Designing a Naturally Ventilated Building in an Air Polluted City

Case study of a library in Milan: challenges, implementation, and energy savings

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ABSTRACT: This paper develops the adoption of natural ventilation (NV) as a sustainable solution for cooling in urban environments, with a focus on the challenging context of Milan. Using the European Library of Information and Culture (BEIC, from Baukuh and Onsite Studio with the help of Atmos Lab) as a case study, the paper delves into the practical integration of NV and its impact on energy efficiency. Analysing critical pollutants (PM2.5, PM10, NO_2, O_3) from 2015 to 2023 in Milan, the study compares concentrations against Italian laws and WHO guidelines. The main pollutants significantly decrease during the natural ventilation season, consistently below recommended thresholds, and exhibit decreasing trends over recent years, supporting the safe implementation of NV. Thermal simulations show a 29% increase in cooling demand with the omission of night cooling strategies and up to 64% without NV entirely. This escalation is further pronounced when accounting for electrical fan usage, resulting in a total increase of 72% and 188%, respectively, thus underscoring the importance of NV strategies in resilient urban design.
KEYWORDS: Natural Ventilation, Air Pollution, Energy Efficiency, Air Quality, Passive Design

1. INTRODUCTION

The increasing global temperatures are inducing a rise in the cooling demand in buildings across Europe, making it the fastest-growing use of energy in buildings [1]. During the last decades, an increase in air pollution in cities started to advocate against the use of natural ventilation [2,3] to provide fresh air and ventilate, which coupled with the easiness of calculation and implementation of mechanical ventilation completely discouraged the use of natural means. At the same time, building energy policies are demanding increasingly well-insulated and airtight envelopes which make buildings more susceptible to overheating, thereby escalating the need for increased cooling. This emphasises the urgency to find solutions for the feasibility of natural ventilation in cities where it ceased to be the norm. This also builds on the increasing attention from policymakers towards air quality, growing public awareness and drastic changes in weather conditions. This paper presents the project for a naturally ventilated library in Milan, a city that ranks among the most polluted in Europe: the European Library of Information and Culture (BEIC), designed by Baukuh and Onsite Studio with the help of the authors as environmental consultants, and currently under construction. The paper delves into the challenges found in designing such a naturally ventilated building and the benefits of implementing the strategy.

2. THE CLIMATE OF MILAN

The climate of Milan is humid subtropical with hot and humid summers and relatively cold winters. Predictions for 2050 indicate a significant impact of climate change on Milan's summers, with an expected average temperature increase of 2.5 °C, reaching an average high of above 30 °C. Prevailing winds, characterised by low velocity, consistently come from southern orientations throughout the year.

3. THE CASE STUDY

The BEIC consists of two naves with a trapezoidal cross-section, extensively glazed, for a total area of around 30,000 m². An atrium in the northern volume, provides space for circulation and social interaction, introduces daylight to the building's core, and acts as a buffer space to reduce winter heat losses from the surrounding heated volume. The traditional library space is in the south nave to benefit from the sun, whereas the Media library is in the north nave to avoid direct contact with the sun, thus preventing the coupling of its high internal gains with the solar ones. The book storage is located underground, to benefit from its stable hygrothermal conditions. The atrium's central position enables cross ventilation with the spaces at each level, collecting exhausted air that mixes with fresh air before being released through high openings on the top floor. (Figure 1)

Figure 1: Nuova BEIC, images, typical plan and section presented in the competition.

3.1 Implementation of the natural ventilation strategy

Operable windows are installed on all facades, with the amount determined by facade orientation and function, optimised via thermal simulations.

In general, the design focused on the number of operable windows per facade, as factors such as the type of opening and discharge coefficient had already been maximized within the constraints imposed by the presence of solar protection mesh on the facade. In most of the facades, ¼ of the panes are operable, allowing for granular control of the openings. In the atrium, a larger proportion of operable windows, particularly in the upper part, were necessary to improve air circulation and maintain the neutral pressure plane higher than the last occupied floor, ensuring that hot air is effectively exhausted without being drawn back into occupied areas (Figure 2).

The optimisation through thermal simulations was aimed at enhancing the building's behaviour in free-running mode (no heating nor cooling) and reducing the cooling demand in active mode. Consequently, thermal simulations guided the definition of operation modes tailored to seasonal conditions (Figure 3): in winter, windows remain closed as outdoor temperatures are largely below those required indoors; during the temperate time of the year (mostly spring, autumn, and some milder summer days), outdoor temperatures are acceptable for human comfort and windows can open during the day; while in the hot season, air conditioning is active during the day and windows are closed, however, when outdoor temperature drop at night, windows can open to dissipate residual heat and prepare the building for the following day.

To facilitate the operation of the window when conditions are favourable, a significant proportion of them are automated. This feature is crucial for supporting night cooling strategies and ensuring control over the windows that are out of the occupants' reach.

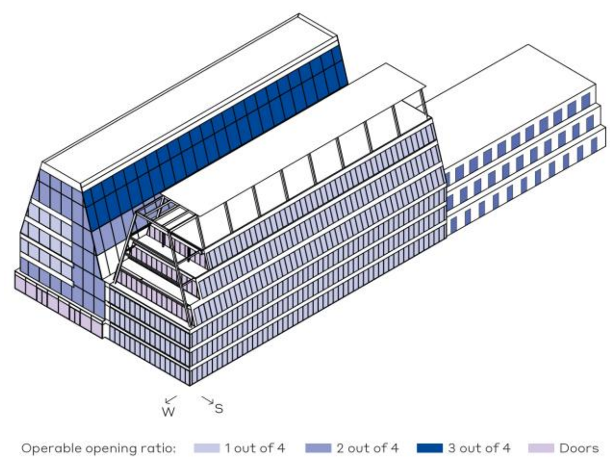

Figure 2: Operable opening ratios by facade.

4. METHODOLOGY

Critical pollutants (PM2.5, PM10, NO_2, O_3) are analysed from 2015 to 2023 using data from ARPA Lombardia´s air quality stations [4], which are classified as Traffic and Background based on proximity to traffic. The urban background station "Milano Pascal Città

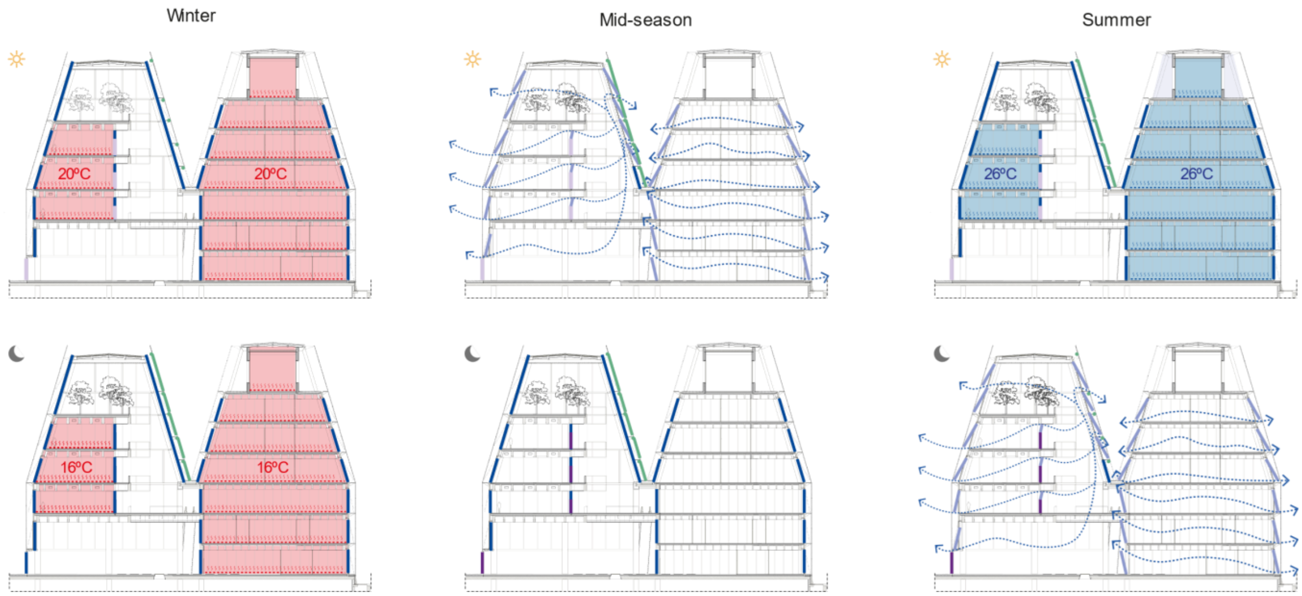

Figure 3: Operation modes of the building during each season of the year.

Studi" is chosen for its comprehensive pollutant collection (not all stations measure all pollutants) and its proximity to the site (2 km). Given the potential discrepancies with urban stations [5], an in-depth examination of all stations was conducted, and no significant differences were observed. Other key pollutants like CO and SO_2 are not reported as they consistently remain well below the recommended limits [6].

Concentrations are compared against Italian legal limits (baseline) and WHO guidelines (target) [3]. While the WHO periodically updates guidelines, the most recent EU (2008) and Italian decrees (2010) [7,8] implement the WHO guidelines from 2005 [9].

Table 1: Italian (and EU) legal limits and recommended AQG targets from WHO Air Quality Guidelines 2021.

Pollutant	Averaging time	Limit value	AQG
PM2.5, µg/m^3	Annual	25	5
	24-hour	25$^{(a)}$	15
PM10, µg/m^3	Annual	40	15
	24-hour	50	45
NO_2, µg/m^3	Annual	40	10
	24-hour	200$^{(b)}$	25
O_3, µg/m^3	8-hour$^{(c)}$	120	100

(a) Lacking a 24-hour limit, it aligns with the annual limit value and 24-hour WHO interim target 4.
(b) The 1-hour limit is adopted.
(c) Daily maximum 8-hour mean.

The analysis focuses on the short-term limits (24-hour and 8-hour) to assess the dynamics with precision. The natural ventilation season is considered from the 1st of April to the 30th of September, for a total of 183 days.

The thermal model was built in EnergyPlus v.22.1 via Honeybee [10] for Grasshopper and Rhinoceros. The benefits are evaluated in terms of reduction in energy demand and energy consumption. Three scenarios were simulated:

I. Day and night NV: baseline scenario that represents the final configuration of the building.
II. Daytime NV only, with night ventilation via mechanical systems.
III. No NV: Cooling relies solely on mechanical systems. Night ventilation is carried out via mechanical systems.

For scenarios I and II, windows open when $T_{in} > 23$ °C and when $T_{in} > T_{out}$. In scenarios II and III, mechanical systems integrate the use of "free cooling", an approach to lower indoor air temperature by introducing external air when it is naturally colder, and it is commonly employed to reduce energy consumption. However, in practice, free cooling is not entirely cost-free, as it requires energy for fans. In the model, it activates when $T_{in} > 23$ °C and when the temperature difference between inside and outside is > 4 °C. This is common practice as it avoids air movement and associated fan energy consumption with little benefit. The efficiency factors for the fans are 1.3 kW/(m^3/s) for supply and 0.9 kW/(m^3/s) for extraction. The conversion from cooling energy demand to electrical consumption is calculated assuming a coefficient of performance (COP) of 3.5.

5. AIR QUALITY IN MILAN

5.1 Context

Milan is one of the most populous cities in the Po Valley, an area that ranks at the top of the most polluted in Europe due to aggressive land use, extensive industrialization, high population densities, and resulting high levels of road transport. The natural confinement formed by the Alps to the north and the Apennine chain to the south, makes the wind speed in this area among the lowest in Europe, around 1.5 m/s on average, favouring air stagnation and winter fog events that trap pollution close to the ground. According to a recent study [11], if Po Valley had the same meteorological conditions typical of central-northern Europe, average monthly concentrations of PM10 and NO_2 would be lowered by 60 to 70% [11].

5.2 Air Quality Analysis

Figures 4, 5, 6 and 7 show the concentration levels of PM2.5, PM10, NO_2, and O_3, also reporting the trend of days exceeding the recommended limit. Table 2 summarises the number of days exceeding the limit and guideline values during the natural ventilation season, highlighting their limited occurrence compared to the entire season and the overall reduction trend over recent years.

The measurements of all pollutants show a marked seasonal behaviour. Concentration levels of PM2.5, PM10, and NO_2 reach maximum peaks during winter, as the need for combustion in domestic heating and increased traffic density cause an increase in emissions [12]. During the warmer months, pollutants are at a minimum as there is a decrease in combustion and improved dispersion, aided by rainfall in the mid-seasons. Therefore, during the natural ventilation season, pollution levels are reduced on average by 32% for PM2.5 and NO_2, and 35% for PM10 compared to annual values. Remarkably, a significant number of days within this period fall below both regulatory limits and guideline values, especially demonstrating favourable trends over recent years.

Ozone presents a pronounced seasonal behaviour with peaks during the hot season. It is formed in the atmosphere by photochemical reactions in the presence of sunlight and precursor pollutants, such as NO_x and VOCs, explaining their higher concentrations in summer. During the natural ventilation season, O_3 concentration exceeds the recommended limit for almost 1/4 of the period and 1/2 of the total days when considering the guideline target. However, despite the summer daily average being higher, O_3 is characterized by a strong diurnal variation due to its significant influence on temperature, relative humidity, and sunshine [13]. This variation reduces night-time levels enough to permit the night cooling needed during the hottest period. It's also important to note that the higher presence of NO in cities contributes to the degradation cycle of O_3, resulting in lower concentrations than in mountain and rural areas, where the air quality wouldn't be considered a threat to natural ventilation. Moreover, ozone filters are not typically included in standard mechanical systems, making it a stretch to consider ozone a constraint on NV implementation.

Table 2: Number of days exceeding the limit (and guideline) value during the natural ventilation season (out of 183 days).

	PM2.5	PM10	NO2	O3
2015	29 (95)	5 (9)	0 (108)	43 (87)
2016	18 (82)	9 (13)	0 (130)	50 (87)
2017	13 (61)	0 (4)	0 (92)	64 (106)
2018	10 (61)	1 (3)	0 (86)	62 (112)
2019	4 (40)	1 (1)	0 (66)	49 (97)
2020	5 (40)	0 (1)	0 (29)	48 (110)
2021	3 (34)	0 (2)	0 (40)	37 (80)
2022	1 (14)	0 (1)	0 (56)	44 (111)
2023	1 (21)	0 (1)	0 (39)	32 (79)

5.3 Future projections of the air quality in Milan

Numerous air quality studies support the hypothesis of a generalised decreasing trend in pollutant emissions in the future [6,14,15], attributed to consistent improvements in citizens' vehicle fleets, with a growing prevalence of carbon-neutral vehicles, or changes in the industrial productive system, showing increased consideration for the environment and emissions control. Notably, the Municipality of Milan is proactively enhancing air quality through regulations and measures restricting activities that generate pollution and promoting the adoption of more sustainable practices. These initiatives aim to further diminish air pollution in the upcoming years, creating opportunities for a wider implementation of natural ventilation strategies.

6. BENEFITS OF USING NATURAL VENTILATION

The benefits of adopting natural ventilation strategies are presented in terms of energy savings calculated through thermal simulations (Figure 8):

- The total cooling demand for the building is 10 kWh/m^2, which is considered low. With a COP of 3.5, the annual electrical consumption is equal to 3 kWh_{el}/m^2.
- Opting for mechanical ventilation instead of natural ventilation for night cooling raises cooling energy demand by 29% to 12 kWh/m^2 (4 kWh_{el}/m^2). When factoring in the electrical energy utilised by fans, the total energy consumption increases by 72%.
- If natural ventilation strategies are completely omitted, cooling demand increases by 64% to 16 kWh/m^2 (5 kWh_{el}/m^2) when compared to the baseline, and up to 188% if including the energy for fans.

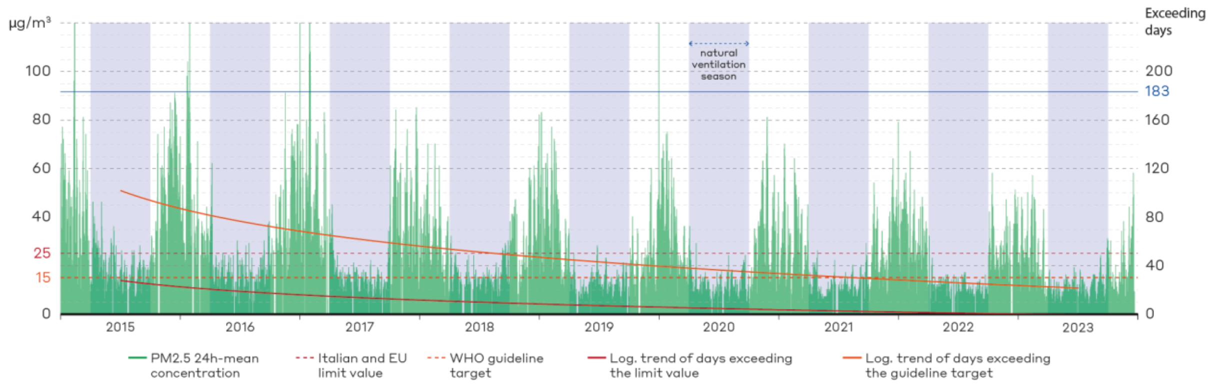

Figure 4: PM2.5 daily mean concentrations, and trend of days exceeding the limit and guideline values from April to September.

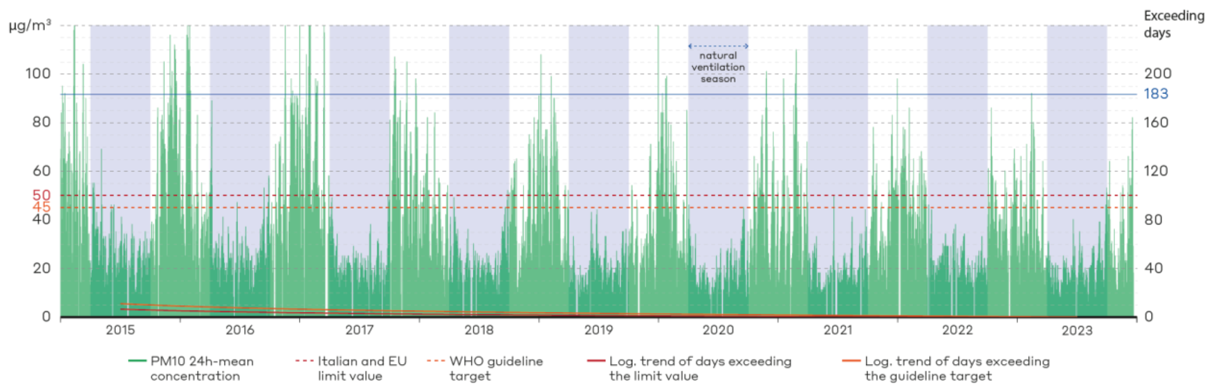

Figure 5: PM10 daily mean concentrations, and trend of days exceeding the limit and guideline values from April to September.

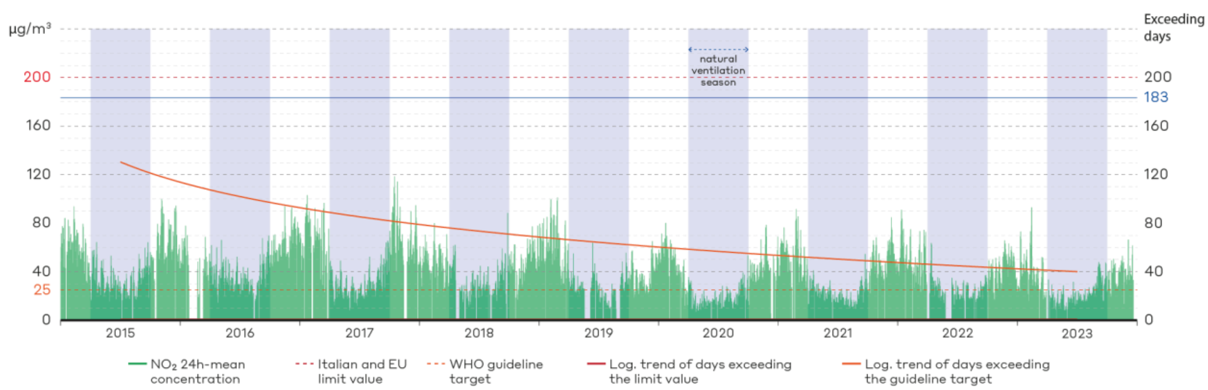

Figure 6: NO_2 daily mean concentrations, and trend of days exceeding the limit and guideline values from April to September.

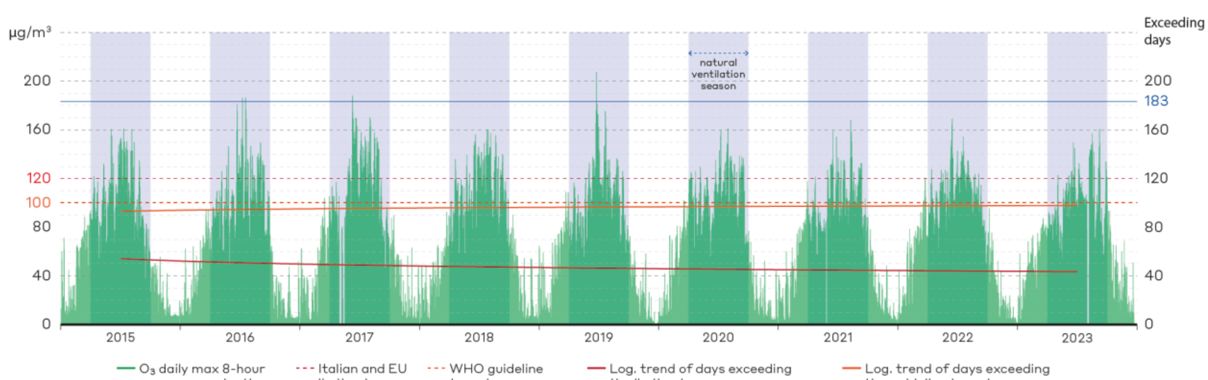

Figure 7: O_3 daily max 8-hour mean concentrations, and trend of days exceeding the limit and guideline values from April to September.

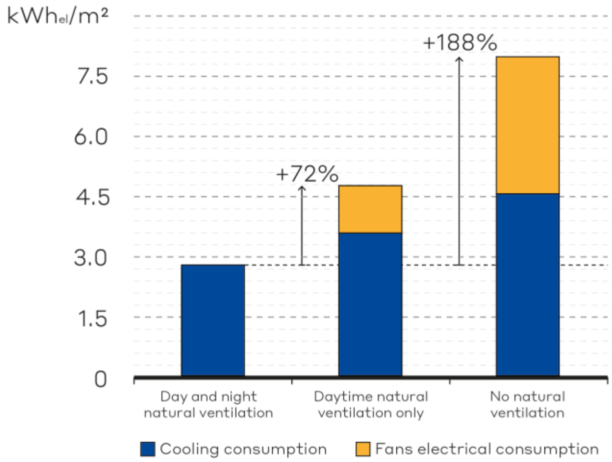

Figure 8: Annual electrical energy consumption in the three ventilation scenarios.

Although scenarios with reduced or absent use of NV integrate free cooling, this does not prove to be as effective as natural ventilation via windows opening, as its operation is limited by more restrictive conditions that prevent the fans from operating for little benefit. Furthermore, the operation of the fans to perform free-cooling proves to be significantly energy-intensive, consuming 25% and 43% of the total electrical consumption, respectively. This increase results in significant operating costs for the building every year, confirming the superiority of natural ventilation in making the building more sustainable and resilient.

7. CONCLUSION

In response to the escalating cooling demand in buildings due to rising temperatures from climate change, this paper supports a transition towards natural ventilation and passive cooling. However, concerns about increased pollutant transport into buildings through open windows necessitate a thorough assessment of air quality during the design process.

The case study of Milan, known for its air pollution challenges, provides the context to assess the feasibility of natural ventilation strategies in urban environments. Analysing critical pollutants (PM2.5, PM10, NO_2, O_3) from 2015 to 2023, the study compares concentrations against Italian and EU limits and WHO guidelines. Despite challenges posed by ozone, potentially limiting natural ventilation implementation during the hottest summer weeks, other pollutants exhibit a marked reduction during the natural ventilation season with values that consistently fall below recommended thresholds for a significant number of days. Results also indicate that Milan's air quality exhibits favourable trends in decreasing pollution levels, supporting a wider implementation of NV strategies in the upcoming years.

A detailed case study of the European Library of Information and Culture (BEIC) illustrates the practical integration of NV. Through thermal simulations, the study quantifies energy savings and underscores the effectiveness of NV in reducing cooling demands. The analysis reveals that choosing mechanical free cooling over NV for night cooling significantly increases cooling energy consumption, and this escalation is further pronounced when accounting for fan usage. When entirely omitting natural ventilation strategies, the impact is magnified.

In conclusion, the BEIC project in Milan serves as a practical example of the effectiveness of natural ventilation in addressing the challenge posed by increasing cooling demands, reducing the reliance on mechanical systems and increasing the resilience of buildings in response to climate change.

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