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A comprehensive evaluation of zero energy buildings in cold regions: Actual performance and key technologies of cases from China, the United States, and the European Union

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Abstract

Evaluation of actual zero energy buildings (ZEBs) performance and identification of its regional characteristics are of great significance for similar future projects. Based on nearly 400 cases in cold regions, this study compared post-evaluation and drivers of ZEBs from China, the United States and the European Union (EU). Results found that ZEB definition, energy drivers, standard, regional policies, technologies used and their adoption ratio determine energy performance of cases. Not all EU and China cases reach the net-zero energy target; however, most ZEBs in the United States do. ZEBs in cold regions adopted multiple technologies to achieve high energy-efficiency. The adoption ratio of passive technologies is higher than that of active technologies, especially in China. The active technologies in cold regions are mainly seen in application of advanced HVAC systems. Such application of active technologies exhibits strong regional characteristics; for example, the EU's carbon emission reduction policies promoted the use of biomass-based technologies. It is recommended that policies should shift from emphasizing the adoption of individual technical measures to cost-optimized integrated design. The analysis also found that energy policies greatly enhance the development of ZEBs, and ZEB certification is another key factor to create market awareness and promote performance transparency.

Keywords

Zero energy building; Cold climates; Renewable energy; Energy policy; Standard; Case study.

Nomenclature

ZEB	Zero energy buildings
U.S. DOE	U.S. Department of Energy
NBI	The New Building Institute
PV	Solar photovoltaic
LEDs	Light-emitting diodes
ST	Solar thermal
BESR	The building energy-saving rate
IECC	International Energy Conservation Code
SHGC	Solar heat gain coefficient
ZERH	Zero Energy Ready Homes
ILFI	International Living Future Institute
RESNET	Residential Energy Services Network
HERS	Home Energy Rating System

IgCC	International Green Construction Code
zEPI	Zero Energy Performance Index
HDD	Heating degree days
CDD	Cooling degree days
EUI	Energy use intensity(kWh/m^{2}a)
RPI	Renewable energy production intensity(kWh/m^{2}a)
ECS	Environmental Control System
GSHP	Ground source heat pump
ASHP	Air source heat pump
ACH	The air exchange rate(/hour)
ITHC	Independent temperature and humidity control system
CHP	Combined heat and power units
BIPV	Building-integrated photovoltaics
EPBD	Energy Performance of Buildings Directive
CA EPBD	The Concerted Action of Energy Performance of Buildings Directive
OBZE	The Advanced Energy Design Guide for Small to Medium Office Buildings Achieving Zero Energy
nZEBT	Technical standard for nearly zero energy buildings
K-12	Advanced Energy Design Guide for K-12 School Buildings Achieving Zero Energy
BEES	California Building Energy Efficiency Standards

1. Introduction

Energy consumption in public and residential buildings worldwide accounts for approximately 20.1% of total energy consumption [1]. According to 2017 data, the energy consumption of the building sector in the United States accounts for about 39% of the total primary energy use [2]. In China, the building sector consumed approximately 20% of the primary energy and approximately 23% of the electricity consumed in 2015 [3]. Buildings are responsible for approximately 40% of energy consumption and 36% of carbon dioxide (CO_2) emissions in the European Union (EU) [4]. These figures signal an urgency to implement building energy efficiency worldwide. Many countries or regions have issued increasingly stringent building energy efficiency standards and corresponding promotion policies, and building standards have evolved through conventional standards, energy efficiency standards, passive house standards, and recent zero energy standards.

Due to their outstanding design concepts and success in reducing carbon emissions and improving building energy-efficiency, zero energy buildings (ZEBs) are widely recognized as promising solutions to environmental and energy issues in the construction sector [5]. The definition of ZEB varies by country, region, and group. It is *nearly-ZEB* [6] in the EU and China, *net-ZEB* in the United States[7], and *zero-emission building* in Australia (For unification, hereinafter referred to collectively as ZEB). The differences in definitions determine the relative stringency of policy outcomes and have spawned a variety of key issues (Fig.1), such as whether off-site energy production is allowed to offset some or all of the on-site energy use, and whether the definition is based on energy or carbon emissions. Because of the ease of regulating and controlling building energy consumption, most countries are committed to zero energy rather than zero emissions.

Some studies use simulation-based methods to optimize ZEBs based on different climatic characteristics and design requirements. Most of the research evaluated the energy efficiency measures by economic cost and determined the optimal technology choice or design scheme based on the cost-optimized goal [8-10]. For example, based on EU climatic conditions, a study established a technical option and optimization framework for zero-energy residential buildings aimed at optimal cost. Their results show that cost-effective ZEBs can save above 90% of building energy [9]. However, these studies just focused on the design stage, and the actual operation of the building was largely overlooked. System strategy or technology adjustment based on actual energy demand can save about 17% of the energy used [11]. There are also very few studies focusing on the practical performance of ZEBs. For example, a study investigated the actual energy use of an office ZEB in Tianjin, China, and compared it with the design energy consumption [12] and found performance differences. Results revealed three main reasons for the differences: (1) the actual equipment configuration mismatch with design caused the design energy consumption to be underestimated; (2) the actual operation strategies needed to be improved; and (3) the weather uncertainty, such as haze, causes the solar photovoltaic (PV) efficiency to be greatly reduced.

The integrated use of various high-performance technologies is the key to achieving a ZEB. The principle of selecting the technologies is to: use a variety of passive technologies to reduce energy demand, use energy-efficient products to reduce building energy use, and then make full use of renewables to reduce the net energy consumption [13]. In terms of passive design and technology, heating energy demand can be reduced by more than 35% just by optimizing a building's shape and orientation [14]. In northern China, high-performance envelopes can reduce building energy consumption by about 22% [15]. Taking the hot summer and cold winter climate zone as an example, the integrated optimization of the building envelope can reduce a building's HVAC energy demand by about 27.86%–33.29%, and extend the annual indoor thermal comfortable hours by about 516.8–560.6 hours, compared to the base building [16]. Natural ventilation plays an important role in reducing building cooling energy demand and improving indoor air quality in various climates and building types [17]. When window ventilation and HVAC fully automate coupling operation, 17%–80% energy savings can be achieved with zero discomfort degree hours [18]. Reasonable use of daylighting can effectively reduce lighting energy consumption; the use of vertical daylight is common in some low-energy buildings, and is achieved through techniques such as light tubes and skylights [19]. In terms of active technologies, due to the high proportion of total building energy use from HVAC use, high-efficiency technologies associated with HVAC systems are particularly important for achieving ZEBs. These include heat pump systems [20], evaporative cooling [21], and air heat recovery [22]. In addition, reducing lighting energy consumption is also critical, especially for commercial buildings; two main approaches are reasonable lighting control [23] and utilization of efficient lighting equipment such as light-emitting diodes (LEDs) [24]. Several studies have found that luminaire-integrated controls reduce energy use between 32% and 47% compared with manual switches [25]. Renewable energy utilization is the key to achieving ZEBs, with solar, wind, geothermal, and biomass energy being used as the major renewable sources. Solar energy is the most widely used due to its high availability and ease of integration with buildings. Solar thermal (ST) and PV are the two main types used [26].

Some studies have summarized key technologies that affect ZEBs. For example, a study introduced several technical measures that are potentially usable for China's ZEBs: including passive techniques, energy-efficient products, renewable energy systems, and design and construction [27]. Another study further introduced the influencing factors of several key technologies and analyzed the applicability of these technologies in China from the perspectives of performance, efficiency ranges, limitations, and challenges [28]. Another study focused on ZEBs in hot and humid climates, based on 34 cases, and analyzed energy performance and the commonality in architectural design features, as well as key technology choices [19].

Based on the above analysis, it's clear that most ZEB studies focus on theories and the optimization of energy saving by means of simulation in the design phase. However, research on the actual operational performance of ZEBs still needs to be conducted. Also, constraints on technology selection due to climate, resource conditions, economic, energy consumption patterns, and living habits have led to differences in technical suitability in various regions. Therefore, it is necessary to investigate the actual choice frequency and application effect of technologies. Based on 385 actual ZEB projects in cold/severe cold climates, this study evaluated the actual operational performance and economic costs of ZEBs in these climates. The cases come from the United States, the EU, and China, and analyze the commonality and individuality of the technology application in ZEBs in three regions.

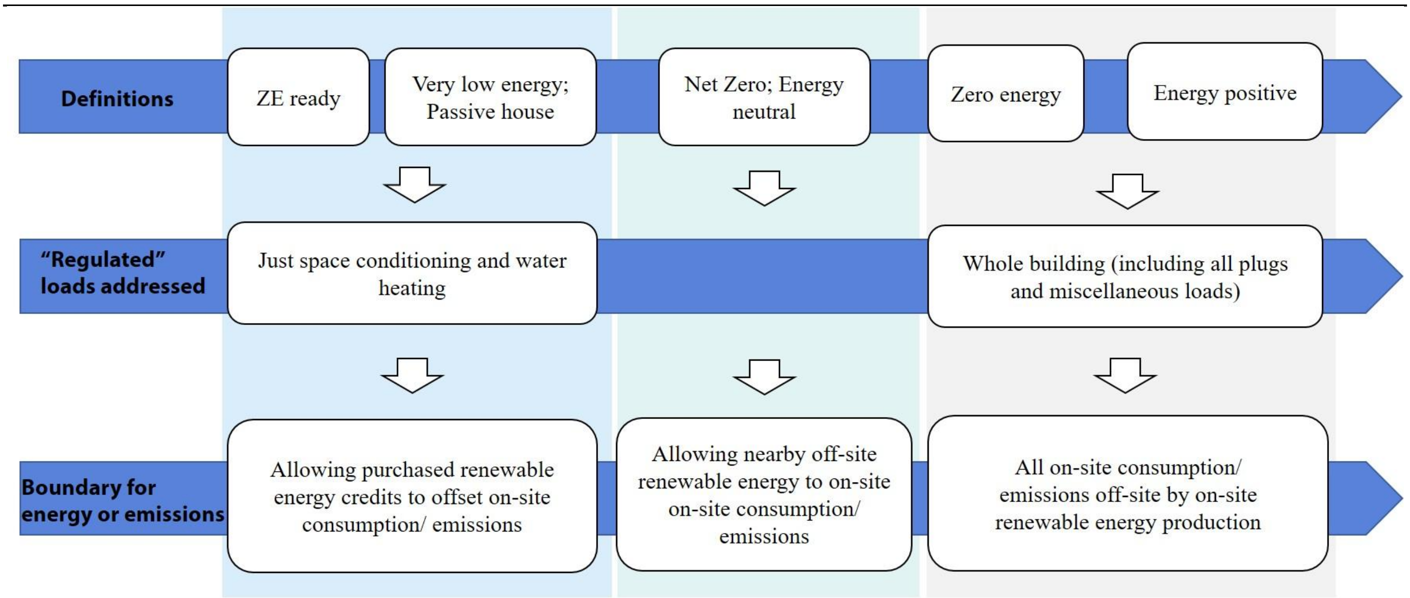

Fig 1. The definitions and boundaries of a ZEB.

2. The policy, standard, and certification

2.1 The policy and energy target

Table 1 summarizes the main ZEB related policies in the three regions. In the United States, the leadership of the federal government in climate action has been withdrawn, and local governments have become the standard-bearers of climate change, leading to new and aggressive carbon reduction targets, with a particular emphasis on architecture. Therefore, states have set ZEB policies within their jurisdictions. The top-down development strategy has been adopted to promote ZEBs in China. Under the leadership of the national government, local governments have also taken measures to promote ZEB development, especially in cold regions. In the EU, the EPBD is the main energy legislation, and each member country develops its own ZEB route on the premise of meeting the EPBD.

The critical first step in achieving a zero energy building is to set an energy use target, and Table 2 summarizes the ZEB goals for each region. The United States provides energy target information, including primary energy and site energy. The energy targets between EU member states vary widely. Different from the United States and EU, China generally uses the building energy-saving rate as the energy target of public ZEBs, or roughly calculates the absolute energy target based on standard buildings.

Table 1. The ZEB policy in three regions.

Region/Country		Name	Year	Main content	Reference
The U.S.	National	The Energy Independence and Security Act	2007	Regulations state that “designs for new buildings or major renovations of Federal government buildings must be fossil fuel-free, and essentially zero net energy beginning in 2030.	[29]
	National	Pan-Canadian Framework on Clean Growth and Climate Change	2017	Starting in 2020, with the goal that provinces and territories adopt a “net-zero energy ready” model building code by 2030.	[30]
	State	State ZEB Policy*	/	/	[31]
EU	EU	EPBD (2010)	2010	By the end of 2020, all new buildings in member states must be nearly-ZEBs, and transform existing buildings into nearly-ZEBs through cost-effective renovation. The EU Member States must develop their nearly-ZEB roadmaps, and develop specific requirements for “nearly-ZEB,” including a numerical indicator of the primary building energy use.	[32]
	EU	EPBD (2018)	2018	Creates a clear path toward a low and zero-emission building stock in the EU by 2050 underpinned by national roadmaps to decarbonize buildings	[32]
China	National	The 13th Five-Year Plan for the Development of Building Energy Efficiency and	2016	A target of 10 million square meters (m^2) of ultra-low buildings and nearly-ZEBs by 2020.	[33]

* The New Building Institute (NBI) aggregates policies for various states and cities and forms an off-line zero energy policy database. As shown in the policy map (Fig. 2), almost all states have issued ZEB policies.

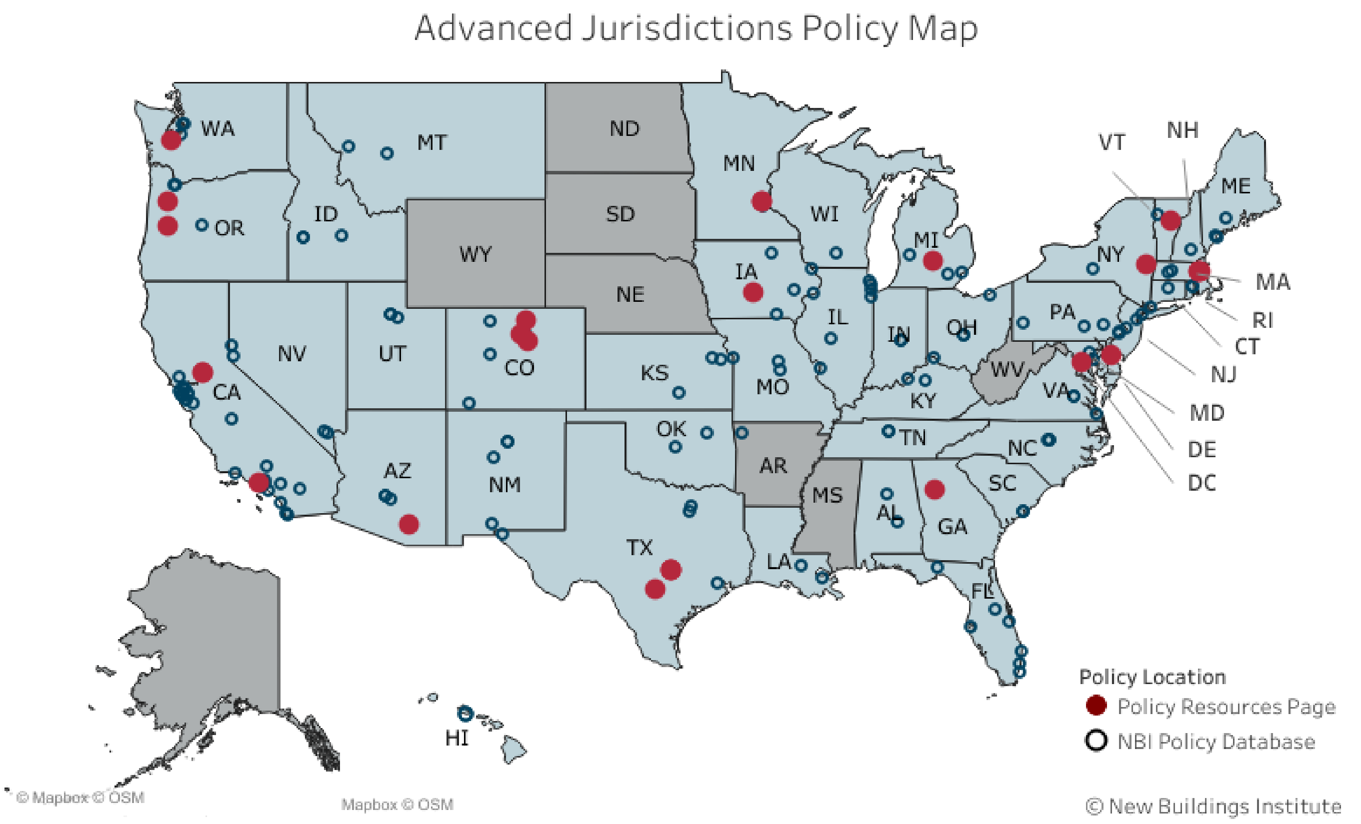

Fig. 2. The ZEB policy map of the United States (Source: NBI).

Table 2. Key parameters and boundaries in ZEB definitions.

Office	U.S.	China	EU
Definitions	net ZEB	nearly-ZEB	nearly-ZEB
Energy targets (primary energy): [kWh/(m^{2}a)][a]	6A: 275.4	BESR ≥60% or 75.9 [b]	20–117 for residential, and 25–110 for non-residential buildings
Energy targets (site energy): [kWh/(m^{2}a)]	6A: 87.4	/	/
Energy targets, including renewable energy	N	Y	N
Carbon emissions	N	N	Y
Contains the plug load	Y	N	N
Reference standard or regulation	OBZE[c]	nZEBT	EPBD2018

Note:

a: Refers to annual energy use per square meter.

b: China uses the building energy-saving rate (BESR) relative to the reference building as the energy targets of public ZEBs. The reference building is a building that meets the building energy consumption requirements of national standards (GB50189-2015). In addition, the "Technical standard for nearly zero energy buildings GB/T5130-2019"(nZEBT) provides a rough estimation method for energy targets, using the typical building model as the reference building to calculate absolute energy targets. For office buildings that is approximately 75.9 kWh/ (m^2a).

c: OBZE is the Advanced Energy Design Guide for Small to Medium Office Buildings Achieving Zero Energy.

2.2 The ZEB codes and standards

Energy codes and standards play a vital role by setting minimum requirements for energy-efficient design and construction. In the United States, codes are published by national organizations and are mandatory. Standard 90.1 and the International Energy Conservation Code (IECC) are the codes for commercial and residential buildings in the United States, respectively. Building standards involve a detailed description of the design methodology and provide guidance to the designer. China's building standards are divided into national standards, industry standards, and local standards. The "GB" and "GB/T" are expressed as mandatory and recommended standards, separately. There are currently no uniform building standards in the EU, however, the cost-optimal design method must be adhered to by each member state. Table 3 summarizes the ZEB-related standards and codes.

For cold regions, building envelope performance is critical for reducing building energy demand. The requirements in the ZEB standard are summarized in Table 4. The minimum requirements in the EU are represented by the average of member states.

Table 3. The ZEB related standard/code in three regions.

Region	Name	Year	Application object	Supplement	Reference
The U.S.	Advanced Energy Design Guide for K-12 School Buildings Achieving Zero Energy (K-12)	2018	kindergarten through the twelfth-grade school buildings	The first U.S. guidance document related to ZEBs. For design, construction, operation	[34]

	OBZE	2019	Office	For design, construction, operation	[35]
	IECC2021	2021	National residential	Provides a Zero Energy Appendix for cities and states residential building, but not mandatory unless specifically stated.	[36]
	ZERO Code	Under development	New buildings	Sets a “zero net carbon” path for new buildings	[37]
EU	the Concerted Action EPBD (CA EPBD)report	2016	Residential and non-residential buildings	Include the ZEB standards/energy regulations of major member states	[38]
China	Technical Guidelines for Passive Ultra-Low Energy Green Building	2015	Mainly residential buildings	Clarify the definition and technical indicators of passive ultra-low energy green buildings in China；For design, construction, operation.	[39]
	Technical standard for nearly zero energy buildings (GB/T 51350-2019)	2019	Residential and public buildings	The first national standard for ZEBs; the design, construction, operation, and evaluation of nearly-ZEBs.	[39]
	National Standard Chart “Passive Low Energy Buildings (16J908-8)	2016	Residential Buildings in Cold and severe Cold Areas	For design, construction	[39]
	Detection and Evaluation Standard for Nearly Zero Energy Building	2019	Residential and public buildings	Detection and Evaluation Standard	[39]

Table 4. Comparison of ZEB component requirements in three regions.

Categories		OBZE					nZEBT		CA EPBD
Components	Parameter	Zone 4	Zone 5	Zone	Zone	Zone 8	Cold	Severe Cold	Zones

				6	7				3–5
Roof	U-value (W/m^2/K)	0.17	0.17	0.17	0.15	0.15	0.10–0.30	0.10-0.20	0.26
Walls	U-value (W/m^2/K)	0.35	0.3	0.27	0.27	0.2	0.10–0.30	0.10–0.25	0.21
Window	U-value(W/m2/K)（fixed)	1.93	1.93	1.82	1.59	1.42	1.2	1	1.52
	SHGC（fixed)	0.34	0.36	0.36	0.38	0.38	winter:≥0.45; summer: ≤0.30	winter:≥0.45 ; summer: ≤0.31	/ /
	U-value（operable)	2.44	2.44	2.27	1.93	1.7	/	/	/
	SHGC（operable)	0.31	0.31	0.32	0.34	0.34	/	/	/

2.3 ZEB certification and programs

ZEB certification is based on the actual operational data of a building to prove that it is indeed running at zero energy. At present, the EU and the U.S. ZEB systems are relatively complete, and the number of certified ZEB cases is large. Table 5 shows the ZEB certification and basic information for the three regions.

Table 5. The ZEB certifications and institutions.

Region	Organization	Certification	Main issue	Reference
The U.S.	U.S. DOE	Zero Energy Ready Homes (ZERH)	Must be verified by a qualified third party and are at least 40%–50% more energy-efficient than a typical new home. This generally corresponds to a Home Energy Rating System (HERS) Index Score lower than 55.	[40]
	International Living Future Institute (ILFI)	Net-ZEB	A review of the actual operating performance to prove that the building is operating at zero energy consumption under the combined use of various renewable energy technologies.	[41]

	Residential Energy Services Network (RESNET)	Home Energy Rating System (HERS)	A scale/metrics for measuring residential building energy performance. The HERS Index score is generally in the range of 0–150. A score of 0, 100, and 130, respectively, represent "net-ZEB," "avg. new home," and "avg. existing home."	[42]
	International Green Construction Code (IgCC)	Zero Energy Performance Index (zEPI)	A scale/metrics for measuring commercial building energy performance. The zEPI sets an absolute scale, and ZEBs have a score of 0.	[43]
EU	The European Commission	EPCs	EPCs are considered to be a mandatory requirement in the EU, and has been written into EPBD 2010.	[44]
	ZEBRA2020	nZEB tracker*	Track the maturity of the ZEB market in the EU and its member states. A total of 10 evaluation indicators from various aspects are involved, and the aggregation result can be performed in a weighted manner. This assessment tool provides an intuitive picture of the ZEB market across the European Union.	[45]
China	At present, China lacks ZEB evaluation and certification system. The call for ZEB at the national level is mainly focused on the design. The ZEB market is still stuck in government-supported demonstration projects; moreover, the follow-up monitoring, evaluation, and certification of the demonstration building needs to be strengthened.			[39]

* Figure 3 shows the assessment results of the ZEB market in the EU in 2014. Some indicators in the figure are 0, which has three possibilities: (a) no data are available; (b) requirements for a criterion are not fulfilled; or (c) the ZEB market is not developed.

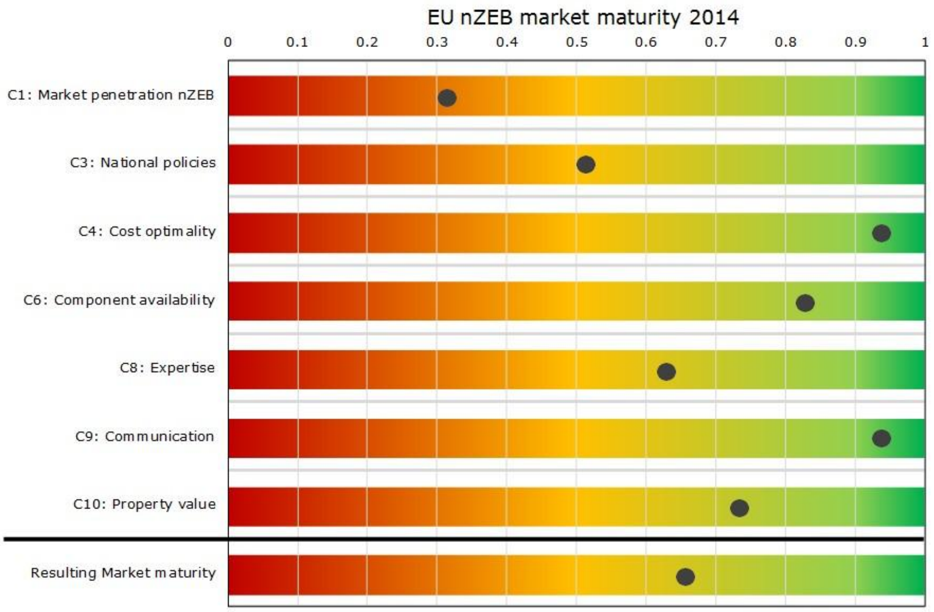

Fig. 3. The EU ZEB market maturity 2014 (Source: [45]).

3. The methodology

3.1 The climates

This article focuses on cold climate zones, which is climate zones 4–8 in the United States, cold and severe cold climate zone in China, and climate zones 3–5 in the EU. Fig. 4 shows the distribution of cold regions in the three regions. For the three regions, the cold climate accounts for about two-thirds of the total area. Moreover, most of the ZEBs are distributed in this area, so it is important to study the actual performance of ZEBs in cold regions. Table 2 summarizes climate indicators of cold regions in each region or country.

Table 6. The climate indicators of cold regions in different regions.

Country/region	Climate zone name	Main climate indicators	Reference
U.S.	Zone 4 (mixed)	CDD50°F ≤ 6,300 and 3,600＜HDD65°F⩽5,400	[46]
	Zone 5 (cool)	CDD50°F⩽6,300 and 5,400 < HDD65°F⩽7,200	
	Zone 6 (cold)	7,200 < HDD65°F⩽9,000	
	Zone 7 (very cold)	9,000 < HDD65°F⩽12,600	

	Zone 8 (subarctic/arctic)	12,600 < HDD65°F	
China	Cold climate	10℃＜The average temperature of the coldest month≤0℃	[47]
	Severe cold climate	The average temperature of the coldest month≤-10℃	
EU	Zone 3 (Dfb)	Temperate continental climate/humid continental climate without a dry season and with warm summer	[48]
	Zone 4 (Cfb / Dfb)	Temperate without a dry season and warm summer	
	Zone 5 (Dfc)	Cold, without a dry season and with cold summer	

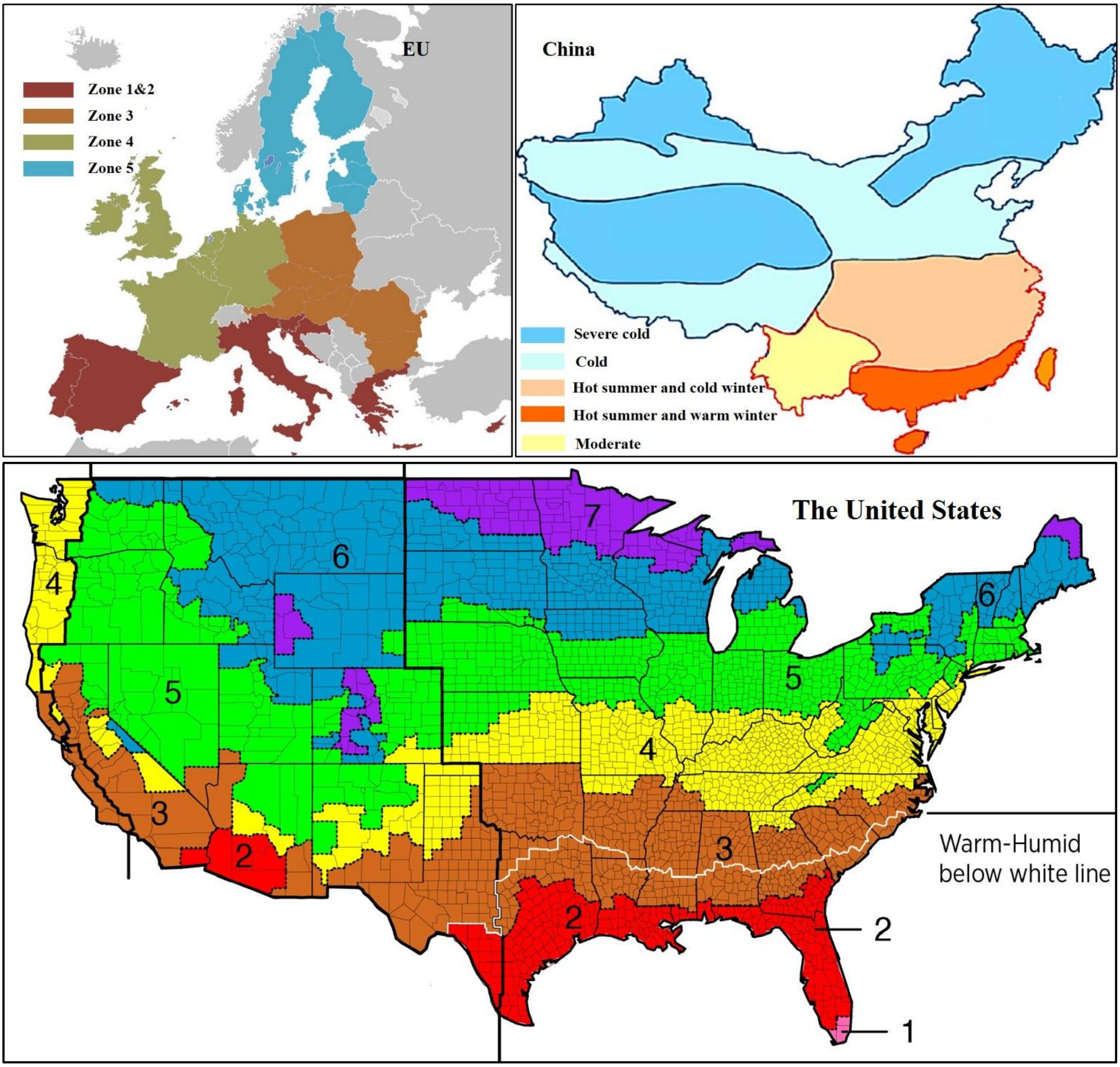

Fig 4. The climates in China, the EU, and the United States.

3.2 The data source

The study is based on 385 ZEB cases, with 247, 95, and 43 cases located in the United States, EU, and China, respectively. These cases were mainly derived from ZEB case reports in several online databases and offline case sets. The main databases are shown in Table 7.Table 7. The database and basic information.

Name	Type of database	Area covered by the database	Reference
NBI	Ultra-low and nearly-ZEB	The U.S.	[49]
DOE ZERH	ZERH	The U.S.	[50]
ILFI	Net-ZEB	North U.S.	[51]
NESEA	Net Zero & Net Zero Ready&Passive house	Cold regions of the U.S.	[52]
Construction 21	Ultra-low & nearly-ZEB	International	[53]
ZEBRA2020	Nearly-ZEB	EU	[45]
UL/ZEB*	Ultra-low & nearly-ZEB	China	Offline Report

* Ultra-low/near-zero energy buildings in China: cases of best practices.

3.3 Data description

The collected case information can be divided into five categories: building basic information, energy performance, cost information, building design, and technology adoption. Basic information includes building type, size, stories, location, built year, and more. Fig. 5 shows the regional distribution of the cases and their building types. The energy performance includes energy use and renewable energy production per square meter of floor space per year. Architectural design information mainly includes parameters of envelope components, such as airtightness indicators, U-value, and SHGC.

Note that not all cases contain complete information. Therefore, in the subsequent detailed analysis of each part there will be differences in the number each is based upon.

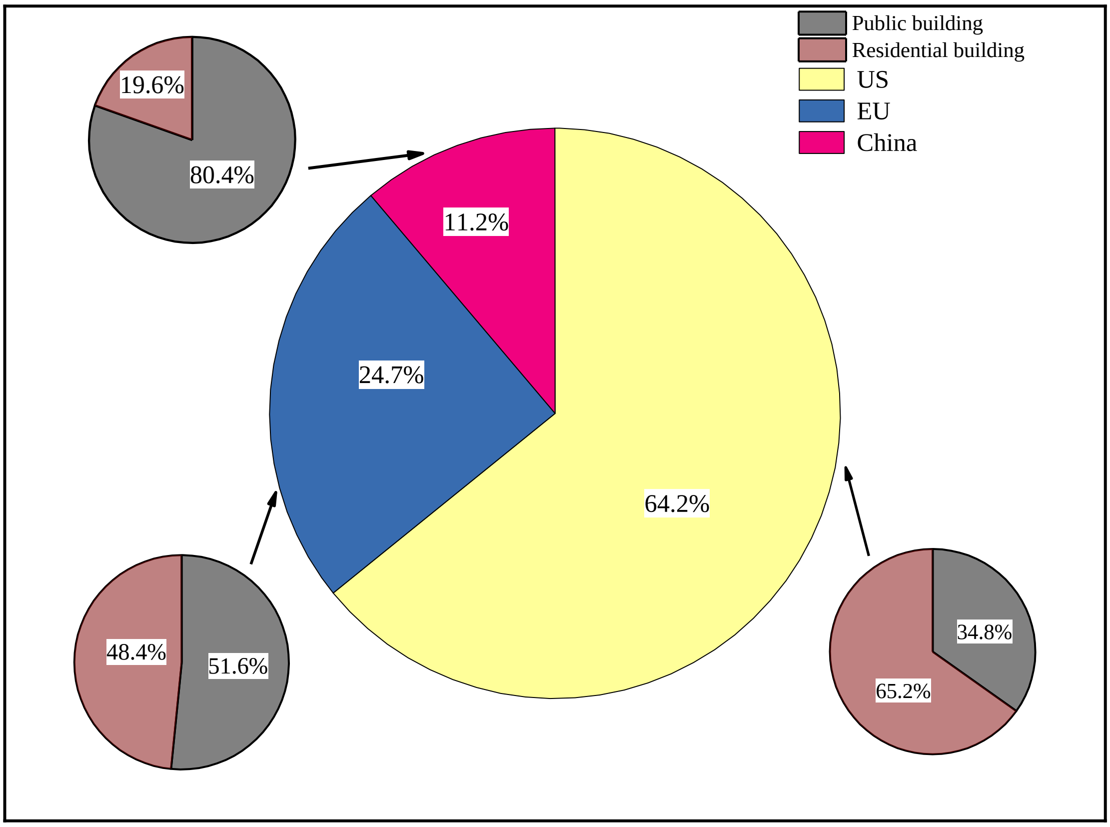

Fig. 5. The regions and building types.

4. Results

4.1 Energy performance of ZEBs

Fig. 6 shows the energy use intensity (EUI) and renewable energy production intensity (RPI) of the three regions, both in primary energy per square meter of building floor space on an annual basis. The balance line is used to assess the proximity of the building to zero energy consumption. For the United States, the verified cases generally all achieved net-zero energy, while most of the emerging cases did not. Compared to public buildings, the net-zero ratio of residential buildings is higher. Comparing the three regions, almost all cases in the EU and China are under the balance line; especially in China, where the RPI of most cases is equal to zero. This phenomenon has a great relationship with local architectural characteristics. The building stock in the United States consists mainly of low-rise buildings, while in the EU and China there are many high-rises and super high-rise buildings. The available area of PV panel installation corresponding to the unit building area is relatively small, which limits the amount of renewable power generated per unit of building area. However, it should be mentioned that the average EUI of the U.S. regional cases is the highest, whether for residential buildings or public buildings. This indicates that ZEBs are not equal to energy-efficient buildings. As long as the RPI is large enough, buildings with high EUI can still reach net zero. As shown in Fig. 7, if the energy target in their ZEB standards is used as the evaluation index, the EU and China ZEB cases have not met expectations. The EUI of U.S. public ZEBs is below standard requirements. There is currently no minimum energy target to directly measure the EUI of residential ZEBs.

Energy consumption information of the ZERH-certified U.S. home building is primarily the HERS index rather than the EUI, so these cases are analyzed separately. According to Fig. 8, the average HERS index for the ZERH cases is 19. The scores are mostly below 60, and in some cases even reach -37.

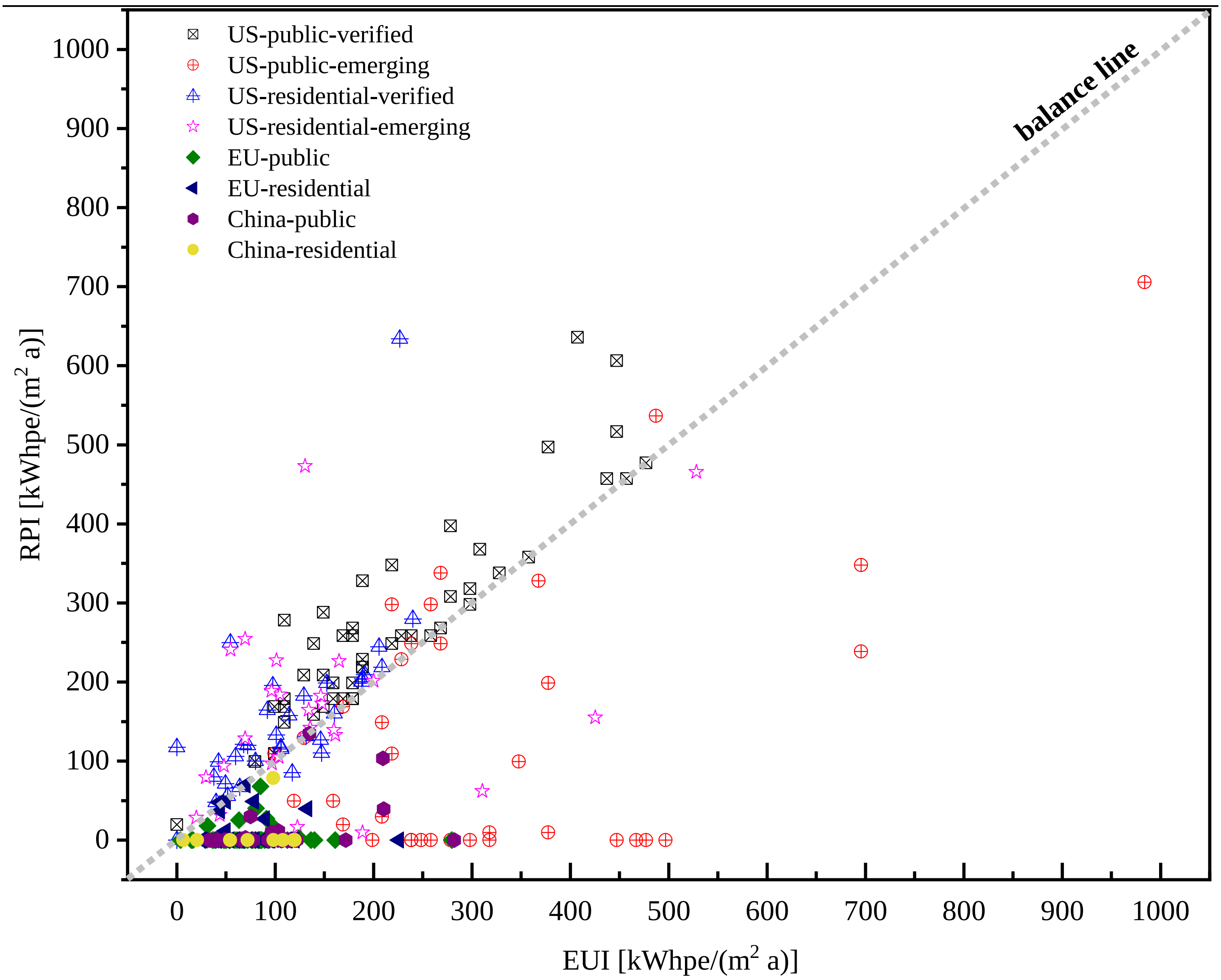

Fig. 6. The energy generation/use balance of selected ZEB cases.

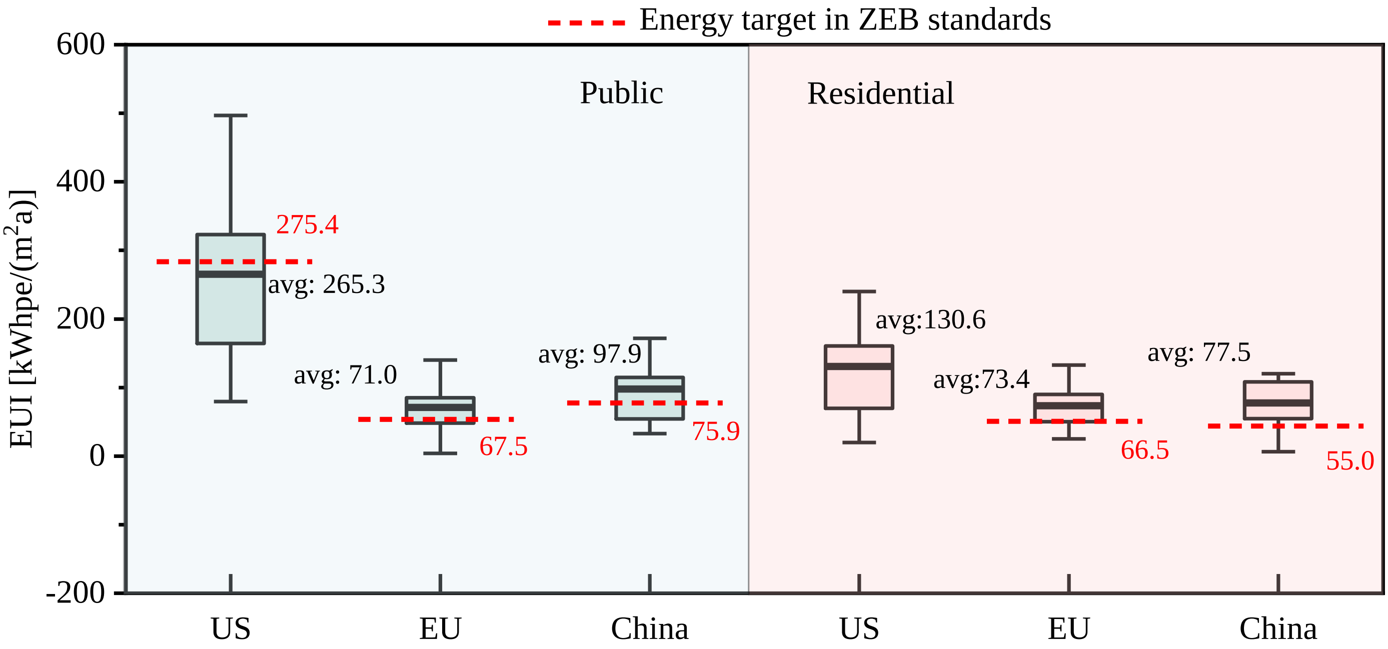

Fig. 7. The cases EUI and energy target.

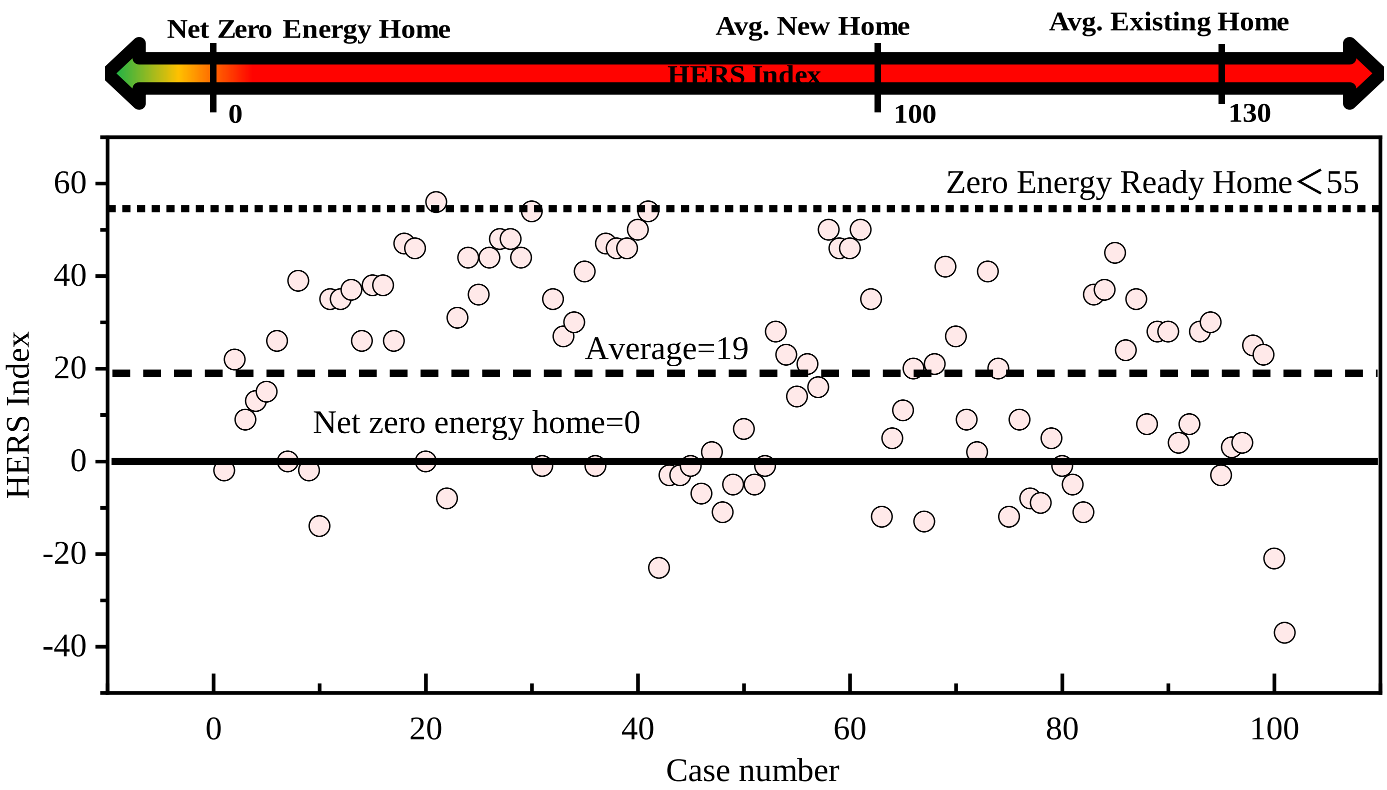

Fig. 8. The HERS Index of U.S. ZERH cases. (cases size:101)

To further understand energy performance between different regions, the study compared the breakdown of energy consumption. Based on 54 cases, Fig. 9 presents the proportion of energy consumption by category to total energy consumption. The breakdown is different in the three regions. In China, it is generally divided into HVAC, lighting, power, and other items, which include hot water, data center energy use, and so on. In the United States and the EU, heating and cooling energy consumption is generally further divided. We found that HVAC energy use constitutes a big portion of an ZEB's total energy use in cold climates—especially heating energy use, which accounts for about 30%–40%. The average proportion of lighting energy use in China, the United States, and the EU is 30.75%, 54.25%, and 15.5%, respectively. Note that the lighting energy use may include some plug energy use in some cases in China, and that in the United States cases includes part of appliance energy use. The EU region has also separately measured the Environmental Control System (ECS), which accounts for about 20% of its total building energy use.

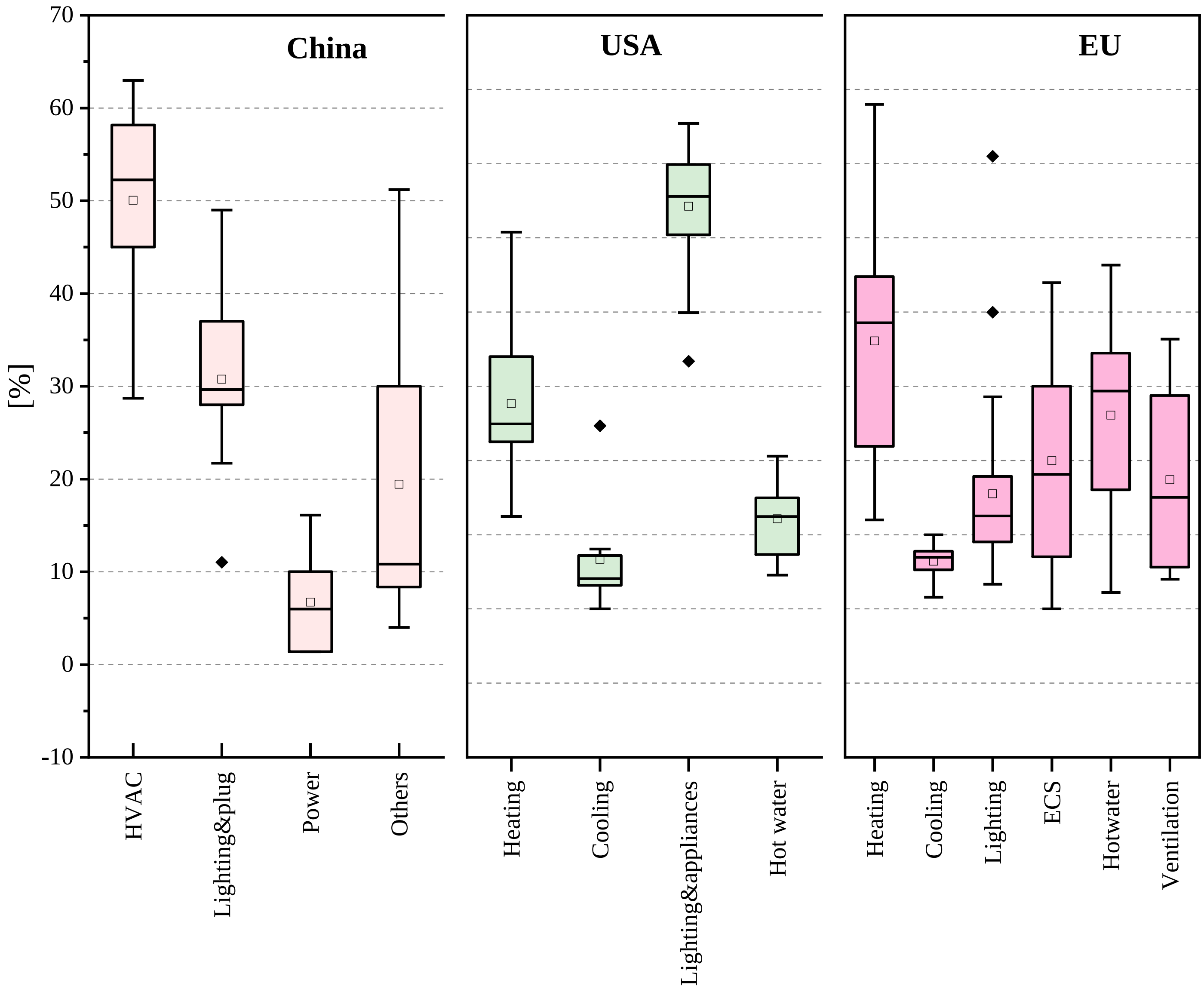

Fig. 9. The breakdown for energy consumption. (Number of cases: China: 10; U.S.: 17; EU: 27)

4.2 The economic analysis

Fig. 10 shows the initial construction costs per region. The costs in China, the EU, and the U.S. are 851, 1,999, and 3,149 US$/m^2, respectively. The world of construction is inherently dynamic. With each passing year, the cost landscape changes. Fluctuations in the cost of raw materials and labor influence construction costs throughout the regions, while new local regulations and taxes create potential hurdles and risks. But the biggest reason China's costs are far lower than those of the EU and the United States is China's low-wage labor force. In addition, when measured by the cost of a standard building of the same type, the statistical costs in China and the United States are higher than the baseline, while in the EU they are lower than the baseline. One potential reason is that differences in tax and fiscal subsidy policies in different EU countries lead to large cost differences.

The incremental cost is broken down according to the technology type to further analyze the net investment composition of ZEB in the different climates. As shown in Fig. 11, the ratios of incremental costs of passive technology, active technology, renewable technology, and automatic control systems are 54.3%, 17.9%, 13.9%, and 10.3%, respectively. Passive technology has the largest incremental cost, which may be related to its higher economic output/input ratio.

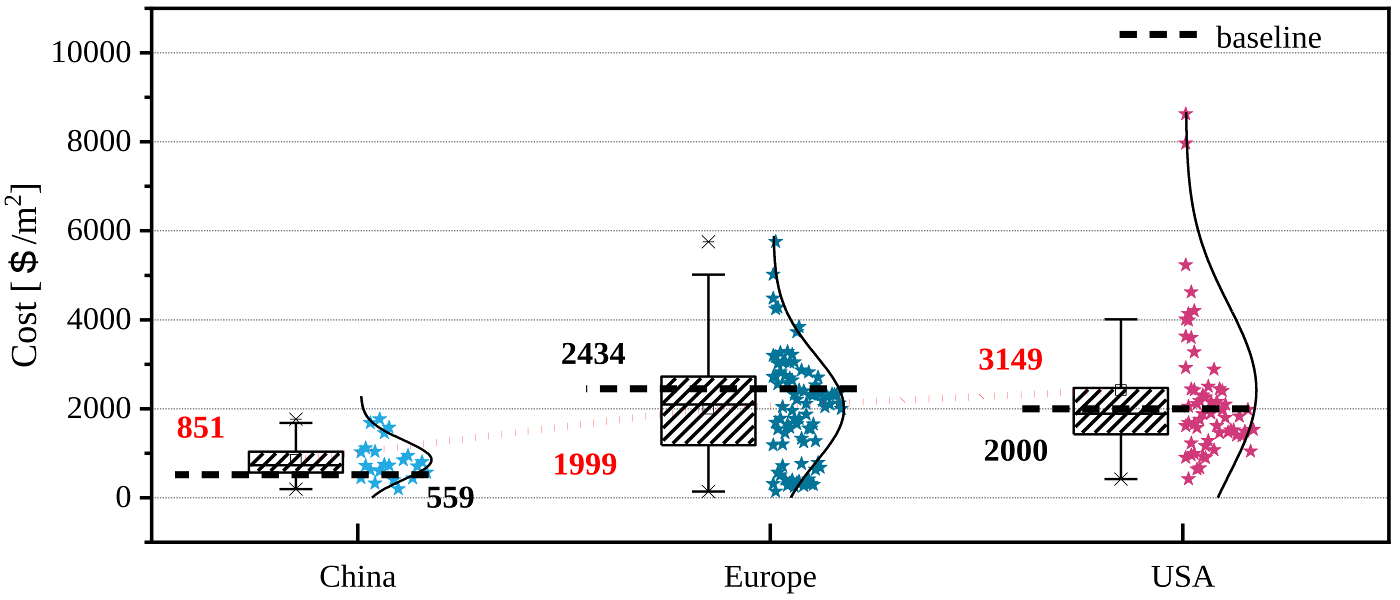

Fig. 10. The construction cost of three regions.

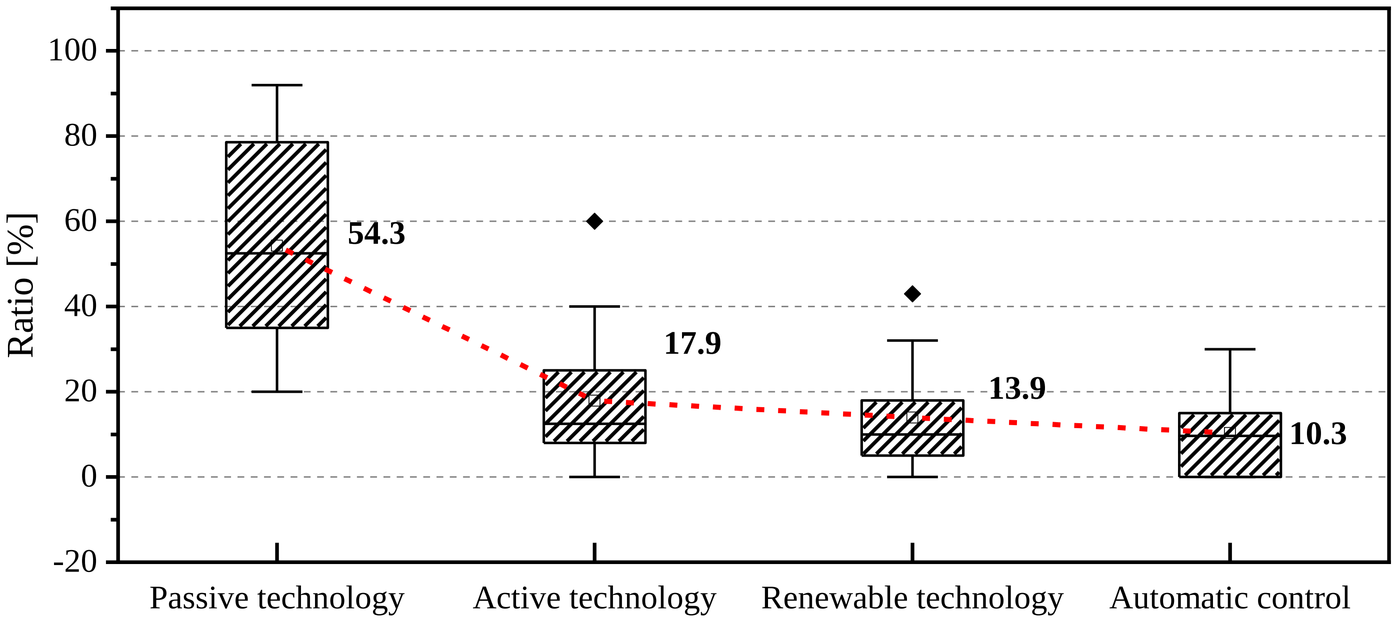

Fig. 11. The statistical proportion of incremental costs for different technology types.

4.3 Renewable technology

Rational utilization of renewable energy technologies is the key to achieving ZEB status, and the specific utilization in different regions will be subject to local resource conditions. Fig. 12 shows the proportion of renewable technology utilization in selected cases of the three regions. In the EU, the U.S., and China, the most widely used renewable technologies are PV, PV, and ground source heat pumps (GSHPs), respectively. This is in line with the comparison of energy performance in the previous section. China's PV utilization is low and renewable power generation is low, and although the PV utilization rate in the EU is high, the installation rate per unit building area is low. The low PV utilization rate in China has resulted in low renewable power generation; and although the PV utilization rate in the EU is high, the installation rate per unit of floor space is low. In addition, solar thermal and wind turbines are used in all three regions. Further, the purpose that solar thermal is used for in ZEBs can be divided into two categories: HVAC and hot water. When applied to HVAC, solar thermal generally provides preheating for GSHP systems. There are also cases where the collected heat is stored. For example, in a case in China's severe cold climate, in addition to meeting the daily hot water supply and the thermal compensation of the GSHP, the remaining heat is discharged into the soil for storage, to prevent the occurrence of "cold accumulation." Although biomass boilers and wood boilers have not been adopted in China and the United States, they have been adopted in the EU. This is mainly related to local policy; EU emission standards are significantly more stringent than U.S. federal and state standards and China's standards. Based on recent national and local government activity in the EU, these regulations are tending toward lower limits [54]. Burning wood biomass is almost a carbon-neutral energy source, because the amount of CO_2, a greenhouse gas, released into the atmosphere when the wood is burned is the same as the CO_2 absorbed by the tree through photosynthesis while it is growing [55].

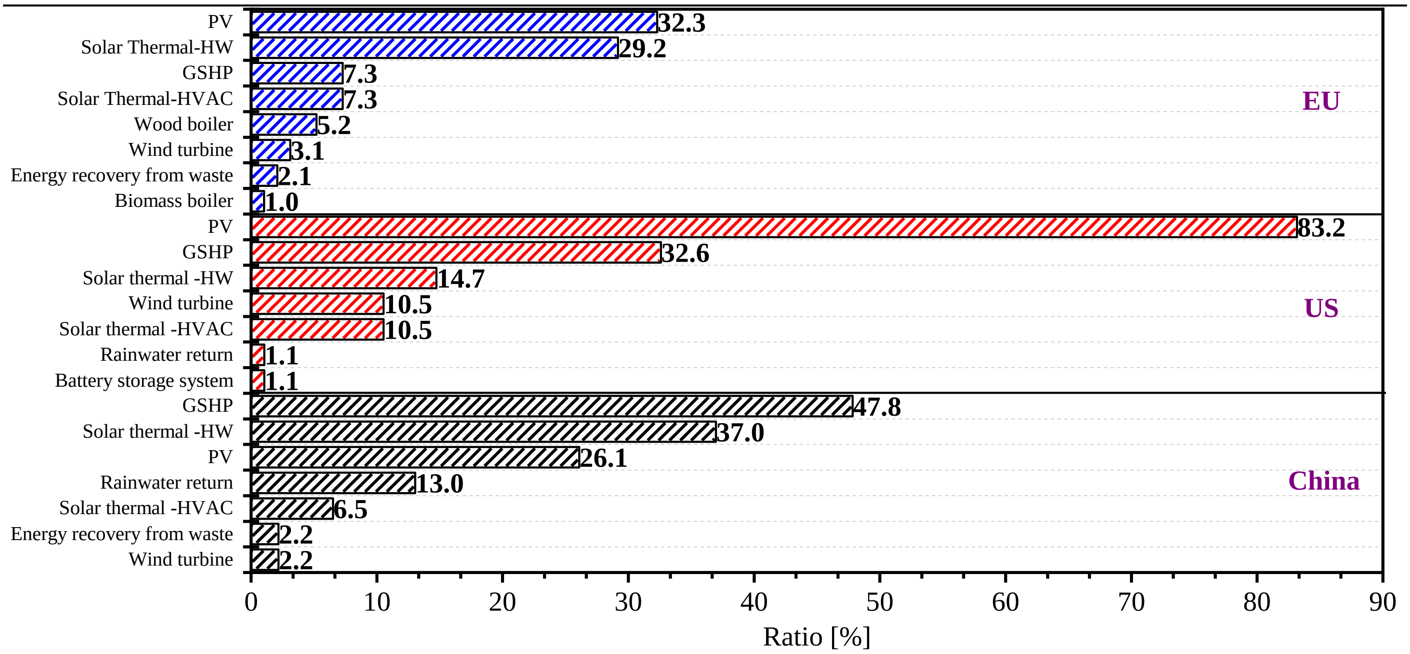

Fig. 12. The utilization ratio of renewable technology.

4.4 The building design and envelope

The envelope performance determines the space heating/cooling energy demand, which in turn affects the energy consumption of the HVAC system. Therefore, the envelope design plays a decisive role in the development of ultra-low / near-zero energy consumption. Especially for severe cold / cold climates, heating energy consumption accounts for a large proportion of the total energy consumption, which is greatly affected by the envelope. The U-value of walls and roofs, as well as the U-value and SHGC of window system, are all important parameters.

Fig. 13 presents the statistical distribution of the U-value in the selected ZEB cases. To more intuitively demonstrate the country/region-related envelope characteristics of ZEBs, the thresholds proscribed by the ZEB standard or guide for each country/region were used to assess the overall level of the selected cases. The average of each member country was used to represent the threshold for the EU region. The average insulation level of cases in the three regions was better than the respective ZEB standards, with the average U-value lower than the thresholds. The average U-value of external wall and roof for ZEBs in cold regions of China was 0.235 W/ (m^2 K) and 0.212 W/ (m^2 K), that of the United States was 0.170 W/ (m^2 K) and

0.109 W/ (m^2 K), and that of the EU was 0.167 W/ (m^2 K) and 0.135 W/ (m^2 K). Comparing the three regions, the order ranks of envelope performance in ZEB cases were matched to the stringency of the ZEB standard/guide.

The external window plays an important role in building envelope performance. It influences the heat gain and loss of the overall building by controlling the permeability, radiation, and heat transfer with the outside. As shown in Fig. 14, two important factors to assess window performance—the average U-value and SHGC for the ZEB cases in the U.S.—were 1.23 W/ (m^2 K) and 0.37, respectively. The average U-value and SHGC for China's ZEBs were higher than those in the U.S., with average values of 1.26 W/ (m^2 K) and 0.45, respectively. In cold regions, in order to obtain more solar radiation in the winter, the higher the SHGC, the better. However, it is essential to simultaneously consider summer insulation. In China's ZEB standard, the SHGC thresholds for winter and summer are separately specified. Therefore, for ZEBs in China, the SHGC of the window should be as large as possible to reduce the heating energy demand. In the summer, the overall SHGC can be reduced by adding a shading device. Due to the lack of emphasis on SHGC in the EU, relevant data were missing from the collected cases. But its average U-value is lower than it is in both the United States and China, with value of 0.96 W/ (m^2 K).

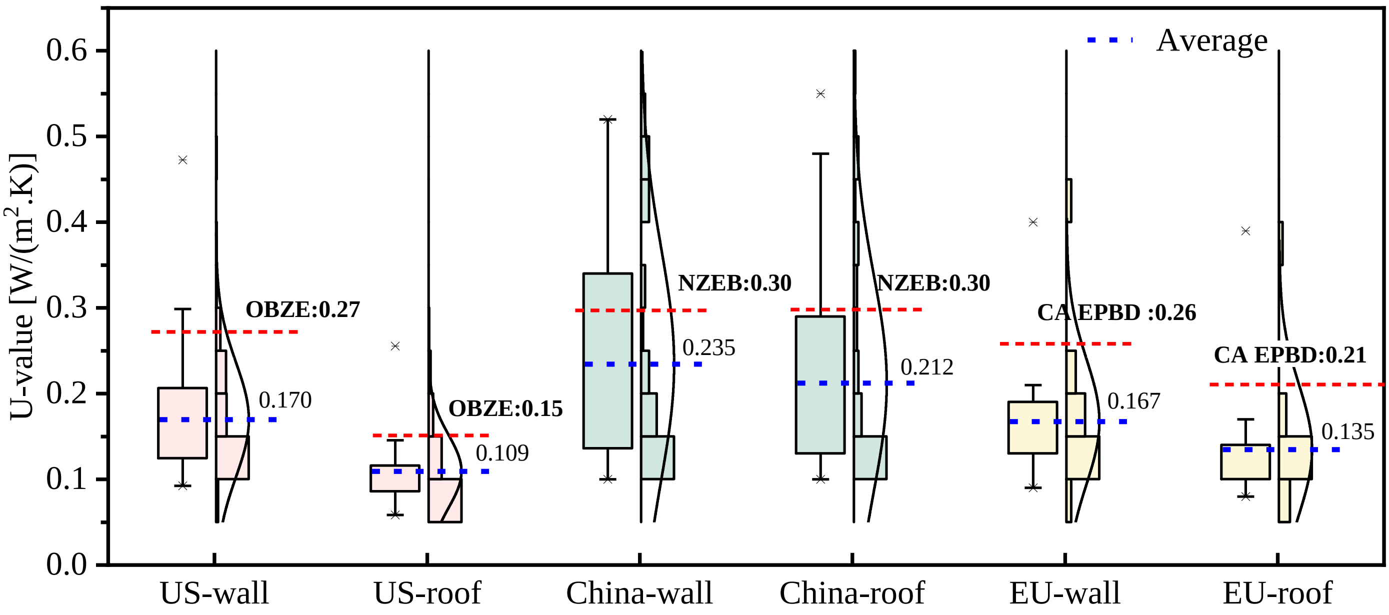

Fig. 13. The U-value of the opaque envelope in ZEB cases.

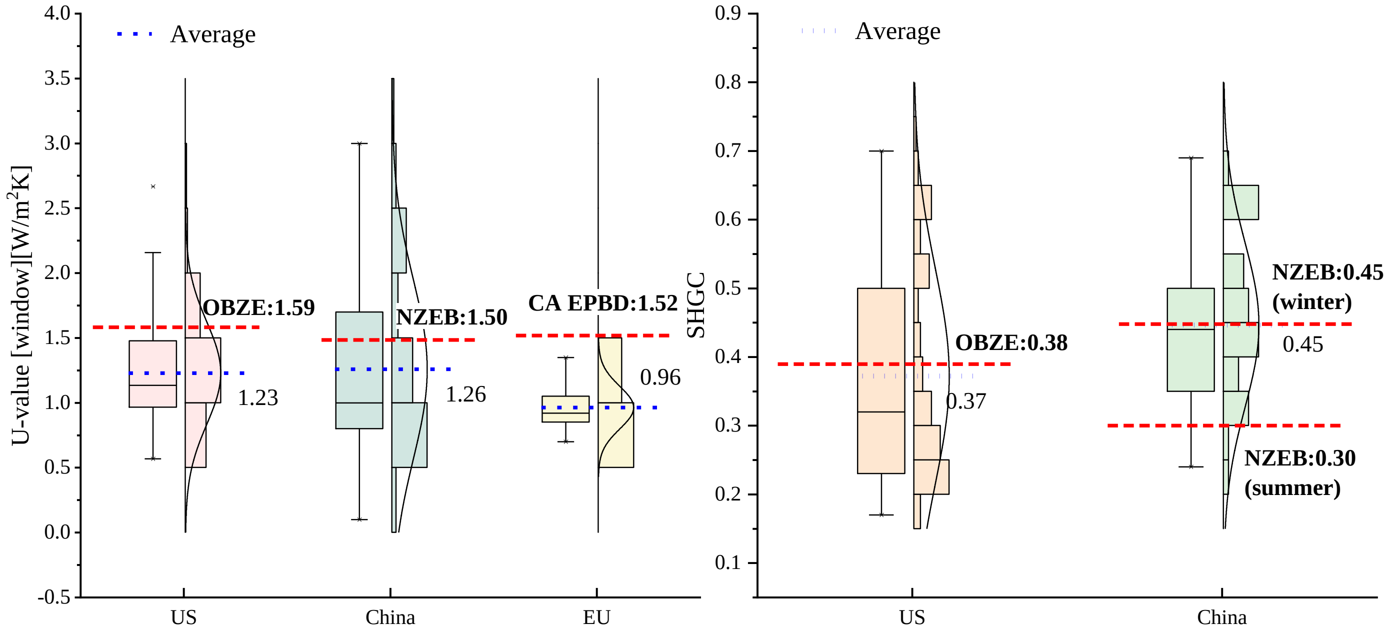

Fig. 14. The U-value and SHGC of windows in ZEB cases.

Building airtightness directly affects building energy consumptions. At present, it is generally evaluated by the air exchange rate (ACH) at a pressure difference of 50 pascals (Pa) between inside and outside air. Lower ACH can relieve cold wind penetration in winter and minimize indoor heat loads. As shown in Fig. 15, the average ACH for ZEB cases in the U.S. and the EU are 0.957 and 0.934, respectively, which is poorer than the threshold of the passive house standard ($ACH_{50} = 0.6$). However, it should be mentioned that although the Chinese cases satisfy the requirements of passive house and ZEB standards, most of the Chinese cases only obtain the design value of ACH due to the lack of overall airtightness testing and evaluation standards in China. The actual test value will be too high, due to unqualified construction technologies and devices.

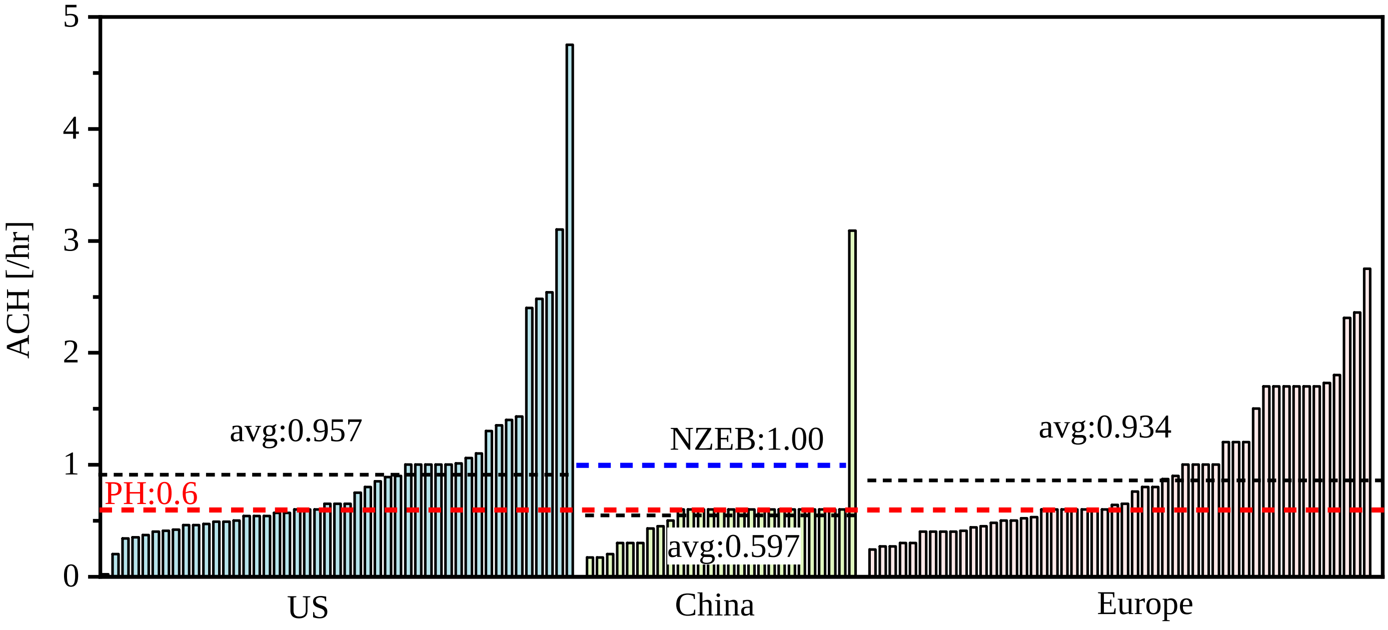

Fig. 15. The airtightness in ZEB cases.

4.5 Energy-saving technology of ZEBs

Buildings that achieve the target of near-zero energy consumption are the result of a combined application of key technologies. The building design should be based on local climatic characteristics and site conditions, reducing cooling/heating demand through passive design and then enhancing the energy efficiency of the active technologies. Fig. 16 shows the architectural design features and technology choices in the U.S. and China. Efficient lighting is the most widely adopted active technology in both countries. The higher proportion of lighting energy consumption in the total energy consumption, and the decreasing production costs of some high-efficiency lamps, make efficient lighting technology the most cost-effective. In addition, air heat recovery, efficient appliances, radiant cooling/heating, air source heat pumps (ASHPs), and passive solar heat gain are also at the forefront of applications. Among the remaining active technologies, due to the weaker restrictions on plug energy, there is no ZEB using plug energy management technology in China. Both the United States and China have optimized control strategies for artificial lighting; in addition to the basic time and space-based controls, they have also adopted the light sensor to further optimize the indoor light environment. Cases in the United States are more concerned with individualized design.

Depending on the purpose of adoption, the passive technologies used in the ZEB cases can be broadly classified into four categories: (1) envelope, (2) ventilation, (3) passive cooling/heating, and (4) lighting. Efficient envelope components are the most critical technology for reducing HVAC energy consumption in cold climates; all Chinese cases and almost all U.S. cases adopted advanced envelope and exterior window technology. As a kind of technology that can dynamically adjust the heat gain of the external window in summer, external sunshade control has been widely used, with adoption rates in China and the U.S. at 56.5% and 8.4%, respectively.

Natural ventilation technology comes in three forms: natural ventilation optimization, skylight ventilation, and chimney ventilation. Compared to the United States, China is more concerned about the natural ventilation effect of the building envelope, and 100% of cases in China optimized natural ventilation. This is because the indoor environmental quality in China is lower than that of Western countries. The fresh air of residential buildings is always supplied by opening windows instead of mechanical ventilation systems in buildings (especially residential buildings). Operable windows technologies can further improve the ventilation effect.

Passive cooling/heating technologies include cooling roofs, passive solar heat gain, thermal mass, and wind tunnels. Passive solar heat gain refers to a design measure that seeks to obtain optimal solar gain by optimizing orientation, layout, and other factors. The thermal mass technology mainly involves two forms of using phase change: storage tanks to improve energy efficiency, and heat storage floors to improve indoor comfort. Tunnel wind technology accounts for 10.9% of the Chinese cases. Its main role in the building is to extend the transition season and to precool/preheat the HVAC system. For example, a school building uses natural ventilation combined with tunnel wind technology. During the transition season, fresh air (after underground heat transfer) is directly introduced into the hall through natural ventilation. There is also a residential building that uses tunnel wind combined with exhaust heat recovery technology, with a recovery rate of 72% and an annual saving of 1,600 kilowatt-hours (kWh).

Skylights, light wells, light tubes, and exterior windows are four daylighting forms. Unlike the United States, China has adopted more diverse lighting measures, including skylights, light tubes, and light wells.

This is mainly related to the unique characteristics of Chinese architecture. China's buildings generally have a large underground space, with relatively low requirements for the lighting environment. The use of light wells and light tubes can fully meet lighting needs.

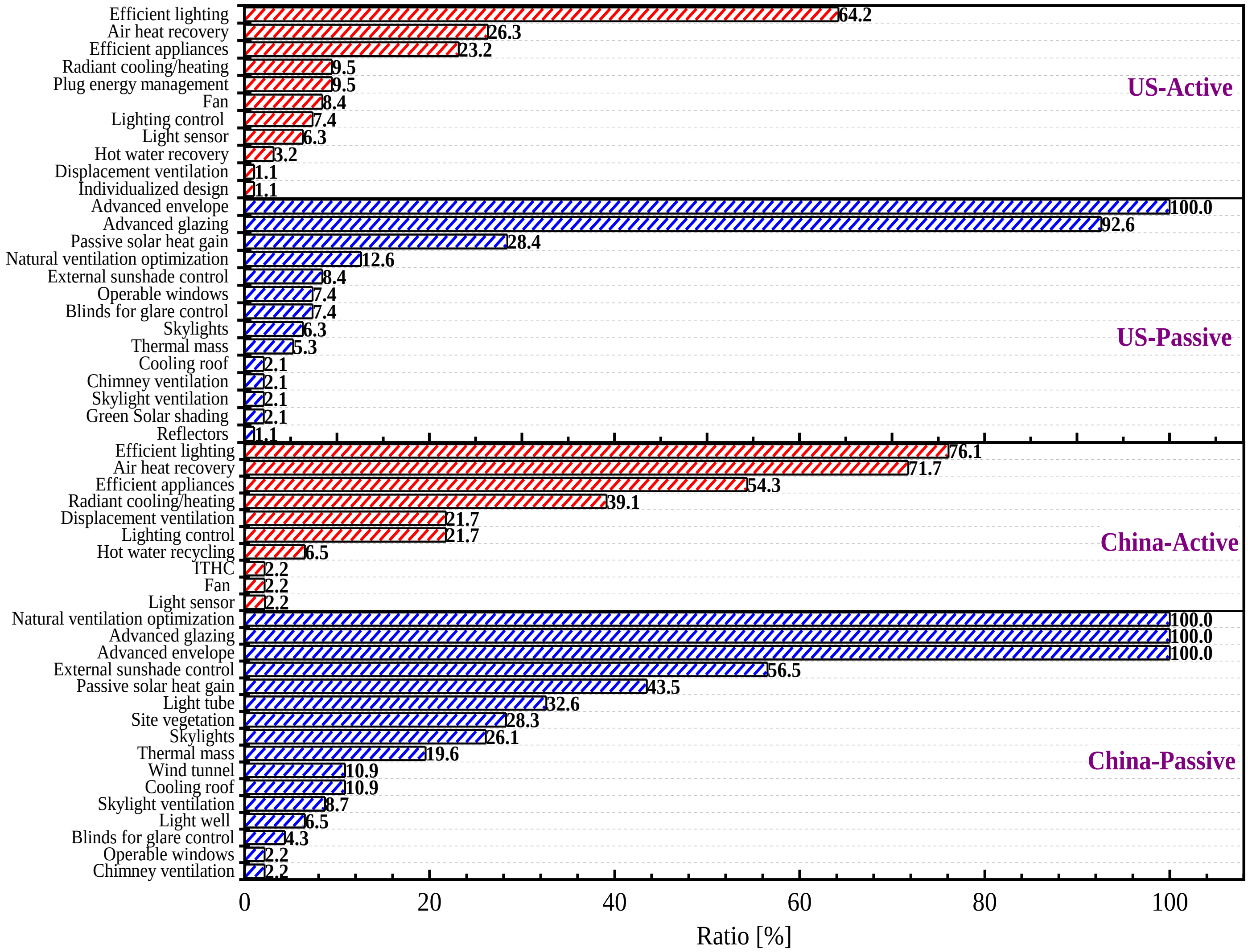

Fig .16. The design features and building technology choices of the ZEB cases. (ITHC: independent temperature and humidity control system)

4.6 The heating source

Fig. 17 shows the heating system technologies for ZEB cases in the three regions. Obviously, ZEBs in the EU have a more diverse heating technologies, and the utilization ratio of each technology is relatively balanced compared to those of the United States and China. A gas boiler, GSHP, and ASHP are the main technologies in the EU, China, and the United States, respectively. This is determined by the local energy structure, policy-driven forms, and architectural features. For example, the flexibility of the ASHP makes it more suitable for U.S. buildings with the characteristics of scattered construction and small size. On the contrary, the density and volume of buildings in China are large, the GSHP has higher energy efficiency there. The types of renewable heating technologies in the EU are more than those in the United States and China, although fossil fuel technologies still dominate, with gas boilers ranked first. This is driven by policy initiatives. The EU Commission proposed an "EU heating and cooling strategy" in February 2016 and integrated efficient heating and cooling into EU energy policies. The policy encourages renewable heating and cooling technologies such as biomass boilers and solar heating systems—as well as some energy-efficient technologies such as combined heat and power units (CHP)—to help to reduce the importance and use of fossil fuels [56].

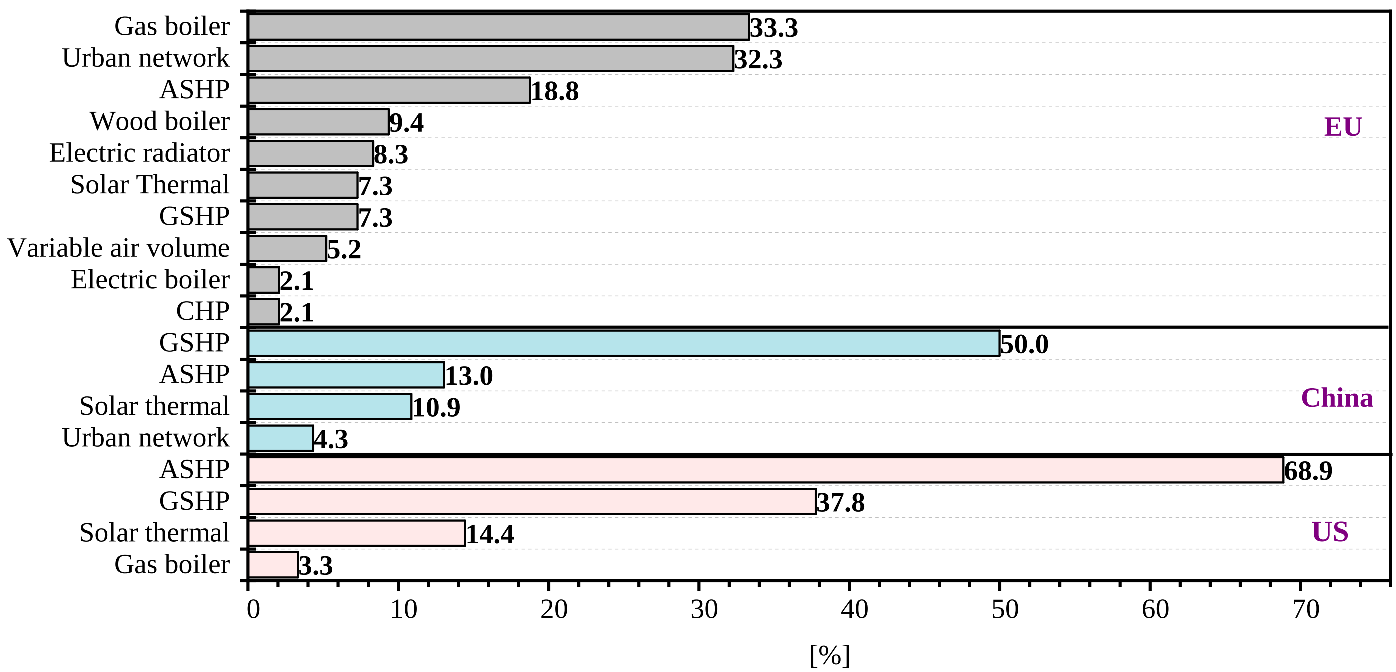

Fig. 17. The heating technologies of ZEB cases in the three regions.

5. Discussion

5.1 Key features of ZEB in the cold regions

Four key features affect ZEBs in cold regions: (1) ZEB form affects its performance, (2) a high-performance envelope is critical, (3) advanced technology is not a necessary condition for a ZEB, and

(4) optimal selection of renewable energy types is influenced by many factors. These are detailed below.

The statistical energy performance results show that the specific embodiment/definition form of ZEB in different regions affects ZEB performance. The ZEB definition determines the renewable energy production and boundaries of energy use. According to cases in this paper, since the EU and China are involved in nearly-ZEB, PRI among their ZEB cases is very low, and nearly, all cases are under the balance line. The U.S. promotes net-ZEB, so most of its cases are close to or even above the balance line. Since the boundaries of energy use on “plug load” varies in different countries, it is inaccurate to directly compare their EUIs. However, the energy target can be used as a measure to reveal the achievement level of the expected goal. In addition, although some buildings achieve zero net energy consumption, they have higher EUI and even exceed the energy targets set by the ZEB standard. Therefore, while emphasizing net energy consumption, the constraints on energy use should also been strengthen.

For cold regions, the high-performance envelope is critical for creating a ZEB. The overall standard requirement levels and actual case building envelope performance in the three regions indicate that EU standards are more stringent than those in the United States, and the U.S. standards are more stringent than those of China. The study results indicate that the building ZEB standard/guide plays an effective guiding role. The design orientation in the U.S. and Chinese standards emphasize the technical measures, while the EU adopts a cost-optimized methodology, which comprehensively assesses the costs and building energy efficiency to reduce the additional investment costs. Combined with the economic analysis in this paper, the average construction cost of the ZEB cases is even lower than the average cost of existing buildings in the EU. Therefore, the design orientation of ZEB standards should be shifted from emphasis on technical measures to cost-optimized life cycle analysis.

Cases in cold regions have adopted multiple technologies at the same time. The utilization type and utilization rate of passive technologies are all higher than active energy efficiency technologies. This indicates that advanced technologies are not a necessary condition for creating a ZEB. The full use of natural resources during the transition season and reducing the impact of the external environment during the air conditioning season are the main architectural design features of this climate. High-performance exterior walls and roofs are highly utilized in the United States and China. In addition, the economic level and the living habits of local residents also affect the tendency of technology selection to a certain extent. The adoption rate of all passive strategies in the Chinese case is higher than that of the United States—especially low-cost measures such as natural ventilation. Basically, all Chinese cases included natural ventilation optimization in the building design.

The selection of renewable energy types is influenced by the maturity of the technology, the local architectural characteristics, and the national policy orientation. For example, as a relatively mature renewable energy technology, solar thermal, has been used widely in cold regions. In addition to conventional hot water supply, ST is also used in HVAC systems for thermal compensation. Due to the difference in architectural characteristics, PV is the most utilized renewable technology in the United States and the EU. Building density in the United States is low, and mainly consists of low-rise buildings, so the area available for PV installation is adequate. However, for China, improving the PV utilization of high-rise buildings is the key to improving the net-zero level. For example, building-integrated photovoltaics (BIPV) can be used to increase the photovoltaic installation rate of building facades, but market research has revealed that high capital costs are the biggest obstacle to using this technology in the construction sector [57]. The utilization of wood and biomass boilers in the EU is higher compared to the U.S. and China, in response to those countries' more stringent emission-reduction policies.

5.2 Drivers for the ZEB market

Two drivers particularly affect the ZEB market: (1) strong energy efficiency policies and (2) certification. The are discussed in more detail below.

Despite the large differences in the levels of ZEB development in the three regions, it is clear that strong energy efficiency policies are a crucial lever driving high efficiencies in new construction projects. On one hand, policies can guide the future development trend of buildings by setting specific energy efficiency targets; for example, the relative strengths of the energy targets set in the three regions covered in this paper and the performance trends of the average performance of their ZEBs are generally consistent. On the other hand, policies and programs can send the distinct market and public benefits signals necessary to drive goal setting and investment around zero energy projects. The ZEB policies in different regions will differ in strength and form, resulting in differences in market incentives. As analyzed in this paper, the jurisdictions of most states in the United States have issued energy regulations and codes related to ZEBs, and financial subsidies are only an aid. These regulations and codes make ZEBs legally enforceable. For example, the ZERO Code for California incorporates 2019 California Building Energy Efficiency Standards (BEES) and is required by the implementing jurisdictions [58]. The policy drive has spurred the U.S. ZEB market. According to an NBI survey, about 46% of the ZE Verified and ZE Emerging projects ZEB were owned by private [59]. The regulations around ZEBs in the EU are more legally binding. EPBD is its legislative tool, and EPBD2018 stipulated that EU countries had until March 10, 2020, to write the new and revised provisions into national law [4]. At present, the main driving force for China's ZEB market is financial subsidies, but the relationship between financial subsidies and incremental costs is difficult to assess. This has led developers to lack sufficient interest in ZEB. Therefore, the ZEBs in China are very narrow in popularity, mostly for demonstration projects funded that are supported by the government [39].

As ZEBs become mainstream, it is increasingly important to conduct ZEB certification through third-party organizations. For example, the relatively complete and mature certification systems in the United States and the EU have effectively increased ZEB market value. The certification results of the actual operational performance demonstrate that zero-energy is achievable, and that proof reduces the uncertainty of stakeholders, including developers and investors on the ZEB market. Countries such as China, where ZEBs are still in their infancy, should establish a ZEB certification system and set up a special training structure to gradually form a complete industrial chain of ZEB design-operation-assessment-certification to accelerate the ZEB process.

6. Conclusion

Based on nearly 400 actual cases, this paper evaluated the actual energy performance of ZEBs, design features, and technology selection in three cold regions. The study took into account the regional differences in natural resources, architectural characteristics, economic level, living habits, and other factors, and compared the evaluation results among the United States, the European Union, and China. Finally, a matching analysis between the actual ZEB performance and policies/standards was conducted. The main findings are as follows:

(1) The energy use boundary in the ZEB definitions in different regions affects the actual performance of their cases. The cases in China and the EU are nearly all zero-energy buildings, and most of the cases in the United States are net-zero-energy buildings. When the energy targets involved in the ZEB standards and energy regulations were used as metrics, the actual EUI in China and the EU regions was higher than expected. The actual EUI of public ZEBs in the United States was lower than the energy target, but residential ZEBs do not yet have clear EUI constraints.

(2) The ZEB standard plays a powerful role in guiding the actual envelope performance. The average performance in the cases of the three regions matches the constraint strength of their ZEB standard. Among them, the EU performs the best. In addition, combined with economic analysis, the average construction cost of ZEBs in the EU is lower than that of existing buildings, which is mainly due to the cost-optimized method. Therefore, future building standards can be transformed from purely emphasizing technical measures to comprehensive life cycle optimization. This is especially true for developing countries where incremental costs are major obstacles to ZEBs.

(3) In cold regions, the adoption ratio and application numbers of different types of passive technologies are higher than those of active energy efficiency technologies. Among them, efficient envelopes and windows are the most common technologies among cases found in the United States and China. In addition, China is more focused on low-cost passive technologies such as natural ventilation, while in the United States, low-cost passive measures are not widely adopted in cold climate regions.

(4) In addition to PV technology, the renewable technology used in this climate zone is mainly applied to HVAC systems. The frequency and type of application are influenced by various factors, such as local building size and local policies. Affected by emission reduction policies, the application frequency of

biomass and wood boilers in the EU is higher than it is in the United States and China. Affected by architectural characteristics, ASHPs and GSHPs are the most widely used renewable energy technologies in the United States and China, respectively.

(5) Energy policy is the main driver of the ZEB market. The EU and some states in the United States have written ZEBs into legislation to broaden the ZEB market. In addition, zero-energy building certification also reduces the uncertainty of developers in the ZEB market.

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