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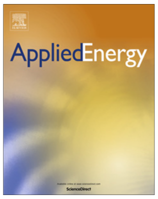

Energy saving potential of natural ventilation in China: The impact of ambient air pollution

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HIGHLIGHTS

- Natural ventilation potential is affected largely by ambient air pollution in China.
- NV hours of 76 Chinese cities based on weather and ambient air quality are estimated.
- Cooling energy savings and carbon reductions of 35 major Chinese cities are estimated.
- 8–78% of the cooling energy usage can be potentially reduced by NV.
- Our findings provide guidelines to improve energy policies in China.

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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 no 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 at each city 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 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.

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 IMF [1], China reached \$17.6 trillion purchasing-power-adjusted GDP in 2014 and became the country with the largest GDP in the world, surpassing the United States (\$17.4 trillion). As

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a result of this rapid growth, energy consumption and associated CO_2 emissions have increased dramatically [2–4].

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 [5,6]. HVAC systems that heat, cool, and ventilate buildings comprise approximately 47% of operational energy consumption in buildings across China [7]. Many advanced technologies have been developed to achieve high building energy efficiency [8–16]. 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 [17]. Europe and the North America already pay a great attention to advanced NV technologies such as wind tower, solar chimney, and automated window controls [18–23], which exhibits a substantial reduction in cooling energy usage by as much as 40–50% in some cities [24–26]. However, the operation of NV in urban environment is affected by a number of factors such as outdoor ambient air pollution and noise [27–31]. In particular, outdoor ambient air pollution is an urgent challenge facing China's development [32]. 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 [33–38]. In the year of 2014/2015, only 25 out of 190 Chinese cities were able to meet the National Ambient Air Quality Standards of China [39]. 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 [40–42], but did not consider the pressing impact of air pollution.

Here we first 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 dioxide emission for 35 major cities are then estimated using a Building Energy Simulation (BES) program and available square footage of newly constructed office building at each city. 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 [43], the country is categorized into five climate zones: Severe Cold, Cold, Hot Summer/Cold Winter (HSCW), Hot Summer/Warm Winter (HSWW), and Mild (Fig. 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 [44].

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 [45]. The AQI threshold for allowing natural ventilation is therefore chosen at 100.

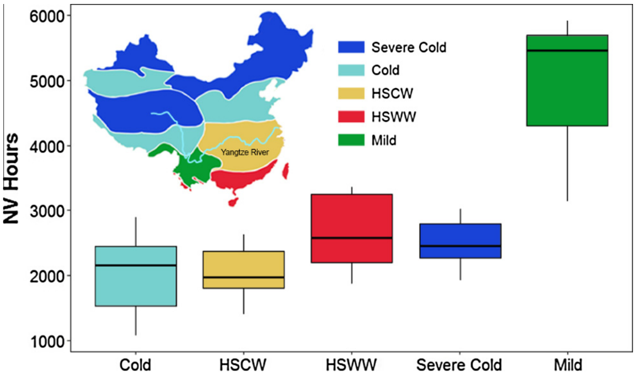

Fig. 1. NV hours in five climate zones.

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).

$$IAQI_p = \frac{IAQI_{Hi} - IAQI_{Lo}}{BP_{Hi} - BP_{Lo}}(C_p - BP_{Lo}) + IAQI_{Lo} \tag{1}$$

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).

$$AQI = \max\{IAQI_1, IAQI_2, IAQI_3, \ldots, IAQI_6\} \tag{2}$$

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 [46]. 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.

$$\rho c_p V \frac{dT}{dt} = \sum_{i=1}^{n} h_i A_i (T_i - T_{int}) + \dot{Q}_{AC} + \dot{Q}_{load} + \dot{Q}_{nv} \tag{3}$$

ρ is the air density. c_p is the specific heat of air. V is the volume of the zone. T_{int} is the indoor air temperature in K. On the left-hand side, $\rho c_p V \frac{dT}{dt}$ represents the rate of energy change in the zone in the unit of W. On the right-hand side, $\sum_{i=1}^{n} h_i A_i (T_i - T_{int})$ denotes the convective heat transfer rate from zone surfaces in W. $\dot{Q}_{AC}$ is the cooling rate due to air conditioning in W. $\dot{Q}_{load}$ is the internal heat load in W. $\dot{Q}_{nv}$ is the heat transfer rate by ventilation (W) and equal to $\rho c_p \dot{V}_{nv}(T_{int} - T_{out})$ where $\dot{V}_{nv}$ is the rate of natural ven-