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A comprehensive provincial-level VOCs emission inventory and scenario analysis for China: Enhanced sectoral resolution through GAINS-China model

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ABSTRACT

Volatile organic compounds (VOCs) are key precursors to secondary organic aerosol (SOA) and ground-level ozone, posing significant challenges to air quality and public health in China. Although previous studies have established VOCs inventories and projected emission trends, many lack the granularity needed to capture sectoral and regional emission variations, especially within the highly contributive solvent use sector. To address this gap, this study aims to develop a detailed VOCs emission inventory for China at the provincial level for 2020, utilizing the GAINS-China model and covering 5 major sectors, 20 subsectors, and 80 distinct emission sources. Uniquely, this inventory subdivides the solvent use sector into 5 subsectors and 22 specific sources, enabling a more precise analysis of VOCs emission sources. Future emission trends and reduction potentials were projected for the period 2020–2050 under two scenarios: reference (REF) and current legislation (CLE). The results revealed that the total anthropogenic VOCs emissions in China were estimated to be 23,114.8 kt in 2020, with solvent use contributing 56.0%, followed by the residential (17.0%), others (11.0%), transportation (10.0%), and industry and power (6.0%) sectors. Under the REF scenario, VOCs emissions are expected to decline to 19,162.2 kt by 2040 but remain stable thereafter. This reduction is driven mainly by the replacement of household solid fuels with clean fuels in the residential sector, especially in Sichuan Province. Compared with those in the REF scenario, the total VOCs emissions in the CLE scenario continuously decreased throughout 2020–2050, with the solvent use sector contributing the most to the reductions (46.1%–81.7%), followed by transport (16.8%–41.3%). A provincial analysis highlights that high-emission regions such as Guangdong, Jiangsu, and Shandong offer the greatest reduction potential. To effectively and precisely reduce VOCs emissions, key subsectors contributing to emissions, including paint use, non-road machinery, industrial processes, and agriculture, should be prioritized for further control measures. This study provides essential insights into sectoral and regional VOCs emissions, offering a robust foundation for formulating targeted emission control policies.

1. Introduction

In China, air pollution from secondary organic aerosol (SOA)-fine particles formed from chemical reactions involving volatile organic compounds (VOCs), and ground-level ozone (O_3) is becoming increasingly prominent, impacting air quality and public health (Liu et al., 2021, 2023a; Li et al., 2022). Despite some progress in reducing particulate matter ($PM_{2.5}$) pollution over recent decades, 180 of 337 cities still failed to meet the National Ambient Air Quality Standard in 2019, which sets an annual mean concentration limit of 35 μg/m^3 for $PM_{2.5}$(Shi et al., 2021; Ministry of Ecology and Environment of the People's Republic of China, 2019). Moreover, O_3 pollution has become an increasingly serious issue in China (Liu et al., 2024). The 90th percentile of the maximum daily 8-h average (MDA8) concentration of O_3 in China has increased by 10.4% during 2015–2019 (Ministry of Ecology and Environment of the People's Republic of China, 2019). The persistent challenges posed by SOA and O_3 pollution highlight the critical need for implementing more targeted emission control measures.

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As important precursors of ground-level O_3 and SOA, VOCs contribute substantially to the formation of O_3 and $PM_{2.5}$ and pose carcinogenic and noncarcinogenic health risks to humans (Liu et al., 2021, 2022; Chen et al., 2023; Mcdonald et al., 2018).

In response to these issues, China has implemented a series of stringent clean air policies to mitigate anthropogenic VOCs emissions in recent years. For example, the Air Pollution Prevention and Control Action Plan in 2013 announced that the petrochemical industry should be required to implement the leak detection and repair (LDAR) program to mitigate VOCs emissions (State Council of the People's Republic of Chinaa). In China's 13th Five-Year Plan (2016–2020), a VOCs emission reduction target was included for the first time, with a target of reducing national VOCs emissions by 10% in 2020 from the 2015 level (State Council of the People's Republic of Chinab). Later, the Three-Year Action Plan for Winning the Battle for the Blue Sky was released in 2018 to further strengthen the VOCs control and guarantee the achievement of the 13th Five-Year Plan target (State Council of the People's Republic of Chinac). In 2019, to tackle the severe and widespread O_3 pollution, the Ministry of Ecology and Environment (MEE) released the Comprehensive Action Plan for VOCs in Key Industries (Ministry of Ecology and Environment of the People's Republic of Chinaa). Even more aggressive measures were implemented for the major source sector, such as industrial coating, packaging and printing, petrochemicals, and chemicals.

Unfortunately, China's anthropogenic VOCs emissions have increased by 21.9% during 2010–2019 (Ye et al., 2020), due to the dramatic growth in activities and the absence of effective control measures. Some studies reported that the growth of VOCs emissions before 2000 was driven mainly by the transportation sector, while the solvent use and industry sectors dominated emission growth during 2000–2010 (Li et al., 2019a). With rapid economic development in China since 2010, a wide range of solvent-using activities, such as paint use, printing use, industrial applications, and household solvent use, drove up VOCs emissions and remain inefficiently controlled nationwide (Zheng et al., 2018; Guo et al., 2024). In economically developed regions such as Guangdong, Zhejiang, and Shanghai, solvent use is the primary contributor to local VOCs emissions, with contribution rates generally exceeding 40% (Wang et al., 2024). As for the industrial sector, primary sources of VOCs emissions included architectural decoration, coke production, plastic manufacturing, and the raw medicine industry, with emission growth ranging from 140 to 700 Gg, between 2010 and 2016 (Simayi et al., 2019).

For policy formulation, many scholars have designed different scenarios to project VOCs emissions in conjunction with technological advances and policy requirements. Li et al. (2019b). analysed VOCs emission trends in China's coking industry from 1949 to 2016, utilizing a database of factory data and emission factors specific to each process. They further projected potential emission reductions for 2020 under three different control policy scenarios. Guo et al. (2021) established an industrial VOCs emission inventory in 2015 for Hebei Province and constructed three scenarios to project emissions for the period 2020–2030, taking into account future economic development trends, population changes, relevant environmental laws and regulations, and pollution control technologies. Simayi et al. (2022) referenced relevant policies, official documents, and industry association forecasts, designed two policy scenarios, and determined the proportions of organized and unorganized emissions and control measures for each industry, predicting emissions for 2030. Wei et al. (2011) set two control scenarios with 2005 as the base year and projected China's anthropogenic VOCs emissions from 2010 to 2020. Zheng et al. (2017) reported that the collaborative control policies considerably reduce industrial VOCs emissions.

Although studies on VOCs emission trends and reduction potentials have developed rapidly, there are still several shortcomings in the following areas. First, the solvent use sector is a significant source of VOCs emissions in China, contributing more than 40% of the total emissions and encompassing multiple subsectors (Li et al., 2019a; Zheng et al., 2018). However, this source has often been analysed as a single sector in current studies, which might complicate implementation and management efforts (Zheng et al., 2018). Second, most current studies have focused on a specific sector in a single city, single province, or at the national level (Guo et al., 2021, 2024; Zhou et al., 2020). Few studies have examined future emission trends and mitigation potentials for VOCs emissions at the intranational level through multisectoral analysis. Third, future control measures must be developed while fully accounting for the latest policies (Cai et al., 2018), such as the Three-Year Action Plan for Winning the Battle for the Blue Sky and the Action Plan, which may fundamentally alter the future emission pathways. However, in previous studies, the base year of most projections was 2015 or earlier, making it difficult to capture the dramatic changes in VOCs emissions during recent years or over the next several years in China (Zheng et al., 2018; Wei et al., 2011).

This study aims to establish a detailed and comprehensive inventory of anthropogenic VOCs emissions across China at the provincial level for the year 2020, leveraging the Greenhouse gas - Air pollution Interactions and Synergies (GAINS) model to include emissions from 5 major sectors and 20 subsectors, covering a total of 80 emission sources. Unlike previous studies, we subdivide the solvent use sector into 5 subsectors and 22 specific sources to provide a more granular analysis of VOCs emissions. Furthermore, the study projects future emission trends and reduction potentials from 2020 to 2050 under two scenarios (reference and current legislation), providing essential insights into the effects of potential control measures. By analysing sectoral contributions at both the national and provincial levels, this study highlights regional emission disparities and identifies high-priority areas for VOCs reduction. Our approach integrates more recent policy developments and provides an updated assessment of reduction potential. The results provide a robust foundation for policymakers aiming to design effective VOCs control strategies in alignment with China's air quality goals. The structure of this paper is organized as follows. After Section 1, Section 2 introduces our research methodology for estimating VOCs emissions via the GAINS model. Section 3 presents VOCs emissions from 2020 to 2050, source distributions, and the emission reduction potential after the application of control measures. Section 4 presents the evaluation of our emission inventory and implications for uncertainties. Finally, we draw conclusions and policy implications in Section 5.

2. Materials and methods

The research area covers 31 provincial administrative regions in China. Due to data unavailability, Hong Kong, Macau, and Taiwan are not included in this study. We employed the GAINS-China model (Amann et al., 2008), a regional version of the GAINS model, to investigate VOCs emission scenarios and reduction effects in China at the provincial level. The ECLIPSE_V6c_CLE_base scenario (Shu et al., 2022), which considers new emission control policies announced under China's 13th Five-Year Plan and several newer emission standards released after 2015, was adopted to estimate the emissions of VOCs from 2020 to 2050. Specifically, activity data, emission factors and control strategies in 2020 were updated for the solvent use sector.

2.1. VOCs emission estimation

VOCs emissions originate from a wide variety of sources, each with distinct technical and economic differences (Simayi et al., 2019; Liu et al., 2023b). To comprehensively account for all solvent-related sources in China, this study supplements and optimizes the emission inventory by incorporating essential sources often overlooked in previous studies, such as coil coating, tire production, and rotogravure in publication. For non-solvent sources, the classification was based on the characteristics of VOCs emission sources in China, the national statistical data reporting system, and the availability of relevant data. For the

GAINS VOCs module, we included 5 sectors (solvent use, residential, transportation, industry and power, and others) and 20 subsectors, incorporating a total of 80 VOCs emitting sources. Table S1 presents the detailed source categories, along with unabated emission factors and relevant references. The fuel production & distribution subsector is included in the 'others' sector. Combustion processes for both fossil fuels and biofuels were included in the analysis for boilers and stoves. The VOCs emissions of each source category distinguished in the model were calculated with the product of the activity rate, the (unabated) emission factor and the removal efficiency of applied emission control devices (accounting for the penetration of emission controls) via Eq. (1) (Klimont et al., 2002):

$$E_{VOC(k)} = \sum_{l,m,n} A_{k,l,m} \times EF_{l,m} \times \left(1 - \eta_{l,m,n}\right) \times X_{l,m,n} \tag{1}$$

where the subscript *k, l, m,* and *n* represent country/region, sector, raw materials/fuel, and abatement technology, respectively; $E_{VOC(k)}$ represents the VOCs emissions in a certain province; *A* and *EF* represent activity data and the unabated emission factor, respectively; $\eta_{l,m,n}$ represents the removal efficiency of sector *l*; *X* represents the actual application rate of control technology *n*.

2.2. Activity data and emission factors

To obtain activity data for 2020, the amount of solvent use (including the consumption of solvent-containing products, paint and ink, as well as production outputs and population), the use of fossil fuels and biofuels, the number of vehicles, and the aggregated quantities of gasoline and diesel from importation, exportation, refinery and vehicle refueling were used as activity units. This sector was divided into 5 subsectors based on the characteristics of each subsector: paint use, other industrial applications, household solvent use, manufacturing industry, and printing use. Ultimately, all subsectors were further classified into 22 types of sources. For paint use, including vehicle refinishing and industrial paint use (continuous processes and other), data for these activities were collected from the China Statistical Yearbook, the China Transportation and Communications Yearbook, the China Automotive Industry Yearbook, the China Paint and Coatings Industry Yearbook, and the China Industry Economy Statistical Yearbook. In terms of solvent use other than paint, such as industrial application of adhesives, wood preservation, domestic use of solvents, the pharmaceutical industry, shoe manufacturing, food production and printing use, solvent consumption amounts were obtained from the China Light Industry Yearbook, the China Forestry Statistical Yearbook, the China Rubber Industry Yearbook, and the China Food Industry Yearbook. Given that activity data for the solvent use sector can be obtained only at the national scale, we allocated the national activity data to provinces based on factors such as construction area, population, vehicle ownership, and cultivation area (Li et al., 2019a). A detailed description of the residential, transportation, industry and power, and 'others' sectors is provided in Supplementary Section 1.2.

The unabated emission factors used in our calculation were determined based on recent measurements or a systematic literature review, including the European Environment Agency (EEA) guidebook (European Environment Agency, 2023), the Compilation of Air Pollutant Emission Factors (AP42 report) (Environmental Protection Agency Compilation of), the Technical Guidelines for the Compilation of Atmospheric Volatile Organic Compounds Emission Inventory (Ministry of Ecology and Environment of the People's Republic of Chinab) and peer-reviewed literature (Klimont et al., 2002; Tsai et al., 2003; Wei et al., 2009; Zheng et al., 2014; Bo et al., 2008). For most solvent use sources, local unabated emission factors measured in China are still limited. In such cases, we mainly refer to data from the EEA guidebook or the AP42 report, combined with source information from local investigations where available. According to the reported literature (Bo et al., 2008; Sun et al., 2018), the industrial technology level in China lags behind that of developed countries such as the U.S. and E.U. by approximately 5–10 years. Consequently, for certain sources, emission factors for a given year in China were derived from emission factor data representing the same sources in developed countries 5–10 years earlier, as provided in the AP-42, rather than using updated emission factor data reflecting current emissions levels in those countries. Table S1 presents the unabated emission factors adopted in this work. Future changes in emission factors were estimated through the effective rates of control strategies.

Control strategies for limiting VOCs emissions cover the solvent use, industry, transport, residential, and fuel production & distribution sectors (Zheng et al., 2018). Strategies commonly used to reduce VOCs emissions from stationary sources fall into three main categories: adopting eco-friendly alternatives (such as low-VOC or water-based products), implementing end-of-pipe control technologies (like adsorption or catalytic incineration), and employing emission management practices (Wang et al., 2023). For example, the Chinese government has introduced standards to limit solvent content in various products, including wood coatings (GB, 18581-2020) (a), architectural paints (GB, 18582-2020) (b), automotive paints (GB 24409-2020) (c), and indoor adhesives (GB, 18583-2008) (d). These regulations have driven a decrease in solvent content in certain products and increased the adoption of low-solvent alternatives, thereby reducing associated emission factors. Table S3 provides details on the adoption rates of key control measures within the solvent use sector. In addition, reductions in VOCs emission from the transportation sector are achieved mainly through fleet turnover, which involves replacing old vehicles with newer models that are subjected to stricter emission standards (Zheng et al., 2018). The latest China VI emission standards were implemented in 2019, and newly registered vehicles must comply with these more stringent emission standards (Ministry of Ecology and Environment of the People's Republic of Chinac; Ministry of Ecology and Environment of the People's Republic of Chinad). VOCs emission from fuel production & distribution can be reduced by installation of internal floating covers for fixed roof tanks or secondary seals for tanks with external floating roofs. To achieve higher reductions, vapor recovery systems need to be installed.

2.3. Scenario settings

Based on the GAINS-China model, we developed two scenarios, i.e., reference (REF) and current legislation (CLE), to explore future VOCs emission pathways from 2020 to 2050, with 2020 set as the base year. Both scenarios are projected under the same future socioeconomic levels and sectoral activities but differ in their assumptions regarding future control technologies. Socioeconomic factors were exogenous in the model, following projections of the World Energy Outlook 2018 (IEA), which is in accordance with the recent economic growth in China and the economic development target of the guidelines to comprehensively promote the development of a 'Beautiful China' (State Council of the People's Republic of Chinad). For example, we assumed that China's gross domestic product (GDP) would increase by a factor of 2.48–2.61 between 2020 and 2050 (Fig. S2). For the REF and CLE scenarios, a continuing urbanization rate of 0.3–2% per year was assumed, consistent with the government development plan for China. Fig. S3 shows residential energy use by key fuels in urban and rural areas for 2020 and 2050. It shows that total energy use in urban areas increased by 2050 over that in 2020, while energy use in rural areas decreased. Moreover, there was a notable shift in the energy mix toward cleaner fuel types, such as electricity and gas (e.g., natural gas and liquefied petroleum gas). These results suggested a population migration from rural to urban areas, accompanied by a transition to cleaner energy sources.

In forecasting future activity data, several key factors were considered: i) The temporal evolution of various industrial activities-such as paint application, printing, degreasing, and solvent use in the chemical and other industries-was linked to shifts in sectoral GDP, with growth rates adjusted using elasticity values based on statistical analysis. These values reflect provincial economic development levels. ii) Certain other activity rates, including those for dry cleaning, household solvent use, vehicle maintenance, and the food industry, were assumed to correlate with population growth and potentially reflect changes in GDP per capita. iii) Activity rate variations for fossil fuel and biofuel combustion were associated with fuel consumption projections specific to each province, derived from the GAINS model energy scenario inputs. For example, paint use activity data are forecasted based on the pattern of change in the average annual growth rate of China's paint consumption in recent years (Fig. S4). The total primary energy consumption at the national level is estimated to have varied by a factor of 0.67–2.07, suggesting a decoupling of energy use from economic growth (Fig. S2).

REF scenario: This is the reference scenario for air pollution control. In this scenario, the end-of-pipe pollutant control technology mix for each sector in China is fixed at the 2020 level for the entire study period (2020–2050). This counterfactual scenario assumes no technology upgrades after 2020 and serves as a reference for evaluating the impact of more stringent end-of-pipe air pollution control strategies.

CLE scenario: This scenario depicts a more realistic technological development path, with strict air pollution control measures, following the Three-Year Action Plan for Winning the Battle for the Blue Sky, the Comprehensive Action Plan for VOCs in Key Industries, the Action Plan for Continuous Improvement of Air Quality (State Council of the People's Republic of Chinae), etc. When setting the control strategies for this scenario, we refer to existing policy documentations for China's VOCs emission control strategies and targets. A detailed policy reference for setting the end-of-pipe control levels in this scenario is presented in Supplement Table S2. The current legislation scenario reflects the effects of announced policies as outlined in the official plans and targets (Amann et al., 2011; Li et al., 2019c). For example, the "Action Plan for Continuous Improvement of Air Quality" emphasizes strengthening the substitution of low- or zero-VOCs content raw and auxiliary materials in industrial coating, packaging and printing, and the electronics industries. This plan aims to achieve a 10% reduction in national VOCs emissions by 2025 compared to 2020 levels. However, as these "upcoming policies" have not yet been fully implemented in the current legislation framework, the scope and timing of their full realization are projected based on expert judgment from IIASA colleagues. In this scenario, the penetration of adsorption and incineration technologies within the automotive manufacturing subsector is expected to continue growing, reaching more than 45% by 2050. Stricter emission standards are expected to be implemented across various industries, including decorative paints, industrial paint use (continuous processes) and screen printing. Details on technology penetration in the residential and transportation sectors are provided in Table S3.

3. Results and analysis

3.1. VOCs emissions in 2020

In 2020, total anthropogenic VOCs emissions in China were estimated to be 23,114.8 kt, including solvent use at 13,028.4 kt, residential (4033.4 kt), 'others' (2563.6 kt), transportation (2282.6 kt) and industry and power (1206.8 kt) (Fig. 1). Solvent use was the largest contributor, accounting for 56.4% of total anthropogenic VOCs emissions. Regarding solvent use emissions, paint use was the primary subsector contributor, responsible for 48.2% of the total emissions from this source, because economic development, urbanization, and increased vehicle ownership have greatly increased the demand for decorative paints, industrial paints, and paints used in vehicle manufacturing and repair (Bo et al., 2008). Other industrial applications (industrial application of adhesives, wood preservation, waxing and underbody treatment of vehicles) accounted for 30.8% of the solvent use emissions, followed by household solvent use (12.2%), manufacturing industry (6.0%), and printing use (2.8%). Owing to relatively low combustion efficiency and lack of controls (Liu et al., 2019), stoves were the dominant subsector of VOCs emissions within the residential sector, with cooking, heating and three-stone stoves contributing 88.7%, 7.5% and 3.1% of total residential VOCs emissions, respectively. The boiler subsector contributed the remaining 0.7% of the emissions. With respect to transportation sector, light-duty vehicles, heavy-duty vehicles and non-road machinery were the main subsectors, accounting for 45.9%, 21.9% and 32.2%, respectively, of transportation VOCs emissions. Emissions from on-road mobile were expected to be twice as high as those from non-road machinery because of the larger population and greater number of vehicle miles travelled by the former. In the 'others' category, the agriculture subsector was the largest contributor, accounting for 54.6% of total emissions, followed by fuel production & distribution (26.6%) and waste (18.9%). Industrial processes and industrial combustion were the dominant subsources of VOCs emissions within the industry and power sector, accounting for 51.4% and 35.2%, respectively. This is due to rapid industrialization driving an increase in various industrial production activities and a growing demand for fossil fuels (Simayi et al., 2022). Power and heating plants and fuel conversion contributed 7.2% and 6.2%, respectively, to this sector. In summary, the major subsectors of VOCs emissions in China in 2020 were paint use, other industrial applications, cooking stoves, household solvent use and agriculture, accounting for 27.2%, 17.4%, 15.5%, 6.9%, and 6.1% of the total emissions, respectively.

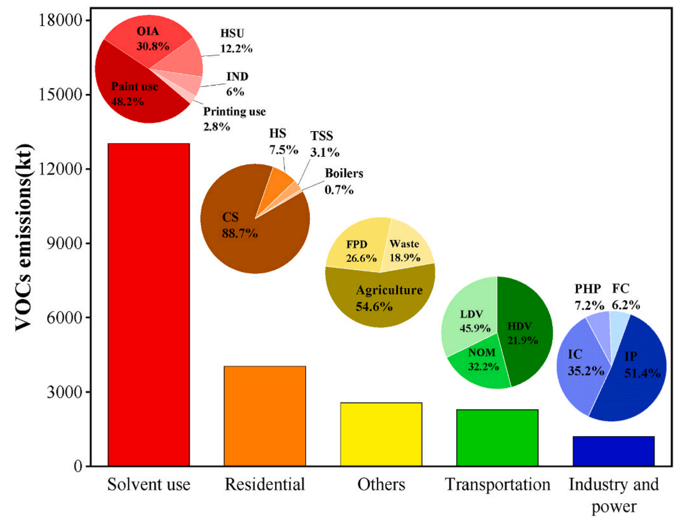

Fig. 1. Contributions of various sources to total VOCs emissions in China in 2020 (OIA: other industrial applications; HSU: household solvent use; IND: manufacturing industry; CS: cooking stoves; HS: heating stoves; TSS: three-stone stoves; FPD: fuel production & distribution; LDV: light duty vehicles; HDV: heavy duty vehicles; NOM: non-road machinery; IP: industrial processes; IC: industrial combustion; PHP: power and heating plants; FC: fuel conversion).

From the perspective of provincial emissions (Fig. 2), the 5 provinces with the highest VOCs emissions were Guangdong (2327.7 kt), Shandong (1689.1 kt), Jiangsu (1672.9 kt), Hebei (1416.1 kt), and Sichuan (1212.4 kt), collectively accounting for 36% of the total emissions. The VOCs emissions in Zhejiang, Hunan, Guangxi, Hubei, Anhui, Shanghai, Fujian, Liaoning, and Heilongjiang ranged from 700.0 kt to 1150.0 kt, with their contributions to national emissions varying between 3.0% and 5.0%. In contrast, Hainan, Ningxia, Qinghai, and Xizang contributed less than 1.0% to national emissions. Moreover, provinces presented distinct source contribution characteristics due to variations in demographic status, economic development levels, and industrial structures. For example, in most provinces, such as Shanghai, Zhejiang, Fujian, Guangdong, Jiangsu, and Beijing, VOCs emissions mainly originate from the solvent use sector, which contributes more than 50% of local VOCs emissions. Potential contributors include paint use, other

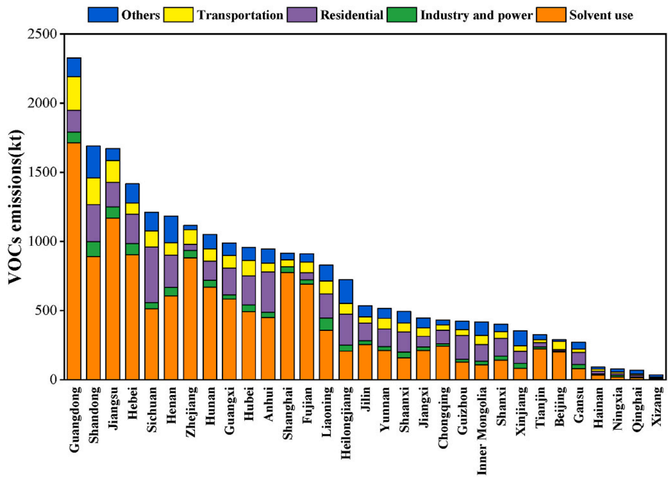

Fig. 2. Total VOCs emissions and source composition by province in 2020.

industrial applications, and household solvent use (detailed subsector VOCs emissions by provinces are presented in Supplement Fig. S1). This phenomenon could be attributed to the more advanced light industries in coastal regions, such as furniture manufacturing and machinery equipment production, which emits substantial solvent-related VOCs emissions (National Bureau of Statistics of the People's Republic of China, 2021). In provinces such as Guizhou, Sichuan, Gansu and Heilongjiang, the residential sector accounted for over 30% of local VOCs emissions, a significantly higher than that observed in other provinces. In the northeastern regions like Heilongjiang and Inner Mongolia, crop residues such as cornstalks and straw were commonly used as free fuel for cooking and heating, particularly during the cold winter months, contributing to higher residential VOCs emissions (Zhao et al., 2018). In Xizang, Qinghai and Xinjiang, 'others' sector was the most significant VOCs contributor. The transportation sector was another important emission source in Beijing, because of the large population of vehicles and frequent idle driving conditions caused by traffic jams (Bo et al., 2008). The contribution of emissions from the industry and power sector was small in most provinces.

3.2. VOCs emissions under the REF scenario

The sectoral and subsectoral VOCs emissions from 2020 to 2050 under the REF scenario are presented in Fig. 3. The projections of emission changes are built upon the modification of current activity levels according to externally provided projections, as outlined in Section 2.3. These projections rely on key factors, including energy forecasts, sectoral GDP growth, and population changes, which are applied across provinces. In the REF scenario, Chinas VOCs emissions decreased from 23,114.8 kt in 2020 to 19,162.2 kt in 2040, then maintained flat during 2040–2050. The reduction before 2040 was attributed mainly to the residential sector due to the replacement of household solid fuels with clean fuels (Shu et al., 2022). As a result, the sectoral proportions of national VOCs emissions shifted, with increasing contributions from the solvent use sector (from 56.4% in 2020 to 73.1% in 2050), decreasing contributions from the residential sector (from 17.4% to 0.1%), and relatively stable contributions from the transportation (from 9.9% to 10.6%), industry and power (from 5.2% to 4.3%), and 'others' (from 11.1% to 11.8%) sectors.

The emission trends by subsector for each major sector (solvent use, residential, transport, industry and power, and others) are further illustrated in Fig. 3(b–f). As the largest contributor to total VOC emissions, solvent use emissions exhibited a modest increasing trend, growing by 4.7% from 2020 to 2050. This slight increase was primarily attributed to the activity growth of paint use and other industrial applications sectors, driven by economic and industrial development. Residential emissions experienced a sharp decrease from 4033.4 kt in 2020 to nearly zero in 2040. This significant downwards trend was due to the migration of millions of rural residents to urban areas and the gradual transition from solid fuels to clean energy sources, such as natural gas and electricity, in rural households (Fig. S3), resulting in a substantial reduction in residential emissions (Liu et al., 2020). Transportation VOCs emissions first increased from 2282.6 kt in 2020–2678.8 kt in 2030 and then decreased to 1979.3 kt by 2050. The light-duty vehicle subsector was the dominant driver of changes in emissions; for example, this subsector's contribution grew from 45.4% in 2020 to 46.1% in 2030 but fell to 31.1% in 2050. The VOCs emissions from the industry and power sector decreased from 1206.8 kt in 2020 to 804.0 kt in 2050, and the decrease was attributed primarily to the industrial combustion subsector. The 'others' sector exhibited a slight decreasing trend, with emissions declining from 2563.6 kt in 2020–2209.7 kt in 2050.

From perspective of province-level, the total VOCs emission reduction from 2020 to 2050 under the REF scenario varied across the 31 Chinese provinces (Fig. S5). Sichuan Province achieved the largest reduction, decreasing VOCs emissions by approximately 402.8 kt, largely driven by a transition from household solid fuels to cleaner energy sources in the residential sector. Conversely, Shanghai experienced an increase in emissions, rising by about 9.5 kt, primarily due to elevated solvent use activities. Sectoral analysis revealed that, in most provinces, the solvent use sector significantly contributed to emission growth, whereas the residential sector accounted for the largest reductions, with provinces such as Sichuan and Anhui showing notable declines due to improved residential energy practices.

3.3. Reduction potential under the CLE scenario

Fig. 4 exhibits sectoral VOCs emission reductions under the CLE scenario compared with those under the REF scenario. The CLE scenario incorporates all existing regulations outlined in Table S2, which are projected to reduce VOCs emissions consistently from 2020 to 2050. By 2050, the CLE scenario achieved a cumulative VOCs emission reduction of 3726.3 kt compared to the REF scenario, with contributions from the solvent use, transportation, others, and industry and power sectors at 81.7%, 16.8%, 1.3%, and 0.2%, respectively (Fig. 4a).

Fig. 4b–g further illustrates the contributions of various subsectors to VOCs reductions from the REF to the CLE scenario in 2050. Within the solvent use sector, the paint use subsector made the largest contribution, achieving a projected VOCs reduction of 2433.5 kt, followed by other industrial applications at 530.2 kt. This significant reduction was largely driven by the increased adoption of high-solids and waterborne paints, along with enhanced removal technologies such as incineration and adsorption, applied in processes like vehicle refinishing and wood preservation. Household solvent use, manufacturing industry, and printing use subsectors contributed a combined reduction of 60.0 kt, underscoring the cumulative effect of improvements across multiple subsectors.

The transportation sector also demonstrated significant potential for VOCs emission reductions, with an estimated decrease of 627.8 kt by 2050 compared to the REF scenario. Heavy-duty and light-duty vehicle subsectors contributed the largest share of these reductions, achieving 362.6 kt and 239.0 kt, respectively. This reduction is primarily attributed to fleet turnover, wherein older vehicles are gradually replaced by newer, cleaner models that comply with stricter emission standards. Specifically, the penetration of China-VIB emission standards for light- and heavy-duty vehicles is projected to increase from 0% in the REF scenario to full compliance (100%) in the CLE scenario, illustrating the substantial impact of enhanced on-road emission standards. However, the non-road machinery subsector was projected to reduce VOCs emissions by only 26.2 kt due to a slower uptake of control technologies under existing legislation.

As VOCs emissions decline under the CLE scenario, the relative

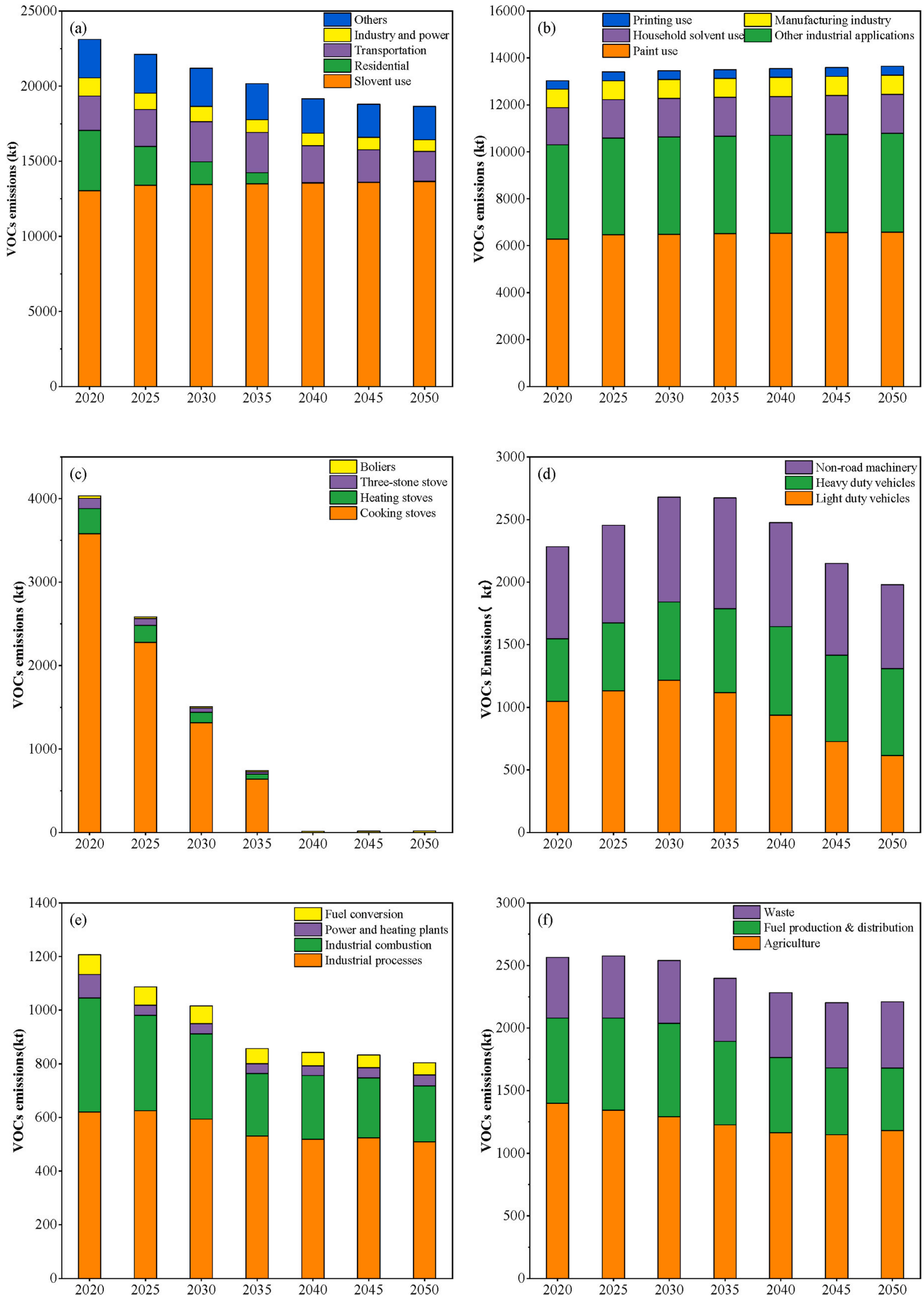

Fig. 3. Temporal changes in China's VOCs emissions from 2020 to 2050 under the REF scenario: (a) Total, (b) solvent use, (c) residential, (d) transportation, (e) industry and power, (f) others.

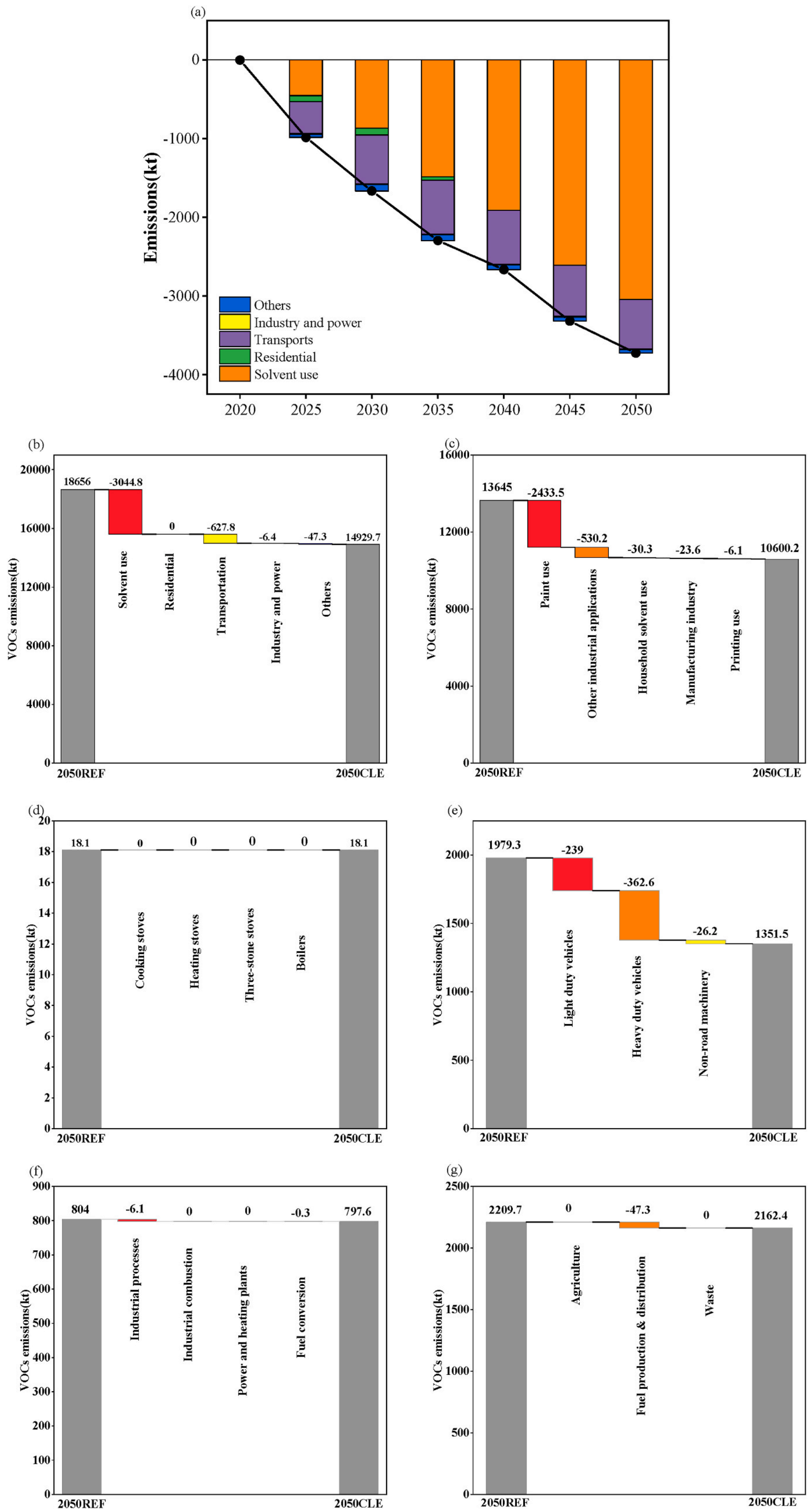

Fig. 4. Changes in China's VOCs emissions by sector under the CLE scenario compared with the REF scenario. (a) Changes in total emissions by main sector and year, as well as changes in solvent use (b), residential (c), transportation (d), industry and power (e), and others (f) sectors by subsector for 2050. The REF emissions are subtracted from the emission data for each year to represent the additional emissions compared with the REF levels.

contributions of various sectors and subsectors to total emissions shift over time (Fig. S5). The solvent use sector, despite achieving the largest overall reduction in VOCs emissions, saw its relative contribution increase from 56.4% in 2020 to 71.0% by 2050, largely due to substantial decreases in residential emissions driven by reduced activity levels. The contributions from the transportation sector remained relatively stable, while those from the 'others' sector increased slightly from 11.1% to 14.5%.

Subsectoral dynamics also shifted within major sectors. Within the solvent use sector, paint use remained the primary contributor to VOCs emissions throughout 2020–2050, while household solvent use and other industrial applications increased their shares from 12.2% to 30.8% in 2020 to 15.4% and 34.6% by 2050, respectively. In the transportation sector, contributions from light vehicles decreased from 45.9% to 27.9%, while non-road machinery rose significantly from 32.2% to 47.7%, becoming the primary source of transportation VOCs emissions by 2050. Limited regulatory measures in subsectors such as industrial processes and agriculture within the industry and power, and 'others' sectors maintained their contributions over the study period.

These findings emphasize that targeted emission reductions in high-contributing subsectors, especially within solvent use and transportation, are essential for maximizing the effectiveness of current legislation in reducing overall VOCs emissions.

Fig. 5 compares the VOCs emission reductions in 2050 under the CLE and REF scenarios for each province in China. Overall, all provinces showed a decrease in VOCs emissions under the CLE scenario by 2050, with the greatest reduction potentials observed in provinces that had the highest VOCs emissions in 2020. For example, Guangdong, Jiangsu, and Shandong-three provinces with the highest emission levels in 2020 (Fig. 2)-achieved the largest reductions under the CLE scenario in 2050, with reductions of 594.5 kt, 374.1 kt, and 257.1 kt, respectively. In contrast, provinces such as Xizang, Qinghai, Hainan, and Ningxia, which had comparatively lower emission levels in 2020, showed smaller reductions in both 2020 and 2050.

Provincial emission reduction potentials from the REF to CLE scenarios in 2050 are different from those observed under the REF scenario during the 2020–2050 period. For instance, while Guangdong, Jiangsu, and Shanghai had the highest reduction potentials under the CLE scenario compared to the REF scenario, their reductions were relatively modest from 2020 to 2050 under the REF scenario (Fig. S5). This discrepancy is likely due to the primary drivers of emission reductions: under the CLE scenario, reductions are largely driven by the implementation of advanced pollution control technologies, while under the REF scenario, reductions are primarily a result of declining activity levels in certain sectors, such as residential energy use.

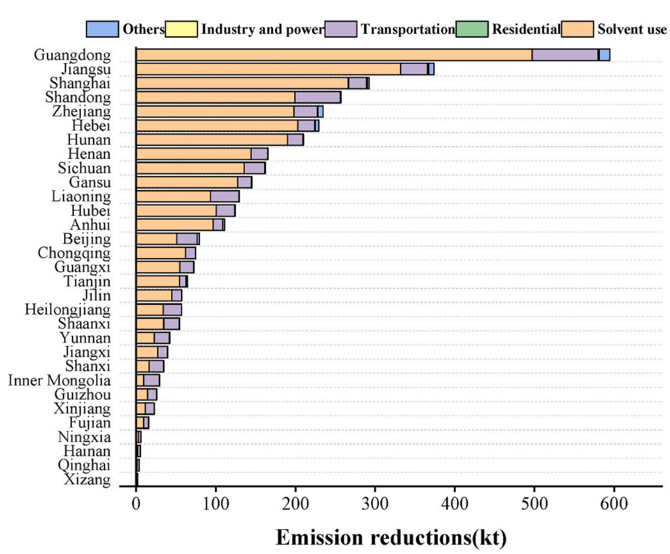

Fig. 5. VOCs emission reductions in various provinces from 2020 to 2050 under the CLE scenario.

From a sectoral perspective, provinces with higher initial emissions in 2020 generally achieved greater reductions by 2050 under the CLE scenario, as larger-scale control measures had more impactful results. In most provinces-such as Shanghai, Hunan, and Jiangsu-the majority of VOCs emission reductions originated from the solvent use sector, reflecting the efficacy of targeted regulations in this sector. However, in regions like Inner Mongolia, Qinghai, Hainan, Xizang, Shanxi, and Ningxia, reductions were primarily driven by the transportation sector, underscoring the sector's significant impact in areas where solvent use is less dominant. Contributions from the residential, industrial and power, and 'others' sectors were comparatively small across all provinces when comparing the CLE and REF scenarios, generally ranging from 0 to 5.0%. These results indicate that tailoring control measures to specific high-emission sectors within each province is crucial for maximizing VOCs reductions.

Fig. 6 illustrates the spatial distribution of total VOC emissions as well as emissions from each sector in 2050 under the CLE scenario. After the implementation of current legislation, VOCs emissions in China in 2050 revealed a clear regional distribution pattern, with total emissions in eastern provinces being significantly higher than those in western provinces. The eastern and southern coastal regions, such as Guangdong, Shandong, Jiangsu, and Zhejiang, were identified as typical high-emission areas. Owing to its substantial contribution to total emissions, the spatial distribution of VOCs from solvent use was similar to that of total emissions. Emissions from the residential, transportation, and industrial and power sectors were also concentrated in the eastern provinces. In contrast, VOCs emissions from the 'other' sector were mainly concentrated in northern provinces, certain central provinces, and Guangdong, with significant biomass burning typically found in all regions except Guangdong. Compared with that in 2020 (Fig. S7), the spatial distribution of VOCs in 2050 under the CLE scenario exhibited minimal change, with a decrease in emissions originating primarily from the solvent use and transportation sectors.

4. Comparison with previous studies and the uncertainty analysis

The VOCs emissions estimated in this study are compared with historical emission inventories and projections from other studies, as shown in Fig. 7. A comparison of base year 2020 emissions suggests that our estimates were lower than those of MEIC version 1.4 (Geng et al., 2024; Multi-resolution Emission Inventory model for), Gao et al. (2022), Wang et al. (2024), Shi et al. (2021) and the projections under the GAINS-ECLIPSE_V6b scenario (Klimont et al., 2017) and BAU-0 scenario from Wang et al. (2014). Wang et al.'s estimates of BAU-1 VOCs emissions for 2020 were consistent with our estimates for the same year. The comparatively higher estimates in the above studies likely arise from two main factors: i) historical estimates were based on emissions primarily calculated for earlier years; ii) projections extended VOCs emissions under regulations up to 2010/2015, potentially leading to overestimated emissions for 2020. Moreover, the use of coarser-resolution activity data, with other VOCs emissions as a proxy for emissions in the solvent use sector, also contributed to higher estimates in ECLIPSE_V6b. The projections across different scenarios exhibited similar temporal trends, with emissions decreasing annually from 2020 to 2050, except for the DPEC-baseline (Cheng et al., 2023; Dynamic Projection model for Emissions) results, which remained flat during this period.

Uncertainties in the emission estimates were assessed using Monte Carlo simulations. These uncertainties stem from variations in activity data and emission factors. We assumed that activity data followed a normal distribution with a 30% uncertainty (Streets et al., 2003), while emission factors also followed a normal distribution, with an uncertainty range of ±50% (Li et al., 2019b). The Monte Carlo simulation was

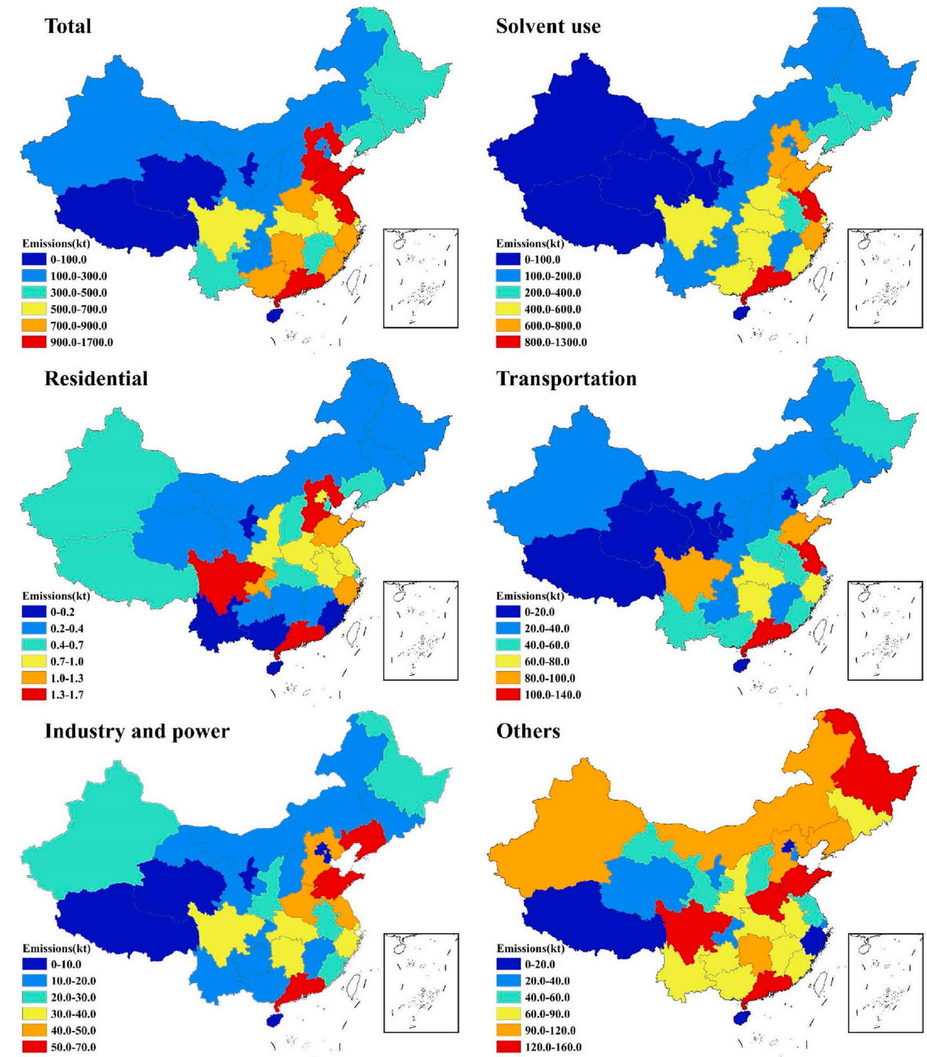

Fig. 6. VOCs emissions in 2050 for the five sectors under the CLE scenario.

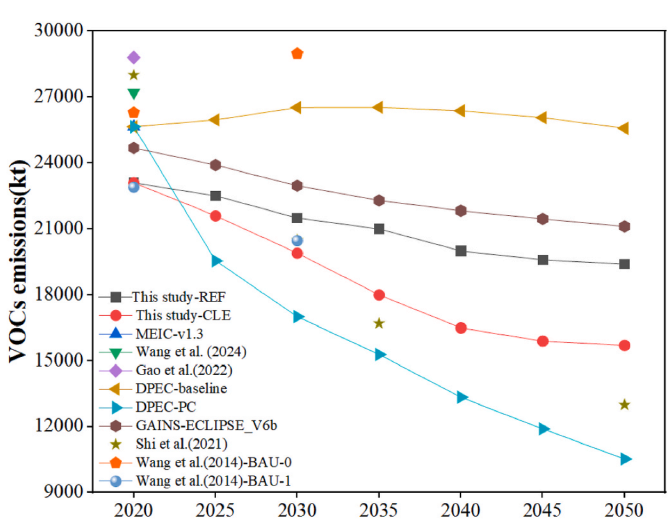

Fig. 7. Estimates of VOCs emissions for China in different studies.

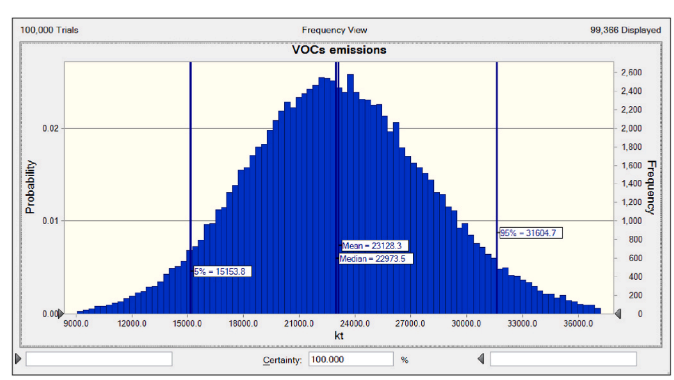

Fig. 8. Probability distributions of VOCs emissions in China in 2020 based on 100,000 Monte Carlo simulations.

conducted 100,000 times based on the probability density distribution. The results, as shown in Fig. 8, indicated a 95% confidence interval of −41% to +45%, with emissions ranging from 15,153.8 kt to 31,604.7 kt in 2020. While these results offer valuable insights into the potential variability of emissions, it is crucial to interpret them as an initial exploration rather than a comprehensive quantification of uncertainty. Specifically, the analysis highlights the variability stemming from the two most impactful parameters but does not encompass the full spectrum of potential uncertainties, such as those related to control measures, regional differences, or temporal shifts. As such, the presented uncertainty ranges should be regarded as indicative rather than exhaustive. To address these limitations, future studies should consider integrating additional parameters into the uncertainty analysis, such as region-specific control technology penetration rates, temporal trends in activity levels, and interdependencies between key parameters.

5. Conclusion and policy implications

In this study, anthropogenic VOCs emission inventories covering 5 sectors, 20 subsectors, and a total of 80 emission sources were estimated for China in 2020 via the GAINS-China model. Moreover, the solvent use sector was categorized into five subsectors and 22 particular sources for VOCs emissions. The future emission trends and mitigation potentials for the period 2020–2050 were evaluated under two different scenarios.

The results revealed that the total anthropogenic VOCs emissions in China were estimated to be 23,114.8 kt in 2020. Solvent use was the largest contributor to total VOCs emissions, accounting for 56.0%, followed by the residential (17.0%), others (11.0%), transportation (10.0%), and industry and power (6.0%) sectors. The main VOCs-emitting subsectors in 2020 were paint use, other industrial applications, cooking stoves, household solvent use and agriculture. With emission control levels fixed at the 2020 level (REF scenario), China's VOCs emissions were expected to decreased from 23,114.8 kt in 2020 to 19,162.2 kt in 2040 and then remained flat from 2040 to 2050. This reduction was driven mainly by the replacement of household solid fuels with clean fuels in the residential sector, especially in Sichuan Province. With the levels of controls following the current legislation trend (CLE scenario), the total VOCs emissions continuously decreased throughout 2020–2050 compared with those in the REF scenario. The solvent use sector was the largest contributor to emission reduction (46.1%–81.7%), followed by transportation (16.8%–41.3%). At the provincial level, regions with higher VOC emissions in 2020, such as Guangdong, Jiangsu, and Shandong, also had the greatest reduction potential in 2050 under the CLE scenario. In contrast, provinces such as Xizang, Qinghai, Hainan, and Ningxia had lower emissions and reduction potentials in 2020 and 2050. After the implementation of current legislation by 2050, despite the significant reductions, the solvent use sector remained a major sector of VOC emissions. Key subsectors contributing to emissions, including paint use, non-road machinery, industrial processes, and agriculture, should be prioritized for further control measures.

Finally, several policy implications are highlighted on the basis of the analytical results.

1) The findings of this study underscore the critical need for stringent regulations aimed at reducing VOCs emissions from the solvent use sector, which currently accounts for 56.0% of total anthropogenic VOCs emissions in China. As indicated in Chinese policy directives, there is an urgent need to accelerate the adoption of low-VOCs content raw materials across various applications, including solvent-based paints, inks, adhesives, and cleaning agents. This could be achieved through the establishment of a comprehensive standard system for VOCs products, along with a robust labelling mechanism to guide consumers and manufacturers towards lower-emission alternatives. In addition, increased funding and incentives for initiatives focused on developing innovative low-VOCs technologies and materials can facilitate the transition towards sustainable practices in the solvent use sector. Collaboration with industry stakeholders and academic institutions is essential for effective knowledge transfer and implementation.
2) Given the interconnected nature of VOCs emissions across various sectors, a coordinated approach involving multiple departments is essential for achieving meaningful reductions in overall emissions. Establishing a multisectoral framework that integrates efforts from the agriculture, transportation, and non-road mobile machinery sectors is crucial. Addressing the agricultural sources of VOCs, particularly those resulting from biomass burning, requires legislative measures that promote sustainable agricultural practices. Prioritizing educational campaigns to inform farmers about the environmental impacts of open burning, along with incentives for adopting alternatives such as straw incorporation or biomass utilization, is vital. Moreover, provincial governments should develop tailored strategies based on their specific emission profiles. Regions with higher emissions, such as Guangdong, Jiangsu, and Shandong, should focus on enhancing control measures in high-contributing sectors such as paint use and non-road machinery. Conversely, provinces with lower emissions should be incentivized to develop sustainable practices to prevent future increases in VOCs emissions.

CRediT authorship contribution statement

Yuhang Zhao: Writing – original draft, Software, Data curation. **Hong Sun:** Validation, Supervision, Conceptualization. **Younha Kim:** Methodology, Investigation. **Yun Shu:** Supervision, Formal analysis, Data curation. **Han Wang:** Validation, Software. **Hui Li:** Validation, Methodology. **Yinhe Deng:** Methodology, Data curation.

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 B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aeaoa.2025.100316.

Data availability

Data will be made available on request.

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