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Review

Review of the U.S. Policies, Codes, and Standards of Zero-Carbon Buildings

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Abstract: The global issue of climate change has accelerated the international commitment to net-zero carbon emission development. Decarbonizing the building sector has been put on several governments' sustainable development agendas. To provide a reference for decarbonizing the building sector, this paper summarizes the U.S. experience in zero-carbon buildings (ZCBs) from the aspects of policies, codes, and standards at the federal and local levels and those of professional societies. Based on the definition and boundaries of ZCBs, this paper introduces policies on building energy efficiency, electrification, on-site renewable energy deployment, and "buy clean", illustrating highlights in building phases, energy systems, materials production, and fiscal incentives. The synergic efforts and coordination between federal and local levels and with professional societies are also introduced. Successful experiences in policy and standard implementation are summarized, including the systemic work of multilevel governance, clearly defined goals and stringent policies, constant upgrades of codes and standards, transparency in reporting and information sharing, and increased financial and investment opportunities. This paper provides concrete recommendations for developing zero-carbon building policies.

Keywords: carbon-neutral; zero-carbon buildings; energy efficiency; codes and standards; embodied carbon emissions

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1. Introduction

In the past three decades, disasters exacerbated by climate change have resulted in the displacement and death of millions of people around the world and have become an emergency that threatens human survival [1]. To address this, more than 190 parties/countries joined the Paris Agreement in 2015 [2] and further reached a consensus that the world would achieve net-zero emissions by the middle of this century to limit the temperature increase to 1.5 °C [3]. China has proposed a "30–60" plan that aims to achieve peak carbon dioxide emissions by 2030 and carbon neutrality by 2060 [4]; the European Union (EU, Brussels, The Kingdom of Belgium) announced the "European Green Deal", which proposes to reduce the EU's greenhouse gas emissions to 55% of the 1990 level by 2030 and achieve carbon neutrality by 2050 [5]; and the United States formulated "Nationally Determined Contribution" (NDC) plans to "create a carbon pollution-free power sector by 2035 and a net-zero emissions economy by no later than 2050" [6]. The United States plans to pass the "Federal Sustainability Plan" that refines the NDC scheme [7]. As of 2022, many states and districts in the United States had passed legislation to set the goal of achieving zero carbon by 2045 or 2050 (Table 1), accounting for nearly one-third of the country's population [8].

In addition, some states have moved toward a clean energy industry and a zero-carbon grid by setting clean energy goals (e.g., Nevada and Maine) or signing executive orders or taking regulatory action (e.g., Minnesota and New Jersey) [8]. In short, the goal of a zero-carbon society and policy promotion has become a trend [9].

Table 1. States that have set zero-carbon/100% renewable energy (grid) goals [8].

Electricity Goals	Target Year	State (Year Passed)
Carbon-free	2045	California (2018), New Mexico (2019), Washington (2019), Maryland (2022)
	2050	Colorado (2019), Nevada (2019), Wisconsin (2019), Virginia (2020), Louisiana (2020), Michigan (2020), New Jersey (2020), Illinois (2021), Massachusetts (2021), North Carolina (2021), Rhode Island (2021), Nebraska (2021)
	2040	New York (2019), Oregon (2021)
100% Renewable	2045	Hawaii (2015)
	2050	Puerto Rico (2019)
	2032	Washington, D.C. (2019)

In addition to efforts in the industry and transportation sectors, the move toward energy efficiency and the decarbonization of the building sector is an important way to achieve a zero-carbon society [10]. The building sector is the main carbon-emissions-producing sector: it accounted for 39% of global energy-related carbon emissions in 2018, including 28% of operational carbon and 11% of embodied carbon, which are attributed to building materials, construction, and transportation (Figure 1a) [11]. It also accounted for 36% of U.S. carbon emissions in 2020, excluding embodied carbon (Figure 1b) [12]. In the EU, building operation emissions also account for 36% of its total carbon emissions [13].

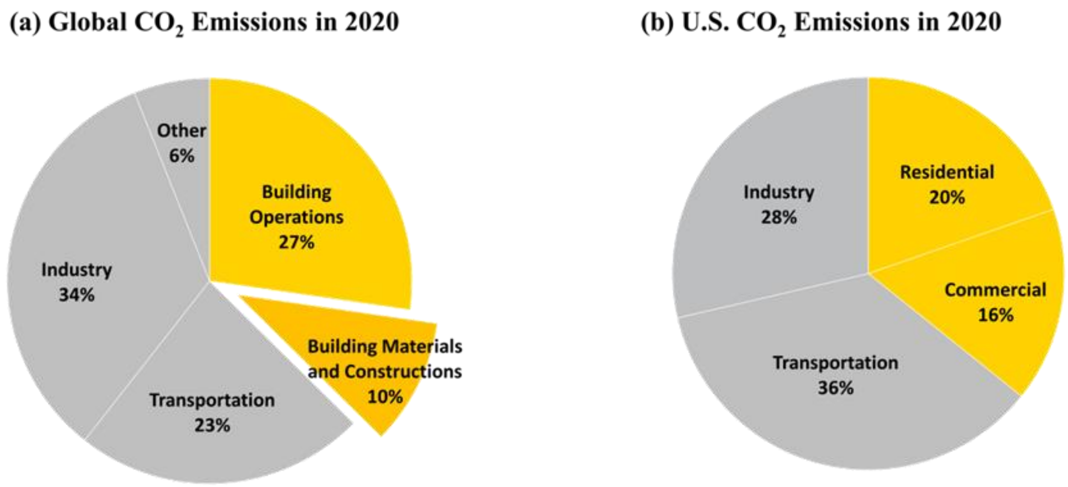

Figure 1. The proportion of carbon emissions by industry: (**a**) global carbon emissions in 2020 [11]; (**b**) U.S. carbon emissions in 2020 (data from the U.S. Energy Information Center [12].

This significant contribution makes zero-/low-carbon buildings an essential part of any decarbonization strategy. The World Green Building Council (WorldGBC, London, UK) released the global "Net Zero Carbon Building Commitment", which advocates reducing or offsetting the carbon emissions of buildings and achieving the goal of halving the emissions of the building and construction sector by 2030 [14]. The multi-partner "Zero Carbon Buildings for All" initiative, featured at the 2019 United Nations Climate Action Summit in New York, aims to decarbonize all new buildings by 2030 and all existing buildings by 2050 [15]. These zero-carbon building initiatives have been adopted and promoted by many industry organizations, including the American Institute of Architects (AIA, Washington, DC, USA); the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, Atlanta, GA, USA); the U.S. Green Building Council (USGBC, Washington, DC, USA); the International Living Future Institute (ILFI, Seattle, WA, USA); and many others [16]. These organizations, together with U.S. federal and local governments, have had success in formulating legislation, implementing standards, and applying zero-carbon building practices.

In this context, by reviewing the policies, codes, and standards of zero-carbon buildings (ZCBs) in the United States, this paper intends to summarize the U.S. experience in this area, provide a reference for the decarbonization of buildings in other countries, and contribute to the mitigation of global warming. To serve this purpose, this paper first clarifies the definition and boundaries of ZCBs, and then it introduces policies in Section 2 and the relevant codes, standards, and certifications in Section 3. To better explain the building energy standard framework in the U.S., various federal, local (state/city), and professional society policies, codes, and standards are introduced separately. Highlights are also illustrated for policies, codes, and standards in both Sections 2 and 3. Afterward, in Section 4, the successful experience and lessons learned from the previous review are discussed. Based on that, the paper concludes in Section 5 with suggestions for carbon neutrality policies in other countries' building sectors.

It should be noted that building carbon emissions and building energy consumption are closely related. Although the two concepts are not equivalent, the relevant policies and standards for (net) zero energy consumption also help lead to the achievement of zero-carbon buildings. Therefore, this study, with a focus on (net) zero carbon, also involves the relevant policies and standards of (net) zero energy consumption.

2. Legislations and Policies

2.1. The Definition and Boundaries of Zero-Carbon Buildings

Despite the broad consensus to reduce carbon emissions in the building sector, there is no internationally accepted term or definition for zero-carbon buildings [17]. Many terms are commonly used to describe ZCBs, including zero carbon, net-zero carbon, carbon-neutral, near-zero energy, zero energy, net-zero energy, zero net energy, energy plus, passive house, fossil fuel-free, 100% renewable, and climate-neutral [18,19]. The differences in terms' expressions, meanings, and contexts may reflect evaluation methods and indicators [20], the balance calculation cycle [17], energy use (whether it includes domestic hot water and cooling) [18], plug load [21], whether it involves the energy production of building materials [22], or allowable emission reduction options and condition requirements [20,23].

Among all zero-carbon-building-related concepts, the core difference lies in the elements and boundaries of the energy balance; that is, the time dimension of the calculation cycle and the geographic boundaries of renewable energy acquisition [17]. The time dimension of the calculation cycle may include only the operational phase or be extended to explore the whole building life cycle [24]. The acquisition of renewable energy may be provided directly on-site, such as solar and wind energy integrated with buildings or generated on-site; it may also be provided off-site, such as biomass transported to the site or the purchase of clean electricity [21]. In summary, depending on the temporal dimension of the calculation cycle and the geographic boundaries of renewable energy access, the balance goals sought by zero-carbon buildings can be grouped into four categories (Figure 2): (1) operational carbon and on-site renewable energy balance; (2) the balance of carbon emissions in the whole life cycle (operational carbon + implied carbon) and renewable energy on-site; (3) operational carbon balance with on-site/off-site renewable energy; and (4) the balance of carbon emissions in the whole life cycle (operational carbon + implied carbon) and renewable energy on-/off-site.

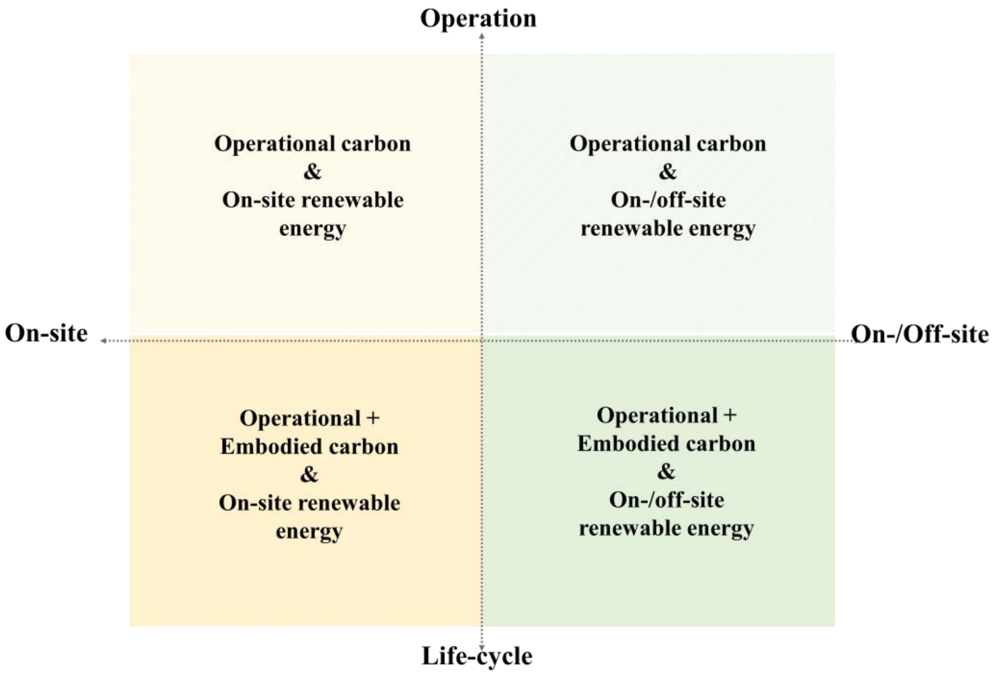

Figure 2. Different expressions of the definition of ZCBs.

The term embodied carbon may refer to materials only or may also include carbon emissions during transportation, construction, and demolition. For example, a zero-carbon building is defined as follows: (1) the balance between energy demand or consumption and new energy generation [17], which belongs to the first category above; (2) the energy embedded in the building's materials and systems during its life cycle is equal to or lower than that produced by the building's in-building renewable energy systems [22], which belongs to the second category; or (3) the flow of energy between facilities [17], which falls into the third or fourth category.

Efforts to promote building energy efficiency and on-site renewable power generation may be undermined by giving too many incentives to off-site renewable power generation, considering the small share of renewable power in the existing grid [21]. Thus, for zero-carbon buildings, currently, more emphasis should be placed on on-site renewable energy than off-site renewable power. On the other hand, as the proportion of renewable energy in the grid increases, the option of an off-site renewable energy power supply will become more common [25].

In addition, the existing literature tends to discuss zero energy together with zero carbon, as carbon emissions are closely related to a building's energy consumption during its operational phase [21]. Both concepts share a similar technical route: both require an energy efficiency improvement in the building itself—including through passive design, the maintenance of structural performance improvements, and efficient equipment—and they both need the generation or purchase of net-zero energy/carbon [16]. However, there are many differences between the concepts of zero energy and zero carbon that involve indicators, units, and the boundaries of the balance [18,19]. The hidden carbon related to the materials and construction/transportation/demolition phases in (net) zero carbon in a full life-cycle calculation is not involved in the assessment of zero energy [26]. In conclusion, zero energy can provide a reference for the realization of zero carbon, but the two concepts should not be mixed.

2.2. Federal Level

At the U.S. federal level, the original form of ZCB policies is related to sustainable buildings (Figure 3). In 1993, as the beginning of the sustainability movement in the U.S., a federal sustainability agenda was established according to Executive Order (EO) 12873, with a focus on eliminating waste and expanding the use of recycled materials [27]. The scope of the agenda was expanded by EO13423: Strengthening Federal Environmental, Energy, and Transportation Management by adding sustainable buildings, renewable energy, environmental management systems, and e-waste recycling [28]. Apart from the agenda, the GreenGov Presidential Leadership Awards were created to recognize exceptional agency and team achievements in net-zero building, electric vehicle fleets, and species conservation [28]. Meanwhile, in 2006, the U.S. Department of Energy (DOE, Washington, DC, USA) and the U.S. National Renewable Energy Laboratory (NREL, Golden, CO, USA) defined four types of zero-energy buildings [29]: net-zero site energy, net-zero source energy, net-zero energy costs, and net-zero energy emissions.

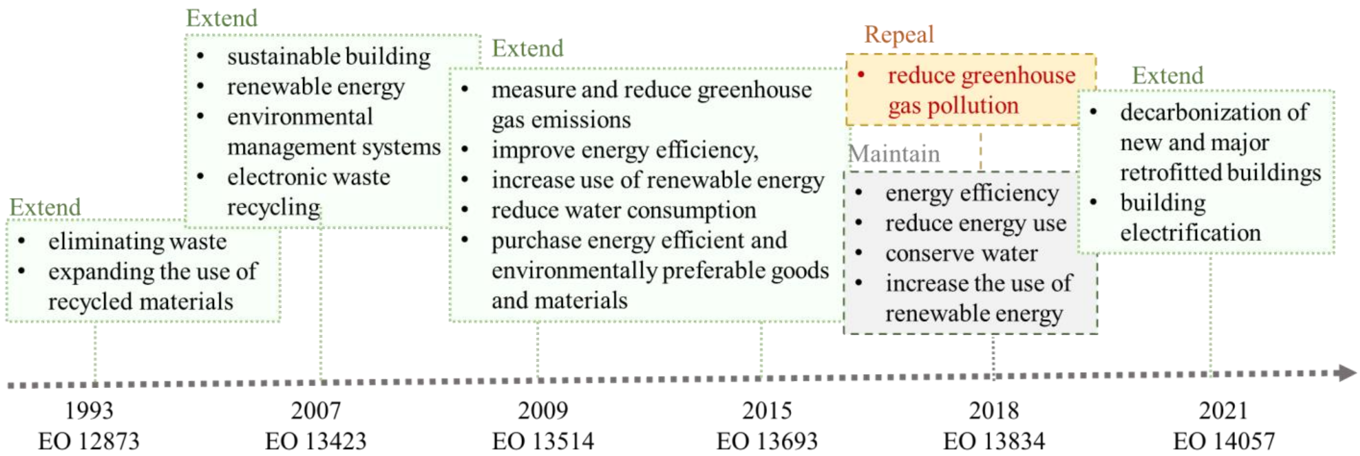

Figure 3. Changes in policies and regulations related to ZCBs in the United States.

The concept of "net-zero energy buildings" was adopted by EO 13514: Federal Leadership in Environmental, Energy, and Economic Performance in 2009 to reduce operational energy, meet the energy demand balance, produce lower net greenhouse gas emissions, and be economically viable throughout the design, construction, and operation of buildings [30]. The policy aims to achieve net-zero energy for all new federal buildings by 2030 [30]. It was superseded in 2015 by EO 13693: Planning for Federal Sustainability the Next Decade [31]. In the same year, the DOE clarified the general definition of a ZEB in the United States: an energy-efficient building with actual annual delivered energy less than or equal to on-site renewable export energy [32]. In 2018, EO 13834: Efficient Federal Operations repealed all requirements to reduce greenhouse gas emissions included in EO 13693. However, it maintained the commitment to energy efficiency and to reducing energy use, conserving water, and increasing renewable energy [33].

When it comes to the Biden administration, the related policy focuses on carbon emissions. In addition to decarbonized power and energy transition, decarbonization strategies for the building sector are listed in Biden's NDC plan [34]: (1) building retrofit programs that support job creation and sustainable affordable housing; (2) the wider use of heat pumps and induction cooktops; (3) the adoption of modern energy codes for new buildings; and (4) support for efficiency upgrades and the high-performance electrification of buildings.

The newly issued EO 14057: Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability, together with the "Federal Sustainability Plan", more specifically describes the relevant policies of building decarbonization and puts forward the goal of achieving net-zero-emission buildings by 2045 [34]. To achieve this goal, the federal government has set a series of policy requirements to promote electrification and reduce energy use in new buildings and major renovations [35]: (1) developing and publishing the first-ever federal building performance standards to improve efficiency and decarbonization; (2) setting key performance benchmarks for different building-type categories, including annual data-driven targets for energy and water reduction by 2030; and (3) using performance contracts to reduce emissions and achieve higher levels of sustainability in federally owned and leased buildings.

On the other hand, policies at the federal level also work to build a circular economy and reduce the federal government's environmental impact for years by focusing on material/product life-cycle sustainability and recycling [36]. Policies such as the Sustainable Materials Management Plan and the National Recycling Strategy of the U.S. Environmental Protection Agency cover a broad range of materials, products, and services in all sectors [36,37]. In addition, the federal government has introduced a "Buy Clean" policy and created a "Buy Clean" task force to identify high-emitting building materials (such as steel or cement), thereby encouraging the use of building materials with lower carbon emissions [7].

2.3. Local Level

At the local level, many states, cities, and counties have developed policies that guide new and existing local buildings to achieve zero carbon/zero energy. Taking California as an example, a net-zero-energy action plan was proposed in 2015 [38]: For new buildings, all residential buildings from 2020 and commercial buildings from 2030 must achieve zero energy. For existing buildings, 50% of commercial buildings will be transformed into zero-energy buildings by 2030, and 50% of the new major national building renovation projects will be zero-energy buildings by 2025 [39].

In 2018, California also passed Senate Bill 100, setting a goal to achieve 100% carbon-free electricity by 2045 and promoting several initiatives: improving the energy efficiency of new and existing buildings, increasing the production of building off-grid carbon technologies, increasing the use of renewable energy, and supporting the transition from fossil fuels [40]. Additionally, California became the first U.S. state to join WorldGBC's global "Net-Zero Carbon Buildings Commitment" [41]. The commitment is to start from the full life cycle of the building through prevention (alternative strategies), reduction and optimization (lean construction processes, the use of low-carbon materials, energy reduction, and energy efficiency), planning (renovation, future adaptation, the potential for recycling, etc.), and compensation (renewable energy balance and compensation for residual emissions).

It also includes other actions to accelerate the market transformation and drive deep collaboration across the value chain, as well as a fundamental shift in the way buildings are designed, constructed, occupied, and deconstructed, thereby advancing net-zero emissions [14]. Los Angeles, San Francisco, San Jose, Santa Monica, New York, and Washington, DC, joined the C40—a network of mayors of world-leading cities collaborating to confront the climate crisis—and have signed on to net-zero-carbon building commitments to achieve net-zero-carbon standards by 2050 for all buildings (old and new) in these cities [42].

In various zero-carbon building policies, the importance of building electrification has been recognized by many research institutions [43]. While the upfront cost of all-electric technology is higher than that of natural gas, it helps to switch from fossil fuels to cleaner energy and is cheaper over the lifespan of the equipment [44]. To this end, California's 2022 Building Energy Efficiency Standard (Energy Code) encourages the use of electric heat pump technology for heating and domestic hot water and establishes electric-ready requirements for single-family homes, enabling homeowners to use cleaner electric heating, cooking, and electric car charging options [45]. Since heat pumps consume a larger share of natural gas use than other appliances (e.g., stoves, water heaters, and clothes dryers), and the combustion of fossil fuels in residential and commercial buildings accounts for 29% of U.S. emissions [43], electric heat pump technology helps to reduce dependence on fossil fuels, thereby reducing carbon emissions [43]. Electric heat pumps are currently used in less than 6% of new home construction in California [45]. It is assumed that heating electrification could lead to a 30–40% reduction in greenhouse gas emissions [43]. While California policy does not mandate a blanket ban on natural gas in new construction, electric heat pumps are the benchmark technology for builders when designing homes that meet state efficiency standards [46]. The efficiency improvement in other parts of the building, such as windows or walls, could compensate for the use of a gas heating system.

Some U.S. cities (such as New York and San Jose) have also begun to pass laws or decrees to prohibit the use of natural gas in new buildings and switch to electric power [47]. For example, the New York City Council approved a measure to ban the use of natural gas for heating and stoves in new buildings [48], which will apply to new buildings under seven stories by the end of 2023 and those more than seven stories in 2027, except for functions such as manufacturing, hospitals, commercial kitchens, and laundromats. The policy will cover heating and cooking for nearly 8.8 million New York residents [47]. Similarly, in San Jose, California, the requirement to ban the use of natural gas in new buildings involves nearly 1 million residents [49]. Of course, phasing out gas-fired boilers and stoves in new buildings is only the first step. Retrofitting older buildings, as well as the electrification of other facilities, remains challenging, and there is still a long way to go before the goal of building electrification—fully electric buildings—is achieved [45]. In California, for example, 50% of single-family homes and 60% of condominiums (representing 14 million residents) were built before the earliest required building energy efficiency standards. Whether this part of the building sector can be updated or not will determine how quickly the state will be able to achieve its energy efficiency and decarbonization goals [45].

In addition to electrification, the integration of renewable energy into buildings is also an important direction for ZCBs. Expanding standards for solar photovoltaic (PV) systems and battery storage is highlighted in California's 2022 Building Energy Efficiency Standard to enable clean energy on-site [50]. This requirement applies to high-rise multifamily residential, hotel, office, medical, retail, catering, school, cultural center, and other building types [45]. California is also pushing some incentives to encourage consumers to install distributed solar PV systems, such as "net metering" rates for solar owners to sell excess electricity to the grid, which can reduce utility bills to eventually balance the cost of installation and other costs. Moreover, the good weather conditions for solar radiation and high utility tariffs in California also make California an ideal place for distributed PV installation. All of these aspects have made California the nation's leader in the solar industry (Figure 4) [50].

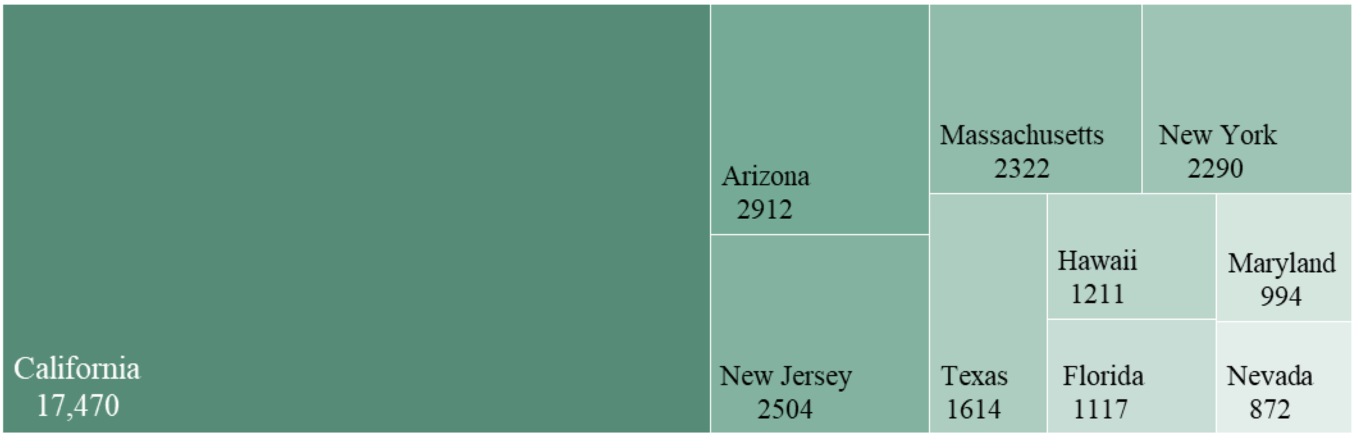

Figure 4. Building distributed solar photovoltaic generation by state in 2020 (in 10^6 kilowatt-hours, adopted from [50]).

In addition, embodied carbon, which includes carbon emitted during the manufacturing and transportation of building materials, cannot be recovered once it is constructed and installed. As a result, "buy clean" policies that focus on low-carbon building materials have been introduced in many states and cities [51]. These policies are assumed to achieve annual emissions reductions of 2 metric tons of carbon dioxide (Mt CO_2) and 10 Mt CO_2 in the United States from public steel procurement using low (10%) and transformative (50%) Buy Clean target scenarios, respectively [51]. The first case of Buy Clean legislation was California's Buy Clean California Act (BCCA), which requires contractors bidding on state infrastructure and construction projects to disclose the emissions of greenhouse gases [52,53]. Colorado passed a similar Buy Clean bill in 2021 [54]. In California, the cities of Los Angeles, Berkeley, Cupertino, and Richmond have all approved the bill as part of a new executive order for ZCBs in the cities [51]. As of January 2020, the city of Portland has required contractors bidding on city construction projects to disclose product-specific environmental product declarations and use them to reduce the greenhouse gas emissions of concrete. In November 2019, Marin County became the first authority to ratify the Low Carbon Code, which adds a low-carbon concrete code to the Marin County Building Code. The code includes compliance with pathways for reducing cement levels or supplementing cement-based products such as fly ash with low emissions [11].

2.4. Policy Highlights

From the U.S. federal level to the local level, ZCB policies involve buildings at the design, construction, and operational phases; renewable energy and clean electricity; building materials production, transportation, and construction; and fiscal policy (Figure 5).

Figure 5. Highlights of policies related to ZCBs.

At the building design, construction, and operational phases, a policy needs to first clarify the definition, goals, and scope of zero-carbon/-energy-consumption buildings within the jurisdiction [38,39]. It also needs to cover the entire life cycle of the building design, construction, operation, and demolition [14,34]. Some policies may focus on improving building energy efficiency and promoting high-performance electrification while setting corresponding benchmarks according to building types [45]. To promote the implementation of zero-carbon strategies, new buildings can be considered as the starting point. Major renovation projects and existing building renovations need to be handled collaboratively [35].

For utilizing renewable energy and clean energy systems, policies can be found on emphasizing the use of end-use energy, supporting the transition from fossil fuels, and guiding or even enforcing the prohibition of the use of natural gas in new buildings [46]. On the other hand, policies can encourage buildings to connect to power grids with a high penetration of clean/renewable energy [11,45]. Furthermore, policies are needed to encourage the on-site provision of clean energy and renewable energy and to expand solar PV systems [50]. Distributed energy storage needs to be promoted, and electric energy storage standards need to be improved [34].

For low-carbon building materials, a special working group was created to conduct pollution assessments for building materials/products (such as steel or cement) and to promote low-carbon building materials/products [51–54].

Fiscal incentives can effectively reduce the cost of renewable energy installation and offset carbon emissions [44], as well as accelerate market transformation and create clean energy employment opportunities. Such incentives can drive deeper collaboration across the value chain [14,35] and eventually improve the economic viability of policies.

3. Relevant Codes and Standards

In the United States, several efforts have been made to promote building code and standard development to meet the requirements of ZCBs. This includes those on both the federal and local levels, as well as those from professional societies.

3.1. Federal Level

At the national level in the United States, the current standards mainly include the International Energy Conservation Code (IECC) (most recent, 2021) [55], ANSI/ASHRAE/IES Standard 90.1: Energy Standards for Buildings Except Low-Rise Residential Buildings (most recent, 2019) [56], and the ANSI/ASHRAE/ICC/USGBC/IES Standard 189.1: Standard for Design of High-Performance Green Buildings (most recent, 2020) [57]. Among them, IECC and Standard 90.1 are the national standards for residential and commercial buildings recognized by the U.S. Congress under the Energy Conservation and Production Act (ECPA) [58]. They are the basis of building energy codes in most states [59].

Both standards are updated every three years. The periodic update of these standards leads to continuously strengthened requirements and technical improvements (Figure 6) [60]. The 2021 IECC version involves the update of energy use requirements for 35 residential buildings, including using high-efficiency lighting, increasing external wall insulation, increasing roof insulation, improving the U-value of doors and windows, and improving the efficiency of mechanical ventilation fans, heat recovery ventilation, and natural lighting (Table 2). Compared with its 2018 version, these new additions can save 9.38% of terminal energy and 8.66% of carbon emissions [61]. As for ASHRAE Standard 90.1, the 2019 version adds 88 supplementary items involving requirements on the design and construction of the building envelope, HVAC, hot water, lighting, and other equipment. It saves 4.7% of terminal energy consumption and 4.2% of carbon emissions compared with the 2016 version of Standard 90.1 [58]. Thus, they lay a technical foundation for the gradual achievement of net zero and guarantee the steady advancement of ZCBs across the United States [62].

Table 2. IECC and ASHRAE 90.1 standard improvements compared to their last versions.

	IECC [55]	**ASHRAE 90.1 [56]**
Update frequency	3 years	3 years
Latest update	2021 version	2019 version
Update	35 requirements	88 supplementary
Content	High-efficiency lighting, external wall insulation, roof insulation, U-value of doors and windows, mechanical ventilation fans, heat recovery ventilation, natural lighting efficiency	Design and construction of building envelope, HVAC, hot water, lighting, other equipment
Improvement	9.38% terminal energy saving 8.66% CO_2 reduction	4.7% terminal energy saving 4.2% CO_2 reduction
Base version	2018 version	2016 version

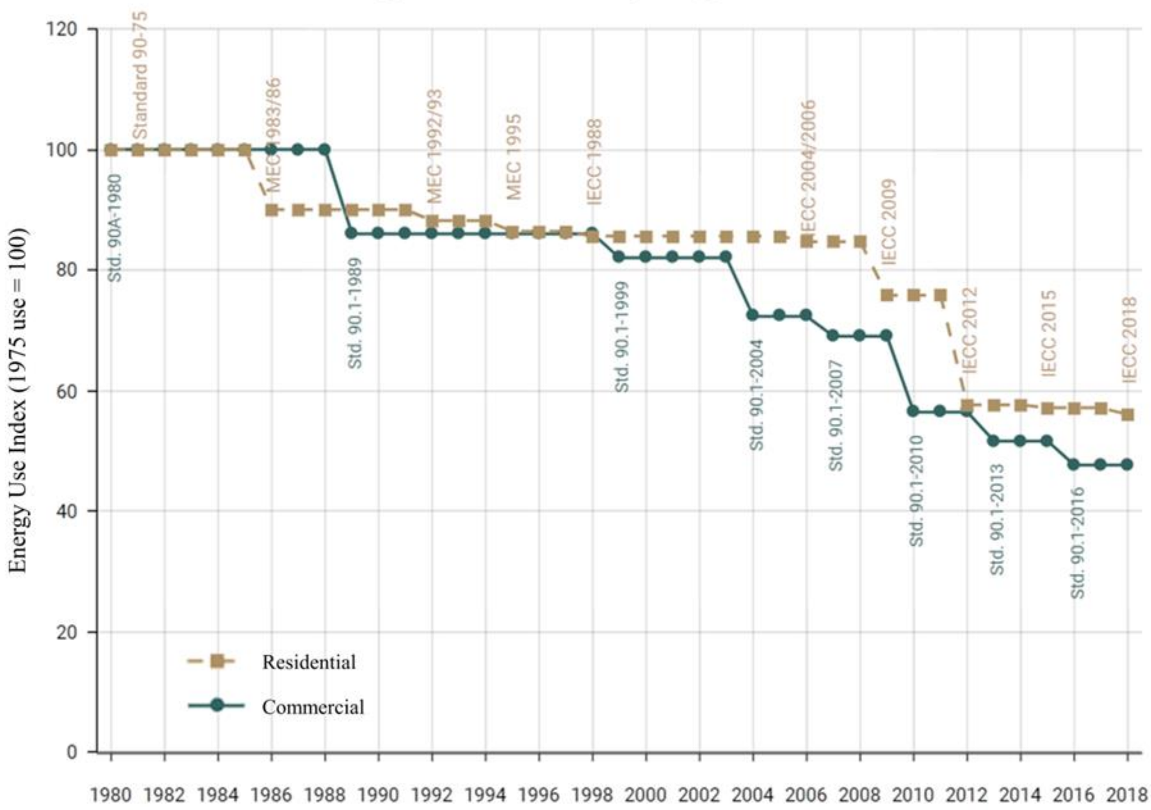

Figure 6. Energy use improvement in commercial and residential standards in the United States from 1975 to 2018 [60].

In addition to these standards, ASHRAE has developed three Advanced Energy Design Guide (AEDG) series—30% Energy Saving (2004–2009) [63], 50% Energy Saving (2011–2015) [64], and Zero Energy Guides (in 2018) [65]—in collaboration with the AIA, the Illuminating Engineering Society (IES, New York, NY, USA), the USGBC, and DOE. These guides provide strategic recommendations for achieving ZCB, including those for a building's design, construction, and operational phases. The AEDG Zero Energy Guides include only two building types: K-12 schools (elementary, middle, and high school) and small to medium office buildings. They adopt the DOE's general definition of the zero-energy building and give the building energy efficiency target for offices and schools without calculating the renewable energy [65]. The AEDG-30% and AEDG-50% series cover more building types: offices, K–12 schools, retail buildings, hospitals and healthcare facilities, highway lodgings, warehouses, and self-storage buildings [63,64]. The design strategy guidance provided in this series aims to increase the energy efficiency requirements by 30% or 50% from the minimum required for buildings in the standard 90.1-1999 or 90.1-2004 edition [63,64]. Together, these series provide different levels and stages of guidance for achieving zero energy consumption.

It should be noted that, with the constant updates of ASHRAE standards, the latest versions of ASHRAE standards 90.1 and 189.1 have exceeded the requirements of AEDG-30% and AEDG-50% [58]. However, the AEDG series was ahead of the ASHRAE standards at that time and played a leading and transitional role in the subsequent update and development of the standards during the process, showing an abstract historical value that cannot be ignored. This way of guiding the next stage of building policy and standard development through the form of guidelines is worth learning from.

Additionally, as mentioned by EO 14057 and the Federal Sustainability Plan in December 2021, a performance standard for federal buildings will be developed and published to establish metrics, goals, and tracking methods for all federal buildings to meet federal carbon emission targets [35]. However, the timetable and specific details for the development of building performance standards have not yet been determined.

3.2. Local Level

According to the Federal Law on Energy Conservation and Production, local codes and standards can be raised according to their conditions based on referencing Standard 90.1 or the IECC to establish local-specific building energy efficiency codes and standards [66,67]. Such a local code or alternative compliance path that partially strengthens/upgrades the local base code to achieve greater levels of energy efficiency is referred to as a "stretch code" [59]. Compared with the baseline, the stretch code has higher requirements for building energy efficiency, but this gap may become smaller or even eliminated with the update of the base code [68]. Therefore, in addition to preventing the basic codes from failing to keep up with the advancement of technology and design practices, strengthening the codes also can help market participants familiarize themselves with future specifications in advance [59], thereby ensuring higher compliance after the adoption of the new mandatory codes [66].

Currently, many local U.S. governments have applied stretch codes (Table 3) [59,66]. Massachusetts, for example, made the Stretch Energy Code an appendix to the state's building code in 2008 [69]. Based on the IECC, the stretch code emphasizes energy performance rather than prescriptive measures [70]. This means that a building complies with the code as long as the energy performance has sufficient efficiency, no matter how it is constructed [70]. Thus, it is a goal-oriented rather than a process-oriented approach.

Table 3. Summary of stretch codes.

	Stretch Energy Code [69]	NYStretch Energy Code [71]	"Reach" Code [72]
Year(s)	2008	2020	2016, 2019
Jurisdiction	Massachusetts State	New York State	Santa Monica city
Improvement	/	10% efficacy	15% less energy
Base standard	2008 Massachusetts Building Code	2020 New York Energy Code	2016 California Energy Code

Similarly, the New York State Energy Research and Development Authority (NYSERDA, Irving, TX, USA) led an effort to develop the NYStretch Energy Code—2020 Version (NYStretch-2020), a voluntary locally adopted stretch energy code that provides municipalities with a more energy-efficient alternative [59], improving the state energy code's efficacy by roughly 10% on average [71]. By accelerating the savings obtained through their local building energy codes, NYStretch-2020 offers a model for New York jurisdictions to meet their energy and climate goals. In addition to state-level governments, municipal-level governments also develop their enhanced codes based on state-level codes [73]. For example, in 2016, the Santa Monica City Council adopted a zero ordinance and stretch code (referred to as a "reach" code) [72] requiring all new single-family homes to use 15% less energy than that mandated by the state under the 2016 California Energy Code [59,72]. They developed a second cycle of the reach code based on the statewide 2019 Building Energy Efficiency Standards, providing two construction options (all-electric and mixed fuel) for builders and developers [74]. Additionally, some states (such as Kansas, Missouri, and Wyoming), although they may have no statewide energy code, allow local governments to adopt and enforce their local codes [75].

Apart from adopting stretch codes, some leading jurisdictions are pushing for zero-energy and zero-carbon goals by developing their energy codes. California is a prime example of this: the California Building Energy Efficiency Standards (Energy Code) was created in 1978 to reduce waste and unnecessary energy consumption in new and existing buildings [76]. Studies have shown that regulations have succeeded in reducing energy consumption: the average house built after 1978 used 8% to 13% less electricity for cooling than similar houses built before 1978 [77]. The Building Energy Efficiency Standards are updated every three years [78]. The 2019 version has improvements in areas such as residential PV systems, facade thermal performance, and nonresidential lighting requirements [79]. Compared with the previous version, the energy consumption of residential and nonresidential buildings would decline by about 53% and 30% respectively, reducing greenhouse gas emissions by 700,000 tons over three years [78].

In addition, the California Green Building Standards Code (known as CALGreen) under Title 24 Part 11 of the California Code is the first mandatory statewide green building code in the United States [80]. The code covers new construction or parts of new construction, additions and alterations, and all occupied nonresidential structures. The International Code Council (ICC, Washington, DC, USA), in partnership with California Building Officials, offers the CALGreen certification exam [80]. In addition to adopting energy use intensity (EUI), some local governments (e.g., Boston and New York) have begun to include annual greenhouse gas emissions as a standard specification for building metrics [81], which will help to align them with carbon emission policy goals (Table 4).

Table 4. Different types of building metrics used by some local governments (adapted from [81]).

Criteria	Cities/States
Annual greenhouse gas emissions	Boston, MA; New York, NY
ENERGY STAR Score	Chula Vista, CA; Washington, D.C.
Weather-normalized on-site EUI	Chula Vista, CA; Denver, CO; Washington State
On-site EUI	St. Louis, MO

3.3. Professional Societies

In addition to official codes and standards, there are many professional society organizations in the United States dedicated to the promotion and certification of ZCBs, such as Architecture 2030, ILFI, and USGBC (Table 5). The certification schemes provided by these organizations have been adopted worldwide.

Table 5. Major aspects involved in ZCB codes and standards.

	ZERO Code [82]	Zero Carbon Standard [83]	LEED Zero [84]
Organization	Architecture 2030	ILFI	USGBC
Metrics	EUI	EUI; CO_{2e}	CO_{2e}
Optional energy/carbon	√	√	√
Embodied carbon		√	
On-site renewable energy	√	√	√
Off-site renewable energy	√	√	√
Carbon offsets		√	√

(1) Architecture 2030 ZERO Code

Architecture 2030 established a ZCB standard (ZERO Code), which defines ZCBs as efficient buildings that use no on-site fossil fuels and produce or procure enough renewable energy to meet the annual energy consumption of the buildings' operations [82]. The code applies to all new commercial buildings, as well as mid-rise and high-rise housing [85]. It combines cost-effective energy efficiency standards with on-site and/or off-site renewable energy to achieve a net-zero target. In terms of energy efficiency, the code requires buildings to first meet the minimum energy efficiency regulations or requirements of ASHRAE or IECC, which are updated with the update of the corresponding standards [85]. Architecture 2030 provides several potential options for the off-site procurement of renewable energy and offers an energy calculator to simplify calculations and provide compliance path assistance [86]. The ZERO Code was included in the 2021 IECC as a voluntary appendix to be adopted by local governments [55,87]. The state of California has now adopted the ZERO $Code_{ca}$ for new commercial, institutional, high-rise residential, and hotel/motel buildings [88]. The specific implementing authority may choose incentives or requirements [88].

ZERO Code$_{ca}$ includes prescriptive and performance paths based on the California Building Energy Efficiency Standard (BEES) and provides the California Building Energy Code Compliance (CBECC-Com) software for calculating building performance to determine compliance with codes [82].

(2) ILFI Zero Carbon Standard

The ILFI Zero Carbon Standard and Certification is a performance-based third-party certification standard that requires 100% of the operational energy use associated with the project to be offset by new on-site or off-site renewable energy and 100% of the embodied carbon impact associated with the project structure and materials to be disclosed and offset [83,89]. The standard is based on actual measurements rather than on modeling or expected performance. As a result, projects must demonstrate actual net-zero carbon by performing against established efficiency targets and be aligned with their stated function over a 12-month performance period of operation [89]. The energy efficiency target of the project should meet the local zero-carbon efficiency target. In the absence of a local target, new buildings (projects whose design and development began after the standard's creation date of 10 April 2018) shall have a 25% reduction in EUI from an equivalent new building compliant with ASHRAE 90.1-2010. Existing buildings (projects whose design and development began before the standard's creation date of 10 April 2018) should have a 30% lower EUI than a typical existing building of the same type, size, and location [89]. In addition, new construction projects must not burn natural gas.

Another feature of ILFI Zero Carbon is that it is for both operational and embodied carbon [83,89]. The project is required to calculate the total embodied carbon emissions of the project using an approved life-cycle assessment (LCA) tool, including the impact of each final building material and process associated with the foundation, structure, enclosure, and interior [24,90,91]. New projects must demonstrate (1) a reduction of at least 10% in the carbon footprint implied by the primary materials compared to a baseline scenario and (2) that the project's total carbon footprint emissions do not exceed 500 kg (kg) of carbon dioxide equivalent per square meter (CO_2 eq/m^2) [89]. One-time carbon offsets of the total embodied carbon should be obtained from approved sources [92]. Acceptable forms of carbon offsets include certified emission reductions and verified emission reduction carbon credits; however, renewable energy certificates are not accepted. Carbon offsets must be certified by Green-e Climate or an equivalent program. Green-e is a certification of clean energy and carbon offset that businesses and individuals can reference to purchase verified clean energy with confidence and that consumers can rely on to choose sustainable products and services [93].

(3) USGBC LEED Zero

Developed by USGBC, the Leadership in Energy and Environmental Design (LEED) Zero (zero carbon, zero energy, zero water, and zero waste) building certification complements the LEED certification series to verify the achievement of net-zero goals in buildings [84]. All LEED Zero certifications (whether zero carbon or zero energy) require all projects to be first certified by LEED Building Design and Construction (BD + C) or LEED Operations and Maintenance (O + M) and provide the required 12-month performance data [94]. LEED zero-carbon certification confirms net-zero carbon emissions from energy consumption by avoiding or offsetting carbon emissions within 12 months, while LEED zero energy identifies the balance of source energy use within 12 months [93]. The carbon balance of LEED zero-carbon certification is calculated as:

$$\text{Carbon Balance} = \text{Total Carbon Emitted} - \text{Total Carbon Avoided}$$

The *total carbon emitted* refers to the energy consumption of the building and the carbon emissions generated by the power grid using fossil fuels to generate electricity and transmit it to the site. The equivalent greenhouse gas emissions are converted from electricity/fuel consumption and transport using the U.S. Environmental Protection Agency's (EPA, Washington, DC, USA) subregional grid mix coefficients for U.S. and Canadian projects [95]. The embodied carbon of water, waste, and materials is not included.

LEED Zero also pays attention to avoiding carbon emissions when on-site-generated energy is exported to the grid [93]. The carbon reduction effect will be reduced when a building exports excess on-site solar energy to a grid that already has considerable renewable energy. Conversely, a greater carbon reduction effect can be produced if the building has both on-site solar production and storage, as the excess electricity can be sent to the grid when the generated electricity is from fossil-fuel outputs [95]. Some jurisdictions in the United States currently have LEED certification (mainly BD + C or O + M) as the standard for new buildings, but the LEED Zero certification is still being explored and updated.

To sum up, all three codes and standards cover operational energy/carbon with requirements on disclosure and energy efficiency, while only ILFI Zero Carbon considers the disclosure and thresholds of embodied carbon (Table 5). Moreover, on-site and off-site renewable energy is suggested in all three codes and standards, including the form of the community renewable solar energy investment fund, self-owned off-site renewable energy certificates, green electricity pricing, and utility renewable energy contracts. On the other hand, carbon offsets with Green-e Climate certification or equivalent are recommended in ILFI Zero Carbon and LEED Zero but are not involved in the Architecture 2030 ZERO Code, since it focuses on energy instead of carbon.

3.4. Highlights for Codes and Standards

In the United States, codes and standards are developed with collaboration at the federal, local, and professional society levels to promote ZCBs (Figure 7). Federal-level standards offer good energy and carbon performance references that could be adopted by localities and professional societies to form local codes or voluntary professional standards [59]. Local-level codes set the minimum requirements for compliance in jurisdictions. They may set higher building performance targets, leading to the next stage of the federal-level standard update [66]. Professional societies serve as pioneers in promoting ZCBs, providing aggressive but voluntary standards and certifications with specific measures, calculation methods, and tools [94]. They provide market guidance and a driving force for the update and implementation of regulatory policies at both the federal and local levels [62]. Professional standards and certifications are partly referenced by codes and regulations [66].

Collaboration also occurs among different types of codes and standards [82,88]. Voluntary zero-energy or -carbon standards are developed to help design zero-carbon buildings beyond the existing code and standard requirements [59]. Technical standards at the national level or professional society level also provide methodologies for high-performance building system testing, performance validation, and common practices to retrofit existing buildings. The development of building codes has transformed from checking prescriptive measure compliance to whole-building compliance to, more recently, actual building operation performance compliance [82,89]. In short, the collaboration system and the periodic update of codes and standards accelerate the pace of energy saving and carbon reduction.

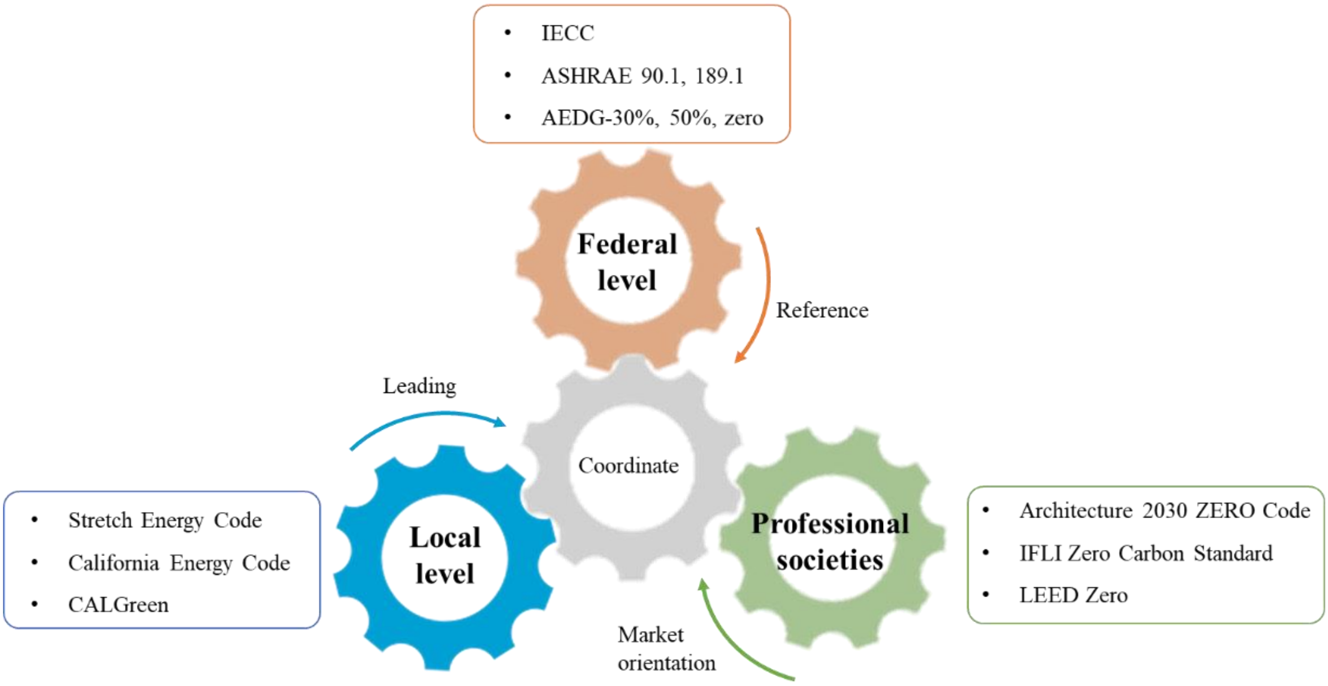

Figure 7. Relationship between ZCB-related codes and standards in the United States.

4. Discussion

4.1. Successful Experience

4.1.1. System Work: Multilevel Governance

As a branch of the global climate issue, the work to achieve ZCB targets involves a complex, multilevel context with a wide array of actors and multiple levels of governance [96]. The concept of multilevel governance (MLG), originally used for the EU governance structure, describes the dynamic interrelationship within and between different levels: the global level, world regions, the national level, the provincial/state level, the city level, local rural communities, and the micro-level of individuals [97]. Such multilevel systems present opportunities for activists: inaction at one level need not stymie progress at another [98]. Take the United States, for example: while on the federal level, attempts to pass binding and comprehensive climate legislation have stalled, thwarted by a trenchant partisan divide [98], the state and city levels feature some vibrant and varied activities. This includes mayoral leadership initiatives, the adoption of climate registries, the diffusion of renewable portfolio standards, legislation with binding carbon emission caps, and regional cooperation on carbon trading [99,100]. According to Derthick, this is called "compensatory federalism"—whereby subnational entities compensate for a lack of meaningful federal action [101]. The smaller the scale of governance, the more similarity between contexts, making it much easier to achieve progress in ZCB targets [97]. Thus, by setting the network between multiple levels, countries have more opportunities to efficiently promote ZCB policies.

4.1.2. Code Enforcement

Developing strong legislation with clearly defined codes and standards is a fundamental way to support ZCB development [102]. While many developed economies, such as the United States and EU countries, have proposed goals and policies for ZCBs [103,104], many developing countries—especially in hot and humid climates—only have demonstration cases, with no clear policies, codes, or standards on the national or local levels [105]. As the urbanization rates of these developing economies rise, more buildings will be constructed with higher requirements for comfortable indoor environments, which will inevitably increase building energy demand and carbon emissions [87].

Meanwhile, differences occur between ZCB definitions worldwide. For example, compared to EU countries and China, the United States defines a broader end use and allows the purchase of renewable energy [106]. Such differences in codes may affect the invention and adoption of advanced techniques [105]. Thus, ZCB policy actions—especially stringent ZCB codes and standards with a clearly defined ZCB concept and boundaries—need to be enacted in the short term for these countries, because buildings constructed now will be consuming energy for many decades [87,105].

4.1.3. Code Compliance

Although countries need to act as soon as possible, they cannot achieve the zero target at once [105]. Multistep codes and standards with different decarbonization levels and continuous upgrades of building codes can gradually help countries achieve their final target. Multistep codes and standards with higher goals (e.g., stretch codes, AEDG-30%, AEDG-50%, and zero-carbon series) can perform as pilots and lead the transformation of the building sector [63,64,66]. In the United States, most building codes are upgraded every three years at both the national and local levels to strengthen requirements step by step [58,107]. This enables the market to gradually adapt to more stringent requirements and thus improve the policy's feasibility [62]. On the other hand, according to Zhang et al., if building energy code requirements are not upgraded, building demand in Asia-Pacific Economic Cooperation (APEC) countries will continue to increase, with no peak before 2050 [87]. This proves that steady advancements in codes and standards are needed to reach net-zero goals in the long term.

4.1.4. Information Transparency

The transparency of ZCB-related information and data is beneficial to supporting informed decision making and building market demand [108]. With this information and data, researchers can analyze national building carbon emission performance, illustrate more accurate and cost-effective ZCB measurement models and tools, predict scenarios and risks for future development, and develop strategies, techniques, and innovations [109,110]. By using the scientific results of the collected information (e.g., predictive models/tools and advanced building technology), the government can partner with businesses to achieve significant strides in energy efficiency [111,112]. It also drives demand for performance that exceeds code requirements (e.g., super-efficient equipment and passive or ultra-low-energy buildings) and directly incentivizes building efficiency retrofits [108,113]. Currently, institutions such as the Energy Information Administration (EIA) and USGBC in the United States have formed open databases collecting the basic information and performance data of new building projects. For many developing countries, such databases for the building sector are rarely seen, or are at least not transparent.

4.1.5. Financial Support and Market Forces

To some extent, ZCB problems can be described as economic issues [98]. Take the United States, for example: ZCB policies generally embrace a mix of regulatory and voluntary approaches and avoid explicit carbon taxation [114]. Many of these policies have attempted to minimize costs and accentuated the anticipated combination of environmental and economic development benefits [114].

To ensure the wider adoption of ZCBs, the market should be cultivated on a societal scale, not only by standards but also through incentives and capacity-building policies [105]. This includes financial support for innovations that increase efficiency, significantly reduce costs, and increase the utilization of clean energy in the building sector [108]. With financial incentives, building owners could overcome the high incremental upfront costs [105]. Additionally, increasing financing and investment opportunities could stimulate behavioral changes and stakeholder demand for efficiency [108]. It could also increase sales, drive innovation, and thus facilitate societal ZCB adoption [115]. Market forces, together with financial support, are important to achieve long-term ZCB goals.

4.2. Lessons Learned

4.2.1. Metric Choice and Embodied Carbon Involvement in ZCB Codes

While most countries have set decarbonization goals, the metrics in codes focus mainly on energy demand and consumption instead of carbon emissions [26]. This may help emphasize energy efficiency, since a building can use more energy but achieve carbon neutrality by applying more clean energy [21]. However, such gaps between metric applications and goals may be misleading. To fill this gap, some professional societies offer carbon-metric-related standards that may be referenced or applied at the local level (e.g., ZERO Code$_{ca}$) but with different means of calculation (e.g., IFLI Zero Carbon Standard versus LEED zero carbon) [116]. Thus, the metrics for ZCBs need to be clearly defined in mandates and reach a consensus at the national level.

On the other hand, the policies and standards of ZCBs tend to address more operational carbon and define less embodied carbon. There are existing policy efforts focused on the material level (e.g., specifying materials with low embodied carbon and requiring the disclosure of environmental impacts) [26]. However, the perspectives on LCA building performance—especially the trade-offs between embodied carbon and operational carbon emissions—have not yet been defined or integrated into any mandates in the United States, although voluntary activities have been conducted [117]. Corresponding efforts to reduce embodied energy and carbon from building construction materials must be pursued to achieve the building sector's decarbonization goals [26].

4.2.2. Embodied Carbon Data Tracking and Benchmarking (Tools, Measurement, and Guidance)

Generally, obtaining complete sets of LCA data is by far the biggest barrier to benchmarking ZCBs, especially when considering embodied carbon [118]. Compared to building operational carbon, embodied carbon tracking requires upstream data collection and downstream data calculation [26]. Specifically, it includes the means, processes, procedures, tools, and capabilities to collect, process, report, transparently communicate, and validate data [24,90]. Existing data are primarily at the material level and focus on the manufacturing process, while the data for transport, construction, and product durability are currently missing in many databases [26].

To fill this knowledge gap, a consensus on an embodied carbon baseline or benchmark is needed [116]. Relying on the self-assessment and reporting of building products from manufacturers alone cannot provide an accurate assessment of a building's embodied carbon [26]. The public accessibility of building-level LCA data needs to be improved. To ensure comparable inputs and outputs, methodological guidance with reference cases for database standardization and whole-building-level LCA tools embedded in building design software is needed [89,119].

4.2.3. Individual Involvement and Education

As part of the MLG system, individual involvement (the micro level) has a strong impact on societal ZCB adoption and promotion through activities such as switching electricity suppliers or taking part in consumer boycotts or internet campaigns [120]. The private ownership of small solar power installations in California could be a good example. However, individual involvement could be restricted because the intervention of individuals comes later in the chain of causation of climate problems, because consumers act at the final stage of the value chain [97]. Meanwhile, split incentives occur; for example, the person who builds or owns a newly constructed building may not be the one who installs the most energy-efficient appliances or pays the energy bill. Thus, lower upfront costs tend to be favored, despite the net lifetime savings through greater energy efficiency [44].

To enhance individual involvement, incentives and education should be provided, with more specific measurement and documentation of ZCB savings, including both the energy and non-energy benefits (such as indoor air quality and occupant productivity) [105]. Meanwhile, barriers remain in the personal capacity of ZCB design, construction, operation, and management [105]. Developing and enhancing the capability of those key stakeholders (e.g., manufacturers, builders, and owners) to collect and report data would benefit embodied carbon data collection and eventually help support the development of LCA guidelines and standards for ZCBs. Moreover, setting up business cases and identifying the best cases are essential steps to building the knowledge infrastructure for manufacturers and house owners [26].

5. Conclusions and Recommendations

Policy advancement is critical to promote zero-carbon buildings in societies. Experience learned from ZCB policies, codes, and standards in the United States can serve as good references for developing zero-carbon roadmaps in other countries. Based on the policy aspects (regulations, codes, and standards) and the characteristics of the multilevel governance system (federal, local, and professional society levels) in the United States, this review offers an overall grasp of the whole picture of U.S. ZCB policies and contributes to the mitigation of global warming.

This review's analysis highlighted the importance of coordination among building construction industries, energy systems, materials production, and government fiscal incentives in order to achieve a zero-carbon building sector. Successful practices such as building energy efficiency, the electrification of building energy demand, on-site renewable energy deployment, and "buy clean" building materials were summarized. The synergic efforts of coordination among different levels of government and professional societies were also introduced. Successful experiences in zero-carbon standards and policies were summarized, such as code compliance and enforcement, information transparency, financial support, and market development. Based on the analysis, the following recommendations are summarized to develop zero-carbon building policies:

First, it is recommended to establish synergic cross-sector targets and roadmaps for zero-carbon building life-cycle development. Setting building sector carbon emission targets is crucial for specifying the system boundaries for the short-, medium-, and long-term development of zero carbon. Specific goals and roadmaps to decarbonize new and existing buildings should be set up in conjunction with overall social decarbonization involving industry, transportation, and clean power sector development. Policy design should consider the building's life-cycle performance, including embodied carbon, the electrification of building end-use energy, and the application of on-site renewable energy.

Second, carbon-index-oriented codes are better, and continuous upgrading is recommended, with advanced standards leading the way. Codes and standards are essential to guide building energy efficiency and decarbonization. The approaches of codes and standards should be gradually converted from the existing energy consumption evaluation-oriented model to a carbon emission index-oriented one, but with a constant emphasis on building energy efficiency improvement. A steady check on and adjustment of codes is recommended to keep up to date with the increased coordination of standards, certifications, and green building evaluation systems.

Third, the information transparency of embodied carbon emissions needs to be increased. For LCA measurement quantification and database standardization, the baseline, benchmark, and example cases should first be provided. Public access to carbon emission data needs to be increased for major building materials such as steel, cement, aluminum, and glass. Data channels need to be developed for carbon emissions from the production, consumption, and transportation of building materials. The establishment of an environmental product declaration (EPD) system could efficiently disclose the carbon emission data of major building material products.

Lastly, it is recommended to increase market guidance and individual engagement with education, technology market penetration, and financial incentives. To better promote zero-carbon buildings, a good social atmosphere and market environment need to be formed. The green/zero-carbon building certifications offered by third-party organizations should be encouraged to guide and enhance awareness among stakeholders.

The industrial chain needs to be upgraded with the market penetration of technology relating to carbon-simulation-based design-aid tools, affordable end-use electrification, integrated on-site renewable energy, clean material/product manufacturing, and carbon absorptance/replacement. Financial incentives are also needed to overcome the obstacle of upfront costs and to create more job opportunities.

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