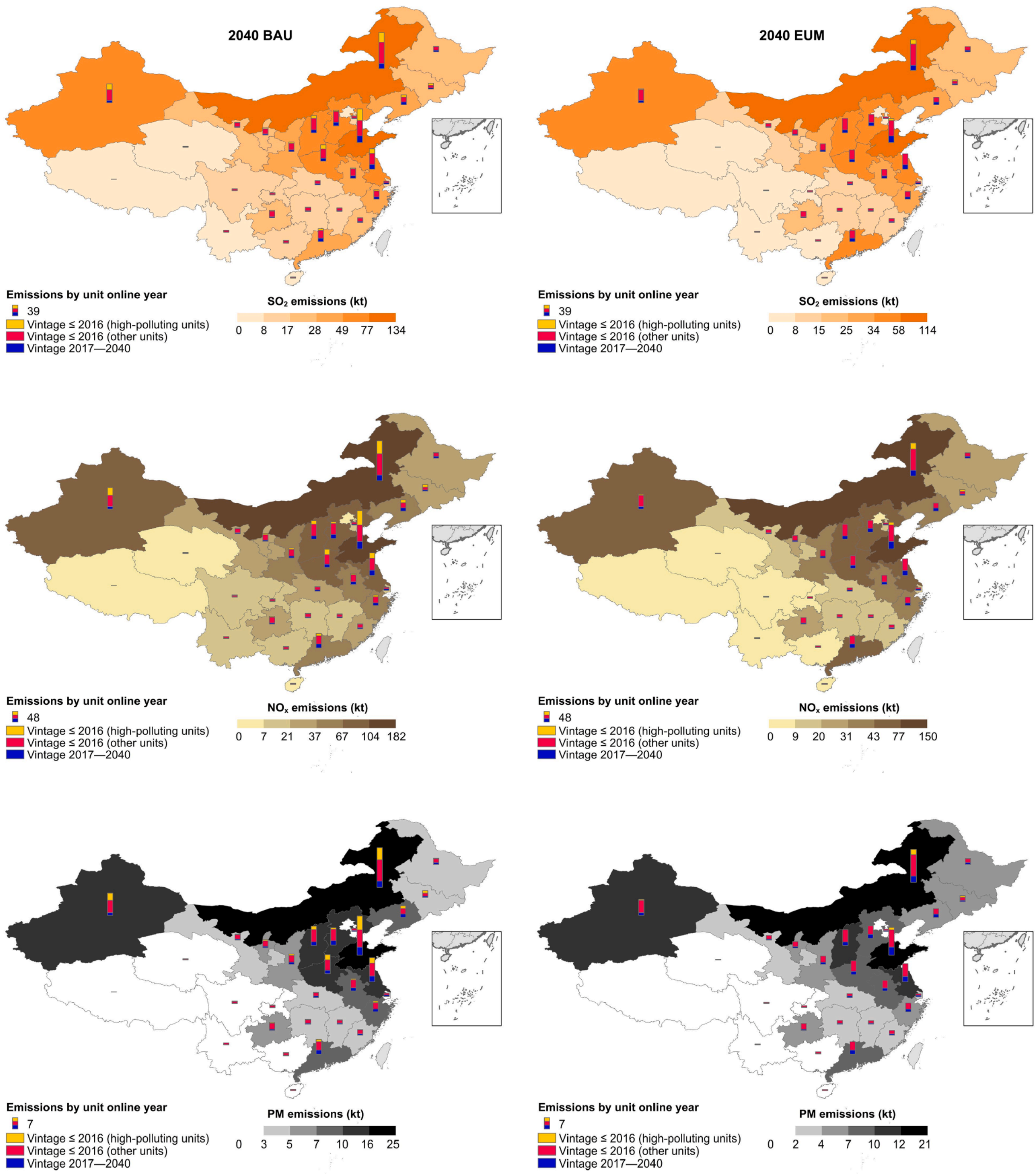

Fig. 5. SO_2, NO_x and PM emissions from coal power units by the vintage year for each province in 2040 under the BAU and EUM scenarios.

contributes to only 5% of electricity demand reductions. Although the smallest reductions are obtained from the Northeast grid, this grid has more opportunities to improve energy efficiency than the other power grids, in a relative sense. This is because the regions (Liaoning, Heilongjiang and Jilin) in the Northeast grid are old industrial bases that operate with substantially less-efficient equipment, leading to large electrical energy losses. The maps also demonstrate the many energy efficiency measures are cost-effective and as such are often preferable to alternatives. In totally, more than 90% of electricity savings between 2030 and 2040 can be accessed by cost-effective measures. Specifically, cost-effective opportunities can provide around 91%, 94%, 91%, 92%, 91% and 89% of electricity savings in the North, Northeast, East, Central, Northwest and Southern grid by 2040, respectively.

3.3. Displaced coal power capacity and synergies of emission reductions

Electricity savings in China's energy-intensive industries can displace a total of 108 GW coal-fired power capacity by 2040, which can help to achieve the target of annually phasing out 4 GW less-efficient units [81]. Retiring coal-fired power plants, coupled with improving demand-side energy efficiency can not only meet future electricity demand, but is particularly important for the transition to a sustainable industry and coal-free power generation. Here, a unit-by-unit phaseout strategy for the coal-fired power plant fleet at grid level is presented in Table 2, which considers less-efficient and high-polluting units to be a priority in substitution. Considering the regional heterogeneity, we find that the industrial efficiency improvements can drive around 84% of the

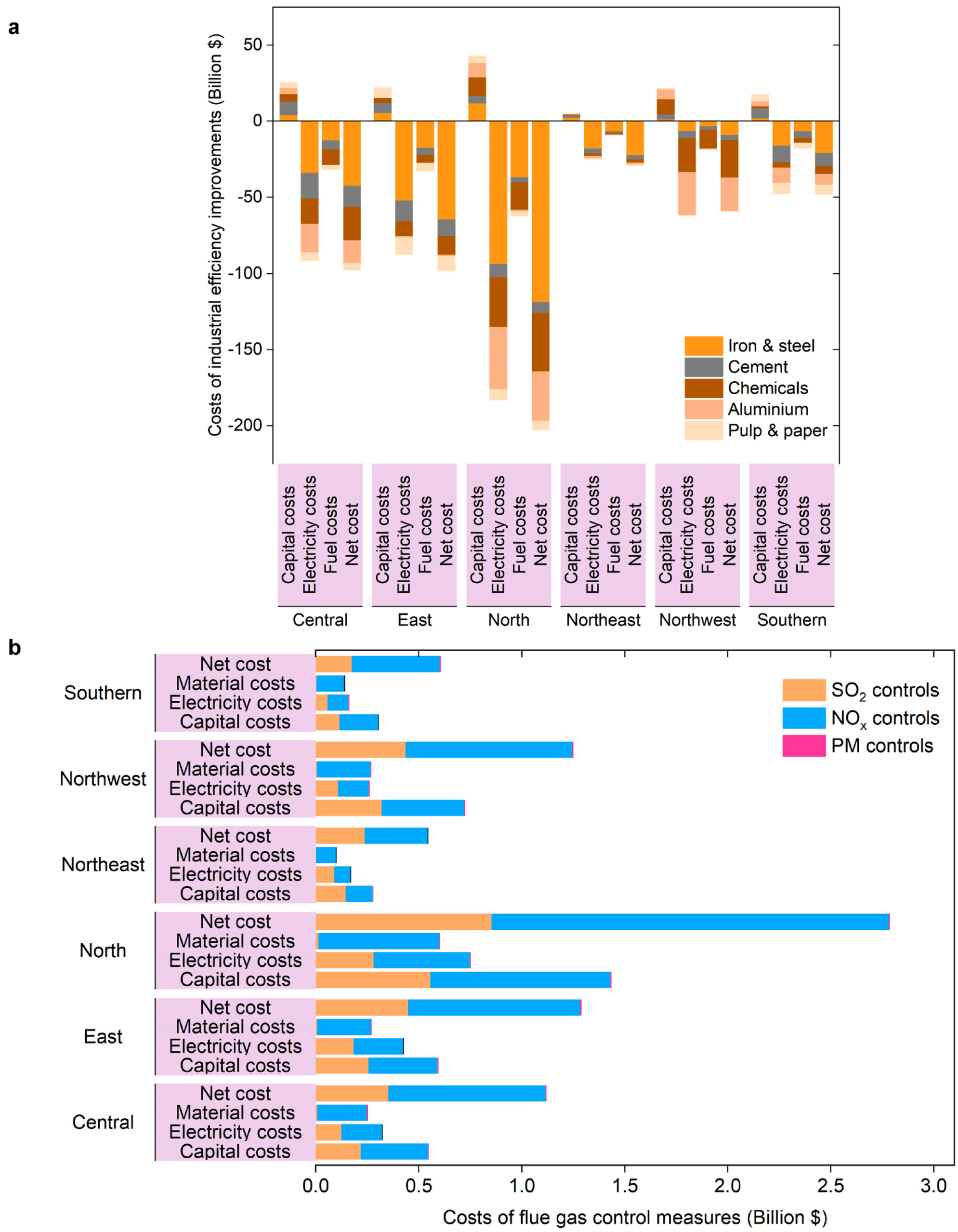

Fig. 6. Cost portfolios of air pollutant reductions by 2040 under EUM (a) and APC (b) scenarios.

most polluting units (existing subcritical units with size < 300 MW) into early retirement and allow an accelerated 38 GW of older power plants phaseout (consisting of 37 GW subcritical and 1 GW supercritical coal power capacity). Besides displaced existing units, around 6 GW of newly proposed coal power projects, particularly subcritical coal plants, can be cancelled under the EUM scenario.

The North grid undoubtedly has the most potential for removing coal power plants (accounting for 28% of the total offset coal capacity), because of the largest electricity savings. An interesting finding is that the Northwest grid has a larger electricity saving than the Central grid, but the displaced coal capacity in the grid (18 GW) is lower than the Central grid (24 GW). This is because the utilization level (capacity factor) of coal generation capacity in the Central grid is much lower than the Northwest grid. The electricity supply by regions located in the Central grid, like Sichuan and Hubei, depends on the renewables power fleet, especially on hydropower. Although the Northwest grid has deployed 29% and 40% of national installed capacity of wind and solar, respectively, the serious wind and solar curtailment issues causes the heavy dependence of the Northwest grid on coal power. Similarly, the Southern grid has deployed a large share of hydropower capacity in power supply system, thus the potential for early retiring coal units in the Southern gird (17 GW) is higher than the East grid (15 GW). Liaoning and Heilongjiang located in the Northeast grid have rich coal resource but poor hydro energy. Compared to the (still) low generation cost of coal, the intermittent generation from wind and solar has a negative market competitiveness in the Northeast grid [4,32]. Only 4 GW of coal power capacity can be taken offline in the Northeast grid because of the low electricity savings.

Fig. 5 depicts the emission levels of air pollutants from coal-fired power plant fleet, distinguished by the vintage year of units, are plotted for the year 2040 under BAU and EUM scenarios. Although the coal power fleet is expanded by 2040, the emissions levels of air pollutants from the coal power fleet in the BAU in 2040 (1021 kt-SO_2, 1381 kt-NOx and 198 kt-PM) are close to the 2016 values. The reason is that

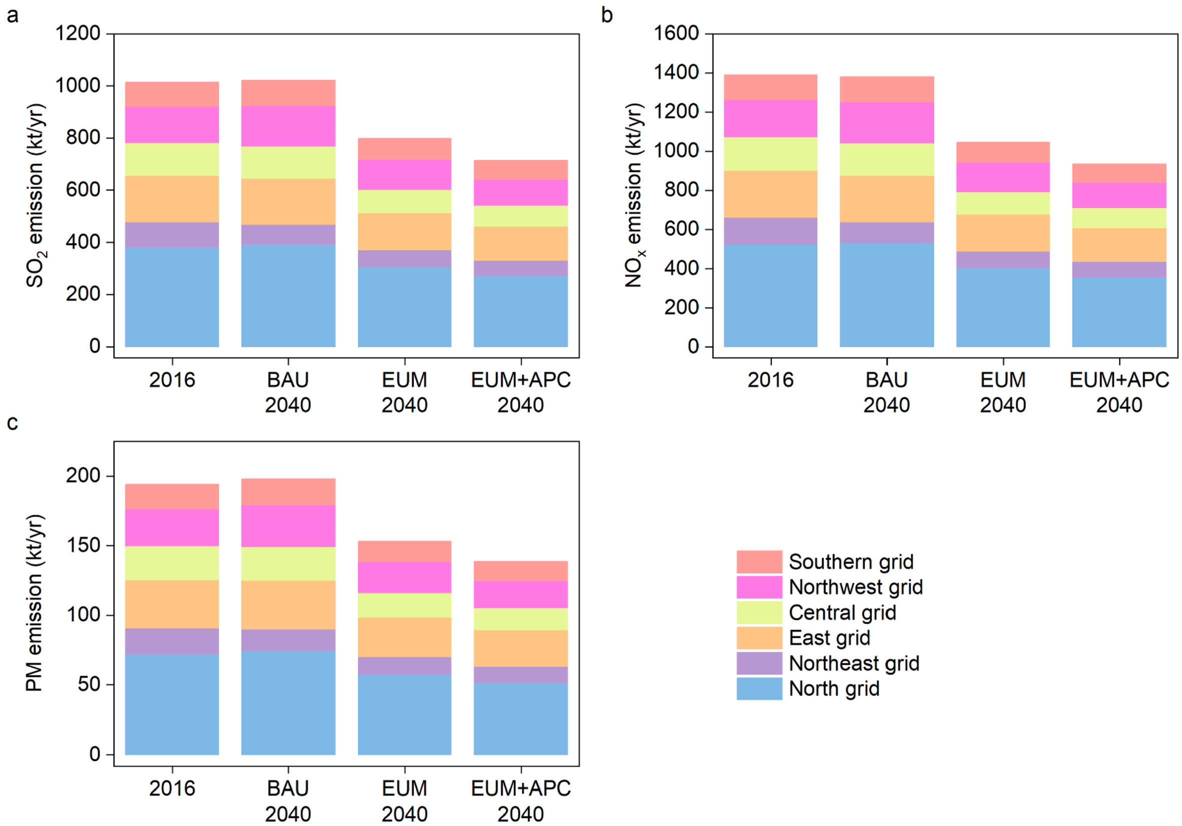

Fig. 7. Air pollutant emissions at power grid level in 2016 and 2040 between different scenarios. Note, the air pollutant emissions in the APC scenario are not shown in this graph. Because we assumed the emissions levels are same as in the EUM scenario (see Methods and Materials).

around 85% of the new capacity are HELE units with low emissions, while some old, less-efficient units are decommissioned in the period up to 2040, at the end of their lifetime (see Fig. 5). The ambient air quality has a significant potential to be improved by the early retirement of super-polluting units (age < 40 years in 2040). The current emission levels of SO_2, NO_x and PM would be decreased by 217 kt, 346 kt and 41 kt, with a reduction of 21%, 25% and 21% by 2040, respectively. Comparing the BAU with the EUM scenarios, air pollutant emissions in the EUM scenario are reduced by 224 kt-SO_2, 336 kt-NO_x and 45 kt-PM in 2040. Around 78%, 81% and 80% of the reduced SO_2, NO_x and PM, respectively, are provided by the early retirement of the most polluting units. Curbed construction of new plants also plays a key role in avoiding air pollutant emissions, which totally contribute to 4%, 3% and 3% of the SO_2, NO_x and PM reductions, respectively.

Due to the different electricity saving potentials and installed share of coal generation technology, the emission reductions of air pollutants vary among the six power grids. The North grid emits 38% of total air pollutants in 2040 in the BAU scenario, including 391 kt-SO_2, 530 kt-NO_x and 74 kt-PM. This is because the regions (e.g. Shanxi, Inner Mongolia and Shandong) located in the North grid have deployed a large number of super-polluting generation units (around 30 GW installed capacity in 2040). Displacing these units due to the reduced electricity load leads the North grid to the largest contributor to the air pollutant emission reductions (avoiding 85 kt, 129 kt and 17 kt of SO_2, NO_x and PM emissions, respectively). Driven by the electricity demand in coastal regions (i.e. Zhejiang, Jiangsu and Fujian), the coal power fleet in the East grid shows a rapid expansion during the period 2016 to 2040, resulting from a share of 23% in newly installed coal-fired power generation capacity, and emits 17% of total air pollutants in 2040. However, the potential of removing coal capacity in the East grid are lower than the Northwest grid (see Table 2), which results in a lower contribution by the East grid to the emission reductions (representing 16%, 15% and 15% of total SO_2, NO_x and PM emission reductions, respectively). Around 38 kt, 59 kt and 8 kt of SO_2, NO_x and PM emissions, respectively, can be avoided in the Northwest grid. It is worth noting that the Central grid can deactivate more coal capacity than the East gird, but decreases air pollutant emissions slightly lower than the East grid. This is because the East grid has more potential on decommissioning the units with the poorest performance, compared to the Central grid. This is also reflected in the Southern and Northeast gird that together contribute to 14% of the total avoided air pollutant emissions (reducing 32 kt-SO_2, 48 kt-NO_x and 6 kt-PM). The displaced coal capacity in the Southern grid is four times as high as in the Northeast grid, while the emission reductions of SO_2, NO_x and PM are only 45%, 48% and 43% higher than the Northeast grid. CO_2 emission reductions are discussed in Section 4.

3.4. Portfolio costs of air pollutant reductions

Fig. 6 compares the costs of air pollutant abatement for six power grids between EUM and APC scenarios. The capital expenditures on energy efficiency improvements in industries are much higher than those of the flue gas control technologies, when avoiding the same levels of air pollutant emissions in both scenarios (see Fig. 5). However, energy efficiency technologies can significantly cut the energy bills because of conserved electricity. Investors can expect to recover all of their initial investment within 2–15 years, whereas costs of pollution abatement equipment are not recovered (without a price for air pollutant emissions). Besides the energy benefits, the curbed coal-fired power plants avoids investing $4 Billion by 2040. However, the installed end-of-pipe treatment measures, in particular the SO_2 and NO_x treatment measures, would further induce additional bills of energy and material (e.g. sorbent and catalyst) consumption (see Fig. 6b). The cost comparison reveals that reducing coal-fired power generation by electricity savings in consumer is a more cost-effective way to clean the air than end-of-pipe

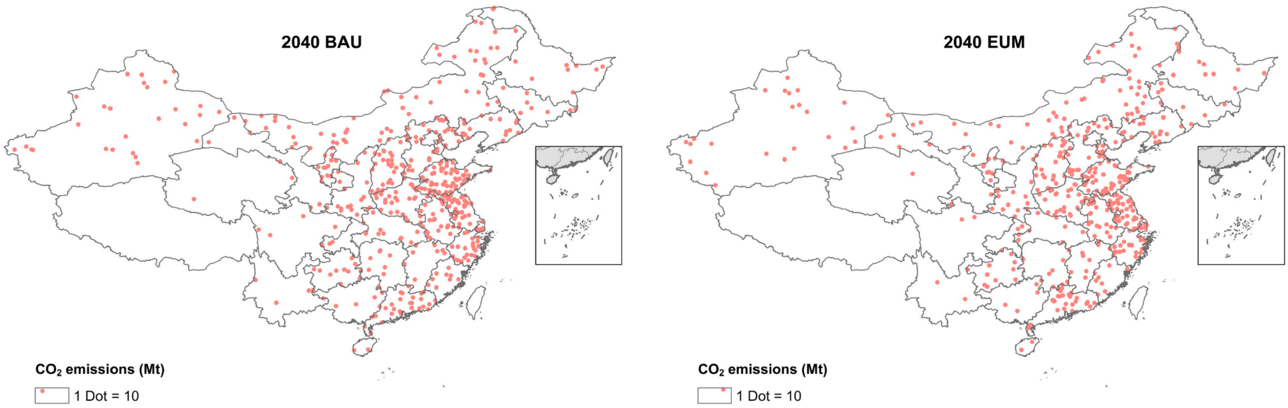

Fig. 8. Provincial CO_2 emissions in 2040 under the BAU and EUM scenarios.

control.

The capital expenditures to conserve electricity, and the energy profits show a large variation per industrial sector (see Fig. 6a). The biggest savings potential in absolute sense is found in the iron & steel industry, followed by the chemical, the aluminium, the cement and the pulp & paper sector. The payback time is shortest for the iron & steel sector, followed by the aluminium and chemical sectors. The cement and pulp & paper sectors have a relatively longer investment return periods, around 10 years. From an economic perspective, these results suggest that policy should prioritize investing in energy efficiency improvements in the iron & steel sector.

The results per grid level show that a massive investment should be allocated to industry in the North grid in both scenarios, due to the large potential to mitigate air pollutants. The investment in end-of-pipe treatment measures is directly related to the air pollutant reductions in the coal-fired power fleet. The net abatement costs for the six grids under the EUM scenario are all negative, which means the energy returns from industrial efficiency improvements offset the initial investments during their lifetime. The largest energy return is gained in the North grid, which reduced \$245 Billion energy costs (representing 37% of total economic returns). This is because the iron & steel plants are mostly located in this grid (e.g. in Hebei and Shandong), which provide substantial potentials of electricity and fossil fuel savings. Interestingly, the Northwest grid requires a lower capital investment (\$21 Billion) to improve energy efficiency but displaces relatively more air pollutant emissions from coal power plants under the EUM scenario, compared to the East and Central grids. However, the energy returns in the Northwest grid (\$81 Billion) are lower than the East and Central grids (\$120 and 123 Billion, respectively). This is particularly because the electricity prices in the Northwest grid (average 0.06 \$/kWh, excl. Tibet) are much lower than that in the East (average 0.10 \$/kWh) and Central grids (average 0.09 \$/kWh). The lowest amount of investment in the EUM scenario is spent in the Northeast grid, providing \$34 Billion of energy conservation income, which is also lower than in the other grids. It is worth noting that the reduction potential of air pollutants in the Northeast grid are considerable, which are similar to the Southern grid as we discussed in Section 3.3. Although electricity prices will affect electricity saving benefits to a certain extent, the expenditures on the efficiency projects would be gained back. The central government should give attention to the North, Northwest and Northeast grids, which provide strong value-for-money emission reductions.

4. Discussion

This study linked demand-side and supply-side, on technology level, to co-manage electricity savings, air pollution and climate change mitigation. An integrated framework was developed to quantify the pivotal role of industrial electricity savings to cut coal-fired power generation on the level of the individual unit to maximize benefits of mitigating air pollutant emissions for China's regional power grids. Furthermore, the costs of industrial efficiency improvements and retrofitting coal power plants with end-of-pipe controls are compared from multi-sectoral and multi-regional levels to understand the economic feasibility and optimize the investments of air pollutant reductions. There are still uncertainties that could impact the results. Therefore, we conduct a sensitivity analyses for three major factors. First, we design a joint scenario (see Methods and Materials) that simultaneously considers electricity load reductions and flue gas controls to model the emission changes of air pollutants. Secondly, the electricity savings measured from five energy-intensive sectors are extrapolated to the whole industry. Thirdly, CO_2 emission reductions are discussed.

Fig. 7 plots air pollutant emissions at power grid level in 2016 and 2040 for different scenarios. The efficient use of electricity that occurs in conjunction with flue gas controls of power plants can deliver deep emission reductions of air pollutants, compared to 2016. Comparing the EUM + APC and EUM scenarios, the total air pollutant emissions in the EUM are further reduced—10.5%, 10.6% and 9.6% of SO_2, NO_x and PM by 2040, respectively, because of decreased emission intensities of electricity generation. However, the additional emission reductions yielded by retrofitting coal-fired power plants with end-of-pipe measures are less important, compared to the phaseout of coal-fired generation units. For example, only 7.4% and 7.7% of emission reductions of total air pollutants in the Northeast and Southern grids, respectively, are attributable to additional flue gas cleaning beyond the EUM scenario. This is because the most polluting units (displaced by electricity savings) still have high emission rates (see Table 1). Furthermore, installing the end-of-pipe control systems would substantially increase initial investments, plus considerable increased operation and maintenance costs. The added costs of the installed controls are particularly significant in the North grid, which has the largest coal-fired power plant fleet of the six power grids (see Fig. 6). Meanwhile, the pollution abatement measures would result in a efficiency penalty of power generation by around 2% for coal-fired units [21,22], and drive the increase of GHG emissions [23]. The results suggest that massive spending on pollution control measures, especially for small high-polluting units, may generally less economically attractive [22,82] to tackle air pollutants compared to improving demand-side efficiency.

This study estimates the technology-driven potentials of electricity savings in five energy-intensive industrial sectors, which represent around 50% of industrial electricity consumption in China. Quantifying technology-level impacts in the entire industry is difficult due to a lack of data. Here, we assume that the electricity savings potential (relative to the BAU scenario) in other industrial sectors is assumed to be the same as the five studied sectors to better understand the role of industrial electricity savings played in removing coal and improving air quality. A total of 595 TWh additional electricity savings is expected to be obtained from other sectors in 2040, of which nearly 60% of the electricity savings are found in the East and Southern grids. The additional reduced electricity load can further displace 133 GW of coal generation capacity by 2040, as a result, which means that nearly all of the most polluting units can be closed. Considering the impacts for the entire industry, the largest potential of coal generation capacity phaseout is provided by the East grid (representing 25% of the total displaced coal capacity), followed by the Southern, Central, North, Northwest, and finally the Northeast grid, which contributes to the smallest reductions in coal-fired capacity (4%). The offset coal-fired capacity provided by the other industrial sectors can significantly decrease the annual emissions of air pollutants in the EUM scenario, i.e. avoiding around 18.2%, 18.8% and 17.8% of SO_2, NO_x and PM emissions by 2040, respectively. The main contributors to the additional emission reductions are the East and North grids, which together account for 54.8%, 56.0% and 55.6% of the additional reductions of SO_2, NO_x and PM, respectively. The sensitivity analysis reveals that the efforts of reducing electricity demand in the other industrial sectors would accelerate the achievement of a coal-free power generation and addressing air quality concerns. Therefore, we suggest that future research considers expanding the analysis to the other industrial sectors (e.g. plastic and textile sectors) at explicit technology level for a more comprehensive assessment.

Besides contributing to air quality, a rapid transition away from coal-generated electricity use is essential to mitigate climate change. Fig. 8 shows the CO_2 emission levels for each region in the BAU and EUM scenario. The CO_2 emissions increase by 36% from 2016 to 2040, with an average annual growth rate of 1.3%, in the BAU scenario. This is because of the continuous expansion of the coal-fired power plant fleet, without the assumption of implementing carbon capture and storage (CCS) systems. Promoting the decommissioning of the least efficient coal-fired power plants in the EUM scenario can effectively slow the annual growth rate of CO_2 emissions to 0.9%, resulting in a total of 460 Mt-CO_2 emission reductions in 2040, compared to the BAU scenario. The largest potential of CO_2 emission reductions is discovered in the North grid, which represents 36% of the total avoided CO_2 emissions. The Northwest (18%), Central (17%), East (14%) and Southern (10%) girds are close behind, and the lowest contribution is provided by the Northeast grid (5%) due to the small electricity savings in this grid. Unlike the avoided air pollutant emissions, the contribution to carbon reductions among the six power grids follows the decline of coal-burning electricity. The thermal efficiency of coal-fired power plants has a small effect on the changes in CO_2 emissions. This indicates that only shutting down the less-efficient coal power units by 2040 is not enough to limit the growing concentration of CO_2 in the atmosphere, threatening the achievement of the Paris temperature goals. An ambitious coal-fired power generation reduction pathway, integrating demand-side savings should be designed to accelerate early decommissioning of existing coal plants and cancel as many newly proposed coal-fired power plants as possible. Although deploying renewable energy to substitute coal in a power grid system can access zero emissions in the power sector [83,84], the intermittent character (e.g. solar and wind) is highly susceptible to the ambient environment [85,86]; challenging the reliability of electricity supply [4,87,88]. End-use efficiency improvements offer a cost-effective way to reduce the electricity load, thus help ensure grid stability and support high renewables penetration.

5. Conclusions and policy implications

5.1. Conclusions

Coal-intensive power supply systems, along with a fast-growing electricity demand driven by industry has caused serious air pollution and health concerns. This study develops a multi-sectoral and multi-regional framework to model the linkages between the industry and power sector to co-manage electricity savings and air pollution on various spatial scales. Cost analyses for different mitigation portfolios are conducted to identify the most cost-effective way to tackle air pollution. The results are processed in ArcGIS to capture the characteristics on provincial, grid and national administrative levels.

China's coal-fired power capacity has increased by 41% from 2010 to 2016, which drives the global expansion of the coal power fleet. The North and East grids include the two largest coal power fleets, holding steady at around 50% of the total installed coal power capacity. The Northwest grid is the fastest-growing region in terms of coal-fired power plants. China's power grids are dominated by subcritical generation technology, which provides 57% of electricity supply in 2016. Subcritical power units, particularly of the size below 300 MW, are often the most polluting. The small subcritical units represent only 14% of total installed capacity, but contribute disproportionately to air pollution (accounting for 36% of total air pollutant emissions). These units should therefore be a priority to shut down in all power grids (due to increasing electricity savings).

Energy efficiency improvements can decrease the industrial electricity demand by 24% in 2040. The iron & steel sector contributes to the largest electricity savings, followed by the aluminium, chemical, cement and pulp & paper sectors. Considering the regional characteristics, the electricity savings per sector differ for the six grids. The biggest electricity savings potential is found in the North and Northwest grids (representing 54% of the total electricity savings). This is because of the high concentration level of iron & steel, aluminium and chemical plants in the included provinces. Furthermore, we find that around 90% of the electricity savings can be achieved cost-effectively.

The reduced electricity load, due to the industrial efficiency improvements, can scale down China's coal power fleet by 108 GW, which is equal to 62% of the existing coal capacity in the European Union. The regional utilization rate of coal-fired power capacity and the electricity saving potentials jointly determine the cut down levels of each power grid. The greatest potential to deactivate coal power plants lies in the North grid (28.1%), followed by the Central (22.0%), Northwest (16.3%), Southern (15.4%), East (14.1%) and Northeast grid (4.1%).

The emission levels of air pollutants in 2040 is expected to reduce by 21.9%, 24.4% and 22.6% of SO_2, NO_x and PM, respectively, due to the closed coal power plants. For the grid level, the largest contribution to air pollutant emission reductions is provided by the North grid. While the avoided emissions in both the Northwest and East grid are higher than the Central grid. The Northeast has the smallest potential in reducing air pollutant emissions. The result shows that the energy and environmental performance of closed coal units are key factors impacting the avoided air pollutant emissions for the six power girds, besides the amount of displaced capacity.

An integrated assessment framework including four modules (industrial electricity demand, coal power generation, air emissions and economic assessment) is newly constructed in this research to measure the pivotal role of targeting industry efficiency to strategically scale down the coal-fired power plant fleet to curb air pollutant emissions from electricity systems. The results imply that a sustainable industry is key to the transition to a coal-free electricity supply system, not only in China but for the countries where electricity use is likewise dominated by industry and heavily dependent on coal-based electricity, such as India, Germany, Poland, The Netherlands, Australia, and South Africa.

5.2. Policy implications

Although the required investments in energy efficiency are higher than when achieving the same emission reduction with implementing flue gas controls, the energy returns delivered by the conserved electricity offset the initial expenditures for energy efficiency. The economic analysis suggests that national policymakers that purpose to co-control coal-intensive electricity use and air pollution need to facilitate the potential contributions of industrial efficiency improvements for optimizing electricity supply systems. The power grid managers need to not only clearly understand the co-benefits of integrating energy efficiency

Table A1
Energy prices for each province.

Region	Electricity ($/kWh)	Coal ($/GJ)	Gas ($/Mbtu)	Oil ($/GJ)	Biogas ($/GJ)	Wood ($/GJ)	Straw ($/GJ)
Beijing	0.11	3.4	7.6	9.1	8.1	4.8	3.5
Tianjin	0.10	3.8	7.6	9.1	8.1	4.8	3.5
Hebei	0.09	3.4	7.5	9.1	8.1	4.8	3.5
Shanxi	0.07	2.6	7.3	9.1	8.1	4.8	3.5
Inner Mongolia	0.07	1.9	5.0	9.1	8.1	4.8	3.5
Shandong	0.09	4.3	7.5	9.1	8.1	4.8	3.5
Liaoning	0.09	3.8	7.5	9.1	8.1	4.8	3.5
Jilin	0.09	3.6	6.7	9.1	8.1	4.8	3.5
Heilongjiang	0.08	3.3	6.7	9.1	8.1	4.8	3.5
Shanghai	0.11	4.1	8.3	9.1	8.1	4.8	3.5
Jiangsu	0.10	4.1	8.3	9.1	8.1	4.8	3.5
Zhejiang	0.10	4.0	8.3	9.1	8.1	4.8	3.5
Anhui	0.09	4.3	8.0	9.1	8.1	4.8	3.5
Fujian	0.09	4.2	8.2	9.1	8.1	4.8	3.5
Jiangxi	0.10	4.9	7.5	9.1	8.1	4.8	3.5
Henan	0.09	4.1	7.7	9.1	8.1	4.8	3.5
Hubei	0.09	4.4	7.5	9.1	8.1	4.8	3.5
Hunan	0.10	4.7	7.5	9.1	8.1	4.8	3.5
Chongqing	0.09	4.2	6.2	9.1	8.1	4.8	3.5
Sichuan	0.08	4.4	6.2	9.1	8.1	4.8	3.5
Shaanxi	0.07	3.2	5.0	9.1	8.1	4.8	3.5
Gansu	0.06	3.3	5.3	9.1	8.1	4.8	3.5
Qinghai	0.05	3.7	4.7	9.1	8.1	4.8	3.5
Ningxia	0.05	2.7	5.7	9.1	8.1	4.8	3.5
Xinjiang	0.06	1.4	4.2	9.1	8.1	4.8	3.5
Tibet	0.10	3.6	6.8	9.1	8.1	4.8	3.5
Guangdong	0.10	4.4	8.3	9.1	8.1	4.8	3.5
Guangxi	0.08	5.0	7.7	9.1	8.1	4.8	3.5
Guizhou	0.07	3.5	6.5	9.1	8.1	4.8	3.5
Yunnan	0.06	3.5	6.5	9.1	8.1	4.8	3.5
Hainan	0.11	4.1	6.2	9.1	8.1	4.8	3.5

Note: the prices of oil and bioenergy are the national level.

strategies in the regional energy system, but also accurately coordinate the reduced electricity load and power generation to decrease the dependency on (poor performing) coal-fired power plants. Meanwhile, the provincial government and investors are suggested to prioritize actions in the iron & steel because of the fastest payback period (within on average three years), followed by the aluminium, chemical, and finally the cement and pulp & paper sectors.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

(See Table A1)

Appendix B. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2020.116241.

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