Highlights

- A literature review of contemporary research related to night ventilation.
- The effect of thermal energy storage on night ventilation efficiency.
- A review of the main parameters and the effectiveness of night ventilation.
- A review of control systems, and supplementary cooling coupled with night ventilation.

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A Literature Review of Night Ventilation Strategies in Buildings

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Abstract

The rising costs of energy usage in the building sector have intensified research interest in passive energy saving strategies such as night ventilation (NV). Night ventilation has been shown to reduce the energy demand for cooling buildings as well as significantly ameliorate thermal comfort. A large number of studies have been undertaken to model and assess the effectiveness of NV across a wide variety of climates and building types. This paper reviews the key research on night ventilation strategies and identifies the main themes and directions present in contemporary research. It also classifies NV performance into three broad groups, namely climate, building and technical parameters. The literature provides evidence that night ventilation strategies are effective across most climate types, but as with most passive design strategies, optimisation is required. Approaches to research within the reviewed literature include computer simulations and empirical studies; testing with full-scale physical prototypes; and monitoring of real world case studies. The effectiveness of different strategies in different climates is examined, as are NV control systems, and the coupling of NV with other systems.

Keywords:

Night Ventilation, Passive Cooling, Thermal Energy Storage, Phase Change Materials, Thermal Mass

1. Introduction

Buildings represent around 40% of total energy expenditure and 30% of all greenhouse gas emissions [1]. Nevertheless, there has been a growth in energy consumption by the building sector. For example, Australia's total energy consumption is predicted to rise by 24% from 2009 to 2020 [2]. Many building designs are not optimised for passive cooling and rely on mechanical systems to maintain an acceptable indoor environment [3]. Not surprisingly, reducing the energy consumption of buildings and utilising passive cooling methods have become prominent features in contemporary building physics research. Given that HVAC constitutes a significant proportion of building energy end use [4], energy efficient heating and cooling are critical to sustainable development. To reduce the energy demand of buildings whilst maintaining comfort levels, the adoption of various passive energy saving techniques such as night ventilation, exclusively or coupled with novel thermal energy storage like phase change materials (PCMs) [5-7] or other energy-efficient systems such as wind-catchers [8], earth to air heat exchange systems [9, 10], atriums [11], and so forth is required.

Night ventilation (NV) is an effective passive cooling technique whereby the daytime heat gain of a building is released at night-time through the intake of the outdoor cool air. That is, the colder nocturnal air that circulates through the building during night ventilation cools the indoor air and building fabric; afterwards, the consequent cooled structure slows the rate at which the internal temperature rises during the day [12-14], thereby decreasing the cooling energy demand [15, 16] and improving occupant thermal comfort [17]. Passive cooling is the interaction of all measures acting to decrease heat gains coupled with accessible heat storage and heat sinks [18]. Ventilation can be achieved by means of fans or by natural air movement; for natural ventilation, windows may be controlled manually or automatically by a central building management system [19]. Since natural ventilation allows the possibility of high fluctuations in the air change rate, hybrid ventilation systems are often employed to ensure a constant airflow rate. Hybrid ventilation is a combination of mechanical and natural forces in a two-mode system where the operating mode differs according to the season and daily fluctuations [20].

In past years, many studies have been conducted with a focus on different aspects of night ventilation in either lone deployment or coupled with additional cooling and thermal improvement strategies [21, 22]. Given the proliferation of studies, a holistic view of night ventilation is challenging. This study reviews related night ventilation research undertaken in the last 20 years (1997 – 2017) to identify the ongoing themes and directions.

This review will first expand on the effectiveness of NV in order to establish the reasoning behind optimisation of this strategy within the global context (Section 2). Section 3 presents the parameters of effective NV. As with many other passive cooling strategies, night ventilation can be combined with other methods, the most notable in the literature being the use of thermal energy storage. The key literature on this topic as it relates to night ventilation is summarised in Section 3.6. A much newer technique utilizing phase-change materials is summarised in this section, before the key issues (limitations and optimisations) as they relate to the literature in the field are identified. The ventilation modes, control methods,

supplementary systems, and barriers of NV are covered in Section 4, which summarises the widespread use of night ventilation in multiple site conditions.

2. Utilization of night ventilation in different climates

Several studies focus on the improvements offered by night ventilation. This section summarises these studies according to climate, with notes on the type of experiment, simulation and analysis. Table 1 demonstrates the key aspects of the main selected articles (climate, methodology, location, building type, and area of research) and the resultant analysis has revealed some recognisable themes and research directions. As shown in Fig 1, which visualises data over the world map using Microsoft's Visual Studio, the utilization of NV is prevalent in many climatic zones throughout the world, including even humid, tropical zones. It is imperative to note that the efficacy of NV is highly contingent upon local climate characteristics stemmed from the effect of urban morphology [23], meteorological conditions and such other microclimatic variables as the urban heat island effect [24, 25]. Urban heat decreases the effectiveness of NV techniques as it gives rise to the reduction of urban air quality and contributes to alterations in the urban microclimate [26]. However, to lessen these adverse impacts there are some useful techniques such as the utilization of cool coatings [27] or green rooves [28]. Additionally, although NV has been used in different types of buildings, its use is more common in non-residential buildings since the absence of personnel at night permits the attainment of higher air change rates. The results also demonstrate that in order to optimise night ventilation systems, coupling with other passive or active systems is of paramount importance. Furthermore, studies have prominently been concerned with improving the thermal energy storage as on one of the main parameters of NV; therefore, in recent years the use of phase change materials as novel thermal energy storage in NV systems has been increasing.

Table 1: Summary of parameters of the reviewed articles.

Climate	Ref	Study Methodology	Location (Köppen and Geiger Climatic classification [29])	Building Type/ Construction System	Area of Research
Arid	[30]	A spreadsheet computer program and action psychometrics software (Sunshine Technology, USA, 1995)	Al-Ain city, United Arab Emirates (BWh)	Low-Rise heavy residential buildings	Improving NV with a combined wall–roof solar chimney
	[31, 32]	A full-scale model (EnergyPlus) derived from an experimental model in Arizona [33]	Yazd, Iran (BWh)	A typical office building with lightweight structure	Combined use of PCMs to optimise NV
	[17]	Simulations of EnergyPlus and the flow solver of Design Builder	Nicosia, Cyprus (BSh)	Vernacular buildings	The impact of natural NV on the thermal comfort of vernacular buildings
Tropical	[34]	Survey from a prior study [35] which is a full-scale experiment	Johor Bahru, Malaysia (Af)	Residential buildings	Optimisation with the use of ceiling insulation and window shading devices
	[36]	Monitoring and analysing experimental test cells, as well as simulations using EnergyPlus	Kumasi, Ghana (Aw)	Test cells with an office schedule were examined. To assess the effect of thermal mass, three different thermal masses, namely solid sandcrete blocks, baked bricks, and concrete were used.	Thermal mass, window size, and NV
	[37]				
Temperate	[38]	The study is a method consisting of analytical evaluations of a model and simulations of a room.	Wuhan, China (Cfa).	A whole-building hygrothermal model. The test cases from the Annexe 41 project [39], and Bednar and Hagentoft [40] calculations	NV combined with AC
	[41]	Quantitative evaluations and analysis of all parameters affecting the thermal mass efficiency in peak cooling load reductions.	Hong Kong, China (Cfa)	A simple office building under daytime air conditioning and NV	NV combined with thermal mass
	[42]	Numerical study of a TRNSYS model developed in an earlier study [43], and a case study of a Cuiller built low inertia timber frame house.	Carpentras, France (Cfa)	Low inertia timber frame houses	NV combined with a Ventilated Internal Double Wall (VIDW)

[44]	Case studies and simulations using the TRNSYS-COMIS tool from a prior study [45].	Ghent, Belgium (Cfb)	Office building	Guidelines for a natural NV design
[46]	Algorithms derived from real building enclosures and numerical simulations with the TRNSYS simulation software	Ghent, Belgium (Cfb)	A typical standard office room; the geometry is described in a prior study by Breesch et al. [45, 47]	The sensitivity of the NV performance to convection algorithms
[48]	The study examined the measurements compared with simulations with TRNSYS-COMIS	Kortrijk, Belgium (Cfb)	A heavy construction office building	NV coupled with an earth-to-air heat exchanger
[49]	Building prototype thermal analysis; monitoring and simulations (TRNSYS software)	Algiers, Algeria (Csa)	A heavy construction residential building	The impact of overhangs and thermal mass on NV
[37]	Experimental research using a numerical model described in a prior study developed by the authors [50]	Seville, Spain (Csa)	Office building	Combined use of PCMs to optimise NV
[22]	Real scale measurements in three free-floating and air-conditioned buildings, and also a series of simulations using the TRNSYS tool	Athens, Greece (Csa)	Building 1: A heavy construction office building (Meletitiki) Building 2: A light construction office building (University) Building 3: A heavy construction office building (National Observatory of Athens' or NOA)	The potential and limitations of NV under different structures, design, ventilation, and climatic conditions
[51]	Measurements conducted in 10 urban canyons and simulations with a transient simulation tool (TRNSYS) and the AIOLOS software tool.	Athens, Greece (Csa)	Urban environment (10 urban canyons); a typical single-zone room	The impact of urban environment on NV energy performance
[52]	Simulations using EnergyPlus validated with experimental data	Athens, Greece (Csa)	A high thermal inertia living space in a single floor open plan built space	Solar thermosiphonic configurations coupled with NV

Cold	[53]	Detailed monitoring of energy data of 214 selected residential buildings that adopted NV systems and simulations using TRNSYS.	Athens (Csa) and Samos (Csa) , Greece	Residential building	The relation between the building cooling demand and NV contribution
	[54]	A standard building recommended by the Australian Building Controls Board was simulated in Energyplus	Adelaide, Australia	A typical commercial office building	NV coupled with different facade constructions
	[21]	A full-scale experimental study of a test building followed by numerical studies using the TRNSYS software	La Rochelle, France (Cfb)	Office and classroom building (University Institute of Technology (I.U.T), La Rochelle)	NV coupled with mechanical cooling
	[55]	Simulations using the BRE high-speed thermal simulation program 3TC [56] and a pre-design tool	Middlesex; England (Cfb)	The study model consists of a thermal and ventilation simulation model of a typical cellular air-conditioned office building.	NV and mechanical ventilation
	[57]	The study consists of simulations using the 'Airflow Network Models' of the building integrated into Energyplus. Pressure coefficients (Cp), derived using the formula of Swami and Chandra, is utilised, as well as, the web-based software Cp Generator, CPCALC+, and, the wind tunnel tests by Tokyo Polytechnic University (TPU).	Bergamo (Cfa) compared with several locations across Europe: Groningen (Cfb), Munich (Cfb), Innsbruck (Cfb), Rome (Csa), Palermo (Csa)	A high thermal inertia isolated six-storey office building	Pressure coefficients (Cp) sources and NV
	[58]	Long term building monitoring and experimental simulations conducted in ESP-r	Prague, Czech Republic (Cfb)	Commercial building	A coupled HVAC system comprised of daytime top cooling and NV
	[59]	Simulations using EnergyPlus	Three cities in northern China: Harbin (Dwa), Shenyang (Dwa) and Beijing (Dwa)	A lightweight construction typical office building	NV performance, and optimising its control strategies
	[60]	Analytical-mathematical models, the self-evident program, Designer's Simulation Toolkit (DeST) developed by Tsinghua University.	Harbin, China (Dwa)	Commercial building (large supermarkets)	Energy saving and cost analysis of NV coupled with AC

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3. The parameters of effective night ventilation

Researchers have presented an overview of night ventilation, covering the critical parameters holistically. Artmann [61, 62] determined the influence of heat gains, air flow rates, heat transfer coefficients, building structure, and climatic conditions, as well as yearly differences in total NV overheating degree hours. Geros et al. [22] also presented the key parameters, which include the effective night-time airflow rate, as well as the indoor-outdoor temperature differential, and the quantity of exposed thermal mass. In this section, the literature relating to the key parameters of NV is examined. The aim is to find the aspects that give the greatest optimisation of and potential for night ventilation.

3.1. Air flow parameters

As with all passive cooling through increased air movement, the velocity at which the air moves translates to the number of air-changes per hour and determines how much air volume is transferred into/out of the building. Artmann [61] showed that NV air change rate sensitivity makes thermal comfort predictions highly uncertain. This is especially true in the case of natural ventilation as the outside wind conditions are stochastic in nature, with a range of 0.2-4 ACH in a case studied. However, once a critical airflow rate is reached, no further improvement is noticeable with NV alone, and the addition of other factors such as thermal storage is needed. To improve the airflow, devices such as solar chimneys were explored in the work of Koronaki [52]; in this case, the wall temperature and orientation become critical parameters as they directly impact on the air flow rate. Duct width, as well as orientation, wall surface temperature, and height all influence the airflow rate. The research revealed that wall height is more influential than duct width in obtaining a faster flow rate.

When mechanical systems are used, the energy consumption of the fans becomes an important parameter. Lain et al. [58] examined the electricity used by the fan systems in a coupled top cooling and night ventilation set up. The research showed that the increased coefficient of performance (COP) of mechanical cooling systems attributable to the energy savings afforded by NV decreases due to the electrical power usage of the fans. They also reported that the internal gains from office equipment are actually much lower than those stated on the equipment labels. Also, Solgi [63] stated that when air change rates of over 15 ACH are required, the energy demand for fans as well as disruptions to the internal spaces make NV unfeasible as a productive and comfortable cooling strategy. Moreover, Liu Y et al. [64] showed that the impact of outdoor air temperatures in improving NV effectiveness was greater than that of increasing airflow velocity.

3.2. Cooling load parameters and reducing daytime cooling loads

The night ventilation potential is significantly improved by the increased cooling energy demand of the building as the increased cooling demand created at night results in more available energy stored in the building during the day. The percentage contribution of NV to the energy performance of a building is not dependent on the initial cooling load, and its relative contribution to the initial cooling load varies between 10 and 40%, with an average of 26%. Buildings with higher cooling loads were shown to benefit more significantly than buildings with lower cooling needs [53] (Fig 2.). The initial cooling load before the application of night ventilation is found to be linearly related to the energy benefit of NV use

for a specified airflow rate. This energy performance of NV is contingent upon the distinct initial cooling load of different air flow rates, especially air change rates of 2, 5, 10, 20 and 30 ACH. However, the airflow benefits of the per unit air change rate per hour of NV significantly decrease at higher airflow rates, especially when the energy performance of NV per unit of airflow change is limited to 3.3, 2.5, 1.8, 1.2 and 0.7 kWh/m²/y, for 2, 5, 10, 20 and 30 ACH of air flow. The variation in NV parameters led Leenknecht et al. [65] to simulate and compare 1008 cases using weighted overheating hours (WOH). It was found that the ACH increased for each instance that the WOH was added; however, this increase plateaus at higher air change rates (Fig 3.).

Fig 2: Calculated reduction in the cooling demand as a result of the use of NV [53].

(1–9: 12 W/m², 10–18: 15 W/m², 19–27: 18 W/m², 28–36: 21 W/m², 37–45: 24 W/m², 46–54: 27 W/m², 55–63: 30 W/m²), with increasing ACH 4–5–6–7–8–9–10–11–12

Fig 3: Difference in WOH compared to the parallel case (same IG and ACH) with CHTC from TRNSYS integrated into calculations [65].

The Fraunhofer building located in Freiburg, Germany was utilised to study NV efficiency parameters experimentally by Pfafferott et al. [66] who revealed that the solar and interior heat gains and air flow rates had the most impact. To examine the influence of critical parameters on night ventilation efficiency, Blondeau et al. [21] analysed daytime temperatures and NV effectiveness by interpreting the resultant temperatures through translation into comfort improvement indices. The results have shown that regardless of weather-related conditions, with a temperature average of just 8.4 °C, NV was able to decrease the daily internal air temperature by about 1.5 to 2 °C.

3.3. Building shape, location, construction and function

Gratia et al. [67] chose a narrow plan building, suited for natural ventilation, to study the use of NV to cool office buildings in the moderate climate of Belgium. With natural ventilation, in addition to the building envelopes, factors such as the shape, size, type and location of the windows were considered important. In order to obtain a specific ventilation rate, the opening area of windows and the type of ventilation differed based on wind protection and wind orientation. The authors ascertained that single-sided ventilation was as efficient as cross night ventilation, in that with 8 ACH, both reduced the cooling load by approximately 40%. The results from the study by Landsman et al. [68] of NV performance regarding indoor environmental conditions, adaptive comfort, and heat removed, demonstrated that the NV performance of each building varied mainly due to the differences in their typology and functionality. The results illustrated that NV strategies in combination with each building's physical construction attributes affect the overall performance.

Geros et al. [51] found no noticeable outcome dissimilarity in utilising single-sided ventilation inside and outside their study related to the effectiveness of night cooling strategies in an urban environment (urban canyons), with airflow between the two locations ranging from 0.2 to 10 ACH. The air flow rate for the two data sets ranged from 4 to 69 ACH, and the impact of wind velocity and direction became more evident for cross-ventilation. In single-sided ventilation, the two profiles of the zone indoor temperature differences inside the canyons ranged between 0.02 °C and 2.6 °C. The zone indoor temperature difference of cross ventilation ranged between 0.2 °C and 3.5 °C, notably higher in comparison to the indoor temperature obtained from outside the canyons. The wind speed outside the urban canyon remained higher than inside, resulting in reduced ventilation airflow rate for zones located inside the canyons. This combined with the higher ambient temperature, resulted inside the canyons had a significant impact especially on single-sided ventilation.

3.4. Temperature differentials

Givoni [69, 70] suggested that the productivity of NV is maximized in desert and arid regions with night-time temperatures below 20 °C, a summer diurnal temperature fluctuation of 15 - 20 °C, and a maximum daytime temperature between 30 and 36 °C. Shaviv et al. [71] investigated the possibility of using a simple design tool capable of predicting the reduction of indoor summer temperature necessitated by NV air change rates and quantity of thermal mass. The results revealed that the decline in maximum indoor temperature was reliant on the main parameters of thermal inertia, the diurnal and nocturnal temperature range of the site, and air change rate, and that the prediction of indoor temperature was a function of these stated parameters (Fig. 4).

Fig 4: The reduction in Maximum Temperature as a function of the Temperature-Swing [71].

3.5. Convective-heat-transfer-coefficients and algorithmic parameters for simulation

Prior studies have established the importance of convective heat transfer coefficients (CHTC) to the efficiency of NV [72]. The cooling performance of conventional NV is reliant on the CHTC from the exposed building mass and the cool night-time air flow; the thermal inertia is recharged by the infrared and solar radiation through the air-to-room convective process in the daytime [44]. Several studies disclose that the convective cooling of the air in the space and thermal inertia have a considerable impact on the predicted performance [45, 65, 73]. However, the studies by Breesch [47] and Artmann et al. [74] utilised arbitrary values by not integrating the ventilation system design, and were independent of the interior, which limits the authority of their findings [75]. The influence of the CHTCs on the energy balance of buildings under heating and free-floating conditions is stated in the International Energy Agency (IEA) Annex 28 Report [76]. For natural NV to be effective, CHTCs require increased air change rates; however, this requirement may not always apply. The simulation study conducted by Blondeau et al. [21] noticed no substantial difference in the indoor air temperature predictions derived from several increased convective coefficients at night-time.

Furthermore, the study of Breesch et al. [44] using different convective heat transfer algorithms in a single occupancy office under single-sided natural ventilation in a moderate climate found that different convective heat transfer coefficients (CHTCs) algorithms alone were not a sufficient indicator of the vast differences in overheating hours. Parameters like the internal heat gains, schedule of occupation, and room characteristics were considered in the study of Vidrih et al. [77] on control matrices derived from Generalized model-based predictive weather control (G-MPWC). As a result, three predetermined air temperature control matrixes were produced: 24 °C in the first two days of operation; 25 °C for the following three days; and 26 °C for the remainder of the testing period (Fig. 5).

Fig 5: Coefficient of performance (COP) of the free cooling system controlled with G-MPWC and optimised G-MPWC algorithm (conventional control algorithm with control at 2 °C) [77].

Simulations using convection should evaluate the CHTC per surface rather than per zone as is currently practised, as shown by Leenknecht et al. [65]. The coefficients can be predicted from the flow pattern. Also, in the prediction of the flow pattern, a more precise classification system is required. Goethals et al. [46] evaluated the impact of employing empirical CHTCs algorithms in the design of NV systems by analysing the applicability of convection correlations for multi-zone energy simulation. They found that the convection algorithm is equally important as the design parameters, with the chosen convection algorithm greatly influencing the energy and thermal comfort predictions. When no NV is active, the chosen convective correlation is of little significance. However, in night-ventilated spaces, an accurate convective heat transfer algorithm is imperative, reinforcing the importance of a precise description of the CHTCs derived from experiments or computational flow dynamics (CFD), particularly for the day and night flow NV regimes. Ramponi et al. [57] stated that the choice of various sources of pressure coefficients (C_p) has a considerable impact on the accuracy of the natural ventilation predicted airflow rate. However, it is not as crucial for the prediction of the passive cooling effects of night ventilation in detached block-shaped low-rise buildings compared with other building simulation parameters like the internal CHTC. The calculated night ventilation rate differences are up to 15% for the entire building and approximately 20% for a single room.

3.6. Thermal energy storage

Utilizing short-term Thermal Energy Storage (TES) is a key ingredient in strategies used to control energy demand. The ability of TES materials to absorb excess energy, and to store and release it at a later time is known as thermal inertia, and when such heat transfer is timed correctly, thermal inertia can be used to improve thermal comfort and reduce auxiliary energy demand [78]. Factors that influence the effectiveness of TES include its exposure, location, diurnal temperature differences, the convective heat transfer coefficient, and its heat capacity [22, 54, 79].

Leenknecht et al. [65] in assessing the role of an exposed thermal mass, found that covering up the thermal mass led to worsening of thermal comfort with a noticeable change in weighted overheating hours (WOH) compared with if the mass was left exposed, as shown in Fig. 6. They also found that the results are highly sensitive to the selection of the convective heat transfer coefficient (CHTC), thus demonstrating that the CHTC and exposure of TES should be assessed jointly when simulation techniques are used.

Fig 6: Correlations comparison for the spread of thermal comfort with and without accessible thermal mass [65].

Shaviv et al. [71] studied the influence of thermal inertia and NV on the peak indoor temperature in summer. The study sought to ascertain the circumstances under which NV and thermal inertia become effective passive cooling strategies in the summer of a hot and humid climate, in four different locations along the coastal plain of Israel (Nahariya, Geva Carmel, Tel Aviv and Gaza). The results showed that the coupling of NV and thermal mass is an effective strategy for passive cooling. The effectiveness, however, is reliant on the diurnal temperature range of the site, which in some instances may be minimal because of high humidity. Notably, a decrease of between 3 °C and 6 °C in indoor temperature was achieved in a building with heavy thermal mass using NV without air conditioning. They also noted the improved thermal performance of light/medium and medium/heavy structures, although a lightweight building performed somewhat like a heat trap, requiring a greater diurnal temperature range to achieve the same effects.

The analysis conducted by Amos-Abanyie et al. [36] found that thermal inertia and window size combined with NV are interdependent influences on reducing peak indoor air temperature (PIAT). The analysis revealed that an increase in thermal mass through materials change led to a drop in PIAT. In their study using an airflow rate of 10 ACH, concrete had the greatest impact on reducing PIAT, followed by solid Sandcrete blocks, and then baked bricks. The results show a decrease of overheating hours for Sandcrete blocks of between 36% and 42%, for baked bricks, 37% to 39%, and for concrete, a reduction of 35% to 39%. Window size reduction was effective in reducing PIAT for all test models, with a decrease in PIAT leading to a reduction of no more than 0.9 °C, while window-shading devices led to lower radiant and conductive heat gains and had little effect on reductions achieved from variations in window sizes. Windowless concrete walls achieved a maximum reduction of 4.3 °C using NV. However, with windows, concrete showed a decrease of about 3 °C, with baked bricks showing a decline of 0.7 °C.

Yang et al. [41] studied the relationship between the amount of thermal mass, the thermal characteristics and convective heat transfer, combined with appropriate external climatic factors in reducing cooling load. They found that the time constant of the thermal mass is significant in influencing the capabilities of the thermal mass to efficiently store heat and alter the peak cooling phase of the load, as shown in Fig. 7. Significantly, by increasing the

time constant to 400 hours, there was a reduction in cooling load of more than 60%. However, with a time constant of more than 1000 hours, there was a possible increase in cooling due to the delay in heat release from the thermal mass until daytime. Thus, to achieve maximum efficiency in the reduction of the cooling load, the internal and external convective heat transfer coefficients must increase correspondingly.

Fig 7: Ratio of the cooling and overall cooling load profiles relative to the time constant [41].

Roach et al. [54] simulated a typical office building to demonstrate that a traditional economizer cycle, operating 24 hours each day, under thermostatic control, delivers energy savings. A number of facade structures were chosen. Afterwards, the impact of altering the location of the thermal mass within the structure was investigated. It was ascertained that, in the warm marine climate zone of Adelaide, Australia, increasing the inside facade mass is preferred to increasing the mass on the outside.

3.6.1. Phase change materials characteristics

The use of thermal mass in a building can reduce the peak heating or cooling load [80-82], and subsequently the building energy consumption [83], particularly when it is integrated with night ventilation [84]. The simplest method to store thermal energy is in the form of sensible heat storage (SHS), which stores thermal energy by increasing the temperature of a solid or liquid. The amount of heat stored depends on such factors as the amount of storage material, changing the ambient temperature, and the specific heat capacity [85]. There are two major advantages of SHS. First, it facilitates system design due to the use of bulk materials. Second, it is inexpensive and reduces the risk of using toxic materials. The main downside of using SHS materials for thermal storage is the volume of space occupied by the SHS material for the amount of stored energy needed [86]. In today's building industry, there are two related reduction strategies that mitigate the inclusion of sufficient thermal mass. These include reducing material usage, and reducing the weight of the construction.

In recent years, latent heat thermal energy storage (LHTES) has gained traction over SHS because at a constant temperature, or within a very low temperature range, LHTES can conserve a relatively high amount of energy [87]. Phase change materials (PCMs) are well known examples of materials using latent heat thermal storage. PCMs are substances with high heat of fusions, melting and solidifying at predictable temperatures. The three main reasons for PCMs receiving increased attention are high thermal density, the wide range of PCMs with different melting/freezing temperatures, and within a range, the relatively steady melting/freezing temperatures [88]. The deployment of PCMs has been shown to reduce the energy consumption for maintaining comfortable conditions in building [89].

PCMs are categorized as organic, inorganic and eutectic compounds, with each group having its typical range of melting temperatures and enthalpy [90]. High thermal energy storage capacity is considered to be the most important characteristic for materials intended for use as PCMs, and generally, this characteristic in inorganic materials is higher than in organic materials. Over the last 30 years, salt hydrates, paraffin waxes, fatty acids, and eutectic organic/inorganic compounds, have been the most employed types of PCMs. There has been much debate on the issue of selecting the most economical PCMs for specific applications and climatic conditions, resulting in the melting temperature factor being the most influential parameter [91].

3.6.2. Night ventilation and phase change materials

Phase change materials have been successfully used for reducing the cooling load of office buildings utilizing naturally or fan-assisted night ventilation [92-94]. Studies in night ventilation have been carried out in different climate zones worldwide with different applications of PCMs. For instance, the effectiveness of PCM to increase NV performance in an office building in Chambéry was studied by Evola et al. [95]. In this study, air change rates of 2–8 ACH between 21:00 and 06:00 were applied, resulting in a decline in the mean daily and peak operative temperatures. In addition, thermal comfort in integrating the proper NV with PCMs compared with using PCMs without NV was outperformed by 10%; meanwhile, the application of more than 4 ACH lacked notable improvements. Seong et al. [96] pointed out that PCMs coupled with NV were highly efficient, in that this combination could decrease annual cooling loads, the peak load, and the highest indoor temperature around 9%, 11% and 0.85 °C, respectively.

Solgi et al. [31, 32] combined PCMs and NV in office buildings of a hot-arid climate, resulting in a 45.5% reduction of the annual cooling load. It illustrated that the application of PCMs throughout the whole building contributed to reducing the cooling load, except for ground floors, where the addition of PCMs resulted in an increase of the cooling load. Moreover, the study on the amalgamation of NV with PCMs for the highest daytime and the lowest night-time temperatures in the warm months revealed that this combination not only reduces the average room temperature substantially but also decreases the peak temperature and moves it away from electricity peak demand. This combination can also reduce the cooling load of AC on the hot days, or even completely eliminate the necessity for AC on moderate days. In addition, the impact of NV on the inner surface temperature of the walls showed that in the majority of occupancy hours, the temperature of wall surfaces was about 0.5°C lower than the room temperature, bringing about the amelioration of thermal comfort conditions.

The workability of passive integration of PCMs as a novel retrofitting option to augment occupant thermal comfort and reduce peak zone temperature in a modern five star energy

rated house in Melbourne was investigated by Jamil et al. [97]. A controlled NV with the schedule of 19:00 to 7:00 for the opening area, which was 20%, was also devised. Owing to the passive installation of PCMs into the ceilings, the results demonstrated up to a 1.1 °C drop in room indoor air temperature during daytime, along with a 34% drop in thermal discomfort hours. This improvement was strongly contingent on occupant behaviour in properly following the NV strategy. It was also observed that provided that windows were left open at night-time for NV and the internal doors were kept closed at all times to hinder any mixture with surrounding zones without PCMs, the deployment of PCMs was effective in reducing thermal discomfort hours. In addition, when the same volume of PCM was spread in the ceiling and walls an additional amelioration of PCM efficacy was observed.

Zhou et al. [98] carried out an investigation using an empirical model to study the thermal performance of a hybrid space-cooling system with night ventilation and thermal storage, using shape-stabilized phase change material (SSPCM). A room of an office building in Beijing oriented towards the south, which includes SSPCM plates as the inner covering of the ceiling and walls, was analysed. The results indicated that in summer in Beijing, the thermal-storage effect of SSPCM plates combined with NV, compared with the case without SSPCM and NV, could improve the level of indoor thermal comfort, while also conserving approximately 76% of daytime cooling energy consumption.

Servando et al. [37] in the MECLIDE project identified some drawbacks of combining PCMs with night cooling ventilation, namely preventing the use of considerable volume of PCM due to the very low convection heat transfer coefficient, the very low application of the stored night cool due to the time lag between when the cool is stored and when it is needed, and the restricted space between PCMs and cool air. It was claimed that using PCMs in hollow core slabs and ventilating facades with fins filled with PCMs (Fig 8) was better than the prevalent application of PCM either for storage capacity or cooling power. Compared to prevalent solutions, the aforementioned innovative solutions increased the contact area between PCM and air by a factor of approximately 3.6, contributing to an exponential increment in the convective heat transfer coefficient, and consequently permitting the cool storage be actually utilized by means of active systems when required.

Fig 8: Integration scheme of MECLIDE solutions [37].

In order to analyse the thermal behaviour of the cooling unit in both day-mode and night-mode, a window-based cooling unit filled with PCMs was designed in a typical south-facing office room in Beijing (Fig 9,10.) [99]. The unit was discharged at night for 8h by natural ventilation, and on the subsequent day, the stored heat was actively released from indoors for 3h. The results revealed that at night, the greatest area of the PCM slabs with optimum thickness (5 mm) could be thoroughly solidified, and that less solidification time could be reached with thinner PCM slabs. During daytime within 1h the cooling unit could decline the indoor temperature by 3.3 °C, and maintain the temperature for 2h over 5 consecutive

days. Moreover, compared to a traditional air conditioner with the same capacity, the cooling unit could save around 1.9 kW/h.

Fig. 9. Cooling unit configuration: (a) perspective view of the cooling unit; (b) PCM layer [99].

Fig. 10. Operation mode: (a) “Down” location of the cooling unit in night mode; (b) “Up” location of the cooling unit in day mode [99].

Nagano et al. [100], by using 30 mm granular PCM in the floor of an office building with a new type of supply air conditioning system, while also using NV over 24h periods, were able to provide 89% of daily cooling needs. In addition, the operation of daytime air conditioning was limited to 3h from 13:00. Barzin et al. [101], in a practical experiment using two test huts with smart control systems, examined the combination of PCMs with NV. In this research, PCM impregnated gypsum boards were used in one hut while the other hut had ordinary gypsum, and fans were only used in the hut with PCMs. The control system was programmed to utilize the AC unit if the next day was forecast to be sunny. Results showed that the PCM room temperature did not drop below 20 °C, even with an outdoor temperature of 15 °C. They also found that while PCMs could produce energy savings, improper use could lead to higher power consumption. Best results occurred when the outdoor temperature was low enough to bring the PCM temperature below its melting point. Additionally, using only AC showed little savings, while night-purge showed a weekly 73% energy saving.

Based on studies which have been carried out, the effective thickness of PCMs depends on their locations in the building. If both sides of the PCM, as opposed to only one side, are exposed to air flow, the effective thickness is doubled. Notably, using excessive thicknesses of PCM is not profitable, as this will not allow phase change to occur [37]. However, one

method for improving the effective thickness of PCMs is increasing their thermal conductivity [102].

4. The effectiveness and barriers of night ventilation

In this section, different aspects of night ventilation are reviewed - the ventilation modes, control methods used and the supplementary systems that can be used in conjunction. At the end, some challenges of night ventilation that have been noted in literature are presented.

4.1. Mechanical cooling (air-conditioning and fan-forced ventilation)

In many studies, the use of night ventilation reduced the daytime cooling demand of air-conditioners. Geros et al. [22] found that night cooling created an average reduction of 3.0°C when night air-conditioning was used (or 0.2°C when passive ventilation was used). Blondeau et al. [21] showed a daytime reduction of 1.5-2.0°C using NV in conjunction with mechanical and evaporative cooling. The investigations of Wu et al. [60] detailed the use of NV in combination with active cooling for large supermarkets located in the cold climates of China. This combination (NV and active cooling) with high thermal mass (including the mass of goods within the buildings) was used to reduce the cooling load and operational time of active cooling systems. In summer, the longest reduction by active cooling achieved was 11 hours. However, both systems simultaneously reduced this efficiency gain. Both NV and active cooling influence each other as active cooling is affected by the NV start-up time, duration, and ventilation rate. As such, NV becomes more efficient when active cooling is turned off. Authors found that the coupled deployment of both active cooling and NV led to a shorter operational duration for active cooling. Zhaojun et al. [59] showed that even light-weight construction benefited from night-ventilation, with a maximum reduction of 3.9°C when an ACH of 10 was used. This study was conducted in the cold climates of Northern China for office blocks. An extensive study for office blocks, educational buildings and production buildings in Germany was conducted by Voss et al. [18] who include night ventilation amongst the effective passive strategies covered. The promising results of their studies of new constructions are optimistic for retrofitting passive systems into older buildings.

Geros et al. [22] predicted energy savings of 39 and 96% when using night ventilation, although flow rates of 10 and 30 ACH would be needed to achieve this. More effective in this presented case study is the use of exposed thermal mass and heavy construction. Finn et al. [103] found that by raising the volume of thermal mass from 887 kg/m² to 1567 kg/m² per unit floor area, a 3 °C reduction in daily temperature can be observed. Moreover, increasing ventilation rates up to 10 ACH can reduce peak temperature up to 1.0 °C. Most studies indicate that beyond a critical air-flow rate, the value of increasing the airflow diminishes and the added energy of running fans becomes an issue.

4.2. Natural cooling (cross and stack driven air-flow)

The impact of daytime ventilation can often be enhanced when night ventilation is used as passive daytime ventilation alone might not be sufficiently effective to provide complete thermal comfort. Kubota et al. [34] present the case of night-ventilated terraced residential buildings in Malaysia (with a hot-humid climate) performing better than daytime ventilation alone, provided some dehumidification is also used (Fig. 11). Landsman et al. [104], whose research is also set in the Malaysian climate, support this result with the recommendation of

using low-energy systems (such as ceiling fans). They show that the elimination of night-time air-conditioning is a possibility, although the daytime temperature could reach unacceptable levels as a result. In their study, NV was shown to produce a significant reduction in the peak indoor air temperature by as much as 2.5 °C on average. The night-time temperature reduction was approximately 2.0 °C. Night-time cross-ventilation was investigated by Aimilios et al. [105] in the mediterranean climate of Cyprus. As with the previous study (Shaviv et al. [71]), heavy vernacular construction led to effective night cooling. Irulegi et al. [106] provided an extensive set of simulations for a variety of configurations within Spain's different climatic zones. Their findings showed the possibility of eliminating air-conditioning during the full working period, and depending on which category of comfort is set, the temperature reduction averages 1 °C. The impact of NV on improving internal thermal comfort levels was studied by Exizidou et al. [17]. The outcomes of the study demonstrate that the average PMV index for the non-ventilated and night ventilated zones was 2.25 and 1.1 respectively. However, there are limitations to using NV strategy concerning the ratio of the opening sizes and proper air velocities. A large-scale study of 214 residential buildings which adopted night ventilation is summarised by Santamouris et al. [53] (set within Athens and Samos). Their findings show that night ventilation reduces the cooling loads of the buildings under study by approximately 40 kWh/m².

Fig 14: Daily SET configurations, Test 1: With daytime ventilation vs. with NV; Test 2: With no ventilation vs. with NV; Test 3: Full-day ventilation vs. with NV [34].

4.3. Control Methods

The enhancement of the efficiency of free cooling by augmented night-time ventilation can be improved considerably by adopting an appropriate operation control algorithm. Zhaojun et al. [59] conducted their study of NV effectiveness in the cold climate of Northern China - Harbin, Beijing and Shenyang. In the control strategies for Harbin, air conditioning was utilised when the outdoor or indoor air temperature exceeded 26 °C. However, during the

daytime with an outdoor temperature lower than the mean radiant temperature of the internal fascia of the building fabric, outside air driven by fans was provided to cool the building. The Shenyang and Beijing control strategies were applicable from 9:00 pm to 7:00 am with a minimum outdoor temperature of 25°C and an air change rate of 10 ACH. The study found that the effectiveness of night ventilation significantly improved by initiating the NV set-up time closer to the active cooling period, and a longer NV operational duration improved the efficiency.

In the Roach et al. [54] research, the control system was set so that when the external ambient temperature was 2 °C lower than the room temperature, the mechanical ventilation system is switched on and continues until the night setpoint temperature (tested for 13°C, 15°C, 17°C and 19°C) was attained. In doing so, although the setpoint of 13 °C brought about the minimum annual cooling energy consumption, owing to overcooling in the morning, a minimum setpoint of 15 °C was selected as the desired setpoint for further analyses. Bozorgchami et al. [107] considered that the most efficient time for NV in office buildings in Yazd, Iran is between 12:00 pm and 7:00 am. However, in this city, Solgi et. al [108] defined an optimum set-point temperature as 30 °C recommending that night ventilation commence when outside temperature is lower than the aforementioned set point. This was to preclude the entry of warm air during operation of night ventilation during hot nights.

Leenknecht et al. [65] explored the flow regiment that would correctly model the surface convection during NV, and found that the Beausoleil-Morrison algorithm [109] may, in fact, leads to an overestimation of cooling efficiency. Vidrih et al. [77] examined the influence of enhanced night-time ventilation for free cooling, and the decrease of energy demand in buildings. The study focused on obtaining control matrices from a generalized model-based predictive weather control algorithm (G-MPWC). The control matrix derived from the G-MPWC is a simple, precise technique for ascertaining the most significant factors of free cooling for enhanced night-time ventilation (Fig. 12). It considers the lesser number of meteorological factors and is intended for dynamically forecasting the thermal comfort of the free-cooling system in the building. The study found that the control matrices used by G-MPWC are capable of reducing the cooling energy demand of the buildings, although differing in levels of complexity and essential user skills for monitoring. Weather-predicted controlling was found to be the most efficient strategy, while the resultant control matrix tends to be static and established for specific buildings. It is also simple to integrate into the control unit of an automated ventilation system and has high accuracy in its predictions.

Fig 12: Operational scheme of the building free cooling by enhanced night-time ventilation [77].

4.4. Night ventilation and supplementary passive cooling

Design features can also be used to improve ventilation rates. The analytical and experimental study conducted by Imessad et al. [44] using a prototype house examined the impact of passive cooling techniques such as insulation, thermal mass, and NV on residential building energy demand and thermal performance in a Mediterranean climate. The study revealed that integrating overhangs and using insulation in the climate of Soudana, Algiers make the use of night ventilation more effective. However, as illustrated in Table 2, NV can be successfully coupled with other energy-efficient techniques, namely ventilated internal double walls, solar thermosyphonic systems, earth to air heat exchange systems, atriums, and solar chimneys. In other words, each of this combination could raise the efficiency of the NV and the level of thermal comfort, but the results and conditions vary according to the type of the supplementary system.

Table 2: Night ventilation coupled with other passive techniques

Ref	Coupled Systems	Images	Outcomes
[42]	Ventilated Internal Double Walls (VIDWs)		<ul style="list-style-type: none"> • Since the thermal mass is especially small and localized, this system is particularly productive in timber-frame houses. • Provided that NV is inside the VIDW, the cooling impact is very noticeable. • To facilitate the convective exchanges, it is imperative to have an adequate air velocity (1–1.5 m/s) in the air gap and a SVIDW/S floor ratio above 0.9, cooling the room effectively. • It is observed that a drop in the maximum room temperature differs from 2°C to more than 5°C based on the SVIDW/S floor ratio. • The introduction of obstacles in the air gap (consisting of about 50%) resulted in 35% increase in performance and the average CHTC.
[52]	Solar Thermosyphonic Systems		<ul style="list-style-type: none"> • A concrete chimney has the capability for NV cooling, whereas its performance is contingent upon orientation and the configuration. • The solar chimney with an attached duct behind the absorber (SC2) facing W had the best performance with 98% higher flow rate compared with the SC1 (conventional solar chimney) oriented S. • The second preferred option would be the conventional solar chimney (SC 1) oriented W with simulated results showing NV achieved through this configuration provided 80% acceptability thermal comfort conditions in a 24-hours period and 90% acceptability within the limit in

an 11-hour period

[48] Earth to Air Heat Exchange (EAHEs)

- Two passive cooling techniques adopted in the building; natural NV and an EAHE system were assessed and compared.
- It was found that natural NV would be 3 to 5 times more efficient in improving thermal summer comfort than EAHEs.

[110] Atriums

- Acceptable thermal comfort conditions can be reached with passive cooling even under extreme climate conditions.
- Not only was an appropriate building operation essential to maintain the room temperature within the required limits but also the behaviour of occupants apropos of opening windows and operating shading systems had an underlying impact.
- An excellent performance of the building in that total primary energy consumption (including heating, cooling, ventilation and lighting) was $115 \text{ kWh m}^{-2} \text{ a}^{-1}$

[111] Atriums and EAHE

- Approximately 10 percent of the working hours operative temperatures is above 25°C .
- To preclude disturbance of the natural ventilation by additional, mechanically driven air flows, Hybrid ventilation strategies ought to be applied.
- Advanced control strategies by virtue of weather forecasts, an adapted simulation model can be utilized.

[30] Solar Chimneys

- An increase of the solar chimney height from 0.15 to 1.65 m results in a 2.6 m/s increase in the airflow rate of the wall - roof solar chimney and results in an air change per hour of 26.
- The optimum height of the wall - roof solar chimney is a 0.15 m inlet with a wall height of 3.45 m, resulting in a significantly improved NV performance in reducing the indoor air temperature from an improved airflow rate.

4.5. Night ventilation barriers

In spite of the advantages outlined in the previous sections regarding the utilization of night ventilation systems, barriers of NV (as opposed to air conditioners) were captured by Kubota et al. [35]. Results demonstrated that while approximately 80% of respondents opened their windows during the daytime, only around 10% did so during night-time. Also, an approximate 38% of interviewees claimed that the intrusion of insects was the main reason, followed by security (35%), rain (22%), dust (18%), air-conditioners (13%). Outside air is flushed through the building to provide cooling, allowing anything in the air to be entered into the building. Hence, careful consideration of ambient air quality and the location of openings is essential. That is, sufficient daytime ventilation needs to be provided to ensure indoor air quality during occupied hours. This strategy can easily allow noise into a building as well. Security is another issue, as this system is contingent upon the feasibility to close the building during the day, and opening it up substantially at night. Moreover, the designer should work out the challenge of extracting the heat by night either naturally or actively; however, in many locations the speed of wind is not adequate at summer nights [79]. Therefore, there are uncertainties related to the effectiveness of NV strategies particularly when the external air temperature is high [45]. Low energy systems are more difficult to establish compared to standard HVAC systems and customarily necessitate a well-integrated synergy across the design, construction and maintenance phases; this is to prevent breakdowns or inefficiencies associated with poor design, installation, operation and maintenance [58].

5. Conclusion

This study set out to determine the effectiveness and limitations of night ventilation across several climates throughout the world. There is uncertainty regarding NV effectiveness when the outdoor temperature is exceedingly high, or the daily temperature amplitude is insufficient. That is, typically climates with high diurnal ranges provide the most convincing situation for utilising night ventilation, while in contrast, hot-humid climates with warmer nights, are generally considered less affected. Extreme weather events and urban microclimates produce atypical conditions that require additional mitigation measures for effective night ventilation. The case of buildings with heavy thermal mass construction; however, presents a situation where NV can have some effect even with high humidity. Both passive and active NV are also capable of reducing the cooling energy demand and improving the indoor thermal comfort for occupants; however, their impacts vary according to some parameters. The parameters that influence NV performance can be classified into three broad groups, namely:

- The climatic parameters such as local outdoor temperatures, daily temperature amplitudes, and topography.
- The building parameters such as the useful thermal inertia available, the solar and internal heat gains, the presence of insulation, level of air tightness and functionality.
- The technical parameters such as the heat transfer coefficient (CHTC), the optimal operation of the adopted cooling technique, the operational time and duration, air flow rates, and the NV control algorithms.

Many different building typologies were utilised in the studies reviewed, including residential, commercial, libraries and laboratories. However, the majority of the studies were conducted in non-residential buildings. This trend is the result of the limitations of NV with regards to the indoor privacy as well as the operational period of the building at night. There is great potential for utilizing PCMs as innovative and lightweight thermal storage for NV systems since combining PCMs with NV considerably reduces the necessity for HVAC systems. This combination gives the potential for buildings in climates with low night-time outdoor temperatures to utilise natural or fan-assisted NV coupled with PCMs to exponentially augment their cooling performance. Additionally, linking NV with other techniques such as VIDW, thermos-syphons, EAHes, atriums, and solar chimneys can be highly effective, in that an acceptable thermal comfort condition can be attained with passive cooling even under extreme climate conditions. The coupled operation of NV and these other strategies is aimed at boosting its effectiveness, especially for climates (warm and humid) or in building typologies (low thermal inertia timber-framed buildings) that cannot support the exclusive deployment of NV in terms of energy savings and improvement of thermal comfort.

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