J. Benefit Cost Anal. 2017; 8(2):147–186
doi:10.1017/bca.2017.10

Yana Jin, Henrik Andersson and Shiqiu Zhang*

China's Cap on Coal and the Efficiency of Local Interventions: A Benefit-Cost Analysis of Phasing out Coal in Power Plants and in Households in Beijing[1]

Abstract: China's Cap on Coal Consumption (CCC) Policy serves as a key strategy to address the serious air pollution in China, and it helps to address coal's climate, environment and health damages. Current implementation of it focuses on substituting coal used in power plants and boilers with natural gas, whereas phasing out household coal use is less emphasized. This study estimates the benefits and costs of interventions for phasing out coal used in power plants and in households in Beijing. The results suggest that the phasing out of household coal use can result in net social benefits. However, coal-to-gas projects for power plants actually bring net social losses, a result largely attributable to the relative high price of natural gas in China. In addition to the actual policy evaluations of phasing out coal, this study outlines how to conduct economic analysis of air pollution policies in China taking into account uncertainty and correlations of key parameters. With the importance at a national and global level to reduce the negative effects of coal consumption, together with the trend of scaling up coal reduction interventions in China from local pioneers to the national level, this study provides implications on how to achieve more socially beneficial results for such interventions.

Keywords: benefit-cost analysis; households; Monte Carlo analysis; power plants; the cap on coal consumption policy.

JEL classifications: D61; Q53; Q58; I18.

---

1 We thank Glenn Blomquist and two anonymous referees for very helpful comments. We also thank the following people for their discussions and suggestions for this study: Denise Mauzerall, Marc Jeuland, Jintao Xu, and Benoit Laplante. This study is supported by the National Natural Science Fund of China (71503279), the Special Fund of State Key Joint Laboratory of Environment Simulation and Pollution Control (17K01ESPCP), the IRG fund of EEPSEA-Worldfish and the China Scholarship Council.
Yana Jin: College of Environmental Sciences and Engineering, Peking University, Beijing, 100871, China
Henrik Andersson: Toulouse School of Economics, University of Toulouse Capitole, 31015 Toulouse Cedex 6, France
***Corresponding author: Shiqiu Zhang,** College of Environmental Sciences and Engineering, Peking University, Beijing, 100871, China, e-mail: zhangshq@pku.edu.cn

1 Introduction

Coal is associated with extensive pollution in its mining and combustion processes, and its carbon intensity is the highest among the major fossil fuels. It therefore plays an important role in producing damages related to health, the environment and the climate. Thus, to adopt coal quantity controls can be a well-motivated strategy. As the world's largest coal consumer this is especially true for China. China is the country that contributes the most to global emissions of carbon dioxide (CO_2) and other greenhouse gases (GHGs) such as black carbon (Chen et al., 2009), and the largest part of these emissions attributes to coal consumption (Boden, Marland & Andres, 2016). From a national Chinese perspective the nationwide severe ambient air pollution, which is largely attributable to emissions from various coal using sectors (NRDC, 2014), and indoor air pollution in rural households as a result of using coal for cooking and heating (THUBERC, 2012), causes substantial health damages (Yang et al., 2013). To address these negative effects from coal use the China State Council (2013) set a cap on its annual coal consumption of 3000 Million Tons of Coal Equivalent to be reached by 2020. Although this Cap on Coal Consumption (CCC) policy scheme was motivated mainly by the need to address ambient air pollution (see Section 2 for more details), it also helps to address the other negative effects from coal use, which would be of benefit to both Chinese citizens and the rest of world.

However, going from a national level CCC strategy to implementing it as local level coal interventions, many issues emerge. Among the many we highlight three. First, coal-to-gas projects were first advocated by central governments and those for power plants were fully implemented in Beijing and then sprang up in other places. Soon, however, the shortage of gas supply was exacerbated and most of the projects, except the ones in Beijing, were suspended and canceled. Second, there have been big controversies over whether to substitute coal for other fuels or to still use coal but to make the combustion process cleaner (Wang, 2015). Disputes also surround the allocation of scarce natural gas resource across sectors and sites (Ni, 2013). Third, there is rich literature on assessing health damage from household coal use in China (Zhang & Smith, 2007), and the results collectively report it to produce almost the same magnitude of health damages compared with those from ambient air pollution (Yang et al., 2013). These findings have not been translated into stringent policies, however. Also, the CCC gives the lowest priority to interventions targeted at phasing out household coal use (discussed later).

We believe one common reason for these issues is that knowledge of the economic efficiency of different coal interventions is limited. Faced with mandatory coal quantity reduction targets, local governments naturally tend to adopt interventions in power plants and big boilers over those where benefits are widespread but affect millions of households. With this approach, the reduced coal amount with its quantity target is more easily measurable and perceived achievable. However, economic analysis of interventions is further needed if the CCC is to reduce health and environmental damages through implementing socially beneficial interventions. It is for this reason that in many countries, benefit-cost analysis (BCA) is often used, sometimes even mandatory in policy making process (Wiener, 2006; Graham, 2008). However, to the best knowledge of the authors, BCA has not to date been used to formally guide policies in China.

This paper aims to provide an analytical framework to account for the social benefits and costs of coal reduction interventions. We describe this framework by conducting BCA of two interventions with different implementation priorities in current policies. One is coal-to-gas for power plants, the other is to phase out household coal use. We look from a social welfare perspective at project level, which corresponds to how the policies are implemented in cities and districts. We extend our BCA by following Jeuland and Pattanayak (2012), Whittington, Jeuland, Barker and Yuen (2012) and use Monte Carlo simulations to characterize the uncertainty of the analysis. The CCC can be seen as part of the global initiative to reduce coal use to avoid global warming and is China's core national strategy to address air pollution in China, and it is to be resolutely implemented (China State Council, 2014). The efficiency of this large-scale energy policy is of high policy relevance and our analysis provides implications for prioritizing coal reduction interventions in targeted sectors, and better ways to deploy alternatives such as natural gas and renewable energy.

2 The CCC: policy background, implementation and implicit priority till 2017

Responding to the $PM_{2.5}$ (fine particulate matter with diameter less than 2.5 μm) crisis in the winter between 2012 and 2013, the China State Council issued the National Action Plan on Air Pollution Prevention and Control (2013–2017) in September 2013 (China State Council, 2013). This National Action Plan first sets specific goals of air quality improvements and then lists ten actions which address all the key aspects of ambient air quality management (see Table A1 in the Appendix). The fourth action is to "Adjust the Energy Structure and Increase the Clean Energy Supply".[2] This action, for the first time in China, clearly states that "mid and long-term national coal consumption control targets shall be

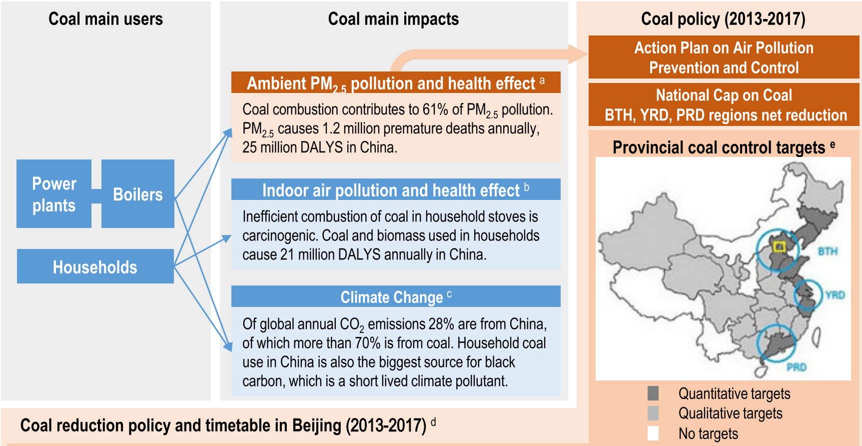
2 Quotes, program names, etc., originally written in Chinese and included in the article have been translated by the authors.

established, and a target responsibility system shall be adopted for implementation and evaluation". Meanwhile, three key regions, the Beijing–Tianjin and Hebei (BTH), Yangtze River Delta (YRD) and Pearl River Delta (PRD), are targeted specifically and are required to display negative growth of coal consumption.[3] Targets of the ten actions are then decomposed annually and geographically, with responsibility agreements signed between each level of government (provincial, municipal and district). As part of this policy process, each government level's annual plan on reducing coal consumption are made, with three groups of government personnel involved: (1) leaders in party and government (e.g., the core leaders in the Beijing Municipal Government), (2) environmental and other relevant departmental officials (e.g., those in Beijing Municipal Environment Protection Bureau and some other bureaus), and (3) leaders in party and government in lower levels (e.g., the core leaders in the Chaoyang district in Beijing).

In upper level government plans on reducing coal consumption, tasks are the amount of coal to be reduced in total level, sectoral level and jurisdictional regional level. Then the plan provides some rough description on how these amounts can be possibly achieved by lower level governments. In lower level government plans, tasks are much more specific, with programs or projects with implementation details and projected quantifiable coal reduction amounts specified. No matter which level of the plans, similarities are: (1) amount of coal reduction is the key policy indicator, (2) responsible person for each task is made explicit, a sign indicating a strong bound of target responsibility, and (3) an implicit priority can be derived – coal reduction tasks start from those focusing on power plants (if they exist in the area), with both largest amount and highest ratio of coal reduction, and specific implementation instructions. Then tasks turn to those focusing on industry and utility boilers, with second largest amount and second ratio of coal reduction, and also implementation details. Last come those focusing on rural and suburban households, with both least amount and lowest ratio of coal reduction, with some unquantifiable principles, and some details on substituting some raw coal by "improved coal".[4] This CCC policy is a typical case of current environmental governance scheme in China (Jin, Andersson & Zhang, 2016). Figure 1 illustrates the main coal users, impacts, and the CCC Policy. Table A2 in the Appendix summarizes the detailed tasks in Chaoyang District (location in the map in Figure A1 in the Appendix) in year 2014 as an example on how the coal reduction targets are implemented at the very local level.

3 China State Council recently issued "Energy Development Strategy Action Plan 2014–2020" (China State Council, 2014), in which the CCC is reinforced.

4 Examples of improved coal are low-sulfur coal, and anthracite (smokeless) coal.



Coal reduction policy and timetable in Beijing (2013-2017) [d]

Final consumers	Power plant	Utility boiler	Industrial boiler	Household coal usage
2013 coal consumption (10^4 ton)	920	552	437	391
Coal reduction target (10^4 ton)	920	220	200	100
Reduction ratio [f]	100%	40%	45%	26%
Proposed substitute	Gas-fired plant	Gas-fired boiler	Gas-fired boiler; Industrial adjustment	Cooking: LPG; Heating: electricity, improved coal

Figure 1 Coal main users, impacts, and the Cap on Coal Consumption Policy system in China. (a, b) Based on Yang et al. (2013), WHO (2014), (c) based on Chen et al. (2009), Marland, Boden and Andres (2015), (d) based on Beijing Municipal Government (2013), (e) in the map of provincial coal control targets: yellow square: Beijing City; blue circles: Beijing–Tianjin–Hebei (BTH), Yangtze River Delta (YRD) and Pearl River Delta (PRD), (f) reduction ratio calculated as coal reduction target divided by the current coal consumption (in 2013).

3 Analytical framework for the estimation of benefits and costs

3.1 Intervention specification and benefit-cost typology

The main interventions related to coal in different sectors currently being discussed in China can be broadly grouped into three types: (1) to substitute coal, (2) to update capital stock and (3) to still use coal but to make the coal combustion processes cleaner. Table A3 in the Appendix provides examples for each type. In this paper, we look at the costs and benefits of two coal substitution alternatives in power plants and in households. The current CCC uses the amount of reduced coal as the enforcement indicator. Local authorities have some freedom to choose the alternatives to implement as long as they meet the upper assigned coal reduction target. This feature provides us the rationale to compare the social net benefits by the same amount of coal reduction in different sectors. We, therefore, set the unit of calculations for

https://doi.org/10.1017/bca.2017.10 Published online by Cambridge University Press

the power sector to be a representative power plant installed capacity in Beijing with an assumed 600,000-ton annual coal consumption (Jian, 2013). The corresponding unit of calculation for households is 200,000 coal using households (3-ton annual consumption per household (China National Bureau of Statistics, 2012*a*,*b*; THUBERC, 2012)).

We consider three household heating intervention scenarios:

(1) house reconstruction for thermal insulation, solar air heat collector system and a biomass pellet fuel heated bed (which is still at a pilot stage, but is proposed as a potential integrated solution) (THUBERC, 2012);
(2) electric-heating stove, such as that currently being promoted in Beijing (Beijing Municipal Government, 2013);
(3) electric-heating stove and house reconstruction for thermal insulation, as the latter is considered able to cut the energy needed for space heating (THUBERC, 2012).

We further account for that households may slip back to using coal (or never stop using coal), by defining two distinct households: (1) a full-use household exclusively uses the new fuel after the intervention, and (2) a nonuse household goes back to using coal even after the intervention. In the subsequent parts of this paper the two types of households are analyzed independently. We also treat those who to some extent use the new alternative fuel but not exclusively, i.e. they also use coal, as nonuse households to keep a conservative estimation of the benefits of the policy. The costs and benefits associated with the two sectors' interventions are summarized in Table 1 with explanations for our estimations. Some key elements of the table, e.g. health effects, will be discussed in more details later. For those effects not quantified, we discuss their influence in footnotes in the main text.

3.2 Intervention costs

Intervention costs include one-time capital costs, changes in operation and maintenance (O&M) cost and incremental fuel costs from switching from coal to other fuels. Capital costs for power plants are investments in the new gas fired plant units, and the gas pipeline system.[5] For households the capital costs are new heating stoves, and reconstruction related costs.[6] The costs are annualized using social

5 We did not quantify capital cost for gas pipeline system. Considering that there are national scale gas pipeline projects, it is difficult to attribute certain investment amount as that for projects in Beijing. However, we believe that this part of capital cost is reflected in the range of the shadow price of natural gas. Moreover, we do not quantify unrealizable fixed assets in power plants (scrap value) due to lack of information. We believe this value to be negligible for our calculations.

6 Again, the scrap value for old coal stoves could also be considered, but it is again assumed to be zero.

https://doi.org/10.1017/bca.2017.10 Published online by Cambridge University Press

Table 1 Benefits and costs of phasing out coal in power plants or in households.[a]

Benefits	**Specific contents and estimation methods**
Substituting coal fired power plants by natural gas fired ones	
Health benefits 1	Reduced mortality and chronic bronchitis morbidity due to a marginal decrease of ambient $PM_{2.5}$
Health benefits 2	Avoided cases of other health endpoints due to ambient $PM_{2.5}$ in Table A4. Usually less than 5% of total health benefits of ambient air quality improvement, see. e.g., US EPA (2011)
Environmental benefit 1	Benefits from reduced CO_2, N_2O and CH_4
Environmental benefit 2	Improved ambient air quality brings better visibility and less materials damage; Environmental benefits due to less coal residue
Operation and Maintenance (O&M) cost saving 1	Net change of operation and maintenance costs, not quantified due to lack of information. Gas fired plants are free of residue treatment burden
Substitution of coal used in households by clean fuels and/or certain reconstructions	
Health benefits 3	Reduced mortality and morbidity from acute lower respiratory infections (ALRI), chronic obstructive pulmonary disease (COPD) and lung cancer for full-use households
Health benefits 4	Avoided cases of other health endpoints due to household air pollution in Table A4 for full-use households. Among them, cardiovascular disease (CVD) risk reduction may be of substantial benefits (WHO, 2014)
Health benefits 5	Potential but unclear health benefits for households who use both coal and new fuel
Health benefits 6	Benefits from reduced health effects from ambient $PM_{2.5}$ attributable to household coal use. The scale can be considerable, see, e.g., Chafe et al. (2014) and Liu et al. (2016)
Environmental benefits 3	Benefits from reduced CO_2, N_2O, CH_4, and black carbon emissions
Time saving	Benefits related to heating and cooking saved time. To substitute coal will slightly save households time as coal is a commercial energy and ready to be used
Aesthetic & Social standing	Benefits related to better cleanness, improvements status by using new fuel/technology
Costs	**Specific contents and scope**
Substituting coal fired power plants by natural gas fired ones	
Capital costs 1	Investment in the new gas fired plant units
Capital costs 2	Investment in the gas pipeline system. Reflected in the range of the shadow gas price. The unrealizable fixed assets in power plants (scrap value) is assumed negligible
Incremental fuel cost 1	Net change of fuel cost from coal-to-gas

Continued on next page.

https://doi.org/10.1017/bca.2017.10 Published online by Cambridge University Press

Table 1 (Continued).

Substitution of coal used in households by clean fuels and/or certain reconstructions	
Capital costs 2	Investment in equipment /stoves/ reconstructions
Operation and maintenance (O&M) costs 2	Net change of costs related to operation and maintenance of new technologies
Incremental cooking fuel cost	Net change from using coal to liquefied petroleum gas (LPG)
Incremental heating fuel cost	Net change from using coal to electricity, bio-pellet fuel and solar
Learning and Program	Time costs related to familiarization with the use of a new technology. Cost of promoting intervention projects, such as salaries and time of program workers, logistics in educational campaigns, and monitoring the banning of coal supply from small mines. The different time saving and time consuming effects in this table to some extend cancel each other out

[a]Items in shaded areas are not quantified.

discount rates and based on assumptions on the expected life of the projects. For fuel cost, the fuel prices need special attention because in China the price of gas used in power generation is regulated and subsidized, whereas the price of coal fluctuates in accordance with the market, but it does not internalize coal's environmental externalities. Information of how we account for the shadow price of gas and coal in base case model is provided in Table A5. For households, all the costs are relevant for a "full-use" household, whereas for a "nonuse" household only the capital cost is relevant in heating scenario 2. For heating scenarios 1 and 3 the saved fuel cost is also relevant due to the better thermal insulation capacity of the houses after the reconstruction. We do not quantify costs such as "learning" (costs of familiarization with a new technology) and "program" (cost of promoting intervention projects).[7]

3.3 Health benefits

3.3.1 Health effects associated with coal-to-gas for power plant

This part of the estimation is to first link Chinese population exposure with emissions from certain sources (i.e., in this study a power plant unit in Beijing) and then

7 Overall, we believe that these nonquantified costs are small compared to the ones quantified. Moreover, the different "time saving" and "time consuming" effects in Table 1 to some extend cancel each other out.

https://doi.org/10.1017/bca.2017.10 Published online by Cambridge University Press

link this with concentration-response (C-R) coefficients from epidemiological evidence. As summarized by Levy, Baxter and Schwartz (2009), the effects for health endpoint k from pollutant j from a certain source, E_{jk}, can be calculated by:

$$E_{jk} = \sum_i Pop_i \cdot \Delta C_{ij} \cdot \beta_{jk} \cdot I_k, \tag{1}$$

where Pop_i is the population size within cell i, and ΔC_{ij} is the contribution of the power plant emission to pollutant j's concentration in cell i ($\mu g/m^3$). The concentration-response (C-R) coefficient with respect to pollution j and health endpoint k is given by β_{jk}, and I_k is the number of new cases of health endpoint k in the population at risk in a given time period.

To estimate $\sum_i Pop_i \cdot \Delta C_{ij}$, models such as CALPUFF[8] focusing on individual power plants (Zhou, Levy, Hammitt & Evans, 2003; Zhou, Levy, Evans & Hammitt, 2006), or Community Multi-scale Air Quality Model (CMAQ) focusing on a sector level (Zhou, Fu, Zhuang & Levy, 2010; Xu, Wang & Zhang, 2013) can be applied. In this study, we estimate on a single power plant unit. Instead of performing new CALPUFF modeling, we follow Cropper et al. (2012) to use an intake fraction (iF) approach. The fraction of emitted pollutant m (either identical to pollutant j or j's precursor) from a certain source that is eventually inhaled by the population, $iF_{j,m}$, is defined as (Bennett et al., 2002; Levy et al., 2009),

$$iF_{j,m} = \sum_i Pop_i \cdot \Delta C_{ij} \cdot BR/Q_m, \tag{2}$$

where Q_m (μg/day) is the emissions of pollutant m from the source, and BR is the breathing rate (20 m^3/day-person). In CALPUFF or CMAQ modeling studies, $iF_{j,m}$ is one of the key modeling results that can be used for the estimation of health impacts. Our study is such an application that the $\sum_i Pop_i \cdot \Delta C_{ij}$ can be calculated with BR, $iF_{j,m}$and emission Q_m. Therefore Equation (1) becomes,

$$E_{jk} = iF_{j,m} \cdot Q_m \cdot \beta_{jk} \cdot I_k/BR. \tag{3}$$

We next clarify the choice of parameter values. We use $iF_{\text{p,primary PM}_{2.5}}$, $iF_{\text{as,SO}_2}$, and $iF_{\text{an,NO}_\text{x}}$ (the impact of primary $PM_{2.5}$, SO_2 and NO_x emissions on ambient concentration of $PM_{2.5}$, secondary ammonium sulfate and secondary ammonium nitrate,[9] respectively) estimated in Zhou et al. (2003). The authors estimated the impact of an 800MW coal fired power plant in Beijing on ambient air quality with CALPUFF modeling domain covering most of China. Compared to other $iF_{j,m}$ estimates in China (Wang et al., 2006; Hao et al., 2007; Zhou et al., 2010, 2014),

8 For more details about the CALPUFF model see, e.g., https://en.wikipedia.org/wiki/CALPUFF.
9 These are also types of secondary $PM_{2.5}$.

these $iF_{j,m}$ match best our objective, since they represent the aggregated national air quality impacts of one power plant located exactly in Beijing.[10] For Q_m, we apply the average emission of SO_2, NO_x and $PM_{2.5}$ per Beijing power plant unit (Luo, 2012). Once a unit becomes a gas fired one, $PM_{2.5}$ and SO_2 emissions will decrease to near zero. However, for NO_x, assuming equal heat supply, the gas fired plant will need higher generation efficiency, leading to even slightly higher NO_x emission levels (Ni, 2013). In our analysis, we conservatively assume zero emissions of $PM_{2.5}$ and SO_2 with intervention, whereas no significant changes in NO_x emissions. For the health endpoint (k), we focus on estimating changes in mortality and in morbidity of chronic bronchitis, because the former usually accounts for more than 90% of health benefits, and the latter is usually the second largest (US EPA, 2011).

We now turn to the choice of β_{jk}. Coal-to-gas for a power plant unit corresponds to a long-term marginal change in $PM_{2.5}$ concentration. We should, therefore, use C-R functions between long-term ambient air pollution and health endpoints. Evidences show that the C-R function may be concave across wide ranges of exposure (Burnett et al., 2014; Pope, Cropper, Coggins & Cohen, 2015), implying that a marginal pollution abatement effort may yield less benefits in China compared with developed countries, since the $PM_{2.5}$ concentration is higher in China than in developed countries. Therefore, one should ideally use Chinese cohort mortality evidence, and to the best of our knowledge, at the time this paper was being written, there are two studies providing Chinese long-term exposure mortality evidence (Cao et al., 2011; Chen, Ebenstein, Greenstone & Li, 2013). The C-R coefficients in these two studies are indeed smaller than those in developed countries, in line with the concave assumption of C-R function. However, the models in Chen et al. (2013) have been found to be overfitting, resulting in implausible causal inference (Gelman & Zelizer, 2015). Cao et al. (2011) is based on total suspended particle (TSP), rather than $PM_{2.5}$. Thus, applicability of these two studies is limited. Recently, an integrated exposure-response (IER) model was developed by integrating available relative risk (RR) evidences for the whole $PM_{2.5}$ exposure range from ambient air pollution to active smoking (Burnett et al., 2014), that can be applied within the range of Chinese ambient $PM_{2.5}$ concentration. However, the RRs in this IER model cannot be directly converted to C-R coefficients, and we therefore, in

10 The studies all verified that iF_s are sensitive to the source location (e.g., in Zhou et al. 2006, iFs for 29 power plant sites throughout China are estimated to be significantly different), population at various distances from the source, and meteorological factors (these factors have not significantly changed over a 10-year period), but much less sensitive to other factors such as the emission rate and stack height (they may change over time as they are subject to power plants' operational decisions). Therefore, iF_s in Zhou et al. (2003) can be applied to Beijing power plants under the current situation. The reason why we apply the same iFs for the four power plants in Beijing is that their locations are very close, all in the city center (Figure A1 in the Appendix).

this paper opt to follow Zhou et al. (2010, 2014) who have accounted for the effect of lower C-R coefficients in China in an analytical context similar to ours: we use a 1% increase in all-cause mortality per 1-$\mu g/m^3$ increase in annual $PM_{2.5}$ concentrations as central estimate, a lower bound of 0.1% and an upper bound of 2.0% in a triangular distribution. It is worth noting that $PM_{2.5}$ health effects overall are very large because there are many sources of $PM_{2.5}$ in big cities like Beijing. Due to the concavity in the C-R function, marginal interventions to reduce $PM_{2.5}$ will have lower benefits now relative to a future where $PM_{2.5}$ emissions from other sources are lowered. And coordinated $PM_{2.5}$ reducing strategies will have greater overall effect than each intervention evaluated individually.

3.3.2 Health effects associated with phasing out household coal use interventions

Most of the research on health effects from household fuel use is based on a "binary exposure classification" which separates the study population into those exposed to certain fuel usage and those not exposed (Desai, Mehta & Smith, 2004; Smith et al., 2014; WHO, 2014). The fraction of disease k in the population by age (s) and gender (t) group attributable to exposure (AF_{kst}) can be calculated by

$$AF_{kst} = \frac{1}{1 + [P_{est}(RR_{kst} - 1)]^{-1}}, \tag{4}$$

where P_{est} is the percentage of the population exposed and RR_{kst} is the relative risk for disease k. We quantify the three major health outcomes following WHO (2014): acute lower respiratory infection (ALRI) for children under 5 years old, chronic obstructive pulmonary disease (COPD) and lung cancer for adults over 30 years old. Then the health effects from disease k attributable to exposure in the population by age (s) and gender (t) group (E_{kst}) are estimated by,

$$E_{kst} = AF_{kst} \cdot I_{kst} \cdot Pop_{st}, \tag{5}$$

where Pop_{st} is the population size by age s and gender t group. Parallel to that for power plants, we clarify that: improved coal, improved stove, or improved emission ventilation can mitigate exposure level to different extent. We follow Desai et al. (2004) and set a ventilation coefficient (a multiplier of P_{est}) to account for the variability of the actual exposure level so that we do not overestimate health benefits. Further, for COPD and lung cancer, we only quantify the completely prevented cases. We choose not to quantify those who have developed the early stages of COPD or have accumulated a high risk for lung cancer over many years' exposure because it is difficult to know to what extent the onset of disease for such individuals could be reduced by an end in exposure (Hutton, Rehfuess, Tediosi & Weiss, 2006).

Lastly, similar to that for the power sector, the IER (Burnett et al., 2014) provides a possibility to estimate health impacts based on actual indoor $PM_{2.5}$ concentration changes. However, we choose to still adopt the "binary exposure classification" method which only classify exposure by exposed and not exposed to household coal usage. The smoke from household coal combustion is a mixture of $PM_{2.5}$ and many other harmful emissions, which may result in toxicity and health impacts different to that from only $PM_{2.5}$. Therefore, we utilize the RR evidences for household coal usage in WHO (2014), rather than those for $PM_{2.5}$ in the IER. Similarly, the reason why a full relative risk is used for household coal use, whereas only a more limited set of coal combustion emissions are accounted for in the power plant intervention, is because coal combustion in household coal stoves and in power plants are very different; the latter is much more complete and the end-of-pipe treatments in power plants are effective, therefore generating much less of emissions other than SO_2, NO_x and PM.

3.3.3 Monetize health effects

We use the value of a statistical life (VSL) to monetize mortality reductions. VSL is the marginal rate of substitution between mortality risk and income (Hammitt, 2000). In China ten VSL studies have been conducted to date and the estimates are from US$150,000 to US$800,000 (Huang, Andersson & Zhang, 2015). Currently there is no "official VSL" in China and we therefore use this range for our estimations. For household intervention, we discount the health benefits related with chronic diseases which have a delay of onset. For their mortality reductions, VSL is adjusted based on income growth assumptions (4%–7%, explained in Table A5) over the years between pollution exposure and health effect onset (hereinafter latency), and by income elasticity of VSL (1–2, see Hammitt & Robinson, 2011). The estimated benefits are then multiplied by the discount factor, $e^{-d \cdot r}$, where d is the years of delay in onset of symptoms (15–25 years) and r is social discount rate. We do not discount for power plants intervention because nearly all of the health impacts of ambient $PM_{2.5}$ were observed within 2 years of exposure, therefore the effect of discounting is minimal[11] (Levy et al., 2009). For morbidities related to power plants, we follow US EPA (2011) and set the value of a statistical case (VSC) of chronic bronchitis to be around 5.5% of the VSL. Regarding household morbidity, we apply the same VSC/VSL ratio and discount factor for COPD morbidity reduction. For lung cancer cases, since the probability of dying, conditional on getting this disease, almost equals one, we do not monetize its morbidity risk to

11 For example, with all other parameters held at base value, simulated discounted (0–2 years of latency) health benefits range from 29.9 to 31.8 million USD.

https://doi.org/10.1017/bca.2017.10 Published online by Cambridge University Press

avoid double counting. Avoided ALRI is monetized with information on the cost of illness (Ministry of Health of China, 2012).

3.4 Environmental benefits

For the power plant sector, the net change on GHG emissions from switching from combusting coal to natural gas is the annual consumption multiplied by their emission factors of CO_2, CH_4 and N_2O, which are the three major GHGs in standard carbon accounting (UNFCCC, 2010). The household sector is more complicated. Whichever heating scenario, for "full-use" households coal will be replaced by certain amount of other fuel or energy (e.g., LPG, electricity or solar). For "nonuse" households, changes in fuel quantities and GHG emissions are also relevant for heating scenarios 1 and 3, since the coal needed for space heating will be reduced due to better thermal insulation capacity brought by the interventions. For the corresponding net change of GHG emissions, besides CO_2, CH_4 and N_2O which apply the same analytical process as that in the power plants, the black carbon emissions from household coal use have a strong greenhouse effect. Therefore, whether or not to include it in the carbon accounting may substantially influence the level of environmental benefits. We follow Jeuland and Pattanayak (2012) and test the influence of black carbon using emission factors of coal used in households estimated by Bond, Venkataraman and Masera (2004). Environmental benefits from net reductions of GHGs are estimated by multiplying the CO_2 equivalent emission amount of different GHGs species[12] with the social cost of carbon (SCC), the economic damages associated with a marginal increase in CO_2 emissions. Our study estimates the benefits and costs within a national scope, implying that the SCC for China is the most relevant monetary unit value in this study (Gayer & Viscusi, 2013). We set the SCC for China as a quarter of the global SCC, following the ratio suggested in Nordhaus (2011). The global SCC (USD/ton CO_2) is set as a triangular distribution with 40 as base estimate, 12 as a lower bound and 200 as an upper bond, based on US EPA (2013). We also examine difference between assumptions taking the global SCC or only Chinese portion of SCC in sensitivity analysis.

12 Apart from CO_2, other species such as CH_4, N_2O and black carbon are converted to equivalent amount of CO_2 using their global warming potential (GWP). The 100 year GWP (CO_2) = 1, GWP (CH_4) = 21, GWP (N_2O) = 310. For details see, e.g., http://epa.gov/climatechange/ghgemissions/gases.html. For household coal use the GWP of fossil fuel soot (containing both Black Carbon and cooling aerosols and particulate matter) is the relevant measure and we use GWP (fossil fuel soot) = 1000.

3.5 Data, modeling, sensitivity and scenario analysis

Following Jeuland and Pattanayak (2012) and Whittington et al. (2012), we use a Monte Carlo simulation based approach to provide cumulative distribution of net present value (NPV) and the rankings of sensitive factors for our interventions. With these results one can tell: (1) whether there is a clear ranking of the efficiency of the interventions, (2) the overall variability of NPV outcomes, and (3) what factors are more influential to outcomes and therefore worthy to be further looked at. To perform the simulations, based on an extensive literature review, we specify base values, ranges and likely correlations for all the parameters (summarized in Tables A5 and A6). Then Monte Carlo simulation is performed in the spreadsheet-based application Oracle Crystal Ball, with 10,000 times of realization for the NPV of each intervention. In each time of realization, all the parameters in Tables A5 and A6 are stochastically draw within their value range, with a uniform distribution assumption unless otherwise specified in Table A5.

We further test some factors' influence on the efficiency of interventions by scenario analysis. These factors are of relevance for different reasons, and they should or could not be subjected to probabilistic risk analysis, i.e. treated as stochastic. First, we construct a power plant unit with worse performance than the current units in use ("dirtier" for short, with year 2000 emission level in Table A7, and upper bound level of coal used per kWh electricity generated in Table A5) to test if the intervention examined could then be justified. Since the actual performance of power plants can be very different in different locations, and change rapidly in a dynamic China, knowing for which power plants the interventions could be beneficial would help decision makers on the order of interventions among power plants with different performance. Second, we test hypothetical scenarios with considerably lower gas prices. In economic impact modeling research, since the results have been found to be very sensitive to fuel prices, it is recommended to specify and examine the effect of plausible fuel price changes in energy market (Morgenstern, 2015). China's proven shale gas reserve is the largest in the world (Hu & Xu, 2013) and if massively exploited, the current high gas price might significantly decrease. Various reasons can possibly lead to this change, for example a more aggressive version of the current CCC policy. If many coal plants were required to shut down in favor of gas plants, incentives for natural gas exploration and development would become stronger, and if this resulted in an abundance of gas supply, gas price would possibly fall. We use three hypothetical gas price scenarios with reference to that in the three major regional markets, North America (where the price is the lowest and where shale gas plays a big role), Europe, and Asia-Pacific (Birol, 2013) and test if conversion from coal-to-gas in power plants can be socially beneficial.

For households, we first address the "use rate" issue. Although experimental studies strongly support the short-term improvement brought by household solid fuel use interventions, long-term field evidence (Hanna, Duflo & Greenstone, 2012) display a low use rate of improved stoves or new fuel. In reality, because interventions are usually implemented for an aggregated number of households (e.g., in a village), policy makers may be more concerned about how high a real use rate would be sufficient to generate a positive NPV. We assume that among the 200,000 households that would apply the intervention, the proportion of full-use and nonuse households will be x and $(1 - x)$. Therefore, by solving for x in Equation (6), we provide a break-even use rate for a positive NPV,

$$x \cdot 200000 \cdot NPV_{\text{full-use}} + (1 - x) \cdot 200000 \cdot NPV_{\text{nonuse}} = 0. \quad (6)$$

We further test how different carbon accounting (applying the UNFCCC method or to further add black carbon) will influence this break-even use rate. Environmental benefits based on different carbon accounting methods would provide references for potential scale of subsidies, which would in turn influence the cost burden of households and their real use rate.

Finally, the above scenarios are further divided into six scenarios with different combinations of SCC at Chinese portion or at global level, and social discount rates (1%, 3% and 5%). In this way, we can test their influence in our simulations without the need to construct any specific nonlinear relationship between the SCC and the social discount rate.

4 Results

4.1 Health effects attributable to one coal fired power plant unit or to 200,000 coal using households

We begin by presenting the physical health effects. Table 2 summarizes the mortality and morbidity changes attributable to a single coal fired power plant unit in Beijing by pollutant type, and to household coal use by disease type. For power plants, the results show that the emissions from one plant unit annually result in 292 premature deaths and 279 cases of chronic bronchitis in total, at median value. Among the three emissions NO_x causes the most deaths and cases of chronic bronchitis. Recall that the coal-to-gas intervention for power plants can only reduce emissions of $PM_{2.5}$ and SO_2, not NO_x, therefore the avoided premature deaths/cases of illness is only the sum of those from $PM_{2.5}$ and SO_2, which gives a total number of 68 deaths and 64 cases of chronic bronchitis avoided from such an intervention,

https://doi.org/10.1017/bca.2017.10 Published online by Cambridge University Press

Table 2 Health effects attributable to 600,000-ton coal used in power plants or in households.[a]

A: One power plant unit						
Pollutant type	**Premature deaths**			**Chronic bronchitis cases**		
	Low	**Median**	**High**	**Low**	**Median**	**High**
1. $PM_{2.5}$	7	15	31	7	14	27
2. SO_2	20	50	108	22	48	93
3. NO_x	71	217	517	76	210	457
Total	117	292	628	128	279	546
Can be avoided by coal-to-gas	30	68	134	33	64	115
B: 200,000 households						
Disease type	**Premature deaths**			**Disease cases**		
	Low	**Median**	**High**	**Low**	**Median**	**High**
1. ALRI	1	2	4	47	78	124
2. COPD	37	70	122	181	345	608
3. Lung cancer	48	83	137	48	83	137
Total and can be avoided	89	155	260	–[b]	–	–

[a] All cases per year. Low and high correspond to the 10th and 90th percentile outcomes from the simulations. Cells for subitems and total are all from simulations therefore total numbers do not equal the summation of subitems.
[b] Since symptoms and outcomes are different, a summation is not informative.

at median value. For households, most premature deaths attributable to household coal use are from COPD and lung cancer. Note that for the households the number of 155 as the sum of chronic and acute deaths is only roughly comparable with the total premature deaths in the power plant sector. To better compare health effects between power plants and households, one should use the monetized benefits (presented later) which discount future health benefits to the same base year.

4.2 Benefits and costs of reducing the same amount of coal in power plants or in households

The simulated low, median and high estimates of benefits and costs in power plants and in households are presented Table 3. For power plants, the incremental fuel cost dominates all monetized items and makes the total cost having a larger order of magnitude than benefits. For households, in most cases, benefits exceed costs, resulting in positive net social benefits. The results support scenario 1's potential in cost saving. For scenario 2, coal-to-electricity, the incremental fuel costs are

https://doi.org/10.1017/bca.2017.10 Published online by Cambridge University Press

Table 3 Annual benefits and costs of 600,000-ton coal reduction in power plants or in households.[a]

	One power plant unit			200,000 full-use households								
1. Health benefits	Low	Median	High		Low			Median			High	
	11.5	31.2	73.1		74			186			416	
				Scenarios for household space heating								
				1			2			3		
2. Environmental benefits[b]				Low	Median	High	Low	Median	High	Low	Median	High
	2.7	9.1	16.7	8.8	31	53	−21[c]	−4.7[c]	3.0	1.8	10	26
3. Costs												
Capital cost	15	17	19	26	43	61	11	13	16	26	30	35
Incremental fuel cost	97.6	157	226	−68	−52	−37	52	78	104	−18	7.5	36
Incremental O&M	–	–	–	1.9	3.1	4.3	1.3	1.6	1.8	1.3	1.6	1.8
4. NPV	−201	−128	−45	111	224	453	−30	87	319	44	161	389

[a] All in million in 2011 USD. Low and high correspond to the 10th and 90th percentile outcomes from the simulations. Cells for subitems and NPV are all from a simulation process and therefore NPV estimates do not equal the summation of subitems.

[b] Based on UNFCCC carbon accounting.

[c] The reason for the potential negative values for environmental benefits for heating scenario 2 is that electricity is a secondary energy (i.e. a product of other energy sources like coal, wind, solar, etc.) and therefore does not necessarily have a lower carbon intensity than coal.

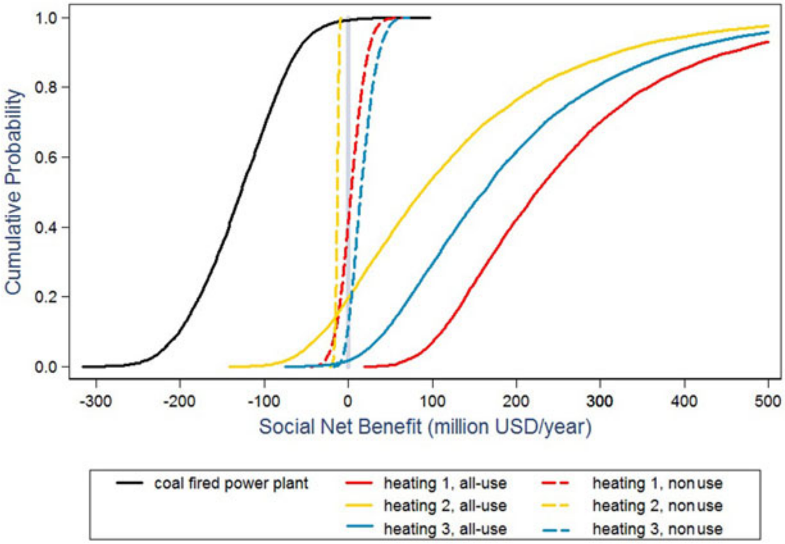


Figure 2 Net benefits of coal-to-gas for power plants and phasing out household coal use.

high and the simulations suggest that even if benefits are expected to exceed the costs, there is a chance for the opposite. Scenario 3 shows that when house thermal insulation reconstruction is added, it indeed saves fuel cost and pulls down the total cost.

The cumulative distribution of the net benefits of different intervention scenarios are presented in Figure 2. For power plants, though the outcomes spread across a considerable range due to the variable parameters, it is close to certain that NPVs are negative. For households, the spreads of outcomes are much wider in the full-use scenarios, simply because more parameters, especially those for health benefits, are involved in the estimation. In contrast, for the nonuse situation, only parameters related with costs and environmental benefits contributes to variability, resulting in a narrower spread. The distribution in reality will lie somewhere between the two sets of curves. Comparing different heating scenarios, though the scenario 1 has the most cases of positive NPV in full-use, it also has a larger risk of negative NPV than the scenario 2 if the use rate is low. Instead, when the use rate is 0, scenario 3 still has a higher chance of positive NPVs, simply attributable to benefits from better insulation. Scenario 2 by simply switching from coal to electricity, has the largest chance of negative NPVs.

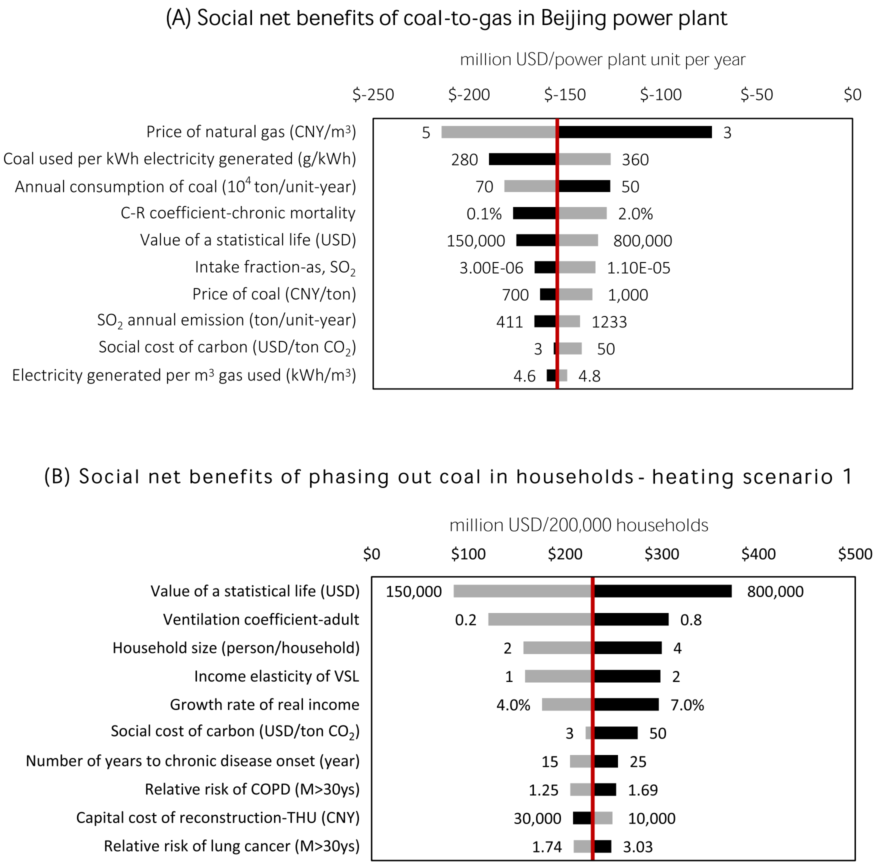


Figure 3 Top 10 parameters contributing to uncertainty of the social net benefits 2011 emission level for power plant. Use rate equals 1 for households. The thick line in the center shows the outcome estimated with base value of parameters. Results for heating scenario 2 and 3 are similar to that for heating scenario 1, and are available from the authors upon request.

4.3 Parameters that contribute most to the variation in social net benefits

Figure 3 shows the top 10 parameters contributing to uncertainty in the NPVs of interventions. As shown in the figure, none of the most significant parameters alone can change the outcome of the analysis, i.e. the NPV always stays negative or positive. For power plants, the gas price dominates the uncertainty, followed by the quantity of coal use per kWh electricity generated, then the price and quantity for coal. Moreover, Figure 3 also reveals that factors such as VSL, iFs, emission

https://doi.org/10.1017/bca.2017.10 Published online by Cambridge University Press

level of SO_2 and C-R coefficients are high ranking factors contributing to uncertainty. These are often the key sensitive parameters in estimating health effects from power plants and industry (Stevens, Wilson & Hammitt, 2005; Levy et al., 2009). For households, though different heating scenarios have varying net benefits, the rankings of parameters' contribution to the uncertainty are very similar. The most important parameters in shifting outcomes are all benefit related ones. This is because that most of the benefits in households come from avoided chronic health outcomes with a long latency. Price and quantity of coal, disease or intervention technology specific parameters are less sensitive.

4.4 Scenario analysis on power plant performance, gas price, carbon accounting, SCC and social discount rate

We construct different scenarios with different SCC and discount rate combinations for "standard" and "dirty" power plants under different gas price levels. Specific scenario settings for these different plants, values taken for the SCC and the discount rate, and each scenario's simulation results are all summarized in Table 4. For all SCC and discount rate levels, simulated NPVs for a "dirty" unit are better (to be interpreted as NPV being positive) than those for a "standard" unit. This means that for a power plant, everything else equal, the lower the efficiency and the higher the emission level is, the better it is to regulate it. Comparing different gas price levels (columns in upper part of Table 4), only if the gas price in China somehow decreases to a level well below 2 yuan/m^3, could NPV for coal-to-gas conversion for "standard" power plants be positive. However, if targeted at the "dirty" plants, a 3 yuan/m^3 gas price is enough. Finally, for both types of power plants, different assumptions for the SCC and the discount rate do not significantly influence the outcomes.

Regarding what use rate among household interventions can realize net social benefits, we also analyze the three heating scenarios under carbon accounting with or without black carbon, and under different SCC and discount rate combinations. As shown in the bottom half of Table 4, in all the scenarios examined, the break-even use rates, at median level, do not have to be high. A lower discount rate with higher SCC, and with global SCC assumptions, further reduce the break-even ratio. When black carbon is included in the carbon accounting, the environmental benefits increase and the break-even ratios slightly decrease. Our break-even use rate results are more optimistic compared to Whittington et al. (2012) who also looked at behavioral indicators in programs in developing countries. In their results, often a considerable use rate is necessary to generate a positive NPV. One reason for this difference is that our study looks at phasing out coal stoves, which are used more for space heating than for cooking. In heating scenario 1 and 3 the houses have been

Table 4 Scenario analysis for phasing out coal in power plants and in households.[a]

Power plant type	China portion or global SCC[b]	Global SCC (USD/ton CO_2)[c]	Social discount rate (%)	Annual net benefits of coal-to-gas for power plants (million USD/unit-year): Scenarios for hypothetical shadow gas price[d] — 3 yuan/m^3 (Asia-Pacific) Low	3 yuan/m^3 (Asia-Pacific) Median	3 yuan/m^3 (Asia-Pacific) High	2 yuan/m^3 (Europe) Low	2 yuan/m^3 (Europe) Median	2 yuan/m^3 (Europe) High	0.5 yuan/m^3 (North America) Low	0.5 yuan/m^3 (North America) Median	0.5 yuan/m^3 (North America) High
"Standard" power plant unit[e]	China	11	5	−122	−94	−57	−57	−32	15	33	63	126
		32	3	−121	−86	−37	−57	−27	16	45	69	114
		90	1	−111	−84	−51	−42	−21	18	45	80	131
	Global	11	5	−121	−89	−51	−60	−31	9	39	66	115
		32	3	−114	−80	−31	−37	−16	15	50	67	112
		90	1	−96	−53	−5	−31	5	45	71	100	142
"Dirty" power plant unit[f]	China	11	5	−25	136	366	43	209	636	118	298	750
		32	3	−19	144	359	21	187	575	172	321	762
		90	1	−36	163	617	55	212	586	148	284	688
	Global	11	5	−41	118	457	38	212	532	113	333	793
		32	3	−19	146	597	29	241	639	124	328	763
		90	1	21	177	599	69	195	488	129	309	607

Continued on next page.

Table 4 (Continued).

Households' break-even use rate for a positive NPV under different carbon accounting												
Carbon accounting method	**China portion or global SCC**	**Global SCC (USD/ton CO_2)**	**Social discount rate (%)**	**Scenarios for household space heating**								
				1			**2**			**3**		
				Low	**Median**	**High**	**Low**	**Median**	**High**	**Low**	**Median**	**High**
UNFCCC carbon accounting	China	11	5	1%	12%	30%	+[g]	13%	99%	+	2%	30%
		32	3	+	2%	14%	+	8%	48%	+	+	6%
		90	1	+	+	1%	1%	5%	27%	+	+	+
	Global	11	5	+	8%	28%	+	12%	90%	+	0%	22%
		32	3	+	2%	11%	+	8%	48%	+	+	4%
		90	1	+	+	2%	1%	5%	28%	+	+	+
UNFCCC with black carbon	China	11	5	2%	11%	29%	+	15%	85%	+	2%	22%
		32	3	+	2%	11%	3%	9%	41%	+	+	4%
		90	1	+	+	2%	2%	4%	14%	+	+	+
	Global	11	5	0%	8%	22%	+	14%	75%	+	1%	13%
		32	3	+	1%	7%	3%	6%	24%	+	+	3%
		90	1	+	+	1%	1%	3%	7%	+	+	+

[a] Low and high correspond to the 10th and 90th percentile outcomes from the simulations.

[b] China portion is one quarter of the global SCC.

[c] Global SCC values corresponds to different discount rate assumptions, the lower the discount rate, the higher the SCC.

[d] Hypothetical gas prices are around the three major regional markets' 2012 price level.

[e] "Standard" unit is simulated based on 320g coal per kWh electricity generated (g/kWh) and 2011 emission level in Table A5.

[f] "Dirty" unit is a low efficiency and high pollution plant unit and is simulated based on 360g coal used per kWh electricity generated and 2000 emission level in Table A7.

[g] For households, simulation results marked as "+" mean that even with no households using the new new fuel after the intervention, NPV is positive.

renovated with better thermal insulation therefore less coal is needed for space heating. Even with a low use rate these interventions can easily have a positive NPV as they save fuel cost and bring environmental benefits.

5 Discussion

Under the current CCC context in China, this study estimates the social economic impacts, such as health, environmental and climate effects, of coal substitution interventions in power plants and households. A BCA model based on methods and evidence from multiple disciplines is constructed for the different interventions examined. We parameterize the model with information from the literature and publicly available sources, and simulate the results using Monte Carlo methods. We show that: (1) The reduction of a specific amount of coal does not translate into a fixed amount of net benefits, rather there is a considerably wide range of likely outcomes for the different interventions across the sectors (power plants and households). (2) Coal-to-gas for standard power plants (e.g., the ones in Beijing) is not socially beneficial – even for the ones with low efficiency and high pollution can the intervention be justified only if the gas price in China significantly decreases. (3) Although a lot of uncertainties are involved, to phase out household coal use can bring net social benefits. Moreover, interventions with house thermal insulation reconstruction integrated should be prioritized.

In summary, it will be more beneficial to first phase out coal use in households, rather than in the conventionally policy-focused sectors, such as power plants. The gas fired power plants examined in our study are already in operation. Because Beijing is prioritized, its gas supply to these power plants will always be guaranteed, even if alternative, more efficient uses are foregone. Hence, there is a risk that policies will not be reconsidered in Beijing despite the analysis suggesting robust evidence of a negative NPV. However, since different coal interventions, as shown in Table A3, are being considered, or already implemented, the same BCA analytical process used here can also be applied to inform policy makers about the efficiency of those other interventions, and the analysis conducted in this study can be useful to better allocate their limited gas resource to generate more socially beneficial outcomes in Beijing and other places in China (and in other countries).

Although the analytical framework in this study can be widely used, a number of caveats and extensions of this analysis should be highlighted. First, whether the conclusion for power plants in this study can be generalized to other places and countries, or to industry and utility boilers, would need further research. More importantly, we do not suggest that coal-to-gas conversion for power plants will always result in social losses. To continue to build conventional coal power plants is committing to enormous future CO_2 emissions, and therefore, substituting coal with gas has value in certain circumstances (e.g., to balance the intermittency of wind and solar energy). What our results suggest is that without significant technology or fuel market changes in the near term, relative fuel price will influence the economic efficiency a lot and cleaner fuels should be more effectively allocated across sectors and sites.

For the household sector, our modeling does not predict the behavior of households. For some of the scenarios with household interventions, not only positive net social benefits but also positive net private benefits are observed. Possible reasons for why households have not invested in technology or changed their behavior in a way that would provide net private benefits include liquidity constraints, lack of (or irresponsive to) information, or behavior that fails to optimize quantifiable private benefits that could be addressed with nudges (Graham, 2016). For example, the main benefits are nonfinancial health benefits that in some cases involve latency. It may, therefore, be difficult for individual households to accurately conduct their own private BCA and realize that it would be in their self-interest to invest in the new technology and to change their energy source. Since we are conducting a BCA of the interventions, such behavioral aspects are not covered by our modeling.

It should be stressed that the modeling itself does not provide direct evidence against the current "improved coal policy" for households. There is a lack of scientifically reliable information of emissions and health risks from improved coal (WHO, 2014), but its use is a favored policy. The improved coal is being massively promoted to be used for households in rural areas for heating (China State Council, 2013). However, two facts suggest abandonment of this policy. One is that improved coal cannot force out the raw coal in the market. A price reduction of the raw coal was immediately observed after the provision of the subsidized improved coal in rural areas (Miyun County Government, 2014). Moreover, the easier it is to accesses coal, the higher the likelihood for households to continue (or to go back to) the use of coal. Therefore, there is no point in promoting the supply of improved coal for households.

We have above discussed nonquantified benefits and costs, but there are potential effects and distributional impacts not considered. Specifically, if the interventions in this paper are implemented at a large scale, significant air quality improvement could result and other benefits, e.g. the hedonic value of clean air and blue skies, may need to be taken into account, and there might be general equilibrium effects not covered by our analysis. But we are in this study examining specific small scale interventions and we believe that any hedonic value of clean air would be small (if existent) and hence not influence our conclusions, and that a general equilibrium analysis is outside the scope of the study. Moreover, it could be argued that multiple and overlapping policies affecting Chinese coal consumption could also affect our analysis and conclusions. For instance, if investments for coal-to-gas projects are being taken for compliance with other policies, the marginal cost of compliance under the CCC may be zero. However, in this study, we are examining the benefits and technical costs of implementing the goals of specific policies and are not examining the costs of specific policy mechanisms. Hence, we believe it is better to interpret the estimated benefits and costs in this paper as for actual project interventions at the very local level, rather than for certain policy mechanisms.

Regarding distributional effects and type of intervention, they are of relevance also for small scale interventions like the ones examined here. For the benefits, there are spatial, demographic distributional differences for health benefits depending on the type of intervention, and whereas power plant interventions lead to fully socialized benefits, household interventions would lead to greater private benefits. On the cost side, since we are examining interventions in power plants, where investments and the increase in fuel costs will likely be covered by the government, and household interventions, where the costs most likely will have to be covered by the households themselves, this distributional difference is also of interest. However, we argue that is mainly of political relevance in our case, and less of economic relevance, since we can consider all costs being financed by households, including government expenses, and the government could also finance the household investments by lump sum transfers and fuel subsidies to the households. Hence, we argue that we can ignore the distributional impacts in our BCA, but that they are of relevance for a discussion on why some policies are favored from political perspectives.

Our findings reinforce the assertion that when implementing well-motivated macro policies, it is important to consider economic efficiency of micro interventions in order to better allocate resources among targeted sectors and achieve macro policy objectives in the most efficient way. A real-world decision process is often based on limited knowledge of sometimes very long impact chains with many factors involved. Different disciplines' research efforts keep producing, or collecting, more detailed information on single or groups of factors, yet uncertainty still remains, and decisions in the end have to be made. Similar to Whittington et al. (2012) where they looked at water, sanitation, and preventive health development programs, we show in a Chinese energy policy setting that with information from different sources it is possible to provide detailed information on a policy program's expected welfare effects, the cumulative probabilistic distributions of the intervention's net benefits, and which individual factors can contribute to the uncertainty. Compared with point estimates of benefits and costs, these results and the analytical process, though not precise, are more useful in decision making. They add transparency and confidence when screening and choosing interventions, and gather attention and discussion on the real relevant issues.

Appendix

Figure A1 Beijing City, spans about 160 km from west to east. Darker gray level for more populated districts. White squares for the four power plants.

Table A1 China National Action Plan on Air Pollution Prevention and Control (2013–2017).[a]

Air quality improvement goal
By 2017, the urban concentration of PM_{10} shall decrease by 10% compared with 2012; annual number of days with fairly good air quality will gradually increase
Concentration of $PM_{2.5}$ in the BTH, YRD and PRD regions shall respectively fall by around 25%, 20% and 15%
$PM_{2.5}$ annual concentration in Beijing shall be controlled below 60 $\mu g/m^3$
Ten tasks
1. Increase effort of comprehensive control and reduce emission of multipollutants
2. Optimize the industrial structure, promote industrial restructure
3. Accelerate the technology transformation, improve the innovation capability
4. Adjust the energy structure and increase the clean energy supply
5. Strengthen environmental thresholds and optimize industrial layout
6. Better play the role of market mechanism and improve environmental economic policies
7. Improve law and regulation system. Carry on supervision and management based on law
8. Establish the regional coordination mechanism and the integrated regional environmental management
9. Establish monitoring and warning system. Cope with pollution episodes
10. Clarify the responsibilities of the government, enterprise and society. Mobilize public participation

[a]In this table, we adopted the translation from Chinese by the Clean Air Alliance of China (CAAC).

https://doi.org/10.1017/bca.2017.10 Published online by Cambridge University Press

Table A2 Coal reduction tasks breakdown in Chaoyang District of Beijing (Chaoyang District Government, 2014).

No.	Tasks belong to “coal reduction” category	Responsible bureau and person	Supportive bureaus
1.	Make and implement the coal reduction plan of Chaoyang District	DRC (Chang S)[a]	EPB, CRA, CHURD, CCAE, CUP, SDO
2.	Finish construction of gas fired plants A and B, stop using coal fired power plant C	DRC (Chang S), CBD (Li G)	CUP, CCAE, EPB
3.	Substitute D coal fired boilers by clean fuel ones	EPB (Guan W)	Working Panel on Boilers in Chaoyang
4.	Realize principle E, strengthen effort F in households, replace cooking coal by LPG, substituting heating coal by improved coal, work hard for G aspects	CRA (Zhao H), DRC (Chang S), CCAE (Kang Z)	CUP, CALE, BLR, CHURD, FB, BQTS
5.	Close or move away factories G and H	DRC (Chang S)	EPB, CCAE
6.	New construction projects shall use electricity, gas or other clean fuel	EPB (Guan W), CUP (Wang X), DRC (Chang S), SDO (42 leaders)	CCAE, BQTS
7.	Improve green energy delivering system	DRC (Chang S), CCAE (Kang Z)	
8.	Strengthen law enforcement, crack down on supply of low quality coal	AIC (Fang S), TPD (Zhang K), CALE (Xing P)	EPB, BQTS
9.	Change I m^3 residential heating metering	CCAE (Kang Z)	CHURD

[a]Names in parentheses are the responsible person for this task. Abbreviations for government bureaus: DRC (Development and Reform Commission); EPB (Environmental Protection Bureau); CCAE (Commission of City Administration and Environment); CUP (Commission of Urban Planning); CRA (Commission of Rural Affairs); AIC (Administration for Industry and Commerce); SDO (Sub-District Office); TPD (Traffic Police Detachment); CALE (Bureau of City Administration and Law Enforcement); CHURD (Commission of Housing and Urban-Rural Development); BLR (Bureau of Land and Resources); BQTS (Bureau of Quality and Technical Supervision); FB (Financial Bureau).

https://doi.org/10.1017/bca.2017.10 Published online by Cambridge University Press

Table A3 Technically feasible interventions at local project level for power plants, boilers and households.

Three types of interventions		Examples
1.	Substitute coal by other energy	Coal-to-gas in power plants Coal-to-gas in boilers Substitute household coal use by other fuels
2.	Update capital stock	Replace several small plants by a big plant Replace household coal stoves by connecting to central heating system Shut down "outdated industrial production facilities"[a]
3.	Still use coal but adopt technology changes	Ultra-low-emission technology for power plants and boilers More end-of-pipe facilities for power plants and boilers Improved household stove Use improved coal in households Coal wash

[a]Outdated as defined in government documents, such as Ministry of Industry and Information Technology (2013).

Table A4 Health effect of ambient $PM_{2.5}$ and household coal combustion.[a]

Health Effect of Ambient $PM_{2.5}$	Health Effect of Household Coal Combustion
$PM_{2.5}$ Adult Mortality	Lung Cancer
$PM_{2.5}$ Infant Mortality	COPD
Chronic Bronchitis	ALRI
Acute Bronchitis	Other respiratory effects
Acute Myocardial Infarction	Lung Development
Asthma Exacerbation	Early childhood height (skeletal) growth
Hospital Admissions	Neurobehavioral development
Emergency Room Visits	Neural tube birth defects
Restricted Activity Days	Low birth weight
Lost Work Days	Acute CO Poisoning

[a]Based on US EPA (2011), WHO (2014).

https://doi.org/10.1017/bca.2017.10 Published online by Cambridge University Press

Table A5 Definition of model parameters, values and ranges.

Parameters	Units	Low	Base	High	Source and note[a]
Global parameters					
All-cause mortality	%	0.64%	0.71%	0.79%	Ministry of Health of China (2012), ±10%
Value of a statistical life	US$	1.50E + 05	3.75E + 05	8.00E + 05	Huang et al. (2015), base = mean of range
Ratio of VSC/VSL	%	3%	5.5%	10%	Following US EPA (2011)
Real, net of inflation, discount rate	%		3%		1% and 5% are also used in scenario analysis
Social cost of carbon	US$/ton CO_2	12	40	200	Corresponds to the values in Interagency Working Group on Social Cost of Carbon United States Government (2013), and triangular distribution.
Income elasticity of VSL		1	1.5	2	Hammitt and Robinson (2011)
Growth rate of real income	%	4%	5.5%	7%	See the note[d]
Intervention specific parameters – power plants					
Concentration-response coefficient-chronic mortality (for 1 $\mu g/m^3$ $PM_{2.5}$)	%	0.1%	1%	2%	Zhou et al. (2010, 2014), triangular distribution.
Concentration-response coefficient-chronic bronchitis (for 1 $\mu g/m^3$ $PM_{2.5}$)	%	0.37%	1.01%	1.56%	Huang and Zhang (2013)
Incidence-chronic bronchitis	%	0.62%	0.69%	0.76%	Huang and Zhang (2013), ±10%
Intake fraction-p, $PM_{2.5}$		9.00E-06	1.50E-05	2.50E-05	
Intake fraction-as, SO_2		3.00E-06	6.00E-06	1.10E-05	Table 2 in Zhou et al. (2003)
Intake fraction-an, NO_x		2.00E-06	6.50E-06	1.50E-05	

Continued on next page.

Table A5 (Continued).

$PM_{2.5}$ annual emission	ton/unit-yr	51	102	153	Total emission in Luo (2012) divided by 16 units, $PM_{2.5}$/TSP = 0.33, ±50%
SO_2 annual emission	ton/unit-yr	411	822	1233	Total emission in Luo (2012) level divided by 16 units, ±50%
NO_x annual emission	ton/unit-yr	1527	3054	4580	
Year2000 SO_2 annual emission	ton/unit-yr	3938	7876	11814	Hao et al. (2007), ±50%
Year2000 $PM_{2.5}$ annual emission	ton/unit-yr	247	494	741	
Breath rate	m^3/day-person		20		Constant, following all literature
Price of coal	yuan/ton	700	800	1000	Lower bound = current price, base and upper value[b]
Price of natural gas	yuan/m^3	2.67	4	5	
Capital cost	billion yuan/unit	1.4	1.6	1.8	Market price, ±0.2 billion yuan
Life of project	year	15	20	25	Market information, ±5 years
Annual consumption of coal	ton/unit-yr	500000	600000	700000	Market information, ±100000 ton of base value
Coal used per kWh electricity generated	g/kWh	280	320	360	Market information
Electricity generated per m^3 gas used	kWh/m^3	4.6	4.7	4.8	Market information
CO_2 emission factor-natural gas	CO_2 eq g/m^3		1961		Calculated based on http://www.eia.gov/oiaf/1605/coefficients.html
CO_2 emission factor-coal for power generation	CO_2 eq g/kg		1903		

Continued on next page.

Table A5 (Continued).

Intervention specific parameters – households					
Ventilation coefficient-child		0.2	0.25	0.3	Desai et al. (2004)[c]
Ventilation coefficient-adult		0.2	0.5	0.8	
Household size	person/hh	2	3	4	Beijing Municipal Bureau of Statistics (2013), discrete distribution with equal probability of 2, 3 and 4.
Percentage (male > 30 ys)	%		31%		China National Bureau of Statistics (2012*a*,*b*)
Percentage (female > 30 ys)	%		29%		
Percentage (child < 5 ys)	%		4%		
Cost of illness-ALRI	yuan/case	200	352.5	500	Ministry of Health of China (2012)
CO_2 emission factor-coal residential	CO_2 eq g/kg		2048		Calculated based on http://www.eia.gov/oiaf/1605/coefficients.html
CO_2 emission factor-coal residential-with black carbon	CO_2 eq g/kg	3140	6908	10676	Calculated based on Bond et al. (2004)
CO_2 emission factor-LPG	CO_2 eq g/kg		2716		Calculated based on http://www.eia.gov/oiaf/1605/coefficients.html
CO_2 emission factor-electricity	CO_2 eq g/kWh	578	804	1030	BM and OM of emission factor following guidance in qhs.ndrc.gov.cn (2013)
Number of years to chronic disease onset	year	15	20	25	Following Jeuland and Pattanayak (2012)
Incidence of ALRI (<5 ys)	%	0.966%	1.208%	1.449%	Calculated from IHME (2016)

Continued on next page.

Table A5 (Continued).

Incidence of COPD (M > 30 ys)	%	0.648%	0.810%	0.972%	Kojima et al. (2007), ±20%
Incidence of COPD (F > 30 ys)	%	0.248%	0.310%	0.372%	
Incidence of lung cancer (M > 30 ys)	%	0.062%	0.078%	0.094%	Beijing Health Bureau (2012), ±20%
Incidence of lung cancer (F > 30 ys)	%	0.038%	0.048%	0.058%	
Mortality of ALRI (<5 ys)	%	0.029%	0.036%	0.043%	Calculated from Institute for Health Metrics Evaluation (IHME) (2016) ±20%
Mortality of COPD (M > 30 ys)	%	0.104%	0.130%	0.156%	
Mortality of COPD (F > 30 ys)	%	0.078%	0.098%	0.117%	
Mortality of lung cancer (M > 30 ys)	%	0.062%	0.078%	0.094%	Beijing Health Bureau (2012), ±20%
Mortality of lung cancer (F > 30 ys)	%	0.038%	0.048%	0.058%	
Relative risk of ALRI (<5 ys)		1.81	2.8	4.34	WHO (2014)
Relative risk of COPD (M > 30 ys)		1.25	1.45	1.69	
Relative risk of COPD (F > 30ys)		1.25	1.45	1.69	
Relative risk of lung cancer (M > 30 ys)		1.64	2.27	3.15	
Relative risk of lung cancer (F > 30 ys)		1.64	2.27	3.15	

Continued on next page.

Table A5 (Continued).

Price of LPG	yuan/tank	100	120	140	Market price, ±20 yuan
Annual consumption of LPG-without intervention	tank/hh-yr	2	3.5	5	China National Bureau of Statistics (2012*a*,*b*)
Annual consumption of LPG-with intervention	tank/hh-yr	6	8	10	1 tank can serve about 1.5 months' cooking
Life of project of intervention	year	15	20	25	THUBERC (2012)
Annual consumption of coal for heating	ton/hh-yr	2	2.5	3	
Heating scenario specific parameters					
Heating scenario 1 (house thermal insulation reconstruction + solar air heat collector + biomass pellet fuel heated bed)					
Capital cost of reconstruction	yuan/hh	10000	20000	30000	THUBERC (2012)
Processing cost of biomass pellet fuel	yuan/ton	50	100	150	
Annual consumption of biomass pellet fuel	ton/hh-yr	2.5	3	3.5	
Capital cost of machine for processing pellet	yuan/machine	80000	100000	120000	
Annual O&M cost	yuan/hh-yr	50	86	150	
Annual electricity consumption of solar system	kWh/hh-yr	60	72	80	

Continued on next page.

Table A5 (Continued).

Heating scenario 2 (coal to electricity)					
Annual consumption of electricity for heating	kWh/hh-yr	7200	9000	10800	Market information
Price of electricity	yuan/kWh		0.5		
Price of electric-heating stove	yuan/stove	4000	5000	6000	
Life of electric-heating stove	year	10	15	20	
Annual maintenance cost of electric-heating stove	yuan/hh-yr	40	50	60	
Heating scenario 3 (coal to electricity plus house thermal insulation reconstruction)					
Capital cost of thermal insulation reconstruction	yuan/hh	6400	8000	9600	THUBERC (2012)
Reduction of energy for heating after reconstruction	%	0.3	0.5	0.7	

[a]± value for certain parameter means a self-judge range for those without information of range, but likely to be nonconstant.
[b]The price of natural gas for power generation in China is controlled and subsidized, whereas the price of coal is relatively a market price but with a limited reflection of its real environmental cost. Without information of the shadow price level of gas and coal in China, we assume ranges of their price with lower bound to be the current price and determine likely base and upper value.
[c]Range self-judged. Higher upper bound for adult accounting for potential longer exposure.
[d]From 1995 to 2014 the growth rate of GDP per capita was between 7% and 14% in China, with 3 years with a growth rate above 10% (WorldBank, 2014). As the growth rate of GDP has been declining to about 6.5% in 2015, it is unlikely that it will rise and stay far above 7%. Here we set a 4% to 7% range of the real growth rate of GDP per capita, with a base value equal to 5.5%. We believe this range is wide enough to cover the possible situations in the following 20 years in China, assuming of course, that no dramatic changes happen.

Table A6 Assumed parameter correlations.

Parameter	Correlated parameters	Low	Base	High	Justification
Price of coal	Price of natural gas	0.2	0.5	0.8	Shadow prices of substituting fuels positively correlate
Annual consumption of coal in power plants	Capital cost; annual SO_2, NO_x, $PM_{2.5}$ emission	0.5	0.7	0.9	Under the current technologies in modern power plants, the plant's scale, emissions are highly correlated with coal consumption. Therefore, the values of correlation are higher
CO_2 emission factor of coal used in households, with black carbon	Price of coal	−0.8	−0.5	−0.2	Raw coal has higher black carbon emission intensity, is less expensive, and corresponds to worse ventilation level in our setting
Incidence of diseases	Mortality of diseases	0.2	0.5	0.8	Places where certain disease happens more, its mortality rate is also higher
Household size	Annual consumption of fuel (biomass pellet, LPG, coal, electricity)	0.2	0.5	0.8	More people in family, consume more fuel, use more frequently new stoves, house is usually larger, costlier in reconstruction
	Annual O&M cost	0.2	0.5	0.8	
	Capital cost of reconstruction	0.2	0.5	0.8	
Reduction of energy for heating after reconstruction	Capital cost of reconstruction	0.2	0.5	0.8	Better reconstruction has better thermal insulation capacity
Lifespan of electric-heating stove/machine for processing biomass pellet fuel	Price of electric-heating stove/machine for processing biomass pellet fuel	0.2	0.5	0.8	Better stove/machine, price is higher, lifespan is longer

https://doi.org/10.1017/bca.2017.10 Published online by Cambridge University Press

Table A7 Emissions of coal fired power plants in Beijing in 2000.[a]

Plant	Unit	Coal consumption (Mt/y)	Generating capacity (MW)	Energy generation (GWh/y)	SO_2 (t/y)	PM_{10} (t/y)	NO_x (t/y)	SO_2 per Mt coal (t)	PM_{10} per Mt coal (t)	NO_x per Mt coal (t)
Jingneng	4	2.5	800	4.77	42979	4693	22971	17192	1877	9188
Datang	8	1.4	600	3.62	24883	2717	13298	17774	1941	9499
Huaneng	4	1.2	770	4.06	6804	120	3552	5670	100	2960
Guohua	4	1.1	400	2.29	19773	2705	13579	17975	2459	12345
Jingfeng	2	0.4	150	0.92	6960	760	3720	17400	1900	9300
Huadian	2	0.4	200	0.38	1098	638	3447	2745	1595	8618
Total (2000)	24	7			102497	11633	60567	13126	1645	8652
Total (2011)	16	9.5			13152	3259	48856	1389	344	5159

[a]Based on Hao et al. (2007), Luo (2012), last three columns self-calculated.

References

Beijing Health Bureau (2012). *White Paper on Health in Beijing* (in Chinese).

Beijing Municipal Bureau of Statistics (2013). *Beijing Statistical Yearbook*. Beijing: China Statistics Press (in Chinese).

Beijing Municipal Government (2013). Beijing Clean Air Action Plan 2013–2017 Key Tasks Decomposition (in Chinese).

Bennett, Deborah H., McKone, Thomas E., Evans, John S., Nazaroff, William W., Margni, Manuele D., Jolliet, Olivier & Smith, Kirk R. (2002). Defining Intake Fraction. *Environmental Science & Technology*, *36*(9), 207–216.

Birol, Fatih (2013). World Energy Outlook. *International Energy Agency*, *39*(1), 127–129.

Boden, T. A., Marland, G. & Andres, R. J. (2016). Global, Regional and National Fossil-Fuel CO_2 Emissions. http://cdiac.ornl.gov/trends/emis/meth_reg.html. November 23 2016.

Bond, Tami, Venkataraman, Chandra & Masera, Omar (2004). Global Atmospheric Impacts of Residential Fuels. *Energy for Sustainable Development*, *8*(3), 20–32.

Burnett, R. T., Pope, C. A. Rd., Ezzati, M., Olives, C., Lim, S. S., Mehta, S., Shin, H. H., Singh, G., Hubbell, B., Brauer, M., Anderson, H. R., Smith, K. R., Balmes, J. R., Bruce, N. G., Kan, H., Laden, F., Pruss-Ustun, A., Turner, M. C., Gapstur, S. M., Diver, W. R. & Cohen, A. (2014). An Integrated Risk Function for Estimating the Global Burden of Disease Attributable to Ambient Fine Particulate Matter Exposure. *Environmental Health Perspectives*, *122*(4), 397–403.

Cao, J., Yang, C., Li, J., Chen, R., Chen, B., Gu, D. & Kan, H. (2011). Association Between Long-Term Exposure to Outdoor Air Pollution and Mortality in China: A Cohort Study. *Journal of Hazardous Materials*, *186*(2–3), 1594–1600.

Chafe, Zoë A., Brauer, Michael, Klimont, Zbigniew, Van Dingenen, Rita, Mehta, Sumi, Rao, Shilpa, Riahi, Keywan, Dentener, Frank & Smith, Kirk R. (2014). Household Cooking with Solid Fuels Contributes to Ambient $PM_{2.5}$ Air Pollution and the Burden of Disease. *Environmental Health Perspectives*, *122*(12), 1314.

Chaoyang District Government (2014). Task Breakdown of Air Pollution Control Measures in 2014 in Chaoyang District (in Chinese). http://hb.bjchy.gov.cn/pages/L2Pageoneline.aspx?Kind=1. December 10 2016.

Chen, Yingjun, Zhi, Guorui, Feng, Yanli, Liu, Dongyan, Zhang, Gan, Li, Jun, Sheng, Guoying & Fu, Jiamo (2009). Measurements of Black and Organic Carbon Emission Factors for Household Coal Combustion in China: Implication for Emission Reduction. *Environmental Science & Technology*, *43*(24), 9495–9500.

Chen, Yuyu, Ebenstein, Avraham, Greenstone, Michael & Li, Hongbin (2013). Evidence on the Impact of Sustained Exposure to Air Pollution on Life Expectancy from China's Huai River Policy. *Proceedings of the National Academy of Sciences*, *110*(32), 12936–12941.

China National Bureau of Statistics (2012*a*). *China Statistical Yearbook* (in Chinese). Beijing, China: China Statistics Press.

China National Bureau of Statistics (2012*b*). *China Yearbook of Household Survey* (in Chinese). Beijing, China: China Statistics Press.

China State Council (2013). Action Plan on Prevention and Control of Air Pollution (in Chinese).

China State Council (2014). Energy Development Strategy Action Plan 2014–2020 (in Chinese).

https://doi.org/10.1017/bca.2017.10 Published online by Cambridge University Press

Cropper, Maureen, Gamkhar, Shama, Malik, Kabir, Limonov, Alexander & Partridge, Ian (2012). In *The Health Effects of Coal Electricity Generation in India*. Resources for the Future Discussion Paper (12–25).

Desai, Manish A., Mehta, Sumi & Smith, K. (2004). In *Indoor Smoke from Solid Fuels*. Assessing the Environmental Burden of Disease at National and Local Levels. Environmental Burden of Disease Series (4).

Gayer, Ted & Viscusi, W. Kip (2013). Overriding Consumer Preferences with Energy Regulations. *Journal of Regulatory Economics*, *43*(3), 248–264.

Gelman, Andrew & Zelizer, Adam (2015). Evidence on the Deleterious Impact of Sustained Use of Polynomial Regression on Causal Inference. *Research & Politics*, *2*(1), 1–7.

Graham, Carol (2016). Unequal Life Chances and Choices: How Subjective Well-Being Metrics can Inform Benefit-Cost Analysis. *Journal of Benefit-Cost Analysis*, *7*(1), 121–146.

Graham, John D. (2008). Saving Lives through Administrative Law and Economics. *University of Pennsylvania Law Review*, *157*(2), 395–540.

Hammitt, James K. (2000). Valuing Mortality Risk: Theory and Practice. *Environmental Science & Technology*, *34*(8), 1396–1400.

Hammitt, James K. & Robinson, Lisa A. (2011). The Income Elasticity of the Value Per Statistical Life: Transferring Estimates Between High and Low Income Populations. *Journal of Benefit-Cost Analysis*, *2*(1), 1–27.

Hanna, Rema, Duflo, Esther & Greenstone, Michael (2012). Up in Smoke: The Influence of Household Behavior on the Long-Run Impact of Improved Cooking Stoves, National Bureau of Economic Research.

Hao, Jiming, Wang, Litao, Shen, Minjia, Li, Lin & Hu, Jingnan (2007). Air Quality Impacts of Power Plant Emissions in Beijing. *Environmental Pollution*, *147*(2), 401–408.

Hu, Desheng & Xu, Shengqing (2013). Opportunity, Challenges and Policy Choices for China on the Development of Shale Gas. *Energy Policy*, *60*(5), 21–26.

Huang, Desheng, Andersson, Henrik & Zhang, Shiqiu (2015). Willingness to Pay to Reduce Health Risks Related to Air Quality: Evidence from a Choice Experiment Survey in Beijing (mimeo), Peking University, Toulouse School of Economics.

Huang, Desheng & Zhang, Shi Qiu (2013). Health Benefit Evaluation for $PM_{2.5}$ Pollution Control in Beijing–Tianjin–Hebei Region of China (in Chinese). *China Environmental Science*, *1*(33), 166–174.

Hutton, Guy, Rehfuess, Eva, Tediosi, Fabrizio & Weiss, Svenja (2006). *Evaluation of the Costs and Benefits of Household Energy and Health Interventions at Global and Regional Levels*. Geneva: WHO Press.

Institute for Health Metrics Evaluation (IHME) (2016). GBD Compare Data Visualization. http://vizhub.healthdata.org/gbd-compare/2013.

Interagency Working Group on Social Cost of Carbon, United States Government (2013). Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866. https://www.whitehouse.gov/sites/default/files/omb/inforeg/social_cost_of_carbon_for_ria_2013_update.pdf.

Jeuland, Marc A. & Pattanayak, Subhrendu K. (2012). Benefits and Costs of Improved Cookstoves: Assessing the Implications of Variability in Health, Forest and Climate Impacts. *PLoS One*, *7*(2), e30338.

Jian, Zhao (2013). Research on the Comprehensive Evaluation of Wujiang Gas Power Generation Project, North China Electric Power University. Master.

Jin, Yana, Andersson, Henrik & Zhang, Shiqiu (2016). Air Pollution Control Policies in China: A Retrospective and Prospects. *International Journal of Environmental Research and Public Health*, *13*(12), 1219–1241.

Kojima, Shigeko, Sakakibara, Hiroki, Motani, Shinichi, Hirose, Kunihiko, Mizuno, Fumio, Ochiai, Masahiro & Hashimoto, Shuji (2007). Incidence of Chronic Obstructive Pulmonary Disease, and the Relationship Between Age and Smoking in a Japanese Population. *Journal of Epidemiology*, *17*(2), 54–60.

Levy, J. I., Baxter, L. K. & Schwartz, J. (2009). Uncertainty and Variability in Health-Related Damages from Coal-Fired Power Plants in the United States. *Risk Analysis*, *29*(7), 1000–1014.

Liu, J., Mauzerall, D. L. & Chen, Q. et al. (2016). Air pollutant emissions from Chinese households: A major and underappreciated ambient pollution source[J]. *Proceedings of the National Academy of Sciences of the United States of America*, *113*(28), 7756.

Luo, Yi. (2012). *Annual Statistical Report on Environment in China* (in Chinese). Beijing: China Environmental Science Press.

Marland, G., Boden, T. A. & Andres, R. J. (2015). Global Regional & National Fossil-Fuel CO_2 Emissions. DOI: 10.3334/CDIAC/00001_V2010.

Ministry of Health of China (2012). *Yearbook of Health in the People's Republic of China* (in Chinese). Beijing: Peking Union Medical College Press.

Ministry of Industry and Information Technology (2013). Lists for Outdated Production Capacity to be Phase-Out within 2013 (in Chinese). http://www.gov.cn/zwgk/2013-07/26/content_2455751.htm. December 12 2016.

Miyun County Government (2014). 2014 Annual Progress Report of "Coal Reduction and Improved Coal Substitution" in Rural Areas in Miyun County (in Chinese). http://www.myag.gov.cn/tongzhi/8a317b2048afb5bf01493c11ec23000d.html.

Morgenstern, Richard D. (2015). The RFF Regulatory Performance Initiative: What Have We Learned?, Resources for the Future Discussion Paper.

Ni, Weidou (2013). Relationship between Emission from Heating Source and $PM_{2.5}$ in Beijing and Control Measures (in Chinese). Reconstruction of Blue Sky in China. Beijing, Energy Foundation.

Nordhaus, William D. (2011). Estimates of the Social Cost of Carbon: Background and Results from the RICE-2011 Model, National Bureau of Economic Research.

NRDC (2014). Scientific Report of Coal's Contribution to Ambient Air Pollution in China (in Chinese). Beijing, China.

Pope, C. Arden, Cropper, Maureen, Coggins, Jay & Cohen, Aaron (2015). Health Benefits of Air Pollution Abatement Policy: Role of the Shape of the Concentration–Response Function. *Journal of the Air & Waste Management Association*, *65*(5), 516–522.

qhs.ndrc.gov.cn (2013). 2013 Baseline Emission Factors for Regional Power Grids in China (in Chinese). http://www.ccchina.gov.cn/archiver/cdmcn/UpFile/Files/Default/20130917081426863466.pdf.

Smith, Kirk R., Bruce, Nigel, Balakrishnan, Kalpana, Adair-Rohani, Heather, Balmes, John, Chafe, Zoë, Dherani, Mukesh, Hosgood, H. Dean, Mehta, Sumi, Pope, Daniel & Rehfuess, Eva (2014). Millions Dead: How Do We Know and What Does It Mean? Methods Used in the Comparative Risk Assessment of Household Air Pollution. *Annual Review of Public Health*, *35*(1), 185–206.

Stevens, G., Wilson, A. & Hammitt, J. K. (2005). A Benefit-Cost Analysis of Retrofitting Diesel Vehicles with Particulate Filters in the Mexico City Metropolitan Area. *Risk Analysis*, *25*(4), 883–899.

THUBERC (2012). *Annual Report on China Building Energy Efficiency* (in Chinese). China Architecture and Building Press.

UNFCCC (2010). Clean Development Mechanism Methodology Booklet. United Nations Framework Convention on Climate Change. Bonn, Germany.

US EPA (2011). The Benefits & Costs of the Clean Air Act from 1990 to 2020: Summary Report.

US EPA (2013). The Social Cost of Carbon. https://www.epa.gov/climatechange/social-cost-carbon.

Wang, Shuxiao, Hao, Jiming, Ho, Mun S., Li, Ji & Lu, Yongqi (2006). Intake Fractions of Industrial Air Pollutants in China: Estimation and Application. *Science of the Total Environment*, *354*(2), 127–141.

Wang, Zhixuan (2015). Eight Misunderstanding on Evaluation of Thermal Power Plans Ultra-Low Emission (in Chinese). China Environment News.

Whittington, Dale, Jeuland, Marc, Barker, Kate & Yuen, Yvonne (2012). Setting Priorities, Targeting Subsidies among Water, Sanitation, and Preventive Health Interventions in Developing Countries. *World Development*, *40*(8), 1546–1568.

WHO (2014). WHO Indoor Air Quality Guidelines: Household Fuel Combustion.

Wiener, Jonathan B. (2006). Better Regulation in Europe. *Current Legal Problems*.

World Bank (2014). System of National Accounts Data.

Xu, Jianhua, Wang, Xuesong & Zhang, Shiqiu (2013). Risk-Based Air Pollutants Management at Regional Levels. *Environmental Science & Policy*, *25*, 167–175.

Yang, Gonghuan, Wang, Yu, Zeng, Yixin, Gao, George F., Liang, Xiaofeng, Zhou, Maigeng, Wan, Xia, Yu, Shicheng, Jiang, Yuhong & Naghavi, Mohsen (2013). Rapid Health Transition in China, 1990–2010: Findings from the Global Burden of Disease Study 2010. *The Lancet*, *381*(9882), 1987–2015.

Zhang, J. J. & Smith, K. R. (2007). Household Air Pollution from Coal and Biomass Fuels in China: Measurements, Health Impacts, and Interventions. *Environmental Health Perspectives*, *115*(6), 848–855.

Zhou, Ying, Fu, Joshua S., Zhuang, Guoshun & Levy, Jonathan I. (2010). Risk-Based Prioritization among Air Pollution Control Strategies in the Yangtze River Delta, China. *Environmental Health Perspectives*, *118*(9), 1204.

Zhou, Ying, Hammitt, James, Fu, Joshua S., Gao, Yang, Liu, Yang & Levy, Jonathan I. (2014). Major Factors Influencing the Health Impacts from Controlling Air Pollutants with Nonlinear Chemistry: An Application to China. *Risk Analysis*, *34*(4), 683–697.

Zhou, Ying, Levy, Jonathan I., Evans, John S. & Hammitt, James K. (2006). The Influence of Geographic Location on Population Exposure to Emissions from Power Plants throughout China. *Environment International*, *32*(3), 365–373.

Zhou, Ying, Levy, Jonathan I., Hammitt, James K. & Evans, John S. (2003). Estimating Population Exposure to Power Plant Emissions using CALPUFF: A Case Study in Beijing, China. *Atmospheric Environment*, *37*(6), 815–826.