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Air quality and climate benefits of long-distance electricity transmission in China

Wei Peng,^{1,2} Jiahai Yuan,³ Yu Zhao,⁴ Meiyun Lin,^{5,6} Qiang Zhang,⁷ David G Victor^{8,9} and Denise L Mauzerall^{1,10,11}

¹ Science, Technology and Environmental Policy (STEP) program, Woodrow Wilson School of Public and International Affairs, Princeton University, NJ 08544, United States of America

² Now at Environment and Natural Resources Program, Belfer Center for Science and International Affairs, J.F. Kennedy School of Government, Harvard University, Cambridge, MA 02138, United States of America

³ School of Economics and Management, North China Electric Power University, Beijing, 102206, People's Republic of China

⁴ State Key Laboratory of Pollution Control and Resource Reuse and School of the Environment, Nanjing University, 163 Xianlin Ave., Nanjing, Jiangsu, 210023, People's Republic of China

⁵ Program in Atmospheric and Oceanic Sciences, Princeton University, NJ 08544, United States of America

⁶ NOAA Geophysical Fluid Dynamics Laboratory, NJ 08544, United States of America

⁷ Ministry of Education Key Laboratory for Earth System Modeling, Center for Earth System Science, Tsinghua University, Beijing, 100084, People's Republic of China

⁸ School of Global Policy and Strategy, University of California, San Diego, 9500 Gilman Drive 0519, La Jolla, CA 92093, United States of America

⁹ The Brookings Institution, 1775 Massachusetts Avenue, NW, Washington, DC 10036, United States of America

¹⁰ Department of Civil and Environmental Engineering, Princeton University, NJ 08544, United States of America

¹¹ Author to whom any correspondence should be addressed.

E-mail: mauzeral@princeton.edu**Keywords:** electricity transmission, air pollution, climate changeSupplementary material for this article is available [online](#)**Abstract**

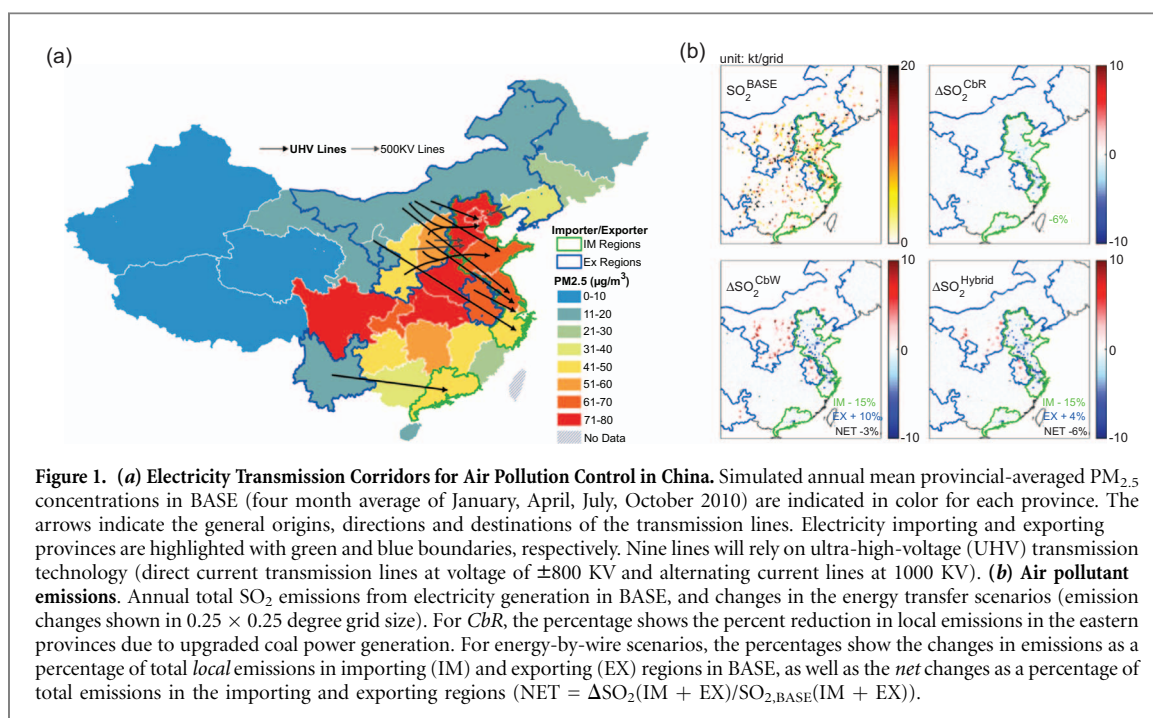
China is the world's top carbon emitter and suffers from severe air pollution. It has recently made commitments to improve air quality and to peak its CO₂ emissions by 2030. We examine one strategy that can potentially address both issues—utilizing long-distance electricity transmission to bring renewable power to the polluted eastern provinces. Based on an integrated assessment using state-of-the-science atmospheric modeling and recent epidemiological evidence, we find that transmitting a hybrid of renewable (60%) and coal power (40%) (Hybrid-by-wire) reduces 16% more national air-pollution-associated deaths and decreases three times more carbon emissions than transmitting only coal-based electricity. Moreover, although we find that transmitting coal power (Coal-by-Wire, CbW) is slightly more effective at reducing air pollution impacts than replacing old coal power plants with newer cleaner ones in the east (Coal-by-Rail, CbR) (CbW achieves a 6% greater reduction in national total air-pollution-related mortalities than CbR), both coal scenarios have approximately the same carbon emissions. We thus demonstrate that coordinating transmission planning with renewable energy deployment is critical to maximize both local air quality benefits and global climate benefits.

1. Introduction

Most countries now recognize that climate change is a serious problem, and are experimenting with ways to cut greenhouse gas (GHG) emissions that align with their national interests. For most developing countries that means finding ways in which reducing GHG emissions facilitates the achievement of local goals such as reduced air pollution with associated

improvements in public health [1]. Given the short time horizon of politicians and the fact that global benefits from reductions in climate change are diffused over all countries, tangible national co-benefits have proved to be more effective in motivating immediate carbon mitigation actions than the long-term threat from climate change [2].

One central finding from the latest report of the Intergovernmental Panel on Climate Change (IPCC)



is that electrification will likely play a central role in decarbonizing energy systems [3]. Decarbonization by electrification is possible in many ways, and many governments are looking at much larger roles for renewables—an option that requires careful long-distance transmission planning since renewable resources are often remote from centers of power demand and often variable and intermittent in supply (especially wind and solar power) [4, 5]. They hence often require transmission systems sized much larger than the useful power they consistently deliver, and require local suppliers of electricity to manage reliability—often by using fossil-based power plants that contribute to local air pollution. However, most transmission lines are powered entirely by fossil-based energy at present. Although electricity transmission could help relocate fossil-based generation and associated air pollution to remote areas, fossil fuel powered ‘energy by wire’ approaches still result in large carbon emissions and global climate impacts. Thus ‘energy by wire’ strategies may involve tradeoffs between local and global benefits. Our paper develops methods to quantify these tradeoffs.

We focus on China, where national policy has emphasized the need to achieve global carbon mitigation goals in ways that maximize national air pollution benefits [6, 7]. China thus serves as a valuable test case for other emerging economies—such as India, South Africa and Indonesia—that also have large potentials for curbing their growing CO_2 emissions but are wary of adopting expensive policies unless they yield large, tangible local benefits. Moreover, China is a pivotal country in global cooperation on energy and climate. The country is the world’s top carbon emitter and largest investor in renewable energy. It has recently made commitments

to peak its CO_2 emissions by 2030 [8]. Most importantly, as a country facing severe air pollution, concerns about air pollution have already inspired the government to move coal power plants out of polluted urban areas in the east and to expand investment in long-distance transmission capacity. Twelve ‘Electricity Transmission Corridors for Air Pollution Control’ are under construction to replace eastern coal power generation with imported electricity in order to reduce local air pollution [9] (figure 1(a) and supplementary table 1, available at stacks.iop.org/ERL/12/064012/mmedia), making it the first time in the world that transmission planning is used for air pollution control. The experience with these transmission systems is likely to guide subsequent investment in China and other countries.

Most previous studies on electricity transmission either focus entirely on the carbon emissions [10, 11] or simply tabulate the reduction of local air pollutant emissions without evaluating the impact of those emissions on air quality and human health [12]. Here we not only account for the carbon emissions, but also conduct a sophisticated evaluation of the air quality impacts on health. We use a regional state-of-the-science air pollution model [13] to fully consider the effect of meteorological factors and atmospheric chemistry, and recent epidemiological evidence that finds decreasing health impacts from a unit increase in $PM_{2.5}$ (fine particulate matter of $2.5 \mu m$ diameter or smaller) at the elevated $PM_{2.5}$ concentrations found in highly polluted parts of China (i.e. concave shape of mortality risk functions) [14, 15]. Furthermore, most prior literature has looked at highly stylized scenarios—such as fully coal-by-wire [16] (which reduces local air pollution but has little global benefit) or almost fully renewables such as wind-by-wire [17] (which can

Table 1. Scenario Summary.

Scenario Name		Percent change in electricity production	
Base Case (BASE)		No change, actual 2010 electricity generation	
		IM regions	EX regions
Coal-by-rail (<i>CbR</i>)		No change in total generation, but use larger, cleaner coal units	No change
Energy-by-wire	Coal-by-wire (<i>CbW</i>)		All from coal
	Hybrid-by-wire (<i>Hybrid</i>)	–31%: Reduce coal power generation from small, dirty units	60% from wind and hydro ^a , 40% from coal
		+48%: Add power generation for transmission	

^a Hydro for Yunnan, wind for the rest of exporting regions. The upper limit of wind power production in each exporting province is from the high estimate of provincial-scale wind resource potential in He and Kammen 2014 [26].

(Note: IM and EX regions indicate importing and exporting regions)

be quite expensive given the variability of wind resources). In contrast, our approach examines scenarios that align with current government plans for the near future of the Chinese power system. Based on current plans, nine of the twelve proposed lines will transmit only coal power. Two are planned to transmit wind power along with coal power (though the exact power mix is not specified in the plan), and a third in southern China will be powered entirely by hydroelectricity. We therefore look at a fully coal by wire scenario, and compare it to a hybrid of renewables and coal by wire scenario considering the renewable resource potentials in the power exporting regions. The current government plan is in between these two ‘by-wire’ scenarios, and likely closer to the fully coal by wire scenario. Due to the geographic mismatch between resource-abundant western provinces and the demand centers in the east, long-distance transmission is critical in both scenarios in order for the eastern provinces to access coal or renewable resources in inland regions. We also compare these two ‘by-wire’ strategies to ‘coal by rail’, the most commonly used energy transfer option at present in which coal (abundant in the west of the country) is transported as primary fuel to wealthier, populous centers in the east where it is burned to generate power [18].

2. Methods and materials

2.1. Energy and emission scenarios

We design a base case (BASE) plus three additional scenarios that are rooted in real-world options for Chinese policy makers (table 1 and online supplementary tables 2–3). The BASE uses the actual electricity generation [19] and emission data (Multi-resolution Emission Inventory, MEIC [20]) for 2010. Two scenarios represent the two main options for coal-fired power: coal-by-rail (*CbR*) and coal-by-wire (*CbW*). We replace small, inefficient coal units in the eastern provinces with larger, more efficient coal power plants added locally in *CbR*, or with imported coal-fired electricity in *CbW* that is transmitted

through long-distance transmission lines in the dozen corridors shown in figure 1(a). Different geographic location of coal power generation in *CbW* and *CbR* can affect population exposure and the health impacts [21]. Third we design a hybrid by wire scenario (*Hybrid*) in which both renewable (wind and hydro, 60%) and coal-fired electricity (40%) is transmitted to replace eastern coal power generation. This 60/40 split is based on a high estimate of provincial renewable resource potential in the exporting regions [22] and the extent to which these regions would allow excess renewable power exports. In other words, our *Hybrid* scenario assumes the largest possible amount of renewable transmission through the proposed lines, whereas the *CbW* scenario assumes no renewable transmission at all. We thus provide a high and low estimate for the potential share of renewables in the fuel mix to power the proposed lines.

We assume the transmission lines operate at an annual average utilization rate of 80% with no transmission losses. These assumptions allow for the largest transmission volume and associated benefits that can be achieved from the proposed lines. Realizing that the actual utilization rate may be lower and the transmission losses can be significant, we conduct sensitivity analyses on a lower utilization rate of 50% (online supplementary figure 12) and 0%–10% transmission losses (online supplementary figure 9). If a transmission line involves more than one recipient province, we assume the imported electricity is distributed among the recipients according to their electricity demand in 2010. If one line involves two exporting provinces, we assume each of them produces half of the coal-fired electricity transmitted through the line. As for the scale, the transmitted electricity could replace one-third of BASE power generation in the importing regions, while requiring production in exporting regions to increase by ~50%. In *Hybrid*, the total penetration of wind generation is 6% for the importing and exporting regions together (online supplementary table 3).

We calculate the changes in annual total emissions of CO₂ and air pollutants by multiplying the changes

in electric power output resulting from the displaced and added generation with the emission factors of the respective generation technology (online supplementary tables 2 and 4). We only consider combustion-related CO₂ emissions from the coal units [23], and air pollutant emissions from the electricity production process. The air pollutant emission factors for the displaced coal units are estimated from a database [24], while those for added coal capacity are based on Zhao *et al* 2014 [25]. We assume no air pollutants or CO₂ emissions from renewable generation. The emissions from non-power sectors and in non-importing/exporting provinces remain unchanged.

2.2. Regional atmospheric chemistry simulation and evaluation

For BASE and the three energy transfer scenarios, we simulate air quality in East Asia for January, April, July and October 2010 using WRF-Chem v3.6 [13] at 27 × 27 km² horizontal resolution with 31 vertical layers from the surface to 100 hPa. The model uses RADM2 gas-phase chemistry and the MADE-SORGAM aerosol scheme, with the meteorological fields nudged towards the NCEP FNL data [27] every 6 h. The chemistry initial and boundary conditions are provided by a global chemistry transport model, MOZART-4 [28]. For BASE, we use anthropogenic emissions from the MEIC database for China (0.25 × 0.25 degree) [20] and the 2006 INTEX-B inventory for regions outside China [29]. For energy transfer scenarios, we allocate annual total emissions to gridded hourly emissions following the spatial and temporal pattern in the BASE inventory. All anthropogenic emissions are emitted to the model surface layer. The BASE simulations are evaluated using observational data from U.S. State Department China Air Quality Monitoring Program [30] and the Acid Deposition Monitoring Network in East Asia (EANET) [31] (online supplementary table 10 and online supplementary figures 1–4). More details are described in online supplementary table 5.

2.3. Evaluating health impacts from air pollution exposure

We focus on ambient fine particulate matter (PM_{2.5}), the air pollutant with the largest impact on human health [32] (see online supplementary figures 4 and 8 for results on ozone). For four diseases associated with long-term exposure to PM_{2.5} (ischemic heart disease, stroke, chronic obstructive pulmonary disease and lung cancer), we use the following equation to calculate the mortality changes relative to the BASE scenario in each province:

$$\Delta \text{Mortality}_d = I_{d,\text{BASE}} \cdot \text{Pop} \cdot \left(\frac{\text{RR}_d(C_s)}{\text{RR}_d(C_{\text{BASE}})} - 1 \right)$$

Pop is the total adult population aged 25 and above in each province, based on county-level China census

data [33]. $I_{d,\text{BASE}}$ is the disease-specific (d) annual average national BASE mortality rate in the total adult population. $\text{RR}_d(C_s)$ and $\text{RR}_d(C_{\text{BASE}})$ are the relative risks (RR) of disease d for adult population at the PM_{2.5} levels of C_s in scenario s and C_{BASE} in BASE, respectively. $I_{d,\text{BASE}}$ and RR are based on the Global Burden of Disease (GBD) database [15]. We use the four-month average of the simulated population-weighted, provincial-averaged PM_{2.5} concentrations to estimate annual mean exposures for each province. Sensitivity analyses on linear RR functions and spatial resolution for exposure assessment are presented in online supplementary figure 11.

3. Results

3.1. Health-related air quality benefits

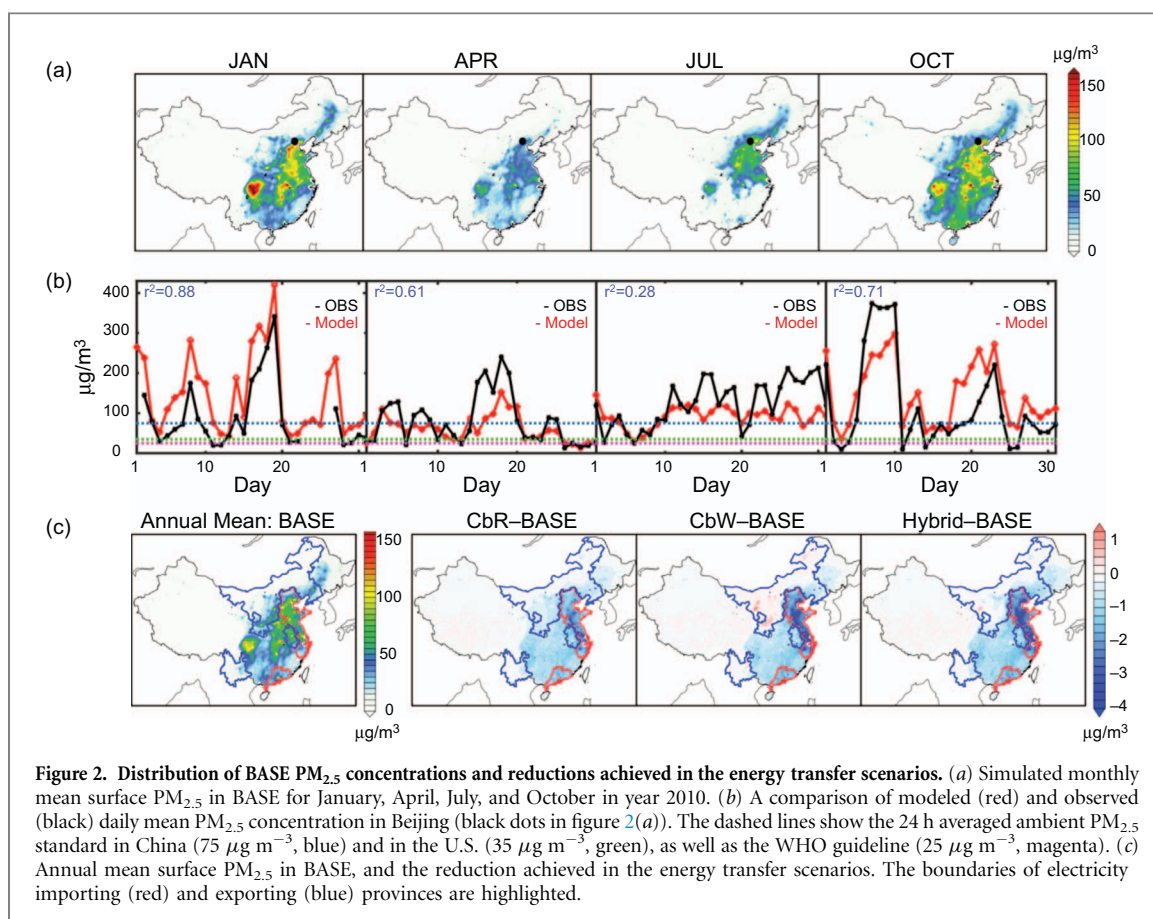
3.1.1. Air pollutant emissions

Power plants emit little PM_{2.5} directly. We hence present results on precursor pollutants of SO₂ and NO_x that form secondary PM_{2.5} in the atmosphere. In *CbR*, air pollutant emissions only decline in the eastern importing provinces (6% and 11% reduction in SO₂ and NO_x emissions). In the energy-by-wire scenarios, eastern emissions decline more (15% and 16% reduction in SO₂ and NO_x emissions), while emissions increase in the exporting regions due to added coal power generation (figure 1(b) (SO₂) and online supplementary figure 5 (NO_x)). As renewable electricity generation has no emissions, *Hybrid* yields smaller increases in power exporting regions (4% and 3% increase in SO₂ and NO_x emissions) than *CbW* (10% and 8% increase in SO₂ and NO_x emissions). Total emission changes across all importing and exporting regions for *Hybrid* are a decrease of 6% and 9% for SO₂ and NO_x respectively, as compared to a decrease of 3% and 7% in *CbW*.

3.1.2. Simulated PM_{2.5} levels

We compare our BASE simulation results with observations, and find that our simulations capture the day-to-day PM_{2.5} variation for four representative months in 2010 in Beijing (figure 2(b)) and other regions in East Asia (online supplementary figures 1–3). The BASE PM_{2.5} concentrations are generally higher in eastern and southwest China, and during autumn and winter (figure 2(a)), which are largely affected by seasonally varying meteorological conditions.

In the eastern provinces—the ones targeted for pollution reduction—electricity transmission irrespective of fuel source results in a 2–3 μg m⁻³ (or 2%–7%) reduction in the annual mean PM_{2.5} concentrations, roughly 1 μg m⁻³ greater than the reduction achieved in *CbR* (figure 2(c)). Although switching from coal to hybrid power transmission does not further improve eastern air quality, adding zero-emission renewable capacity would avoid the



PM_{2.5} increase in some northern exporting regions observed in *CbW*. Since downwind regions of the eastern importing provinces can also benefit from the air quality improvement there, even in *CbW* we find the PM_{2.5} levels in the exporting regions located in the northeast or surrounded by the importing regions are slightly lower than their BASE levels. We also find small PM_{2.5} reductions in southern and central China in all three scenarios, because these regions are downwind of the eastern provinces for the most time throughout the year (see online supplementary figures 6 and 7 for monthly PM_{2.5} results and wind fields). Such results are robust under meteorological conditions favorable for pollution formation and accumulation (see online supplementary figure 10). Since our BASE simulation does not show systematic biases, the general pattern of the PM_{2.5} reduction in each scenario and the ranking of the three scenarios should be robust.

3.1.3. Air-pollution-related deaths

We estimate the national total annual premature deaths associated with the exposure to outdoor PM_{2.5} to be 0.85 million in BASE (comparable to 0.86 million in GBD study [34]). Compared with BASE, *Hybrid* avoids 16% more premature mortalities nationally than *CbW* (~16 000 and 14 000 cases, respectively). Most of the additional avoided deaths occur in the exporting regions, due to slightly lower PM_{2.5} concentrations there when more renewable generation

is utilized for transmission. In comparison, the two coal-based scenarios yield similar scale of avoided deaths (only 6% higher for *CbW* than *CbR*) (figure 3 (b)). Therefore, at the national level, *CbW* has modest additional health-related air quality benefits compared with *CbR* despite the fact that Chinese planners have focused on wiring coal precisely for its air pollution advantages. Instead, *CbW* shifts the geographical pattern of mortality impacts by avoiding more deaths in polluted eastern cities but fewer deaths in the rest of the country compared to *CbR*. Such results are largely driven by the concavity of the relative risk functions. While a small PM_{2.5} decrease in less polluted, southern regions results in nontrivial reduction in mortality risk and hence premature mortality, the flattening of RR functions is relevant at the BASE PM_{2.5} levels in many eastern provinces, leading to smaller mortality risk reductions there (figure 3(a)). Applying linear RR functions would increase the magnitudes of avoided deaths in the energy transfer scenarios and the differences across them (online supplementary figure 11).

Besides PM_{2.5}, ground-level ozone is also associated with negative health impacts, but with a smaller mortality risk compared with exposure to PM_{2.5} [35, 36]. We find a small increase in eastern ozone concentrations in the three scenarios because lowered NO_x emissions increase ozone concentrations due to non-linear chemistry. However, the mortality impacts associated with such a small change in ozone exposure

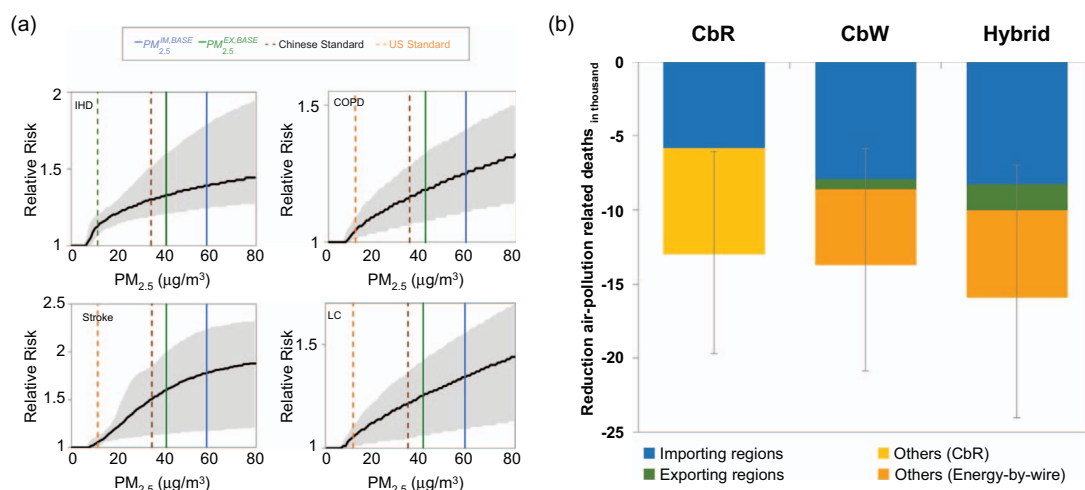


Figure 3. Relative risk functions and reduction in air-pollution-related deaths. (a) Relative risk functions for four causes of air-pollution-related deaths at annual $PM_{2.5}$ exposure levels of 0–80 $\mu g m^{-3}$ (95% CI: the grey area; Data source: the GBD study [37]): ischemic heart disease (IHD), stroke, chronic obstructive pulmonary disease (COPD) and lung cancer (LC). The blue and green solid lines represent the average population-weighted BASE $PM_{2.5}$ concentrations in the importing and exporting provinces, respectively. The brown and orange dashed lines indicate the annual mean $PM_{2.5}$ standard in China (35 $\mu g m^{-3}$) and the US (12 $\mu g m^{-3}$). (b) Reduction in total air pollution-related deaths in the three energy transfer scenarios relative to BASE. The blue bars indicate the change in importing/eastern regions. For CbR, the light orange bar indicates the change in the rest of the country. For the Coal-by-wire (CbW) and Hybrid scenarios, we separate the change in the exporting provinces (green) and other non-importing and non-exporting regions (dark orange). The net decreases in CbR and CbW are largely because the newer coal power plants are cleaner than the ones being replaced. The small reduction in the exporting regions in CbW is because we present the net health impacts across all the exporting provinces that have increased or decreased $PM_{2.5}$ levels relative to BASE. Error bars reflect the confidence intervals of the relative risk functions.

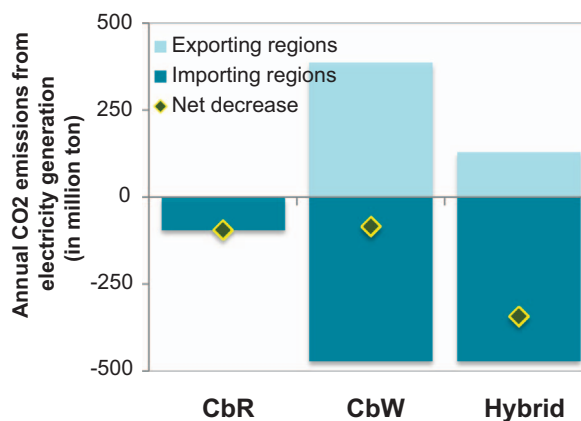


Figure 4. Change in annual total carbon emissions from electricity generation relative to BASE.

is unlikely to be substantial (More details in online supplementary figures 4 and 8).

3.2. Carbon emissions

With zero-emitting renewable energy displacing coal power generation, a net annual reduction of roughly 340 million tons of CO₂ emissions is obtained in *Hybrid*, equivalent to a 4% decrease in national total all-sector carbon emissions. By contrast, *CbW* and *CbR* have little effect on carbon emissions, as reductions only result from efficiency improvements in the new coal units relative to the displaced ones. The scale of the net reduction in *CbR* and *CbW* is nearly identical, as the same new coal power generation

replaces old coal generation in both scenarios though in different locations (figure 4). *Hybrid* reduces carbon emissions three times more than either coal-based scenario, suggesting large global climate benefits of utilizing transmission lines to deliver a hybrid of renewable and coal power instead of coal power alone. The importance of the power mix in determining the carbon implications of electricity transmission has also been found in prior studies on carbon emissions embodied in inter-regional transmission in China [11]. Although our results do not consider transmission losses, the effect of transmission losses on carbon emissions are generally small as shown in our sensitivity analyses (online supplementary figure 9).

4. Discussion

Our evaluation of the air quality and climate benefits of the three energy transfer scenarios is subject to four main sources of uncertainty: transmission losses, meteorological variation, shape of the concentration-response relationships, and potentially a lower utilization rate of the transmission lines than we assumed in our *Hybrid* scenario. By conducting sensitivity analyses (section 5 in the online supplementary Materials), we find our main conclusion that Hybrid-by-wire results in greater air quality and climate benefits than coal-based options is still robust.

Here we discuss the cost-effectiveness of various energy-by-wire strategies by combining available cost data with the national total air quality and climate benefits evaluated in the previous section. We report the economic values in inflation-adjusted 2010US\$.

a) *CbW* vs. *CbR*

When coal is the fuel choice, our analysis suggests similar climate benefits and only slightly larger health-related air quality benefits from *CbW* as compared to *CbR* at the national scale (6% greater reduction in national total premature deaths in *CbW* than *CbR*). On the cost side, *CbR* incurs coal transport costs, which lead to higher delivered coal prices for coal power generation in the eastern importing provinces than inland exporting provinces. As such, based on province-specific levelized cost of coal-fired electricity (online supplementary table 7), we find that the annualized coal power generation costs are US\$4bn higher in *CbR* than *CbW* due to coal transport costs. The transmission cost to enable *CbW*, however, is difficult to estimate, due to limited existing cost data for transmission lines that use advanced ultra-high-voltage (UHV) technologies. Davidson *et al* estimated the UHV transmission cost to be 0.095 (low: 0.076, high: 0.126) RMB kWh⁻¹ and 0.111 (low: 0.088, high: 0.147) RMB kWh⁻¹ from Northeast or Northwest China to the Sanhua regions (the combination of Central, East and North China), respectively. Such estimates are also comparable with the current price for inter-regional transmission in China determined by the central government (roughly 0.12 RMB kWh⁻¹) [38]. Therefore, we estimate the annual total transmission costs to be roughly US \$6.7bn (low: \$5.3bn, high, \$8.9bn; more details in online supplementary table 8 and 9). This indicates that at present it may cost more to transmit coal power than to transport coal by rail followed by electricity generation. Our evaluation hence provides no evidence that the *CbW* strategy would be more cost-effective than *CbR* in curbing national total air pollution impacts or global climate impacts, although in the targeted eastern provinces, *CbW* indeed reduces air pollution and health impacts more than *CbR*. Since UHV transmission is a new and advanced technology, future UHV costs are likely to

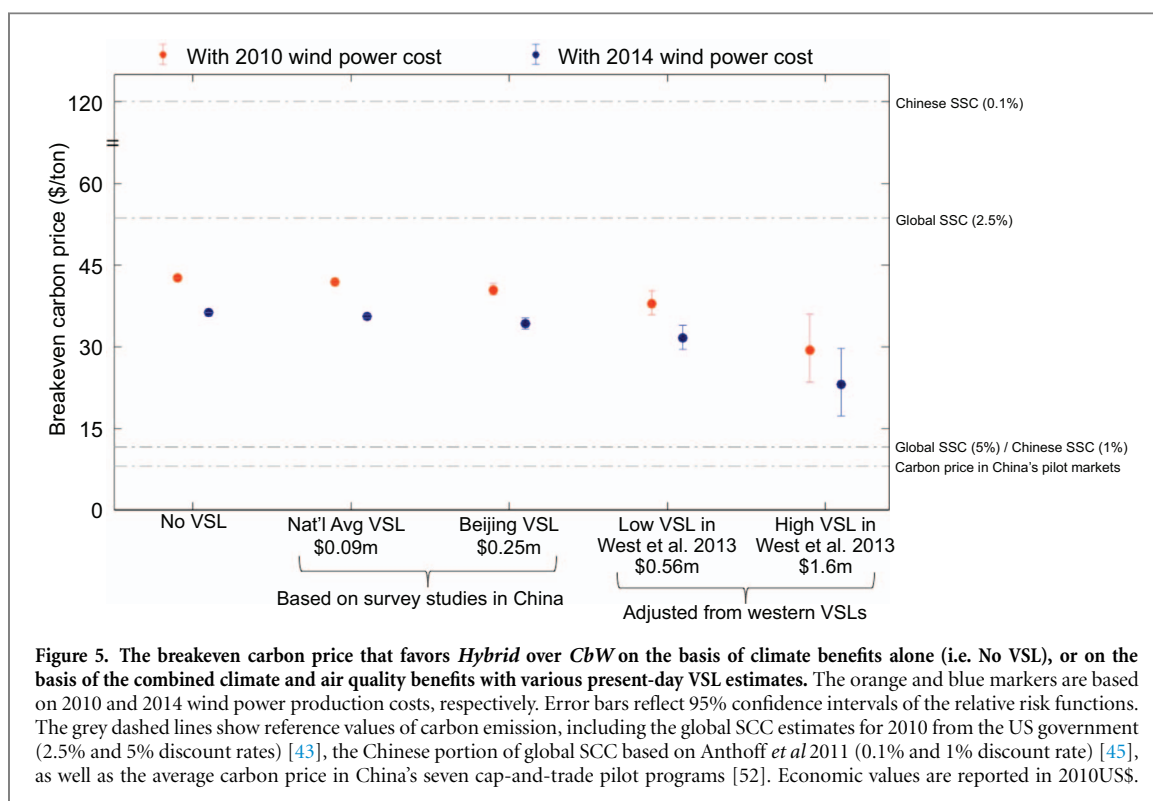
decrease as learning progresses, which will increase the competitiveness of the *CbW* strategy. Our results are consistent with previous findings that cost-effectiveness is determined by a combination of the investment costs for new infrastructure and the quantity of energy transported [16].

b) *Hybrid* vs. *CbW*

To evaluate the relative cost-effectiveness of transmitting a hybrid of renewable plus coal power as compared to coal power alone, we estimate that in 2010 the total power generation cost in *Hybrid* to be US\$11bn higher than *CbW*, due to higher generation costs for wind than coal (average levelized cost of electricity for wind and coal in exporting regions in 2010: US\$72 MWh⁻¹ and US\$36 MWh⁻¹, see online supplementary table 7). Here we neglect the potential costs to manage the transmission of variable wind power supply as compared to reliable coal power supply. It is likely that these costs have decreased since 2010, however.

On the benefit side, we find that *Hybrid* reduces 16% more air-pollution-related deaths (~2000 cases) and three times more carbon emissions (~260 million ton) than *CbW*. However, monetizing these air quality and climate benefits is controversial and is often based on the value of a statistical life (VSL, a measure of people's willingness to pay to reduce their mortality risk) and social cost of carbon (SCC, the marginal global societal cost of emitting an additional ton of carbon emissions), respectively. The VSL estimates vary substantially across countries, income groups, age groups [39], and implicitly involve some value judgment [40]. The SCC estimates range from \$20 to higher than \$200 ton⁻¹ in the literature [41–45], and may still be underestimated due to the high social discount rate being applied [41] and the omission of other damages [42, 46]. Therefore, instead of choosing specific VSL or SCC values, we calculate the breakeven VSL to favor *Hybrid* over *CbW*, above which the monetized value of the additional air quality benefits in *Hybrid* can justify the more expensive costs for renewable generation. We also estimate the breakeven carbon price under a range of VSLs above which the monetized air quality and climate benefits would justify the higher renewable costs in *Hybrid*.

Considering only the air quality benefits, a VSL higher than US\$5.0 m (confidence intervals due to RR functions: 3.5 m, 10.2 m) would favor *Hybrid* over *CbW*. Such breakeven VSL is more than twenty times higher than China's present-day VSL estimated from survey studies (low and high estimates \$90 000 [47] and \$250 000 [48]), or three times as high as the estimate obtained by adjusting the US 2005 VSL with income elasticity (high estimate of \$1.6 m for 2005 VSL in West *et al* 2013 [49]). Considering the climate benefits alone, we find a breakeven carbon price of \$43 ton⁻¹ to favor *Hybrid* (figure 5). Considering combined air quality and climate benefits, the



breakeven carbon price would only be slightly lowered under VSL estimates based on surveys (\$40–42 ton^{-1}).

To what degree do these benefits from using renewables accrue nationally? A full analysis should look not just at national air pollution benefits but also the benefits from lessening climate impacts that may occur domestically. That requires decomposing SCC into national and global impacts—a task not done much in the literature. However, Anthoff *et al* 2011 [45] found that 48% (or 31%) of total global climate damages will occur in China under a 0.1% (or 1%) discount rate. That suggests a global SCC of around \$80 ton^{-1} (or \$120 ton^{-1}) would yield a Chinese portion of costs in the \$40 ton^{-1} level that we find favor *Hybrid*. This range of global SCC is consistent with the values found in the extensive western literature on the global impacts of carbon emissions [41–45].

Therefore, based entirely on plausible national benefits—mainly improvements in public health and to a lesser degree lower impacts from climate change—the strategy of transmitting a hybrid mix of renewables and coal already appears to be the favorable fuel choice. The *Hybrid* strategy will likely become more attractive in the future with a decline in renewable technology costs and a growing economic valuation of the benefits. The drop in wind technology costs in China from 2010 to 2014 [50–51] could already lower the wind LCOE in exporting regions by 6%, hence narrowing the cost difference between *Hybrid* and *CbW* and lowering the breakeven carbon price (figure 5). People's willingness-to-pay to reduce mortality risk (i.e. the VSL) may also increase with growing income level in the future, which consequently favors *Hybrid*.

5. Conclusion

We highlight three policy implications. First, coordinating transmission planning with renewable energy deployment is critical to maximize combined air quality and climate benefits from energy by wire strategies. In China for example, wind and solar resources are abundant in northern and western regions, while air pollution is severe in eastern population centers. Using electricity transmission to connect renewable production areas with highly populated and polluted regions can better exploit renewable resources in remote areas, integrate variable with dispatchable resources [55], reduce carbon emissions, and maximize air quality and health benefits [53]. As many countries also need to expand transmission to support a scale-up of renewable energy [5, 17], we suggest that grid planners, acting in the national interest, consider the air quality implications of transmission capacity investment in order to increase both potential health co-benefits and carbon mitigation efforts.

Second, we highlight that work of this type—which aims to quantify the national benefits of policies that could have global consequences—requires future improvements in calculating national and global benefits in economic terms. The integrated assessment method in this analysis provides a rigorous evaluation of the health-related air quality impacts and carbon emissions. However, monetizing the impacts currently rely on VSL estimates, which in emerging economies are particularly hard to pin down, as well as concepts such as the SCC, which co-mingles national and global benefits. More robust

economic evaluations are needed for reliable cost benefit analyses [54].

Third, while we focus on air quality and climate impacts in this analysis, long-distance transmission may pose other local environmental impacts especially in the electricity exporting regions. For instance, relocating coal power generation to arid western regions may exacerbate water scarcity and extensive development of hydropower may have major impacts on local ecosystem. We thus suggest that grid planners consider the overall impact of long-distance electricity transmission on the environment at regional, national and global scales.

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