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Investigating natural ventilation potentials across the globe: Regional and climatic variations

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A B S T R A C T

Natural ventilation (NV) that reduces building energy consumption and improves indoor environment has become a key solution to achieving sustainability in the building industry. The potential for utilizing NV strategies depends greatly on the local climate, which varies widely from region to region in the world. In this study, we estimated the NV potentials of 1854 locations around the world by calculating the NV hour. Energy saving potentials of the world's 60 largest cities were calculated with Building Energy Simulation (BES). We demonstrated that NV hour derived from outdoor meteorological data can measure maximum energy saving potential of NV without conducting detailed BES. Our analysis shows the subtropical highland climate, found in South-Central Mexico, Ethiopian Highland, and Southwest China, is most favorable for NV, because spring-like weather occurs all year with little variation in temperature and almost no snowfall. Another climate where NV can be beneficial is the Mediterranean climate, which occurs not only near the Mediterranean Sea, but also in California, Western Australia, Portugal, and Central Chile. In certain regions with desert climate and large diurnal temperature range such as the Middle East and Central Australia, greater-than-expected NV hours are observed due to significant potential of night-purge ventilation. Countries in Southeast Asia, e.g., Singapore and Malaysia, are shown to have little to no NV potential as a result of hot and humid weather all year. These findings provide valuable guidelines for architects and policy makers around the world to effectively utilize NV designs that meet local climatic conditions.

1. Introduction

It is estimated by the United Nations that more than two thirds of the world's population will live in cities by 2050 [1]. Such rapid urbanization has led to significant increase in the energy consumption of buildings due mostly to population growth, climate change, and increased demand for thermal comfort [2–4]. Studies have shown that the building sector accounts for 23–47% of total primary energy consumption in developed and developing countries worldwide [5–11]. Given this enormous energy consumption, many advanced technologies have been developed to achieve high building energy efficiency [6,12–24]. Among them, natural ventilation (NV), which supplies and removes air to and from an indoor space using natural forces of wind and buoyancy, shows great potential to reduce the energy required for cooling and ventilating buildings while still provide acceptable indoor environmental quality [25–34]. To help realize the potential benefits of natural ventilation, a variety of design elements such as solar chimneys, wind towers, and double-skin façades are often used to promote wind or buoyancy driven air movement. In addition to “pure” natural ventilation that is often constrained due to building type and climate suitability, mixed-mode ventilation (i.e., using natural ventilation for periods when the external weather conditions are allowed, but mechanical ventilation takes over when external weather conditions are not suitable) has been proven as a practical and reliable solution for buildings that aim to incorporate NV principles [35].

The design strategy for buildings with natural ventilation systems relies heavily on the characteristics of local climate, which varies considerably from region to region across the globe. Researchers in the past have investigated various aspects with regard to naturally ventilated buildings across different climate zones in the world. Table 1 summarizes existing studies on natural

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ventilation by location. For example, Yang et al. [36] developed a simple prediction model for natural ventilation potential in Chinese residential buildings, and introduced pressure difference Pascal hours (PDPH) as a metric to predict NV potential. Yao et al. [37] investigated the natural ventilation cooling potential of office buildings in five climate zones of China using the Thermal Resistance Ventilation model, and demonstrated that the NV cooling potential depends on climate, building thermal characteristics and internal gains. Tong et al. [6] quantified the energy saving potential of natural ventilation at 35 major Chinese cities, considering the impact of ambient air pollution, in which they introduced the methodology for estimating NV hours defined as the number of suitable hours for using natural ventilation per year. Tantasavasdi et al. [38] conducted a study in Bangkok, Thailand, suggesting that natural ventilation can provide a thermally comfortable indoor environment for 20% of the year. The natural ventilation threshold for indoor air velocity was derived from the climate and thermal comfort analysis. Calautit et al. [39], Bahadori [40], and Bouchahm et al. [41] discussed the physics behind the design of wind towers, and how they are utilized to improve natural ventilation in the Middle East and North Africa, both of which have an arid and hot desert climate. Artmann et al. [42] evaluated the passive cooling of buildings by night-time ventilation by analyzing climatic data at 259 stations in Europe. Their results showed a high potential for night-time natural ventilation cooling potential over Northern Europe and significant potential in Central and Eastern Europe, and certain areas in Southern Europe. Oropeza-Perez and Ostergaard [43] estimated the natural ventilation potential in Denmark, showing that 90% of the hours for which mechanical ventilation was used can be potentially reduced through the use of natural ventilation during summer. Van Hooff and Blocken [44,45] introduced a coupled CFD (Computational Fluid Dynamics) modeling approach for urban wind flow and indoor natural ventilation, and applied it to study a large semi-enclosed stadium in Netherlands. They demonstrated the importance of meteorological conditions and surrounding urban environment for natural ventilation analysis at building-scale. Hiyama and Glicksman [46] presented target air change rate as a desired criterion for designing buildings with natural ventilation, and provided maps of target air change rate of 60 cities in the United States. Tong et al. [47] estimated NV potential for high-rise buildings in major cities from six climate zones in the United States. An in-house boundary-layer meteorology model was developed to quantify the effect of atmospheric stability on the vertical structure of NV potential for high rises. Cândido et al. [48] proposed guidelines for naturally ventilated buildings in Brazil that consider occupants' adaptive potential as well as thermal and air movement acceptability. The guidelines were based on results from field experiments in different climatic zones and existing studies. Deuble and de Dear [49] investigated the effect of mixed-mode ventilation on occupant comfort in an academic office building using 1359 subjective comfort questionnaires in Sydney, Australia. Their findings suggested that the building's mode of operation such as air-conditioned and naturally-ventilated modes has a greater impact on thermal perceptions than the objective indoor climate conditions.

Existing studies focus largely on natural ventilation systems at a specific region in the world. The regional variations in natural ventilation potentials have never been investigated from a global perspective. Building ventilation strategies are highly dependent on climatic conditions at the location of interest. As climate varies from region to region in the world, it is critical to understand the variation between regions in order to utilize natural ventilation more effectively. Our objective is to assist policy makers and architects in recognizing quantitatively the natural ventilation potentials at various regions and climates around the world, and in properly developing sustainable strategies considering local climatic characteristics.

In this study, we have provided an early effort to estimate, visualize, and understand regional natural ventilation potentials by analyzing available climate data at 1854 locations from six continents (Africa, Asia, Europe, North America, Oceania, and South America). Energy savings potentials of the world's 60 largest cities

Table 1
Summary of past studies on natural ventilation sorted by method and location.

Author and Year	Location	Method	Ref.
Yang et al. (2005)	China	Simulation	[36]
Luo et al. (2007)	China	Simulation	[50]
Yao et al. (2009)	China	Simulation	[37]
Yin et al. (2010)	China	Simulation	[51]
Tong et al. (2016)	China	Simulation	[6]
Indraganti (2010)	India	Survey & experiment	[52]
Tantasavasdi et al. (2001)	Thailand	Simulation	[38]
Liping et al. (2007)	Singapore	Data analysis	[53]
Kubota (2009)	Malaysia	Survey & Experiment	[54]
Bahadori et al. (1994)	Middle East	N/A Review	[40]
Ayata et al. (2006, 2007)	Middle East	Simulation	[55,63]
Calautit et al. (2013)	Middle East	Simulation	[39]
Mathews (1986)	South Africa	Simulation & Experiment	[56]
Bouchahm (2011)	Algeria	Simulation & Experiment	[41]
Artmann et al. (2007)	Europe	Data analysis	[42]
Kolokotroni and Aronis (1999)	U·K.	Simulation	[57]
Pasquay (2004)	Germany	Experiment	[58]
van Hooff and Blocken (2010)	Netherlands	Simulation & Experiment	[44,45]
Oropeza-Pereza and Østergaardb (2014)	Denmark	Simulation	[43]
Germano (2007)	Switzerland	Data analysis	[59]
Ballestinia et al. (2005)	Italy	Simulation	[60]
Santamouris et al. (2008, 2010)	Greece	Experiment & Simulation	[61,62]
Hiyama and Glicksman (2015)	U.S..	Simulation	[46]
Dutton et al. (2013)	U.S.	Experiment	[64]
Malkawi et al. (2016)	U.S..	Simulation	[13]
Tong et al. (2017)	U.S..	Simulation	[47]
Oropeza-Pereza and Østergaardb (2014)	Mexico	Simulation	[65]
Cândido et al. (2011)	Brazil	Experiment & Survey	[48]
Deuble and de Dear (2012)	Australia	Experiment & Survey	[49]

were calculated using Building Energy Simulation (BES). The paper is organized as follows. We first describe our methodology with regard to climate data, natural ventilation potentials, and BES. Next, we present and discuss the results by different regions in the world, followed by a summary of key findings at the end.

2. Methodology

2.1. Global climatic classification and data sources

Climate varies greatly over the Earth's surface. It is assessed by patterns of variations in temperature, humidity, atmospheric pressure, wind, precipitation, and other meteorological parameters at any given location over long periods. The typical meteorological year data of 1854 locations worldwide were used in this study, which are derived from several sources as follows. Typical Meteorological Year 3 (TMY3) data are available for locations in the U.S. derived from a 1991–2005 period of record. TMY3 represent typical rather than extreme condition, in the format of hourly values of meteorological elements for a one-year period. Solar and Wind Energy Resource Assessment (SWERA), funded by the United Nations Environment Program, includes typical year hourly data for 156 locations in Belize, Brazil, Cuba, El Salvador, Ethiopia, Ghana, Guatemala, Honduras, Kenya, Maldives, Nicaragua, and Sri Lanka. International Weather for Energy Calculations (IWEC) comprises typical weather files suitable for use with building energy simulation programs for 227 locations outside the U.S. and Canada. The files are derived from up to 18 years (1982–1999 for most stations) of hourly weather data. Chinese Standard Weather Data (CSWD) includes 269 typical hourly weather files developed by Tsinghua University and China Meteorological Bureau. In many parts of the world especially Africa and South America, meteorological data are unavailable. Combining surface and satellite-derived meteorological measurements could be a promising means to overcome this issue and develop natural ventilation maps with global coverage. This is subject to future study.

Current energy codes and standards contain numerous requirements based on global climate classification. Köppen-Geiger classification is one of the most widely used climate classification based on temperature and precipitation indices [66], which divides the world climate into five major groups, namely, tropical, arid, temperate, continental, and polar. Each major group is subcategorized into different types and subtypes. The climate designations from the Köppen-Geiger system are descriptive, and thus used here to describe the climatic variation around the world. For the BES, we employed a statistical climate classification scheme introduced by Briggs et al. in ASHRAE Standard 169–2006 [67,68], which is based on grouping of mutual similarities from different locations. Table 2 shows the climate zone classficiations according to ASHRAE Standard 90.1–2007 based on cooling degree days (CDD) and heating degree days (HDD).

2.2. Definition of NV hour

The NV hour is employed as an indicator to measure the maximum natural ventilation potentials for each location. It is defined as the number of hours in a typical year (out of 8760 h) when outdoor weather condition (e.g., wind speed, temperature, humidity) is suitable for utilizing natural ventilation. Since NV hour is derived from outdoor meteorological data alone, it measures the maximum number of hours when the outdoor weather is favorable for natural ventilation. Mechanical ventilation can take place during NV hours if natural ventilation alone cannot meet satisfactory thermal comfort due to high building internal load. Detailed methodologies regarding NV hour can be seen in previous studies [6,13,47]. A brief review is presented here. Instead of using a fixed upper temperature threshold throughout the year, we employed the adaptive comfort model proposed by de Dear and Brager (2002), which is based on the idea that outdoor climate affects indoor comfort because humans can adapt to various temperatures during different times of the year. The upper threshold of temperature T_{up} varies by month, and is calculated according to Eqn. (1) where T_{out} is the monthly average outdoor temperature determined from TMY weather data. ΔT is the mean comfort zone temperature band. For 80% acceptability, $\Delta T_{80\%}$ is equal to 7 °C. The temperature thresholds are chosen when the outdoor dry-bulb temperature is below the upper threshold, T_{up} and greater than $T_{low} =$ 12.8 °C (the lowest supply air temperature specified in ASHRAE 55 and ASHRAE Handbook—Fundamentals to avoid unpleasant draft to occupants) [13]. The upper threshold for dew point temperature is 17 °C for the sake of humidity control by combining the ASHRAE winter and summer comfort zones [46,69].

$$T_{up} = 0.31T_{out} + 17.8 + \frac{1}{2}\Delta T_{80\%} \tag{1}$$

The maximum allowable indoor air velocity, $u_{in,max}$, is chosen at 0.8 m/s, according to ASHRAE Standard 55 [70]. The corresponding outdoor wind velocity, u_{out}, is calculated based on an empirical relationship Eqn (2) developed by Phaff et al. [71], which takes into account the combined effect of wind, temperature, and turbulence on natural ventilation.

$$u_{in,max} = \sqrt{C_1 u_{out,up}^2 + C_2 h \Delta T_{max} + C_3} \tag{2}$$

where h is the vertical height of the opening; ΔT_{max} is the hourly maximum temperature difference between the outdoor temperature and indoor temperature during NV hours. Here, we approximated ΔT_{max} by taking the difference between the upper temperature threshold T_{up} determined from the adaptive comfort model and the lowest supply air temperature T_{low}; C_1 is the wind speed coefficient; C_2 is the buoyancy coefficient, and C_3 is the turbulence coefficient. Their values are determined from the study by Phaff et al. [71], in which $C_1 = 0.001$, $C_2 = 0.0035$ $[\mathrm{m \cdot s^{-2} \cdot K^{-1}}]$, and $C_3 = 0.01$ $[\mathrm{m^2 \cdot s^{-2}}]$. The outdoor wind velocity threshold $u_{out,up}$ is then calculated by solving Eqn. (2) for $u_{out,up}$. The vertical variation of wind speed as a function of height is not considered here due to lack of certain meteorological data (e.g., surface roughness length, atmospheric stability, and upper air weather data) at many cities across the world. Although NV hour is independent of building type and does not take into account building-scale details, it provides valuable information to conveniently assist architects and energy policy makers in evaluating the feasibility of using natural ventilation at a large scale without conducting building energy simulation for each building at the early design stage.

2.3. Building energy simulation (BES)

The energy savings potential of office buildings in the world's 60 largest cities among the 1854 stations were estimated using EnergyPlus, a validated and physics-based BES program developed by U.S. Department of Energy [72]. A brief model description is shown here. The core of the model is based on fundamental heat balance principle. The energy balances at each zone is described in Eqn. (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

Table 2
International climate zone definitions according to ASHRAE standard 90.1–2007.

Zone Number	Zone Name	Thermal Criteria (SI Units)
1A and 1B	Very Hot – Humid (1A) Dry (1B)	5000 < CDD10 °C
2A and 2B	Hot-Humid (2A) Dry (2B)	3500 < CDD10 °C ≤ 5000
3A and 3B	Warm – Humid (3A) Dry (3B)	2500 < CDD10 °C ≤ 3500
3C	Warm – Marine (3C)	CDD10 °C ≤ 2500 AND HDD 18 °C ≤ 2000
4A and 4B	Mixed-Humid (4A) Dry (4B)	CDD10 °C ≤ 2500 AND HDD 18 °C ≤ 3000
4C	Mixed – Marine (4C)	2000 < HDD18 °C ≤ 3000
5A, 5B, and 5C	Cool-Humid (5A) Dry (5B) Marine (5C)	3000 < HDD18 °C ≤ 4000
6A and 6B	Cold – Humid (6A) Dry (6B)	4000 < HDD18 °C ≤ 5000
7	Very Cold	5000 < HDD18 °C ≤ 7000
8	Subarctic	7000 < HDD18 °C

the zone. 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 natural ventilation (W) and equal to $\rho c_p \dot{V}_{nv}(T_{int} - T_{out})$ where $\dot{V}_{nv}$ is the rate of natural ventilation (m^3/s) as a function of wind and thermal stack effects given in Eqn. (4).

$$\dot{V}_{nv} = \sqrt{\left(\dot{V}_{wind}\right)^2 + \left(\dot{V}_{stack}\right)^2} \tag{4}$$

The wind-drive ventilation rate $\dot{V}_{wind}$ in m^3/s is given by Eqn. (5) according to the ASHRAE Handbook–Fundamentals [69].

$$\dot{V}_{wind} = C_w A_{opening} F_{schedule} u \tag{5}$$

u is local wind speed. $A_{opening}$ is the opening area. $F_{schedule}$ is a schedule value ranging from 0 to 1, used here to indicate the fraction of windows that are opened. C_w is the opening effectiveness. On the other hand, the ventilation rate (m^3/s) due to stack effect is described in Eqn. (6).

$$\dot{V}_{stack} = C_D A_{opening} F_{schedule} \sqrt{2g \Delta H_{NPL} \frac{|T_{int} - T_{out}|}{T_{int}}} \tag{6}$$

C_D is the discharge coefficient for opening, determined using Eqn. (7) from ASHRAE Handbook–Fundamentals [69]. ΔH_{NPL} is the height (m) from the midpoint of the lower opening to the neutral pressure level.

$$C_D = 0.4 + 0.0025|T_{int} - T_{out}| \tag{7}$$

In our EnergyPlus model, a three-story office building with a gross floor area of 4982 m^2 was chosen from the U.S. Department of Energy (DOE) commercial reference building database [73], which represents realistic building characteristics and construction practices. The thermal characteristics (e.g., U factor) of the building envelope in each climate zone are shown in Table 3 according to IECC (International Energy Conservation Code) 2009 [74].

The modeled office building is assumed to be served by a variable air volume (VAV) system, which is commonly utilized in newly developed office buildings with large square footage. Economizer operation is not modeled. In addition to VAV system, we conducted simulations for other type of HVAC system such as FCU (Fan Coil Unit) in 20 cities from various climate zones. The differences in energy saving percentage from natural ventilation between VAV and FCU systems are within 6%, although the energy consumptions are very different. The total cooling energy consumption investigated also includes those from auxiliary systems such as fans and pumps. The overall window-to-wall ratio is set at 33%. The plug load is 10.76 W/m^2 and lighting power density is 10.76 W/m^2. The fresh air rate is set as 10 L/s-person. The cooling and heating setpoint temperatures for mechanical ventilation are 24 °C and 21 °C, respectively. The operation schedule of HVAC system is set as 7:00–22:00 from Monday to Friday. The coefficient of performance (COP) in the simulation complies with IECC Standard. The building is assumed to operate under mixed-mode ventilation, in which natural ventilation is utilized for periods when the external weather conditions are allowed, but mechanical ventilation takes over when external weather conditions are not suitable. The mixed-mode operation was simulated using Energy Management System (EMS) in EnergyPlus. At each simulation time step, the program check the indoor mean air temperature, outdoor dry-bulb temperature, outdoor dew point temperature and wind speed to see if the outdoor condition is suitable for natural ventilation, and if the natural ventilation alone can provide sufficient indoor thermal comfort. If all requirements are met, windows will be open and HVAC will shut down. In the next time step, if any of the requirements is not met, the windows will be closed and HVAC will turn on. The thermal comfort thresholds for natural ventilation are determined according to the adaptive thermal comfort model established by de Dear and Brager [75].

3. Results and discussion

Climate has a significant impact on the energy usage of most commercial and residential buildings. The local climate is influenced by a variety of factors, including latitude, elevation, ocean currents, topography, vegetation, prevailing winds, etc. Here, the

Table 3
U-factor of buildings in different climate zones according to IECC 2009.

Climate Zone	Fenestration	Skylight	Roofs	External Wall	Floor	Basement Wall
1	U-0.50	U-0.75	U-0.048	U-0.142	U-0.322	C-1.140
2	U-0.50	U-0.65	U-0.048	U-0.142	U-0.107	C-1.140
3	U-0.46	U-0.55	U-0.048	U-0.110	U-0.076	C-1.140
4 except 4C	U-0.38	U-0.50	U-0.039	U-0.104	U-0.076	C-0.119
5 and 4C	U-0.38	U-0.50	U-0.039	U-0.078	U-0.074	C-0.119
6	U-0.36	U-0.50	U-0.032	U-0.078	U-0.064	C-0.119
7 and 8	U-0.29	U-0.50	U-0.028	U-0.061	U-0.055	C-0.092

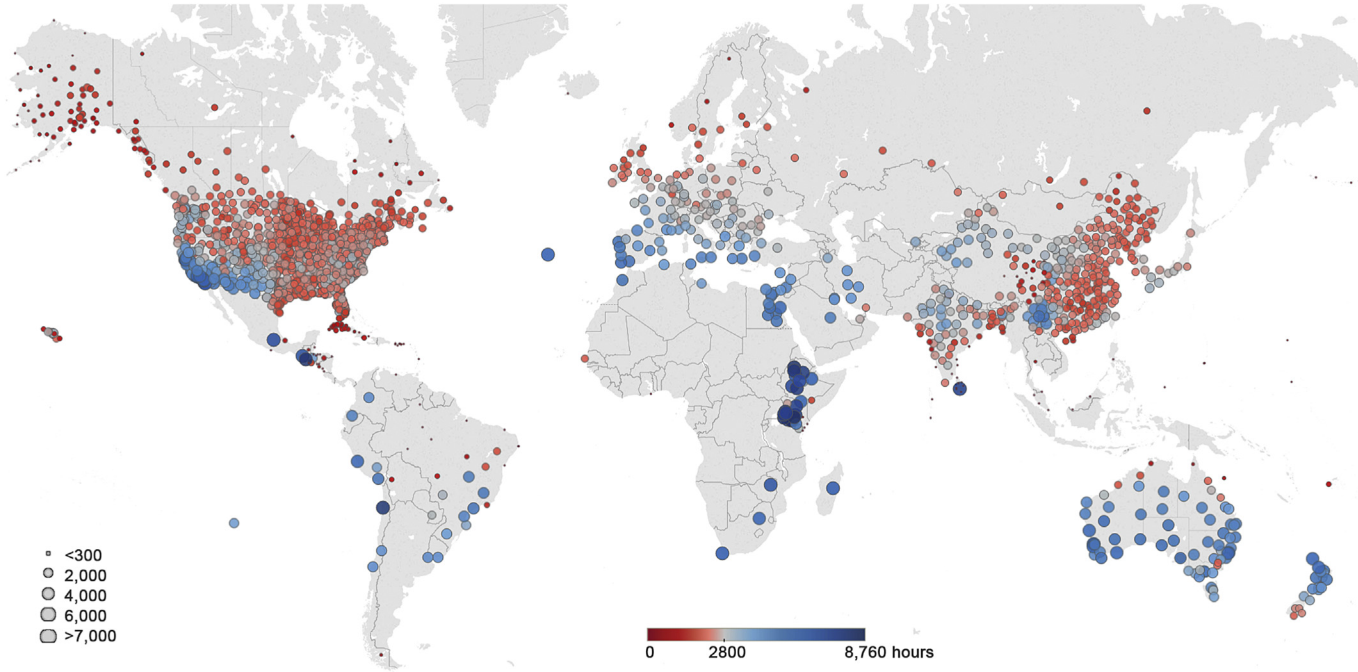

Fig. 1. Geographic map of NV hours in 1854 locations.

first part discusses the natural ventilation potentials from various regions across six continents using NV hour. The second part shows the energy savings calculated with BES from using natural ventilation in the world's 60 largest cities.

3.1. Global natural ventilation potentials

Globally, many regions are found with great potential for utilizing natural ventilation Fig. 1. In particular, the subtropical highland climate, in which spring-like weather occurs year-round with little variation in temperature and almost no snowfall, shows a significantly large amount of NV hours. This climate type exists in Mexico City, Mexico (7161 h); Nairobi, Kenya (8435 h); Bahir Dar, Ethiopia (8136 h), and Kunming, China (5566 h). The other climate that is favorable for utilizing natural ventilation is the Mediterranean climate. It is found not only around the Mediterranean Sea, but also in California, Western Australia, Portugal, and Central Chile. Representative cities include Los Angeles, California (7197 h); Perth, Australia (6094 h); Faro, Portugal (5673 h); and Antofagasta, Chile (8204 h). In addition, cities in the desert climate display greater-than-expected natural ventilation potentials, ranging from 3000 to 4000 NV hours. Although it is hot during summer days, the temperature drops considerably at night due to radiation loss under clear skies. As a result, night-purge ventilation can be largely employed in these regions including the Middle East, Central Australia, and Egypt. Another explanation is the use of the adaptive thermal comfort model that is based on the theory that humans can adapt to different temperatures during different times of the year [75]. Raising the upper temperature threshold by a few degrees could result in significant increases in the amount of NV hours. However, this increase varies from region to region. The additional NV hours gained by using the adaptive thermal comfort model is shown in Fig. 2. Cities in the polar climate zone show almost no increase, while cities associated with desert and semi-arid climates (e.g., Central Australia, Central East Africa, Middle East) display large increases in NV hours over 1000. The histogram of global NV hour distribution at 1854 studied locations is shown in Fig. 3a. The distribution is left-skewed with a peak at around 2500 NV hours. The right tail goes all the way up to 8565 h, and the left tail goes down to zero. Among studied locations, the median number of NV hours is 2598 h with a standard deviation of 1296 h. There are 108 locations (6%) with NV hours greater than 5000, and 44 locations (2.5%) with less than 100 NV hours, such as Kuala Lumpur, Malaysia and Salvador, Brazil.

Boxplots of NV hours at each continent is presented in Fig. 3b. Africa is not plotted due to the lack of sufficient climate data in many African countries. Cities in Oceania show the largest natural ventilation potentials with a median NV hours of 4630. Due to the diverse climate, cities in South America display the widest range of NV hours from nearly zero in the Amazon Rainforest to over 8000 NV hours in Central Chile. The distribution of NV hours in Asia and North America shares many similarities with median NV hours both around 2500 as a result of similar latitude. In general, cities in Europe have slightly greater NV hours (the median is 3002) than Asia and North America, as Europe mostly lies in temperate climate zone.

3.1.1. Africa

Africa mostly lies in the intertropical climate zone. A variety of warm and hot climates prevails over the whole continent except the northernmost, and the southernmost fringes, and in places at very high elevations. Many parts of Africa show considerable amounts of NV hours, especially those with a Mediterranean climate (dry summers and mild winters). For example, Bahir Dar in Ethiopia is estimated to have 8136 NV hours, and Nairobi, Kenya 8435 NV hours. Cape Town in South Africa (southernmost fringe) is estimated to have 6477 NV hours.

3.1.1.1. Egypt. In general, Egypt has a desert climate. The climate is moderate along the coast, while temperature can exceed 40 °C in the summer of the central and southern part of the country. Cairo has 4886 NV hours, and Alexandria has 4739 NV hours.

3.1.1.2. Kenya. The climate in Kenya varies from a tropical climate

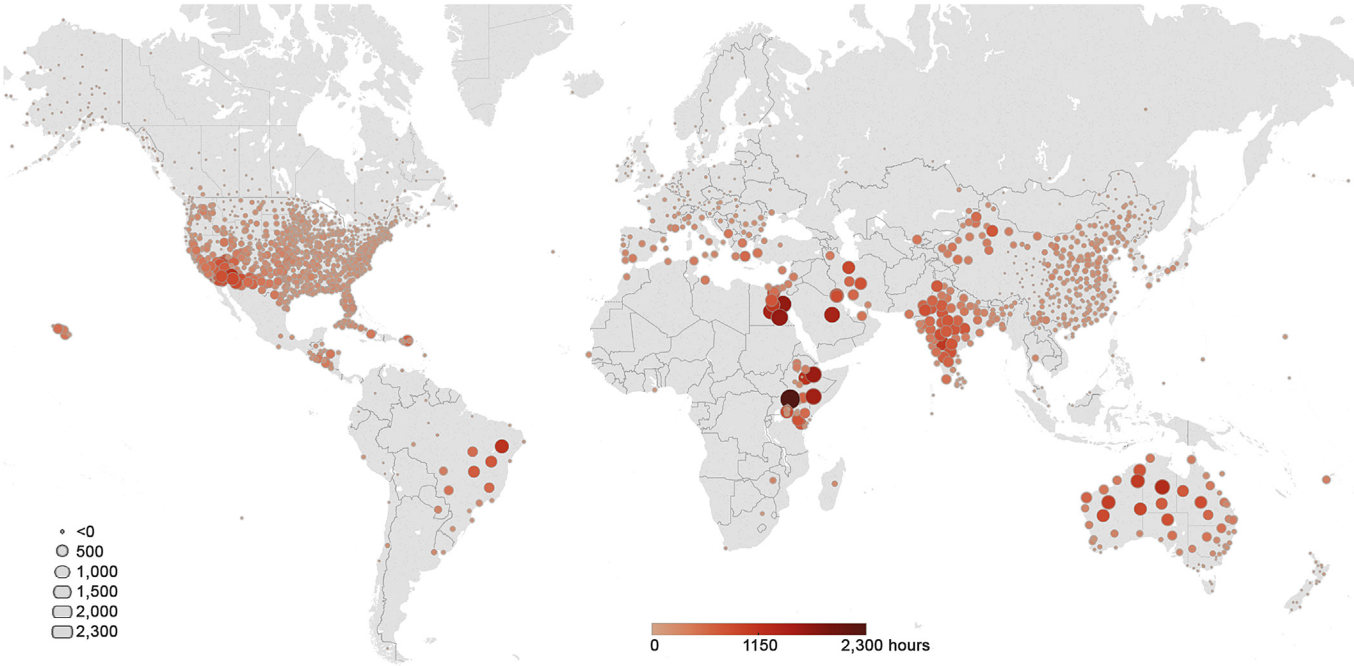

Fig. 2. Geographic map of additional NV hours gained by using adaptive thermal comfort model.

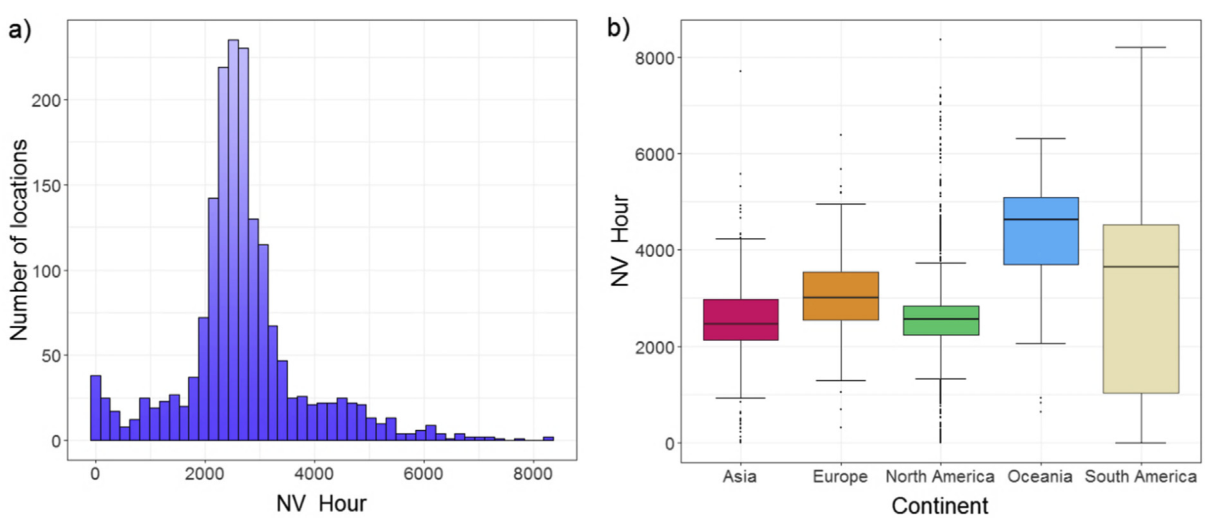

Fig. 3. a) Histogram of NV hours in 1854 locations; b) boxplot of NV hours by continent. Africa is not plotted due to the lack of sufficient climate data.

along the coast to a temperate climate inland on the plateau. The variation in elevation is a key factor in determining natural ventilation potential. Cities with higher altitudes show much cooler temperature than those along the coast. As a result, there are cites with small amount of NV hours, such as Mombasa (117 h), but also places that are able to greatly utilize natural ventilation year-round, such as Nairobi (8435 h) and Nakuru (7606 h).

3.1.1.3. Ethiopia. Ethiopia lies in the tropical zone. Ethiopian Highlands cover most of the country, resulting in a cooler climate than other regions on the Equator. Most major cities are located in elevated regions over 2000 m with mild climate throughout the year. For example, Addis Ababa, the capital city, is estimated to have 7204 NV hours. Bahir Dar in the northwest of the country displays more favorable weather for natural ventilation (8136 h).

3.1.2. Asia

Asia, the world's largest and most populous continent, has a mix of many different climates. The northeastern parts such as Siberia have short summers, and long and extremely cold winters, while the climate in Southeast Asia is mainly tropical with hot and humid weather throughout the year. With regard to humidity, it is mostly dry across the inland and humid across the southeast. The number of NV hours varies from region to region in Asia. For example, countries in Southeast Asia such as Indonesia and Malaysia show nearly no natural ventilation potential. In contrast, places in southwest China display a significant amount of NV hours.

3.1.2.1. China. China has a great diversity of climates due to its massive land coverage and varied terrain conditions. The northeastern region has freezing cold winters and hot dry summers.

Representative cities in this region are Shenyang (2182 h), Changchun (2352 h) and Harbin (2356 h). North China has a continental climate with large seasonal temperature differences, in which summers are warm and hot, and the winters are cold. For instance, Beijing, the capital city, is located in this region with 2651 NV hours. Other cities include Hohhot (2943 h), Shijiazhuang (2651 h), Taiyuan (2949 h) and Zhengzhou (2553 h). The Southeast China generally features a warm humid temperate climate with distinct seasons. Representative cities in this region are Shanghai (2302 h), Hangzhou (2193 NV hours), Nanjing (2246 h), Fuzhou (2924 h), and Guangzhou (2434 h). The Qinghai-Tibet plateau has cold winters and cool dry summers (e.g. Lhasa with 2689 h). The southwestern region has a mild climate and little variation in temperature throughout the year (e.g., Kunming, 5566 h).

3.1.2.2. India. India comprises a wide variety of climates, ranging from a desert climate in the west, to a humid tropical climate in the south, to alpine tundra in the north. For most of India, summer is very hot except the alpine zone. The humidity level in the northeast is generally high except during the winter season. In terms of natural ventilation potentials, New Delhi, the capitol city of India, has a subtropical climate. The number of NV hour is considerable (3331 h) due to mild and dry winters. Mumbai lies on the west coast of the country and shows only 1373 NV hours due to high temperature and humidity for the most of the year.

3.1.3. Europe

Most of Europe lies in the temperate climate zone. The cold weather can be seen in Russia and Scandinavia, with daily highs around 0 °C in the winter, while the mild winters can be seen in southern Spain and southern Italy, with an average about 15 °C during the day. Hot summers often occur in southern Spain, while warm summers can be found north of the Mediterranean Sea. As a result, the number of NV hours is around 2000 h in cities located in Northern Europe (e.g., Oslo, Norway, 2360 h; Stockholm, Sweden, 2229 h; Helsinki, Finland, 1930 h; Copenhagen, Denmark, 2459 h; St. Petersburg, Russia, 2164 h; Moscow, Russia, 2378 h). In contrast, significantly more NV hours are available in warm climate zones in Southern Europe (Faro, Portugal, 5673 h; Valencia, Spain, 4534 h; Barcelona, Spain, 3803 h; Palermo, Italy, 4731 h; Athens, Greece, 4942 h; Izmir, Turkey, 4646 h). For the rest of the Europe, the average NV hour is around 3000 h (Geneva, Switzerland, 3065 h; Brussels, Belgium, 2978 h; Amsterdam, Netherland, 2845 h; Vienna, Austria, 3294 h; Prague, Czech Republic, 2733 h).

3.1.3.1. United Kingdom. The climate in the United Kingdom is categorized as temperate oceanic climate with warm summers and cool winters. The variation in temperature throughout the year is moderate, with average annual temperature ranging from 8.5 °C to 11 °C. The average number of NV hours is around 2000, with slightly higher NV hours in the south (e.g., London, 2885 h) and slightly lower NV hour in the North (e.g., Aberdeen, 1756 h).

3.1.3.2. France. In general, France shares the same climate classification with the United Kingdom. In particular, the western part of the country has a temperature oceanic climate with moderate annual temperature variations (Brest, 3111 h). The central and eastern part has a continental climate with cold winters and hot summers (Paris, 3451 h). The southeastern part has a Mediterranean climate with warm dry summers and wet mild winters (Nice, 3909 h).

3.1.3.3. Germany. Germany has a temperate climate for the most part with cold winters and moderately warm summers. In the northwest, the climate is oceanic. The winters are mild and summers are warm. In the east of Germany, the climate is more continental, where winters can be very cold and summers very warm. Specifically, Berlin located in the east is one of the most favorable cities in the country for natural ventilation with 3130 NV hours, followed by Frankfurt (3126 h), Stuttgart (2822 h), Hamburg (2645 h), and Munich (2533 h).

3.1.4. North America

3.1.4.1. United States. The climate of the United States varies from region to region due to its massive expanse of land and complicated terrain. As shown in Fig. 1, the number of available weather stations is the largest around the world, followed by China and Australia. The California coast has a Mediterranean climate, with daily highs ranging from 21 to 27 °C in the dry summer and 10 to 16 °C in the wet winter. Cities in this region generally have high NV hours, such as Los Angeles (7197 h), San Diego (6864 h), and San Francisco (5337 h). Cities in the Southwest such as Phoenix and Las Vegas have a desert climate, with average highs over 38 °C during the summers and average highs from 10 to 16 °C during the winters. Northern Arizona, New Mexica, central and northern Nevada, and most of Utah have a semi-arid climate with colder winters. Dry air in these regions results in large temperature differences between day and night. Despite the high temperature in the daytime, the suitable temperature and humidity at night often allows the use of night-purge natural ventilation especially for office buildings. Cities in these regions show a considerable amount of NV hours such as Phoenix (4591 h) and Las Vegas (4295 h). The Gulf Coast and South Atlantic states feature a humid subtropical climate with hot and humid summers and mostly mild winters. Representative cities are Houston (2248 h) and New Orleans (2622 h). The region from the southern states of the Great Plains, to the lower Midwest, eastward to the central East Coast has a temperate climate. Cities in this region include Pittsburgh (2801 h) and Washington, D.C. (2601 h). The northern Midwest, Great Lakes, and most of the New England share a humid continental climate with four distinct seasons. The summers are warm to hot and often associated with high humidity. The winters are long and cold. Therefore, the amount of NV hours for cities in these regions is moderate. Cities in this climate zone include Boston (2745 h), Minneapolis (2468 h), and Chicago (2608 h).

3.1.4.2. Canada. Canada borders the United States, and constitutes 41% of the continent's area. Most of central and northern Canada lies in subarctic and Arctic climates. The summer is short and winter is long, with temperature often below −20 °C. Most Canadian cities are within 300 km of the southern border, where the climate is continental with warm summers. Among the major cities, Vancouver located in the southwest corner of the coastal province of British Columbia has a Mediterranean climate with warm summers and mild winters. It is estimated to have 2959 NV hours. Other cities include Toronto (2489 h), Montreal (2480 h), and Ottawa (2473 h).

3.1.4.3. Mexico. The climate of Mexico varies depending on the region. The northern region experiences either an arid or a semi-arid climate, and winters can be cold with some snowfall. South of the Tropic of Cancer, the climate is tropical, and hot and humid year-round, particularly along the coastal plains. The capital, Mexico City, is located in the high plateaus at the center of Mexico at an altitude of 2240 m. It has a subtropical highland climate, which generally features a mild weather nearly all year. Therefore, it is a city with one of the greatest natural ventilation potentials in North America (7161 h).

3.1.5. Oceania

3.1.5.1. Australia. Most of Australia experiences desert or semi-arid climate. The northern part of Australia has a tropical climate, and the southeast and southwest corners have a temperate climate. As shown in Figs. 1 and 2, natural ventilation potential is generally abundant in this country even in cities with a desert climate. For example, Alice Springs is situated in the central desert region. In the summer, the average temperature is about 28 °C, and the dew point is about 8.6 °C. In the winter, average temperature is about 12 °C and the dew point is about 2 °C. The number of NV hours is 4952, which greatly benefits from the proper outdoor conditions for night-purge ventilation in the summer and from mild weather in the winter. The largest city by population in Oceania is Sydney, Australia, which is located on the country's east coast. The climate is temperate with an average temperature in the summer around 22 °C and dew point about 15 °C. Winters are mild with an average temperature about 14 °C and a dew point about 5.5 °C. Sydney has the highest NV hours (5816 h). Other major cities including Melbourne (5025 h), Adelaide (5477 h), and Brisbane (5002 h) generally see significant potentials for natural ventilation as well.

3.1.5.2. New Zealand. New Zealand is an island country, mainly consisting of two islands. The country mostly has an oceanic climate that is similar to the southeast corner of Australia. The summers are warm and the winters are mild. Generally, the number of NV hours is greater in northern cities than southern cities. Auckland, on the North Island, is the largest city in the country, and is estimated to have 5995 NV hours.

3.1.6. South America

3.1.6.1. Brazil. Brazil covers nearly half of the area of South America. Most of the country has a tropical climate with warm temperature throughout the year, except the temperate southern regions. Most major cities including Sao Paulo, Rio de Janeiro, and Belo Horizonte are located in the southeastern region of the country. For example, Sao Paulo, the most populous city in Brazil, is located on a plateau with an average elevation of about 800 m above sea level. It experiences a temperate climate with moderately warm summers and mild winters. Similar to many cities within the same climate type, the natural ventilation potential of Sao Paulo is substantial with 5164 NV hours. Rio de Janeiro is the largest coastal city in Brazil with a tropical savanna climate. Unlike Sao Paulo, natural ventilation is only available for a small portion of the year (1518 h) due to hot and humid weather last nearly all year.

3.1.6.2. Argentina. Argentina is located in the southern part of the continent, and shares a long border with Chile. The country has diverse climates, although the most populous cities are located in the temperate climate zone. The capital city and the largest city of Argentina, Buenos Aires, is on South America's southeastern coast. The city experiences a temperate climate, and is mild year-round with no major extreme temperatures. As a result, significant natural ventilation potential is observed with 4514 NV hours.

3.1.6.3. Chile. Chile lies between latitudes 17° S and 56° S, and occupies a long strip of land between the Andean Mountains and the Pacific Ocean. Climate in Chile is therefore diverse, ranging from an arid desert climate in the north, to a Mediterranean climate in the center, to alpine tundra in the south. The capital city of the country is Santiago, which has a Mediterranean climate. Like many other cities in this climate, summers are dry with an average temperature around 20 °C, and winters are mild with average temperature about 10 °C. Natural ventilation can be a practical option in this region with 4297 NV hours.

3.2. Energy saving potentials

Fig. 4 presents NV hours, non-NV hours due to hot temperature and high humidity ($Non\text{-}NV\ hour_{hot\&humid}$), energy saving hour percentages *NV%* of the world's 60 largest cities (based on urban land area and population) among 1854 locations, and corresponding energy savings percentage by natural ventilation *ES%* calculated with BES [76]. A $Non\text{-}NV\ hour_{hot\&humid}$ is defined as an hour where the outdoor temperature and humidity exceed the upper thresholds. We introduced this term here because it is the time period when cooling energy must be consumed. Energy saving hour percentage *NV%* is defined according to Eqn. (8). In addition to $Non\text{-}NV\ hour_{hot\&humid}$, the sum of *NV hour* and $Non\text{-}NV\ hour_{hot\&humid}$ represents the maximum time period when cooling energy consumption can occur, as mechanical ventilation can take place during NV hours if natural ventilation alone cannot meet satisfactory thermal comfort due to high building internal load. The ratio between *NV hour* and the sum of *NV hour* and $Non\text{-}NV\ hour_{hot\&humid}$ therefore indicates the maximum time fraction when cooling energy savings can occur.

$$NV\% = \frac{NV\ hour}{NV\ hour + Non\text{-}NV\ hour_{hot\&humid}} \tag{8}$$

The energy saving percentages *ES%* is defined in Eqn. (9). E_{mech} is the total cooling energy consumption of mechanical ventilation simulated with BES, which also includes fan and pump electricity usage. E_{mixed} is the total cooling energy consumption of mixed-mode ventilation simulated with BES.

$$ES\% = \frac{E_{mech} - E_{mixed}}{E_{mech}} \tag{9}$$

Our analysis demonstrates a strong correlation between *ES%* and *NV%* among the 60 cities with a correlation coefficient (r) of 0.93. Thus, the advantage of the NV hour approach is that it can assess maximum energy saving potentials without running detailed BES, which is especially useful in the early design stage.

In Fig. 4, places with a tropical climate such as Manila, Bangkok, Chennai, Kuala Lumpur and Singapore shows both nearly zero NV hour and *ES%*, due to the hot and humid climate year-round. In contrast, cities with a cold climate such as Moscow and St. Petersburg still display moderate NV hours but high *ES%* over 30% due to favorable weather in the summer. Large cities with a temperate climate including Mexico City, Los Angeles, and Johannesburg, display substantial NV hours greater than 6000 and *ES%* greater than 30%. For the rest of cities on the list such as Tokyo, New York, and Beijing, NV hours typically range from 2000 to 3000, and energy saving percentages *ES%* are between 20% and 30%.

4. Concluding remarks

Buildings that rely on either natural ventilation or mixed-mode ventilation have demonstrated significant potential of energy savings and improvements of indoor environmental quality in favorable climatic conditions. As climate varies widely from region to region in the world, we estimated the natural ventilation potentials at 1854 locations across Africa, Asia, Europe, North America, Oceania, and South America, using the approach of NV hour. Energy savings potentials of the world's 60 largest cities were calculated with EnergyPlus. The advantage of the NV hour approach is that it can assess maximum energy saving potentials without conducting detailed BES, which is especially useful in the early design stage.

According to our analysis, subtropical highland climates show significant amounts of NV hours due to year-around mild weather. Such climates exist in Mexico City, Mexico (7161 h); Nairobi, Kenya

City	NV hour	Non-NV hour (hot and humid)	NV%	ES%	City	NV hour	Non-NV hour (hot and humid)	NV%	ES%
Tokyo	2633	2131	55.3%	27.5%	Nagoya	3031	2241	57.5%	24.9%
Delhi	3331	4572	42.1%	13.3%	Hyderabad	2471	6283	28.2%	6.0%
Manila	7	8753	0.1%	0.0%	Chicago	2808	1368	67.2%	20.7%
Seoul	2423	1967	55.2%	26.5%	Johannesburg	6105	219	96.5%	30.3%
Karachi	2701	5799	31.8%	7.6%	Shenyang	2182	1682	56.5%	20.1%
Shanghai	2302	3325	40.9%	20.8%	Wuhan	2122	3433	38.2%	16.1%
Mumbai	1373	7387	15.7%	1.9%	Kuala Lumpur	0	8760	0.0%	0.0%
New York	2966	1573	65.3%	23.0%	Hong Kong	2840	5671	33.4%	16.8%
Sao Paulo	5164	3215	61.6%	27.2%	Boston	2745	1136	70.7%	27.3%
Beijing	2651	1907	58.2%	21.7%	Zhengzhou	2553	2404	51.5%	17.5%
Mexico City	7161	104	98.6%	32.3%	Hangzhou	2193	3428	39.0%	17.8%
Guangzhou	2434	5358	31.2%	15.1%	Dusseldorf	3294	136	96.0%	46.5%
Dhaka	2240	6428	25.8%	4.6%	Toronto	2489	702	78.0%	26.3%
Osaka	2969	2381	55.5%	24.2%	Dallas	2938	3174	48.1%	16.9%
Moscow	2378	193	92.5%	31.7%	San Francisco	5337	57	98.9%	49.2%
Cairo	4886	3187	60.5%	26.1%	Nanjing	2246	3015	42.7%	19.8%
Bangkok	606	8154	6.9%	0.8%	Madrid	4074	703	85.3%	36.1%
Los Angeles	7197	526	93.2%	49.8%	Santiago	4297	565	88.4%	39.2%
Buenos Aires	4514	1690	72.8%	39.2%	Houston	2927	4595	38.9%	16.9%
Kolkata	1785	6928	20.5%	4.5%	Miami	1906	6675	22.2%	6.4%
Tehran	4253	1240	77.4%	24.0%	Riyadh	4916	3110	61.3%	24.7%
Istanbul	3577	1436	71.4%	28.5%	Singapore	0	8760	0.0%	0.0%
Tianjin	2643	2076	56.0%	19.3%	Xi'an	2735	2145	56.0%	21.7%
Rio de Janeiro	1518	7241	17.3%	3.6%	Philadelphia	2883	1775	61.9%	25.4%
Lima	5974	2784	68.2%	38.9%	Nairobi	8435	179	97.9%	43.5%
Chengdu	2660	3153	45.8%	24.2%	Milan	3221	934	77.5%	28.9%
Paris	3451	161	95.5%	45.4%	Atlanta	2674	2798	48.9%	21.3%
Bangalore	3100	5660	35.4%	7.3%	St. Petersburg	2164	82	96.3%	37.2%
London	2885	57	98.1%	45.9%	Washington	2601	2169	54.5%	22.5%
Chennai	120	8640	1.4%	0.0%	Barcelona	3803	1776	68.2%	38.1%

Fig. 4. NV hours (out of 8760 h), non-NV hours due to hot temperature and high humidity (out of 8760 h), energy saving hour percentages *NV%* of the world's 60 largest cities, and corresponding energy savings percentage by natural ventilation *ES%* calculated with BES. The list of world's largest cities is from DWUA report (2017). Cities without typical weather data are excluded in the list.

(8435 h); Bahir Dar, Ethiopia (8136 h); and Kunming, China (5566 h). The Mediterranean climate also greatly favors natural ventilation. Characterized by dry summers and mild winters, this climate is found not only around the Mediterranean Sea, but also in California, Western Australia, Portugal, and Central Chile. Representative cities include Los Angeles, United States (7197 h); Perth, Australia (6094 h); Faro, Portugal (5673 h); and Antofagasta, Chile (8204 h). In addition, greater-than-expected natural ventilation potentials, ranging from 3000 to 4000 NV hours, are displayed in the desert climate, such as the Middle East, Central Australia, and Egypt. Despite high heat during summer days, the temperature can drop considerably to a comfortable level at night due to sky radiant cooling. For example, a good ventilation strategy in this region is to shade and insulate the house against the heat of the day and flush out any stored heat during the cooler nights. The region with the least natural ventilation potential is Southeast Asia (e.g., Singapore, Malaysia, and Indonesia), which display practically no NV hours, as a result of hot and humid weather throughout the year.

As different climates pose different environmental challenges, the design of natural ventilation systems can be customized to accommodate local climatic features with the goal of reducing energy consumption and improving indoor environmental quality. Although site-specific information is not taken into account here, the purpose of this study is to understand the broad geographic and climatic variations of natural ventilation potentials at a global scale. It thus provides valuable information to architects and policy makers seeking effective ventilation designs that meet local climatic conditions.

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