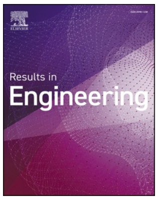
Results in Engineering 23 (2024) 102769

Contents lists available at ScienceDirect

Results in Engineering

journal homepage: www.sciencedirect.com/journal/results-in-engineering



Review article

Recent improvements to heating, ventilation, and cooling technologies for buildings based on renewable energy to achieve zero-energy buildings: A systematic review

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ARTICLE INFO

Keywords:
Zero energy buildings
Energy efficiency
HVAC
Renewable energy
Hybrid systems

ABSTRACT

Due to global climate change and energy market turmoil, the world is seriously pushing to switch to renewable and diversifying energy sources. The building sector consumes an amount of energy, accounting for approximately 40 % of global energy. Therefore, the concept of zero-energy buildings has become more realistic than before. This study reveals the latest developments in zero-energy buildings through a comprehensive literature review of the past ten years. Emphasis has been placed on buildings' heating, ventilation, and cooling systems, as they constitute the most important part of the energy demand. Also, the role of negative energy resulting from an improved building envelope through the design of a building compatible with the surrounding environment, thermal insulation materials, phase change materials, vegetation cover, etc. A review was also made of the most significant renewable energy technologies, which include solar energy installations, wind turbines, and geothermal heat exchangers. The study showed that three main axes must be achieved to reach an energy-free building: Reducing energy waste through the energy-conserving building envelope and improving HVAC systems. Raising the efficiency of the performance of renewable energy facilities by using hybrid systems with the ability and flexibility to respond to changing energy demand. These three axes are an integrated approach to achieving ZEBs; none can be neglected. This study provides important references for researchers, institutions, and decision-makers to unify efforts to achieve ZEBs. It also aims to attract attention and focus research by raising questions and identifying gaps that future research efforts can address.

Nomenclature

Abbreviations	Meaning	Abbreviations	Meaning
ZEBs	zero energy buildings	EEV	electronic expansion valve
HVAC	heating, ventilation, and cooling	GEAHE	geothermal earth–air heat exchanger
PV	photovoltaics	IAQ	indoor air quality
DHW	domestic hot water	MMV	mixed-mode ventilation
HPWH	heat pump water heaters	MEE	membrane energy exchangers
PCM	phase-change materials	BAPV	building-applied photovoltaics
HP	heat pump	BIPV	building-integrated photovoltaics
ASHP	air source heat pump	PV/T	photovoltaic and thermal systems
COP	coefficient of performance	BIPV/T	building integrated photovoltaic-thermal
DSCHP	double stage coupled heat pumps	TE	thermoelectric

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https://doi.org/10.1016/j.rineng.2024.102769
Received 21 June 2024; Received in revised form 10 August 2024; Accepted 21 August 2024

(*continued*)

Abbreviations	Meaning	Abbreviations	Meaning
WSHP	water source heat pump	TEG	thermoelectric generator
ASAHP	air source absorption heat pump	HAWT	horizontal-axis wind turbines
GSHP	ground source heat pump	VAWT	vertical-axis wind turbines
VCASHP	vapor compression air source heat pump	EATHE	earth air tunnel heat exchanger
VRF	variable refrigerant flow		

1. Introduction

Action to reduce the impact of climate change is crucial. In the Paris Agreement, member states set several goals that must be achieved to control the rise in global temperature. One of these objectives is a low-carbon energy sector, which accounts for two-thirds of world emissions. Renewable energy can provide 90 % of the CO2 emission reductions required by 2050 when combined with improvements in energy efficiency [1]. Statistics show that worldwide energy consumption can be defined by three main consumer sectors that combine different contributions: the industrial, transportation, and construction sectors. Energy consumption in the building sector in the United States and the European Union is about 40 %, while in China, it is 27.3 % [2–4]. The energy intensity of buildings in China is much lower than in the United States and the European Union, where the most significant influence in China is related to the industrial sector [5].

Zero-energy buildings (ZEBs) are any building or facility characterized by their total energy consumption equal to zero for a given period and their carbon emissions equivalent to zero. This building typically uses less energy than traditional buildings [6]. These types of buildings generate and then consume their energy. Therefore, most buildings are independent of the electricity grid [7]. Here, we must point out that the construction of these buildings was aimed at applying the proposed stringent environmental standards to address serious environmental issues [8]. The concept of the ZEBs has been proposed since the 1970s in the context of the oil shock of the time and fears of the consequences of becoming utterly dependent on fossil fuels [6,9]. ZEBs rely on renewable sources to meet their energy needs. For this purpose, several technologies suitable for installation are used in buildings. The most prominent technologies currently available are solar thermal collectors, photovoltaic panels (PV), small wind turbines, geothermal heat exchangers, biomass technologies, and micro-hydropower. In addition to energy storage technologies, batteries are the most prominent technologies for storing electricity. Also, hydrogen cells are a promising energy storage technology that needs further development [10]. When dealing with the issue of ZEBs, it is essential to know their exact energy consumption patterns. The energy consumption pattern in buildings is impacted by several factors, including climate, energy costs, availability of natural resources, local and national energy policies, technological development, and social and cultural factors [11–14]. With different energy patterns, it isn't easy to define a single methodology for achieving ZEBs that can be applied anywhere. Each region's way of attaining ZEBs may share parts and differ in other parts [15,16].

By reviewing the literature that dealt with the issue of ZEBs, three main axes can be identified that must be addressed to achieve ZEBs. The first axis is towards negative energy technologies, including designing the building's outer envelope, window and door area, thermal insulation methods, waste energy reduction, etc. The second axis is achieved using energy-saving building services, such as HVAC systems, hot water, and lighting. The third axis will be the energy generation from renewable sources and the selection of appropriate technologies in line with the region's climatic conditions, as in Fig. 1 [6,17–19]. This study will focus on the energy required for heating, ventilation, and cooling (HVAC) in ZEBs. HVAC systems make up the most significant amount of energy

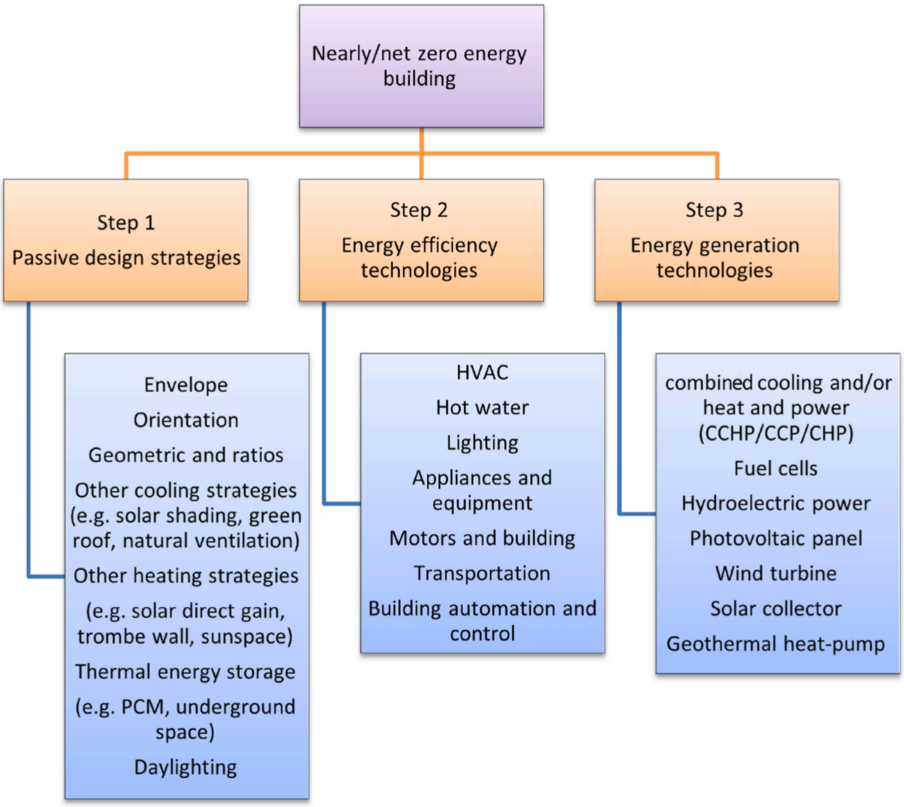

Fig. 1. The main axes towards achieving zero-energy buildings (ZEBs) [18].

consumption in buildings. If this part of energy consumption is neutralized by relying on renewable energy sources, we have come a long way in achieving ZEBs. This study differs from previous review studies by following a more comprehensive and precise scientific methodology in selecting and reviewing relevant literature for the last ten years, which will be explained in detail in the second section of this study.

The rest of this paper is structured as follows: The next section presents the methodology employed in this study to choose relevant review papers. The subsequent section centers on energy efficiency measures within Zero Energy Buildings (ZEBs), specifically addressing the design aspects of building envelopes and windows. The subsequent section delves into heating, cooling, ventilation, and heat recovery systems, encompassing both passive and active approaches. Moving on to the fifth section, we examine the subject of energy generation for ZEBs through renewable sources, such as solar, wind, and geothermal energy systems, whether independent or hybrid configurations. The sixth section is devoted to discussion to clarify and criticize previous studies. Finally, the seventh section encapsulates the review's conclusions and provides recommendations for future research endeavors.

2. Methodology

This study was based on a literature review published in scientific journals. The research methodology used Scopus and Web of Science databases because these two databases contain most of the scientific papers interested in this topic [20,21]. The research resulted in 14,520 scientific papers using keywords such as ZEBs, HVAC technologies for buildings, building energy efficiency, and renewable energy sources. Then, systematic filtering was conducted based on criteria to select the most recent and relevant papers to the subject of the study, etc., to obtain 436 papers [22]. A comprehensive bibliometric analysis was carried out using the R and R Studio software to identify the chronological development of the topic, the frequency analysis of keywords, and the cross-citation analysis of publications and prominent authors [23]. After that, a careful manual textual screening was conducted to select 167 papers to be the reference for this study.

3. Energy efficiency measures

Energy efficiency measures in ZEBs can generally be divided into two main categories: reducing energy consumption and meeting energy demand more efficiently [19]. Applications of reduced energy consumption include improved building designs (envelope, orientation, layout, etc.), efficient occupant behavior (opening windows when outdoor conditions are favorable, turning HVAC off when not in use, and a DHW drawing profile to match the capacity of HPWH production, etc.), and solar shading. By choosing efficient mechanical systems (e.g., HVAC and hot water), appliances and controls, and efficient appliances of buildings (refrigerators, lighting, dryers, washers, etc.), the load can be met with less energy expenditure [19].

The first step in achieving the goals of ZEBs is to integrate the building with the surrounding environment, where the architecture of the building plays a significant role in the exterior design that considers the local climatic conditions. Thus, these measures will reduce the need for HVAC and lighting without compromising interior comfort, significantly reducing energy consumption in the building. Passive techniques can be applied in a cold climate with little solar irradiance, and at the same time, there is energy consumption resulting from the area's heating and hot water supply [24]. Passive technologies may confront a greater challenge in climates with high temperatures and humidity to achieve indoor comfort and reduce as much energy consumed by refrigeration equipment as possible [25].

There is also an excellent role for the behavior of occupants, which is often overlooked or not given critical importance, as an individual's cultural, social, and economic level determines their way of living and daily energy consumption patterns inside the building [26]. The greater the societal awareness of the dangers of excessive energy consumption, the more positively it will be reflected in the optimal use patterns. Ouyang et al. [27] observed that electricity consumption was reduced by 10 % when raising awareness among occupants through awareness campaigns directed at rationalizing energy consumption.

3.1. Building envelope design

The most economical measures to lower a building's energy usage are typically adopted during the design phase [28]. The ZEBs design is different from traditional construction methods to achieve energy-efficient use. ZEBs designers typically combine passive solar principles with the HVAC and lighting requirements for indoor comfort within a building. Sunlight, prevailing breezes, and the ground coolness beneath a building can maintain constant indoor temperatures with minimal mechanical equipment.

In general, when designing buildings, environmental, social, cultural, and functional aspects are considered, and recently, the focus has begun on internal thermal comfort, energy consumption reduction, and sustainable development. However, no unified approach to building design achieves these goals [29]. This is primarily because of the intricate interplay between systems for producing, consuming, and storing energy, as well as systems that are controlled automatically and manually. Also, despite the continuous development of climate-adapted buildings, they cannot be considered mature yet [30].

The external walls of the building have the most significant role in conserving energy inside the building as they bear the burden of different climatic conditions. However, they are not the only ones that require good insulation; there are several places where leakage can occur. Therefore, different insulators must be used to conserve energy inside the building [31]. Insulating materials can also be classified according to their chemical composition, such as organic or inorganic materials, compounds, or new technological compounds, as shown in Fig. 2 [32]. Researchers sought low-cost and high-efficiency alternatives to commonly used insulating materials. Cuce et al. [33] proposed using novel insulating plaster with different thicknesses. While the heat transfer coefficient (U-value) before insulation was 5.5 W/m^{2}K, its total value became 2.86 W/m^{2}K, decreasing 47.9 % after using the novel insulating plaster. Amani and Kiaee [34], analyzing the condition of a building in an area with a cold winter and hot summer, found that multilayer insulating materials could cut energy demand by up to 70 %. They considered this an effective way to upgrade traditional buildings to ZEBs. To improve the insulation of traditional building envelopes and make them more energy efficient, Cuce et al. [35] introduced the use of aerogel in a 1930s building in the UK by reinforcing the walls with an aerogel blanket. The results showed an improvement in the heat loss coefficient (HLC) from 17.15 to 6.29 W/K.

The building envelope improvement is not limited to adding insulating materials only. There are innovative methods that can be applied to achieve multiple goals. Recent studies have shown that using materials reflecting solar radiation on the building walls reduced the energy consumption needed to cool indoor spaces the building in regions with warm climates. It can also contribute to reducing the phenomenon of heat islands in cities due to the surfaces absorbing solar radiation during the day and re-emitting it at night [36–38]. In an interesting recent experimental investigation, Cuce et al. [39] proposed using bamboo fiber-reinforced briquettes as a sustainable solution with high thermal insulation properties. Indeed, the results showed that the heat transfer coefficient (U-value) value was (4.698, 3.94, 2.77) W/m2K when using bamboo fibers at rates of (2 %, 4 %, 6 %), a reduction of 49.9 % at 6 %.

Using phase-change material (PCM) [40,41] or high-density materials such as soil and concrete [42,43] can raise the building's thermal mass through the slow reactions of these materials in gaining and losing heat, which reduces the temperature change between night and day. However, increasing the building's thermal mass may not be helpful in

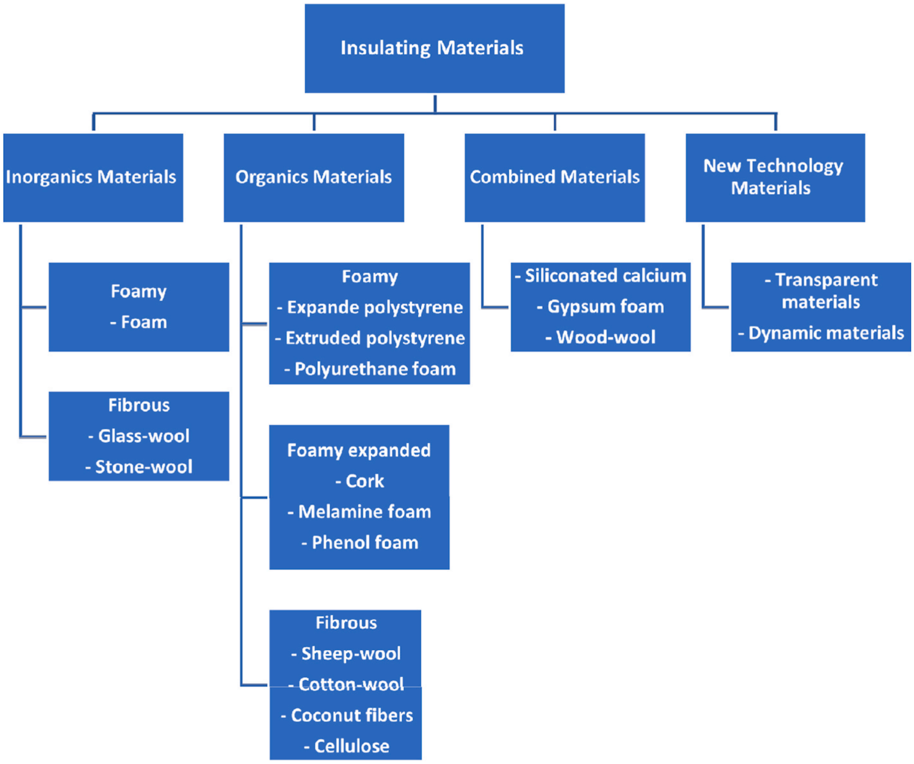

Fig. 2. Classification of widely used insulating materials [32].

all climatic conditions or irregular usage patterns.

On the other hand, Domjan et al. [44] presented the idea of an all-glass building consisting of advanced glass composed of six layers and building-integrated photovoltaic facade structures while measuring the performance in different climatic conditions. Results showed a 36 %–48 % reduction in overall energy demand. However, we must note that this type of building may not be suitable in hot climatic conditions with long hours of sunshine, which may cause the phenomenon of glass houses, in addition to the cultural and social determinants of the region.

It is possible to insulate the building and mitigate the effect of temperature fluctuations in the surroundings of the building by making the outer wall consist of two double layers with an air tunnel between them; the outer layer is often transparent, allowing solar radiation to pass through. When the air mass is heated, it rises to the top of the tunnel, thus achieving an air current that separates the building from its surroundings to achieve the principle of the solar chimney. This technology can contribute to interior building space ventilation without using mechanical devices. There are many ideas for the solar chimney presented

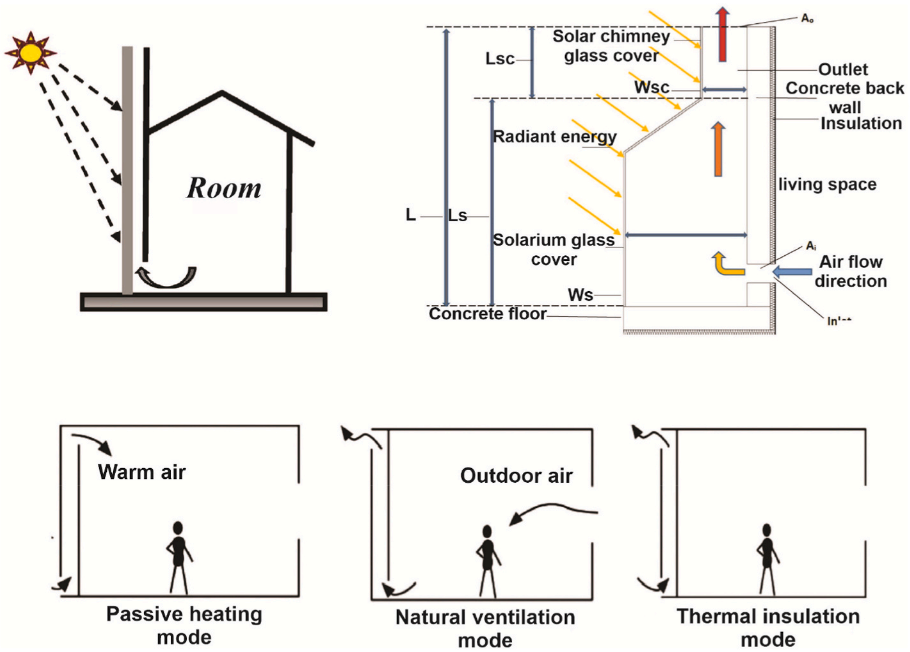

Fig. 3. Solar chimney patterns integrated with the facade of the building [45,47,49].

by researchers to achieve isolation and ventilation in the building. Still, they differ in the mechanism of work and installation [45–49], as in Fig. 3.

Vegetation cover can also be an effective solution for building insulation [50,51]. Vegetation cover is applied to the roofs and walls, as studies have reported that it can prevent 80 % of the heat from leaking through the walls. Green roofs also consume less energy, at 2.2–16.7 % less than traditional roofs. [52], In addition to increasing green spaces in urban areas. This type is classified into two main categories: green facade and living wall, as shown in Fig. 4.

3.2. Windows

Windows are considered a significant building component and cannot be dispensed with except in exceptional cases. They play an important role in HVAC and passive lighting inside the building. They also provide visual comfort and an inside-out view [49]. However, the windows are the weakest part of the building envelope, primarily if implemented without considering climatic conditions. They are responsible for much of the wasted energy inside the building [53].

High-performance windows allow sunlight to pass through in winter and reflect in summer, providing better thermal comfort inside the building [54]. There are several techniques to achieve improved window glass specifications, which include multilayer glazing, low-emittance coatings, vacuum glazing, photovoltaic glazing, self-cleaning glazing, PCM glazing, smart glazing, suspended films, gas-filled glazing, aerogel glazing [40,55–57]. Not only that, but there are creative solutions, including reversible windows, transparent insulation materials-filled windows, solar-absorbing windows, ventilated double-glazed windows, and switchable electrochromic windows [58,59]. Some windows can control the amount of solar energy transmitted and reflected, including anti-reflective coated glass, tinted glass, and reflective glass [60–62], as shown in Table (1).

On the other hand, by precisely calculating the azimuth and solar declination angles, the building design can shield the windows from direct exposure to solar radiation. The position and direction of the windows can also be determined by the shape and length of the overhang at the window top [63].

4. Efficient HVAC systems

Heating, ventilation, and cooling systems regard buildings' largest energy consumption share. Its energy consumption increases in cold and hot areas, especially with mechanical equipment that requires high energy. Recent studies have sought passive or low-energy alternatives to achieve ZEBs without compromising indoor thermal comfort. The quantities consumed by the HVAC systems can indicate that the building is energy efficient.

4.1. Heating

Heating the interior spaces of buildings is a significant concern in cold areas. Heating systems are classified according to their source and can be classified into two parts: The first is district heating, often available in urban areas with a high population density, as it is challenging to implement in rural areas but does not constitute a high percentage. For example, district heating makes up only 9 % of the heating in the European Union [72]. District heating also depends on many heating technologies and energy sources, including fossil fuels and renewable energy.

The second part is the local heating systems, where heat is produced in the areas to be heated. It has several forms, the most important of which is (an open fireplace, fireplace with embedded heat exchanger, fireplace with room air circulation chamber, wood and pellet burning stoves, electric heaters, and room air conditioners), which use fossil fuels and wood to produce heat, or it can rely on renewable energy sources, or it may combine the two types in hybrid systems [73].

The heat pump (HP) is the most common home heating type. One of its applications is air source heat pumps (ASHP), which are easy to install and maintain [74]. Bertsch and Groll [75] proposed a system ASHP that operates in two stages to increase its efficiency in a frigid climate and then experiment in a low temperature of −30 °C. The results showed that it is possible to reach a coefficient of performance (COP) of 2.1. Also, Wang et al. [76] presented a heating system with double stage coupled heat pumps (DSCHP) to improve working conditions and provide heating in cold climates. The technique combines ASHP and a water source heat pump (WSHP). It was field tested for a month, and the results showed a significant improvement in operation compared to the traditional ASHP system. Wu. et al. [77] proposed a double-stage coupled ASAHP system to improve the energy-saving capabilities of single-phase ASAHP in cold regions. The results showed an energy-saving rate of more than 20 %.

It is possible to raise the heat pump system's COP value in conjunction with solar energy systems by integrating a solar collector, which increases operating flexibility in different demand conditions and increases heating efficiency. Liang et al. [78] reported an increase in COP and an energy-saving rate of 11.22 %.

Likewise, the ground source heat pump (GSHP) is characterized by its high energy efficiency. However, its high initial cost is considered an obstacle to its implementation [79].

Comparing the performance of GSHP with ASHP in dehumidification and ventilation of HVAC in climates with high humidity, Wu et al. [80] observe that the ASHP with dedicated dehumidifying reduced HVAC energy by 7.3 % and the energy of the building by 3.9 %, with lower

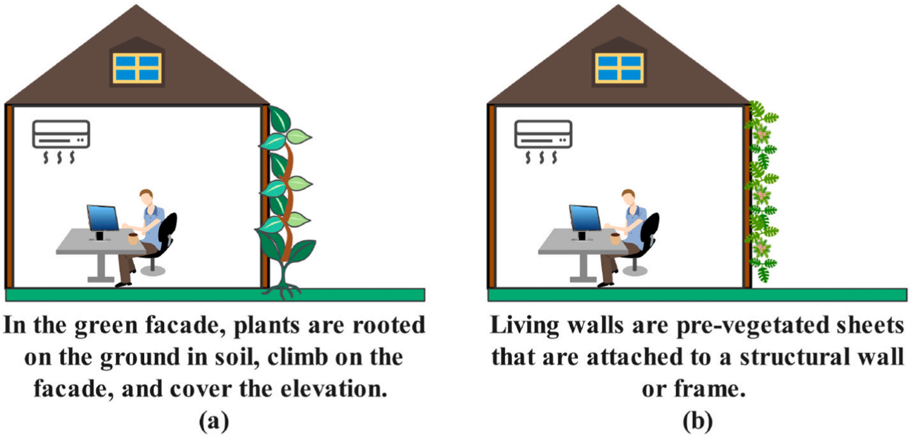

Fig. 4. Insulating vegetation covers the walls of the building of both types: green facade and living wall [52].

Table 1
Shows some of the techniques used to improve the thermal insulation of windows.

Reference	Authors	Technique	Major findings
[64]	Mujeebu and Ashraf	double-glazed windows	Saving energy demand for cooling by 18 %–28 %
[65]	Wang et al.	Determine the optimum distance between argon-filled Transparent Insulation Slats.	Improve the thermal resistance of windows by 39.47%–74.07 %
[66]	Cuce and Riffat	Use of heat insulating solar glass (HISG)	The shading coefficient of HISG glass is only 0.136, resulting in approximately 80 % reduction in solar heat gain compared to regular glass. 100 % UV and 99 % IR blocking.
[67]	Cuce	Determination of U-value by numerical and experimental analysis of argon-filled double-glazed windows.	U-value is 0.89 W/m^{2}K from computational fluid dynamics (CFD) analysis. U-value is (1.23, 1.18 and 1.31 W/m^{2}K) for the top, center, and bottom positions of the window sample from environmental chamber tests. Thermal bridging and edge effects play a major role in the actual U-value performance of glass products.
[68]	Hashemi et al.	Investigation of the effect of Vacuum Insulation Panel (VIP) with thermal conductivity of 0.005–0.008 W/mK.	Significant reduction in heat loss. Thermal bridge is the important factor affecting the thermal insulation value.
[69]	Bao et al.	WPU/DHTS composite film-coated glass (waterborne polyurethane, double-shell hollow TiO2@SiO2 spheres).	The temperature rise rate is 26 % lower than uncoated glass.
[70]	Cuce and Riffat	Experimental and numerical investigation of thermal performance efficiency of vacuum tube window technology	The optimal vacuum tube diameter is 60 mm. The U-value is 0.40 W/m2 K, five times better than argon-filled double-glazed windows.
[71]	Magzoub et al.	Investigation of the performance of Energy Active Window (EAW) with HVAC air reuse technology.	Lowering the temperature of the inner window surface by 4–7 °C.

initial costs but worse thermal comfort and high humidity levels. In comparison, the GSHP system reduced the HVAC energy by 26 % and the energy of the building by 13.1 % using two wells, with a percentage of 29.2 % and 14.7 % for three wells.

4.2. Cooling

Cooling indoor space, like heating, requires a lot of energy consumption, especially in climates with high humidity, which requires dehumidification equipment to achieve thermal comfort [81]. The dehumidification process often requires large amounts of energy, so the researchers worked to find suitable solutions to reduce the energy needed for the operation while achieving thermal comfort [82]. In temperate climates, an air conditioner coupled with a desiccant dehumidifier can achieve thermal comfort by removing moisture and providing dry air at an acceptable temperature while saving energy [83].

As we mentioned earlier, heat pumps in heating also have broad uses in building cooling systems. One of its applications is the vapor compression air source heat pump (VCASHP) system. Zhang et al. [84] reviewed recent developments in this field, and they mentioned three categories: single-stage, two-stage, and multi-stage. The two-stage compression system can also be classified into quasi-two-stage, two-stage, and cascade compression systems based on the number of compressors and separate loops.

Recently, variable refrigerant flow (VRF) systems appeared and quickly gained popularity due to their ability to reduce energy consumption, respond to load variables, and ease installation and maintenance. They can be installed in both public and residential buildings [85]. In a recent review of VRF system components, Hernandez and Fumo [86] note that tests determined by various compressor configurations, electronic expansion valve (EEV) placement, and airflow operations affect performance and thermal comfort, as well as the system's response and sensitivity, depending on the number of internal evaporators connected to the system, as in Fig. 5.

Despite the heat pump's (HP) strong effectiveness in the cooling process, its downside is that it consumes a lot of energy, especially when the air temperature is high. Accordingly, the researchers worked hard to find ways to raise their efficiency and make them more sustainable [87, 88]. One of the proposed solutions is the incorporation of evaporative condensers that improve heat removal through the evaporative cooling effect. Harby et al. [89] comprehensively reviewed the latest evaporative condenser technology in residential cooling systems. They found that an evaporative-cooled condenser instead of an air-cooled condenser could reduce energy consumption by up to 58 %. The COP of systems with cooling capabilities ranging from 3 to 3000 kW can be increased by roughly 113.4 %.

Another essential problem is frost formation on the evaporator; when it accumulates, it weakens the heat exchange capacity and decreases the device's performance. Several techniques remove frost or prevent its formation, divided into two types: passive and active [90]. Passive methods focus on treating surfaces by changing the shape of the surfaces or coating them with an anti-frost material [91–94]. The active methods it is done through several techniques, the most important of which are ultrasonic vibration methods, hot gas reverse cycle, low-frequency oscillation, electrodynamics (EHD), desiccant dehumidifiers, and electric heater [95–100].

Studies have dealt with other methods of cooling buildings to reduce dependence on electricity and have less environmental impact. Also, if there is a shortage of electricity supplies, these methods can be a

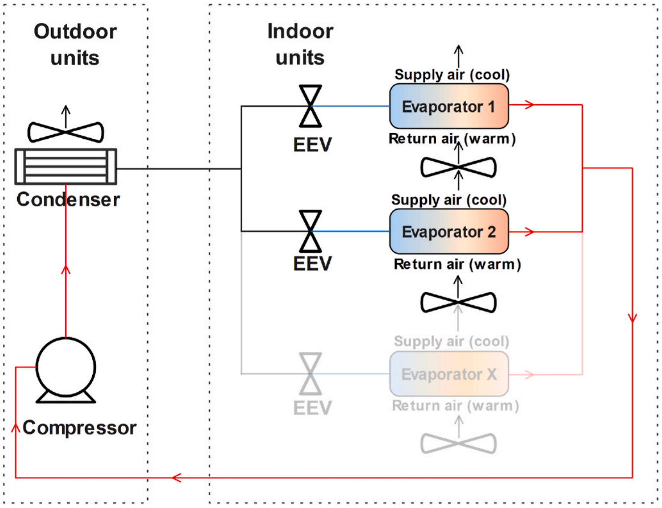

Fig. 5. Schematic of a variable refrigerant flow system [86].

successful alternative in cooling buildings [101]. Geothermal cooling systems can be a successful solution in hot climates where the ground temperature is sufficient to provide indoor comfort [102] (Fig. 6). These systems use water or air as a heat transfer medium [103]. Gautier et al. [104] claimed that by relying on a water-based geothermal cooling system, interior thermal conditions could be kept within acceptable limits for most building areas, using 50 % of the electrical power compared to the standard chiller process with a maximum power reduction of 60 %.

4.3. Ventilation and Heat recovery

Through the literature review, two ventilation methods in buildings can be identified: natural (passive) and mechanical (using dedicated equipment) [106,107]. Natural ventilation driven by temperature differences and the principle of convection buoyancy can provide good air quality and acceptable indoor thermal comfort without consuming energy [108]. Natural ventilation can contribute to the cooling process by removing excess heat inside the building [109]. There is no specific form of natural ventilation as it is implemented differently. Al-Obaidi et al. [110] suggested a strategy of attic ventilation in tropical climates to eliminate the accumulation of heat inside the building and possibly to couple it with a turbine fan in the exit hole that helps in a steady airflow. Duan et al. [111] presented another form of ventilation using the solar chimney installed at the top of the building. The solar radiation heats the air mass inside the chimney, thus generating an air current that moves from inside to outside. A mechanical fan can also be used in the entrance hole to maintain a constant flow rate at night and during climatic conditions in which solar radiation is weak, as in Fig. 7.

Windcatchers are one of the oldest technologies used in natural ventilation in buildings, and they are still being used with some improvements that can advance high performance in providing a suitable indoor environment and reducing CO_2 levels. Jomehzadeh et al. [112] comprehensively reviewed the most important forms of windcatchers. They focused on indoor air quality (IAQ) and comfort, claiming that IAQ levels were generally satisfactory using windcatchers.

Mixed ventilation is a different technique that combines mechanical and natural ventilation. Salcido et al. [113] review the most prominent mixed-mode ventilation (MMV) technologies that maintain IAQ for occupants by providing suitable interior environmental conditions, noting that mixed-mode buildings can save 40 % of HVAC energy and 75 % alternate between natural and mechanical ventilation. It should be noted that this type of ventilation has a high flexibility in responding to the requirements of the building.

Building ventilation is accompanied by the loss of part of the internal heat, which requires more energy to compensate for this lack of heat. With efforts to reduce energy consumption, studies have sought to find effective ways to recover heat. Heat recovery systems are divided into two systems: passive recovery heat systems and active recovery heat systems. The working principle of passive heat recovery systems includes taking advantage of the difference in the temperature or enthalpy between the fresh air entering the building and the exhaust air leaving the building through a heat exchanger to reduce the heat load of the outside air [114]. Passive heat recovery systems are classified into five categories based on design and function: flat plate, rotatory wheel, run-around, heat pipe, and membrane energy exchanger (MEE) [115,116]. Active heat recovery systems can efficiently regulate the temperature and humidity of the fresh air while recovering the latent heat from the exhaust air. These systems are characterized by their high efficiency and flexibility of control. Active heat recovery systems include heat pump air-to-air energy recovery systems and thermoelectric ventilators [117].

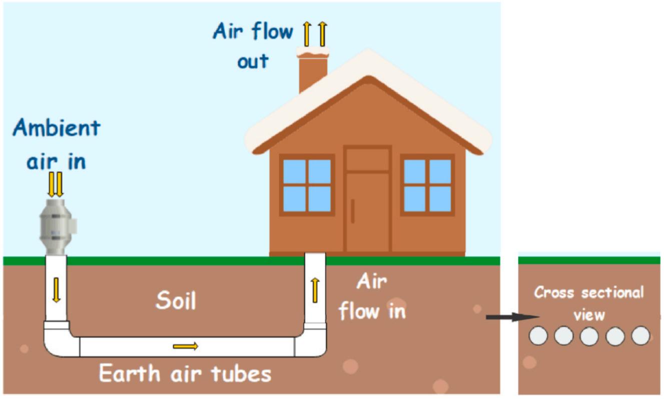

Fig. 6. The geothermal earth–air heat exchanger (GEAHE) concept [105].

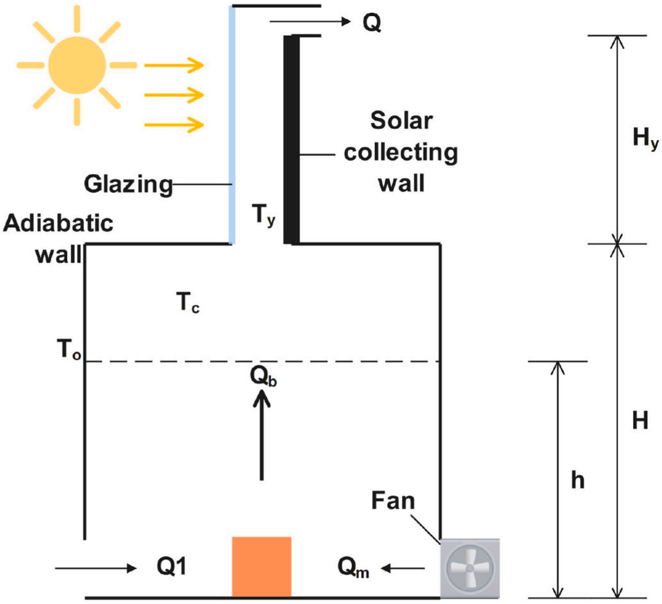

Fig. 7. Ventilation of buildings using solar chimney technology and fan [111].

5. Energy production with renewable energy sources

ZEBs obtain their energy from renewable sources, which contributes to reducing greenhouse gas emissions, diversifying energy sources, and achieving better energy security. The energy produced on-site, or district energy, is used for heating and cooling spaces, hot water, and buildings' electricity. Each renewable energy source can be used independently, or two or more sources can be combined into hybrid systems with high performance, diverse outputs, and flexibility in supply in exchange for variable demand (Fig. 8) [118,119].

Choosing the appropriate renewable energy technology is based on the location and climatic conditions (solar radiation intensity, speed, and direction of the prevailing winds), economic factors (the cost of renewable energy installations, energy fees, the economic level of individuals, and government policies supporting this trend), and technical aspects (the availability of the possibility of installing and maintaining renewable energy facilities) [120].

Energy storage, whether electricity or heat, enhances the possibility of applying renewable energy technologies in ZEBs and provides excellent reliability in responding to energy demand [121]. Today, energy storage technologies are still in their early stages, and their efficiency has not reached a high level, but research continues to develop this field. The most important forms of energy storage, batteries, hydrogen cells, flywheels, compressed air, pumped hydro, heat storage, and other technologies, are still in the field of research and development [122–124].

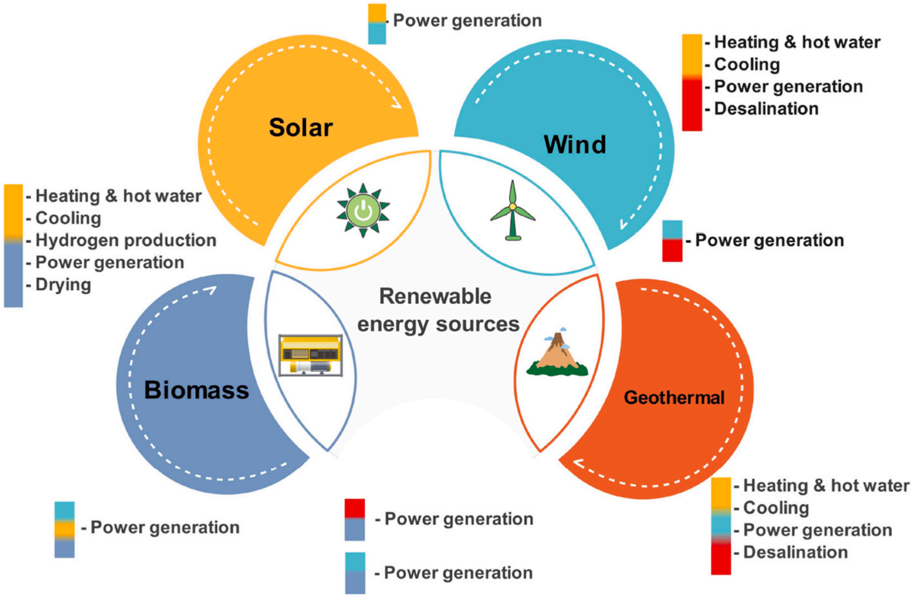

Fig. 8. Orientation towards the use of hybrid renewable energy [118].

Decarbonization and the inclusion of renewable energy can benefit from the flexible connections of the electricity and heating sectors [125]. There are many ways to achieve this flexibility, including flexible thermal generators, different types of energy storage, demand-side interventions, grid-connected electric vehicles, geographic balancing through transmission, and adjustments to the layout, siting, and distribution of variable renewable energy. The flexible use of electricity for heating, frequently in conjunction with heat storage, has recently drawn more attention as another upcoming source of system flexibility, even though producing heat from electricity has not traditionally been a preferred option in fossil fuel-based energy systems [126].

5.1. *Solar energy*

Solar energy is one of the most widely used types of renewable energies, and photovoltaic cells are often the most common solar technology in producing energy for buildings. Various factors affect the performance of PV panels. Fouad et al. [127] summarized the main essential factors, which include the environmental, installation, PV system, and cost factors in addition to various other factors, and each of these main factors branched out into other secondary factors.

It can be installed on the roofs and walls of buildings with what is known as building-applied PV (BAPV) or building-integrated PV (BIPV) to be part of the building envelope instead of traditional building materials [128]. Or to be installed independently of the building if sufficient space is available [129–131]. BIPV has a promising future and recently began to receive broad interest. There is a lot of research to improve its performance and achieve multiple goals. In addition to the electricity generated by this PV, they give an attractive appearance to the building and insulate it by creating an air current between the PV and the walls and ceiling of the building (Fig. 9). However, one of the disadvantages of this technology is the high temperature of the solar panels, especially during the summer in hot climates, and thus the low generation efficiency [132].

One proposed solution to eliminating heat is using hybrid systems that combine photovoltaic and thermal systems (PV/T). Baljit et al. [134] compare BIPV systems and building integrated photovoltaic-thermal (BIPV/T) systems; BIPV refers to designs with or without ventilated fluid (air or water), which can cool PV panels, increase electrical output, then dissipate the heat to the environment. For BIPV/T, ventilation fluid is used as a working fluid to collect heat from PV panels for heating or drying purposes.

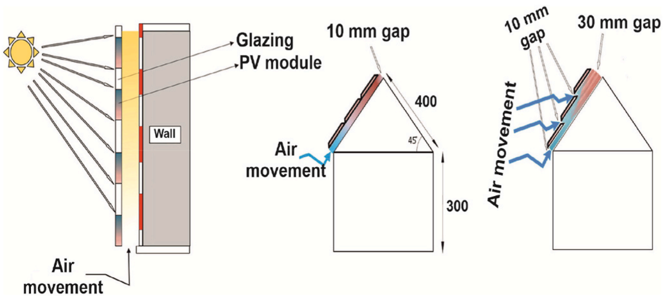

Fig. 9. A staggered installation on the walls and roof of the building for BIPV [132,133].

Multiple designs for PV/T systems differ in the method of installing PV cells with the thermal collector; the fluid used also has a role in determining the shape of the design. Aste et al. [135] presented a comprehensive review of flat plate PV–thermal collectors that use water as a heat transfer medium. They were classified into four types according to the cover components and the insulation material. They have observed that in the uncovered systems, the PV systems work with high efficiency equal to or more than the PV systems that operate alone due to the cooling of the cells resulting from the heat-transferring liquid; however, the heat generated from the thermal system is low. As for the covered systems, it is the opposite of the uncovered systems, where the generated electricity is low because of the high temperature of the photovoltaic cells, which reduces efficiency. Despite the negatives, the energy demand of the building determines which systems are best. For example, there is a high demand for heat in regions with cold climates, so covered PV/T systems are appropriate. In regions with hot temperatures, electricity is demanded to operate the cooling equipment; simultaneously, the building does not need a lot of heat, so the uncovered PV/T systems are appropriate. It can also determine the nature of energy demand according to the variation between summer and winter [136,137].

Solar energy can be used to cool spaces in buildings, and considering the modernization of solar energy installations, high-performance solar-powered cooling technologies have become available. Such as solar photovoltaic and thermal cooling (adsorption and absorption) [138].

Traditional refrigeration devices with an electric compressor consume large amounts of energy, so solar energy systems that operate by absorption and adsorption can replace them [139,140]. Eicker et al. [141] studied and analyzed absorption cooling systems covering most climatic regions worldwide. They concluded these systems could cover 80 % of the solar cooling fraction except for humid climates. They indicated absorption cooling systems are more economically feasible in hot climate regions than in temperate climates.

Another hybrid solar technology suitable for building applications is integrating PV and thermoelectric (TE) systems. The working principle of TE systems includes converting temperature differences into electric potential, in what is known as the (Seebeck effect). Irshad et al. [142] reviewed PV systems integrated with TE systems. They noted that these systems increase the potential for energy savings by 22 % and contribute to reducing the internal temperature of the building from 5 to 10 °C under the surrounding climatic conditions. Qasim et al. [143] studied a hybrid PV-TEG system by connecting a PV panel with 32 TEG modules. The waste heat from the PV panel can be absorbed by the TEG and converted into electricity. The results showed an improvement in the hybrid PV-TEG system, as the voltage increased by 9.21 %, and the efficiency increased by 18.16 % compared to the photovoltaic panel alone. Also, at a temperature of 40 °C, the efficiency of the hybrid PV-TEG system improved by 27 % compared to the photovoltaic panel.

TE systems can also generate electricity by using solar heat to heat one side and cool the other. Qasim et al. [144] experimentally investigated a thermoelectric generator (TEG) system. They measured the maximum generated voltage by direct exposure to solar radiation on one side and cooling with tap water on the other. The system is made up of multiple thermoelectric units that are linked in parallel. The results showed that the maximum open circuit voltage was 11.75 V.

5.2. Wind energy

The wind is one of the renewable energy sources that man has harnessed since ancient times. Given the energy crisis and environmental concerns, the wind energy sector has witnessed significant growth in recent decades. Countries worldwide aim to reach 1000 GW by 2030 [145]. Wind turbines are one of the technologies used to produce energy. Wind turbines can be an independent energy source or integrated with other sources in ZEBs. For example, wind turbines can compensate for the low generation of solar energy installations at night or in weather conditions with weak solar radiation. Also, in the absence of sufficient spaces with high energy demand, as in most large cities with a high population density, wind turbines are considered a successful solution, as they do not need large areas such as solar panels [136]. In regions with appropriate wind speeds and high frequency, wind turbines can be relied upon as a significant source of electricity generation, considering the economic feasibility, as the initial costs of wind turbines differ from solar panels [146]. Iqbal [147] conducted simulations to choose the optimal system for energy production for a house located in an area with an annual wind speed average of 6.7 m/s. The performance of each method was measured accurately, and the results indicate that wind energy is of higher feasibility in energy generation.

Wind turbines are divided into two types: horizontal-axis wind turbine (HAWT) and vertical-axis wind turbine (VAWT) [148,149]. Based on the rotor diameter and generation capacity, HAWT can be divided into six categories (micro, mini, small household, small commercial, medium commercial, and large commercial).

VAWTs are characterized by high transportation and installation flexibility, making them more suitable in urban areas and ZEB applications. They are highly efficient and produce higher energy in turbulent and variable-direction wind environments. However, VAWTs are less efficient than HAWTs in stable winds and have a low ability to self-start and continue to generate positive torque. Hence, the studies worked on adding improvements to the design of the VAWTs to raise their efficiency, such as increasing wind inlet speed and reducing negative torque [147].

Recently, a new approach has begun in the architectural design of buildings that aims to integrate with the use of renewable energy sources, including wind energy [150]. VAWTs have proven their ability to adapt to wind turbulence caused by buildings in urban areas. Lee et al. [151] investigated VAWTs in environments with wind turbulence greater than 30 %, and the results indicate the flexibility of VAWTs in rapid response to changing operating conditions.

5.3. Geothermal energy

Geothermal heat is a vital renewable energy resource. It has high operating reliability and stable performance that is not affected by day and night or seasons. Geothermal heat can produce high heat at great depths from the earth's surface and is usually used in power plants. It can also be used at shallow depths from the earth's surface at medium temperatures. Nevertheless, it is suitable for use in buildings and is usually cheaper. Geothermal heat provides building heating, ventilation, and cooling energy [152].

There are many applications for exploiting geothermal heat. The ground source heat pump (GSHP) is a common application [153]. The principle of operation of the GSHP is based on heat exchange with the ground through heat exchangers. Heat exchangers operate in two systems: the open-loop system and the closed-loop system [154]. The open loop system transfers heat by exchanging water with surface water or groundwater boreholes (Fig. 10) [155]. Open loop systems are characterized by their high ability to heat exchange and their effective contribution to heating and cooling when suitable conditions are available for their application. However, they are more affected by climatic changes and require special equipment for their implementation as they deal with water of different chemical compositions. In addition, several controls related to preserving ground and surface water from pollution and changing its physical and chemical properties must be considered when implementing these systems [156,157].

As for the closed-loop system, there is no direct contact with the soil or groundwater. The heat exchange occurs through a liquid moving in a closed loop of pipes. The closed-loop system can be applied in any location where it does not require the availability of specific materials, such as an open-loop system; however, the initial installation costs are relatively high [158,159]. Closed-loop heat exchangers are installed in two different ways: horizontal systems and vertical systems [153]. Horizontal systems are applied at a small depth from the earth's surface, ranging between 1 and 2 m, but they require ample space compared to vertical systems [160]. The pipe network is installed in parallel or the form of a series, and the required area can be reduced by installing the pipes in a spiral or inside a trench [161]. Vertical systems are characterized by stable performance and are not impacted by weather conditions, as they are implemented at great depths. Still, it requires more energy to move the liquid inside the pipe [162]. Vertical systems are installed by laying pipes in a borehole and are connected in parallel or

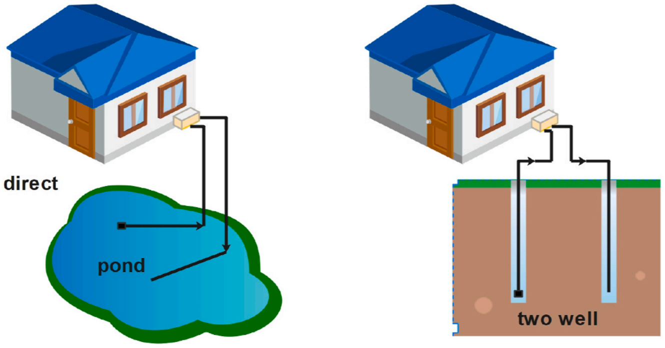

Fig. 10. The open-loop system ground heat exchanger [155].

series. The system may need more than one borehole, so a sufficient distance separating the boreholes must be maintained [163,164].

Another technology that uses geothermal heat as an energy source and contributes to providing HVAC energy and internal thermal comfort for buildings. This technology is known as the earth air tunnel heat exchanger (EATHE) system, which has recently begun to gain interest. Singh et al. [165] conducted a comprehensive review of the recent developments in the EATHE system. They concluded that this system could be independently or hybrid with traditional HVAC techniques or integrated with other renewable energy systems to reduce greenhouse gas emissions and contribute to reducing the impact of energy crises.

To achieve the most significant benefit from geothermal energy, studies have presented several hybrid systems that integrate geothermal technologies with other renewable energy technologies, such as solar chimneys, cooling towers, solar thermal collectors, nocturnal radiative cooling, and others [166]. Nouri et al. [167] reviewed the GSHP systems supported by solar energy. The results showed a high system efficiency and a COP of 13.5 for the system and the heat pump 5.7, and it also led to higher economic returns with a payback period of 5 years due to lower operating costs.

6. Discussion

A comprehensive review of energy efficiency measures in ZEBs identifies a range of strategies and technologies to reduce energy consumption and enhance efficiency. By organizing these measures into those focused on minimizing energy use and those targeting more efficient energy demand management, the review underscores the critical role of building design, particularly through improvements to the building envelope and solar shading. Nevertheless, the significant impact of occupant behavior is often underestimated, suggesting a need for more empirical data to demonstrate how behavioral changes can be effectively implemented and sustained across various contexts. The review also explores innovative insulation materials, such as insulating plaster and bamboo fiber, highlighting the importance of comparing these materials' costs and benefits across different climatic conditions while considering challenges like installation complexity and material durability. Solar chimneys are presented as promising solutions for achieving natural ventilation and reducing reliance on mechanical systems, though their application in existing buildings requires further investigation, particularly in terms of costs, maintenance, and the feasibility of retrofitting older structures. Similarly, integrating vegetation on roofs and external walls as thermal insulation offers significant potential, yet long-term effects on building integrity, maintenance costs, and water resource requirements in arid regions need further exploration. Additionally, advanced glazing technologies are recognized for their ability to reduce heat loss and improve energy efficiency. Still, future studies should address the economic aspects of these technologies, such as installation and maintenance costs, and their impact on natural lighting and indoor comfort across various climates.

Current studies provide a detailed overview of HVAC systems, emphasizing energy efficiency as a key factor in achieving ZEBs by thoroughly discussing heating technologies like district heating, air source heat pumps (ASHP), and ground source heat pumps (GSHP), and highlighting their advantages, such as efficiency and compatibility with renewable energy sources, with the analysis being supported by data and studies that add credibility. However, although the studies cover technological developments well, it would have been better if they had delved deeper into the economic, environmental and practical challenges of implementing these systems; for instance, the high initial costs of GSHP and the reliance on specific climatic conditions for optimal performance could hinder widespread adoption, and integrating these systems into older buildings or in regions with limited technical expertise presents further challenges that warrant discussion. In the cooling section, studies effectively explore technologies such as variable refrigerant flow (VRF) systems and geothermal cooling, emphasizing their energy-saving potential, but could expand towards the long-term sustainability of these systems, especially as climate change affects temperature extremes, and address the complexity of installation and maintenance, particularly in retrofitting existing structures. Similarly, in ventilation and heat recovery systems, studies present the most important techniques, distinguishing between passive and active methods while highlighting their energy-saving potential, but could address the practical challenges of integrating these systems into existing buildings and the maintenance costs associated with them, which may impact their long-term viability.

Researchers provide an insightful overview of how ZEBs can leverage renewable energy sources for energy independence and sustainability. Integrating renewable energy is crucial for reducing greenhouse gas emissions and enhancing energy security. The distinction between building-applied PV (BAPV) and building-integrated PV (BIPV) is well-articulated, showing an understanding of the architectural implications of solar energy integration. However, the research could be enhanced by a more detailed analysis of the economic and aesthetic trade-offs between building-applied PV and building-integrated PV. While BIPV offers aesthetic and insulation benefits, it also comes with higher costs and potentially lower efficiency due to increased temperatures, especially in hot climates. This balance between cost, efficiency, and aesthetic appeal could be critically evaluated to provide a more nuanced view of the adoption potential of BIPV in different contexts. The discussion of hybrid systems, such as photovoltaic-thermal systems, offers an innovative solution to the problem of efficiency loss due to high temperatures in photovoltaic panels. However, a deeper exploration of the practical challenges faced by these hybrid systems, such as the complexity of installation and maintenance and the economic viability of these systems compared to conventional PV systems, could be beneficial. Additionally, while studies discuss the potential of solar energy for cooling, they do not adequately address the technical and economic barriers to the widespread adoption of solar cooling technologies, especially in regions with varying climatic conditions. The same is true of wind energy. Studies have provided a strong overview of the potential of wind turbines in ZEBs, especially the flexibility of VAWTs in urban environments. However, the argument can be more critical of the limitations of VAWTs, such as their lower efficiency compared to HAWTs. Additionally, while studies acknowledge the economic viability of wind energy in certain areas, they can provide a more detailed analysis of the cost-benefit ratio of wind energy in urban environments, where space is limited and the economic viability of wind energy is often disputed. The environmental and aesthetic impacts of integrating wind turbines into urban landscapes can also be highlighted, which are often important factors in adopting renewable energy technologies. Studies have shown the advantages of geothermal energy in providing reliable and stable energy for HVAC in buildings. While studies indicate higher initial costs for closed systems, they do not adequately address the long-term economic impacts, including maintenance costs and the potential for performance degradation over time. Furthermore, a more detailed examination of the environmental effects of geothermal systems, particularly groundwater contamination and land use, could be provided. While studies note the need to consider these factors, a more critical assessment of the trade-offs between the environmental benefits and potential risks of geothermal energy would provide a more balanced view of its role in ZEBs.

7. Conclusions and areas for future study

7.1. Conclusions

This paper reviewed the most important literature on Zero Energy Buildings (ZEBs) over the past ten years, focusing on HVAC energy in buildings, which constitutes the most significant part of the energy demand. Three main axes must be addressed to achieve ZEBs: energy efficiency measures, passive and active HVAC systems, and renewable energy production technologies. Limited energy production resources, economic burdens, and global climate change due to greenhouse gas emissions necessitate conserving energy in buildings and finding solutions to reduce energy waste. Various passive and active techniques for building envelopes, such as insulation materials, phase change materials, and vegetation cover, were examined. However, few studies have considered factors like cultural, social, and economic influences and climatic conditions. It's crucial to consider the community's architectural and cultural identity, verify the costs of building materials, and address the specific needs of existing traditional buildings. HVAC methods, especially heat pumps (ASHP, WSHP, GSHP), were extensively studied, but relying solely on them can be energy-intensive, particularly in extreme climates. Thus, integrating multiple HVAC sources is recommended to reduce energy consumption and provide thermal comfort, which many studies have overlooked. Renewable energy sources, such as solar, wind, and geothermal, aim to reduce greenhouse gas emissions and diversify energy supplies. Technologies like photovoltaic panels, solar heat collectors, small wind turbines, and ground heat exchangers were discussed. Solar energy is the primary system for energy generation, while wind and geothermal technologies need further development. Factors like climatic conditions, initial costs, and space availability are critical for selecting appropriate energy systems. The studies did not clearly address the financial aspect, particularly the high initial costs and whether ZEBs should be a governmental or individual approach. Solutions for integrating systems into small spaces and improving efficiency are needed, especially in high-density cities.

7.2. Areas for future study

As for the prospects for future studies, the authors suggest:

Multidisciplinary Approaches: Investigate the intersection of cultural, social, and economic factors with energy-efficient building technologies to create more inclusive and adaptable ZEB solutions.

Retrofitting Traditional Buildings: Develop strategies and technologies specifically designed for retrofitting existing traditional buildings, considering their unique architectural and structural characteristics.

Integrated HVAC Solutions: Explore integrated HVAC systems that combine various technologies (e.g., heat pumps, natural ventilation, advanced insulation) to improve overall energy efficiency and occupant comfort.

Renewable Energy in Urban Settings: Study innovative solutions for installing renewable energy systems in limited spaces, such as high-rise buildings and densely populated urban areas.

Economic Viability and Policy Frameworks: Conduct detailed analyses of the financial implications of ZEBs, including cost-benefit analyses, funding mechanisms, and the role of government incentives versus private investment.

Climate-Specific ZEB Technologies: Research how ZEB technologies can be tailored to different climatic conditions to ensure their effectiveness and feasibility across diverse environmental settings.

Long-Term Performance and Maintenance: Examine the long-term performance, durability, and maintenance requirements of ZEB technologies to ensure their sustainability and reliability over time.

CRediT authorship contribution statement

Baseem A. Aljashaami: Funding acquisition, Formal analysis. **Bashar M. Ali:** Methodology, Investigation. **Sajjad A. Salih:** Resources, Project administration. **Naseer T. Alwan:** Software. **Milia H. Majeed:** Visualization. **Obed M. Ali:** Data curation, Conceptualization. **Omar R. Alomar:** Writing – review & editing. **Vladimir I. Velkin:** Writing – original draft. **Sergey E. Shcheklein:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

Support from the Ministry of Science and Higher Education of the Russian Federation (Ural Federal University Program of Development within the Priority-2030 Program) is gratefully acknowledged: Grant Number FEUZ-2022-0031.

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