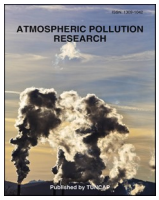
Atmospheric Pollution Research 14 (2023) 101937



Contents lists available at ScienceDirect

Atmospheric Pollution Research

journal homepage: www.elsevier.com/locate/apr





The impacts of clean energy policies on air pollutants and CO_2 emission reduction in Shaanxi, China

Xin Bo [a,b,1], Qian You [c,1], Minjie Sang [d], Peng Wang [e], Shaobo Chen [a,b], Xin Xu [a,b], Wanyue Shan [a,b], Ying Yang [a,b], Bertrand Bessagnet [f], Hongmei Li [c,*], Yong Xiao [a,b,**]

[a] Department of Environmental Science and Engineering, Beijing University of Chemical Technology, Beijing, 100029, China
[b] BUCT Institute for Carbon-Neutrality of Chinese Industries, Beijing, 100029, China
[c] School of Management and Engineering, Capital University of Economics and Business, Beijing, 100070, China
[d] Beijing Capital Air Environmental Science & Technology Co., Ltd., Beijing, 100176, China
[e] 3Clear Technology Co., Ltd., Beijing, 100029, China
[f] European Commission, Joint Research Centre (JRC), Ispra, 21027, Italy

ARTICLE INFO

Keywords:
Air pollutant emission
Energy structure
Wind power
Photovoltaic power
Energy policy
Scenario analysis

ABSTRACT

In response to environmental problems, China has implemented many policies to control its emission of air pollutants and CO_2. As a significant source of pollutant emissions, energy use has received special attention. Shaanxi Province is a region of China with major thermal power generation, which consumes a large amount of fossil fuel and causes severe deterioration in ambient air quality. However, it is rich in natural resources that could support the development of solar energy, wind energy, and other renewable clean energies, making it a typical example of a region suitable for energy structure transformation. On the basis of environmental statistical data, field surveys, and data from the Shaanxi Provincial Bureau of Statistics, this study developed an inventory of anthropogenic source emissions of seven pollutants in 2017 in Shaanxi Province. In accordance with the established inventory, various scenarios were considered to analyze the impact of energy structure transformation on air pollutant emissions. In comparison with the Business-as-Usual scenario, the comprehensive clean energy use scenario reduced SO_2, NO_x, CO, PM_{10}, $PM_{2.5}$, VOCs, NH_3 and CO_2 emissions by 32.50%, 33.10%, 14.56%, 26.64%, 16.72%, 2.88%, 4.36% and 36.85%, respectively. Ambitious development of clean energy, such as wind and solar, could greatly reduce the emission of air pollutants, especially CO_2, SO_2 and NO_x, that are derived mainly from fossil fuel combustion, showing that strict control of the energy structure could reduce pollutant emissions. This work is important for quantifying the impact of energy restructuring on regional air quality and providing pollution control policies for environmental managers.

1. Introduction

Over the past 20 years, China's total energy consumption (equivalent to standard coal) has increased by 209%. Coal, oil, gas, and other fossil energy account for more than 80% of China's total energy consumption (NBSC, 2021), the emissions from which cause serious air pollution and drive climate change (Dong, 2019; Hu and Guo, 2020; Li and Liu, 2020; Zhan et al., 2018). Poor air quality has harmful effects on both human health and economic growth (Almetwally et al., 2020; Cassell et al., 1965; Dong, 2019; McCarroll et al., 1965; Meng et al., 2021; Schmidt, 2002; Stokstad). The economic burden of premature mortality and morbidity associated with air pollution in China in 2013 was 157.3 billion yuan or 1.16% of the gross domestic product (GDP) (Word Bank, 2007). Extended exposure to harmful air pollutants can also have a serious impact on different organs (Mabahwi et al., 2014). Shaanxi Province is a major energy province in China. Coal is the main energy source in Shaanxi Province, and the amount of coal used in 2017 was 20.07 million tons, accounting for 74.80% of the province's total energy

Peer review under responsibility of Turkish National Committee for Air Pollution Research and Control.
* Corresponding author. 121 Zhangjialukou, Huaxiang Fengtai District, Beijing, China.
** Corresponding author. No.15 North Third Ring Road, Chaoyang District, Beijing, China.
E-mail addresses: hongmeil@cueb.edu.cn (H. Li), xiaoyong@buct.edu.cn (Y. Xiao).
[1] Represents that the first two authors contributed equally to this paper.

https://doi.org/10.1016/j.apr.2023.101937
Received 1 July 2023; Received in revised form 19 September 2023; Accepted 25 September 2023
Available online 29 September 2023
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consumption (equivalent to standard coal). This level of coal consumption represented 5.13% of China's total consumption, ranking Shaanxi Province ninth nationally (NBSC, 2018; SPPG, 2022). Therefore, Shaanxi Province is a suitable case study for the impact of energy restructuring on the reduction of air pollutants and CO_2 emissions.

Adjusting the energy structure and using clean energy sources can reduce the emission of pollutants (Yang et al., 2016). The implementation of renewable energy policies has reduced mortality from air pollution in the Latin America and Caribbean countries (Koengkan et al., 2022). Renewable energy policies can reduce atmospheric emissions of mercury in Europe, and simulations of the power sector showed that mercury emission reductions have synergistic benefits with other air pollutant reductions due to changes in the energy mix, with higher synergistic benefits in regions where coal is the main energy source (Rafaj et al., 2014). Nuclear and renewable energy sources can reduce global air pollutant emissions, with wind energy being the most effective source of global energy to combat pollution and climate change (Horobet et al., 2022). The power sector, especially thermal power generation, is a major contributor to atmospheric pollutants and climate change (Zheng et al., 2018). The transformation of the energy structure of the power industry and the vigorous development of green energy are effective measures to reduce pollutant emissions. Han et al. (2023) analyzed the spatial and temporal characteristics of China's wind farms, and the carbon reduction efficiency of China's wind power has increased year by year, and the development of the northwest region has been faster since 2015. The Chinese government has developed policies through the development of clean energy such as wind power and photovoltaic power generation to reduce pollutant emissions (NEE, 2022). Northwest China is an important region for photovoltaic power generation in China, and the carbon emission reduction efficiency of photovoltaic power generation in Shaanxi Province was improving year by year (Ren et al., 2020). Therefore, selecting typical provinces with large energy consumption and analyzing the impact of adjusting energy structure adjustment on air pollutant emissions from different industries can reflect its emission reduction effect more specifically and provide more favorable data support for policy formulation.

In 2017, the total power generation in Shaanxi Province was 181.4 billion kWh, of which thermal power accounted for 87.47%, and clean energy accounted for 12.53%, in which hydroelectric power, wind power, and photovoltaic power accounted for 7.84%, 2.80%, and 1.89% of the total power respectively (DEES, 2018b). Shaanxi Province is an important part of the Fenwei Plain. Most atmospheric $PM_{2.5}$ on the Fenwei Plain comes from industrial emissions (30.5%) and coal combustion (28.3%) (Liu et al., 2022), and thus the Fenwei Plain is one of three key areas identified for air pollution control (Chen et al., 2020). At the same time, photovoltaic power generation in Shaanxi Province has developed rapidly and is a key area for China to develop clean energy (Liao et al., 2022). Currently, the Multi-resolution Emission Inventory for China (MEIC) has done the emission inventory of Shaanxi Province for 2017. However, its data on energy consumption comes from Chinese Energy Statistics, and this data is not refined to individual sectors (Li et al., 2017; Zheng et al., 2018).

Therefore, this study establishes an enterprise-level high-resolution air pollutant and CO_2 emission inventory for Shaanxi Province. To investigate the impact of energy structure adjustment on air pollutants and CO_2 emissions, we constructed four scenarios based on emission inventories, the 14th Five-Year Plan targets, and the resource endowment of Shaanxi Province. The air pollutant and carbon emissions under each scenario are projected for Shaanxi Province in 2025 and 2030. The impact of energy structure transformation on air pollutant emissions was assessed to provide a reference for pollutant control in other provinces with similar energy structures.

2. Material and methods

2.1. Study domain

The study region of Shaanxi Province covers an area of approximately 20.56×10^4 km^2 (31°42′–39°35′N, 105°29′–111°15′E), has 10 prefecture-level cities, and had a population of 38.35 million residents in 2017 (Fig. 1). The GDP of Shaanxi Province of 2189.88 billion RMB in 2017 ranked fifteenth in China (NBSC, 2018). Among the five northwestern provinces, Shaanxi Province ranks first in terms of total GDP, per capita GDP, per capita disposable income, and fiscal revenue. According to the Department of Ecology and Environment of Shaanxi Province, the average proportion of "good air" days in Shaanxi Province in 2017 was 65.3%, i.e., lower than the national average proportion of good air days at the prefecture level and above (78.0%) (DEES, 2018a; MEE, 2018a; MEE, 2018b). Shaanxi Province is under pressure to reduce its air pollutant emissions (Luo and Zhang, 2018; Xu et al., 2017). The terrain of Shaanxi Province is high in the north and south, and low in the middle, with plateau, mountain, plain, and basin. The north is the loess plateau area of northern Shaanxi; The central part is the Guanzhong Plain; The south is the Qinba Mountains in southern Shaanxi. Northern Shaanxi and Guanzhong have a temperate climate, strong northwesterly winds in winter and spring in this region. While southern Shaanxi has a northern subtropical environment. The wind and solar energy resources in the north of Shaanxi Province are endowed with good resources, excellent construction conditions, and conditions for sustainable large-scale development (NBSC, 2018; SPPG, 2022).

2.2. Emission inventory

According to the socioeconomic characteristics of Shaanxi Province, this work divided the sources of pollutant emissions into nine broad categories: fossil fuel combustion, industrial processes, solvent use, on-road mobile sources, non-road mobile sources, agriculture, dust, storage and transportation sources, and waste disposal. Each category was then subdivided based on fuel type, consumption of products, and air pollution control technology. Further details on the emission source categories are presented in Table S1.

Data on the activity levels of industrial sources such as thermal power generation and steel, cement, and flat glass manufacturing were obtained through on-site surveys. Information on aircraft movements and landings at civil aviation airports was obtained from the annual report issued by the Civil Aviation Administration of China (CAAC, 2018). Data on the activity level of agricultural sources, on-road mobile sources, and storage and transportation sources were obtained from the official website of the Bureau of Statistics, by consulting the Statistical Yearbook (NBSC, 2018). The emission factors and removal efficiency used in this study were derived mainly from a literature review. The calculation methods of each pollution source are shown in Text S1, and the emission factors adopted are presented in Text S2.

Using a geographic information system, the inventory of emissions in Shaanxi Province was allocated spatially onto a 3×3 km grid according to appropriate allocation surrogates (Table S2). Emissions from point sources with precise location data, such as cement and power plants, were assigned to corresponding grid cells. Line sources were allocated based on the traffic road network and population density. Area sources (pesticide use, residential-based combustion and non-road mobile sources) were allocated spatially based on population density. The temporal variation was derived from monthly production data for the corresponding region.

2.3. Emission reduction scenarios

According to the emission inventory for 2017 developed in this study, the primary sources of atmospheric pollutants in Shaanxi Province were fossil fuel combustion sources, especially coal-fired thermal

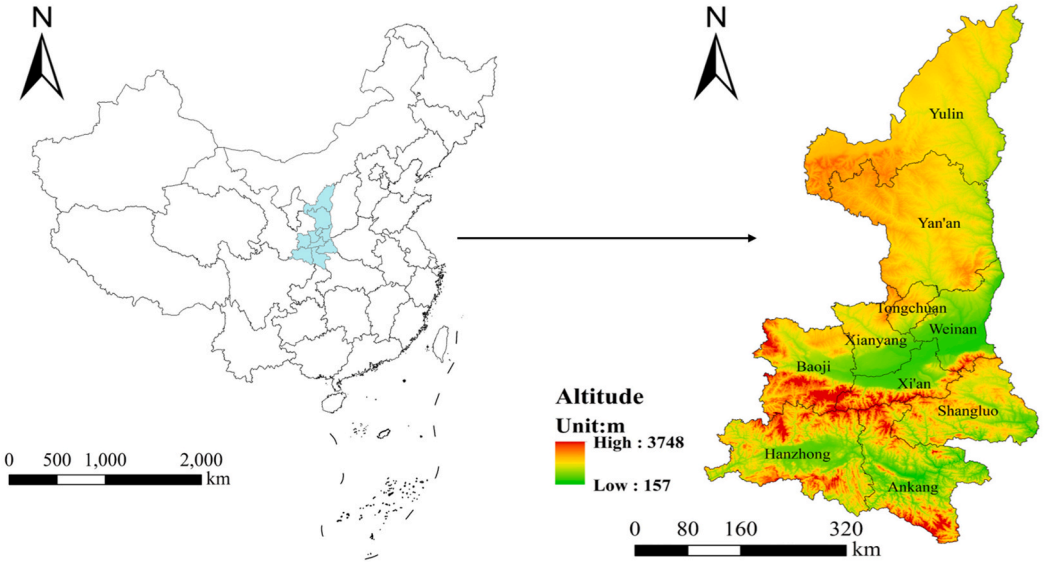


Fig. 1. Location of the study domain of Shaanxi Province within China (Note: In this work, Yangling District was grouped into the Xianyang City for the study. Altitude data from: https://srtm.csi.cgiar.org/srtmdata/).

power generation. Consequently, China's policy formulation plan promotes clean energy development in the power industry; therefore, this study specifically considered adjusting the energy structure in the power industry. To assess the impact of energy structure on pollutant emissions, on the basis of emission inventory in 2017, a reference Business-as-Usual (BAU) scenario and three energy structure scenarios were devised, with 2030 set as the target year. Table 1 shows the specific energy scenario settings. The trends of energy demand and air pollutant emissions in Shaanxi Province were affected by many macro-scale–microscale factors and were closely related to GDP and energy consumption. From the perspective of energy supply, they were also associated with factors such as the clean energy utilization rate and the energy structure of various industries.

2.3.1. *Business-as-usual (BAU) scenario*

The BAU scenario assumes that the clean energy utilization rate, power system structure, end-of-pipe treatment technology, and other indicators of various departments in Shaanxi Province are maintained at the level of the base year. According to the details of the 14th Five-Year Plan, energy consumption is proportional to socioeconomic development (i.e., GDP). The growth rate of GDP and the energy consumption rate per unit of GDP are shown in Table S3. The increase in electricity production is shown in Fig. S4.

2.3.2. *Clean power generation (CPG) scenario*

This scenario considers the development of clean energy, such as wind power and photovoltaic power generation, while the energy structure of other pollution sources remains consistent with that of 2017. According to the 14th Five-Year Plan for National Economic and Social Development in Shaanxi Province and the outline of the 2035 vision, the proportion of non-fossil energy power generation is projected to reach approximately 39% in 2025. The total installed capacity of electricity will be more than 136 million kW, of which 65 million kW will comprise renewable energy. Wind power, photovoltaic power, hydropower, and biomass power generation will reach 20, 38, 6, and 1 million kW, respectively. In 2030, the proportion of clean energy development will be 50%.

Table 1
Energy scenario setting.

Energy scenarios	Description
BAU	Energy consumption is constrained according to the prediction results, and the energy structure remains unchanged.
CPG	Vigorous development of wind, photovoltaic, and other clean energy power generation
ECPG	Considering the pollution sources of non-power consumption energy Such as civil combustion sources and road mobile sources, clean energy is used.
CCEU	Simultaneously adjust the energy structure of the power industry and non-power industry.

2.3.3. *Except clean power generation (ECPG) scenario*

This scenario considers the pollution sources of non-power-consumption energy, such as civil combustion sources and road mobile sources, and uses clean energy. According to the 14th Five-Year Plan for "Ecological Environment Protection in Shaanxi Province," the proportion of non-fossil energy in total energy consumption will reach 16% in 2025, and the ratio of non-fossil energy consumption will run approximately 20% by 2030.

2.3.4. *Comprehensive clean energy use (CCEU) scenario*

This scenario considers the CPG and ECPG scenarios and adjusts the energy structure of both the power industry and the non-power industry.

According to the resource endowments and policies of Shaanxi Province, the specific parameters of this scenario are presented in Table S3. In order to achieve the goal of clean energy, Shaanxi Province has taken many measures. Policies on the development of clean energy since 2017 in Shaanxi are presented in Table S4.

3. Results and discussion

3.1. *Status of air pollutant emissions in Shaanxi Province in 2017*

Table 2 shows the emission inventory for Shaanxi Province in 2017. CO_2 was the most significant emitted pollutant with 30658.80 kt. Except for NH_3, point sources were the primary source of pollutants, accounting for approximately 35.32%–89.66% of total pollutant emissions.

The contribution of each subcategory to the total emissions of the seven pollutants is shown in Fig. 2, and the contribution of each city is shown in Fig. S1. The main source of SO_2 emissions was fossil fuel combustion, which accounted for 64.33% of the total. Power plants, residential combustion, and coal production were the main subcategories of this source of SO_2, accounting for 56.99%, 12.99%, and

Table 2
Emission of pollution in Shaanxi Province (2017) (Unit: kt).

	SO_2	NO_x	CO	PM_{10}	$PM_{2.5}$	VOCs	NH_3	CO_2 (10^4t)
Fossil fuel combustion	82.18	167.76	603.67	103.41	28.21	58.38	11.88	19502.26
Industrial processes	45.19	63.76	873.48	167.96	89.88	608.18	32.67	7258.92
Solvent use	0.00	0.00	0.00	0.00	0.00	15.61	0.00	0.00
On-road mobile sources	2.98	132.56	313.98	3.84	3.52	34.44	2.71	3628.10
Non-road mobile sources	0.60	17.61	16.43	1.49	1.39	3.75	0.00	269.52
Agriculture	0.00	0.00	0.00	0.00	0.00	0.00	152.87	0.00
Fugitive dust	0.00	0.00	0.00	2.82	1.92	0.00	0.00	0.00
Storage and transportation source	0.00	0.00	0.00	0.00	0.00	14.94	0.00	0.00
Waste disposal source	0	0	0	0	0	2.37	5.92	0.00
total	130.95	381.68	1807.57	279.52	124.93	737.67	206.05	30658.80

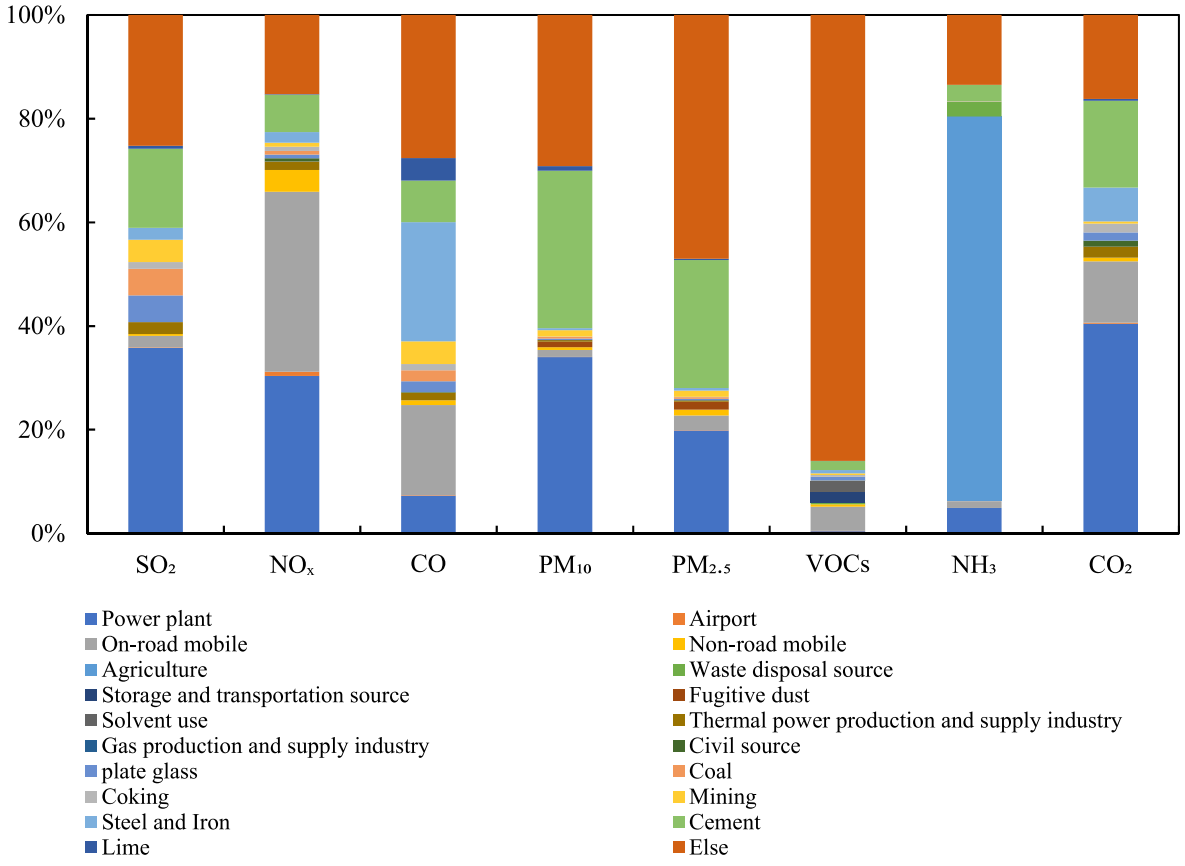


Fig. 2. Pollutant emission source by subcategories in Shaanxi (2017)

8.19%, respectively, of the emissions from fossil fuel combustion sources. If left unchecked, the increasing demand for electricity associated with the rapid socioeconomic development of Shaanxi Province is expected to further increase SO_2 emissions from power plants in the future. Therefore, measures to control the emission of pollutants from power plants should be strengthened.

In terms of the largest contributor to fossil fuel combustion sources (45.05%), power plants were the subcategory that contributed the most NO_x emissions, accounting for 69.12% of the total emissions from fossil fuel combustion sources. Of on-road mobile sources (35.60%), heavy trucks contributed the most to NO_x emissions, accounting for 57.66% of the total. Although there were not many heavy trucks, their diesel engines burn fuel more efficiently than the engines of cars that run on gasoline. Therefore, raising vehicle emission standards in the future, promoting clean energy vehicles, and improving fuel quality are crucial to controlling NO_x emissions.

The major contributors to PM emissions were industrial process sources and fossil fuel combustion. Industrial process sources accounted for 59.93% and 71.79% of total PM_{10} and $PM_{2.5}$ emissions, respectively. The principal subcategory was the cement industry, which accounted for 47.78% and 34.43% of the total PM_{10} and $PM_{2.5}$ emissions, respectively, released through the kiln tail gas, cement production, and other industrial waste gases. The main subcategory of fossil fuel combustion sources was power plants, which were also major contributors to PM_{10} and $PM_{2.5}$, accounting for 34.11% and 19.23% of total emissions, respectively.

Fossil fuel combustion sources were the most significant contributor to CO emissions (43.39%), followed in descending order by industrial process sources (32.89%) and mobile sources (22.57%). Emissions from power plants were the largest, accounting for 21.84% of emissions from fossil fuel burning. In terms of mobile sources, passenger cars contributed 52.04% of CO emissions.

The major contributor of volatile organic compounds (VOCs) was industrial processes (82.30%). The subcategory of the manufacturing of ceramic building products accounted for 37.10% of the total emissions of VOCs. Passenger cars and the industrial coating industry contributed

10.81% of the total emissions of VOCs. Different from other pollutants, emissions of NH_3 were mainly from the agriculture sector (71.86%) rather than from industrial sources. This is because of the large number of livestock and the large area of agricultural cultivation in Shaanxi Province. Therefore, the subcategory of livestock accounted for 51.19% of total NH_3 emissions, followed by nitrogen fertilizer use, which accounted for 19.32%. 63% of CO_2 emissions came from fossil fuel combustion sources. This was because energy-consuming behaviors

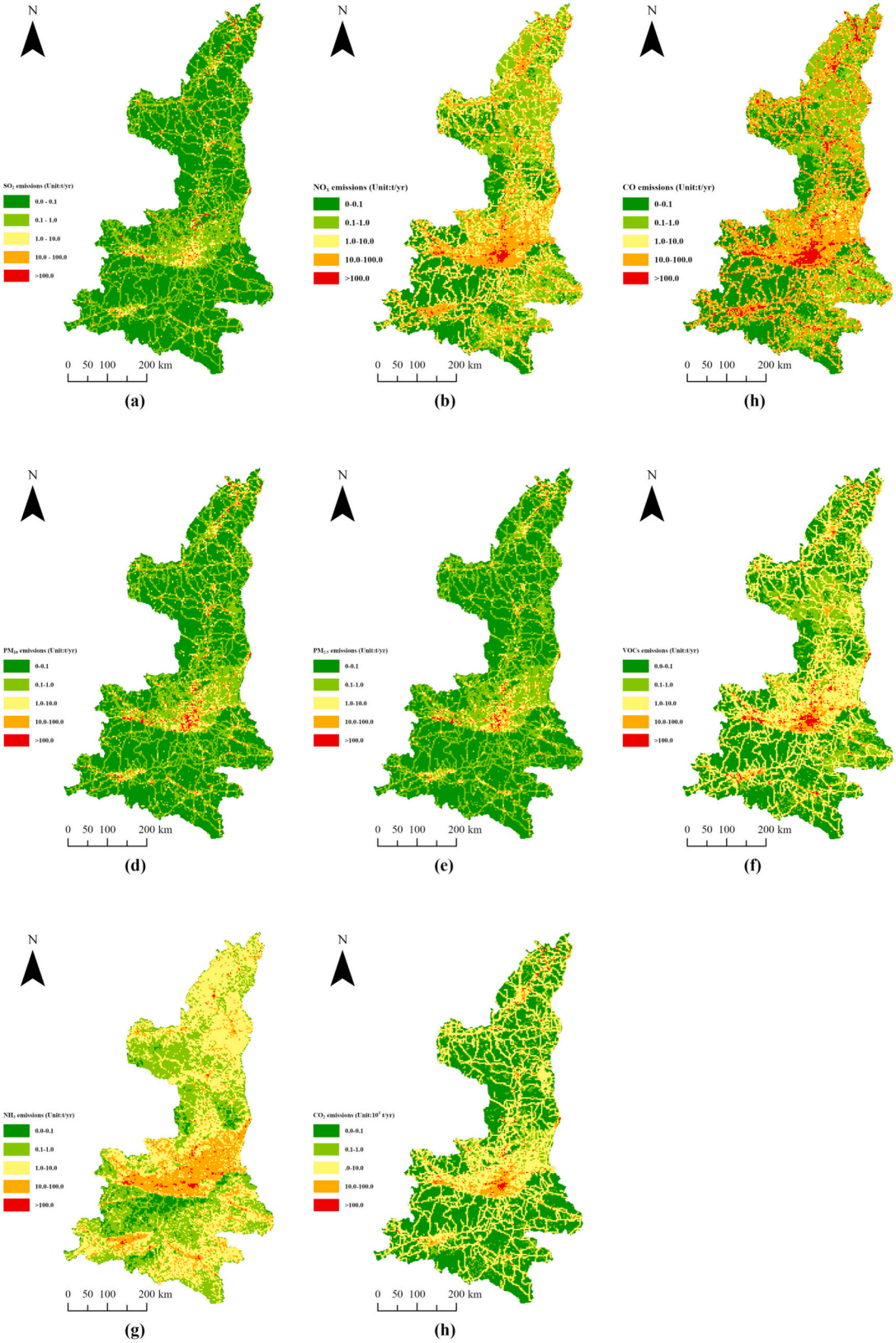


Fig. 3. Spatial emission characteristics of pollution at 3*3 km resolution in Shaanxi (2017)

such as coal-fired power generation release large amounts of CO_2. Emissions of CO_2 were concentrated in Yulin (31.53%).

3.2. Spatial distribution characteristics of air pollutants in Shaanxi Province in 2017

The spatial distribution of the emissions of each of the eight pollutants of interest in Shaanxi Province in 2017 is shown in Fig. 3. Fig. S1 illustrates the contribution of eight pollutants to total emissions in Shaanxi at the urban level. The Guanzhong area is an important area of pollutant emissions in Shaanxi Province, particularly around Xi'an and Xianyang. This area is the economic center of Shaanxi Province and even Northwest China, with developed industry, high traffic flow, and high population density (Fig. S2). Industry in Yulin, Xianyang, Weinan, and Tongchuan has developed rapidly with many factories being built, which consume large amounts of fossil fuel and produce high levels of SO_2 emissions. The distributions of PM, CO, and NO_x have a direct relation to the dense distribution of factories (point sources) and road networks (line sources) in Yulin, Baoji, and Xi'an. Emissions of VOCs were mainly concentrated in areas with highly developed industries, e.g., Yulin, Baoji, and Weinan. Owing to the high level of agricultural and animal husbandry activities, the regions responsible for significant emissions of NH_3 were primarily in western parts, e.g., Weinan, Xianyang, Xi'an, and Baoji. The main source of CO_2 emissions was Yulin, which was due to the fact that Yulin has a large number of power plants in Shaanxi.

3.3. Characteristics of temporal variation of pollutant emissions in Shaanxi Province in 2017

The monthly (Jan–Dec) variations of pollutant emissions were characterized based on industrial production data output by the National Bureau of Statistics. Generally, pollutant emissions from power plants were lowest in September and highest in December because of the cold weather conditions in winter.

The monthly variations of the emissions from the major subcategories of industrial processes are shown in Fig. S3. The emission rate of thermal power generation was affected substantially by season. Owing to the need for heating (cooling) in winter (summer), thermal power generation peaked in December (July). Marked differences were observed in the monthly distribution across industrial sectors. In January, February, and December, the output of the cement industry was low owing to the influence of seasons and holidays, especially the Spring Festival. During March–August, the climate was more suitable for construction activities, demand was generally stable, cement output was relatively high, and associated pollutant emissions were reasonably large. Monthly changes in pollutant emissions associated with steel, flat glass, and coke production showed an overall trend of gradual increase with slight fluctuation.

In comparison with other pollution sources, the characterization of non-road mobile sources was more uncertain owing to the lack of field survey data. The emissions of NO_x were affected by the quantity of agricultural equipment, annual usage time, and emission factors, and thus the associated uncertainty was relatively considerable. Generally, emissions from point sources contributed less uncertainty, except those of NO_x.

3.4. Emission reduction analysis with four scenarios

The projected emissions of air pollutants under different energy structure scenarios are shown in Fig. 4. During 2017–2030, despite the expected decrease in energy consumption per unit of GDP, emissions of various anthropogenic air pollutants in Shaanxi Province are expected to continue to increase because of the overall growth of GDP, which will still consume a considerable amount of fossil energy (Huo et al., 2014). It is assumed that air pollutants and CO_2 emissions from clean energy

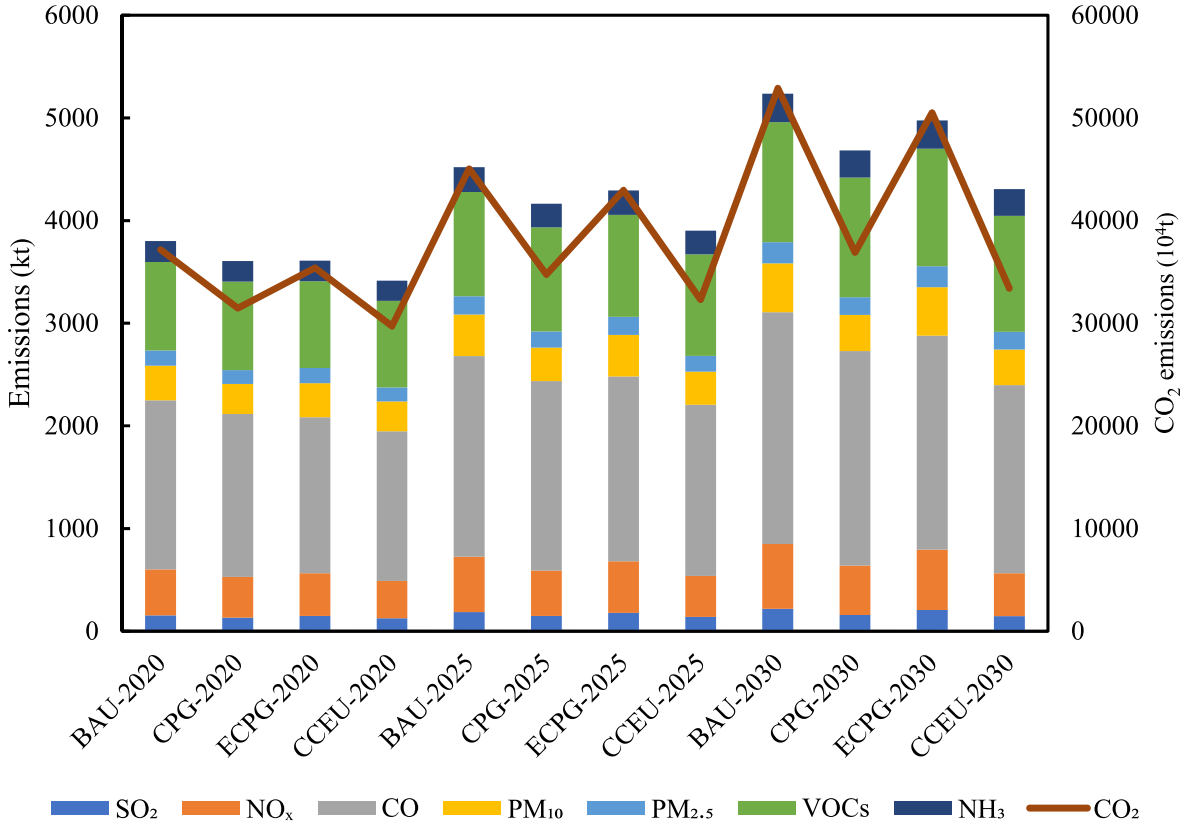


Fig. 4. Emission inventory under different energy structure scenarios.

sources such as wind power and hydropower are zero. Pollutant emissions from other energy sources are proportional to energy consumption. Increased electricity in the forecast years comes from clean energy sources. Under the BAU scenario, the total emissions in 2020, 2025, and 2030 are projected to be 1.21, 1.46, and 1.72 times greater than those in 2017, respectively.

Among the seven pollutants studied, CO_2, SO_2, and NO_x emissions are affected most by the energy structure. Under all energy adjustment scenarios, emissions of NH_3 are projected to be slightly lower than those under the BAU scenario in the same year. This is primarily because the main source of NH_3 emissions is agricultural activities, the emissions of which are affected less by the energy structure.

Under the CPG scenario, the reduction rate of SO_2 is the largest among the seven kinds of pollution. It is estimated that compared with the BAU scenario, the reduction rate of SO_2 in 2030 and 2025 will be 26.97% and 20.35%, respectively. In 2025, the installed capacity of photovoltaic power generation will reach 38 million kW in Shaanxi Province, accounting for 50.48% of the total clean energy resource, and wind power will account for 30.77%. The northern part of Shaanxi Province, which extends across the desert and the Loess Plateau, has abundant solar and wind resources, making it a region highly suitable for the development of photovoltaic and wind power.

In comparison with the CPG scenario, the ECPG scenario has a less effective controlling effect on pollutant emissions, which is attributed to the fact that the largest source of pollutant emissions in Shaanxi Province is thermal power generation. The transformation of thermal power plants, optimization of the power structure, and reduction of dependence on thermal power generation are important measures with which to control pollutant emissions.

In the CCEU scenario, the reduction in emissions of SO_2, NO_x, CO, PM_{10}, $PM_{2.5}$, VOCs, NH_3 and CO_2 is projected to be 72.77, 213.80, 425.46, 126.87, 34.61, 33.81, 14.45 and 194927.02 kt, respectively, 32.50%, 33.10%, 14.56%, 26.64%, 16.72%, 2.88%, 4.36% and 36.85% lower than those under the BAU scenario. The CCEU scenario is a comprehensive scenario of the measures incorporated in the ECPG and CPG scenarios, but the overall emission reduction effect is better than that of a single measure. When adjusting the energy structure, in addition to focusing on key polluting industries, control sources with relatively small pollutant emissions, such as road mobile sources and civil combustion sources, need to be controlled. In terms of source types, In 2030, compared to the BAU scenario, the total amount of air pollutants and carbon from point, line, and surface sources under the CCEU scenario will be 25642.53, 2728.54 and 339.32 million tons respectively, and the emission reduction ratios will be 39.06%, 20.00% and 9.74%. Point sources will be the most efficient at reducing emissions, which is attributed to the use of cleaner ways of generating electricity, such as wind and solar.

Under the CPG, ECPG, and CCEU scenarios, air pollutant emissions are projected to maintain a trend of increase, but the rate of growth is markedly slower than that under the BAU scenario. Therefore, controlling energy consumption and adjusting the energy structure will play an important role in reducing pollutant emissions, especially those of SO_2, NO_x, PM and CO_2. The distribution of wind power and photovoltaic power generation cities in Shaanxi Province is shown in Table S5. The wind power and photovoltaic power generation projects in Yulin and Yan'an in the northern part of Shaanxi Province account for 30.97% of the total, which to a certain extent alleviates the emission pressure in the Guanzhong area. Other regions should fully exploit their own natural resources, actively explore the development of clean energy, and seek sustainable development.

3.5. Comparisons and uncertainty

To assess the quality of our emission inventory in 2017, this study compared it to MEIC (Li et al., 2017; Zheng et al., 2018), which also includes results for Shaanxi Province in 2017. As can be seen from Table 3, the emissions of VOCs, PM_{10} and NH_3 estimated in this study are broadly consistent with the MEIC calculation results. However, the emissions of SO_2 and NO_x estimated in this study are much lower than those in the MEIC, which is mainly due to the difference in control efficiency. Since the CO_2 calculation method in this study references CHRED3.0A (Gao et al., 2022), the data sources and emission factors were the same as it, and the activity levels of the main sources of CO_2 in Shaanxi Province did not change much in 2017 and 2018, the calculated CO_2 emissions were approximately the same.

The marked differences between the MEIC and the inventory compiled in this study might also be attributable to the classification of activity data and removal efficiency. This study used city-level activity data, which are more accurate than provincial- or national-level data. The removal efficiencies used in this study were based on field surveys and thus were considered more realistic.

In this study, Monte Carlo simulations were performed using R (version 4.2.0) to assess the uncertainty of the compiled inventory. Detailed probability distribution data of emission factors and activity data are shown in Tables S6–S13. Overall, 5000 simulation experiments were performed using the Monte Carlo framework and the 95% confidence interval of the emissions. Specific steps were described in Text S3. This analysis indicated that the results of this work could be considered acceptable, with 2 standard deviations within 2.99%, 7.13%, 3.39%, 4.62%, 4.55%, 6.63%, 6.45% and 2.53% for total emissions of SO_2, NO_x, CO, PM_{10}, $PM_{2.5}$, VOCs, and NH_3, respectively.

4. Conclusions

To investigate the impact of different energy structures on the discharge amount of air pollutant emissions, we developed a high-resolution spatial and temporal emission inventory of seven air pollutants in Shaanxi Province, China. On the ground of the 2017 emission inventory and energy policy of Shaanxi Province, one baseline scenario and three energy structure scenarios were established. The main contributors of SO_2, NO_x, and CO were fossil fuel combustion sources. In the context of comprehensive consideration of the energy structure adjustment of thermal power and other energy-consuming industries (CCEU scenario), the emission of SO_2, NO_x, CO, PM_{10}, $PM_{2.5}$, VOCs, and NH_3 was projected to decrease by 33.24%, 33.80%, 18.83%, 26.73%, 16.80%, 3.39%, and 6.25%, respectively, compared with that under the BAU scenario in 2030. From the perspective of pollutants, the reduction of emissions from the main source of fossil fuel pollutants (CO_2, NO_x and SO_2) is remarkable. From the perspective of emission reduction measures, ambitious development of wind power and photovoltaic power generation, and comprehensive adjustment of the energy structure of road mobile sources and civil combustion sources are more conducive to reducing air pollutant emissions. Notably, adjustment of the energy structure alone will substantially slow the rate of increase in air pollutant emissions by 2030, but will not reduce pollutant emissions. Therefore, in addition to adjusting the energy structure, we should

Table 3
Comparison of emissions calculated in our study with those of the MEIC (unit: 10^4 t).

Reference	Year	Region	SO_2	NO_x	PM_{10}	VOC_S	NH_3	CO_2
MEIC	2017	Shaanxi	33.70	54.72	29.42	81.13	27.84	
CHRED3.0A	2018							30971.41
This study	2017	Shaanxi	13.10	38.17	27.95	73.77	20.61	30658.80

incorporate industrial structure adjustment, progress terminal treatment technology, and introduce other comprehensive measures to improve emission control efficiency. As a region of large thermal power generation, Shaanxi Province could provide other similar provinces with ideas for reducing their pollution and carbon footprint.

Funding This work was supported by grants from the National Natural Science Foundation of China (No. 72174125), Fundamental Research Funds for the Central Universities (buctrc202133), and State Key Laboratory for Clean and Efficient Coal-fired Power Generation and Pollution Control/National Energy Research Center for Thermal Power Generation Energy Conservation, Emission Reduction and Pollution Control Open Subjects (D2022FK075).

Credit author statement

Xin Bo: Conceptualization, Methodology, Writing – original draft, Validation, Funding acquisition.; Qian You: Formal analysis, Writing – original draft, Validation, Methodology.; Minjie Sang: Investigation, Data curation Conceptualization, Data collection and investigation.; Peng Wang: Data curation, Visualization, Data collection and investigation.; Shaobo Chen: Writing - review & editing, Data collection and investigation.; Xin Xu: Investigation, Writing-review & editing.; Wanyue Shan: Data collection and investigation.; Ying Yang: Visualization.; Bertrand Bessagnet: Writing-review & editing.; Hongmei Li: Conceptualization, Supervision, Methodology, Writing-review & editing.; Yong Xiao: Conceptualization, Supervision, Methodology.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apr.2023.101937.

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