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Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade

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ABSTRACT

Energy consumption has dramatically increased in buildings over the past decade due to population growth, more time spent indoors, increased demand for building functions and indoor environmental quality, and global climate change. Building energy use currently accounts for over 40% of total primary energy consumption in the U.S. and E.U. Nevertheless, significant energy savings can be achieved in buildings if they are properly designed, constructed and operated. For this reason, building energy efficiency can provide key solutions to energy shortages, carbon emissions and their serious threat to our living environment. This paper offers a brief overview of building energy-consumption situations, relevant energy-saving approaches, and the influence of global climate change. Building energy-consumption situations based on data derived from international energy reports are initially compared between the U.S., China and the E.U. Both similarities and differences are found in aspects of building energy end-uses and final energy fuel-types among these top three building energy consumers. We then introduce the current concept of the zero-energy building (ZEB). State-of-the-art approaches for ZEB technologies are summarized in three categories: passive energy-saving technologies, energy-efficient building service systems and renewable energy production technologies. The feasibility of these technologies is reviewed. In addition, we briefly discuss the influence of global climate change on the evolution of building energy use in the future. We find that climate change significantly impacts building energy performance, particularly in space heating and cooling. Improvements on building envelope and ventilation can play an important role in reducing space heating and cooling consumption levels. We also provide some suggestions for further developing ZEBs.

1. Building energy consumption status

According to the U.S. Energy Information Administration (EIA) [1], global totals of primary energy consumption and CO_2 emissions have grown by 85% and 75% from 1980 to 2012, with average annual increases of 2% and 1.7%, respectively (Fig. 1). Coal accounts for approximately 25% of total energy consumption in most of these years, thus causing substantial CO_2 emissions. Total global energy consumption, coal consumption and CO_2 emissions are projected to increase by approximately 32%, 19% and 16% from 2012 to 2035 under the new policies scenario, respectively [2]. The growth of coal consumption is projected to be slowing after 2012 due to reforms in the energy structures in countries such as the U.S. and China. Most of the increase in energy consumption and CO_2 emissions is thought to be contributed by developing countries. By 2010, China had outpaced the U.S. as the largest consumer of energy in the world, with a 20% share of total world energy consumption. Energy consumption in the US decreased by 2% to 97.8 quads (quadrillion Btu) between 2008 and 2010, whereas China's energy consumption increased by 22.9% to 104.6 quads [3].

Most people currently spend 90% of their daily lives indoors and relying on mechanical heating and air conditioning, thus leading to buildings becoming the largest energy consumers worldwide. The ratio of building energy consumption to total energy consumption increased from 33.7% to 41.1% between 1980 and 2010 in the U.S. [3]. The EIA predicted that this growth would slow down due to the economic recession until 2016 but resume steady growth through 2035. Building energy consumption in China increased by 40% from 1990 to 2009, making China the second largest building energy consumer in the world after the U.S. Chinese building energy

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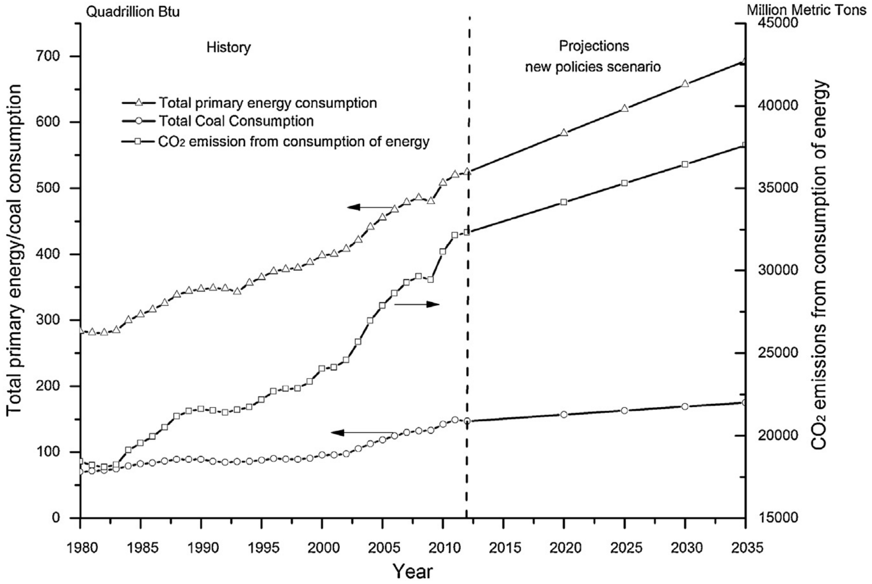


Fig. 1. Global primary energy consumption, coal consumption and CO_2 emissions from energy consumption from 1980 to 2035 [1,2].

consumption accounted for 27.3% of total energy consumption in 2010, including the use of biomass energy in the residential sector [4].

However, per capita building energy consumption in China is still far less than that in the U.S., as shown in Fig. 2. The high energy-insensitive behaviors of occupants in the U.S. may be attribute to the historically low energy prices, especially relative to their income levels. Compared to the U.S., the per capita building floor area and energy intensity are much lower in China. Nevertheless, with the rapid development of the Chinese economy, per capita building energy consumption quickly increased from 6.17 MBtu/capita in 1996–14.49 MBtu/capita in 2012, whereas the level was maintained at approximately 125 MBtu/capita in the U.S. The China to U.S. building energy intensity ratio has increased from 7% in 2001–12% in 2012. In the European Union (E.U.), buildings are also the largest end-use sector, accounting for approximately 40% of total energy consumption and 55% of electricity consumption in 2012 [5].

1.1. Building energy end-uses

Fig. 3 shows the breakdown of building energy end-uses for the U.S., China and the E.U. in 2010, based on the data derived from Ref. [6]. As shown in Fig. 3, heating energy (space heating and water heating) clearly comprises the largest portion of total energy consumption in these regions. In the residential sector, space heating and water heating are the major end-uses, followed by appliances, cooking and lighting. Space cooling occupies the smallest portion of final energy demand. In the services sector, space heating and cooling are the dominant energy end-use, followed by appliances and other equipment, water heating, and lighting.

There are also differences in the fraction of energy end-uses between the U.S., China and the E.U. In the U.S., energy consumed by space heating accounts for 37% of residential energy consumption and more than 25% of service sector energy consumption; water heating accounts for a 15% overall share of total building energy end-uses. Energy consumed by appliances and service equipment in the U.S. is clearly higher than in China and the E.U. In China, space and water heating account for 71% and 68% of total final energy demand in the residential and services sectors, respectively, and cooking approaches 16%—much higher than the U.S. and E.U.; this may be due to the high usage of traditional biomass in rural areas. Meanwhile, appliances and equipment only account for 13% of energy use in the Chinese services sector, which is relatively lower than the others. In the E.U., space heating is the greatest end-use in terms of final energy consumption, accounting for 66% of residential energy use and 39% of service sector energy consumption—a higher level as a whole than the U.S. and China. The ratios of energy usage from space cooling and lighting are generally similar between these countries and regions.

In the U.S., heating benchmarks for existing large office buildings after 1980 ranged from 9800 Btu/square foot (30.9 kWh/m^2) in Baltimore (climate zone 4A, mix-humid) to 19600 Btu/square foot (61.8 kWh/m^2) in Minneapolis (climate zone 6A, cold-humid) [3]. In the urban area of northern China, the energy used for space heating accounts for 24% of total building energy consumption, with a unit energy use of 15.1 kgce/m^2 that was equivalent to 47.5 kWh/m^2 in 2013 [7]. It is notable that heating energy use experienced a 34% drop compared to 2001, showing significantly improved energy efficiency for district heating systems in northern China. Moreover, space heating has also become popular in the hot summer and cold winter zone in China. The floor area in this region increased from 1.3 billion m^2 to 5.8 billion m^2 between 1996 and 2010 and the unit level of energy consumed for space heating was 6.8 kWh/m^2 in 2010, increasing by 50% since 2005 [8]. Total heating energy consumption has nearly tripled in Chinese urban residential buildings between 1996 and 2008 [9]. In European buildings, space heating comprises the greatest portion of energy usage, consuming over 50% of their primary energy demand [10]. Fig. 4 shows the average space heating energy usage in E.U. countries; it can be observed that heating energy has decreased in most countries since 2000 due to improvements in energy efficiency. Significant differences do exist among E.U. countries, from 60 to 90 kWh/m^2 in southern countries with lower heating needs to 175–235 kWh/m^2 in colder countries in northern and western Europe. Based on the above data, the heating energy usage per unit area in China is still lower in the U.S. and E.U.

Building energy end-uses are projected to increase in the future due to increasing population, economic growth and climate change. Zhou et al. [11] predicted future Chinese building energy consumption in two development scenarios and found that consumption will continue to increase in subsequent decades, even with the application of energy-saving technologies. Different countries will require their own strategies to maintain building energy con-

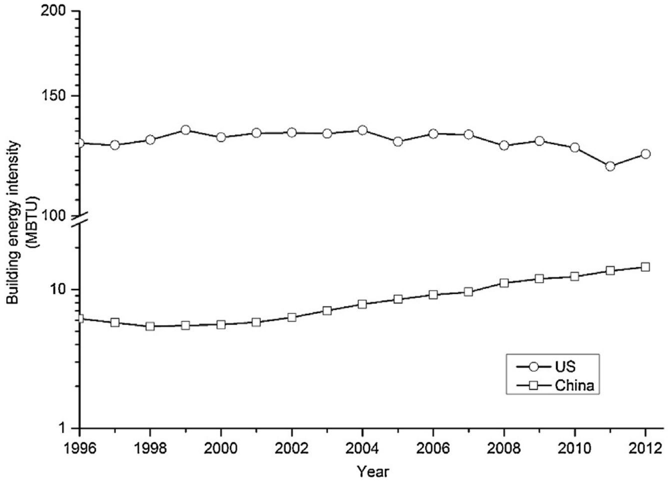
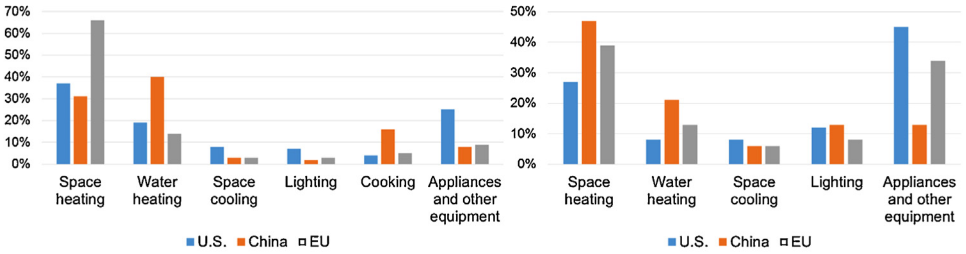


Fig. 2. Building energy consumption per capita in the U.S. and China.

Data Source: the U.S.: EIA; China: China Statistical Yearbook. Calculation method: 2007 Annual Report on China Building Energy Efficiency.



Residential sector

Total energy uses：U.S.: 11.2EJ; China:14.9EJ; EU: 12.8EJ

Services sector

Total energy uses：U.S.: 8.6EJ; China:2.8EJ; EU: 6.5EJ

Fig. 3. Breakdown of building energy end-uses in the U.S., China and the E.U., 2010.

Data Source: IEA [6]

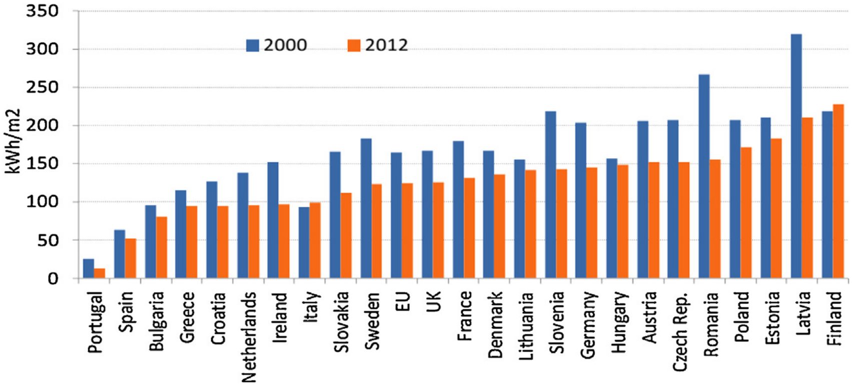


Fig. 4. Space heating energy usage per m^2 in European countries [5].

sumption at an acceptable level. Rapid economic growth and urbanization in China record the steepest expand in building stock worldwide, and inevitably rapid increase in building energy use. Therefore, China is predominant in global building energy saving movement. In China, different climatic zones have a strong influence on energy-saving technology options. In northern areas, improving district heating energy efficiency is a priority, whereas in moderate climatic regions, bi-modal heat pumps may be preferred; advanced cooling technologies are preferred in southern region. In northern China, strong incentives for energy savings can be provided by the low energy pricing and reform heat metering in district heating systems. China also needs to seek the balance between the increasing building energy demand and the improvement in comfort and services. It is beneficial to appropriately maintain the low-consumption tradition (natural ventilation, moderate indoor temperature set and partial conditioning).

The primary energy-saving task for the E.U. is increasing space heating efficiency through renovations in building envelopes and heating equipment in existing building stock. The building stock in the E.U. is characterized by a high share of existing building. Long existing building lifetimes make the thermal efficiency retrofit essential. Update appliances and equipment are also crucial to reduce electric demand in buildings and peak grid loads, especially in the residential sector. For instance, it is helpful to replace conventional electric heater with the heat pump for space and water heating progressively.

Appliances consume a large share of the total consumption in the U.S. Therefore, energy-efficient appliances and equipment have significant energy savings potential in the U.S., Currently the U.S. has already adopts very aggressive mandatory standards of appliance and equipment. The services section consumes considerably high share of the total U.S. building energy uses. This suggests substantial opportunities for energy savings in public and commercial buildings. Space heating and cooling should be addressed in both new construction and the retrofitting of existing buildings. Generally, building retrofits can provide significant potential energy savings in countries with high levels of energy intensity such as the U.S. and E.U. In contrast, improving energy efficiency in new buildings is more effective for countries experiencing rapid urbanization and robust new construction such as China.

1.2. Building energy consumption by fuel types

Fig. 5 depicts building final energy consumption by fuel types in the U.S., China and the E.U. in 2010 [6]. It can be observed that electricity and natural gas are the primary fuels sources for building energy use in the U.S., with shares of nearly 50% and 40% of final energy usage, respectively. Electricity is the largest final energy source in the U.S. building sector and is primarily used for heating, cooling, lighting and appliances. When considering source-to-site losses, electricity actually accounts for 72.9% of the total primary energy used in the building sector in 2010 [3]. However, conventional heating and cooling equipment fueled by natural gas and oil are still widespread in the U.S., and natural gas is also the primary fuel source for water heating. Coal and renewable energy only account for 3.2% of the total building final energy usage in the U.S. Conversely, biomass and waste are the dominant energy sources in the residential building sector in China due to their use for heating and cooking. The residential sector in China consumes more than 5 times the energy consumed by the services sector. Therefore, switching fuel sources from traditional biomass to modern fuel choices is crucial for reducing the overall energy used, largely in rural areas. In addition, coal accounts for 14.3% of Chinese building final energy use—a much higher level than that in the U.S. and E.U. However, the use of electricity for commercial heat sharply increased during the last decade. In 2013, electricity accounted for 57% of total building energy consumption in China [7]. In the E.U., final energy usage is dominated by electricity and natural gas, similar to trends in the U.S. Biomass and other renewables account for 9% of building final energy use, mostly for heating purposes.

Fig. 6 shows the building final energy mix in different regions of the E.U. In the residential sector, gas is the most common fuel in all regions. District heating, renewables and solid fuels are most popular in central and eastern regions. District heating and solid fuels are not found in southern regions due to low heating demand. In the services sector, electricity is the dominant final energy usage. It is estimated that unit energy consumption in the services sector is 280 kWh/m^2, at least 40% greater than in the residential sector [12].

As shown above, fossil fuels (coal, oil, and natural gas) account for the largest portion of global building energy use. In addition to its direct use in the building sector, the combustion of fossil fuels provides most of the electric power generation. For example, almost 67% of total electricity demand was provided by the combustion of fossil fuels in the U.S. in 2015 [13]. With the promotion of environmental awareness, people have learned that the combustion of fossil fuels leads to serious air pollution and carbon emissions. Therefore, the decarburization of electricity generation is a priority for both energy savings and emissions reduction and renewable and clean energy is obviously a better choice than fossil fuels. Future buildings will not only require energy conservation technologies but also reforms of the current energy structure.

1.3. Concept of zero-energy building (ZEB)

Building energy consumption plays a crucial role in global energy requirements; significant energy savings can be achieved in buildings if they are properly designed, constructed and operated. For this reason, building energy efficiency is viewed today as a key solution to address energy shortages, carbon emissions and their threat on our living environment. Significant efforts have been made to implement innovative energy conservation technologies and formulate green building policies. In particular, the current concept of a zero-energy building (ZEB) has received increased interest during the past decade. The concept of a ZEB was first mentioned in 2000 and became a mainstream idea in 2006 [14]. ZEBs are considered to be the ultimate solution for mitigating the negative impacts of future building energy consumption. In the E.U., the recast Directive on Energy Performance of Buildings (EPBD) set the ZEB as the target for all new buildings by 2020 [15]. In the U.S., the Energy Independence and Security Act of 2007 set a zero-energy target of 50% for new commercial buildings by 2040 and for all new commercial buildings by 2050 [16]. The development of ZEB in China is relatively late and less organized. However, China have a great potential and resources to implement ZEB designs on a massive scale. The latest 5-Year plan has required that green buildings should account for 20% of the total floor space newly constructed by 2015. There are already numbers of individual ZEB projects in China, e.g. Pearl River Tower in Guangzhou.

A ZEB is a new next-generation design concept that combines the ideas of traditional green building and renewable energy generation. There are a number of definitions and calculation methodologies for ZEBs [17] that consider different aspects such as balance metrics, balancing periods, the type of balance, renewable energy supply options and connections with energy infrastructure. The balance metrics (credits) include delivered energy, primary energy, carbon emissions and energy cost. Specifically, a ZEB can be interpreted as the zero emission building in term of carbon emission: the carbon emissions generated from on/off-site fossil fuel based energy use are balanced by the renewable energy productions. The carbon emissions may include those generated from construction, embodied energy of the structure, operation and demolition, depending on the defined boundary. The balancing periods can be a month, a year or even an entire life cycle. Annual balance is now the most favored balancing period. There are two types of balance: (1) energy demand vs. renewable energy generation (design phase) and (2) imported energy vs. energy feed-in to the grid (monitoring phase during operation). The first type of balance are more commonly-used, for applicable in the design phase. Also the off-grid ZEB can only use the first balance. The renewable energy options can be either on-site generation (solar, wind) or off-site generation (biomass, transportation needed). In addition, investment in off-site technologies or directly purchase of green energy or CO_2 credit can also offset the energy use in a broader view.

Considering the connections with infrastructure, there are two types of ZEB: grid-connected ZEB and autonomous/stand-alone ZEB. The grid-connected ZEB is also called a net ZEB (NZEB), which refers to a ZEB that is connected to other energy infrastructure [18,19]. Fig. 7 shows the basic elements for a grid-connected ZEB [18]; near- or net-zero energy can be achieved through the energy balance between the buildings and grids. An autonomous ZEB is a self-sufficient building that has the capability to store adequate renewable energy for internal use [17]. It is typically more challenging to design an autonomous ZEB because it is off-grid and highly dependent on an energy storage system. In general, NZEBs receive

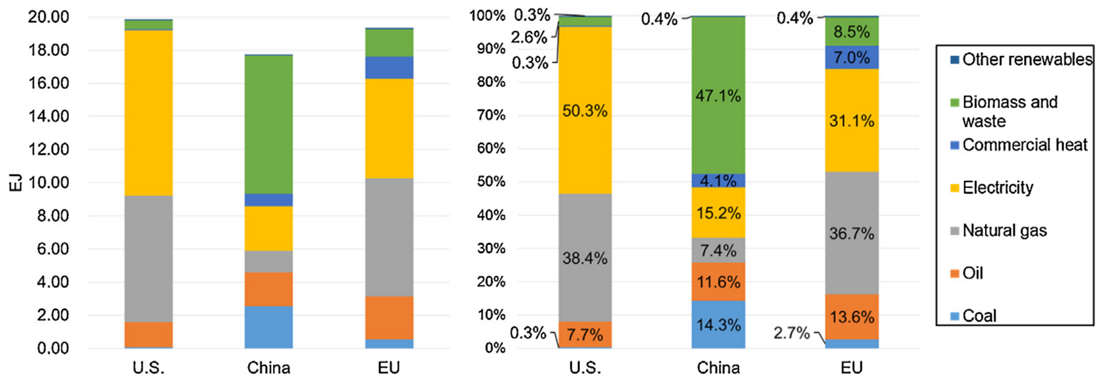


Fig. 5. Building final energy consumption by fuel types in the U.S., China and the E.U., 2010.

Data Source: IEA [6]

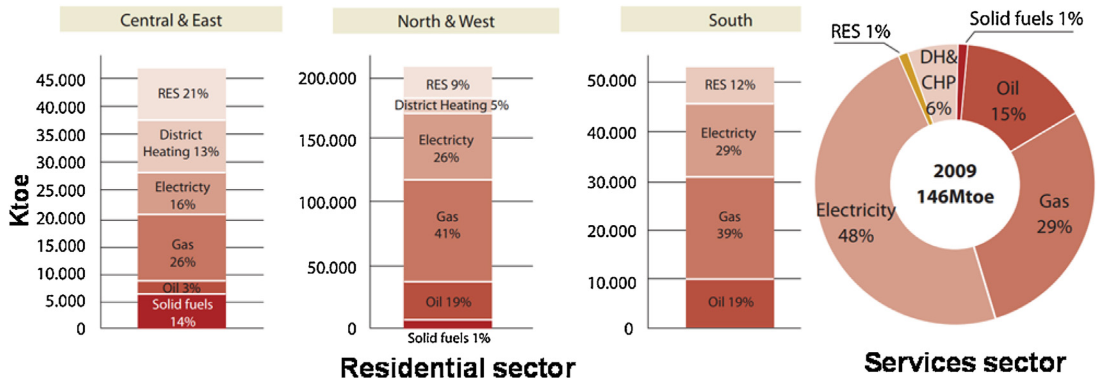


Fig. 6. Final energy mix in European buildings, 2009.

Data sources: BPIE [12]

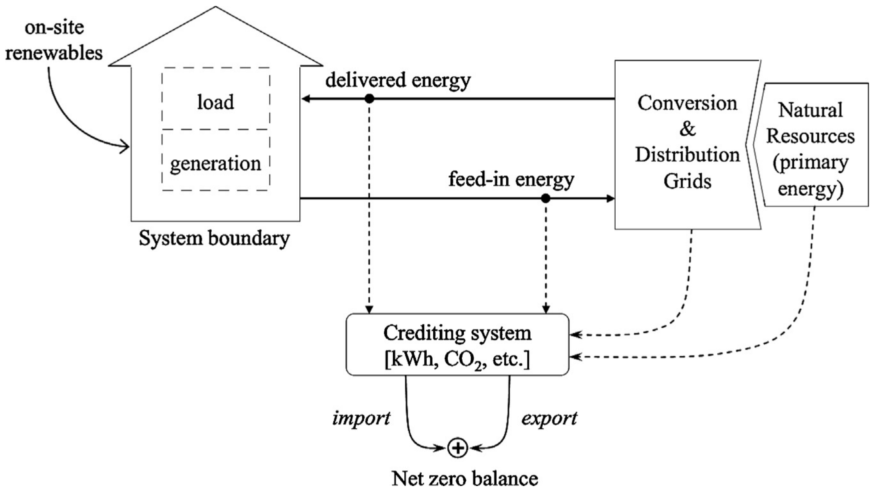


Fig. 7. Schematic of a typical NZEB [18].

more attention due to their interactions with existing urban grids. Autonomous ZEBs are only considered when there is no access to an external grid, such as on islands or in rural areas [20].

A straightforward definition given by the EPBD is "*a nearly zero-energy building means a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby*" [15]. Here a cost-optimal, nearly zero-energy building can be interpreted as a building for which the energy need for heating and cooling is less than 30 kWh/m^2/y by 2021 [21]. Based on this definition, two approaches can be used to achieve a ZEB: energy-efficient measures and renewable energy generation. First, building energy consumption can be obviously reduced by applying suitable energy-efficient measures. Second, renewable energy generation systems are also needed to compensate for building energy consumption. The near- or net-zero building energy consumption is then fulfilled by the balance between energy demand and generation over a certain period, typically a year or even the lifetime of the building. A ZEB can also be a traditional building supplied by powerful renewable energy generation systems. However, applying energy-efficient measures is typically a prerequisite because renewable energy generation options can be limited or intermittent for many ZEBs. A brief overview of recent progress on ZEBs is presented in the section below and is based on recent publications from English language journals.

2. State-of-the-art technologies for zero-energy building (ZEB)

2.1. Passive building energy saving technologies

Implementation of passive energy saving technologies is a fundamental way to improve building energy efficiency. Passive strategies primarily include advanced building envelopes, passive heating or cooling, and thermal energy storage. Sadineni et al. [22] summarized the advanced energy-efficient strategies used in different building envelope components, including walls, fenestration and roofs. Building envelopes are crucial for thermal comfort levels and energy savings because they separate indoor and outdoor environments. According to their review, improving building envelopes primarily relies on two approaches: reducing thermal transmittances (U-values) and combining with passive heating or cooling. The U-values of building envelopes significantly influence building energy consumption levels by reducing heat gain/loss, particularly under harsh climate conditions. Thermal insulation is a simple and effective approach to lower the U-values of walls and roofs, thus achieving energy savings in space heating and cooling. In envelope-load dominated buildings such as rural buildings and residences, thermal insulation is a major factor in improving building energy efficiency. Shan et al. [23] investigated the passive energy savings effect of a retrofitted single-story house in a Beijing suburb. They applied an adhesive polystyrene granule layer as thermal insulation on the interior walls and the roof. The simulated results indicated that the overall energy savings effect was 57% and the payback period for the retrofit was 5–6 years. Cao et al. [24] numerically studied the heating energy consumption of a high-rise residential building that used a central heating system and glass fiber boards as interior building envelope insulation. They found that the appropriate insulation thickness was 20 mm and the heating energy savings potentials were 12.27% and 11.36% in Harbin (severe cold climate) and Beijing (cold climate), respectively.

Fenestration is a vital factor for both visual comfort and cooling loads in building environments. To minimize overall heat gain/loss, one must reduce the window-to-wall ratio and use window glazing materials with low U-values. There have been recent advances in energy-saving glazing technologies such as vacuum glazing, low-emissivity (low-e) glazing and dynamic glazing [25]. It should be noted that an optimal balance between solar heat gain and daylight must be considered when selecting glazing types and layers [26]. In cooling-dominated buildings, the appropriate utilization of daylight not only provides a visually comforting environment but also effectively decreases electricity consumption for both lighting and air conditioning applications [27].

Passive heating technologies are essentially dependent on solar heat gain. For example, a solar gain wall (Trombe wall) is a typical passive heating device that efficiently traps and transmits solar energy into a building. Eshraghi et al. [28] investigated a solar ZEB that utilized a Trombe wall, roller shading and thermal mass in Tehran (warm climate). In their study, the use of a Trombe wall led to a 42% load reduction in a large bedroom. Passive cooling [29] can be achieved through ventilation, ground cooling, shading and other solar heat prevention techniques. Nighttime building ventilation uses colder night air to attenuate heat gains during the daytime, thus avoiding summer overheating and reducing cooling energy consumption [30]. The cooling efficiency of ventilation is influenced by the difference between the indoor and outdoor temperatures, the airflow rate, and the integration with thermal mass. Nighttime ventilation is primarily driven by natural forces, though it can be supplemented by fans when the wind pressure difference is low. Schulze and Eicker [31] systematically investigated the controlled natural ventilation effects on the annual thermal comfort and energy savings of office buildings in moderate climate locations. They found that the proposed natural ventilation system could save between 13 and 44 $\mathrm{kWh/m^2}$ cooling net energy per year in Stuttgart, Turin and Istanbul. The savings in electrical energy from using a fan were approximately 4 $\mathrm{kWh/m^2}$ per year. Ground cooling techniques are based on earth-to-air heat exchangers (EAHE) [32]. An EAHE is an underground cooling system with a network of pipes buried at a reasonable depth below the earth's surface. Ventilated air is cooled through recirculation in the underground pipes. Bisoniya et al. [33] studied the energy metrics for an EAHE system under hot and dry climate conditions in India. The total yearly energy output of an EAHE system with an air velocity of 5 m/s was 1290.53 kWh with a payback period of 1.29 years. Solar heat prevention techniques primarily consist of solar shading and green roofs. Li et al. [34] investigated the performance of a building integrated with a solar thermal shading system. The proposed shading system was predicted to save 5.3% of total primary energy, improve the useful daylight level and reduce the excessive daylight level. The payback period was approximately 8.5 years. A green roof is a practical way to lower indoor temperatures and mitigate urban warming [35]. A recent study showed that a green roof system covering an area of 10000 $\mathrm{m^2}$ helped reduce the annual cooling needs of an Athens office building by 19% [36]. However, in ZEB applications, green roofs may conflict with the installation of renewable energy systems. In this situation, hybrid photovoltaic (PV) green roofs appear to be a new solution that provides the benefits of both green roofs and PV electrical generation [35].

Passive thermal energy storage is another practical approach for building thermal control that primarily relies on latent heat storage and release by a building's thermal mass or phase-change materials (PCMs) [37]. PCMs have received increased research interest in the past decade. A recent search shows 1437 articles on PCM applications in buildings published in the leading Elsevier energy journals through 2014 [37]. It has been suggested that integrating PCMs with nighttime ventilation can achieve greater energy efficiency. Thus, PCMs are more effective in office buildings that are unoccupied during the night [38].

It should be noted that the effects of passive energy saving technologies are highly sensitive to local climate conditions [39]; this should be seriously considered in any design stage. In cold climates, thermal insulation and passive solar heat gain are typically the most effective measures. Nighttime ventilation and passive thermal storage are more desirable in moderate/Mediterranean climates where large temperature differences exist between day and night in summer. In tropical climates, ground cooling, solar shading and green roofs tend to be the best options for passive cooling.

2.2. Energy-efficient building service systems

HVAC, domestic hot water (DHW), lighting and appliances account for most of the energy use in building service systems. In particular, HVAC systems account for almost half of building energy consumption and approximately 10–20% of total energy consumption in developed countries, which demonstrates great energy saving potential. Therefore, enacting energy-efficient measures for building service systems is a worthy approach for achieving ZEBs.

2.2.1. HVAC systems

The energy-saving strategies for energy-efficient HVAC systems [40] primarily consist of evaporative cooling, active thermal storage, heat recovery, radiant heating/cooling, chilled beams, variable air volume (VAV) and variable refrigerant flow (VRF). Evaporative cooling is considered a cost-effective method compared to vapor compression air-conditioning applications [41]. Evaporative cooling techniques cool air by increasing its moisture content, with the cooling capacity limited by the wet bulk temperature of the handling air. For this reason, evaporative cooling is more suitable under hot and arid climate conditions. Active thermal storage systems can shift energy consumption from on-peak to off-peak periods to avoid peak charges or balance energy supply and demand [42]. Ice and chilled water are the two most commonly used mediums for thermal storage. The ice or chilled water stored in tanks can be used to cool the indoor air during peak electricity usage periods. More detailed information regarding thermal energy storage systems for air conditioning can be found in Ref. [42]. Heat recovery techniques [43] use heat exchangers to transfer heat between fresh air and exhausted air, thus recovering a significant amount of energy. There are two types of heat recovery techniques: sensible heat recovery and enthalpy heat recovery. Current heat recovery systems can recover 60–95% of wasted energy and provide additional ventilation [43]. However, the energy savings from heat recovery must be balanced against the electrical power consumed by fans [44].

Radiant heating/cooling systems [45] have been gaining popularity due to their high thermal comfort, energy-efficiency, low noise and limited space occupation. Radiant heating/cooling systems must be integrated with structural components such as floor heating, chilled ceiling, and thermally activated building systems. Floor heating systems are typically applied in cold climates and chilled ceilings are widely used in mild or hot climates. Radiant cooling systems cannot moderate air humidity and can lead to condensation on radiant surfaces, especially when employed in hot and humid climates. In this situation, desiccant dehumidification is regarded as a supplement to radiant cooling systems to avoid the condensation issue [46]; it provides a good example for the concept of independent control of air temperature and humidity. In a hot and humid climate, it is better to treat the sensible heat and latent heat separately in an energy saving and thermal comfort air conditioning design. In addition, radiant heating/cooling systems can also be coupled with other ventilation systems for removing latent heat such as displacement ventilation. Chakroun et al. [47] studied the performance of a combined chilled ceiling and displacement ventilation system in a test office in Kuwait. Energy consumption was 15–20% lower than a conventional system. Active and passive chilled beam systems are also water-based heating/cooling systems. However, unlike radiant heating/cooling systems, these technologies deliver the majority of their cooling and heating through convection and low-volume ventilation. Chilled beam systems are suitable in buildings with high sensible loads and seamlessly integrate with displacement ventilation or underfloor air distribution [48].

VAV-based air-conditioning systems are one of the most energy efficient systems in use today [49]. VAV maintains the indoor air temperature by varying the supplied air volume instead of supplied air temperature. Compared to constant air volume (CAV) systems, VAV systems only provide needed ventilation according to a varying load and are thus very effective for partial-load conditions. Obviously, an optimal control strategy is crucial for improving overall energy savings through VAV systems [49]. Ahmed et al. [50] investigated the performance of a demand-controlled VAV chilled beam system in a LEED Platinum office building in Finland. The results indicated that the VAV system saved 7–8% of primary energy compared to a CAV system with equivalent indoor air quality and thermal comfort. VRF systems change the refrigerant flow rate through variable speed compressors and electronic expansion valves located in each indoor unit to remove the corresponding load [51]. VRF systems are well suited for office buildings, schools, hotels and hospitals where individualized air conditioning for each room is needed. However, the cost of VRF systems is much higher compared to conventional systems. In a 200-t cooling system in a commercial building, VRF could save 30–40% of the energy used by an air-cooled chiller system with a payback period of 1.5 year [52]. VRF systems should operate with additional ventilation systems and optimal control strategies. A recent study [53] presented a combined VRF and VAV system to solve the problem of VRF systems using outdoor air ventilation. The results indicated that the optimal control strategy contributed an energy savings of 32.17% in summer and 2.47% in winter for the combined system.

2.2.2. Other building service systems

The energy-efficiency measures for domestic hot water (DHW) systems are primarily based on the utilization of solar thermal energy and integration with HVAC systems [54]. Solar water heaters (SWHs) can reduce both the energy and greenhouse gas emissions required for water heating. SWHs have been commercialized worldwide and significantly contribute to both domestic and industrial sectors in many countries [55]. China currently dominates the global SWH market with a 70% share. The cumulative capacity of SWHs in China amounted to 217 GWTh in 2013, with a total installed collector area of 310 million m^2 [56]. The classification of SWHs is primarily based on the type of working fluid or the thermal energy storage system [57]. SWHs can also be categorized as passive or active circulation systems depending on the circulation types. Passive circulation systems use thermosyphonic methods in which the density difference induces the circulation of the fluid. An integrated collector storage SWH is a passive system that utilizes the solar collector as a both a combined storage tank and an absorber to collect solar radiation. This technique has the potential to reduce environmental impacts by up to 40% and also provides a high collection efficiency factor [58]. However, integrated collector storage SWHs can suffer from high thermal losses under night/overcast sky conditions. To overcome this shortage, latent heat storage using PCMs can be applied to SWH applications to take advantage of high storage density and heat transfer at a constant temperature [57]. Active circulation methods use a pump or a fan to force the circulation. A solar-assisted heat pump system [59] is an active technique for a SWH application that uses a solar collector as an evaporator and transfers thermal energy for DHW storage. There has been growing interest in developing these integrated systems for both HVAC and DHW production to provide hybrid energy solutions for ZEBs. Integrated HVAC and DHW systems can provide multi-energy outputs such as space cooling, space heating, DHW production and electricity with one type of energy input [54]. These combined cooling, heating and power (CCHP) systems can simultaneously generate electricity and thermal energy while reducing primary energy consumption and carbon emissions. In addition, CCHP systems can be integrated with renewable energy sources (solar energy, bioenergy, heat pump) as a holistic solution for ZEB power supplies. Developing optimal strategies will be necessary when scheduling the operations of CCHP systems.

Lighting systems are also significant consumers of electricity, particularly in office buildings [60]. Combined electricity costs for lighting and relevant cooling loads account for almost half of the total electricity demand in conventional office buildings [27]. The general methods for achieving lighting electricity energy saving are advanced lighting technologies and daylight harvesting strategies. Light-emitting diodes (LEDs) have the potential to become the predominant lighting technology in the next decade due to their long service life and good lighting efficacy. However, it should be noted that approximately 75–85% of the light electric power consumed by LEDs is still generated as convective heat, which may have a negative effect through increasing indoor cooling load [61]. Daylight harvesting is also an effective way to reduce artificial lighting electricity consumption. For example, lighting electricity use can be significantly reduced by using on/off or dimming control strategies integrated with daylight. Chen et al. [62] studied the effects of lighting control strategies on energy savings in a large industrial plant in Tianjin. They found that the electricity saving potential of on/off and dimming controls integrated with daylight were 36.1% and 41.5%, respectively. Moreover, the benefits of daylight not only provide simple energy savings but also increases in work productivity and visual satisfaction.

Appliances also significantly contribute to increased electricity consumption in buildings. According to IEA's Energy Technology Perspectives, worldwide appliance electricity consumption in 2030 is expected to be twice that in 2000. Cabeza et al. [63] summarized the development trends of worldwide electricity consumption by appliances. Trends in different countries all show that appliances account for an increasing amount of building energy consumption. Therefore, the utilization of energy-efficient appliances is critical for reducing building energy consumption and is significantly influenced by occupant behavior and social guidance. Kavousian et al. [64] offered a novel method for ranking appliance energy efficiency in households in 4231 buildings in Ireland. They found that appliance energy efficiency was primarily affected by structural factors, socio-economic factors and behavioral factors. Their finding also validated the crucial role of educational programs in increasing awareness about home energy efficiency. Another review article presented 62 factors that potentially influence domestic electricity use, and 37 of these factors were appliance related [65]. A recent study focused on the impact of appliance ownership and usage on electrical energy demand in 183 U.K. homes [66]. The results indicated that households were likely to be high electricity consumers with specific appliances including desktop computers, laptop computers, large-screen TVs, upright freezers, dishwashers, tumble dryers or electric showers. Finally, smart scheduling is also suggested for the optimal management of appliances in the domestic sector. For example, an artificial neural network/genetic algorithm was applied to smart appliance scheduling [67]. Schedules were successfully implemented in a four-bedroom house, with grid energy usage reduced by up to 40%.

2.3. Renewable energy generation technologies

Even with applying the various energy-efficient measures mentioned above, more or less energy is still required to maintain the daily operation of a building. In ZEBs, energy consumption is usually supplemented by renewable energy generation. The major renewable energy sources available for buildings are solar energy, wind energy, geothermal energy and bioenergy. Realizing the efficient and reasonable use of these renewable energy sources is the final step in ZEB designs.

As mentioned in Section 1.2, using renewable energy not only decreases carbon emissions but also offers a series of additional benefits such as clean air and energy security. Renewable energy is now considered a key to achieving climate and sustainability objectives, as reinforced by the 2015 United Nations Climate Conference in Paris. Currently, most of the contribution of renewables still comes from traditional biomass used for space heating and cooking in the residential sectors of developing countries [2]. This use is unsustainable due to the low conversion efficiency and harmful emissions produced. In the E.U. and U.S., more modern renewables (clean bioenergy, geothermal and solar thermal) are used instead of the combustion of traditional biomass. More than 40% of the heat generated by modern renewables is consumed in Europe, mostly in the form of clean bioenergy for space heating. China is also a rapidly developing market for modern renewables, as driven by the growing deployment of the solar water heater.

The International Renewable Energy Agency (IRENA) proposed a project named REmap that aims to double the share of modern renewables in the world's energy mix by 2030 [68]. They predict that China (20%), the U.S. (15%) and the E.U. (14%) will become the three largest renewable energy consumers, eventually reaching a combined global share of 49%. With these REmap options [68], the share of coal in the global power generation will shrink to 25% by 2030, compared to 43% today. Under the same scenario, wind power will be prominent renewable option, growing from 3% to 14%, and solar photovoltaic (PV) power will also increase from less than 1% to almost 7% from 2014 to 2030.

2.3.1. Solar energy and wind energy

PV or building integrated photovoltaic (BIPV) are the most widely used techniques to convert solar energy into electricity for ZEBs. PV technologies directly convert incident solar energy into electrical energy by using the photoelectric effect [69]. Pandey et al. [70] systematically reviewed recent advances on PV technologies; they found that the efficiency of PV systems varies from 10% to 23%. A large portion of the solar radiation incident on the surface of the PV panel is converted into thermal energy, thus reducing conversion efficiency by increasing the working temperature of the PV cells. The integration of electricity generation and thermal collection is a promising solution for this technical problem. Hybrid photovoltaic-thermal (PV/T) systems simultaneously generate electricity and heat [71]. This can lead to high total energy generation efficiency and space savings per module in ZEBs. However, the PV/T market is still much smaller than that for PV and solar thermal technologies [70]. Challenges remain in improving the performance of PV/T systems. Good et al. [72] compared the performance of solar thermal, PV and PV/T systems in residential ZEBs in Norway. Their results showed that the building with only highly efficient PV modules was closest to reaching a zero-energy balance. A system with uncovered PV/T modules can provide good electricity output, but the thermal output is still small and of low temperature.

PV arrays are typically installed on roofs in both urban and rural areas. However, the roof area can be limited, particularly for high-rise buildings. BIPV systems integrate PV modules with onsite building envelopes such as walls, rooftops and windows and can significantly increase total electricity output. Moreover, BIPV systems can reduce the space, material and infrastructure costs of the building, which may lead the trend for future ZEB designs. Ng and Mithraratne [73] numerically studied the performance of commercially available semi-transparent BIPV modules for window applications in Singapore. Based on their study, the energy payback time was no more than 2 years, whereas the energy return could be as high as 35 times the initial cost. Thus, when buildings have limited rooftop areas but large facade areas, adopting semi-transparent BIPV windows is a good option.

It should be noted that the electricity generation of PV modules is highly dependent on local climate conditions. Geographically, PV systems are more effective in tropical and sunny regions with increased solar irradiation. In addition, PV systems are very suitable for tropical climates where a tremendous electricity demand exists for air conditioning in summer. The energy output of PV systems can be reliably forecast based on seasonal and daily patterns. Moreover, PV panels equipped with sun tracking systems [74] can reduce the influence of variable sky conditions, but these systems are considerably more expensive.

Unlike solar energy, wind energy is generally more stochastic and less predictable, with hourly and daily variations. Geographically, good wind sites are typically located offshore, in open rural spaces and on hills. Wind turbines are the main technology used to harness wind energy. Generating power from wind turbines varies with the wind speed. For ZEB applications, using building-mounted and small-scale wind turbines is a suitable choice. There are three common types of wind turbines for buildings: horizontal axial wind turbines, vertical axial Darrieus and Savonius turbines [75]. Designing appropriate building-mounted wind turbines requires the consideration of several important factors: prevailing wind conditions, neighboring geometry scenarios, building layouts and assembly forms [75]. Computational fluid dynamics (CFD) can be used to predict annual wind flows over buildings to analyze, locate, and design building-mounted wind power systems for both receiving high wind speeds and avoiding turbulence layers. Abohela et al. [76] used CFD to study the effect of roof shape, wind direction, building height and urban configuration on the design of roof-mounted wind turbines. Their results showed that an increase in energy yield could reach 56.1% in the case of a vaulted roof with an informed wind assessment above the roof. Policy guidance also has a significant influence on wind turbine applications in buildings. Liu and Ho [77] assessed the challenges and strategies of small wind energy system exploitation for Taiwanese buildings. The assessment objectives that engendered the highest consensus degree of importance were government policy promotions, followed by systems of economic costs. In addition, hybrid PV-wind systems [78] appear to be an alternative choice for improving overall energy generation efficiency when considering the variability in weather conditions. In this case, optimization approaches are necessary to analyze the energy-cost performance of different hybrid system configurations [79].

2.3.2. Geothermal energy

Geothermal energy utilizes the fact that the earth has a relatively constant temperature at a certain depth. A ground source heat pump (GSHP) has been promoted as an efficient building energy system that uses the earth's temperature as a heat source in a heating mode and a heat sink in a cooling mode. In general, a GSHP has a higher coefficient of performance (COP) than an air source heat pump for cooling due to a lower condensing temperature [80]. The performance of GSHP systems rely on a good match between condensing heat released to the ground in summer and evaporation heat absorbed from the ground in winter, which can be considered a type of seasonal thermal storage. Therefore, GSHPs generally have better performance in climates where building heating and cooling loads are well balanced all year round. However, when building loads are practically unbalanced and variable, an optimized combined operational strategy is suggested for a dynamic match between the energy demand and supply [81]. A long-term assessment of soil temperature is also vital for improving the performance of GSHPs. Liu et al. [82] investigated the feasibility and performance of a GSHP in a Chinese cold climate zone. They indicated that the inlet/outlet temperature of the buried pipe and the soil temperature would require a ten-year assessment to evaluate the feasibility of the GSHP system. Specifically, in heating-dominated buildings in harsh climate conditions, hybrid GSHP systems with solar collectors are preferred to avoid the heat depletion of the ground. The collected solar heat produces DHW in summer and recharges the borehole during the winter months. Emmi et al. [83] investigated the performance of a solar-assisted GSHP in cold climates. Based on their simulations, the energy performance of the heat pump decreased by approximately 10% in cold climates without solar thermal collectors over a ten-year period. The ratio between the solar heat collected and rejected to the ground was between 80% and 95%.

2.3.3. Bioenergy

Bioenergy is a high-demand energy source for multiple uses in the building sector that derives from waste products from agricultural and forestry activities. Biomass boilers apply a vast range of residual resources for the production of both electricity and space heating. A recent study was conducted to evaluate the energy, economic and environmental factors of the combustion of wood briquettes for heating a family house in northeastern Poland during three heating seasons [84]. This study showed that the cost of heat production from briquettes was low compared to fossil fuels. In addition, using wood briquettes led to a considerable reduction in greenhouse gas emissions compared to hard coal, heating oil or natural gas. In rural households in northern China, kangs heated by traditional biomass cooking stoves are still widely used [85]. A kang is a device suitable for utilizing waste heat from the fuel gas of traditional cooking stoves, but has a poor heating effect during the severe cold season. Commonly used biomass heat sources for kangs include corn stalks, straw, corncobs and energy plants. Efforts were recently made to improve the heating efficiency of kangs by incorporating forced convection [86]. Bioenergy can also be used for cooking and DHW production. Almost half the world's population uses different types of biomass fuels for cooking. A comprehensive review highlighted recent improvements to biomass cook stove designs [87]. The ultimate goal of a biomass cook stove is to achieve the quality of energy services comparable to that from liquefied petroleum gas (LPG). Moreover, biomass combustion can be used as renewable energy resource for CCHP applications [88]. Electricity generated from clean biomass can be an appropriate measure for greenhouse gas mitigation [89]. In short, bioenergy is currently a popular renewable energy resource worldwide but still can be improved to be more energy efficient and environmentally friendly.

Table 1 summaries the technologies aforementioned in this section. The costs are estimated category-specifically and subject to change in different situations. Some high-cost techniques are currently not widely-used, such as high R window, thermal storage, solar-assisted heat pump, CCHP, VAV/VAF, BIPV/T and wind turbine etc. However, these technologies may have great potential and benefits for ZEB on the long run, and deserve more exploration and research.

3. Future challenge of building energy

3.1. Impact of global climate change on building energy demand

Given the long lifespan and high initial cost of buildings, designers should consider the probable influence of climate change. According to the IPCC [90], 1983–2012 was likely the warmest 30-year period of the last 1400 years in the Northern Hemisphere. Isaac et al. [91] developed a model for predicting the key factors affecting building energy consumption and concluded that, in the reference scenario, global residential heating demand would decrease by 34% and cooling demand would increase by 72% by 2100. The global energy demand for cooling in buildings will overtake heating by 2070. Fig. 8 shows their predictions on residential building energy demand for heating and cooling final energy demands in the next century [91]. The heating energy demands in Europe will decrease because of decreasing population, lower heating intensity and a warming climate. For China and the U.S., heating energy demands of the residential sector will increase throughout the century. A 0.7% annual increase in heating energy demand in the U.S. will be driven by rising population and housing areas, whereas increasing heating intensity will lead to a 1.7% annual increase in China before 2040. Cooling demands will increase dramatically in developing countries such as China and India because of rapidly increasing ownership of air conditioners and a warming climate. In contrast,

Table 1
Summary of the reviewed technologies for ZEB.

Category		Technology	Principle	Applicability/feature	Cost	Ref.
Passive design	Building envelope	Thermal insulation	Lower the U-values to reduce thermal gain/loss	Better under cold climate; envelope-load dominated buildings	Low	[23,24]
		Energy-saving glazing technologies	Reduce thermal gain/loss; improve visual comfort	Balance between solar heat gain and daylight needs to be considered	High	[25–27]
	Passive heating	Trombe wall	Trap and transmit solar energy into a building	Better under cold climate	Medium	[28]
	Passive cooling	Nighttime ventilation	Reduce cooling loads by temperature differences between day and night in summer	Better under moderate climate	Low	[30,31]
		Earth-to-air heat exchangers (EAHE)	Cool ventilated air through recirculation in the underground pipes	Better under hot and dry climate	Medium	[32,33]
		Green roof	Reduce cooling loads and mitigate carbon emission	Better under tropical climate; Can be integrated with PV	High	[35,36]
	Thermal energy storage	Phase-change materials (PCMs)	Control building thermal with latent heat storage and release	Better integrate with nighttime ventilation	High	[37,38]
Service systems	HVAC	Evaporative cooling	Cool air by increasing its moisture content	Better under hot and dry climate	Low	[41]
		Active thermal storage	Shift energy consumption from on-peak to off-peak periods	Buildings with high cooling, short duration demands	High	[42]
		Heat recovery	Transfer heat between fresh air and exhausted air	Better under moderate climate	High	[43,44]
		Radiant heating/cooling	Handle sensible heat by radiant and convective heat transfer	Cannot moderate air humidity; condensation at cold surface; better integrate with desiccant dehumidification/displacement ventilation	Medium	[45–48]
		Variable air volume (VAV)/variable refrigerant flow (VRF)	Change the supplied air volume/refrigerant flow rate to meet the varying loads	Buildings with partial-load and individualized requirement; need optimal control strategy	High	[49–53]
	DWH	Solar water heater (SWH)	Heat water with solar energy collector and thermal energy storage	Less effective under night/overcast sky conditions; better integrate with PCMs	Low	[55–58]
		Solar-assisted heat pump system	Use a solar collector as an evaporator and transfers thermal energy for DHW storage	Low temperature water heating	High	[59]
		Combined cooling, heating and power (CCHP)	Generate electricity and thermal energy simultaneously	Better integrate with renewable energy sources; need optimal control strategy	High	[54,88,89]
	Lighting	Light-emitting diodes (LEDs)	Energy-saving light with long service life and good lighting efficacy	Office buildings; may increase indoor cooling load	High	[60,61]
		Daylight harvesting	Reduce artificial lighting electricity consumption; improve visual comfort	Better under sunny regions; need optimal control strategy	Medium	[62]
	Appliances	Energy-efficient appliances	Reduce building energy cost with high energy-efficiency appliances and better usages	Influence by occupant behavior and socio-economic factors; better integrate with smart scheduling	Medium	[63–67]

Table 1 (*Continued*)

Category		Technology	Principle	Applicability/feature	Cost	Ref.
Renewable energy generation	Solar energy	PV; building integrated photovoltaic (BIPV)	Convert incident solar energy into electrical energy by photoelectric effect	Better under tropical and sunny regions; relatively low conversion efficiency; BIPV can reduce the space, material and infrastructure costs	Medium	[69,70,73]
		Hybrid photovoltaic-thermal (PV/T)	Generate electricity and heat simultaneously	Low temperature thermal output; less commercialized; high energy generation efficiency per module	High	[71,72]
	Wind energy	Wind turbine	Generate electricity from wind energy	Sensitive to location and weather; need CFD-assisted design; can be integrated with PV	High	[75–79]
	Geothermal energy	Ground source heat pump (GSHP)	Use the constant earth's temperature as a heat source in a heating mode and a heat sink in a cooling mode	Better to balance the building heating and cooling loads all year round; high COP	High	[80–83]
	Bioenergy	Biomass boiler	Produce space heating by the combustion of biomass	Better under cold climate; air pollution with inappropriate use	Low	[84]
		Chinese kangs	Utilize waste heat from the fuel gas of traditional cooking stoves for space heating	Poor heating effect; heating efficiency can be improved by incorporating forced convection	Low	[85,86]
		Biomass cook stove	Cooking by the combustion of biomass fuels	Widely-used; energy efficiency needs improvement	Low	[87]

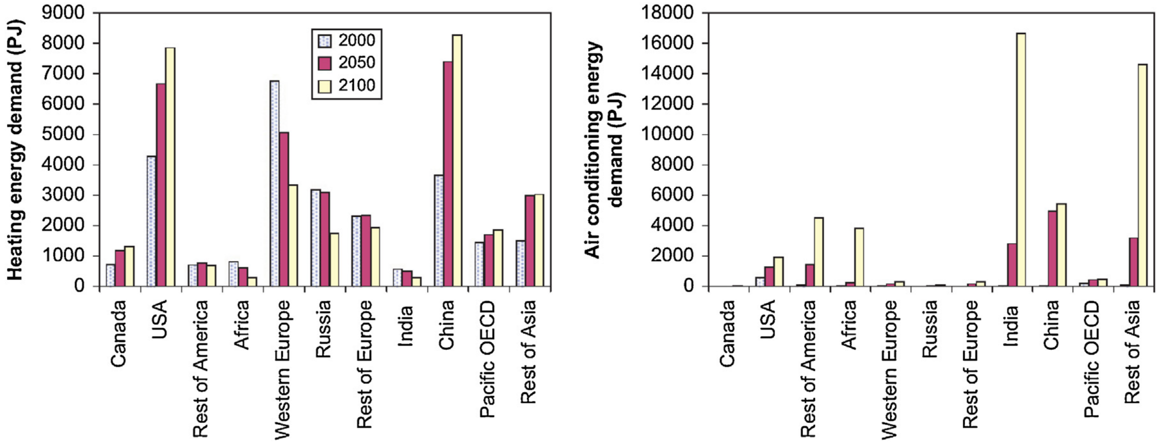


Fig. 8. Residential building energy demand for heating (left) and cooling (right) in 2000, 2050 and 2100 [91].

cooling loads in the U.S. and Europe will only slightly increase in the next century. It can be concluded that the effect of climate change depends on local weather and economic conditions. Total energy demand for heating and cooling will primarily increase in cooling-dominant and less-developed regions.

Climate change may influence energy-saving technologies in the future. Wang et al. [92] accessed the effect of nighttime natural ventilation in San Francisco, San Diego, and Seattle. They found that natural ventilation was no longer suitable for San Diego due to the global warming, but still acceptable in San Francisco and Seattle. Lomas et al. [93] insisted on evaluating the resilience of naturally ventilated buildings to climate change because of the possibility of overheating. When global warming becomes severe, previous scenarios for decreasing carbon emissions may be less effective for cooling-dominated or temperate climate zones [94]. These studies highlighted the possible deterioration of energy-saving technologies with climate change. Suitable energy saving approaches can also mitigate global warming trends and reduce GHG emissions. In IEA's Energy Technology Perspectives 2012, two scenarios for evaluating future building energy consumption are proposed: a 6 °C scenario (6DS) and a 2 °C scenario (2DS) [6]. The 6DS is a baseline scenario, largely an extension of current trends. The 2DS serves as a target driven scenario with significant efforts to limit the increase in global average temperature to 2 °C. In the 6DS, total energy demand in the building sector would increase from 117 EJ in 2010 to 173 EJ in 2050. In the 2DS, energy consumption in the buildings sector would only increase to 130 EJ by 2050—only 11% higher than in 2010 despite a 68% increase in the number of households. In the 6DS, CO_2 emissions from the building sector are expected to increase to 12 Gt CO_2 by 2050. In the 2DS, total CO_2 emissions will surprisingly decrease from 8.3 Gt to 2.7 Gt CO_2 by 2050 due to the decarburization of the power and heat generation sectors.

3.2. Influence of building envelope and IAQ on space heating/cooling

Building envelopes account for a significant portion of a space heating/cooling load. Thus, improving building envelopes is crucial for reducing energy usage and CO_2 emissions with the trend in global warming. Advanced designs of building envelopes could reduce heating and cooling loads by 40%. For example, in the reductions of heating and cooling energy demands between the 6DS and the 2DS, 40% could be directly attributable to improvements in building envelopes [6]. Reductions in heating and cooling capacity further lead to the benefits of downsizing equipment. Fig. 9 shows the energy saving potential and payback period in 2030 for advanced building envelope technologies in the U.S. [95]. It can be observed that air-sealing systems and highly insulated windows are the two most cost-effective technologies for reducing space heating and cooling demands.

Although they consume over 30% of total global primary energy globally, existing buildings still suffer from poor indoor air quality (IAQ). According to the WHO, 4.3 million people died prematurely as a result of indoor air pollution in 2012 [96]. The U.S. Environmental Protection Agency (EPA) suggested three measures for improving IAQ: control of indoor pollution sources, ventilation improvements and air cleaners [97]. Adequate outdoor fresh air can remove and dilute airborne pollutants coming from indoor sources; this reduces the concentration of contaminants and improves IAQ. However, fresh air also increases energy costs due to the temperature difference between indoor and outdoor air. In the past, more attention was paid to energy conservation than indoor air quality. For example, the ASHRAE standard 62-1989 only required 14.3% and 6% of outside air in air supplies for small and large offices, respectively, corresponding to approximately 2 cfm/person [98]. Indoor polluted air is therefore continuously recycled, causing occupants to suffer from illnesses or sick building syndrome [99]. Subsequent research showed that inducing more fresh air is an efficient way to improve IAQ [100,101]. ASHRAE now requires 5 cfm/person of outside air for office buildings [102]. However, the increased ratio of fresh air results in the growth of building energy consumption. In 2016, the energy consumed by handling outdoor air in office buildings was 1.5 times higher than in 1989 [102]. Heat recovery ventilators [43] are an efficient way to bring outdoor air into the home with lower space heating and cooling energy costs. Joo et al. [103] proposed a method to evaluate the minimum energy consumption for ensuring acceptable indoor CO_2 levels. Their case study showed that an approximately 22.1% energy reduction could be achieved by using an optimum ratio of makeup air to recirculation air. However, they did not consider the effect of fresh air on other air pollutants such as VOC and sVOC [104]. More studies are needed to address the dilemma between building energy consumption and IAQ.

3.3. Cost-optimal design

The high initial investment is always a great barrier for the ZEB development. The optimal integration of different energy-saving and generation technologies that meet building energy demand with minimum cost is the primary principle for achieving a ZEB target. Designers must apply holistic design principles to ensure a cost-effective, environmentally friendly and energy balanced ZEB while providing a comfortable living environment. It is a multifaceted issue addressing both energy and cost efficient. In general, design strategies should consider several factors such as local climate/site conditions, future climate change trends, building types, energy cost, systems operation and techno-economics. There are many methods for optimizing the design solutions of different ZEBs [105], and many efforts have been made on single-objective and multi-objective optimization models for hybrid energy system designs. The Hybrid Optimization Model for Electric Renewables (HOMER) is a design optimization software that has been used to facilitate the design optimization of renewable energy systems based on net present cost. Rezzouka and Mellit [106] used HOMER to optimally design a stand-alone photovoltaic–diesel–battery hybrid energy system in northern Algeria. However, HOMER can only solve a single objective function for minimizing the net present cost; in actual ZEBs, designers must often deal with conflicting design objectives such as energy consumption, thermal comfort and cost. Various methods can be used to perform multi-objective optimal modeling in built environments [107]. For the multi-objective optimization of ZEB solutions, the most commonly used algorithms [108] are the multi-objective genetic algorithm (MOGA), the particle swarm optimization (PSO) and the linear programming method. MOGA is the most popular of various optimization methods and has been integrated into commercial software such as Matlab and modeFRONTIER (with types of MOGAs). For example, Congedo et al. [109] applied modeFRONTIER in the cost-optimal design of near-zero energy office buildings located in Italy (warm climate). To obtain an accurate cost-optimal solution, 256 combinations (4 walls, 4 frames, 2 generations, 2 heating/cooling systems and 4 PV systems) of design variants were considered. The results showed that the optimal variant selection was able to decrease primary energy consumption by 39% and CO_2 emissions by 41% at the lowest cost. In addition to objective optimization, the sensitivity analysis of key variations is also of great importance in ZEB design. For instance, Sun [110] conducted sensitivity analysis of macro-parameters in the system design of a ZEB. He found that the most sensitive parameter for building system sizes and overall initial investment cost was the indoor temperature set-point, followed by the system COP and internal gain intensity. The PV efficiency had different impacts on different system sizes and overall cost.

3.4. Control and scheduling strategies

Control and scheduling strategies are crucial for overall ZEB performance with hybrid energy systems. Building (Home) energy management systems (BEMS) [111] can be responsible for communication and energy coordination between ZEBs and the grid. In BEMS, scheduling controls, tariff and load controls, and smart homes/environments are the three main functions for achieving energy savings ranging from 11.39% to 16.22% [112]. Fig. 10 shows an application of a BEMS in a ZEB home [113]; the BEMS can connect and control different household devices (appliances, lighting and HVAC), renewable energy systems (solar PV, wind turbine and geothermal energy) and interact with a smart grid (smart meter and energy storage). The scheduling of hybrid systems can be optimized with a BEMS, thus avoiding the problem of high peak demand [111]. Therefore, the implementation of a BEMS and smart meters allows occupants or systems to modify parameter settings to achieve energy balance, maintain indoor environment quality and provide smart responses to the electricity grid. Networking technologies are needed for connecting a BEMS with different devices and electricity grids. Wireless technologies such as ZigBee [114] are certainly suitable for providing in-house networking in a smart building.

The energy production levels of many renewable energy systems are weather dependent and therefore difficult to control in meeting building demands during operation. In this situation, fluctuations in energy generation and building demand may lead to the instability of a conventional one-way communication grid. The integration of renewable energy generation also poses major chal-

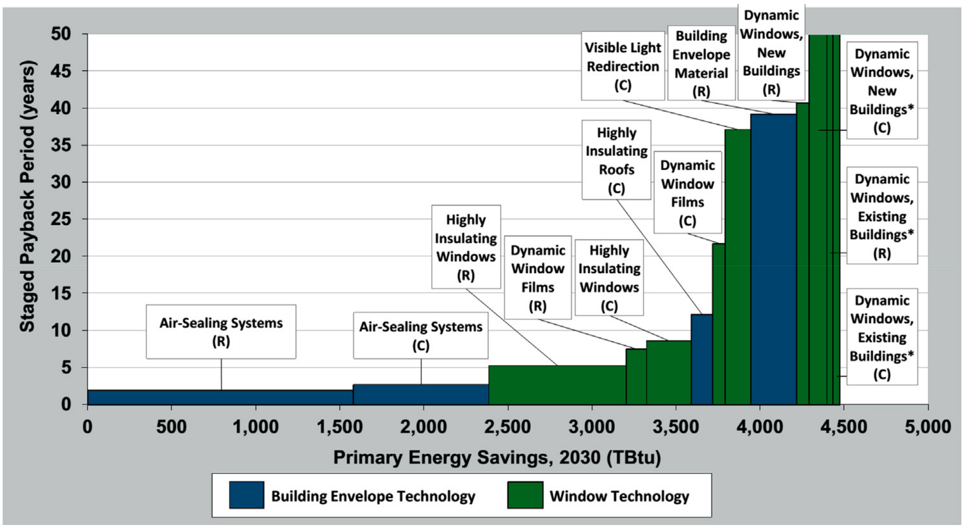


Fig. 9. Maximum adoption potential and payback period in 2030 for advanced building envelope technologies in the U.S. residential (R) and commercial (C) building sectors [95].

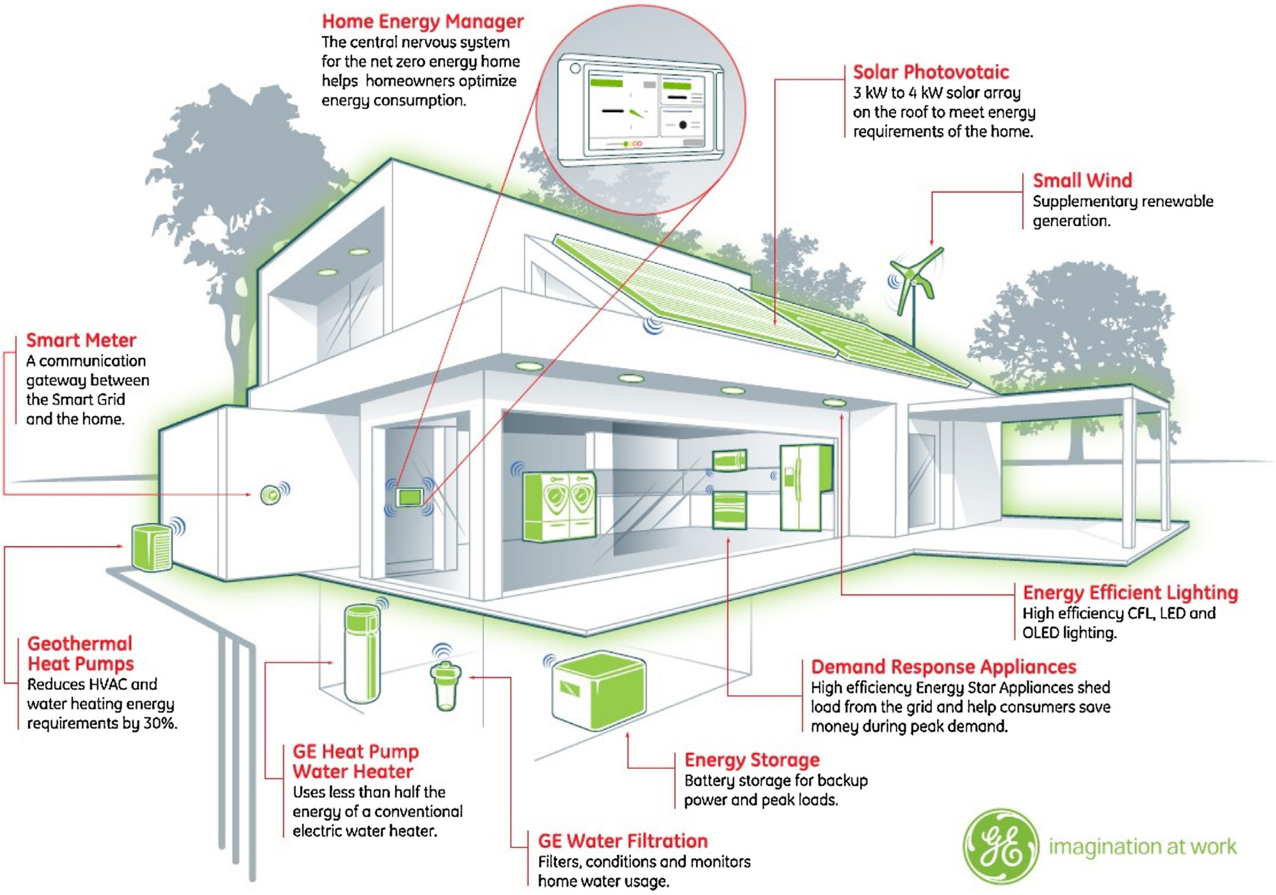


Fig. 10. Application of a BEMS in a typical NZEB [113].

lenges for distribution grid operators [115]. Because a conventional grid cannot meet the communication requirements of a BEMS, a smart grid is necessary for ZEB applications. The smart grid is considered an integrated solution to intelligently realize a two-way communication or interaction between buildings and national grids. Although a significant amount of research and development exists on smart grids [116], there are still opportunities for continued research in forecasting, reliability, power flow optimization, battery energy storage systems, cloud computing and renewable energy source integration [116]. With sustained effort, smart grids will undoubtedly play a crucial role in attaining energy sustainability and environmental conservation in future smart cities [117].

3.5. Development trend

The concept of ZEBs has been popularized worldwide. However, significant differences still exist in the development situations of ZEBs between different regions. In fact, economics and education play important roles in the development of ZEBs. ZEB projects have been well established in developed countries, especially in the E.U. and the U.S. The rapid growth of ZEB projects in these developed countries were promoted by comprehensive policies, regulations and research programs. For instance, an IEA-SHC (solar heating and cooling) research program named "Towards Net Zero Energy Solar Buildings" (IEA-SHC Task 40/Annex 52) was launched in 2008 and finished by 2013 [118]. The aim of this project was to study near/net ZEB projects worldwide and develop a common understanding, an international definition framework, tools, innovative solutions and industry guidelines for ZEBs. More than 300 ZEB projects worldwide are shown on a map based on this research program [119] and over 90% of these projects are located in the E.U. and U.S. Challenges remain in popularizing ZEBs in developing countries due to their shortcomings in economics, policies and education. For example, except for some modern metropolitan areas, most regions in China are still rural and less developed. In these rural areas, buildings typically have very poor energy efficiency and indoor environmental quality, primarily due to the use of coal and traditional biomass as primary energy sources and unreasonable building envelope designs. However, this situation also shows the tremendous energy savings potential in Chinese rural areas. If 80% of Chinese villages could achieve a "zero coal village" by 2030, a total emissions reduction of 400 million tons of CO_2, 370 million tons of SO_2, 110 million tons of NO_x, and 270 million tons of PM2.5 would be achieved [23]. This would provide significant energy conservation and environmental benefits.

Great progress has been made towards sharing ZEB ideas worldwide. Solar Decathlon is an internationally competition to design, build, and operate the energy-efficient and comfortable house powered exclusively by solar energy, founded by the U.S. Department of Energy in 2002 [120]. The scientific knowledge behind the Solar Decathlon can be found in a special issue in Energy and Buildings [121], such as passive solutions [122], electrical energy balance [123] and BIPV [124], etc. This competition provide a great opportunity to share the latest design strategies and demonstration of ZEB to the industry and public. There is also a Solar Decathlon Europe since 2007, under a memorandum of understanding between the Spain and America. The first Solar Decathlon China was held in 2013, established with the signing of a memorandum of understanding between the U.S. and China. These competitions together to make people aware of the importance of developing sustainable buildings all around world.

Nevertheless, barriers still remain to the development of ZEBs in developing countries. The main barriers are high initial investment, insufficient incentive and less positive social attitudes concerning ZEBs. Public education seems an effective solution to overcome these barriers. Public education can help form positive social attitudes towards the environment and sustainable development. A general public with higher levels of environmental concern will tend to be less accepting of less-than-ideal indoor built environments and more supportive of investments of energy saving technologies in green buildings [125]. There is no doubt that developing countries will play an ever-growing role in the global transition to ZEBs.

4. Conclusions

This paper provides an overview of building energy consumption situations and the recent proposal of ZEBs to address increasing building energy demands. Several conclusions remarks can be drawn:

(1) Buildings consume approximately 40% of the total primary energy use in the U.S. and E.U. and 27.3% in China. The building energy intensity in China is far lower than in the U.S. and E.U. Space heating and water heating dominates the total building energy end-uses in all these regions. Electricity and natural gas are the primary fuel sources of building energy use in the U.S. and E.U. Electricity is the largest energy source in the U.S. building sector, with a 50.1% share of final energy use and over 70% of total energy consumption. In the European residential sector, natural gas is the most commonly used fuel for heating purposes in all regions. Traditional biomass dominates the final building energy uses in China at 47.1%, primarily due to the high usage for heating and cooking in rural areas. Switching fuel types from traditional biomass to modern fuel choices in Chinese rural buildings is imperative. In short, fossil fuels (coal, oil, and natural gas) account for the largest portion of global building energy use. The decarburization of the electricity generation and the utilization of modern renewables must be a priority in switching the current energy structure.

(2) Three steps are required to successfully institute a ZEB: passive energy savings, energy-efficient building service systems and renewable energy generation. Passive energy saving technologies are highly sensitive to local climate conditions. Optimally combining different energy-saving measures must be carefully considered in the design stage. The major renewable energy sources for buildings are solar energy, wind energy, geothermal energy and clean bioenergy. The cost-optimal integration, control and scheduling strategies of hybrid energy systems are crucial for improving overall ZEB performance. Smart-grid connected ZEBs will play an important role in future smart cities.

(3) Global climate change has a significant impact on space heating and cooling demands. Under one supposed scenario, global residential heating demand will decrease by 34% and cooling demand will increase by 72% in the next century. Total energy demand for heating and cooling will primarily increase in cooling-dominant and less-developed regions. The advanced design of building envelopes can help reduce heating and cooling loads by 40%. Suitable energy saving approaches can mitigate global warming trends and reduce GHG emissions. In a high energy-saving scenario named 2DS, building energy consumption would only increase from 117 EJ to 130 EJ and total CO_2 emissions would surprisingly decrease from 8.3 Gt to 2.7 Gt CO_2 by 2050.

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