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Natural Ventilation Potential of Residential Buildings in China Considering the Combined Effect of Indoor and Outdoor Air Pollution

Bo Lin [1,2,3,4], Changhong Xie [5], Yan Chen [1,4,6,7,*] and Xu Xu [1]

1 College of Civil Engineering and Architecture, Wenzhou University, Wenzhou 325035, China; linbo@wzu.edu.cn (B.L.); xuxuwzu@wzu.edu.cn (X.X.)
2 Zhejiang International Science and Technology Cooperation Base of Ultra-Soft Soil Engineering and Smart Monitoring, Wenzhou 325035, China
3 Wenzhou Engineering Technical Research Center on Building Energy Conservation and Emission Reduction & Diaster Prevention and Mitigation, Wenzhou 325035, China
4 Wenzhou Key Laboratory of Traffic Piezoelectric Engineering Technology, Wenzhou 325035, China
5 School of the Built Environment, University of Reading, Reading RG6 6EN, UK; hg889651@live.reading.ac.uk
6 Key Laboratory of Engineering and Technology for Soft Soil Foundation and Tideland Reclamation of Zhejiang Province, Wenzhou 325035, China
7 Zhejiang Collaborative Innovation Center of Tideland Reclamation and Ecological Protection, Wenzhou 325035, China
* Correspondence: yanchen@wzu.edu.cn

Abstract: With its rapid economic development, China has had to confront the serious issues of high energy consumption and air pollution. Natural ventilation is regarded as an effective method to reduce building energy consumption, but it is largely influenced by indoor and outdoor air pollution. However, most of the previous studies estimating natural ventilation potential (NVP) in China do not consider air pollution. This research estimated the NVP for residential buildings in major cities from four climate regions in China (Guangzhou, Chengdu, Shanghai, Beijing, and Shenyang) while considering the combined effect of indoor and outdoor air pollution. We compared the yearly NVP in three different scenarios, namely without considering air pollution, only considering outdoor air pollution, and considering both outdoor and indoor air pollution. The results show that Guangzhou had the highest yearly NVP, followed by Shanghai, Beijing, Shenyang, and Chengdu. The impact of air pollution could reduce the annual NVP in China by 78–95%. In addition, the main factors causing a low NVP differed between the four cities. The key factors for Chengdu and Guangzhou were natural ventilation flow rate and indoor air pollution, respectively. Beijing and Shenyang were mostly influenced by outdoor air pollution. Shanghai had two main factors with similar influence degrees, namely outdoor air pollution and indoor air pollution. The findings of this study will guide architects and policymakers in better forming natural ventilation strategies.

Keywords: natural ventilation potential; residential building; air pollution; natural ventilation hours; pressure difference Pascal hours

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1. Introduction

Rapid economic expansion and urbanization have led to an increasing energy demand in China [1]. With the growing number of buildings, the energy consumption of these buildings is enormous, and the building sector's life-cycle energy consumption accounts for more than 40% of the overall energy use in China [2,3]. Heating, ventilation, and air conditioning (HVAC) systems make up 47% of the operational energy use of buildings in China [4].

Many advanced technologies have been developed to improve building energy efficiency, including intelligent control, high-efficiency systems, and passive design [5–8].

Many studies on passive design have been carried out and have proved that passive design approaches are effective in reducing building energy consumption [9–12]. Natural ventilation, one of the passive cooling strategies, can significantly abate indoor heat load to reduce energy consumption [13–16]. Moreover, it can also provide fresh air to support human metabolism and ensure indoor air quality [17–19].

In order to better understand and utilize natural ventilation, natural ventilation potential (NVP) was proposed to estimate the performance of natural ventilation [20]. Natural ventilation potential is defined as the possibility, or probability, that acceptable indoor air quality and thermal comfort can be achieved with natural ventilation only [21,22]. Different methods have been proposed to assess NVP in previous studies. Roulet et al. proposed a multicriteria method to estimate site NVP by using geographic information systems (GISs) [23]. This method was beneficial in choosing a well-ventilated location, but it was largely limited by the lack of local GIS data. Germano and Roulet attempted to integrate the Qualiflex method into the multicriteria method of NVP [24]. The impact of different parameters, including wind effects, stack effects, air pollution, and noise level, was considered. However, this method is difficult to validate as there is a lack of validation in the existing construction [24]. Axley and Emmerich proposed climatic suitability assessments and established a heat balance model to calculate a range of criteria (outdoor air temperature and dew point temperature) to determine when natural ventilation was acceptable [25]. NVP was presented as the percentage of acceptable natural ventilation hours divided by the total number of hours in a year in their model. This model was further developed by adding new criteria, such as relative humidity, humidity ratio, height of the building, $PM_{2.5}$, and wind direction [26–29]. However, this type of method largely relied on local typical climate data, and the mass flow rate was set through standards. The impact of the building and the driving force of natural ventilation were ignored. Later on, the degree-hours method was proposed together with the comfort region concept to define NVP as the hourly sum of outdoor air temperatures in the comfort region [30–32]. Similar to the climatic suitability method, the degree-hours method is merely based on local typical climatic data but cannot present the real NVP. Yang et al. further proposed pressure difference Pascal hours (PDPH) to define the NVP as the hourly sum of the positive differences between the hourly effective pressure and required pressure, which could better represent the real NVP by integrating wind effects, stack effects, and a heat balance model [20]. Moreover, Luo et al. introduced an adaptive thermal comfort zone to replace the constant indoor air temperature assumption, which made the PDPH model more realistic [22]. Later, many new constraints were added to the PDPH model, including solution multiplicity, window opening percentage, air velocity, humidity, and thermal mass [21,33,34].

In recent years, considering the significant negative influence of air pollution on human health, e.g., the morbidities of cardiovascular disease and lung-related diseases and mortality [35,36], the impact of air pollution was introduced into the study of natural ventilation. Yamamoto and Tanabe investigated the natural ventilation conditions of 42 buildings in Japan and showed a significant decrease in natural ventilation hours in real cases due to outdoor air pollution [37]. Relying on local weather and air pollution data, Tong et al. found that 8- 78% of cooling energy consumption could be potentially decreased by natural ventilation [1]. Martins and Carrilho da Graça found that natural ventilation in non-domestic buildings was largely limited by air pollution [29]. Chen et al. showed the significant effect of outdoor air quality on the NVP of commercial buildings in the US [38]. There is a serious air pollution issue in China, with only one-seventh of Chinese cities being able to meet the National Ambient Air Quality Standard [39]. The serious problem of air pollution has a dramatic negative effect on the use of natural ventilation in China [14,40]. However, the impact of air pollution (including outdoor air pollution and indoor air pollution from cooking emissions) on the NVP of residential buildings in China has rarely been investigated. Residential buildings are important places where people stay for long periods of time. It is highly necessary to take into account the impact of air pollution on NVP estimation for residential buildings.

This paper is organized in two parts. In the first part, a new PDPH model is developed to capture the impact of air pollution on the natural ventilation potential, considering the impact of both indoor and outdoor air pollution. In the second part, the model is applied to estimate the yearly NVP in five Chinese cities from four different climate zones in three different scenarios, i.e., without considering any impact of air pollution, considering the impact of outdoor air pollution, and considering the impact of both outdoor air pollution and indoor pollution from cooking emissions.

2. Methodology

2.1. Model Development

There are three steps in the development of the model, namely the establishment of the building natural ventilation model, the introduction of constraints in the model, and the calculation of PDPH.

(1) Building natural ventilation model

Natural ventilation of residential buildings is more complex than that of industrial buildings as there are multiple separate rooms, but it is hard to define a typical building to represent local NVP for different cities in China. Hence, for simplicity, macroscopic analysis with some assumptions is used here to achieve better practical applications.

We assume that the building model is located in an open area of suburbs far from the crowd and city. The assumptions in the models of Yang et al. and Luo et al. are also adopted, i.e., uniform indoor air distribution, uniform opening distribution of walls, same opening areas of south and north walls, and south-oriented building model [20,22]. In this study, the building model is assumed to have porous openings on the south and north walls. The size of opening areas is defined by the wall porosity (η), which is the same for each wall. Figure 1a shows the heat balance diagram of the model. The size of the building model is defined as 10 m × 6 m × 3 m, as shown in Figure 1b. Li and Delsante suggested that an analytical solution cannot be obtained if thermal mass exists [41]. Following this assumption, the heat balance Equation (1) is established based on Figure 1a, considering the impact of solar, human, and indoor heat sources, following Luo et al. [22].

$$E_d + E_i = \rho C_p q(t_i - t_o) + \sum U_j A_j \left(t_i - t_{solar\text{-}air,j}\right) \tag{1}$$

$$t_{solar\text{-}air} = t_o + \frac{\lambda I}{h} \tag{2}$$

where E_i is indoor heat gain (W); E_d is direct solar heat gain (W); t_i is the indoor air temperature (K); t_o is the outdoor air temperature (K); I is the solar radiation intensity; ρ is the air density (kg/m^3); C_p is the specific heat capacity (kJ/kg·m^3); q is the natural ventilation flow rate (m^3/s); U_j is the coefficient of heat transfer on the jth wall (W/m^2·K); A_j is wall area on the jth orientation (m^2); $t_{solar\text{-}air}$ is the solar temperature (K); and h and λ are the convective heat transfer coefficient and absorption coefficient on the exterior surface of the wall, respectively.

Substituting Equation (2) into Equation (1), we can obtain

$$t_i - t_o = \frac{E}{\rho C_p q + \sum U_j A_j} \tag{3}$$

where

$$E = E_i + E_d + \sum U_j A_j \frac{\lambda I}{h} \tag{4}$$

E is the sum of the indoor heat gain (E_i), direct solar heat gain (E_d), and indirect solar heat gain through the wall. Equation (3) presents the relationship of t_i and t_o in the natural ventilation building. In our case, the natural ventilation flow rate (q) is one of the crucial parameters in Equation (3) and must be calculated in terms of thermal buoyancy and wind forces, as shown in Equation (5).

$$q = \sqrt{q_s^2 + q_w^2} \tag{5}$$

where q_s is the rate of natural ventilation via thermal buoyancy (m^3/s) and can be presented as

$$q_s = \frac{1}{3} C_d A_{tot} \sqrt{gH \frac{t_i - t_o}{t_o}} \tag{6}$$

$$A_{tot} = (A_n + A_s)\eta \tag{7}$$

where C_d is the discharge coefficient; H is the height of the opening (m); A_n and A_s are the north and south walls, respectively (m^2); η is the wall porosity; and A_{tot} is the total opening area in the south and north walls (m^2).

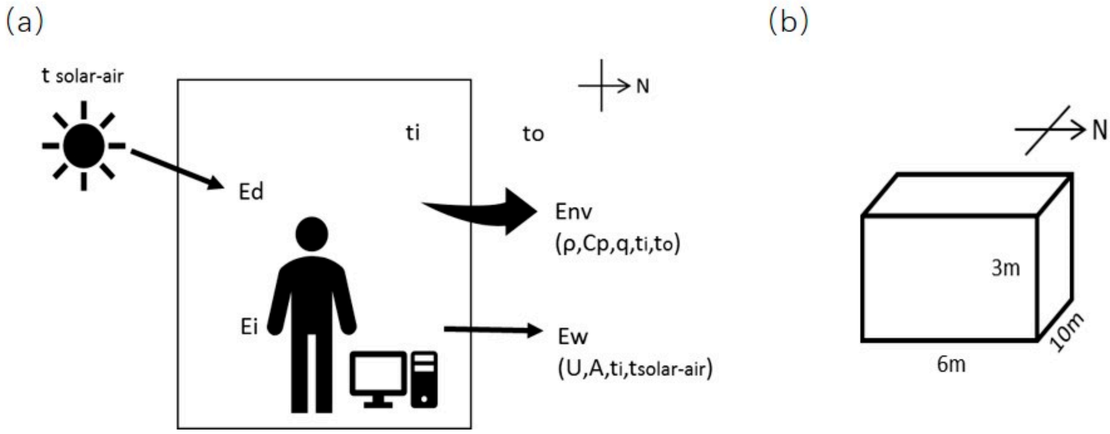

Figure 1. (**a**) Heat balance diagram of the model; (**b**) size of the building model.

q_w is the rate of natural ventilation via wind effect (m^3/s) and can be presented as

$$q_w = C_d A^* \eta \sqrt{\frac{2|\Delta P_w|}{\rho}} \tag{8}$$

$$\Delta P_w = \frac{1}{2} \rho C_{pn} v^2 - \frac{1}{2} \rho C_{ps} v^2 \tag{9}$$

$$A^* = \sqrt{\frac{A_n^2 A_s^2}{A_n^2 + A_s^2}} \tag{10}$$

$$v = \mathrm{k} v_o H^a \tag{11}$$

where C_{pn} and C_{ps} are the wind pressure coefficients of the north and south walls, respectively; ρ is the air density (kg/m^3); A^* represents the effective wall area (m^2); v is the wind speed at the opening (m/s); v_o is the wind speed at the weather station (m/s); and k and a depend on terrain conditions.

When Equations (9)–(11) are substituted into Equation (8), q_w is presented as

$$q_w = C_d \frac{A_n A_s \eta k H^a v_o}{\sqrt{A_n^2 + A_s^2}} \sqrt{|C_{pn} - C_{ps}|} \tag{12}$$

Moreover, when Equations (3), (6) and (12) are substituted into Equation (5), the natural ventilation flow rate is the root of Equation (13).

$$q^3 + \alpha q^2 - \beta q - \alpha\beta - \gamma = 0 \tag{13}$$

where

$$\alpha = \frac{\sum U_j A_j}{\rho C_p} \tag{14}$$

$$\beta = \frac{C_d^2 A_n^2 A_s^2 k^2 H^{2a} \eta^2 v_o^2}{A_n^2 + A_s^2} |C_{pn} - C_{ps}| \tag{15}$$

$$\gamma = \frac{C_d^2 A_{tot}^2 g H E}{9 \rho C_p t_o} \tag{16}$$

Only one positive root of Equation (13) is adopted, as follows:

$$q = \frac{\omega}{6} + \frac{6\beta + 2\alpha^2}{3\omega} - \frac{\alpha}{3} \tag{17}$$

where

$$\omega = \sqrt[3]{\frac{72\alpha\beta + 108\gamma - 8\alpha^3}{12\sqrt{-12\beta^3 + 24\alpha^2 + \beta^2 - 12\beta\alpha^4 + 108\alpha\beta\gamma + 81\gamma^2 - 12\gamma\alpha^3}}} \tag{18}$$

A basic natural ventilation building model has been established. The values of other basic parameters are taken from the design standard, as shown in Table 1. According to climate data and the parameters in this table, the natural ventilation flow rate can be calculated.

Table 1. Summary of input parameters.

Input Parameter	Value
$A_n = A_s$	30 m^2
C_d	0.61
a	0.17
C_p	1.005 kJ/kg·m^3
$U_{ceiling}$	0.48 W/m^2·K
A_f	60 m^2
ρ	1.2 kg/m^3
N_p	9
λ	0.9
η	0.4
k	0.68
E_i	588 W
U_{wall}	1.5 W/m^2·K

(2) Constraints in model

The purpose of natural ventilation is to meet human thermal comfort requirements, and the impact of air pollution on NVP is significant. When indoor thermal comfort or air quality cannot meet the standards, natural ventilation cannot be accepted. These hours are called unacceptable natural ventilation hours (NVh). In this part, we introduce two constraints into our model, which are the thermal comfort standard and indoor air quality standard, to filter out unacceptable NVh from our result. Here, we consider adaptive thermal comfort and $PM_{2.5}$ as the representative air pollution as two constraints.

(a) Thermal comfort

According to Richard and Gail, people have higher heat adaptation in naturally ventilated buildings than in air-conditioned areas [42]. With different outdoor temperatures, the range of comfortable indoor temperatures is different [43]. In many previous studies, the Adapted Comfort Standard (ACS) [42] is used to evaluate the thermal comfort in naturally ventilated buildings [22,44]. Equation (19) presents the relation between comfort temperature (t_{comf}, °C) and mean monthly outdoor air temperature (t_{out}, °C).

$$t_{comf} = 0.31t_{out} + 17.8 \tag{19}$$

However, this equation cannot fit all climatic regions. In China, Su et al. revised the ACS and obtained a new equation, Equation (20), which is more applicable in China [45].

$$t_{comf} = 0.30t_{out} + 19.7 \tag{20}$$

We adopt 80% acceptability in this study. The upper 80% acceptability limit (t_{upper}, °C) is

$$t_{upper} = \begin{cases} 24.7, & 0 \le t_{out} < 5, \\ 0.3t_{out} + 23.2, & 5 \le t_{out} \le 33, \\ 33.1, & 33 < t_{out} \le 40, \end{cases} \tag{21}$$

and the lower 80% acceptability limit (t_{lower}, °C) is

$$t_{lower} = \begin{cases} 17.7, & 0 \le t_{out} < 5, \\ 0.3t_{out} + 16.2, & 5 \le t_{out} \le 33, \\ 26.1, & 33 < t_{out} \le 40, \end{cases} \tag{22}$$

When the outdoor temperature is below 0 °C or above 40 °C, thermal comfort cannot be secured by natural ventilation.

The constraint of indoor thermal comfort means natural ventilation is acceptable when the calculated indoor temperature aligns with the thermal comfort standard. The thermal comfort zone is between the upper and lower 80% acceptability limit.

(b) Indoor air quality

Indoor air quality is another constraint considered in the model. Natural ventilation refreshes indoor air quality while also leading to a 4~5 times increase in indoor exposure to outdoor air pollution [29]. The use of natural ventilation is largely limited by outdoor air pollution. In addition, in residential buildings, cooking, as a daily behavior, is the major indoor air pollution source. Cooking increases the indoor $PM_{2.5}$ concentration [46]. Natural ventilation is acceptable only when indoor air pollution concentration is below the standard level for healthy indoor air quality.

In recent years, $PM_{2.5}$ has been one of the most serious outdoor air pollution in China [47]. More than 73% of urban residents live where the average $PM_{2.5}$ concentration exceeds 70 $\mu g/m^3$ [48]. In our case, $PM_{2.5}$ is assumed to be the air pollution constraint, and hourly indoor $PM_{2.5}$ concentration considering both indoor and outdoor sources will be calculated. According to the standard of indoor air quality, only ASHRAE and WHO published 24 h $PM_{2.5}$ limits: 35 and 25 $\mu g/m^3$, respectively [49,50]. This study focuses on residential buildings where people stay for a long time, so the threshold of WHO is a better choice for residents' health. Thus, the constraint of indoor air pollution means the indoor $PM_{2.5}$ concentration must be below 25 $\mu g/m^3$ with natural ventilation.

Regarding the estimation of indoor $PM_{2.5}$ concentration, we use a simple mass balance model to calculate indoor $PM_{2.5}$ [51]. In buildings with natural ventilation, an increase in indoor $PM_{2.5}$ results from both outdoor sources and indoor cooking emissions. In the meantime, indoor deposition and natural ventilation reduce the indoor $PM_{2.5}$ concentration [52].

The dynamic mass balance equation of this model is

$$\mathrm{V} \cdot \frac{dC_I}{d\tau} = C_o \cdot \mathrm{q} + \mathrm{S} - C_I \cdot k \cdot \mathrm{V} \tag{23}$$

where C_I is the indoor $PM_{2.5}$ concentration (μg/m^3), C_o is the outdoor $PM_{2.5}$ concentration (μg/m^3), q is the natural ventilation flow rate (m^3/s), S is the cooking $PM_{2.5}$ emission rate (μg/s), k is the deposition rate of $PM_{2.5}$ (s^{-1}), and V is the volume of the model (m^3).

Then, the dynamic mass balance equation can be described by a discretized form for the indoor $PM_{2.5}$ concentration at time step $\tau + \Delta\tau$.

$$C_I|_{\tau+\Delta\tau} = C_I|_{\tau} \cdot e^{-k\Delta\tau} + \frac{C_o|_{\tau+\Delta\tau} \cdot q + S|_{\tau+\Delta\tau}}{kV}\left(1 - e^{-k\Delta\tau}\right) \tag{24}$$

If the air exchange rate is high enough or the time step is long enough in the model, Equation (24) can be considered as a steady-state model. Hence, Equation (25) is transformed as follows:

$$C_I = \frac{C_o \cdot q + S}{kV} \tag{25}$$

In Equation (25), C_o, q, and V can be easily obtained through local weather data and previous calculations. k is one of the main factors in the air pollution mass balance model, and it represents the decay rate of the indoor $PM_{2.5}$ concentration [53]. It is set as 0.5 h^{-1} according to the results of previous experimental studies [54]. As for the value of S, it is set to match the result of Saborit et al., which is 1.7 mg/min [55]. In our cases, cooking emissions are produced at 7, 12, and 19 o'clock at breakfast, lunch, and dinner time in China, and the first hours are assumed as steady-state. Each cooking lasts for one hour. Then, the hourly indoor $PM_{2.5}$ concentration for the whole year is obtained.

In summary, the constraint of indoor air pollution means natural ventilation is acceptable when the calculated indoor $PM_{2.5}$ concentration is below the standard level, 25 μg/m^3.

(3) PDPH calculation

The original definition of PDPH is the hourly sum of the positive value of the pressure difference, which is shown in Equation (26).

$$PDPH = 1h \cdot \sum_{hours} \left(\Delta P_{eff} - \Delta P_R\right) \tag{26}$$

where

$$\Delta P_{eff} = \frac{\rho_o q^2}{2C_d^2 A_{tot}^2} \tag{27}$$

$$\Delta P_R = \frac{\rho_o q_R^2}{2C_d^2 A_{tot}^2} \tag{28}$$

$$q_R = 0.0075 * N_p + 0.0001 * A_f \tag{29}$$

In Equations (26)–(28), ΔP_{eff} is the effective pressure difference (Pa) and ΔP_R is the required pressure difference (Pa). ΔP_{eff} and ΔP_R are calculated using the total natural ventilation flow rate (q) (m^3/s) and the required minimum natural ventilation flow rate (q_R) (m^3/s), respectively. N_p is the number of people; A_f is the area of floor (m^2) [49].

However, the introduction of constraints limits acceptable natural ventilation hours, which also leads to a new definition of PDPH. Based on the consideration of the new constraints, PDPH can be defined as follows:

> "The hourly sum of the positive value of air pressure difference, when indoor $PM_{2.5}$ concentration is below standard level, and the indoor air temperature fits the thermal comfort zone".

Its equation form is

$$PDPH = 1h \cdot \sum_{hours} \left(\Delta P_{eff} - \Delta P_R\right) \left\{ \begin{array}{c} C_I \le 25\mu g/m^3 \\ t_i = 0.3 \cdot t_o + 19.7^\circ C \end{array} \right\} \tag{30}$$

where the units of t_i and t_o are °C.

In summary, the revised model is taken into practice using the following three steps: Firstly, a basic building natural ventilation model is established to calculate the natural ventilation flow rate and indoor temperature. Secondly, acceptable natural ventilation hours are filtered by constraints of indoor thermal comfort and indoor air quality. Thirdly, in acceptable natural ventilation hours, the sum of the positive value of the air pressure difference is calculated. Calculated using this process, NVP can be demonstrated as the capacity of natural ventilation to maintain both indoor air quality and thermal comfort.

2.2. Model Application

NVP can be estimated using the revised PDPH model considering the impact of air pollution. Figure 2 illustrates the locations of five major Chinese cities for NVP estimation. They are shown as red stars and are located in four major climatic regions in China. These cities represent most Chinese cities with similar climatic characteristics. The results of their NVP are representative and characteristic. The wind directions of the five cities are shown in Figure 3. The annual average wind speeds of Beijing, Shanghai, Guangzhou, Chengdu, and Shenyang are 2.5 m/s, 3.1 m/s, 2.1 m/s, 1.2 m/s, and 2.9 m/s, respectively.

Figure 2. Map of climate zones in China.

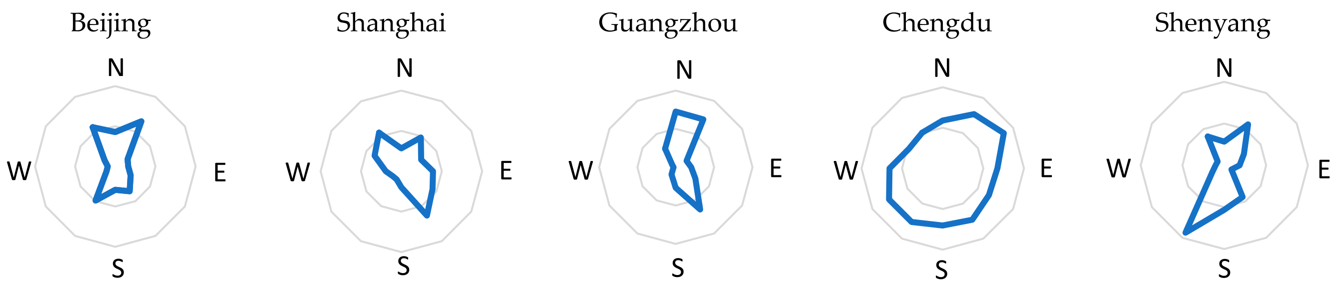

Figure 3. Wind directions of the five cities.

Furthermore, we set up three scenarios to better reflect the impact of air pollution on NVP. The first scenario does not consider any impact of air pollution, which is similar to the original PDPH model. The second scenario considers the impact of outdoor air pollution. The last scenario contains the impact of both outdoor air pollution and indoor pollution from cooking emissions. Indoor temperature and natural ventilation flow rate, as basic parameters in the methodology, are contained in all scenarios. Regarding weather and air pollution data ($PM_{2.5}$ concentration), they are representatively obtained from EnergyPlus and the U.S. Department of State Air Quality Monitoring Program [56,57].

3. Results and Discussion

In this calculation, the natural ventilation flow rate is one of the basic parameters for estimating NVP. The natural ventilation flow rate can reflect wind and stack effects in our model [41]. Without considering other constraints, a higher natural ventilation flow rate contributes to higher NVP. Figure 4 shows the box plot of the yearly natural ventilation flow rate in the five Chinese cities. Shenyang and Chengdu have the highest and lowest average yearly natural ventilation rates at 53 m^3/h and 21 m^3/h, respectively. The average yearly natural ventilation rates of Shanghai, Beijing, and Guangzhou are 42 m^3/h, 48 m^3/h, and 41 m^3/h, respectively. Aside from Chengdu, the other four cities have similar natural ventilation flow rates, and most natural ventilation flow rates in these four cities are between 20 and 80 m^3/h.

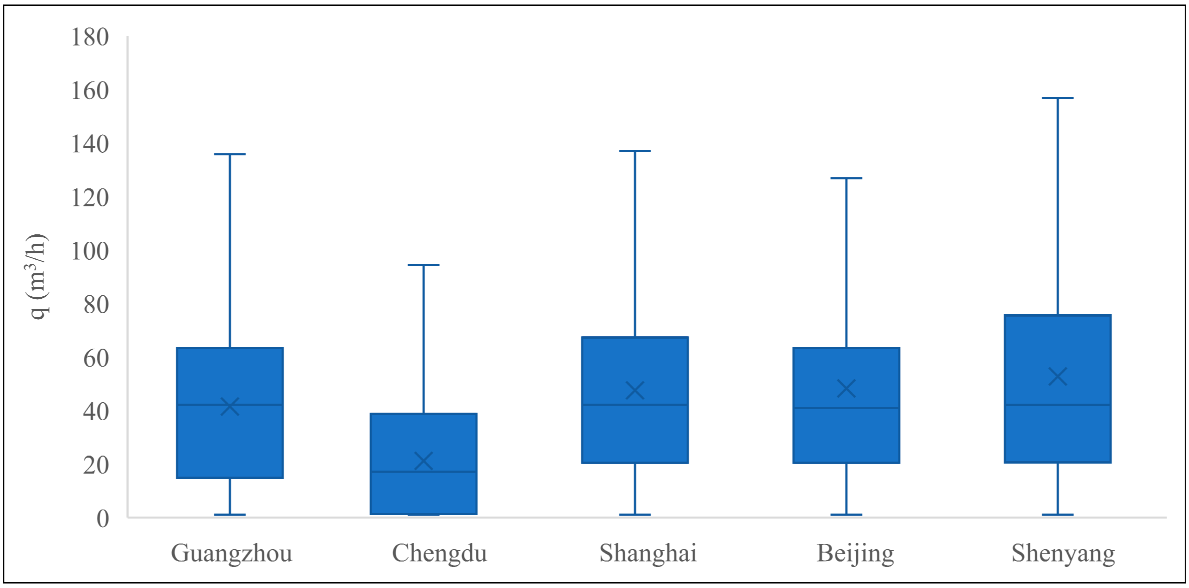

Figure 4. Yearly natural ventilation flow rate in five cities in China.

Scenario 1 does not consider air pollution. In terms of NVh, it shows that cities located in warmer climate regions have higher NVh (see Figure 5). In scenario 1, the NVP is constrained by indoor temperature. Natural ventilation is acceptable when the indoor temperature fits the ACS. Guangzhou, located in the hot summer–warm winter region, has the highest NVh, 4578, of the five cities. This covers more than half the time of a year. Shenyang, located in the severe cold region, has the lowest NVh, 1796, with only 40% of the NVh in Guangzhou. The NVh values of the other three cities in the cold region and the hot summer–cold winter region are between the NVh values of Guangzhou and Shenyang. Shanghai and Chengdu, in the same climate region of the hot summer–cold winter region, have similar NVh values at 2827 and 2654, respectively. Beijing, located in the cold region, has a lower NVh value (2130) than Shanghai and Chengdu due to the colder climate. Overall, the natural ventilation in the five cities is acceptable between 20% and 52% of the time throughout the year. This demonstrates that the five cities have abundant potential for the usability of natural ventilation theoretically without considering air pollution.

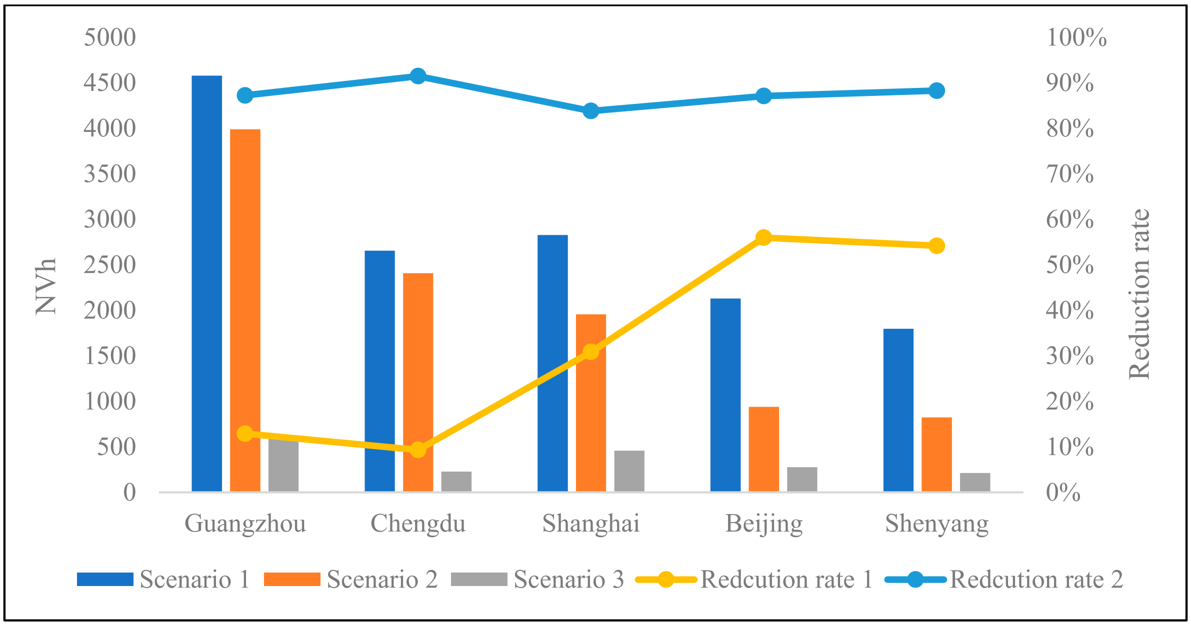

Figure 5. Natural ventilation hours (NVh) in five cities in China.

PDPH is an indicator of NVP influenced by NVh and the natural ventilation flow rate. As for PDPH in scenario 1 shown in Figure 6, Guangzhou has the highest value of 38,746, followed by 38,152 in Shanghai. The city with the lowest PDPH is Chengdu at 6734. Beijing and Shenyang have PDPH values of 34,889 and 29,012, respectively. Although these PDPH values are similar, the dominant parameters are different. According to the previous comparison, Guangzhou has a higher NVh value than Shanghai. On the contrary, Shanghai has a higher overall natural ventilation flow rate than Guangzhou. Guangzhou and Shanghai have similar PDPH values, with the effect of the natural ventilation flow rate and NVh. Beijing and Shenyang have high natural ventilation flow rates. The PDPH values of these two cities are limited by NVh through indoor temperature. As for Chengdu, the PDPH is the lowest among the five cities, although the climate region of Chengdu is the same as that of Shanghai. This is due to the insufficient natural ventilation flow rate.

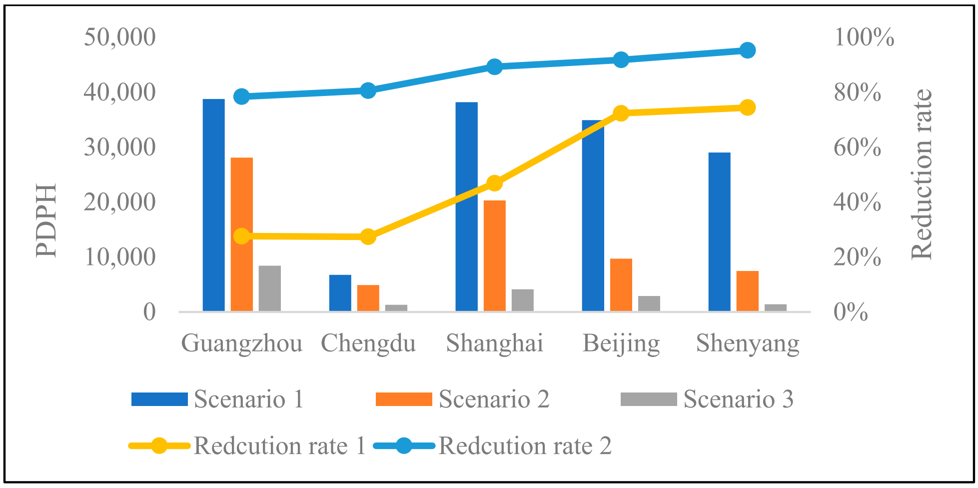

Figure 6. PDPH in five cities in China.

From the comparison of NVh and PDPH in scenario 1, we can see that among the five cities, the NVh of Chengdu is moderate, but the PDPH is the lowest. This is caused by the low natural ventilation flow rate in Chengdu. The natural ventilation flow rate is an important parameter in the calculation of PDPH, but it is not considered in the calculation of NVh. According to Equations (26) and (27), PDPH is positively correlated with the natural ventilation flow rate in scenario 1. Chengdu has the lowest average natural ventilation flow rate (see Figure 4). This causes the natural ventilation flowing into buildings to be poor during acceptable NVh.

Scenario 2 considers outdoor air pollution in estimating NVP. Figure 7 shows the outdoor $PM_{2.5}$ concentration in the five Chinese cities. Guangzhou has the best air quality in the five cities with an average outdoor $PM_{2.5}$ concentration of 33, followed by Shanghai with an average outdoor $PM_{2.5}$ concertation of 45. Chengdu, Beijing, and Shenyang have similar high average outdoor $PM_{2.5}$ concentrations at 73, 72, and 78, respectively. Scenario 3 considers both outdoor and indoor air pollution. Figures 5 and 6 illustrate the NVh and PDPH of the five Chinese cities in three different scenarios and the NVh and PDPH reduction rates of scenario 2 and scenario 3 compared with scenario 1. Reduction rate 1 and reduction rate 2 represent the NVh and PDPH decrease rates of introducing outdoor air pollution and both outdoor air pollution and indoor air pollution from cooking emissions, respectively, into the model of scenario 1.

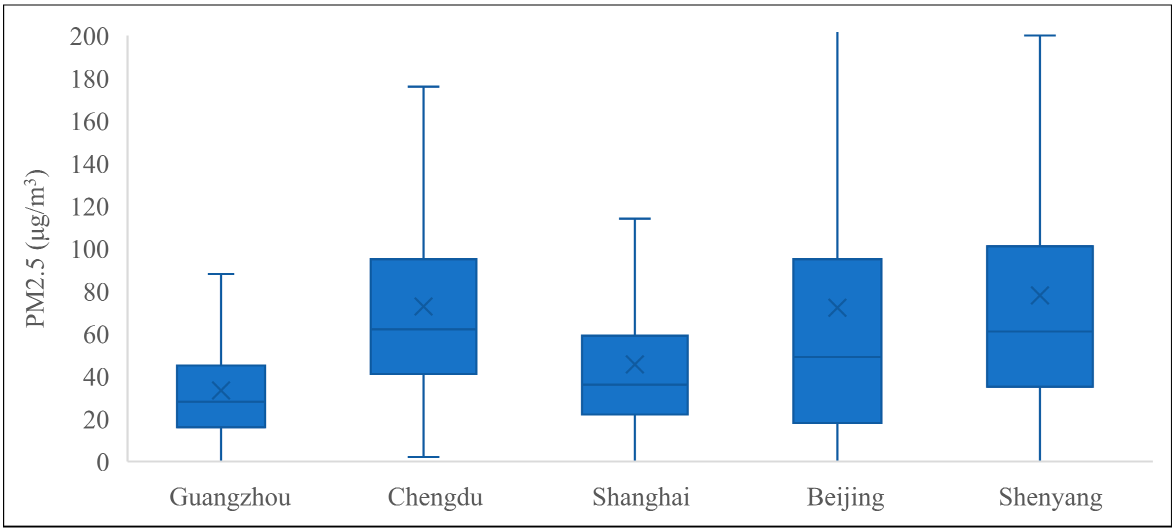

Figure 7. Yearly outdoor $PM_{2.5}$ concentration in the five Chinese cities.

In scenario 2, NVh and PDPH decrease under the environment with local outdoor $PM_{2.5}$. Guangzhou still has the highest NVP with NVh of 3988 and PDPH of 28,062. Shenyang has the lowest NVh value of 823, and its PDPH is also relatively low at 7432 compared with the other four cities. Chengdu has the lowest PDPH of 4893, but its NVh is 2407, higher than that of the other cities except for Guangzhou due to its natural ventilation flow rate. Shanghai and Beijing have the NVh values of 1955 and 938, respectively, and PDPH values of 20,291 and 9676, respectively. As shown by reduction rate 1, NVh decreases dramatically by up to 56% due to outdoor air pollution in Beijing, and the lowest reduction rate is close to 10% in Chengdu. The reduction rate of PDPH is higher than that of NVh, reaching 27~74%. According to the NVh, PDPH, and $PM_{2.5}$ concentration in five Chinese cities, worse outdoor air quality usually contributes to more NVh loss and a higher reduction rate of PDPH (see Figures 5–7). However, this tendency was not found for Chengdu. Compared with Shanghai, Chengdu has a higher $PM_{2.5}$ concentration but a lower reduction rate of NVh and PDPH. This phenomenon is caused by the low natural ventilation flow rate in Chengdu. The natural ventilation flow rate has a significant impact on the indoor environment. According to the mass balance model, both Equations (24) and (25) show that the impact of the outdoor air pollution concentration on the indoor air pollution concentration is influenced by the natural ventilation flow rate. In scenario 2, indoor air pollution from cooking emissions is not counted, so Equation (25) can be transferred to Equation (31).

$$C_I = \frac{C_o \cdot q}{kV} \tag{31}$$

where k and V are constant values. The actual influence of outdoor pollution on NVh is limited in a place where the natural ventilation flow rate is low. In other words, low natural ventilation flow decreases the negative influence of outdoor air pollution on indoor air quality and consequently reduces the reduction rate of NVh and PDPH. In summary, worse outdoor air quality contributes to more PDPH loss if the natural ventilation flow rate is high. A low natural ventilation flow rate reduces the impact of outdoor air pollution on the loss of PDPH.

In scenario 3, to identify the impact of air pollution on NVP, we consider both outdoor air pollution and indoor air pollution from cooking emissions. In this scenario, Guangzhou still has the highest NVP with an NVh value of 585 and a PDPH value of 8393, followed by Shanghai with an NVh value of 458 and a PDPH value of 4126. Beijing ranks third with an NVh value of 275 and a PDPH value of 2892. Shenyang and Chengdu have the lowest NVP with NVh values of 211 and 227, respectively, and PDPH values of 1392 and 1310, respectively. The impact of air pollution could reduce NVh by 84–91% and PDPH by 78–95% in the five Chinese cities. Shenyang has the largest reduction rate of PDPH (95%), and Chengdu has the largest reduction rate of NVh (91%). The data analysis reveals that the PDPH in the five Chinese cities is limited, considering both outdoor air pollution and indoor pollution from cooking emissions.

There are four factors considered in comparing the NVP in the five Chinese cities in scenario 3, namely the natural ventilation flow rate, indoor temperature, outdoor air pollution, and indoor pollution from cooking emissions. These factors influence the NVP to varied degrees. According to overall consideration, the main factor causing low NVP in Chengdu is the natural ventilation flow rate. The low NVP in Beijing and Shenyang is mainly due to outdoor air pollution. Indoor air pollution from cooking emissions is the main reason contributing to the low NVP in Guangzhou. The main factors leading to the low NVP in Shanghai are outdoor pollution and indoor pollution from cooking emissions, and these two factors have similar degrees of impact on the NVP in Shanghai.

Through the comparison of the yearly NVP of five Chinese cities in three scenarios, it can be seen that Guangzhou has the highest yearly NVP assessed using PDPH, followed by Shanghai, Beijing, Shenyang, and Chengdu.

4. Conclusions

Previous estimations of NVP using PDPH did not consider the impact of air pollution [20,22]. Some studies proved that the impact of air pollution on natural ventilation is significant [1,28,29]. This research adds air pollution as a constraint in estimating the NVP in China. In this paper, the natural ventilation potential for residential buildings is estimated in five cities located in four different climate regions of China. The yearly NVh and yearly PDPH are calculated in three different scenarios, namely without considering air pollution, considering outdoor air pollution, and considering both outdoor air pollution and indoor pollution from cooking emissions. The results show that Guangzhou has the highest yearly NVP, followed by Shanghai, Beijing, Shenyang, and Chengdu in three scenarios. Aside from Chengdu, the other four cities in China have abundant NVP without considering air pollution. However, air pollution (including outdoor air pollution and indoor air pollution from cooking emissions) contributes to low NVP in all five cities. The impact of air pollution could reduce the annual NVP by 78–95% in China. Worse outdoor air quality causes more NVP loss if the natural ventilation flow rate is high. The key factors causing low NVP in the five cities are different. The natural ventilation flow rate and indoor air pollution from cooking emissions are the main factors in Chengdu and Guangzhou, respectively. The main factor in Beijing and Shenyang is outdoor air pollution. Shanghai is mainly influenced by outdoor air pollution and indoor pollution from cooking emissions to a similar degree.

However, there are still some limitations in this research. Due to a data source constraint, no city in the temperate region was studied, while many cities in southwest China are in the temperate region. There are only five cases in this study. The limited dataset will negatively influence the broad applicability of findings. The issue of $PM_{2.5}$ in other cities might not be as serious as the cases in this research, so the impact of air pollution on NVP might be different from our estimation. Also, this research assumes the buildings are south-oriented. If the other orientations are considered, the NVP will change. This research assumes the buildings are located in an open area of suburbs far from cities. This building model neglects the influence of the surroundings, such as streets and other buildings, while most urban buildings in China are surrounded by streets and buildings. In addition, this building natural ventilation model does not consider the constraints of window open percentage, air velocity, and humidity. This building natural ventilation model combines climate information and thermal characteristics of buildings and requires a powerful computer and much time to simulate. It is less practical and economically viable to estimate NVP by using this method at the beginning of the design stage. In addition, this research only considers the air pollution of $PM_{2.5}$ and neglects other forms of air pollution, such as CO_2. The CO_2 concentration is an important indoor air quality indicator [58,59]. Natural ventilation is necessary to reduce not only cooking emissions but also indoor CO_2 emissions. Despite these limitations mentioned above, this research will help architects and policymakers in the development of natural ventilation strategies. In future research, the NVP of cities in the temperate region will be assessed. Also, more cities should be studied to show the condition of NVP in China. In addition, more constraints will be considered in the development of the building natural ventilation model. Moreover, the impact of other forms of air pollution, such as CO_2, could be investigated.

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References

1. Tong, Z.; Chen, Y.; Malkawi, A.; Liu, Z.; Freeman, R.B. Energy Saving Potential of Natural Ventilation in China: The Impact of Ambient Air Pollution. *Appl. Energy* **2016**, *179*, 660–668. [CrossRef]
2. Zhang, Y.; He, C.Q.; Tang, B.J.; Wei, Y.M. China's Energy Consumption in the Building Sector: A Life Cycle Approach. *Energy Build.* **2015**, *94*, 240–251. [CrossRef]
3. Cao, B.; Zhu, Y.; Li, M.; Ouyang, Q. Individual and District Heating: A Comparison of Residential Heating Modes with an Analysis of Adaptive Thermal Comfort. *Energy Build.* **2014**, *78*, 17–24. [CrossRef]
4. Tsinghua University. *Tsinghua University Annual Report on China Building Energy Efficiency*; Tsinghua University: Beijing, China, 2014.
5. Chua, K.J.; Chou, S.K.; Yang, W.M.; Yan, J. Achieving Better Energy-Efficient Air Conditioning—A Review of Technologies and Strategies. *Appl. Energy* **2013**, *104*, 87–104. [CrossRef]
6. Niachou, K.; Hassid, S.; Santamouris, M.; Livada, I. Experimental Performance Investigation of Natural, Mechanical and Hybrid Ventilation in Urban Environment. *Build. Environ.* **2008**, *43*, 1373–1382. [CrossRef]

7. Wang, Z.; Yi, L.; Gao, F. Night Ventilation Control Strategies in Office Buildings. *Sol. Energy* **2009**, *83*, 1902–1913. [CrossRef]
8. Roisin, B.; Bodart, M.; Deneyer, A.; D'Herdt, P. Lighting Energy Savings in Offices Using Different Control Systems and Their Real Consumption. *Energy Build.* **2008**, *40*, 514–523. [CrossRef]
9. Tariq, R.; Torres-Aguilar, C.E.; Xamán, J.; Zavala-Guillén, I.; Bassam, A.; Ricalde, L.J.; Carvente, O. Digital Twin Models for Optimization and Global Projection of Building-Integrated Solar Chimney. *Build. Environ.* **2022**, *213*, 108807. [CrossRef]
10. Tariq, R.; Torres-Aguilar, C.E.; Sheikh, N.A.; Ahmad, T.; Xamán, J.; Bassam, A. Data Engineering for Digital Twining and Optimization of Naturally Ventilated Solar Façade with Phase Changing Material under Global Projection Scenarios. *Renew. Energy* **2022**, *187*, 1184–1203. [CrossRef]
11. Novoselac, A.; Srebric, J. A Critical Review on the Performance and Design of Combined Cooled Ceiling and Displacement Ventilation Systems. *Energy Build.* **2002**, *34*, 497–509. [CrossRef]
12. Chen, X.; Yang, H.; Lu, L. A Comprehensive Review on Passive Design Approaches in Green Building Rating Tools. *Renew. Sustain. Energy Rev.* **2015**, *50*, 1425–1436. [CrossRef]
13. Ramponi, R.; Gaetani, I.; Angelotti, A. Influence of the Urban Environment on the Effectiveness of Natural Night-Ventilation of an Office Building. *Energy Build.* **2014**, *78*, 24–34. [CrossRef]
14. Ben-David, T.; Waring, M.S. Impact of Natural versus Mechanical Ventilation on Simulated Indoor Air Quality and Energy Consumption in Offices in Fourteen U.S. Cities. *Build. Environ.* **2016**, *104*, 320–336. [CrossRef]
15. Shi, J.; Zhao, C.; Liu, Y. CFD Analysis of Building Cross-Ventilation with Different Angled Gable Roofs and Opening Locations. *Buildings* **2023**, *13*, 2716. [CrossRef]
16. Zheng, Y.; Miao, J.; Yu, H.; Liu, F.; Cai, Q. Thermal Analysis of Air-Cooled Channels of Different Sizes in Naturally Ventilated Photovoltaic Wall Panels. *Buildings* **2023**, *13*, 3002. [CrossRef]
17. Sujatha, P.; Mahalakshmi, D.V.; Ramiz, A.; Rao, P.V.N.; Naidu, C.V.; Wang, Z. Ventilation Coefficient and Boundary Layer Height Impact on Urban Air Quality. *Cogent Environ. Sci.* **2016**, *2*, 1125284. [CrossRef]
18. King, D. Natural Ventilation. *Technical* **2009**, *19*, 47–48.
19. Walker, A. Natural Ventilation. Whole Building Design Guide. 2010. Available online: https://www.wbdg.org/resources/natural-ventilation?r=env_wall (accessed on 25 November 2023).
20. Yang, L.; Zhang, G.; Li, Y.; Chen, Y. Investigating Potential of Natural Driving Forces for Ventilation in Four Major Cities in China. *Build. Environ.* **2005**, *40*, 738–746. [CrossRef]
21. Sun, X.; Zhou, J.; Shen, W.; Peng, C.; Zhang, G.; Zhang, L. Estimating Natural-Ventilation Potential Considering Thermal Mass. In Proceedings of the 2010 International Conference on Digital Manufacturing & Automation, ICDMA 2010, Changcha, China, 18–20 December 2010; Volume 1, pp. 666–669. [CrossRef]
22. Luo, Z.; Zhao, J.; Gao, J.; He, L. Estimating Natural-Ventilation Potential Considering Both Thermal Comfort and IAQ Issues. *Build. Environ.* **2007**, *42*, 2289–2298. [CrossRef]
23. Roulet, C.; Germano, M.; Allard, F. Potential for Natural Ventilation in Urban Context: An Assessment Method. *Proc. Indoor Air* **2002**, *2*, 830–835.
24. Germano, M.; Roulet, C.A. Multicriteria Assessment of Natural Ventilation Potential. *Sol. Energy* **2006**, *80*, 393–401. [CrossRef]
25. Axley, J.W.; Emmerich, S.J. A Method to Assess the Suitability of a Climate for Natural Ventilation of Commercial Buildings. In *Indoor Air 2002: Proceedings of the 9th International Conference on Indoor Air Quality and Climate, Monterey, CA, USA, 30 June–5 July 2002*; National Institute of Standards and Technology: Gaithersburg, MD, USA, 2002; Volume 2, pp. 854–859.
26. Causone, F. Climatic Potential for Natural Ventilation. *Archit. Sci. Rev.* **2016**, *59*, 212–228. [CrossRef]
27. Tong, Z.; Chen, Y.; Malkawi, A. Estimating Natural Ventilation Potential for High-Rise Buildings Considering Boundary Layer Meteorology. *Appl. Energy* **2017**, *193*, 276–286. [CrossRef]
28. Martins, N.R.; Carrilho da Graça, G. Simulation of the Effect of Fine Particle Pollution on the Potential for Natural Ventilation of Non-Domestic Buildings in European Cities. *Build. Environ.* **2017**, *115*, 236–250. [CrossRef]
29. Martins, N.R.; Carrilho da Graça, G. Impact of Outdoor $PM_{2.5}$ on Natural Ventilation Usability in California's Nondomestic Buildings. *Appl. Energy* **2017**, *189*, 711–724. [CrossRef]
30. Ghiaus, C.; Allard, F. Assessment of Natural Ventilation Potential of a Region Using Degree-Hours Estimated on Global Weather Data. In Proceedings of the Conference on EPIC2002, Lyon, France, 23–26 October 2002.
31. Haase, M.; Amato, A. An Investigation of the Potential for Natural Ventilation and Building Orientation to Achieve Thermal Comfort in Warm and Humid Climates. *Sol. Energy* **2009**, *83*, 389–399. [CrossRef]
32. Chiesa, G.; Grosso, M. Geo-Climatic Applicability of Natural Ventilative Cooling in the Mediterranean Area. *Energy Build.* **2015**, *107*, 376–391. [CrossRef]
33. Yin, W.; Zhang, G.; Wang, X.; Liu, J.; Xia, S. Potential Model for Single-Sided Naturally Ventilated Buildings in China. *Sol. Energy* **2010**, *84*, 1595–1600. [CrossRef]
34. Yin, W.; Zhang, G.; Yang, W.; Wang, X. Natural Ventilation Potential Model Considering Solution Multiplicity, Window Opening Percentage, Air Velocity and Humidity in China. *Build. Environ.* **2010**, *45*, 338–344. [CrossRef]
35. Pope, A.C.; Burnett, R.T.; Krewski, D.; Jerrett, M.; Shi, Y.; Calle, E.E.; Thun, M.J. Cardiovascular Mortality and Exposure to Airborne Fine Particulate Matter and Cigarette Smoke Shape of the Exposure-Response Relationship. *Circulation* **2009**, *120*, 941–948. [CrossRef]

36. Künzli, N.; Kaiser, R.; Medina, S.; Studnicka, M.; Chanel, O.; Filliger, P.; Herry, M.; Horak, F.; Puybonnieux-Texier, V.; Quénel, P.; et al. Public-Health Impact of Outdoor and Traffic-Related Air Pollution: A European Assessment. *Lancet* **2000**, *356*, 795–801. [CrossRef]
37. YAMAMOTO, Y.; TANABE, S. The Criteria of Outdoor Conditions for Operating Natural Ventilation Openings. *J. Environ. Eng. (Transactions AIJ)* **2016**, *81*, 375–384. [CrossRef]
38. Chen, J.; Brager, G.S.; Augenbroe, G.; Song, X. Impact of Outdoor Air Quality on the Natural Ventilation Usage of Commercial Buildings in the US. *Appl. Energy* **2019**, *235*, 673–684. [CrossRef]
39. Zhang, Y.-L.; Cao, F. Fine Particulate Matter (PM 2.5) in China at a City Level. *Sci. Rep.* **2015**, *5*, 14884. [CrossRef]
40. Quang, T.N.; He, C.; Morawska, L.; Knibbs, L.D. Influence of Ventilation and Filtration on Indoor Particle Concentrations in Urban Office Buildings. *Atmos. Environ.* **2013**, *79*, 41–52. [CrossRef]
41. Li, Y.; Delsante, A. Natural Ventilation Induced by Combined Wind and Thermal Forces. *Build. Environ.* **2001**, *36*, 59–71. [CrossRef]
42. Richard, J.D.D.; Gail, S.B. Thermal Comfort in Naturally Ventilated Buildings: Revisions to ASHRAE Standard 55. *Energy Build.* **2002**, *34*, 549–561.
43. Song, X.; Yang, L.; Zheng, W.; Ren, Y.; Lin, Y. Analysis on Human Adaptive Levels in Different Kinds of Indoor Thermal Environment. *Procedia Eng.* **2015**, *121*, 151–157. [CrossRef]
44. Lei, Y.; Lin, Z.; Xiao, F. Natural Ventilation Potential Analysis of Rural Residential Buildings in China. In Proceedings of the 2011 International Conference on Electric Information and Control Engineering, Wuhan, China, 15–17 April 2011; pp. 4292–4297.
45. Su, X.; Zhang, X.; Gao, J. Evaluation Method of Natural Ventilation System Based on Thermal Comfort in China. *Energy Build.* **2009**, *41*, 67–70. [CrossRef]
46. Gao, J.; Cao, C.; Wang, L.; Song, T.; Zhou, X.; Yang, J.; Zhang, X. Determination of Size-Dependent Source Emission Rate of Cooking-Generated Aerosol Particles at the Oil-Heating Stage in an Experimental Kitchen. *Aerosol Air Qual. Res.* **2013**, *13*, 488–496. [CrossRef]
47. Fang, D.; Wang, Q.; Li, H.; Yu, Y.; Lu, Y.; Qian, X. Mortality Effects Assessment of Ambient $PM_{2.5}$ Pollution in the 74 Leading Cities of China. *Sci. Total Environ.* **2016**, *569–570*, 1545–1552. [CrossRef]
48. Song, C.; He, J.; Wu, L.; Jin, T.; Chen, X.; Li, R.; Ren, P.; Zhang, L.; Mao, H. Health Burden Attributable to Ambient $PM_{2.5}$ in China. *Environ. Pollut.* **2017**, *223*, 575–586. [CrossRef]
49. ASHRAE. Ventilation and Acceptable Indoor Air Quality. 2016. Available online: https://static1.squarespace.com/static/6320b844c3820725e4d5688f/t/6372af076022e56f815dc7f5/1668460297956/ASHRAE+62.1-2022+(1).pdf (accessed on 25 November 2023).
50. World Health Organization WHO. *Air Quality Guidelines for Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide: Global Update 2005: Summary of Risk Assessment*; WHO: Geneva, Switzerland, 2006; Volume 22, pp. 2070–2071. [CrossRef]
51. Turner, W.J.N.; Logue, J.M.; Wray, C.P. A Combined Energy and IAQ Assessment of the Potential Value of Commissioning Residential Mechanical Ventilation Systems. *Build. Environ.* **2013**, *60*, 194–201. [CrossRef]
52. Yuan, Y.; Luo, Z.; Liu, J.; Wang, Y.; Lin, Y. Health and Economic Benefits of Building Ventilation Interventions for Reducing Indoor $PM_{2.5}$ Exposure from Both Indoor and Outdoor Origins in Urban Beijing, China. *Sci. Total Environ.* **2018**, *626*, 546–554. [CrossRef]
53. Chen, Z.; Chen, C.; Wei, S.; Wu, Y.; Wang, Y.; Wan, Y. Impact of the External Window Crack Structure on Indoor $PM_{2.5}$ Mass Concentration. *Build. Environ.* **2016**, *108*, 240–251. [CrossRef]
54. He, C.; Morawska, L.; Gilbert, D. Particle Deposition Rates in Residential Houses. *Atmos. Environ.* **2005**, *39*, 3891–3899. [CrossRef]
55. Özkaynak, H.; Xue, J.; Spengler, J.; Wallace, L.; Pellizzari, E.; Jenkins, P. Personal Exposure to Airborne Particles and Metals: Results from the Particle Team Study in Riverside, California. *J. Expo. Anal. Environ. Epidemiol.* **1996**, *6*, 57–78.
56. EnergyPlus Weather Data. Available online: https://energyplus.net/weather (accessed on 10 April 2023).
57. U.S. Department of State Air Quality Monitoring Program StateAir. Available online: http://www.stateair.net/ (accessed on 20 April 2022).
58. Sánchez-Fernández, A.; Coll-Aliaga, E.; Lerma-Arce, V.; Lorenzo-Sáez, E. Evaluation of Different Natural Ventilation Strategies by Monitoring the Indoor Air Quality Using CO_2 Sensors. *Int. J. Environ. Res. Public Health* **2023**, *20*, 6757. [CrossRef]
59. Stabile, L.; Dell'Isola, M.; Russi, A.; Massimo, A.; Buonanno, G. The Effect of Natural Ventilation Strategy on Indoor Air Quality in Schools. *Sci. Total Environ.* **2017**, *595*, 894–902. [CrossRef]

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