Journal of Environmental & Earth Sciences
https://journals.bilpubgroup.com/index.php/jees

REVIEW

Low-Carbon Building Codes and Standards: Comparative Evaluation of Global Regulatory Frameworks and Their Environmental Impacts

Haibo Lu, Zhanpo Yuan* *, *Xiaoming Zhang

Logistics Management Office (Infrastructure Construction Office), TianGong University, Tianjin 300387, China

ABSTRACT

The construction industry contributes a considerable portion of the world's energy demand and emissions of greenhouse gases; therefore, it is an important area where efforts should be directed in reducing the climate change. Building codes and standards. Low-carbon building codes and standards have become major controlling tools with the aim of enhancing building performance and minimizing environmental impacts. This review offers a comparative analysis of key low-carbon building codes and standards across the world, how they are designed, how they are implemented, and what environmental impacts they report. Both the mandatory building codes and voluntary standards are taken into consideration in both mature and developing areas with varied climates, economic, and institutional backgrounds. The analysis draws out the significant difference in regulatory strategies, such as prescriptive and performance-based models, disparities in implementation capacity, and uneven adoption of carbon-based and life-cycle performance indicators. Literature evidence suggests that reinforced building codes have provided substantial operational energy consumption and emissions containment, especially where a robust compliance system is in place. Voluntary standards tend to show a better level of performance, but are restricted by the market coverage. With the decarbonization of electricity systems, the proportion of embodied carbon and life-cycle emissions becomes significant, and the drawbacks of the existing regulatory frameworks, which continue to emphasize mainly operational energy efficiency, can be seen. The review provides such methodological issues in the evaluation of environmental effectiveness as the use of ex-ante modeling and a lack of post-occupancy data. It concludes with policy implications and further suggestions for improving the low-carbon building regulation through life-cycle-

*CORRESPONDING AUTHOR:
Zhanpo Yuan, Logistics Management Office (Infrastructure Construction Office), TianGong University, Tianjin 300387, China;
Email: hb79123@163.com

ARTICLE INFO
Received: 6 March 2026 | Revised: 20 June 2026 | Accepted: 25 June 2026 | Published Online: 19 August 2026
DOI: https://doi.org/10.30564/jees.v8i8.13269

CITATION
Lu, H., Yuan, Z., Zhang, X., 2026. Low-Carbon Building Codes and Standards: Comparative Evaluation of Global Regulatory Frameworks and Their Environmental Impacts. Journal of Environmental & Earth Sciences. 8(8): 1061–1073. DOI: https://doi.org/10.30564/jees.v8i8.13269

oriented metrics, enhanced enforcement, and the exchange of international knowledge.

Keywords: Low-Carbon Buildings; Building Codes; Energy Efficiency; Carbon Emissions; Regulatory Frameworks

1. Introduction

The construction industry is a key participant in the world in the quest to reduce climate change, considering it comprises a significant portion of the total energy use and greenhouse gas (GHG) emissions internationally [1,2]. International analyses indicate that buildings contribute about one-third of the total final energy consumption and a similar percentage of the energy-related carbon dioxide emissions in the world when the operational and construction-related effects are taken into account [3]. The fast urbanization and population growth, as well as the improvement of living standards, especially in the emerging economies, will further put pressure on energy consumption by buildings in the next few decades. It is in this context that a redesign of regulation structures that define building design, construction, and operation has emerged as a key strategy of attaining national and world climate targets.

Building codes and standards that focus on low carbon have become one of the best policy tools to guide the building industry towards low energy consumption and carbon emissions [4,5]. These regulatory tools can affect decisions that are made at the earliest building life cycle stage, and long-term environmental effects are formed mostly by establishing minimum levels of performance or encouraging best practices. Compared to retrofit-oriented policies, building codes and standards are especially effective as a source of climate mitigation because they can ensure decades of energy and carbon savings. Consequently, governments in the global arena have increasingly tightened building energy requirements, created performance metrics with a carbon focus, and advanced voluntary green building criteria to support the mandatory requirements.

Although all aim at minimizing environmental impacts, the low-carbon building codes and standards in different regions are different in their regulatory design, technical scope, and implementation mechanisms. In other jurisdictions, e.g., European Union, building standards are linked to long-term decarbonization strategies and focus on performance-based standards, including almost zero-energy building goals. In other countries, especially in the developing and emerging economies, codes might prioritize the slow gains in energy efficiency and put them into practice without certain difficulties regarding enforcement capabilities and market preparedness. Voluntary requirements like green building certification programs also contribute to this heterogeneity since they bring market-based methods that usually extend beyond minimum regulatory expectations. This heterogeneity makes it difficult to determine the effectiveness of low-carbon building regulations in general and to determine best practices that can be transferred [6,7].

Another complexity is caused by the changing meaning of the low-carbon performance of the building sector. Conventionally, the building codes have been more oriented toward operational energy efficiency, which covers the areas of thermal insulation, heating and cooling, and lamp performance. Nevertheless, increasing awareness of the importance of embodied carbon, the emissions related to the manufacture, distribution, construction, and other end-of-life processes of building materials, has led to a progressive increase in regulatory coverage in certain areas. Although few jurisdictions have started to implement life-cycle assessment methods or embodied carbon limit-setting in building standards, these and other approaches are not well-adopted and, in many cases, do not feature in compulsory codes. This raises exquisite concerns about the fullness and viability of current frameworks of low-carbon buildings in the long term [8,9].

The methodological difficulties about building code and building standards are also about the evaluation of the environmental impacts of design. A modeling study, compliance simulation, or post-occupancy evaluation with different assumptions and system boundaries is usually used to provide empirical evidence on actual energy saving and emission reduction. The disparity in their climatic conditions, types of buildings, and the use of buildings also makes cross-regional comparisons difficult. In addition, although numerous papers have documented high potential energy savings and carbon pollution that can be ascribed to tighter codes, few have offered a strong ex-post analysis of actual performance.

Consequently, how much low-carbon building regulations achieve their desired environmental dividend is a research and debate concern [10,11].

The literature has looked at individual national or regional building codes, individual green building standards, or individual technical measures that seek to enhance building performance. Nevertheless, detailed comparative reviews that critically assess the building regulatory frameworks worldwide, as well as the environmental impacts they have recorded, are few. Specifically, it has a lack of synthesis that brings together regulatory design characteristics, implementation settings, and evidence of empirical impact under one analytical framework. This kind of review is fundamental to the discovery of effectiveness trends, contextual dependence, and to the subsequent development of regulations on building policies in line with the more and more ambitious climate targets [12,13].

To address these gaps, the proposed review article is a comparative assessment of significant low-carbon building codes and standards across the world, considering their regulatory nature and environmental performance. The review covers both the compulsory building energy and carbon codes and those that are popular as voluntary standards in the developed and developing areas. The article attempts to determine how regulatory design impacts environmental performance by analyzing the differences in stringency, scope, compliance mechanisms, and carbon coverage. Moreover, the empirical data regarding energy conservation and GHG emission cuts are integrated to determine the efficiency of these frameworks in various climatic, economic, and institutional scenarios [14–16].

This review has threefold objectives. The first one is to chart the low-carbon building codes and standards around the world and showcase some major similarities and differences between major regulatory approaches. Second, it reviews the environmental effects that are mentioned in the literature and defines both successes and shortcomings of the current evaluation methods. Third, it explains the implications to policymakers and researchers, such as an opportunity to make regulations more ambitious, increase enforcement, and become more life-cycle carbon conscious. It is in this comparative view that the article attempts to make a contribution to the current debate on how building regulations can better aid the transition towards a low-carbon built environment [4,17,18].

This review distinguishes itself from previous syntheses in three key respects. First, while existing reviews have largely focused on specific regions (e.g., Li et al. [17] on China, Yu et al. [19] on the US) or isolated technical dimensions (e.g., Enker and Morrison [4] on transition effects, Lu et al. [20] on non-compliance), the present study offers a systematic cross-regional comparison that includes both mature and developing economies under varying climatic, economic, and institutional conditions. Second, unlike prior work that treats regulatory design and environmental outcomes separately, we explicitly link regulatory features (prescriptive vs. performance-based, carbon coverage, enforcement mechanisms) to reported empirical impacts, including operational and emerging life-cycle considerations. Third, we address a critical and rapidly evolving gap, the shift from operational to embodied carbon as electricity grids decarbonize, which has not been systematically integrated in earlier comparative reviews. Collectively, these elements provide a novel contribution to the literature on low-carbon building regulation.

2. Overview of Major Low-Carbon Building Codes and Standards

The building codes and standards Low-carbon building codes and standards, represent a wide range of regulatory and quasi-regulatory tools that are intended to minimize energy use and greenhouse gas emissions throughout the building life cycle [4,5]. These frameworks have vastly different scopes, legal status, and technical focus, but tend to drive building performance by minimum requirement, performance objectives, or incentive-based means. In a global sense, the low-carbon building regulations can be generally interpreted in terms of their regulatory nature, the nature of their regions, and the technical aspects to which they are addressing. This part gives a summary of these frameworks in order to have a point of reference to make further comparative assessments. Examples of building codes and standards representative of low-carbon building codes in different regions of the world differ in terms of type, focus, and legal status, as summarized in **Table 1**.

Table 1. Representative low-carbon building codes and standards across regions, including type, primary focus, and legal status.

Region	Regulatory Framework	Type	Primary Focus	Legal Status
North America	IECC	Building code	Operational energy efficiency	Mandatory (adopted locally)
North America	ASHRAE 90.1	Technical standard	Energy performance	Mandatory/Referenced
Europe	EPBD (EU)	Directive	Nearly zero-energy buildings	Mandatory
Europe	National NZEB codes	Building codes	Energy and carbon performance	Mandatory
China	Building Energy Codes	Building codes	Climate-zone-based efficiency	Mandatory
Japan	Building Energy Efficiency Act	Building standard	Performance evaluation	Mandatory
Global	LEED	Green building standard	Energy, carbon, sustainability	Voluntary
Global	BREEAM	Green building standard	Environmental performance	Voluntary

2.1. Mandatory Building Codes and Voluntary Standards

One of the main differences between low-carbon building schemes is the difference between the mandatory building codes and the voluntary standards [20,21]. Mandatory codes are regulations that are legally binding and embraced by governments in the country or sub-country, and usually define the minimum acceptable energy efficiency, thermal performance, and system efficiency. Building permits and occupancy approvals usually need compliance with these codes, such that they become one of the key tools to realizing baseline improvements throughout the building stock. Most jurisdictions have, over time, increasingly increased these requirements, with an expansion in building technologies and growing policy ambition in dealing with climate mitigation.

Conversely, voluntary standards and certification systems are market-driven tools that co-exist with mandatory codes [22]. These frameworks are usually created by industry organizations or non-governmental organizations and promote greater levels of environmental performance through issuing certification, recognition, or in terms of market differentiation. Voluntary standards often cover more of the criteria of sustainability, such as energy efficiency, carbon emissions, water consumption, materials, and indoor environmental quality. Although these standards are not legally obligatory, they can have a strong impact on the market demands, the policy of public procurement, and correspond to the corporate sustainability objectives. Voluntary standards have also been used in various areas as an experimental ground for new performance measures that are subsequently used to create compulsory standards.

2.2. Regional Characteristics of Low-Carbon Building Frameworks

Low-carbon building codes/standards have been designed and implemented differently in different regions depending on the climate conditions, economic development, institutional capacity, and priorities of policy. The building energy regulation in North America is typified by the use of model codes and standards, which are adopted and adapted by the states or local jurisdictions. Traditionally, these frameworks have focused on energy efficiency via prescriptive and performance-based routes, and more recent versions have been adding more measures to carbon emissions and grid interaction. The region has also been promoted in the use of high-performance buildings in voluntary certification systems [17,19].

Supranational policy efforts and long-term goals have been important influences on low-carbon building regulation in Europe. The regulatory environment has focused on performance-based requirements and has gradually shifted to almost zero-energy building concepts in new construction. European building standards tend to be more holistic in their assessment, most often incorporating standardized calculation processes and benchmarking, which allow comparability and enforcement between member states. There has been a movement as well towards life-cycle-oriented regulation, with many countries starting to consider regulatory strategies specifically based on embodied carbon [23,24].

There is a great diversity in building structures across the Asia-Pacific region with low carbon. Other developed economies like Japan and South Korea have introduced advanced building energy standards which lay focus on performance assessment and ongoing enhancement. There is a multi-level system of building energy codes that China has come up with, depending on the climate region and type of building, which is backed by the national policy goals in the areas of energy security and reduction of emissions. Most economic urbanization processes in the rapidly urbanizing countries have building codes geared towards enhancing baseline efficiency whilst keeping affordability and building capacity at par, which is more incremental than transformative regulation [25–27].

The implementation and application of low-carbon building codes are not evenly spread in developing areas such as parts of Africa, Latin America, and South Asia. Although some countries have established building energy policies or voluntary green building policies, institutional capacity, compliance monitoring, and informal building are some of the issues that limit the extent to which they work. This notwithstanding, the spread of building energy codes and the localization of global best practices have been growing with the support of international cooperation programs and development efforts [28,29].

2.3. Technical Scope and Performance Dimensions

The low-carbon building codes and standards vary not only in their regulation form and their location but also in the technical aspects on which they focus. Historically, the majority of frameworks have concentrated on the operational energy efficiency, which strives to meet the building envelope performance, heating, cooling, lighting, and equipment energy efficiency. These actions will help cut the energy requirement at the utilization period of structures, which has been recorded to contribute the greatest proportion of life-cycle emissions [30].

The more recent developments in regulation have broadened this to cover more dimensions that are pertinent to mitigating carbon. Inclusion of renewable energy systems on-site, demand-side management abilities, and electrification of building services are now encouraged or mandated by some codes and standards. Whole-building energy or carbon measures are becoming more popular as the foundation of performance-based approaches without compromising environmental goals. Meanwhile, voluntary standards have been on the leading edge in regard to the implementation of life-cycle assessment practices to consider the embodied carbon of materials and processes used in construction [31,32].

Although these have been made, the incorporation of life-cycle carbon considerations into mandatory building codes is not widespread globally. In the case of embodied carbon, it is typically done in the form of reporting requirements, benchmarking, or pilot programs as opposed to compulsory limits. This disproportionate technical scope stresses that present building regulations on low-carbon are transitional and emphasize that more comprehensive strategies are required, which would consider both operational and embodied emissions [33].

2.4. Evolution and Convergence of Regulatory Approaches

Building codes and standards on low-carbon buildings are not fixed tools, but they change through the advancement of technology, transformation of the market, and learning about policies. Several jurisdictions have, over time, moved beyond prescriptive requirements to performance-based, or result-oriented regulation, which is the desire to promote innovation and, at the same time, deliver quantifiable environmental advantages. Voluntary standards have frequently been a catalyst to this movement through proving the validity of higher performance goals and more inclusive sustainability measures [34,35].

On the international level, gradual convergence in regulatory practices can also be observed as a result of international climate commitments, knowledge sharing, and harmonization. Some of the prevailing trends are the rising energy performance requirements, the rising importance of carbon measures, and the recognition of life-cycle impacts. Nonetheless, there remains a substantial disparity regarding the ambition, capacity, and market preparedness related to the regulation. It is necessary to understand these similarities and differences in order to determine the environmental performance of low-carbon building frameworks, which is discussed in the following parts of the present review [9].

3. Comparative Evaluation of Regulatory Design and Implementation

Although low-carbon building codes and standards have similar goals, they both vary in terms of their efficacy depending on the regulatory design and application. The comparative analysis of these frameworks must be done by not only paying attention to the strictness of the technical requirements, but also to how compliance is obtained, observed, and executed. The paper will discuss some of the critical aspects of regulating design, such as the performance strategies, coverage of carbon, structure of compliance, and contextual factors influencing the results of implementation in the regions [17].

3.1. Prescriptive and Performance-Based Regulatory Approaches

The decision between prescriptive and performance-based regulation methods is one of the greatest areas of contention between low-carbon building frameworks. The prescriptive codes describe specific technical standards of the components of a building, e.g., minimum insulation, window performance, or equipment efficiencies. These methods are easy to understand and implement, especially where there is low technical expertise or experience in energy modeling. Consequently, prescriptive requirements are still common in most jurisdictions, particularly in developing areas and to smaller-scaled residential construction [21].

In comparison, performance-based strategies establish general goals of building energy consumption or carbon emissions, which gives designers more room to achieve the regulatory goals. These methods are becoming popular in the more progressive regulatory community, where they are able to support multiple solutions to design and promote creativity. Performance-based codes tend to be based on a standardized method of calculation or simulation to illustrate compliance, which can enhance congruence with actual building performance when it is implemented adequately. Nevertheless, the methods also need more technical skills, strong modeling assumptions, and efficient verification procedures that can restrict their fitness to some situations [34,36].

Practically, most building codes implement hybrid designs that incorporate requirements like using backstop prescriptively and optional performance pathways. **Table 2** contrasts major design elements concerning prescriptive codes, performance-based codes, and voluntary standards, pointing out the differences in compliance, flexibility, and integration of carbon metrics [20]. This twin strategy is a sign of trying to strike a compromise of regulatory simplicity and flexibility, but slowly moving markets to more result-oriented regulation. The degree to which performance-based options are used is quite varied, and it is conditioned by the level of local professional capacity, the regulatory culture, as well as visualized compliance risks.

Table 2. Comparison of main regulatory design features of prescriptive codes, performance-based codes, and voluntary standards.

Feature	Prescriptive Codes	Performance-Based Codes	Voluntary Standards
Compliance method	Component requirements	Whole-building metrics	Certification scoring
Design flexibility	Low	High	High
Carbon metric usage	Rare	Emerging	Common
Life-cycle assessment	Absent	Limited	Often included
Innovation potential	Moderate	High	High

3.2. Scope of Carbon Coverage and Life-Cycle Considerations

The other important facet of regulatory design is the area of carbon emission that is covered by building codes and standards [4]. Conventionally, the majority of the obligatory rules have been concerned with the operational energy consumption, implicitly presupposing that the decrease in energy demands would directly result in a decrease in carbon emissions. Although this assumption was true in fossil fuel-dominated energy systems, decarbonization of electricity grids has changed the relative significance of operational and embodied emissions.

In their turn, certain regulatory frameworks have started to directly include carbon-based performance indicators, whether through the application of the carbon intensity factors to energy consumption or through the establishment of direct operational carbon emissions limits [37]. These methods serve to enhance consistency between building governance and the bigger environment, climate policy goals, particularly in jurisdictions having distinctly dynamic energy mixes. However, explicit carbon metrics are much less widespread than energy-based requirements, and are commonly done as pilot programs or voluntary standards.

Life-cycle carbon considerations are an even more recent and less widely adopted low-carbon building regulation. Wanted criteria have front-run the incorporation of embodied carbon assessment utilizing life-cycle assessment techniques, material statement needs, and benchmarking. Contrary to this, voluntary codes that deal with embodied emissions are illustrious and even exclusive to certain building categories or major projects. This is because the absence of standard data, the complexity of methods, and regulatory burden have hindered larger-scale adoption, despite the increasing evidence of the importance of embodied emissions throughout the building life-cycle [38].

3.3. Compliance, Enforcement, and Institutional Capacity

Low-carbon building codes and standards are not only effective based on their formal requirements, but also based on the strength of the compliance and enforcement measures [4,39]. In locations where there is a high institutional capability, compliance is normally incorporated into building permitting procedures, backed by standardized documentation, third-party verification, and post-construction inspections. These systems would help to increase the credibility of regulations and decrease the performance differences between the design and the real use.

In comparison, in areas where administrative staff are limited, building code enforcement can be unevenly applied or not achieved. The compliance may be compromised by informal construction standards, lack of unified regulatory control, and lack of inspector training, even with formal regulations. In that regard, stringent regulatory provisions can have few environmental payoffs when they fail to be accompanied by the proper implementation frameworks. Voluntary standards embrace other compliance models and frequently use indirect methods based on independent certification agencies and market forces instead of law enforcement. Although this may allow a greater performance level and experimentation, it is usually restricted to certain market segments like commercial or high-end residential buildings. Consequently, voluntary standards do not in and of themselves provide the means of achieving large-scale emissions cuts, but can be used in complement to these controls through awareness creation, capacity building, and future regulatory revisions [14].

3.4. Adaptability, Policy Alignment, and Market Readiness

Another aspect that determines the performance of the low-carbon building frameworks is that they are flexible to the fluctuating technological, economic, and policy environments [17,40]. Standard codes and standards that are updated frequently and according to national climate strategies can be in a better position to stand the test of time. Construction standards are also clearly associated with decarbonization strategies in the long run, in multiple areas, which allows the requirements to be tightened gradually in accordance with the transformation of the market and the decrease in the cost of the technologies.

The market readiness is also important in the feasibility and effects of regulatory measures [41,42]. Compliant materials, technologies, and qualified professionals are available, which impacts compliance costs and industry acceptance. Where ambition to regulate is faster than the capacity of the market, stakeholder resistance and imbalanced application are possible. On the other hand, correctly tuned regulations have the potential of spurring innovation, economies of scale, and learning effects that will save costs over time. Combined, these dimensions indicate that the environmental performance of low-carbon building codes and standards cannot be evaluated only by referring to their pronounced requirements. The design decisions of regulations, the implementation capacity, and context interact complexly to influence actual results. This knowledge of these interactions would give us the necessary background to discuss the environmental impacts of low-carbon building frameworks, as we shall see in the next section. **Figure 1** illustrates how regulatory design elements, compliance mechanisms, and contextual factors interact to determine implementation outcomes.

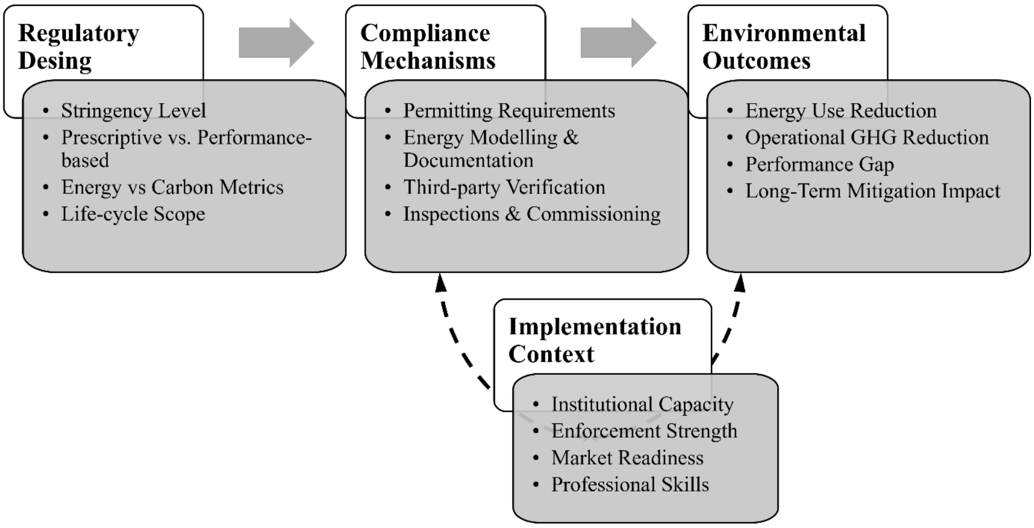

Figure 1. Conceptual pathway from regulatory design to implementation outcomes, highlighting enforcement, market readiness, and performance gaps.

4. Environmental Impacts and Effectiveness Assessment

Evaluation of the environmental effects of low-carbon building codes and standards is critical in evaluating whether these regulatory measures attain the desired effect of mitigation. Although the regulatory ambition and design are essential indicators, their final worth is quantifiable in terms of energy-saving and greenhouse gas emissions [43]. This part is a synthesis of the literature on reported environmental outcomes and how methodology is applied to determine or test effectiveness, as well as the significant sources of variability and uncertainty in impact assessments.

4.1. Reported Energy and Emission Reduction Outcomes

There is a large body of literature that suggests that building energy code's introduction or tightening is linked to large-scale modeled and measured energy use in new buildings. Comparisons of higher intensity of energy in buildings built using more stringent codes or regulations are always recorded in the studies involving various regions. The most significant of such reductions can be seen in the demand for space heating and cooling, which shows an increase in building envelope performance as well as system efficiency. In countries where codes have long and frequent renewal, cumulative energy savings at the building stock level can be high over time [44,45].

Greenhouse gas emission reductions across the board have been reflected in the trends of energy use, but findings are more situation-specific. **Table 3** summarizes the representative studies that report on energy and emission reduction by various frameworks. When the generation of electricity is still carbon-intensive, efficiency in building energy is converted into significant operational reductions in emission levels. On the other hand, at sites where grids are decarbonizing at a high rate, the marginal carbon payoff of additional operational energy savings becomes less, and the focus changes to other sources of emissions. Consequently, the building code environmental effectiveness is becoming more and more reliant on how compatible building codes are with greater energy system transitions [46].

Table 3. Reported environmental impacts associated with low-carbon building codes and voluntary standards, including study type, region, building type, and outcomes.

Study Type	Region	Building Type	Reported Impact
Simulation-based	Europe	Residential	20–40% energy reduction
Post-occupancy	North America	Commercial	Lower EUI than baseline codes
Comparative analysis	China	Urban residential	Significant heating energy savings
Certification analysis	Global	Commercial	Reduced operational emissions

Voluntary building standards often have better-reported energy and carbon savings than mandatory codes because they have ambitious performance targets [14]. Certified buildings typically have reduced intensities of energy use and, in other cases, net-zero or net-positive energy use. They are mainly, however, restricted to a fairly small portion of the total building market, limiting their aggregate effects on the environment on the national or regional level.

4.2. Evidence from Empirical and Post-Occupancy Studies

In addition to modeling-based measurements, empirical research, and post-occupancy analysis, offers the essential information about the practical performance of the buildings that have been controlled in terms of the low-carbon schemes. These studies demonstrate that, though code-compliant buildings tend to perform well as compared to the aged ones, there are usually differences between expected and actual energy consumption. Elements like building construction, practices in commissioning, and occupancy behavior may greatly affect the performance in terms of operations, and as such, the result is commonly referred to as an energy or performance gap [47,48].

There is also post-occupancy evidence that regulatory methods that focus upon integrated design, commissioning, and verification have a higher probability of providing consistent environmental results [49]. To this end, there are certain voluntary standards that involve continuous performance monitoring or disclosure, which have shown better coordination between design and operational outcomes. However, the empirical assessment of impact is limited in value by the fact that the presence of large-scale, longitudinal post-occupancy data after occupancy is limited, especially in developing regions.

4.3. Comparative Effectiveness across Contexts

Comparative studies suggest that building codes and standards of low-carbon buildings are not effective in all climatic, economic, and institutional settings. Stringent envelope requirements in cold and temperate climates result in large savings of heating energy demand, and in hot climates, savings are attributed more to cooling efficiency and passive design measures. The economic aspects, such as the cost of energy and the cost of construction, also determine the size of the achieved savings and the reaction of the stakeholders to the regulatory demands [50].

There is also the decisive role of the institutional capacity and rigor of enforcing institutions to the outcome of the environment [51]. Courts that uphold compliance systems are also likely to record more steady gains in performance, whereas lax enforcement can decimate anticipated gains by a significant margin. These results highlight that regulatory stringency is not a sufficient predictor of environmental effectiveness, but that quality of implementation has to be taken into consideration in comparative assessments.

4.4. Co-Benefits, Trade-Offs, and Broader Impacts

Besides direct energy and emission reductions, low-carbon building codes and standards have a variety of co-benefits that enhance sustainability objectives on a broader scale. Higher thermal performance and system efficiency may boost the quality of the indoor environment, thermal comfort, and occupant health, and minimize exposure to energy price volatility. On the macro level, energy-saving buildings will help to reduce the load on energy infrastructure and serve to achieve energy security [52,53].

Meanwhile, there are trade-offs and unintended consequences, which are found in the literature. Higher initial construction costs due to higher performance standards can become an issue of affordability, especially in the low-income housing markets. Poor incorporation of operational and embodied carbon may also result in burden shifting, with a decrease in operational carbon partially being compensated by increases in embodied carbon in materials or technologies [54]. Such trade-offs demonstrate the significance of assessment frameworks in the assessment of environmental impacts that are holistic. **Table 4** defines several issues of low-carbon building regulation and possible options to improve the situation in the future.

4.5. Methodological Limitations and Evidence Gaps

Although there is an increasing amount of evidence of beneficial environmental effects, current evaluations of low-carbon building codes and standards have a number of methodological shortcomings. Numerous research works are based on ex-ante modeling instead of measured performance data, which may overstate the real savings in case of assumptions that do not apply to the actual situation. The cross-study comparisons are further complicated by the differences in the boundaries of the systems, the definition of the baseline, and performance measures [55].

Table 4. Challenges and future directions in low-carbon building regulation across carbon coverage, enforcement, data availability, and market readiness.

Dimension	Current Challenge	Future Direction
Carbon coverage	Focus on operational energy	Life-cycle carbon regulation
Enforcement	Inconsistent compliance	Capacity building and verification
Data availability	Limited post-occupancy data	Performance monitoring and disclosure
Market readiness	Cost and skill barriers	Gradual tightening and incentives

Besides, a significant absence of standardized methods of determining the effects of life-cycle carbon impacts among regulatory assessments also exists [17,38]. Limitations of data, especially of embodied emissions, make it difficult to come up with strong comparisons across regions and building types. With regulatory schemes steadily broadening on carbon-based and life-cycle-based measures, it will be crucial to address these gaps in the methodology in order to measure effectiveness properly.

All in all, the evidence available indicates that low-carbon building codes and standards have provided significant energy consumption and operational emissions savings, especially with effective enforcement and supplementary policies [20]. Nevertheless, their overall environmental performance will become more reliant on the introduction of life-cycle carbon aspects, better empirical assessment techniques, and compatibility with the changing energy systems. The latter are also addressed in the conclusion of this review.

5. Conclusions

Building codes and standards. Low-carbon building codes and standards are emerging as a focus tool in world policies to minimize energy use and greenhouse gas emissions in the built environment. The present review has given a comparative analysis of the key regulatory frameworks in the world with an analysis of their design features, the implementation settings, and the environmental effects reported. Collectively, the results highlight how much progress the construct of regulation has made and the challenges that still persist that restrict the mitigating capacity of regulation. The review notes that mandatory building codes have been useful in creating a basis of improvement on building energy performance, especially where there are a strong institutional capacity and frequent revision of the regulations. Such performance-based methods and increasingly strict requirements have allowed achieving significant decreases in energy consumption in operations and the resultant emissions in new buildings. These attempts have been supplemented by voluntary standards that show a greater degree of ambition, increase the scope of sustainability concerns, and provide trial grounds for novel performance measures. Nevertheless, their total effectiveness is limited due to the low penetration into the market and dependence on voluntary adoption.

Comparative analytical work indicates that the effectiveness of low-carbon building frameworks in terms of the environment is influenced by regulatory stringency as well as the quality of implementation and the mechanisms of enforcement, and the willingness of the market. The jurisdictions that have a strong compliance framework and professional ability are likely to experience a more stable performance results, and the ineffective enforcement and the off-the-book construction activities can undermine the projected advantages considerably. These results underline the fact that the design of regulations and institutional setting are intertwined in the aspect of establishing actual environmental effects.

The production of evidence on impact suggests that current codes and standards have provided significant operational energy consumption and emission reductions, although their comparative effectiveness is being subjected to greater restructuring of energy systems changes. With decarbonization of electricity grids, marginal carbon gains associated with additional operational efficiency gains are smaller, and embodied emissions and life-cycle effects are brought into the limelight. Although voluntary standards and a limited range of regulatory programs have started to focus on these aspects, life-cycle carbon implications have not been incorporated into a large percentage of required building standards.

This review has a number of gaps in existing regulatory and research practices. In impact assessment, methodological constraints such as the use of ex-ante modelling and the absence of post-occupancy data limit the accuracy of the quantification of the environmental outcomes and comparison of effectiveness between regions. Also, the lack of standardized life-cycle assessment methods and quality embodied carbon data can create a serious challenge to the further implementation of carbon-based regulation. These gaps will be critical to address as the building codes will develop to meet more ambitious climate goals.

In the future, a more adaptive and integrated regulatory paradigm would be needed in order to shift to truly low-carbon buildings. The priorities are the progressive integration of life-cycle carbon measures in obligatory codes, enhancing the ability of the building regulation to meet the national decarbonization strategies, and stepping up reinforcement and capacity-building processes, especially in developing worlds. Evidence-based policy development can also be advanced by improved data collection, performance monitoring, and exchange of knowledge across the borders. To sum up, low-carbon building codes and standards have already become potent means of decreasing the environmental footprint of the building industry, yet the role thereof has to be further modified due to the technological and policy context changes. Through the lessons of comparative international experience and the reduction of existing shortcomings, policymakers and researchers can increase the role played by building regulation in the global shift towards a low-carbon built environment.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Not applicable. No new data was created and analyzed.

Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

References

[1] Jackson, D.J., 2020. Addressing the Challenges of Reducing Greenhouse Gas Emissions in the Construction Industry: A Multi-Perspective Approach [PhD Thesis]. The University of Edinburgh: Edinburgh, UK.
[2] Liu, Z., Feng, K., Davis, S.J., et al., 2016. Understanding the energy consumption and greenhouse gas emissions and the implication for achieving climate change mitigation targets. Applied Energy. 184, 737–741.
[3] Ürge-Vorsatz, D., Danny Harvey, L.D., Mirasgedis, S., et al., 2007. Mitigating CO_2 emissions from energy use in the world's buildings. Building Research & Information. 35(4), 379–398.
[4] Enker, R.A., Morrison, G.M., 2017. Analysis of the transition effects of building codes and regulations on the emergence of a low carbon residential building sector. Energy and Buildings. 156, 40–50.
[5] Dawood, S., Crosbie, T., Dawood, N., et al., 2013. Designing low carbon buildings: A framework to reduce energy consumption and embed the use of renewables. Sustainable Cities and Society. 8, 63–71.
[6] Björklund, M., von Malmborg, F., Nordensvärd, J., 2023. Lessons learnt from 20+ years of research on multilevel governance of energy-efficient and zero-carbon buildings in the European Union. Energy Efficiency. 16(8), 98.
[7] Zhang, L., Li, Q., Zhou, J., 2017. Critical factors of low-carbon building development in China's urban area. Journal of Cleaner Production. 142, 3075–3082.
[8] Lai, X., Liu, J., Georgi, G., et al., 2017. Driving forces for low carbon technology innovation in the building industry: A critical review. Renewable and Sustainable Energy Reviews. 74, 299–315.
[9] Wang, H., Chen, W., Shi, J., 2018. Low carbon transition of global building sector under 2-and 1.5-degree targets. Applied Energy. 222, 148–157.
[10] Vaughan, E., Turner, J., 2013. The Value and Impact of Building Codes. EEIS: Washington, DC.
[11] Suh, S., Tomar, S., Leighton, M., et al., 2014. Environmental performance of green building code and certification systems. Environmental Science & Technology. 48(5), 2551–2560.

[12] Zhang, Y., Wang, H., Gao, W., et al., 2019. A survey of the status and challenges of green building development in various countries. Sustainability. 11(19), 5385.

[13] Zhang, Y., Wang, J., Hu, F., et al., 2017. Comparison of evaluation standards for green building in China, Britain, United States. Renewable and Sustainable Energy Reviews. 68, 262–271.

[14] Lee, W.L., Yik, F., 2004. Regulatory and voluntary approaches for enhancing building energy efficiency. Progress in Energy and Combustion Science. 30(5), 477–499.

[15] Li, R., Ramanathan, R., 2018. Exploring the relationships between different types of environmental regulations and environmental performance: Evidence from China. Journal of Cleaner Production. 196, 1329–1340.

[16] Wang, X., Du, Q., Lu, C., et al., 2022. Exploration in carbon emission reduction effect of low-carbon practices in prefabricated building supply chain. Journal of Cleaner Production. 368, 133153.

[17] Li, Y., Li, S., Xia, S., et al., 2023. A review on the policy, technology and evaluation method of low-carbon buildings and communities. Energies. 16(4), 1773.

[18] Ozorhon, B., 2013. Response of construction clients to low-carbon building regulations. Journal of Construction Engineering and Management. 139(12), A5013001.

[19] Yu, F., Feng, W., Leng, J., et al., 2022. Review of the US policies, codes, and standards of zero-carbon buildings. Buildings. 12(12), 2060.

[20] Lu, Y., Karunasena, G., Liu, C., 2022. A systematic literature review of non-compliance with low-carbon building regulations. Energies. 15(24), 9266.

[21] Tuohy, P., 2009. Regulations and robust low-carbon buildings. Building Research & Information. 37(4), 433–445.

[22] Hale, L.A., 2017. Experimental Standards in Sustainability Transitions: Insights from the Building Sector [PhD Thesis]. Copenhagen Business School (CBS): Frederiksberg, Denmark.

[23] Burman, E., Mumovic, D., Kimpian, J., 2014. Towards measurement and verification of energy performance under the framework of the European directive for energy performance of buildings. Energy. 77, 153–163.

[24] Andaloro, A.P., Salomone, R., Ioppolo, G., et al., 2010. Energy certification of buildings: A comparative analysis of progress towards implementation in European countries. Energy Policy. 38(10), 5840–5866.

[25] Kim, J.T., Yu, C.W.F., 2018. Sustainable development and requirements for energy efficiency in buildings–the Korean perspectives. Indoor and Built Environment. 27(6), 734–751.

[26] Huang, B., Mauerhofer, V., Geng, Y., 2016. Analysis of existing building energy saving policies in Japan and China. Journal of Cleaner Production. 112, 1510–1518.

[27] Liu, Z., Zhou, Q., Tian, Z., et al., 2019. A comprehensive analysis on definitions, development, and policies of nearly zero energy buildings in China. Renewable and Sustainable Energy Reviews. 114, 109314.

[28] Ghasemi, E., Azari, R., Zahed, M., 2024. Carbon neutrality in the building sector of the global south—A review of barriers and transformations. Buildings. 14(2), 321.

[29] Gaum, T., Laubscher, J., 2022. Building energy codes: Reviewing the status of implementation strategies in the Global South. International Journal of Built Environment and Sustainability. 9(1), 39–53.

[30] Jørgensen, B.N., Ma, Z.G., 2025. Energy efficiency and decarbonization strategies in buildings: A review of technologies, policies, and future directions. Applied Sciences. 15(21), 11660.

[31] Li, Q., Ma, R., Yang, M., et al., 2025. Net zero energy buildings for low-carbon cities: Progress, challenges, and future directions. Journal of Building Design and Environment. 3(3), 202559.

[32] O'Shaughnessey, E., Shah, M., 2021. The Demand-Side Opportunity: The Roles of Distributed Solar And Building Energy Systems in a Decarbonized Grid. National Renewable Energy Lab.(NREL): Golden, CO, USA.

[33] Cabeza, L.F., Barreneche, C., Miró, L., et al., 2013. Low carbon and low embodied energy materials in buildings: A review. Renewable and Sustainable Energy Reviews. 23, 536–542.

[34] Berry, S., Davidson, K., Saman, W., 2014. Defining zero carbon and zero energy homes from a performance-based regulatory perspective. Energy Efficiency. 7(2), 303–322.

[35] Van der Heijden, J., 2018. The limits of voluntary programs for low-carbon buildings for staying under 1.5 °C. Current Opinion in Environmental Sustainability. 30, 59–66.

[36] Raslan, R.M.S., 2010. Performance Based Regulations: The Viability of the Modelling Approach as a Methodology for Building Energy Compliance Demonstration. UCL (University College London): London, UK.

[37] Bordass, B., 2020. Metrics for energy performance in operation: The fallacy of single indicators. Buildings & Cities. 1(1), 260–276.

[38] Pan, W., Li, K., Teng, Y., 2018. Rethinking system boundaries of the life cycle carbon emissions of buildings. Renewable and Sustainable Energy Reviews. 90, 379–390.

[39] Pan, W., Garmston, H., 2012. Building regulations in energy efficiency: Compliance in England and Wales. Energy Policy. 45, 594–605.

[40] Crawford, J., French, W., 2008. A low-carbon future: Spatial planning's role in enhancing technological innovation in the built environment. Energy Policy. 36(12), 4575–4579.
[41] Atkinson, J.G., Jackson, T., Mullings-Smith, E., 2009. Market influence on the low carbon energy refurbishment of existing multi-residential buildings. Energy Policy. 37(7), 2582–2593.
[42] Gillingham, K., Sweeney, J., 2012. Barriers to implementing low-carbon technologies. Climate Change Economics. 3(4), 1250019.
[43] Xiong, L., Wang, M., Mao, J., et al., 2024. A review of building carbon emission accounting methods under low-carbon building background. Buildings. 14(3), 777.
[44] Yang, X.E., Liu, S., Zou, Y., et al., 2022. Energy-saving potential prediction models for large-scale building: A state-of-the-art review. Renewable and Sustainable Energy Reviews. 156, 111992.
[45] Heidarinejad, M., Mattise, N., Dahlhausen, M., et al., 2017. Demonstration of reduced-order urban scale building energy models. Energy and Buildings. 156, 17–28.
[46] Laustsen, J., 2008. Energy Efficiency Requirements in Building Codes, Energy Efficiency Policies for New Buildings. IEA: Paris, France.
[47] Mahdavi, A., Berger, C., Amin, H., et al., 2021. The role of occupants in buildings' energy performance gap: Myth or reality? Sustainability. 13(6), 3146.
[48] De Wilde, P., 2014. The gap between predicted and measured energy performance of buildings: A framework for investigation. Automation in Construction. 41, 40–49.
[49] Qiao, J., Zhang, X., Hao, C., et al., 2023. Post-occupancy evaluation of the actual performance of a low-carbon building. Energy Reports. 10, 228–243.
[50] Toochukwu, A.C., 2025. Sustainable construction practices: Balancing cost efficiency, environmental impact, and stakeholder collaboration. International Research Journal of Modernization in Engineering Technology and Science. 7(1), 4118–4140.
[51] Schwartz, J., 2003. The impact of state capacity on enforcement of environmental policies: The case of China. The Journal of Environment & Development. 12(1), 50–81.
[52] Kvon, G.M., Prokopyev, A.I., Shestak, V.A., et al., 2018. Energy saving projects as energy security factors. International Journal of Energy Economics and Policy. 8(6), 155–160.
[53] Karim, S., 2019. Co-Benefits of Low-Carbon Policies in the Built Environment: An Australian Investigation into Local Government Co-Benefits Policies [PhD Thesis]. UNSW Sydney: Sydney, Australia.
[54] Giesekam, J., Barrett, J.R., Taylor, P., 2016. Construction sector views on low carbon building materials. Building Research & Information. 44(4), 423–444.
[55] Xi, C., Cao, S.-J., 2022. Challenges and future development paths of low carbon building design: A review. Buildings. 12(2), 163.