Ventilation Systems for Efficient Energy Use

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1 Introduction

Any indoor space must be properly ventilated in order to maintain a healthy environment. During ventilation, contaminated indoor air is replaced with fresh air from outside to maintain good air quality by removing pollutants and circulating fresh air [1]. When airflow is inadequate, harmful gases and particles can build up, causing headaches, dizziness, or respiratory problems [2]. Additionally, proper ventilation can help regulate temperature and humidity levels, creating a more comfortable and productive environment. This can be done by reducing the build-up of humidity and removing excess heat from the indoor environment. According to ASHRAE Standard 62.1 [3, 4], the amount of outdoor air required in the breezing zone should not be less than the minimum rate (V_{bz}) that is calculated by the following equation:

$$V_{bz} = R_p \times P_z + R_a \times A_z \tag{1}$$

where R_p, R_a, P_z, A_z are the outdoor airflow rate required per person, outdoor airflow rate required per area, number of people during space use, and floor area, respectively. The ventilation can be natural, mechanical, or a combination of both through cracks, windows, or openings in the building envelope (air infiltration) or persistently provided through natural or mechanical means (hybrid or mixed-mode ventilation)

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[5]. Mechanical ventilation distributes airflow throughout the building through fans and ductwork, with air terminals or diffusers conducting the air into the room. In some cases, however, this process requires high levels of energy consumption, particularly if mechanical systems are used as part of the process. This power is used to move air in and out of buildings and to condition that air to the desired temperature and humidity levels. Depending on the building's size and number of occupants, and the level of indoor air quality desired, the amount of energy required can vary. Properly designing and maintaining ventilation systems can minimize energy consumption, and adequate ventilation can still be provided. Consequently, balancing energy efficiency with adequate ventilation is essential. In some cases, providing the system with the needed energy requirements can be done by different types of renewable energy resources. The system can be supplied with the required energy levels in some cases using a variety of renewable energy resources. Renewable energy plays a crucial role in mitigating climate change. Unlike fossil fuels, renewable energy sources such as solar and wind do not emit greenhouse gases that contribute to global warming [6]. Additionally, renewable energy technologies have become more cost-effective and efficient in recent years, making them a viable, sustainable alternative. Several solar and wind energy technologies can be exploited for building ventilation [7–9]. In this paper, a comprehensive review of different types of ventilation methods that are being utilized in buildings is presented. This includes reviewing numerous types of natural ventilation systems, mechanical ventilation systems, hybrid ventilation systems, and renewable energy-based ventilation systems.

2 Natural Ventilation

Natural ventilation (NV) is the process of supplying and removing air from an indoor space without the use of mechanical systems [10]. It relies on natural forces such as wind and temperature differences to create airflow. This method can improve indoor air quality and reduce energy consumption. NV can be achieved by opening windows, using vents, and creating air pathways. However, it should be designed in accordance with the climate, orientation of the building, and needs of occupants [11]. Several decades ago, scientists studied, analysed, and refined natural ventilation techniques [12]. Pabiou et al. [13] mentioned in their study that natural cross-ventilation is considered a promising solution to fulfil thermal comfort conditions in the summer season. However, in order to utilize this technique in hot climatic regions, the heat rate that should be dissipated must be predicted first for system effectiveness. NV schemes are an effective way to improve indoor air quality and reduce energy depletion. They work by using natural airflow to circulate fresh air throughout a building, reducing the need for mechanical ventilation systems. This can lead to significant energy savings and a healthier indoor environment. Some common natural ventilation strategies include single-sided ventilation, high-level roof ventilation, cross-ventilation, and ventilation chimneys. Figure 1 shows schematic diagrams of each of those methods. The effectiveness of these strategies depends on factors such as building design, climate, and occupancy patterns. However, when implemented properly, natural ventilation schemes can provide a cost-effective and sustainable solution for improving indoor air quality.

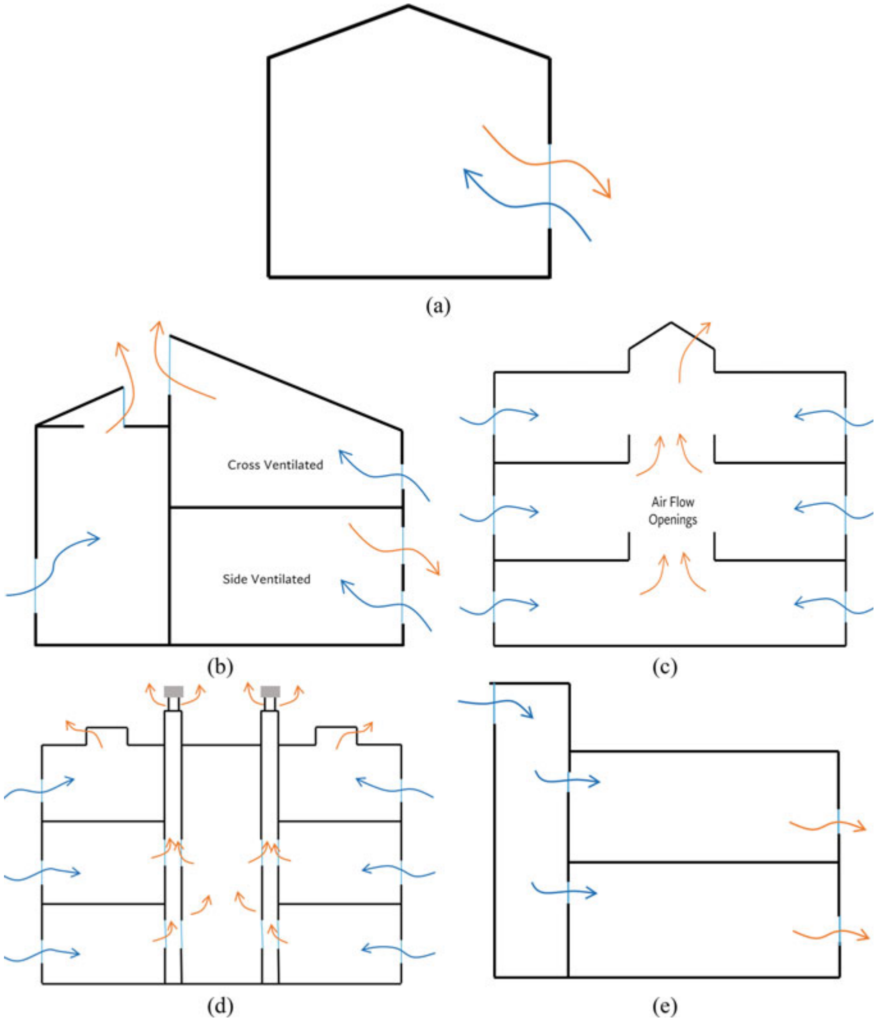

Fig. 1 Natural ventilation schemes: **a** single-sided ventilation, **b** high-level roof ventilation, **c** crossflow ventilation, **d** ventilation chimneys, **e** wind scoop

2.1 Single-Sided Ventilation

In single-sided ventilation, openings are generally placed on one side of the external wall, facing the wind as presented in Fig. 1a. This method can naturally ventilate spaces with limited areas [14]. Single-sided ventilation systems are commonly utilized in construction projects where cross-ventilation is not feasible due to various restrictions such as structural or environmental factors. These systems allow for satisfactory air circulation and exchange, ensuring a comfortable and healthy indoor environment. Additionally, single-sided ventilation systems are often more cost-effective and energy-efficient compared to other ventilation options. Gan [15] predicted theoretically the temperature distribution, airflow profile, and depth of air distribution of a single-sided ventilation scheme in a building. The findings revealed that the air distribution depth can be defined by using the internal heat of the building and outdoor temperature. Aflaki et al. [16] studied single-sided ventilation for high-level buildings in tropical climates as it is favourable in comparison with the crossflow type. The study considered the investigation of the impact of this scheme on the humidity, indoor temperature, and air velocity. At an air velocity of 0.52 m/s, the highest floor's thermal comfort conditions have been obtained by 90%.

2.2 High-Level Roof Ventilation

High-level roof ventilation is a system that is located in the upper part of a roof. It is designed to allow air to circulate through the roof space (Fig. 1b), which can help in reducing the temperature and humidity levels inside the building. The system typically consists of a series of vents or louvers that are placed at strategic locations along the roofline. These vents can be opened or closed, depending on the weather conditions and the needs of the building [17]. High-level roof ventilation effectively improves indoor air quality and reduces the risk of moisture damage to the roof structure.

2.3 Crossflow Ventilation

Crossflow ventilation is a method of natural ventilation that involves the movement of air through a building, from one side to the other [18]. It is achieved by opening windows or vents on opposite sides of the building (Fig. 1c), which allows air to enter one side and exit from the other. This method of ventilation is often used in buildings where mechanical ventilation is not practical or desirable, such as in residential homes or small commercial buildings. Crossflow ventilation can help to improve indoor air quality, reduce the risk of mould and mildew growth, and lower energy costs by reducing the need for air conditioning. It is important to ensure that the windows or vents used for crossflow ventilation are properly sized and located to maximize airflow and minimize the risk of drafts. Chu and Chiang [19], investigated theoretically and experimentally the crossflow scheme of a building and the validation of a rule of thumb stating that the building length should be five times the building height for better ventilation rates. The findings revealed proof of the rule of thumb. However, ventilation rates decreased when increasing the building length further.

2.4 Ventilation Chimneys

The chimney effect, also called the stack effect, is constantly used in vertical buildings to provide ventilation through vertical airflow. It is a natural phenomenon that occurs in buildings. It is caused by the temperature, pressure, and densities differences between indoor and outdoor air [20]. It involves ushering cool air in and warm air out with help from strategically placed openings in a building. Warm air rises and escapes through openings in the upper part of the building (Fig. 1d), clerestory, zenithally openings, or wind exhausts. On the other hand, cooler air is drawn in through openings in the lower part of the building. This creates a continuous flow of air through the building and guarantees the building's natural ventilation. The chimney effect can positively and negatively affect a building's energy efficiency and indoor air quality. Proper ventilation and insulation can help to mitigate the negative consequences of the chimney effect. Ding et al. [21] studied theoretically and experimentally the possibility of integrating the solar chimney with a double-skin façade. The study revealed that increasing the solar chimney height would lead to rising the ventilation rate and ensure better pressure difference distribution. However, the authors recommended that the height should exceed two-floor high.

2.5 Wind Scoop

A Wind Scoop is a passive ventilation system that can be installed on the roof of a building to improve indoor air quality and thermal comfort. It captures the natural wind flow and directs it into the building, creating a cooling breeze [12] as presented in Fig. 1e. Wind Scoops are particularly effective in hot and dry climates, where air conditioning can be expensive and energy intensive. They are also environmentally friendly, as they do not require any electricity or mechanical components. Studies have shown that buildings with wind scoops have lower indoor temperatures and reduced energy consumption. Khan et al. [22] have reviewed various types of wind scoops in their recent study and suggested one with the ability to rotate with the wind direction. Overall, Wind Scoops are a cost-effective and sustainable solution for improving indoor air quality and thermal comfort in buildings.

3 Mechanical Ventilation

Mechanical ventilation (MV) is a system used in buildings to provide fresh air and remove stale air by means of mechanical devices [23, 24]. It is typically used in buildings where natural ventilation is not sufficient or not possible. Mechanical ventilation systems can be either central or local. Central systems are designed to serve the entire building, while local systems are designed to serve individual rooms or areas. The type of system used depends on the building's size, layout, and occupancy. They can be designed to provide a variety of airflows, depending on the building's needs. These systems are typically designed to meet specific standards and codes to ensure that they are safe and effective.

- Central ventilation systems are an imperative component of prevailing buildings. They serve to circulate fresh air throughout the building and remove stale air, odours, and pollutants. These systems typically consist of a network of ducts and vents that are connected to a central unit. A centralized ventilation system usually uses fewer, but larger, air handling units (AHUs) as shown in Fig. 2a. These are usually located on the roof of the building or indoors in technical rooms. The system's size and capacity depend on the building's size and the number of occupants. Regular maintenance and cleaning are essential to ensure the system operates efficiently and effectively.
- In terms of local ventilation systems, help to maintain a healthy and comfortable indoor environment by removing pollutants and excess moisture from the air. These systems are typically designed to meet specific requirements based on the size and usage of the building. They can be installed in a variety of locations, including bathrooms, kitchens, and industrial workspaces such as fans. Several points should be taken into consideration when selecting a suitable fan such as power consumption, current consumption, air volume, fan speed, noise, and the net fan weight. Proper maintenance and regular cleaning are necessary to ensure that these systems continue to function effectively.

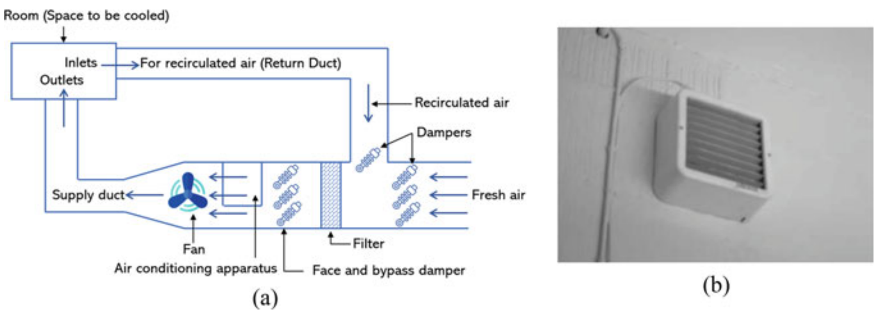

Fig. 2 **a** Central ventilation system, and **b** local system: wall-fan

4 Hybrid Ventilation Systems (Mixed Mode)

Hybrid ventilation (HV) technology depends on utilizing both natural and mechanical ventilation systems to ensure the thermal comfort conditions of the indoor space are met [24, 25]. Sometimes, a switch between different technologies can be made depending on the year's season. Therefore, by implementing this method, the capital cost and energy consumption can be reduced in comparison with the MV systems. In addition, vigorous indoor air quality (IAQ) and air conditioning conditions can be met. As a result, hybrid ventilation systems are becoming increasingly popular. Utilizing HV technologies in the building is subject to two main approaches. The contingency approach depends on the use of natural ventilation and utilizing mechanical systems to provide further cooling and ventilation to the building. Usually, this approach can be implemented when an old building is being renovated and strict policies should be met. On the other hand, a complementary approach is when both natural and mechanical systems are designed and integrated for operation. However, this approach takes the advantage of the outdoor ambient conditions to maintain the required indoor air quality and thermal conditions when the outside air conditions are not suitable. Figure 3 shows different configurations of HV systems for improving air quality.

5 Renewable Energy-Based Ventilation Systems

Renewable energy-based ventilation systems are becoming increasingly popular due to their many benefits. These systems use clean energy sources such as wind and solar power to operate, reducing reliance on non-renewable sources. Additionally, they are environmentally friendly as they do not emit harmful pollutants into the atmosphere. Furthermore, they can help reduce energy costs in the long run as they require less maintenance and have a longer lifespan compared to traditional ventilation systems. They are, also, a practical and sustainable solution for modern buildings. Figure 4 shows different possible renewable energy options that can be implemented for ventilating a building. However, a combination of these technologies can be used under specific design conditions. The next subsections will discuss different renewable energy applications for building ventilation.

5.1 Solar Energy Systems

5.1.1 Photovoltaics

Photovoltaics (PV) are semi-conductor devices that absorb incident solar energy and convert it into electrical energy [26–29]. The PV system consists of a PV panel,

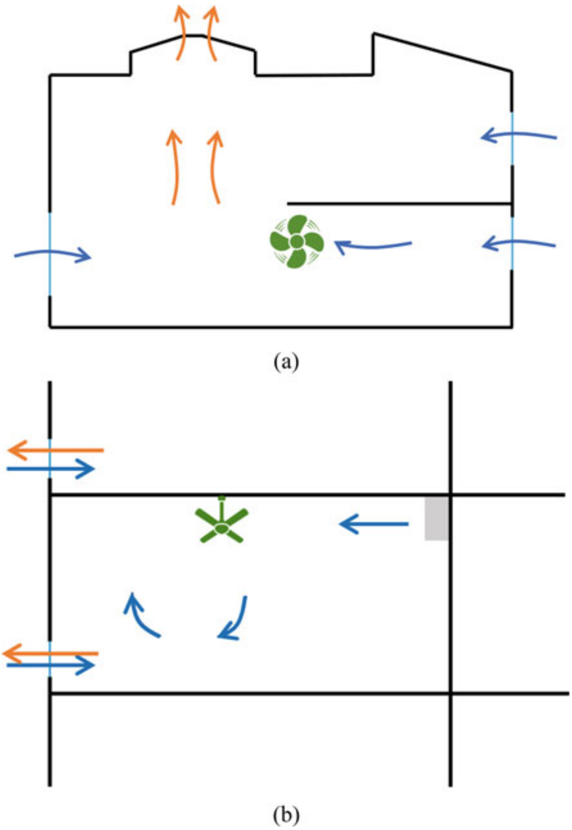

Fig. 3 Different configurations of HV systems when utilizing **a** wall fan, **b** ceiling fan

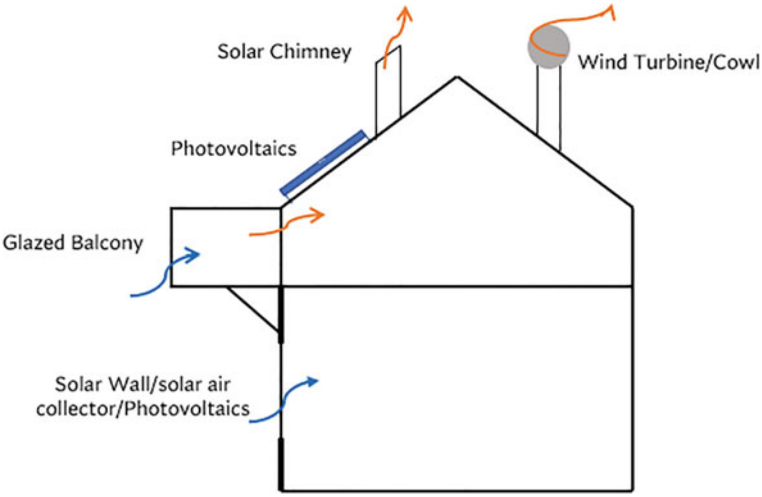

Fig. 4 Different scenarios of renewable energy-based ventilation systems

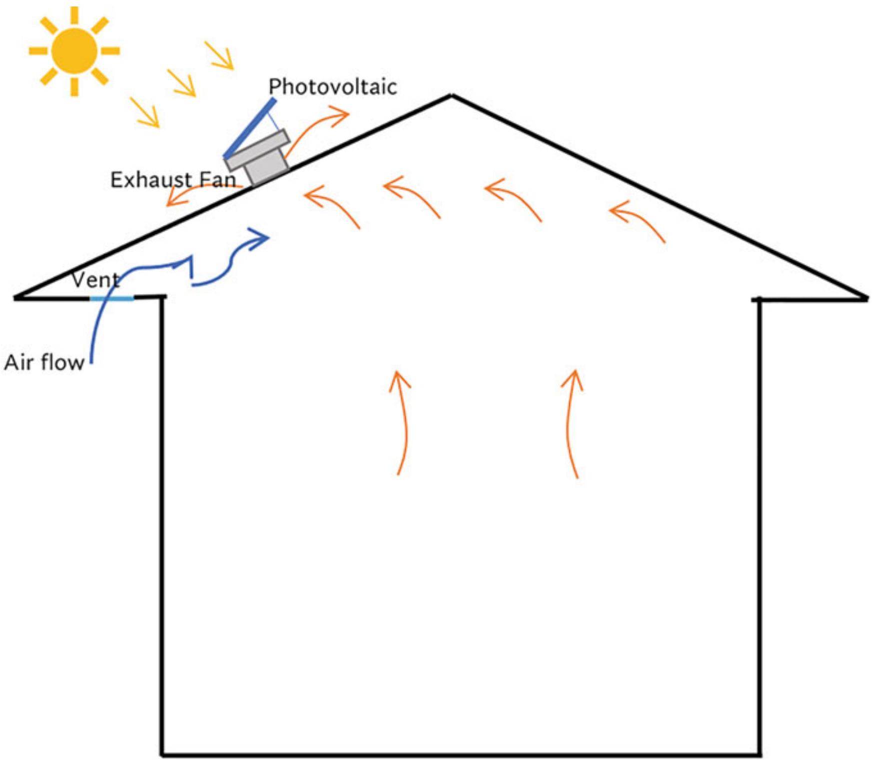

Fig. 5 Solar powered exhaust fan

inverter, and battery if it is not connected to the grid. This system is most suitable to be established in locations that have high levels of incident solar irradiances for reliable operation. The geographical location of the building, and PV installation to prevent the shadowing which may occur to the solar cells are crucial parameters for system feasibility. Overall, the best operating conditions are when the PV system faces the south and the optimum tilt angle is assured. Using the power produced by the PV system, some ventilation system components can be powered [30]. These components may be actuators as they require low energy demand. Therefore, small PV modules may be suitable. However, fans require high energy consumption, involving larger PV modules and a battery bank (Fig. 5).

5.1.2 Other Solar Systems

The ventilation system may involve different solar energy technology in addition to the photovoltaic technology discussed above [30, 31]. In glazed balconies, the air enters and is heated by the sun directly in a closed space. However, this method may cause air overheating especially in summer. Therefore, regions with shorter summer

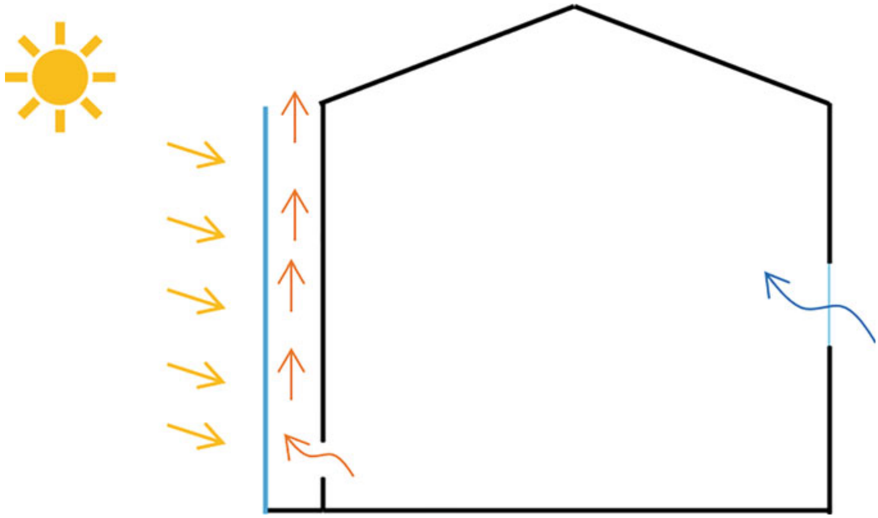

Fig. 6 Solar chimney concept

seasons are favourable for implementing this option. In addition, the heated moist air may be condensed on the building's window which is counted as an additional limitation. However, this method is believed to be a cost-effective option that doesn't require regular maintenance. Another option is by using a solar collector in which the air absorbs the heat of the incident solar energy. Usually, a fan is used to force the air to pass through the solar collector and is then reheated in the central heating system of the building to increase the heat further. The system cost depends mainly on the building location and the heating level requirements (Fig. 6).

5.2 Wind Energy Systems

By using a wind turbine, the kinetic energy due to the air movement can be converted into electrical power or mechanical energy [32–34]. This technique depends mainly on wind direction and speed. The enclosed space can be ventilated by placing this small wind turbine in the attic or the rooftop of the building. Fresh air can flow and enter through the building by using intake and exhaust vents as shown in Fig. 7a. This can reduce the temperature of the internal space, recirculate the air to ensure indoor air quality is obtained, and certain comfort conditions have been met. The type of intake vent that is used depends on the building structure, the system design criteria, and the area where the system is to be installed. To ensure a balanced process and a sufficient flow of air through an attic, exhaust vents must be applied simultaneously with intake vents.

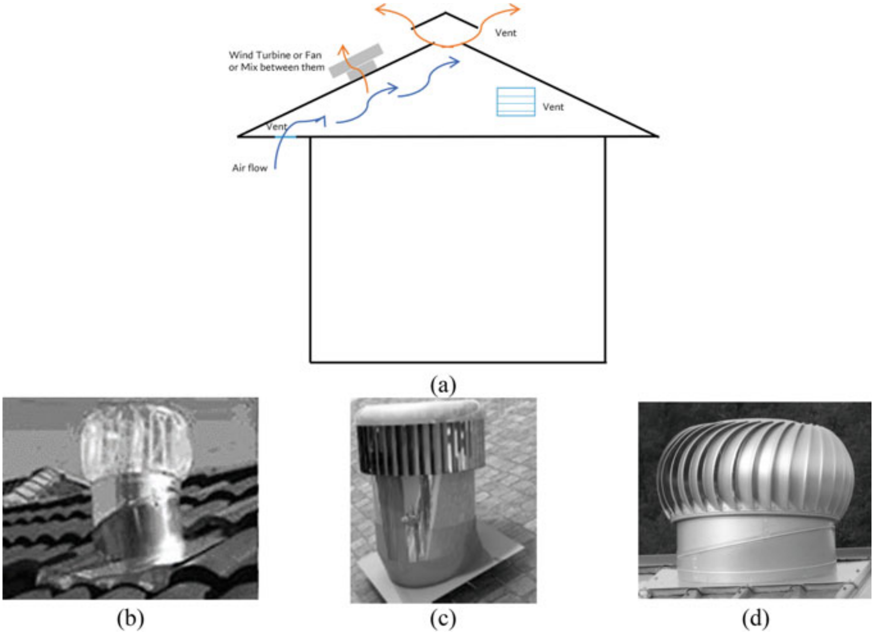

Fig. 7 **a** Principles of using wind turbine with or without a fan for air ventilation, examples of **b** straight vane turbines with a curved side [12], **c** straight vane turbines, and **d** curved vane turbines

Several types of wind turbines can be utilized in ventilation systems [35] such as straight vane turbines with a curved side, straight vane turbines, and curved vane turbines as shown in Fig. 7b–d. Designed for light winds, straight vane turbines with a curved side consist of polycarbonate blades with vertical vanes and an aluminium neck. On the other hand, straight vane turbines have a vertical design made from lightweight aluminium. They work efficiently for extracting smoke. Curved vane turbines are manufactured from galvanized mild steel or lightweight aluminium. A slight breeze or convection current will activate these types of vents. Sometimes these turbines cannot be effective in providing enough air circulation. Therefore, several researchers have proposed integrating wind turbines with a fan to increase the air change rate. In some cases, this may require a power supply that can be supplied by photovoltaic panels as presented in Fig. 8. In some scenarios, the wind turbine can be integrated with photovoltaics such as a study provided by [36]. The authors suggested this prototype to enhance the ventilation rate. The system consists of a wind turbine and an inner fan powered by a photovoltaic panel as shown in Fig. 8. This combination has been found to be more effective in low wind speeds than the original design, which relies solely on wind turbines. Another study was introduced by [37] where they developed a prototype of a conventional wind turbine with the integration of a solar-driven extractor fan. The results revealed that the air temperature was reduced by about 1 °C in comparison with the original case. Overall, it might

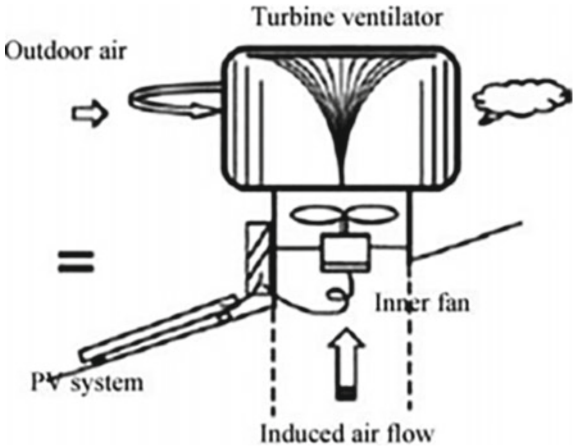

Fig. 8 Different configurations of a wind-solar ventilation system [36]

be the most efficient way to achieve energy efficiency is to integrate different types of renewable energy for building ventilation which still needs further research.

6 Conclusion

This paper reviews air ventilation technologies to achieve proper indoor air quality and reduce heat stress. Previous research studies of each ventilation method and its working principles have been covered. From the literature, it seems that relying on mechanical ventilation technologies alone may require high levels of energy consumption. However, natural ventilation methods may also be not sufficient, particularly at low wind speeds. Therefore, a combination of these two methods may be a more efficient and reliable option. However, for a more sustainable way to reduce greenhouse gas emissions and save more energy. The paper has suggested that integrating two or more renewable energy resources to provide electrical power for the mechanical parts would be the best way as it saves energy, reduces carbon emissions, and provides a uniform airflow and temperature distribution according to the season. This is considered a new direction and reliable way to achieve energy efficiency in buildings.

7 Recommendation

Based on this review, it is recommended to employ a combination of mechanical and natural ventilation methods for efficient and reliable ventilation in buildings. Integration of multiple renewable energy resources to power the mechanical parts is the most energy-efficient and eco-friendly option. To achieve sustainable ventilation, building stakeholders must adopt integrated design and management practices that prioritize indoor air quality, energy consumption, and environmental impact. Implementing these recommendations can significantly contribute to the Sustainable Development Goal of affordable and clean energy.

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