International Institute for Applied Systems Analysis
I I A S A www.iiasa.ac.at

Address: IIASA, Schlossplatz 1, A-2361 Laxenburg, Austria
Email: repository@iiasa.ac.at **Telephone:** +43 (0)2236 807 342

YSSP Report
Young Scientists Summer Program

Costs and benefits of household fuel policies and alternative strategies in the Jing-Jin-Ji region

Wenjun Meng
mengw@iiasa.ac.at

Approved by

Supervisor: Gregor Kiesewetter, Shaohui Zhang
Program: Energy, Climate and Environment Program (ECE)
30.09.2021

This report represents the work completed by the author during the IIASA Young Scientists Summer Program (YSSP) with approval from the YSSP supervisor.

It was finished by 30.09.2021 and has not been altered or revised since.

This research was funded by IIASA and its National Member Organizations in Africa, the Americas, Asia, and Europe.

This work is licensed under a Creative Commons Attribution-NonCommercial 4.0 International License.
For any commercial use please contact repository@iiasa.ac.at

YSSP Reports on work of the International Institute for Applied Systems Analysis receive only limited review. Views or opinions expressed herein do not necessarily represent those of the institute, its National Member Organizations, or other organizations supporting the work.

ZVR 524808900

Table of Contents

Abstract

Air pollution is still one of the most severe problems in northern China, especially in the Jing-Jin-Ji region. In recent years, China has implemented many stringent policies to address this issue, including promoting energy transition towards cleaner fuels in residential sectors. But till 2020, even in the Jing-Jin-Ji region, nearly half of rural households still use solid fuels for heating. For residents who are not covered by the clean heating campaign, we propose five potential mitigation strategies and evaluate their environmental and health benefits and costs. We estimate that the clean fuel scenarios reduced more air pollution and premature mortality, while the scenario of biomass pellet and gasifier stoves has the highest value in terms of benefit ratio due to its relatively low-cost investment, making it a more feasible strategy. Moreover, adopting the largest emission reduction plan for non-residential sectors and residential sectors at the same time would lead to the maximal public health benefits, avoiding 19,000 premature deaths in 2030.

Acknowledgments

This work was supported by IIASA's Young Scientists Summer Program (YSSP) sponsored by the National Science Foundation of China (42111540214).

About the authors

Wenjun Meng is a YSSP participant 2021 and a PhD student in College of Urban and Environmental Sciences, Peking University. (Contact: mengw@iiasa.ac.at)

Costs and benefits of household fuel policies and alternative strategies in the Jing-Jin-Ji region

Wenjun Meng

Introduction

North China is densely populated and industrially concentrated, making it currently one of the regions with the highest $PM_{2.5}$ (particulate matter with an aerodynamic diameter less than 2.5 μm) concentration[1]. It is estimated that in 2017 China's $PM_{2.5}$ exposure caused 1.24 million premature deaths, of which 24% occurred in Beijing, Tianjin and surrounding areas[2]. In addition, since people spend most of their time indoors, premature deaths caused by $PM_{2.5}$ are mainly due to indoor air pollution[3]. As one of the major emission sources of air pollutants, residential solid fuel burning for cooking and heating in China contributed significantly to air pollution. Among all the sources in Beijing, Tianjin and Hebei, domestic sources contributed around 20% of total ambient concentration in 2015[4]. On top of that, indoor air pollution is also influenced mainly by solid fuel burning through direct stove leakage[5], which leads to relatively high exposure and large disease burdens consequently[6], making it an even more significant contributor to current environmental and public health issues.

Since 2013, various clean air actions such as the Air Pollution Prevention and Control Action Plan have started to be taken in order to combat with the severe air pollution in China, but most of the mitigations took place in industry and transportation sectors.[7,8] In residential sectors, a strict policy was not implemented until 2017, which is the Clean Heating Plan for Northern China in Winter for 2017–2021[9]. It was launched to substitute coal with electricity or natural gas in northern China, and Beijing, Tianjin, together with the majority of Hebei contained in the regions with higher attention and more strict targets. Largely due to the intervention of the control action plan and the clean heating plan, the air quality in China, especially in the Jing-Jin-Ji region, has substantially improved[8,10]. From 2013 to 2017, the overall annual population-weighted ambient $PM_{2.5}$ concentration was reduced from 61.8 $\mu g/m^3$ to 42.0 $\mu g/m^3$, among those the strengthening industrial emission standards in power plants and industries, upgrades on industrial boilers, phasing out outdated industrial capacities, and promoting clean fuels in the residential sector contributed 6.6 $\mu g/m^3$, 4.4 $\mu g/m^3$, 2.8 $\mu g/m^3$, and 2.2 $\mu g/m^3$ respectively.[8]

However, due to the arising financial burden and the natural gas shortage reported shortly after the start of the campaign, some prefectures were not able to afford the full implementation of this substitution.[11] According to the government reported data, till 2019, there is a large variation in implementation rates across prefectures.[12] Moreover, based on socioeconomic factors, a differential penetration rate has been shown to be more feasible and more beneficial for environmental and population health.[11] On this basis, the effects of alternative solutions for the households with no substitution yet, such as clean coal or biomass pellet, need to be addressed to explore the further mitigation pathways in the residential sectors.

It is of interest to analyze the costs and benefits of different options. In this study, we established alternative strategies from 2020 to 2030 for the areas not covered by the substitution plan in northern China and characterized the impacts of these strategies on ambient air quality and population health. Furthermore, the costs and benefits of each strategy were quantified to provide scientific evidence for policymakers.

Methods

GAINS model

The Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model for east Asia (EAN) version 4.01 developed by International Institute for Applied Systems Analysis (IIASA) was used in this study (https://gains.iiasa.ac.at/models/gains_models4.html). The GAINS model is a scientific tool for comprehensive policy evaluation on greenhouse gases and air pollution. It provides pathways from various policy measures to their impacts on environmental air pollution, health impacts and cost assessment. The GAINS model also contains various information about the economic, energy and agricultural development, emission control strategies and costs, and atmospheric dispersion. As a widely used integrated policy assessment tool, the GAINS model can provide pathways in several major sectors, including power plants, industry, agriculture, transportation, and domestic sectors. The model considers emissions of ammonia (NH_3), carbon dioxide (CO_2), methane (CH_4), nitrogen oxides (NO_x), nitrous oxide (N_2O), particulate matter (TSP, PM_{10}, $PM_{2.5}$ and PM_1), sulfur dioxide (SO_2), volatile organic compounds (VOC) and carbon monoxide (CO).

Pathway scenarios

Three alternative energy pathways were considered in this study, based on the World Energy Outlook 2020 from the International Energy Agency (IEA): STEPS (Stated Policies Scenario), SDS (Sustainable Development Scenario) and NZE (Net-Zero Emissions).[13] STEPS reflects the influence of the existing policy framework and the policy intentions of the current plans. Its purpose is to establish a path for the realization of current policymakers' plans, and to illustrate their impact on energy use, emissions, and energy security. To achieve three main energy-related SDGs (Sustainable Development Goals) simultaneously, SDS provides an ambitious and pragmatic vision for the development of global energy sectors. The scenario starts with the realization of the SDGs and then in turn determines the conditions required to achieve these goals in a realistic and cost-effective manner, which is also aligned with the 2 degree target of Paris Agreement. NZE establishes the goal of achieving net zero emissions of global carbon dioxide emissions by 2050 in addition to SDS in the next ten years, which is consistent with the path used by the Intergovernmental Panel on Climate Change for the Special Report on Global Warming of 1.5 °C (IPCC SR1.5)[14].

Representations of these three energy scenarios were already implemented in GAINS prior to this project, using IEA World Energy Model output at the national level and then downscaled to provincial level based on sectoral fractions in the China Statistic Yearbook in 2010[15]. However, during the past years, lots of mitigation policies have been taken into action, and the provincial data in 2015 start to diverge with the newest one, which necessitated calibration. We used two methods to update urban and rural data separately. For urban areas, the per-capita consumption is directly taken from the China Statistic Yearbook[16], and we used the population density as the definition of urban and rural to obtain the total consumption[17]. Then the consumption data was projected till 2030 using the original trends derived from the GAINS model. On the other hand, the consumption data for rural households were from national energy surveys by Tao et al.[18]. In previous studies, the time fraction of using each fuel (in prefecture level) is used to derive the fraction of population using each fuel, and the total consumption of each type of fuel in rural residential sector was calculated together with the fuel consumption per household per day for cooking and heating (derived from the fuel-weighing campaign)[18-20]. And since the clean heating campaign was almost entering the closing phase, the reported progress of the clean heating campaign was collected in the previous study and reflected in the consumption data in 2020 to better analyze the current situation.

For the remaining rural households which have not been covered by substitution by 2020, five household pathway scenarios have been established as follows: 1) S-e: full electricity substitution; 2) S-g: full pipeline natural gas substitution; 3) S-eg: combined choice of electricity and pipeline natural gas as the fraction of the provincial targets by 2020; 4) S-c: clean coal with new stoves; S-b: biomass pellet with gasifier stoves or highly efficient stoves. The detailed scenarios combinations were listed in Table 1. The STEPS was taken as the baseline for all other sectors, against which the five policy scenarios were evaluated for the explicit analysis of costs and benefits of household policy options. Then three combined scenarios were established where specific corresponding alternative household fuel policy scenarios were embedded in the three IEA scenarios. Within these, specific choices were made regarding additional electricity demands from the residential sector: In STEPS, the additional electricity would be generated by coal and gas power plants with the original fraction. For SDS and NZE scenarios, solar and wind power plants would be constructed to meet the enlarged demands. And the three combinations would be STEPS with clean coal, SDS with biomass pellet, and NZE with all electricity.

Table 1 Scenarios description

scenario name	IEA scenario	household fuel policy scenario
S-baseline	STEPS	
S-e	STEPS	all electricity
S-g	STEPS	all natural gas
S-eg	STEPS	combined electricity and natural gas
S-c	STEPS	clean coal with efficient stoves
S-b	STEPS	biomass pellet with gasifier stoves
NZE-baseline	NZE	
NZE-e	NZE	all electricity
SDS-baseline	SDS	
SDS-b	SDS	biomass pellet with gasifier stoves

Emissions and $PM_{2.5}$ concentration simulation

The emission inventory for major pollutants was established using the "bottom-up" method through the GAINS model combining the energy consumption for each sector with the corresponding emission factors. The urban and rural distribution information was obtained from Shen et al.[17]. Two types of data sources, including the remote sensing data and the nighttime light (NL) data were combined to extract urban expansion across China from 1980 to 2012. The future projection was derived according to urban expansion forecasts.[17] Here we used the fixed definition in 2020. The ambient $PM_{2.5}$ concentration simulation in 0.1° × 0.1° grid were also conducted using the GAINS model. Atmospheric dispersion and chemistry calculations relied on the global GAINS atmospheric transfer coefficients[21] which are based on perturbation simulations with the EMEP chemistry transport model[22]. For primary PM, calculations were improved here to reflect changing spatial distribution of emissions, using a novel capacity of EMEP to track the grid-to-grid dispersion of $PM_{2.5}$ emissions[23]. The indoor concentration was calculated by combining fuel fraction with indoor air quality databases, as well as the infiltration from outdoor concentration. Households that use solid fuels and clean energy were calculated separately. Based on the collected literature data, an indoor $PM_{2.5}$ concentration database of stove-energy combinations was established during heating and non-heating seasons[24]. In addition, the stove location is also a key factor in the calculation. For example, for a household that uses solid fuel and a stove whose kitchen is connected to other rooms, the average indoor $PM_{2.5}$ concentration is compiled as the average value and standard deviation of various stove-energy combinations in the corresponding season. For non-solid fuel users or households that use solid fuel stoves outdoors or in isolated rooms, a simple infiltration model[25] and window opening time in the literature are used[26]. The stove location information was collected from a nationwide survey. [18]

Exposure and health impact assessment

The total population-weighted exposure was derived using the weights of four age groups (<5, 5–14, 15–65, >65) and genders at the 0.1° × 0.1° grid resolution based on the calculated indoor and outdoor $PM_{2.5}$ concentrations and the time-activity pattern of people[27]. Gender and age distributions were derived from the China Statistic Yearbook[28]. For the future years with no data available, the data were estimated based on the original data from the three scenarios (i.e., STEPTS, SDS, NZE scenarios) of the GAINS model. The detailed equations are as follows:

$$EXP_{j,f,s} = \sum_{\mathrm{k}} t_{j,k} \cdot q_{k,f,s}$$

where $EXP_{j,f,s}$ is the annually averaged exposure concentration of population group j using fuel type f coupled with stove type s, the population group has been divided by both gender (male and female) and age (<5, 5-14, 15-65, >65); $t_{j,k}$ is the time fraction of population group j spent in environment k (outdoor, kitchen, living room/bedroom, other); $q_{k,f,s}$ represents the $PM_{2.5}$ concentration in environment k for households using fuel type f and stove type s. Based on the average exposure concentration, we can derive the population-weighted exposure as follows:

$$PWE_{c,y} = \frac{1}{\mathrm{P_{c,y}}} \sum_{\mathrm{j,f}} (EXP_{j,f,s} \cdot p_{c,y,j} \cdot Frac_{c,f,s,y})$$

where $PWE_{c,y}$ is the population weighted exposure of region c in year y; $p_{c,y,j}$ is the population of group j of region c in year y; and $Frac_{c,f,s,y}$ is the proportion of households using fuel type f and stove type s of region c in year y.

$PM_{2.5}$ exposure-associated premature deaths from acute lower respiratory infections (ALRI) for children under five, lung cancer (LC), ischemic heart disease (IHD), cerebrovascular disease (stroke), and chronic obstructive pulmonary disease (COPD) were quantified based on the estimated exposure and the updated Integrated Exposure Response function (IER) for various age/gender groups from the Global Burden of Disease (GBD) 2019[29]. The five diseases used in this study are the same as those in GBD studies[30], which provides background deaths in mainland China till 2019. For the years after 2019, the trends of background deaths and population age structure in the three IEA's scenarios (i.e. STEPS, SDS, and NZE scenarios) of the GAINS model were taken for projection. To estimate the spatial variation, background deaths for each disease at the provincial level in mainland China were collected from previous GBD studies[31], which were calibrated using the latest national total background death from GBD and the underlying mortality rate of various diseases in mainland rural China[32]. This study employs the risk model used in the Global Burden of Disease 2019[33]. The related equations are as follows:

$$\mathrm{RR_x} = \begin{cases} 1, & X \leq \mathrm{tmrel} \\ \dfrac{MRBRT(X)}{MRBRT(tmrel)}, & X > \mathrm{tmrel} \end{cases}$$

where X is the respiratory exposure concentration, tmrel is the oretical minimum risk exposure level and $MRBRT$ is the meta-regression—Bayesian, regularized, trimmed fitted models. We calculate a population attributable fraction (PAF) of deaths as follows:

$$\mathrm{PAF} = \frac{\sum_I P_i (RR_i - 1)}{\sum_I P_i (RR_i - 1) + 1}$$

The population attributable risk fraction is the weighted average of the relative risk of the population group and the control group according to the population. In the formula, P_i is the population of each gender, age, fuel and stove group, and RR_i is the corresponding relative risk of the population[34].

Costs and benefits analysis

The cost analysis includes investment cost and operation and maintenance cost. Investment includes heating devices in households, power plant construction and electricity grid or natural gas pipeline. The total cost was annualized to 2030 using 4% interest rate and adjusted using the inflation rates into the euro in 2020 as the unit. The unit costs of power plants were taken from the World Energy Outlook 2019[35]. The inflation rate was reflected in the Consumer Price Index (CPI), which was from the International Monetary Fund (IMF)[36].

Annualized investment costs are calculated using the following equation.[37]

$$AIC_m = \frac{r}{(1 - (1 + r)^{-l_m})} \times I_m$$

Where r represents discount rate, in this study r is set as 4%. l represents the technical lifetime of the measure m. I refers to the investment cost of the measure m.
Health benefits from the reduction of premature deaths induced by $PM_{2.5}$ and co-benefits from CO_2 emission reduction in 2030 were monetized as the total benefits in this study in order to compare with the total costs in each policy scenario. For health benefits monetization, we adopted the parameter of value of a statistical life (VSL) from Zhang et al. and used the GDP per capita to adjust the standard VSL into the target year, which was also in line with the method in Zhang et al.'s work[37]. The VSL represents an individual's willingness to pay (WTP) for a marginal reduction in the risk of mortality.[38] To assess how the co-benefits of selected energy efficiency measures will affect the economics, CO_2 reduction and social carbon cost (SCC) were used to monetize the benefits of CO_2 reduction. SCC represents the monetized climate damage caused by the gradual increase in CO_2 emissions in a given year.[39] And in this study, the value of 50 $ per ton of CO_2 in 2030 was used from the Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis[40]. The overall modeling framework is presented in Fig.1.

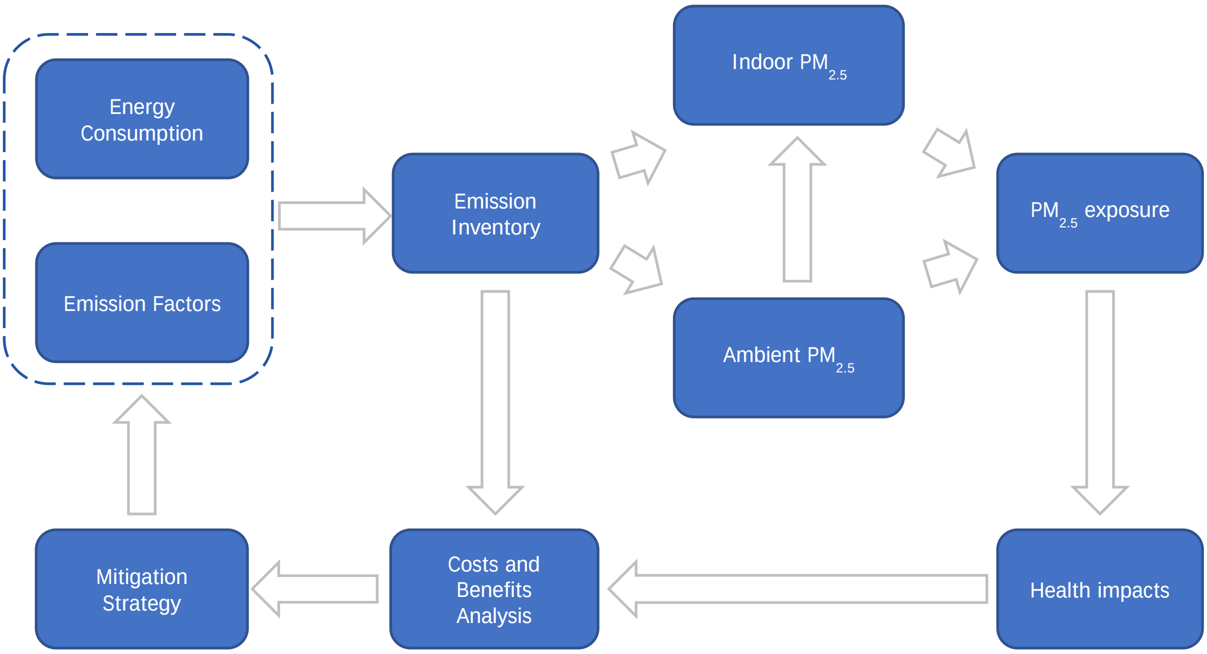

Fig. 1 Overall modeling framework

Results and Discussion

Air pollution trends under current policies

The default activity data in China used in GAINS were taken from IEA (International Energy Agency) and then distributed to provinces using the provincial consumption data from China Statistic Yearbook as the proxy. In residential sectors, the fuel patterns have changed dramatically due to the recent mitigation policies such as the Winter clean heating plan for the northern China.[3] After the calibration as stated in Methods, the urban and rural residential coal consumptions in the Jing-Jin-Ji region in 2015 were 93.2 PJ and 257.9 PJ, respectively. With the strong mitigation implemented, instead of the rather smooth trends of the earlier (GAINS default) energy pathway, the residential coal consumption in study region dropped by around 50% (to 48.8 PJ and 125.9 PJ for urban and rural households respectively).
For major air pollutants emissions in the study region, the total primary $PM_{2.5}$ emissions were reduced from 786 Gg (2015) to 610 Gg (2020). Emissions from household fuel use decreased from 294 Gg to 126 Gg, which accounted for more than 95% of the total reduction. Since residential sectors dominated the emission reductions, their relative contribution also declined from 37% to 21%. In

contrast, the CO_2 emission did not change much, as the total emission was 961 Tg in 2015 and 986 Tg in 2020. And even though the relatively low-quality coal and not so efficient stoves in households brought much higher $PM_{2.5}$ emission factors than other sources, the CO_2 emission factors in residential sectors were not significantly different within the same fuel category[41,42]. Hence, unlike $PM_{2.5}$ emissions, the residential contributions in CO_2 emissions were rather small and steady (6.5% in 2015 and 6.2% 2020).

Ambient $PM_{2.5}$ concentrations were simulated by GAINS model, as explained in Methods section. In the Jing-Jin-Ji region, the population-weighted ambient $PM_{2.5}$ concentrations were slightly higher for urban areas than for rural areas, but they exhibited similar trends from 2015 to 2020. The ambient concentrations for urban and rural areas were 54.5 $\mu g/m^3$ and 51.7 $\mu g/m^3$ in 2015, and declined to 42.9 $\mu g/m^3$ and 40.9 $\mu g/m^3$ in 2020 respectively. And both in urban and rural areas, Hebei had the highest $PM_{2.5}$ concentration in 2015. Due to the vast territory and rather uneven population distribution[17,43], the variation in rural areas were higher than in urban regions, with coefficients of variation of 33% and 27% respectively. Although the policy intervention intensity was different between urban and rural areas, among which the main reason was the different source attribution[8], the reduction rate till 2020 in urban and rural areas were quite similar (both dropped by around 21% compared to 2015). However, the disparity of mitigation benefits among provinces were not neglectable. More specifically, Beijing had ranked first with 28% reduction on account of its stringent regulation and while the reduction ratios in Hebei and Tianjin were only around 20%.

Indoor $PM_{2.5}$ concentrations were calculated through an integrated method combining an indoor database and the infiltration from outdoors, which was also explained in the Methods section. The disparity between urban and rural households were enlarged in terms of indoor air quality, because the measured indoor concentration for households using solid fuels was significantly higher than the ones using clean fuels[24]. In 2015, the average indoor $PM_{2.5}$ concentration for urban and rural households were 37 $\mu g/m^3$ and 148 $\mu g/m^3$, which decreased to 30 $\mu g/m^3$ and 90 $\mu g/m^3$ in 2020, respectively. And among the Jing-Jin-Ji region, Hebei had the highest concentration due to its higher solid fuel fraction in the start year and its higher ambient concentrations.

Under the rapid economic development and urbanization, various ambitious legislations targeting emission reduction from the major sectors were put into action in China[44,45]. The pathway from STEPS scenario in the GAINS model was adopted as baseline, which assumes implementation of current stated policies. In 2030, the total $PM_{2.5}$ emissions in the study region would reduce to 492 Gg, in which 75 Gg were from residential sectors. Similar to the trends in current stage, the CO_2 emissions were projected to stay relatively steady from 2020 (961 Tg) to 2030 (949 Tg). The simulated $PM_{2.5}$ concentration would decrease to 38.4 $\mu g/m^3$ and 36.6 $\mu g/m^3$ for urban and rural areas in 2030, respectively, which is not as sharp a decline compared with the change from 2015 to 2020 (10% vs. 21%). One reason might be that the least-cost emission reductions potential in the selected regions are narrowed, especially for residential building sector.

The premature mortality of five diseases related to particulate matter was calculated to represent the health impacts of the mitigation policies, which were derived either from only the ambient concentration or from the combined total exposure. In the rural Jing-Jin-Ji region, the premature mortality induced by $PM_{2.5}$ ambient exposure was 91,000 in 2015. Among the five diseases taken as the endpoint of health impacts, IHD and Stroke took account of 40% and 49% of the total premature deaths. But there would be a 22% increase till 2030 despite of the declining rural population in this region, which would be mainly driven by population aging. The respective premature mortality rate for Beijing, Tianjin and Hebei were 0.38‰, 0.45‰, and 2.74‰ in 2030, showing even larger variation among the Jing-Jin-Ji region compared to exposure. When considering the combined total exposure, the estimated premature deaths in 2015 and in 2030 were 116,000 and 141,000, which were around 28% higher than the results calculated with only ambient exposure.

Environmental and health benefits of alternative strategies for household fuel use

The clean heating campaign had major effects in northern China[11]. However, due to the arising financial burden, some prefectures could not afford the full implementation[11]. On this basis, for the households with no substitution in rural areas, we established five household policy scenarios to address the alternative substitution strategies: S-e: all electricity; S-g: all pipeline natural gas; S-eg: combined electricity and pipeline natural gas; S-c: clean coal with new stoves; S-b: biomass pellet with gasifier stoves or highly efficient stoves.

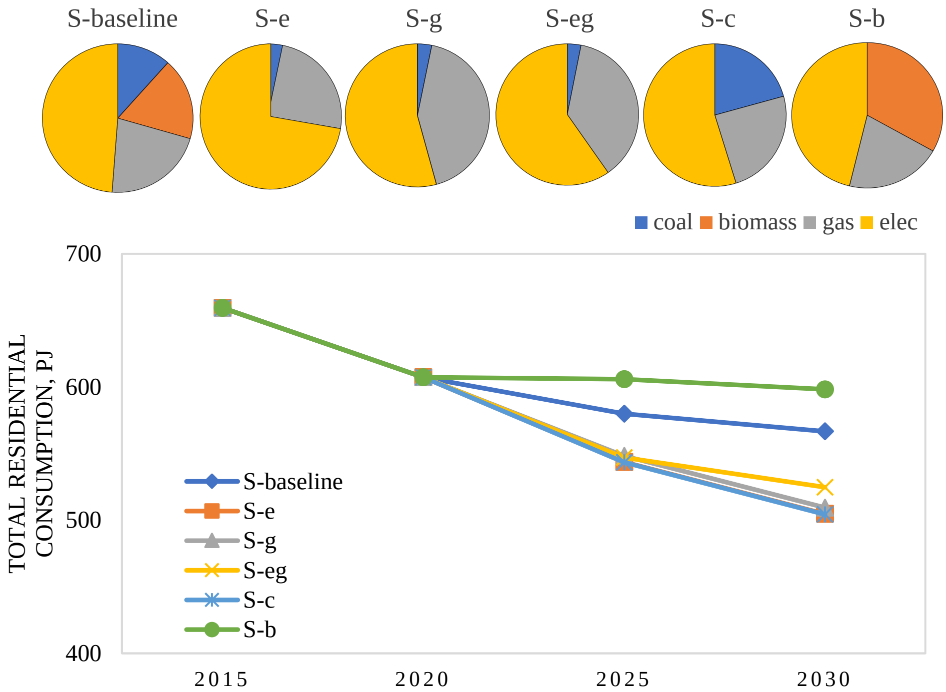

Fig. 2 The rural residential consumption of solid fuels, electricity and gas for cooking and heating in the Jing-Jin-Ji region and their relative contributions

Fig. 2 illustrates the rural residential consumption of solid fuels, electricity and gas for cooking and heating in the Jing-Jin-Ji region, and the relative contributions of difference fuels in each scenario are also shown in the pie charts. According to a previous study, due to relatively steep terrain slope and low population density, full substitution with gas or electricity is not feasible. In other words, a fraction of the population could not be covered by the substitution plan, amounting to 8% of population for rural Beijing, 1% for rural Tianjin and 6% for rural Hebei, respectively[11]. This is also the reason for the remaining small fraction of coal left in 2030 even in the clean fuel scenarios. As the solid fuels are switched to cleaner fuels, the $PM_{2.5}$ emissions would drop significantly from the baseline for all the alternative strategies. However, the $PM_{2.5}$ emissions from rural households in the scenario with biomass pellet substitution (S-b) were 25 Gg in 2030, about twice as high as in the other scenarios (10.5~12.5 Gg). On the other hand, S-b would bring the most benefits in CO_2 emissions reduction. Among the alternative strategies, S-b was predicted to lead with 5.7 Gg CO_2 emissions avoided in 2030, while S-eg and S-c would even increase the CO_2 emissions by 0.6 Gg and 3.4 Gg. Even though the mitigation would bring a large benefit in primary $PM_{2.5}$ emissions, given that the residential contributions already were at a quite low level till 2030 in baseline, the alternative strategies would not have much effects on ambient $PM_{2.5}$ concentrations. In 2030, the population-weighted ambient concentrations would only benefit 3~4% solely from the household policies. The spatial distributions of the ambient $PM_{2.5}$ concentration for baseline scenario and the benefits from the mitigation were presented in Fig. 3. The significant reduction is consistent with the higher concentration, which means the areas with higher concentration would benefit more from the mitigation policies.

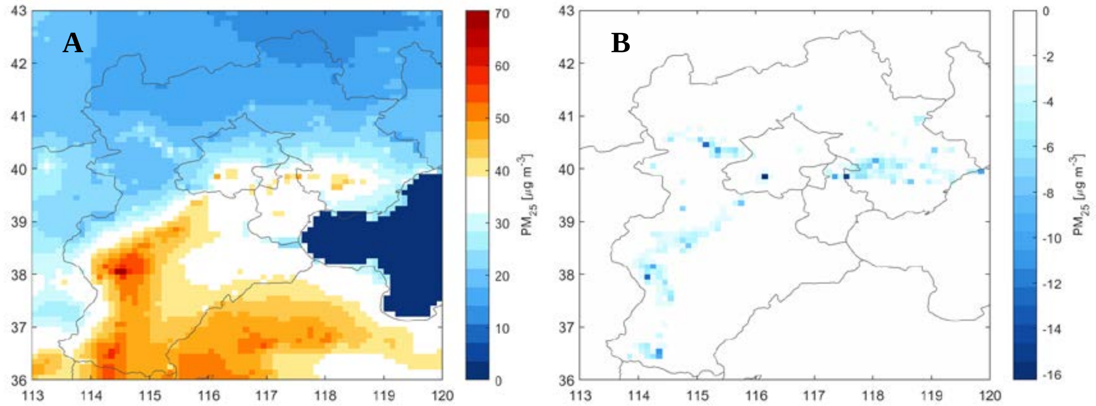

Fig. 3 Ambient $PM_{2.5}$ concentration for baseline scenario (A) and the difference between S-e and S-baseline (B) in 2030

Indoor concentration was categorized into two parts: solid fuel users and clean fuel users. For the former, an indoor air quality database established for rural and urban households in previous studies is used[11,24]; for the latter, the indoor concentration is calculated by the infiltration from outdoor with the varied parameters in different seasons and provinces[25,27]. As a result, changes in the fuel pattern would bring much more benefits from the alternative household fuel policies and there would be a larger difference among scenarios in indoor concentration than in ambient concentration. In 2030, the averaged indoor $PM_{2.5}$ concentrations would be 25 μg/m^3 for clean fuel scenarios, 39 μg/m^3 for S-b and 43 μg/m^3 for S-c. Even though the indoor $PM_{2.5}$ in S-c was about 65% higher than that in S-e, the relatively severe indoor air pollution situation in baseline made the benefits quite large for all the household policy scenarios (40%~60% decrease compared to the baseline in 2030). Since over 80% time activity is indoors, the integrated total exposure would have similar trends with indoor patterns, which were 25 μg/m^3 for clean fuel scenarios and about 35 μg/m^3 for solid fuel scenarios.
To better examine the benefits of fuel switching in households, the two methods using either just ambient $PM_{2.5}$ concentration or integrated total exposure were considered. The health benefits of an alternative scenario were defined as the difference between its projected premature mortality and baseline. Fig. 4 illustrates the premature deaths avoided using the two methods in the rural Jing-Jin-Ji region in 2030. Through the ambient exposure method, the benefits seemed less significant, with about 4% reduction in clean fuel scenarios and 3% reduction in other scenarios. Because the removal of solid fuel directly reduced indoor concentration, the health impacts reduction was much higher when using the total exposure. Even though in the baseline the integrated method would cause more premature deaths in 2030, with the influence of fuel pattern changes, the clean fuel scenarios would actually have less premature mortality. In S-e, the premature deaths using the two methods were 107,000 and 84,000 in 2030, respectively. But in the two solid fuel scenarios S-c and S-b, using only ambient concentration would lead to 107,000 and 108,000 while using the total exposure would have 108,000 and 112,000 premature deaths in the rural Jing-Jin-Ji region. That is due to the certain solid fuels fraction left in S-c and S-b, the absolute premature mortality would still remain slightly higher than the ambient exposure method.

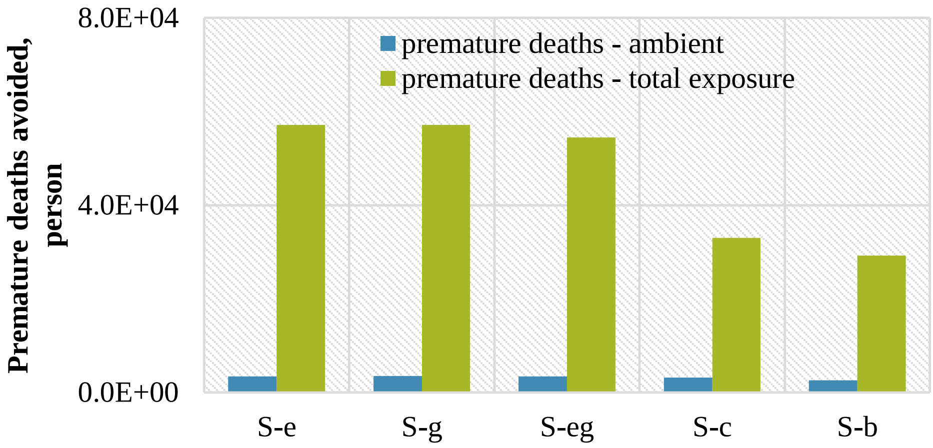

Fig. 4 Premature deaths avoided using two methods in the rural Jing-Jin-Ji region in 2030.

Even though the alternative mitigation would only occur in rural areas, they would also have some impacts on urban areas. Fig.5 shows the premature deaths spatial distribution using ambient concentration method under S-baseline (A) and the benefits of five households fuel scenarios (B-F) in 2030. If only the ambient $PM_{2.5}$ concentration was considered in health impacts, the health benefits of rural-to-urban impacts would reach slightly more than half of its benefits in rural areas. Taking S-c as an example, in 2030, the mitigation in rural would save 3,200 premature deaths while its impacts on urban would save another 1,800. However, in spite that the inclusion of indoor concentration was supposed to narrow the underestimate of the benefits, the impacts on urban areas were consequently influenced. In the same scenario, the proportion of urban premature deaths avoided would drop drastically from 54% to 5%, which was the result of the enlarged rural benefits induced by the rapidly changing fuel patterns. Other than rural impacts on urban areas in the Jing-Jin-Ji region, due to the meteorological transportation of gases and aerosols, the ambient air quality in the surrounding provinces would also have some benefits from the mitigations in the Jing-Jin-Ji region. For the modeled $PM_{2.5}$ concentration, Henan, Shanxi, Shandong and Liaoning benefited the most among all the surrounding provinces. The health impacts of the intervention in the Jing-Jin-Ji region would save 1,900 premature deaths induced by $PM_{2.5}$ exposure when only considered the ambient effects. Similar with the situation in rural impacts on the urban Jing-Jin-Ji region, since the fuel using time-sharing remained unchanged, the health benefits considering both indoor and outdoor $PM_{2.5}$ exposure would appear less significant.

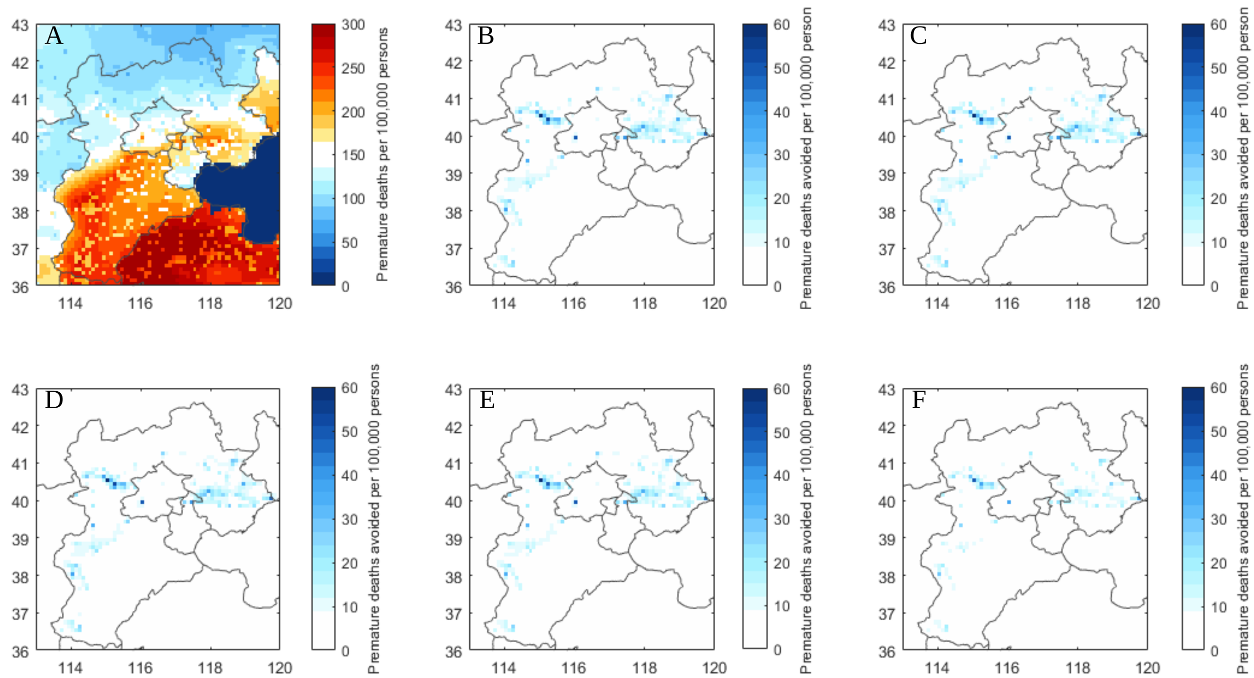

Fig. 5 Premature deaths spatial distribution using ambient concentration method under S-baseline (A) and the premature deaths avoided of five households fuel scenarios (B: S-e; C: S-g; D: S-eg; E: S-c; F: S-b) in 2030

Costs analysis and comparison with benefits

The cost assessments of each scenario were presented in Fig. 6, whose main parameters such as averaged investment costs per household of electricity grids construction, capital costs per kW installed were listed in the Table 2. For almost all the policy scenarios, fuel costs would be an important part, with the highest fraction occurred in S-c (83%) and the lowest in S-e (42%). The differences of fuel costs brought by fuel saving were also considered in the calculation. Other than that, the investment costs of heating devices in households also accounted for 17%-53%, among which the costs of electric heating devices were about one magnitude higher than others. Overall, the costs calculated for clean fuel scenarios were much higher than solid fuel scenarios, not only due to the rather expensive costs of electricity and natural gas compared with clean coal and biomass pellet but also the additional natural gas pipeline and electricity infrastructure needed.

Table 2 The main parameters for costs analysis

Measures	invest cost per stove	gas pipeline/electricity grid cost per stove	operation cost per stove	fuel price	Capital cost for power plant
unit	US $2015	US $2015	US $2015	Euro/ GJ	$2019 per kW
clean coal stove	208.9		288.0	5.2	
pellet stove	309.5		278.6	3.6	
gas heating device	707.5	795.0	190.8	10.4	
electric heating device	3155.7	2782.4	318.0	12.9	
raw coal			191.4	3.4	
power plant - steam coal					800
power plant - gas					720

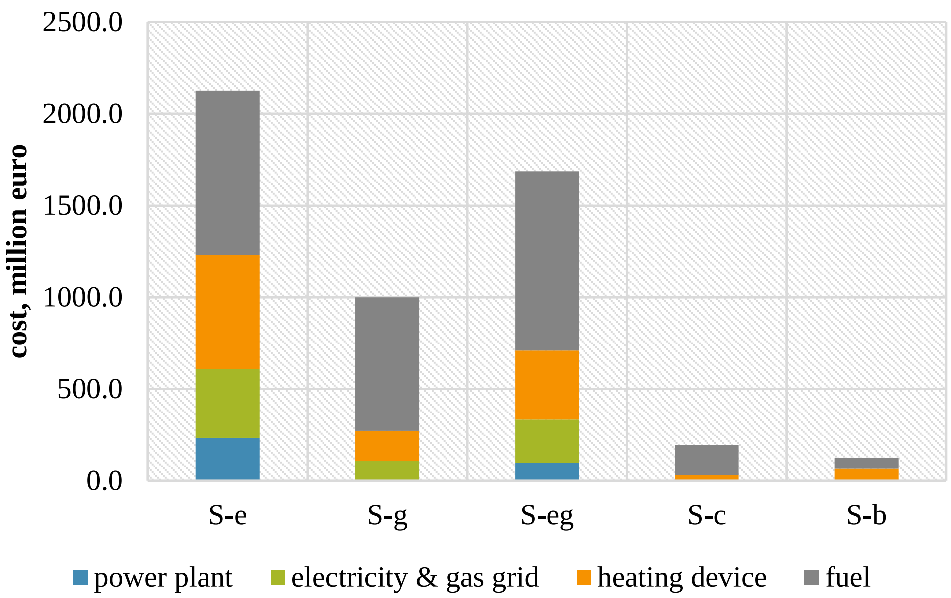

Fig. 6 Annualized incremental costs of household fuel policy scenarios in 2030

To show the difference between different scenarios in the relationship between costs and health benefits, we calculated the cost per premature deaths avoided, which is presented in Fig. 7 (A). Even though the health benefits of clean fuel scenarios were higher, the more significant difference in costs would still make it more expensive to save a life in the first three scenarios. Here the total exposure was used for the health impacts. The highest value of cost per premature deaths avoided was found in S-e, with 36,600 euros in 2030, while the S-c and S-b had the least and closed value with 4,900 euros and 3,100 euros respectively. In order to compare the benefits and costs, two major parameters were adopted to monetize health benefits and CO_2 emission reduction as the co-benefits, which are VSL - the value of a statistical life and SCC - social cost of carbon respectively. The annual monetized health benefits, co-benefits and the total benefits in 2030 were shown in Fig. 7 (B-D).

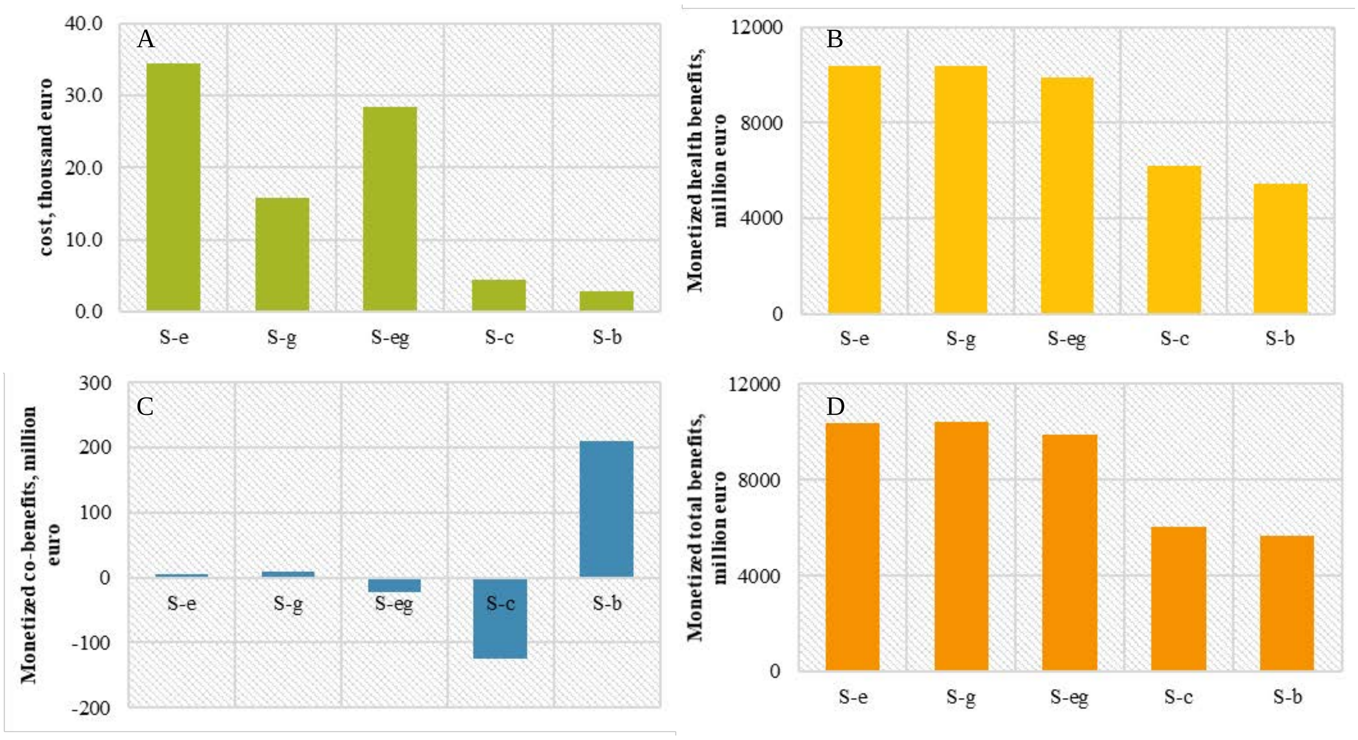

Fig. 7 Cost per premature deaths avoided (A) and monetized health benefits (B), co-benefits (C) and total benefits (D) under the household fuel policy scenarios in 2030

The monetized health benefits were 9,277~9,774 million euros for the clean fuel scenarios and only 5,205 and 5,514 million euros for the S-b and S-c in 2030. The biomass pellet scenario has the most significant positive benefits of reducing CO_2 emissions because biomass is usually considered carbon-neutral[46], which makes it a rather decarbonizing strategy. It is worth noticing that the S-eg and S-c had even negative effects on reducing CO_2 emissions as a result of the fuel switching from carbon-neutral biomass. Compared to the ambient $PM_{2.5}$ driven health benefits in all the scenarios, the monetized CO_2 emission reduction would contribute 18% of the total benefits in 2030. However, the co-benefits seemed too negligible when using the total exposure to calculate the health benefits, even for S-b with the highest CO_2 reduction and lowest health benefits the proportion for co-benefits was only 4%.

To better understand the relationship with total benefits and total costs, the ratio between them was taken as the benefit ratio. It's interesting to see that when considering only ambient $PM_{2.5}$ concentrations, all clean fuel scenarios have negative benefit ratios. In contrast, when using the total exposure method which also takes into account indoor concentrations, all the policy scenarios showed large positive benefit ratio. With the total exposure method, the benefit ratio of biomass pellet is the highest (62 in 2030) despite its lowest benefits, making it the most feasible strategy to take in this region under the current situation. And because of the relatively high investment costs of clean fuel scenarios, they do not perform well in terms of benefit ratios, especially for the low population density and mountain areas since in general costs to install facilities for electricity or PNG heating in mountainous areas with steep terrain and/or remote areas and dispersed households can increase dramatically.[47]

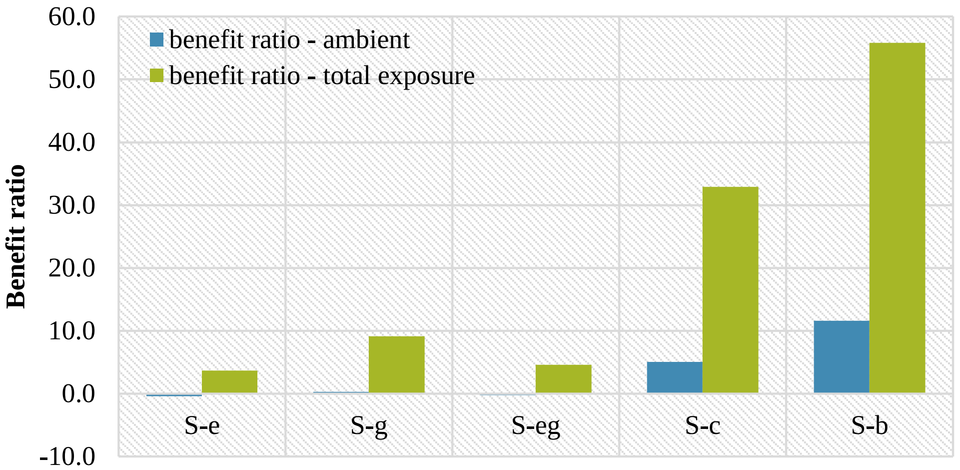

Fig. 8 The benefit ratio under five household fuel policy scenarios in 2030 using two methods

Environmental and health benefits of combinations with more sustainable scenarios

To better reflect the combined effects on the total ambient $PM_{2.5}$ concentrations in consistent storylines for mitigation policies in all sectors, the explicit household policy scenarios were combined with the SDS and NZE scenarios. Among the five household fuel policy scenarios, the contribution from clean coal with efficient stoves strategy to air quality improvement in the selected region was assessed in the STEPS. Given stricter mitigations included in other major sectors such as power plants, industry, transportation, even for the STEPS, SDS and NZE had significant decrease on ambient $PM_{2.5}$ concentration. For the rural Jing-Jin-Ji region, under the baseline scenarios (without the effects from household fuel policies), the ambient $PM_{2.5}$ concentration would reduce from 36.6 μg/m^3 (STEPS) to 27.3 μg/m^3 (SDS) and 25.7 μg/m^3 (NZE) in 2030. Coupled with the corresponding household fuel policy scenarios, the total ambient $PM_{2.5}$ concentration would decrease 0.4 μg/m^3 more for both SDS and NZE in 2030. A similar drop was also projected to occur in urban areas with 24% and 28% decrease for baseline in SDS and NZE scenarios, but only 1% more reduction for combined household fuel policies observed since the major mitigation would take place in rural households and the urban areas would only benefit from the meteorological transportation. On the other hand, the indoor benefits are limited as the fact that household fuel use determines indoor air pollution. And even though the SDS and NZE made great efforts on reaching a more sustainable future, the fuel use patterns for solid fuel users were not that much different for baseline scenarios. Hence, unlike the ambient $PM_{2.5}$ concentration change patterns, compared to the differences among the baseline in STEPS, SDS and NZE, the indoor $PM_{2.5}$ and the integrated total exposure concentrations experienced much larger benefits from the combined household fuel policy scenarios. The baseline indoor $PM_{2.5}$ concentrations changed from 70.2 μg/m^3 in STEPS to 66.0 μg/m^3 in SDS and 48.8 μg/m^3 in NZE for the rural Jing-Jin-Ji households, while coupled with biomass pellets and all electricity substitution strategies separately the indoor $PM_{2.5}$ concentrations dropped sharply to 21.2 μg/m^3 and 19.3 μg/m^3 for SDS and NZE in 2030, which are about 20% lower than the cleanest strategy in STEPS scenarios. Since we did not change the time activity patterns, the total exposure concentrations are expected to have the similar trends with indoor $PM_{2.5}$ concentrations. In 2030, the population weighted total exposure for rural Jing-Jin-Ji residents were predicted as 55.7 μg/m^3, 49.7 μg/m^3 and 48.8 μg/m^3 for STEPS, SDS and NZE baseline scenarios. Coupled with selected household fuel policy scenarios, the total exposure concentrations would decrease to 34.7 μg/m^3, 20.7 μg/m^3 and 18.9 μg/m^3, respectively. Due to the non-linear dose-response functions, the difference of premature deaths induced by $PM_{2.5}$ exposure among the three baseline IEA scenarios would be narrowed comparing with the total exposure. It is worth noticing that the absolute health benefits in the rural Jing-Jin-Ji region of replacing STEPS with NZE for baseline scenarios were 8,000 premature deaths avoided while the benefits would be heavily enlarged when replacing the same for the all electricity scenarios (up to 19,000). The similar situation was also observed in replacing baseline with all electricity separately for STEPS and NZE scenarios. The premature deaths avoided in STEPS was projected to be 57,000 but as high as 68,000 in NZE. That is also because of the non-linear response functions where the decrease in the lower concentration levels would be sharper than in the higher concentration levels, which indicates the air pollution mitigation collaboration in several sectors would bring more benefits than the sum of their individual effects.

Conclusion and discussion

Overall, residential fuel use is one of the most important sectors contributing to high air pollution in the Jing-Jin-Ji region, and the mitigation policies already made great efforts to combat both indoor and outdoor air pollution. For the rural residents that have not been covered by the clean fuel substitution, the five household fuel mitigation strategies proposed in this study would bring additional large benefits to environment and public health. In 2030, the average ambient $PM_{2.5}$ concentrations in the study region would decrease from 36.6 $\mu g/m^3$ in the baseline scenario to 35.0 $\mu g/m^3$ in the clean fuel scenarios and 35.2 $\mu g/m^3$ in the solid fuel scenarios. And even though the energy switching from solid fuels to clean fuels has limited impacts on ambient air quality which is essentially due to its already much reduced role by 2020, the indoor concentration would significantly benefit from the fuel pattern changes, which will lead to much larger health benefits. Here we only quantified mortality from ALRI, LC, IHD, STROKE and COPD as the health impacts. The avoided premature deaths for the study region in 2030 in the clean fuel scenarios and solid fuel scenarios would be 56,000 and 31,000 persons respectively.

Other than the significant health benefits, co-benefits brought by the CO_2 emission reduction is also one of the key concerns especially under the carbon neutrality pledge before 2060 (2050 for Beijing). Among the household fuel mitigations, the biomass pellets are usually considered carbon-neutral, hence this scenario promotes the carbon neutrality pledge the most with 5,673 kt CO_2 emission reduction solely in the rural Jing-Jin-Ji region. However, the residential sector is not the main contributor to CO_2 emission[3], and more mitigations for other sectors like in scenarios SDS and NZE were evaluated. In particular the NZE is a scenario which achieves the carbon neutrality pledge, and it also has the lowest $PM_{2.5}$ concentrations and premature mortality. Hence, the results show the co-benefits also for CO_2 reductions from air pollution related action.

For alternative solutions in rural households which were not covered in the clean heating campaign, this study only considered full substitution with the proposed five solutions. Among them, the benefit ratios of clean coal and biomass pellet scenarios are much higher than that of clean fuel scenarios. In this study, the infrastructure costs (i.e., electricity grid and gas pipeline), which would be brought by the steep terrain and scarce population[47], were not included because of data availability. On account of that, the benefit ratios for the clean fuel scenarios would be even lower.

Even though this study focused on the residential sectors in Beijing, Tianjin, and Hebei regions, other sectors also play important roles in improving air quality[8]. As shown in the STEPS, SDS and NZE baseline and combined household fuel policy scenarios, the collaboration between sectors and regions would bring more benefits, which also encourages the policy makers to implement more integrated mitigations rather than targeting one sector at a time. Aiming at the northern China region, the clean heating campaign also left a large proportion of rural households out of substitution in the other provinces. As a pilot project, this study only included Beijing, Tianjin and Hebei, which are among the areas with the highest attention. Considering the meteorological transportation of gases and aerosols, not only the targeted areas but also the surrounding areas would enjoy the benefits[44]. At the same time, the investment and fuel costs vary among different provinces and even prefectures, which indicates the joint prevention and control could lead to a more cost-beneficial solution and need to be addressed for further work. Due to the different source apportionments of major air pollutants between provinces, decision makers in each province should formulate more efficient air quality improvement targets based on accessibility, economic feasibility and also sustainability. In general, policy makers should not only pay attention to the direct benefits of air quality targets, but also the related co-benefits and the side-effects of various measures, such as energy security, fuel saving, greenhouse gases mitigation, the impacts of indoor air quality, and the affordability of the region.

References

1 Xu, W. Y. *et al.* Characteristics of pollutants and their correlation to meteorological conditions at a suburban site in the North China Plain. *Atmos. Chem. Phys.* **11**, 4353-4369, doi:10.5194/acp-11-4353-2011 (2011).

2 Yun, X. *et al.* Residential solid fuel emissions contribute significantly to air pollution and associated health impacts in China. *Science Advances* **6**, eaba7621, doi:10.1126/sciadv.aba7621 (2020).

3 Meng, W. *et al.* Energy and air pollution benefits of household fuel policies in northern China. *Proceedings of the National Academy of Sciences* **116**, 16773-16780, doi:10.1073/pnas.1904182116 (2019).

4 Cai, W. *et al.* The 2020 China report of the Lancet Countdown on health and climate change. *The Lancet Public Health* **6**, e64-e81, doi:10.1016/S2468-2667(20)30256-5 (2021).

5 Shen, G. *et al.* Fugitive Emissions of CO and PM2.5 from Indoor Biomass Burning in Chimney Stoves Based on a Newly Developed Carbon Balance Approach. *Environmental Science & Technology Letters* **7**, 128-134, doi:10.1021/acs.estlett.0c00095 (2020).

6 Zhang, J. & Smith, K. R. Household Air Pollution from Coal and Biomass Fuels in China: Measurements, Health Impacts, and Interventions. *Environmental health perspectives* **115**, 848-855, doi:10.1289/ehp.9479 (2007).

7 State Council of the People's Republic of China. *Air Pollution Prevention and Control Action Plan* (2013).

8 Zhang, Q. *et al.* Drivers of improved PM2.5 air quality in China from 2013 to 2017. *Proceedings of the National Academy of Sciences* **116**, 24463-24469, doi:10.1073/pnas.1907956116 (2019).

9 National Development and Reform Commission. *Winter cleaning and heating plan for the northern region (2017-2021)* **2018** (2017).

10 Zhong, Q. *et al.* PM2.5 reductions in Chinese cities from 2013 to 2019 remain significant despite the inflating effects of meteorological conditions. *One Earth* **4**, 448-458, doi:10.1016/j.oneear.2021.02.003 (2021).

11 Meng, W. *et al.* Differentiated-Rate Clean Heating Strategy with Superior Environmental and Health Benefits in Northern China. *Environmental Science & Technology* **54**, 13458-13466, doi:10.1021/acs.est.0c04019 (2020).

12 *https://www.xianjichina.com/news/details_107749.html*.

13 IEA. *International Energy Agency*, <https://webstore.iea.org/statistics-data> (2017).

14 International Energy Agency. *World Energy Model Documentation* (2020).

15 National Bureau of Statistics of China. *China Statistical Yearbook* (2011).

16 National Bureau of Statistics of China. *China Statistical Yearbook* (2020).

17 Shen, H. *et al.* Urbanization-induced population migration has reduced ambient PM2. 5 concentrations in China. *Science advances* **3**, e1700300 (2017).

18 Tao, S. *et al.* Quantifying the rural residential energy transition in China from 1992 to 2012 through a representative national survey. *Nature Energy* **3**, 567-573, doi:10.1038/s41560-018-0158-4 (2018).

19 Shen, G. *et al.* Impacts of air pollutants from rural Chinese households under the rapid residential energy transition. *Nature Communications* **10**, 8, doi:10.1038/s41467-019-11453-w (2019).

20 Zhu, X. *et al.* Stacked Use and Transition Trends of Rural Household Energy in Mainland China. *Environ Sci Technol* **53**, 521-529, doi:10.1021/acs.est.8b04280 (2019).
21 Amann, M. *et al.* Reducing global air pollution: the scope for further policy interventions. *Philosophical transactions of the Royal Society of London. Series A: Mathematical, physical, and engineering sciences* **378**, 20190331, doi:10.1098/rsta.2019.0331 (2020).
22 Simpson, D. *et al.* The EMEP MSC-W chemical transport model – technical description. *Atmospheric chemistry and physics* **12**, 7825-7865, doi:10.5194/acp-12-7825-2012 (2012).
23 Wind, P., Rolstad Denby, B. & Gauss, M. Local fractions – a method for the calculation of local source contributions to air pollution, illustrated by examples using the EMEP MSC-W model (rv4_33). *Geoscientific model development* **13**, 1623-1634, doi:10.5194/gmd-13-1623-2020 (2020).
24 Chen, Y. *et al.* Estimating household air pollution exposures and health impacts from space heating in rural China. *Environment International* **119**, 117-124, doi:https://doi.org/10.1016/j.envint.2018.04.054 (2018).
25 Xiang, J. *et al.* Reducing Indoor Levels of "Outdoor PM2.5" in Urban China: Impact on Mortalities. *Environmental Science & Technology* **53**, 3119-3127, doi:10.1021/acs.est.8b06878 (2019).
26 Duan, X. Exposure Factors Handbook of Chinese Population. (2013).
27 Duan, X. *et al.* Household fuel use for cooking and heating in China: Results from the first Chinese Environmental Exposure-Related Human Activity Patterns Survey (CEERHAPS). *Applied Energy* **136**, 692-703, doi:https://doi.org/10.1016/j.apenergy.2014.09.066 (2014).
28 National Bureau of statistics of China. *China Statistical Yearbook* (2018).
29 Vos, T. *et al.* Global burden of 369 diseases and injuries in 204 countries and territories, 1990-2019: a systematic analysis for the Global Burden of Disease Study 2019. *The Lancet* **396**, 1204-1222, doi:10.1016/S0140-6736(20)30925-9 (2020).
30 Institute for Health Metrics and Evaluation. *Global Burden of Disease Results Tool* (2020).
31 Vos, T. *et al.* Global, regional, and national incidence, prevalence, and years lived with disability for 328 diseases and injuries for 195 countries, 1990-2016: a systematic analysis for the Global Burden of Disease Study 2016. *The Lancet* **390**, 1211-1259, doi:10.1016/S0140-6736(17)32154-2 (2017).
32 National Health Family Planning Commission. *China's Health And Family Planning Statistical Yearbook* (2014).
33 *Global Burden of Disease Study 2019 (GBD 2019) Particulate Matter Risk Curves*, <http://ghdx.healthdata.org/record/ihme-data/global-burden-disease-study-2019-gbd-2019-particulate-matter-risk-curves> (2021).
34 Lim, S. S. *et al.* A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study. *Lancet* **380**, doi:10.1016/s0140-6736(12)61766-8 (2012).
35 IEA. *World Energy Outlook 2019*, <https://www.iea.org/reports/world-energy-outlook-2019> (2019).
36 International Monetary Fund. *World Economic Outlook* (2021).
37 Zhang, S. *et al.* Modeling energy efficiency to improve air quality and health effects of China's cement industry. *Applied Energy* **184**, 574-593, doi:https://doi.org/10.1016/j.apenergy.2016.10.030 (2016).
38 Wang, X. & Mauzerall, D. L. Evaluating impacts of air pollution in China on public health: Implications for future air pollution and energy policies. *Atmospheric Environment* **40**, 1706-1721, doi:https://doi.org/10.1016/j.atmosenv.2005.10.066 (2006).
39 Buonocore, J. J. *et al.* Health and climate benefits of different energy-efficiency and renewable energy choices. *Nature Climate Change* **6**, 100-105, doi:10.1038/nclimate2771 (2016).
40 Interagency Working Group on Social Cost of Greenhouse Gases, United States Government. *Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis* (2016).

41 Wang, R. *et al.* High-resolution mapping of combustion processes and implications for CO2 emissions. *Atmospheric Chemistry and Physics* **13**, 5189-5203 (2013).
42 Han, P. *et al.* Province-level fossil fuel CO2 emission estimates for China based on seven inventories. *Journal of Cleaner Production* **277**, 123377, doi:https://doi.org/10.1016/j.jclepro.2020.123377 (2020).
43 Reuter, H. I., Nelson, A. & Jarvis, A. An evaluation of void-filling interpolation methods for SRTM data. *Int. J. Geogr. Inf. Sci.* **21**, 983–1008, doi:10.1080/13658810601169899 (2007).
44 Liu, J. *et al.* Mitigation pathways of air pollution from residential emissions in the Beijing-Tianjin-Hebei region in China. *Environment International* **125**, 236-244, doi:https://doi.org/10.1016/j.envint.2018.09.059 (2019).
45 Peng, L., Zheng, Y., Zhang, Q., Xue, T. & Yao, Z. Underreported coal in statistics: A survey-based solid fuel consumption and emission inventory for the rural residential sector in China. *Applied Energy* **235**, 1169-1182 (2018).
46 Azar, C., Lindgren, K., Larson, E. & Möllersten, K. Carbon Capture and Storage From Fossil Fuels and Biomass – Costs and Potential Role in Stabilizing the Atmosphere. *Climatic Change* **74**, 47-79, doi:10.1007/s10584-005-3484-7 (2006).
47 Liu, G., Dong, X., Jiang, Q., Dong, C. & Li, J. Natural gas consumption of urban households in China and corresponding influencing factors. *Energy Policy* **122**, 17-26, doi:https://doi.org/10.1016/j.enpol.2018.07.016 (2018).