Energy Saving Potential of Natural Ventilation in China: The Impact of Ambient Air Pollution

Energy saving potential of natural ventilation in China: the impact of ambient air pollution

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Abstract

Natural ventilation (NV) is a key sustainable solution for reducing the energy use in buildings, improving thermal comfort, and maintaining a healthy indoor environment. However, the energy savings and environmental benefits are affected greatly by ambient air pollution in China. Here we estimate the NV potential of all major Chinese cities based on weather, ambient air quality, building configuration, and newly constructed square footage of office buildings in the year of 2015. In general, little NV potential is observed in northern China during the winter and southern China during the summer. Kunming located in the Southwest China is the most weather-favorable city for natural ventilation, and reveals almost zero loss due to air pollution. Building Energy Simulation (BES) is conducted to estimate the energy savings of natural ventilation in which ambient air pollution and total square footage must be taken into account. Beijing, the capital city, displays limited per-square-meter saving potential due to the unfavorable weather and air quality for natural ventilation, but its largest total square footage of office buildings makes it become the city with the greatest energy saving opportunity in China. Our analysis

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shows that the aggregated energy savings potential of office buildings at 35 major Chinese cities is 112 GWh in 2015, even after allowing for a 43 GWh loss due to China's serious air pollution issue especially in North China. 8–78% of the cooling energy consumption can be potentially reduced by natural ventilation depending on local weather and air quality. The findings here provide guidelines for improving current energy and environmental policies in China, and a direction for reforming building codes.

Keywords

Natural ventilation, energy saving, China, air pollution, AQI, CO_2 emission

1. Introduction

China has experienced rapid economic expansion and industrial development for the last two decades, making it the engine of the world's economic growth. According to the International Monetary Fund (2014), China reached $17.6 trillion purchasing-power-adjusted GDP to become the country with the largest GDP in the world, surpassing the United States ($17.4 trillion). As a result of this rapid growth, energy consumption and associated CO_2 emissions have increased dramatically (Liu et al., 2013; 2015a; Zhang and Cheng, 2009).

The building sector is a critical contributor to China's energy consumption, and the sector's life-cycle energy consumption accounts for over 40% of China's total energy use (Cao et al., 2014; Zhang et al., 2015). HVAC systems that heat, cool, and ventilate buildings comprise approximately 47% of operational energy consumption in buildings across China (TU, 2014). Many advanced technologies have been developed to achieve high building energy efficiency (Chen et al., 2016; Chou et al., 2004; Chua et al., 2013; Cui et al., 2016; Li et al., 2016; Luo et al., 2015; Ramponi et al., 2014; Tong et al., 2016b). Natural ventilation that supplies and removes air to and from an indoor space without the use of mechanical systems shows great potential to reduce energy consumption and the cost of the HVAC system (Allocca et al., 2003). Europe and the North America already pay a great attention to advanced NV technologies such as wind tower, solar chimney, and automated window controls (Artmann et al., 2007; Axley, 2001; Brager and de Dear, 1998; Chen, 2009; Hughes et al., 2012; Malkawi et al., 2016), which exhibits a substantial reduction in cooling energy usage by as much as 40–50% in some cities (Cardinale et al., 2003; Gratia and De Herde, 2004; Oropeza-Perez and Østergaard, 2014). However, the operation of NV in urban environment is affected by a number of factors such as outdoor ambient air pollution and noise (Nicol and Wilson, 2004; Tong et al., 2016c; Tong et al., 2012). In particular, outdoor ambient air pollution is an urgent challenge facing China's development. A large number of cities in China suffer from the degradation of air quality and associated health risks, such as respiratory symptoms and cardiovascular diseases (Chan and Yao, 2008; Gong et al., 2012; Seaton et al., 1995; Tong et al., 2016a; Zhang et al., 2014a; Zhang et al., 2014b). In the year of 2014/2015, only 25 out of 190 Chinese cities were able to meet National Ambient Air Quality Standards (Zhang and Cao, 2015). The impact of air pollution on NV operation is clearly significant. A few studies estimated the natural ventilation potential at several representative cities in China with simplified building models (Yang et al., 2005; Yao et al., 2009; Zhang et al., 2010), but did not consider the pressing impact of air pollution.

Here we estimate the NV potential in terms of NV hours of 76 Chinese cities based on local weather and ambient air pollution data from Aug. 2014 to Aug. 2015. The NV potential in terms of energy savings from cooling, and the reductions in carbon emission for 35 major cities are estimated using a Building Energy Simulation (BES) program and available square footage of newly constructed office building at each city for office buildings. To our knowledge, this is the first study to quantify the energy savings potential of natural ventilation in China considering the impact of ambient air pollution.

2. Methodology

2.1 Climate data

The climate in China varies from region to region due to the massive expanse of land and complicated terrain. According to the Standard on Division of Climate Zones for Buildings (GB50178-93, 1993), the country is categorized into five climate zones: Severe Cold, Cold, Hot Summer/Cold Winter (HSCW), Hot Summer/Warm Winter (HSWW), and Mild (Figure 1). In general, the northern part of China is characterized into Severe Cold and Cold zones where space heating dominates energy use in buildings. In the central part of China, covered by HSCW zone, both space heating and cooling are required in buildings. Southern China is mostly categorized into HSWW zone where space cooling is needed in the summer. The hourly Chinese Standard Weather Data (CSWD) developed by the China Meteorological Bureau and Tsinghua University are employed for Building Energy Simulation (2005).

2.2 Air quality data

Air quality index (AQI) is used to inform the public about levels of air pollution and associated health risks. The AQI approach is based on the maximum value of individual pollutants in China. In general, as AQI increases, a larger percentage of the population is likely to experience severe adverse health effects. In this study, hourly AQI data are downloaded from the China National Environmental Monitoring Center website (http://113.108.142.147:20035/emcpublish/). We choose one-year data from Aug. 2014 to Aug. 2015 due to the largest available coverage of Chinese cities (76 cities). According to the health effects defined in each AQI level (Table 2), the ambient air pollution start to cause negative health effects for sensitive groups when AQI is greater than 100 (GB3095, 2012). The AQI threshold for allowing natural ventilation is therefore chosen at 100.

In our analysis, the spatial variation of AQI within each city is not considered due to limited data availability. The AQI defined by Ministry of Environmental Protection of the People's Republic of China is based on the Eq. 1.

(1)

where $IAQI_p$ is the index for pollutant p; C_p is the rounded concentration of pollutant p; BP_{Hi} is the breakpoint that is greater than or equal to C_p; BP_{Lo} is the breakpoint that is less than or equal to C_p; $IAQI_{Hi}$ is the AQI value corresponding to BP_{Hi}; $IAQI_{Lo}$ is the AQI value corresponding to BP_{Lo}. IAQI and corresponding thresholds of each pollutant is displayed in Table 1. The overall AQI is the maximum of the individual AQIs as shown in Eq. 2.

(2)

Table 1: Individual AQI and corresponding thresholds of six pollutants

Individual Air Quality Index	**Sulfur Dioxide (SO_2)**	**Sulfur Dioxide (SO_2)**	**Nitrogen dioxide (NO_2)**	**Nitrogen dioxide (NO_2)**	**Carbon Monoxide (CO)**	**Carbon Monoxide (CO)**	**Ozone (O_3)**	**Ozone (O_3)**	**Particulate Matter**	
									PM 2.5	**PM 10**
	(μg/m³) [24h]	(μg/m³) [1h] (1)	(μg/m³) [24h]	(μg/m³) [1h] (1)	(mg/m³) [24h]	(mg/m³) [1h] (1)	(μg/m³) [8h]	(μg/m³) [1h]	(μg/m³) [24h]	(μg/m³) [24h]
0	0	0	0	0	0	0	0	0	0	0
50	50	150	40	100	2	5	100	160	35	50
100	150	500	80	200	4	10	160	200	75	150
150	475	650	180	700	14	35	215	300	115	250
200	800	800	280	1200	24	60	265	400	150	350
300	1600	(2)	565	2340	36	90	800	800	250	420
400	2100	(2)	750	3090	48	120	(3)	1000	350	500
500	2620	(2)	940	3840	60	150	(3)	1200	500	600

(1) 1-hour concentration of SO_2, NO_2, CO is only used for hourly report. 24-hour concentration should be used in daily report.
(2) If 1-hour SO_2 concentration exceeds 800 μg/m³, 24-hour concentration should be used instead.
(3) If 8-hour O_3 concentration exceeds 800 μg/m³, 1-hour concentration should be used instead.

Table 2. The health categories and definitions for Air Quality Index (AQI)

AQI	Health Risk Category	Meaning
0-50	Good	Air quality is considered satisfactory, and air pollution poses little or no risk.
50-100	Moderate	Air quality is acceptable; however, for some pollutants there may be a moderate health concern for a very small number of people who are unusually sensitive to air pollution.
101-150	Unhealthy for sensitive groups	Children, older adults, and people with lung and heart disease are likely to be affected.
151-200	Unhealthy	Everyone may begin to experience health effects; members of sensitive groups may experience more serious health effects.
201-300	Very unhealthy	Health warnings of emergency conditions. The entire population is more likely to be affected.
301-500	Hazardous	Health alert: everyone may experience more serious health effects.

2.3 Building Energy Simulation

The per-square-meter cooling energy savings at each Chinese city is estimated using EnergyPlus, a validated and physics-based Building Energy Simulation (BES) program developed by U.S. Department of Energy (Crawley et al., 2001). A brief description of the model is presented here. The core of the model is based on fundamental heat balance principle. The energy balance on each zone is described in Eq. 3, which assumes a well-mixed indoor air temperature.

$$\rho cpVdTdt=i=1nhiAiTi-Tint+QAC+Qload+Qnv \quad (3)$$

ρ is the air density. cp is the specific heat of air. V is the volume of the zone. On the left-hand side, $\rho cpVdTdt$ represents the rate of energy change in the zone in the unit of W. On the right-hand side, $i=1nhiAiTi-Tint$ denotes the convective heat transfer rate from zone surfaces in W. QAC is the cooling rate due to air conditioning in W. $Qload$ is the internal heat load in W. Qnv

is the heat transfer rate by ventilation (W) and equal to $\rho cpVnv(Tint-Tout)$ where Vnv is the rate of natural ventilation (m^3/s) as a function of wind speed and thermal stack effect given in Eq. 4.

$$Vnv=Vwind2+Vstack2 \tag{4}$$

The wind-drive ventilation rate $Vwind$ in m^3/s is given by Eq. 5 according to ASHRAE Handbook of Fundamentals (2009).

$$Vwind=CwAopeningFschedulеu \tag{5}$$

u is local wind speed. $Aopening$ is the opening area. $Fschedule$ is the value of ventilation schedule. Cw is the opening effectiveness given by Eq. 6.

$$Cw=0.55-0.25\cdot \alpha eff-\alpha wind180 \tag{6}$$

$\alpha eff-\alpha wind$ is the difference between effective angle of wind entrance and wind direction. This equation is a linear interpolation using values suggested in the ASHRAE handbook (2009). On the other hand, the ventilation rate (m^3/s) due to stack effect is described in Eq. 7.

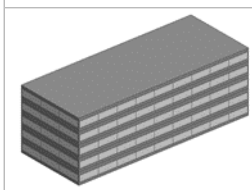
$$Vstack=CDAopeningFschedule2g\Delta HNPLTint-ToutTint \tag{7}$$

CD is the discharge coefficient for opening shown in Eq. 8 according to ASHRAE Handbook (2009). $\Delta HNPL$ is the height (m) from midpoint of lower opening to the neutral pressure level.

$$CD=0.4+0.0025Tint-Tout \tag{8}$$

In our EnergyPlus model, a five-story office building with a gross floor area of 5000 m^2 (1000 m^2 each floor) is created based on Chinese Building Design Standard as shown in Table 3 (PGB50189, 2015). The thermal characteristics (e.g., U value) of the building in each climate zone are shown in Table 3. Sensitivity study on different building configurations is presented in Section 3.3.

Table 3: Building thermal characteristics of each climate zone in China; U value and solar heat-gain coefficient are obtained from the Chinese Design Standard for Energy Efficiency of Public Buildings

Building Model	Climate Zone	Roof	Wall	Ground Floor	Window	Window SHGC
		U [W/m^2·K]	U [W/m^2·K]	U [W/m^2·K]	U [W/m^2·K]	
	Severe Cold	0.25	0.35	0.25	1.76	0.68
	Cold	0.39	0.46	0.46	1.77	0.37
	Cold Winter Hot Summer	0.39	0.54	0.46	2.3	0.32
	Warm Winter Hot Summer	0.44	0.72	1.32	2.4	0.2
	Temperate	0.44	0.72	1.32	2.4	0.2

The percentages of different type of HVAC system installed in office buildings of major Chinese cities are unavailable. We assumed that the modeled building is served by a fan coil unit (FCU) due to its popularity in China, which consumes much less energy than the variable air volume (VAV) system, therefore suiting the energy structure in China (Han, 2010). The cooling energy consumption investigated also includes those from auxiliary systems such as fans and pumps. The overall window-to-wall ratio is set as 50% and the operable window ratio is 30%. The plug load is 15 W/m^2 and lighting power density is 9 W/m^2. The fresh air rate is set as 8.3 L/s-person. The cooling and heating set-point temperatures for mechanical ventilation are 26 °C and 20 °C, respectively. The operation schedule of HVAC system is set as 7:00 - 18:00 from Monday to Friday. The coefficient of performance (COP) in the simulation complies with Chinese Building

Design Standard (PGB50189, 2015). For mixed-mode ventilation where both mechanical and natural ventilation are used, the thermal comfort thresholds for natural ventilation are determined according to the adaptive thermal comfort model established by de Dear and Brager (2002). Given the fact that not the entire Chinese building stock is suitable for natural ventilation and the difficulty to retrofit existing buildings, here we only used the square footage of one-year newly constructed office building to estimate the NV potential. The cooling energy savings at each city is approximated by multiplying the per-square-meter saving by the 10-year-averaged square footage of annual newly constructed office building at each city according to the National Bureau of Statistics of the People's Republic of China (2014). Uncertainty analysis on some of the model assumptions is presented in Section 3.3.

2.4 Carbon Emission Calculation

The CO_2 emission factor of power grid in each province is derived according to Eq. 9 (National Development and Reform Commission (NDRC), 2013).

$$EF_P = \frac{Em_p + \sum_n EF_n \times E_{imp,n,p} + \sum_k EF_k \times E_{imp,k,p} + (EF_{Grid,i} \times E_{imp,i,p})}{E_p + \sum_n E_{imp,n,p} + \sum_k E_{imp,k,p} + E_{imp,i,p}} \quad (9)$$

where EF_p is CO_2 emission factor of province p in $kgCO_2/kWh$; Em_p is direct CO_2 emission from electricity generation of province p given by Eq. 10 in $tonCO_2$; EF_n is the average CO_2 emission factor of n provinces that have net electricity export to province p in $kgCO_2/kWh$; $E_{imp,n,p}$ is net electricity export from n provinces to province p in MWh; EF_k is the average CO_2 emission factor of k countries that have net electricity export to province p in $kgCO_2/kWh$; $E_{imp,k,p}$ is net electricity export from k countries to province p, MWh; $EF_{grid,i}$ is the CO_2 emission factor of regional grid i in $kgCO_2/kWh$; E_p is the annual electricity generation of province p in MWh.

$$Emp=m(FCm\times NCVm\times EFm/1000) \qquad (10)$$

where FC_m is the consumption of fossil fuel for electricity generation in province p in ton or m^3; NCV_m is the net calorific value of fossil fuel m in GJ/ton or GJ/m^3; $E_{imp,i,p}$ is net electricity export from regional grid i to province p in MWh. It is given by Eq. 11.

$$Eimp,i,p=\max((Eu,p-Ep-nEimp,n,p-kEimp,k,p),0) \qquad (11)$$

where $E_{u,p}$ is the annual electricity consumption of province p in MWh. EF_m is the CO_2 emission factor of fossil fuel m in $tonCO_2/TJ$ given by Eq. 12.

$$EFm=CCm\times OFm\times 4412 \qquad (12)$$

where CC_m is the carbon content factor of fossil fuel m in tonC/TJ; OF_m is the oxidation factor of fossil fuel m in percentage. The estimations of CC_m and OF_m are from our previous studies (Liu et al., 2015b).

3. Results and Discussion

3.1 NV hours across China

NV hours (in the unit of number of hours per year) is defined as when outdoor weather and air quality are suitable for natural ventilation. The temperature and dew point threshold are chosen as when outdoor dry-bulb temperature is below upper threshold of adaptive thermal comfort model and higher than 12.8˚C (the lowest supply air temperature specified in ASHRAE 55 and fundamental handbook to avoid unpleasant draft to occupants), and the dew point is below 18˚C for the sake of humidity control (ASHRAE 55, 2004; ASHRAE, 2009; de Dear and Brager, 2002; Malkawi et al., 2016; Rijal et al., 2007; Zhu et al., 2016). The air quality threshold is chosen at AQI = 100, according to China National Ambient Air Quality Standards (GB3095, 2012). Although NV hour does not consider specific information at building scale, it is intended to provide a straightforward method to assist architects and energy policy makers in evaluating the regional feasibility of natural ventilation at a large scale without conducting detailed simulation. Since NV hour derived from meteorology and air quality data is independent of building types, it can be applied to both office and residential buildings. Building-scale simulation for estimating energy saving is discussed in section 3.2. Figure 1 presents the air-pollution-adjusted NV hours with box plot at five climate zones in the year of 2015. The national average NV hours is 2,324 (out of 8760 hours/year), with a standard deviation of 778. Clear differences in NV hour are observed across five climate zones. The Mild climate zone includes cities with the most NV hours. It is the most favorable climate for utilizing natural ventilation mainly due to the suitable outdoor temperature throughout the year. On the other hand, Hot Summer/Cold Winter (HSCW) is the least favorable climate for natural ventilation due the long hot/humid summers and cold/humid winters.

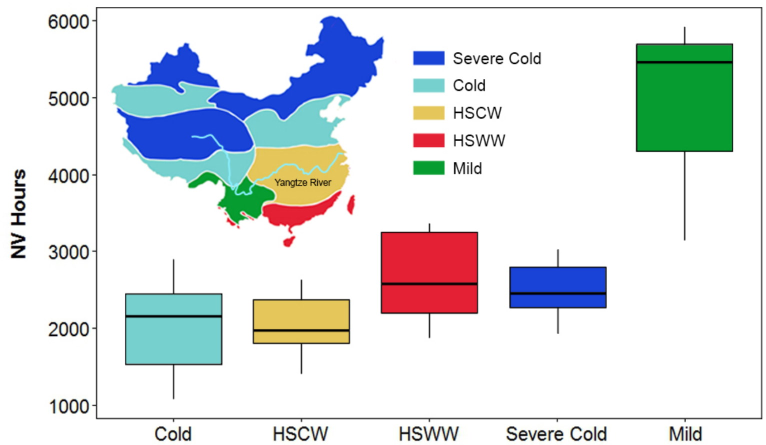


Figure 1. NV hours in five climate zones

Figure 2 displays the NV hours considering weather and ambient air pollution data in 76 major cities. The red wedge in the pie chart represents the reduction of NV hours by ambient air pollution. The Southwest region of China includes cities with the greatest NV potential. For instance, Kunming, the capital city of Yunnan Province, has 5913 NV hours. The city is located in the Mild climate zone with an annual average temperature of 15.5°C and little variation in temperature throughout the year. The cities with the least NV potential are located in south-central China that fall within hot-summer-cold-winter zones. NV hours are reduced greatly by ambient air pollution in northern China, where there is an enormous coal consumption for power generation (Chan and Yao, 2008). As highlighted in Figure 2, Zhengzhou, the capital of Henan province, displays the largest loss of NV hours (1655) due to air pollution among studied cities. In contrast, NV hours is reduced little by air pollution in the Northeast region (i.e., Liaoning, Jilin, Heilongjiang) which falls into Severe Cold climate zone, due mainly to the long and extremely cold winter seasons that prohibit natural ventilation regardless of the serious ambient air pollution from coal-firing heat generation. Compared with HSCW zone, the smaller loss in NV hour due to air pollution in the Northeast China does not imply better ambient air quality.

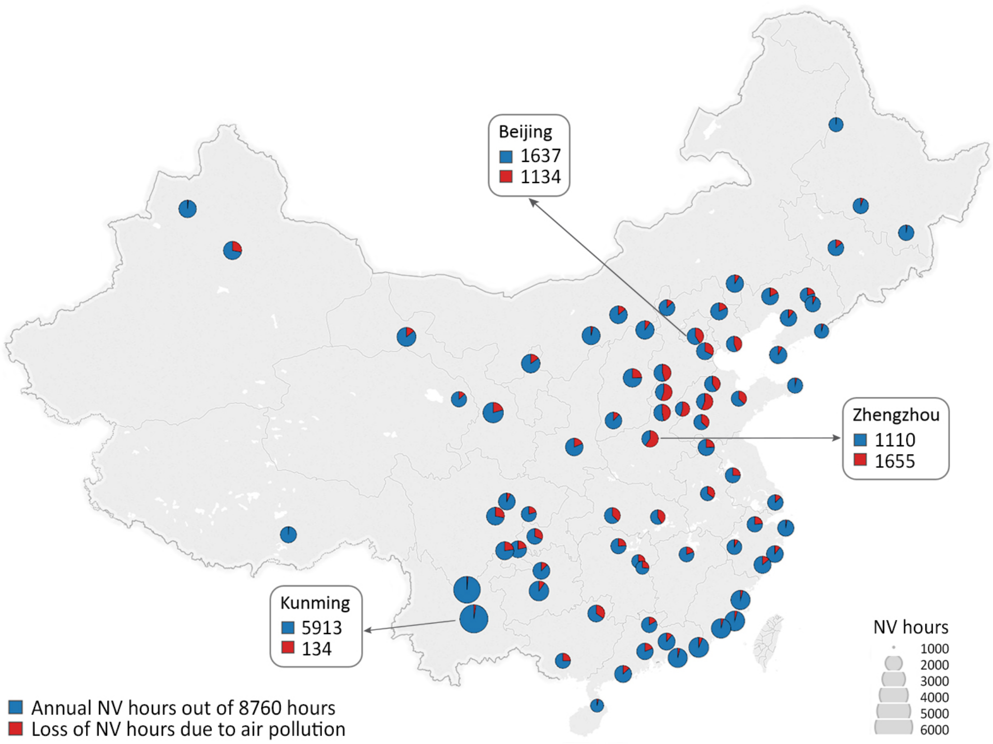


Figure 2. NV hours affected by ambient air pollution in 76 Chinese cities. Beijing, Zhengzhou, and Kunming are highlighted, and the corresponding NV hours and loss of NV hours due to air pollution are displayed. The unit is in hours per year. The area of the scale bars in the legend of Figure 2 represents NV hours.

Spring and fall show the largest mean and smallest deviation in NV hours across China (Figure 3). The national average of NV hours is 794 in spring compared to 207 in winter. In the summer, most cities located in the south of the Yangtze River experience hot and humid weather, which gives little potential for natural ventilation. Cities in the north offered much greater NV potential for cooling energy savings during the summer months. In winter, the northern part of China generally has almost no NV potential due to the cold weather, and the NV hours increase gradually with decreasing latitude from north to south.

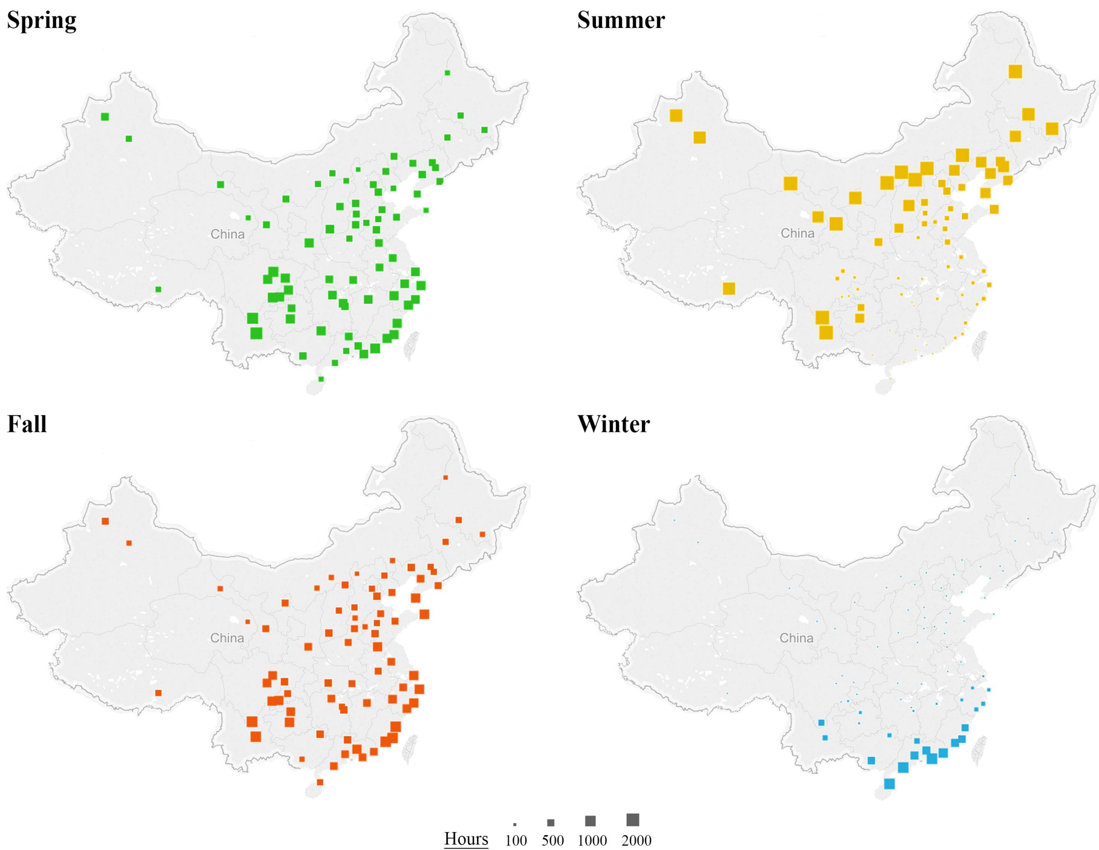


Figure 3. Seasonal variation of air-pollution-adjusted NV hours in China. The unit is in hours per year.

3.2 Energy savings and carbon dioxide reduction

In this section, the per-square-meter cooling energy savings and carbon reduction potential are estimated using available square footage data of newly constructed office building in 35 major Chinese cities. The main focus of this section is on office buildings where energy saving potentials can be quantified. Residents in China typically ventilate their homes based on personal behavior and thermal comfort preference rather than using fixed set points and schedules. Therefore, there is not enough information to estimate the natural ventilation potential for residential buildings due to the difficulties of collecting such datasets across major cities in China. Ten-year-averaged annual square footage data of office buildings from 2005 to 2014 is used to eliminate large yearly fluctuation at each city. Figure 4 shows the per-square-meter cooling energy consumption and savings potential for office buildings. The red wedge indicates the potential cooling energy savings by natural ventilation. The yellow wedge indicates the additional cooling energy savings if air quality is improved (i.e., AQI remains below 100 for the majority of time). The per-square-meter cooling consumption is generally larger in cities south of the Yangtze River due to the hot weather in the summer. Among 35 studied cities, Kunming is the most favorable for natural ventilation in terms of both weather and ambient air quality. It has a per-square-meter cooling consumption of 20.7 kWh/m^2, and 78% of it could be saved with natural ventilation. The city with the least per-square-meter energy savings potential (2.4 kWh/m^2) is Chongqing, which is a major city in southwestern China. Chongqing has hot and humid weather in the summer months, with an average temperature of 27.1°C and relative humidity of 79%, which make the city unfavorable for utilizing natural ventilation.

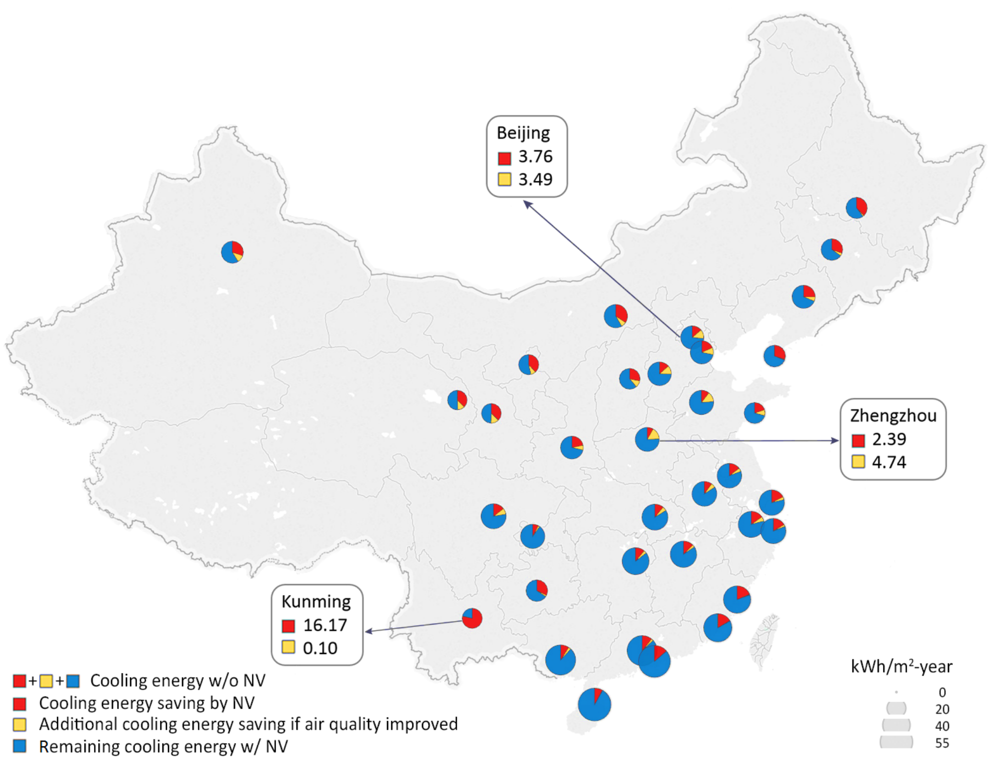


Figure 4. Per-square-meter office building cooling energy consumption of 35 major Chinese cities in kWh/m^2; the red wedge represents the cooling energy savings potentials by NV. The yellow wedge indicates the additional cooling energy savings if air quality is improved. The blue wedge indicates the remaining cooling energy consumption with NV. Beijing, Chongqing, and Kunming are highlighted, and the corresponding energy savings and additional energy savings if air quality is improved are displayed.

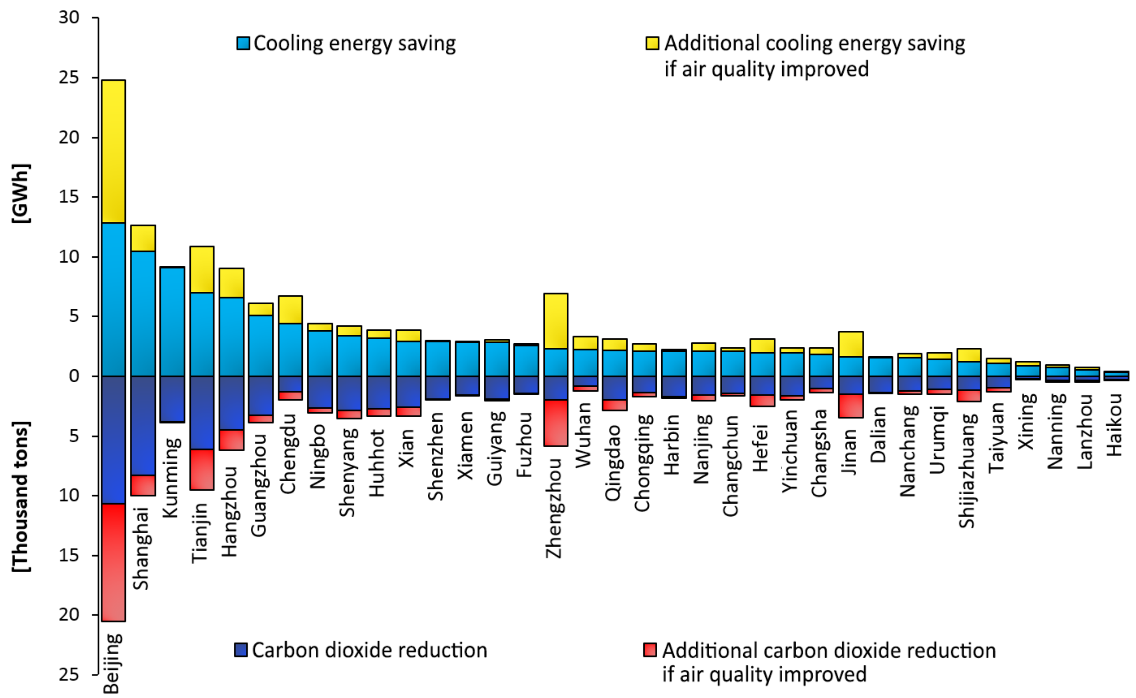


Figure 5. (Top) energy savings potential and additional cooling energy savings (if air quality is improved) in GWh of 35 major Chinese cities for office buildings ranked from high to low; (Bottom) carbon dioxide reduction potential in thousand tons and the additional cooling energy saving (if air quality is improved) at 35 major Chinese cities for office buildings.

The total savings in cooling energy by city presented in Figure 5 (Top) considers the total square footage at each city in the estimation. The aggregated energy savings potential of the 35 cities in the year of 2015 is 112 GWh, after a loss of 43 GWh due to air pollution. Beijing, the capital city of China, shows limited per-square-meter savings potential due to the unfavorable weather and air quality for natural ventilation. However, Beijing has the largest square footage of office buildings, and this creates an enormous energy saving opportunity. As shown in Figure 5, Beijing shows the largest potential of total energy savings (25 GWh) among 35 major cities in China, followed by Shanghai, Kunming, and Tianjin. These cities (except Kunming) are the most economically developed cities in China, with a large amount of government and private office space, although the per-square-meter savings from them are not among the top. For cities in northern China, savings potential is reduced greatly. For instance, Beijing shows the largest additional energy savings potential of 12 GWh (if air quality is improved), which is equivalent to the sum of the energy savings potential of the bottom ten cities (Figure 5).

In Figure 5 (Bottom), the top four cities with the greatest carbon dioxide reduction potential are Beijing, Shanghai, Tianjin, and Hangzhou. The aggregated carbon dioxide reduction potential by utilizing natural ventilation in office buildings at 35 major cities is estimated to be 79,000 tons, with a potential to reach 112,000 tons if AQI remains below 100 for the majority of time. Wuhan and Chengdu are located in the provinces with abundant hydro resources and, therefore, they have a smaller reduction in CO_2 emissions per kWh of electricity saved.

3.3 Sensitivity Analysis

The sensitivity of our methodology is presented in this section. In addition to the baseline five-story medium office, a one-story small office and a ten-story large office are created to examine how the building configurations affect the per-square-meter energy saving (Table 4). Three major cities with large total square footage are selected (Beijing, Shanghai, and Guangzhou in three distinct climate zones). As displayed in Figure 6a, the per-square-meter cooling energy savings by natural ventilation from the three office configurations are very close to each other with a variance less than 8%, despite the large difference in building sizes. Therefore, this analysis confirms that it is reasonable to estimate the NV potential based on the medium office configuration. The second test looked at the effect of plug load, which is varied by ±5 W/m^2 from the baseline (15 W/m^2). As shown in Figure 6b, the per-square-meter savings do not vary significantly with load at the same selected cities. This is mainly because when the internal load is less than the baseline load, more cooling energy is required when the indoor temperature is near the lower threshold for natural ventilation, but less cooling energy is required when the indoor temperature is close to the upper threshold. Likewise, the trend of cooling energy usage near the upper and lower threshold is the opposite when the internal load is greater than the baseline load. In addition, due to the large yearly fluctuation in the square footage of newly constructed office building, the third sensitivity study generates error bars for the NV potential at each city based on the standard deviation of the yearly square footage from the past ten years. Figure 7 displays the error ranges of the air-pollution-adjusted energy saving and carbon dioxide reduction potential at each city.

Table 4. Small, medium and large office buildings for the sensitivity analysis;

	Number of Floors	**Floor Dimensions**
Small	1 Floor	20m x 20m
Medium	5 Floors	20m x 50m
Large	10 Floors	50m x 50m (core 20m x 20m)

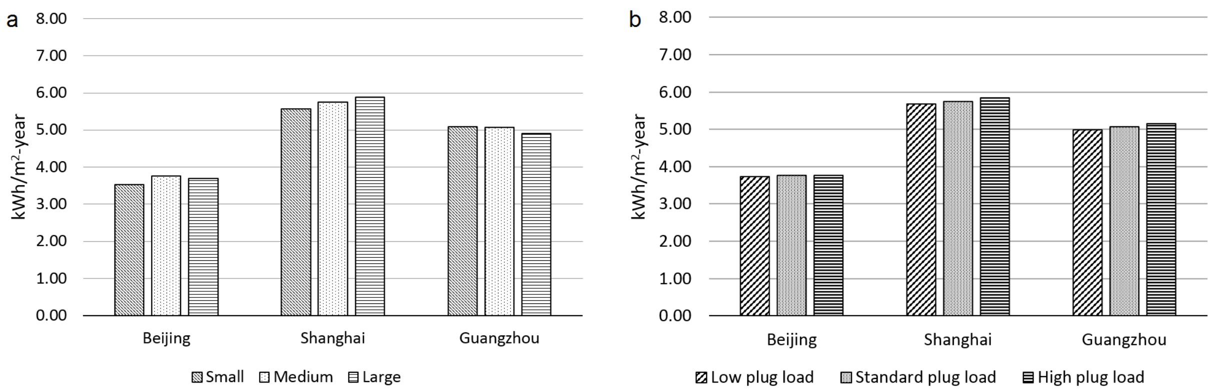


Figure 6. Per-square-meter cooling energy savings by natural ventilation; a) small, medium, and large building; b) low internal load (10 W/m^2), baseline plug load (15 W/m^2), and high internal load (20 W/m^2) in Beijing, Shanghai and Guangzhou

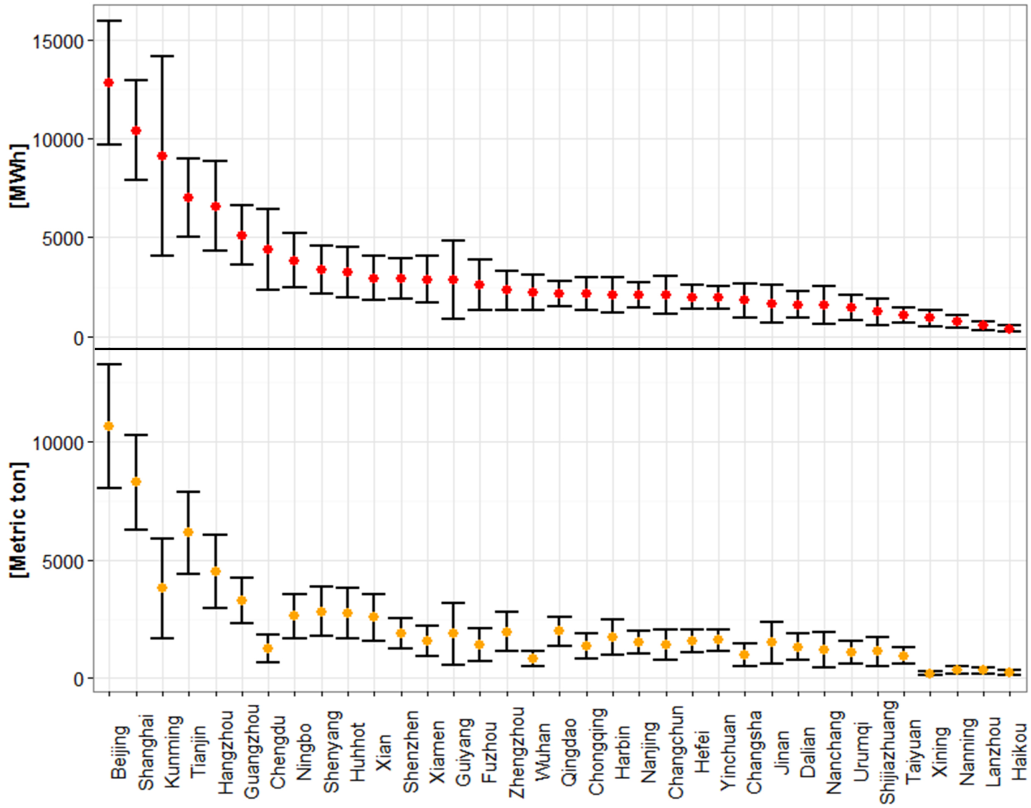


Figure 7: Sensitivity analysis on the air-pollution-adjusted energy saving and carbon dioxide reduction potential at each city in China. The error bar is generated using the standard deviation of yearly square footage from the past ten years

4. Concluding Remarks

As one of the most important green building features, natural ventilation has become an increasingly attractive design option that provides a comfortable working environment and promising energy savings potential. According to our analysis, ambient air quality and the total square footage at each city must be taken into account when evaluating the reality of NV's total energy savings potential. The aggregated energy savings potential of office buildings at 35 major Chinese cities is 112 GWh in the year of 2015, even after allowing for a 43 GWh loss due to severe air quality problems, especially in North China. Beijing shows a limited per-square-meter savings potential as a result of unfavorable weather and air quality for natural ventilation. However, it is the city with the most promising energy saving potential in China (25 GWh) due to its largest total square footage of office buildings. The aggregated carbon dioxide reduction is

79,000 metric tons based on provincial emission factor in China. It can reach 112,000 metric tons if AQI remains below 100 during non-air-pollution-adjusted NV hours, indicating a substantial impact that air pollution has on this issue.

The utilization of natural ventilation creates tremendous energy saving potential, reducing the emissions associated with coal-fired power generation, especially in North China. In addition, the integration of natural ventilation to office buildings would result in lower initial construction costs as a result of downsizing HVAC systems. Contrary to case studies that focus on a particular building or site, the methodology presented here cannot fully take into account neighborhood-scale characteristics such as surroundings, building configurations, and variation of AQI within each city due to limited data availability. However, the purpose of this study is to estimate the NV potential at a national level and therefore contribute to the development of energy and environmental policy in China. Our results demonstrate the co-benefits for NV's energy saving and carbon emission mitigation from reducing outdoor air pollution. While the air pollution is currently a serious environmental issue in China, the human-induced climate change driven by carbon emissions is a global problem facing mankind. Here we show the interactions between local and global challenges. Meanwhile, the natural ventilation potential estimated from this study will be valuable to architects and building operators to better implement different ventilation strategies in order to reduce building energy consumptions based on local climate and air quality conditions throughout China.

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