Libyan Journal of Sustainable Development Research
المجلة الليبية لأبحاث التنمية المستدامة
E-ISSN: 0000-0000
Volume 1, Issue 1, 2025
Page No: 45-51
Website: https://ljsdr.ly/index.php/ljsdr/index

Decarbonizing Buildings at Scale: Energy Codes, Innovation Pathways, and the Net-Zero Transition

Muftah Ali[1], Mohamed Khaleel[2]*
[1]Department of Electrical and Electronics Engineering, Faculty of Engineering, Karabuk University, Karabuk, 78050, Türkiye
[2]Libyan Center for Sustainable Development Research, Al-Khums, Libya

إزالة الكربون من المباني على نطاق واسع: قوانين الطاقة، ومسارات الابتكار، والانتقال إلى صافي انبعاثات صفرية

مفتاح علي[1]، محمد خليل[2]*
[1]قسم الهندسة الكهربائية والإلكترونية، كلية الهندسة، جامعة كارابوك، كارابوك، تركيا
[2]المركز الليبي لأبحاث التنمية المستدامة، الخمس، ليبيا

*Corresponding author: mkhaleel@lsd.ly

Received: October 04, 2025 Revised: November 16, 2025 Accepted: November 29, 2025
Published: December 06, 2025

Abstract:
The building sector is central to global decarbonization efforts, accounting for a substantial share of energy-related carbon dioxide emissions and representing one of the most cost-effective domains for near-term mitigation. This article examines the critical role of the 2020s as a decisive decade for aligning the global building sector with the International Energy Agency’s Net Zero Emissions by 2050 (NZE) Scenario, with a particular focus on achieving zero-carbon-ready performance for new and retrofitted buildings by 2030. Drawing on recent policy developments and regulatory trends, the analysis highlights the rapid expansion of building energy codes worldwide, the increasing adoption of performance-based and stretch code frameworks, and their function as transitional mechanisms toward more stringent net-zero standards. The study further explores the technological, financial, and institutional barriers constraining progress, including high upfront investment costs, fragmented regulatory environments, and skills shortages across the construction and retrofit value chain. Emphasis is placed on the need for coordinated action among policymakers, industry stakeholders, and end users to accelerate the deployment of clean and energy-efficient technologies, scale up deep renovation rates, and integrate buildings into low-carbon, renewable-dominated energy systems. The findings underscore that achieving net-zero-ready buildings delivers multiple co-benefits beyond emissions reduction, including enhanced energy security, improved occupant comfort, lower energy bills, and job creation. The article concludes that timely regulatory reform, innovative financing models, workforce development, and consumer engagement are essential to closing the implementation gap and ensuring the building sector’s alignment with long-term net-zero targets.

Keywords: Net-zero buildings; Building energy codes; Decarbonization pathways; Clean energy technologies.

الملخص:
يُعدّ قطاع المباني محورًا أساسيًا في جهود إزالة الكربون على المستوى العالمي، إذ يسهم بنسبة كبيرة من انبعاثات ثاني أكسيد الكربون المرتبطة بالطاقة، كما يُمثّل أحد أكثر القطاعات فعالية من حيث التكلفة لتحقيق خفض الانبعاثات على المدى القريب. تستعرض هذه المقالة الدور الحاسم لعقد العشرينيات من القرن الحادي والعشرين بوصفه العقد الفاصل لمواءمة

قطاع المباني العالمي مع سيناريو صافي الانبعاثات الصفرية بحلول عام 2050 الصادر عن الوكالة الدولية للطاقة(NZE) ، مع التركيز على تحقيق جاهزية المباني الجديدة والمجددة للوصول إلى الحياد الكربوني بحلول عام 2030. واستنادًا إلى أحدث التطورات في السياسات والأطر التنظيمية، يسلّط التحليل الضوء على التوسع السريع في تطبيق أكواد كفاءة الطاقة للمباني على مستوى العالم، والاتجاه المتزايد نحو اعتماد الأكواد القائمة على الأداء والأكواد المتقدمة(Stretch Codes) ، ودورها كآليات انتقالية نحو معايير أكثر صرامة لتحقيق صافي الانبعاثات الصفرية. كما تتناول الدراسة التحديات التكنولوجية والمالية والمؤسسية التي تعيق التقدم، بما في ذلك ارتفاع التكاليف الأولية للاستثمار، وتجزؤ الأطر التنظيمية، ونقص المهارات عبر سلسلة القيمة الخاصة بالبناء والتجديد. ويؤكد البحث على أهمية التنسيق الفعّال بين صانعي السياسات وأصحاب المصلحة في الصناعة والمستخدمين النهائيين لتسريع نشر التقنيات النظيفة والموفرة للطاقة، ورفع معدلات التجديد العميق للمباني، ودمج قطاع المباني في أنظمة طاقة منخفضة الكربون تعتمد بدرجة متزايدة على مصادر الطاقة المتجددة. وتُبرز النتائج أن تحقيق مبانٍ جاهزة لصافي الانبعاثات الصفرية يحقق منافع مشتركة تتجاوز خفض الانبعاثات، تشمل تعزيز أمن الطاقة، وتحسين راحة المستخدمين، وخفض فواتير الطاقة، وخلق فرص عمل جديدة. وتخلص المقالة إلى أن الإصلاح التنظيمي في الوقت المناسب، وتطوير نماذج تمويل مبتكرة، وبناء القدرات البشرية، وتعزيز دور المستهلكين، تُعد عناصر أساسية لسد فجوة التنفيذ وضمان مواءمة قطاع المباني مع الأهداف طويلة الأجل لصافي الانبعاثات الصفرية.

الكلمات المفتاحية: مبانٍ خالية من الانبعاثات الكربونية؛ قوانين الطاقة في المباني؛ مسارات إزالة الكربون؛ تقنيات الطاقة النظيفة.

1. Introduction

The accelerated uptake and scaling of clean energy technologies in the building sector, alongside structural and behavioural demand-side shifts such as improved thermostat set-points, reduced energy wastage, and more efficient occupancy practices, can deliver substantial near-term emissions abatement by 2030 [1-4]. When these measures are supported by coherent innovation strategies (including targeted R&D, commercialization support, standards development, and market-shaping policies), they not only reduce operational carbon dioxide (CO_2) emissions but also help lock in long-lived performance improvements across the building stock. Collectively, such interventions constitute a pivotal enabler of the International Energy Agency's Net Zero Emissions by 2050 (NZE) Scenario, which requires a rapid transition toward a predominantly zero-carbon building stock through deep energy retrofits, electrification of end uses, high-efficiency equipment, and integration of on-site renewables and low-carbon district energy where feasible [5-8].

From an emissions-accounting perspective, buildings are a major driver of energy-related emissions because their operational energy demand is met by a combination of direct fuel combustion (e.g., gas or oil used for space and water heating) and indirect upstream emissions arising from electricity and heat generation. Consequently, building operations, through both direct and indirect pathways are responsible for approximately 30% of global energy-sector emissions. This magnitude underscores the sector's centrality in global mitigation strategies: decarbonizing buildings requires simultaneously improving energy efficiency (to reduce absolute demand), decarbonizing electricity supply (to lower the carbon intensity of electrified services), and accelerating deployment of low-carbon end-use technologies (such as high-performance envelopes, heat pumps, smart controls, efficient appliances, and building-integrated renewables) [9-15].

Within the IEA Net Zero Emissions by 2050 (NZE) Scenario, a pivotal near-term milestone for decarbonizing the global building sector is that all newly constructed buildings and all major retrofits achieve "zero-carbon-ready" performance by 2030 [16-19]. Meeting this benchmark implies more than incremental efficiency gains; it requires systematic compliance with rigorous criteria encompassing (i) high energy-performance standards (e.g., advanced envelopes, efficient HVAC and appliances, and smart controls), (ii) the substitution of high-emission fuels with low- or zero-emission alternatives (notably electrification and renewable-based heating solutions), (iii) transparent life cycle–based CO_2 emissions reporting that accounts for both operational and embodied emissions, (iv) technical compatibility with electricity systems characterized by high penetrations of variable renewable energy, including demand flexibility, load shifting, and smart-grid interoperability, and (v) enhanced resilience to evolving climate hazards, such as rising cooling demand, heat waves, and other extremes that can undermine performance and occupant safety [20-25].

Despite the centrality of this target, progress from the 2020 baseline indicates a substantial implementation gap: only about 5% of new building construction was assessed as zero-carbon-ready at that time. Achieving 100% by 2030 therefore requires a broad policy and market transformation, including the rapid strengthening and enforcement of building energy codes, mandatory minimum energy performance standards, incentives and financing mechanisms that de-risk early adoption, workforce capacity building across the construction value chain, and supply-side scaling of high-efficiency and low-carbon technologies and materials [26-28].

The retrofit dimension is even more constrained because of the inherent inertia of the existing building stock. Buildings are long-lived assets, and turnover through demolition and replacement is slow; consequently, roughly two-thirds of the floor area currently in use is expected to remain operational in 2040. This persistence makes deep renovation indispensable to meeting sectoral decarbonization goals. Accordingly, the NZE trajectory calls for retrofitting 20% of the existing building stock to the zero-carbon-ready level by 2030, which in practical terms requires raising annual renovation rates to at least 2% by 2030, compared with below 1% today [29-33]. Reaching these rates demands not only expanded capital investment and accessible financing (including on-bill mechanisms, green mortgages, and performance-based contracting), but also coordinated delivery models, such as standardized retrofit packages, industrialized renovation approaches, and robust measurement, reporting, and verification (MRV), to ensure that renovations translate into verifiable, durable emissions reductions at scale.

This article contributes a consolidated, policy- and technology-oriented synthesis of the buildings sector transition required under the IEA Net Zero Emissions by 2050 (NZE) Scenario, with particular emphasis on the 2030 milestone of achieving zero-carbon-ready performance for all new construction and major retrofits. It advances the literature by clarifying how regulatory architectures, especially the evolution from prescriptive codes toward performance-based, hybrid, and stretch-code pathways, function as practical transition instruments for scaling high-efficiency, low-carbon building practices, while improving grid compatibility and climate resilience. In addition, the article identifies the principal implementation bottlenecks, upfront capital costs, fragmented governance and compliance regimes, and workforce capacity constraints, and frames them within an integrated delivery logic that links financing innovation, code harmonization, supply-chain coordination, and user behaviour to accelerate deep renovations and clean technology deployment. By explicitly connecting decarbonization outcomes with co-benefits such as energy security, affordability, comfort, and employment, the study provides a structured basis for policymakers and practitioners to design context-specific strategies that close the gap between current progress and NZE-aligned trajectories.

2. Stretch Codes as a Transitional Mechanism for Accelerating Net-Zero-Ready Building Standards

Drawing on the IEA's most recent tracking assessment of building envelopes, approximately 80 countries have now adopted mandatory or voluntary building energy codes. Relative to the post-Paris baseline (2015), this reflects an estimated 30% expansion in the number of jurisdictions implementing such codes, suggesting that the Paris Agreement helped catalyze and accelerate earlier diffusion trends. In parallel, building energy-efficiency measures and energy codes have emerged as one of the most frequently referenced mitigation levers in countries' Nationally Determined Contributions (NDCs), underscoring the sector's perceived cost-effectiveness and scalability in national decarbonization strategies [34,35].

Against a rapidly evolving technology landscape, many governments have increasingly shifted from general efficiency aspirations toward performance-oriented regulatory frameworks that explicitly aim to reduce energy use intensity (EUI) and promote lower-carbon energy carriers (e.g., electrification and cleaner district energy). Importantly, jurisdictions with existing energy codes are not only expanding their scope (across building types and end uses) but also tightening technical requirements to accommodate advanced construction practices, high-efficiency equipment, and digitalized design and compliance workflows [36,37]. This "ratcheting" dynamic, periodic code updates that systematically increase stringency, reflects a deliberate effort to move baseline construction practice closer to carbon neutrality and, ultimately, zero-carbon-ready performance. Early institutional signals of this direction include initiatives such as California's 2022 Zero Code and the Massachusetts Energy Zero (E-Z) Code in the United States, as well as multi-actor commitments including the C40 Net Zero Carbon Buildings Declaration and the World Green Building Council's Net Zero Carbon Buildings Commitments. In federal or multi-level governance systems, code adoption is frequently administered at state or provincial levels, often through the adaptation of a national model code, which can improve coherence while preserving local discretion [38-40].

From a regulatory-design standpoint, building energy codes are typically implemented through two principal compliance architectures. The more common prescriptive approach specifies minimum requirements on a component-by-component basis (e.g., insulation levels, window performance, HVAC efficiencies). This approach is often favored by practitioners because it offers clear, verifiable requirements and relatively straightforward enforcement pathways. However, strict prescriptive frameworks may constrain design optimization, as they limit the ability to make system-level trade-offs (for example, compensating a higher glazing ratio with enhanced envelope insulation and airtightness). To address this limitation, many jurisdictions are increasingly incorporating performance-based compliance options, particularly for a widening set of building categories. Performance pathways generally rely on whole-building energy modeling, establish an upper bound on energy consumption or EUI, and permit more flexibility in how designers achieve compliance, thereby enabling market actors to select the most context-appropriate efficiency package [41,42]. This flexibility, however, comes with higher demands for technical capability, modeling competence, and quality assurance, because performance outcomes depend on complex interactions among building subsystems and must be demonstrated through software-based assessment.

In practice, "performance-based" regimes rarely eliminate prescriptive safeguards altogether. Many retain mandatory minimum provisions to secure baseline performance for critical components and to reduce risks associated with health, moisture management, and long-term durability. In addition, hybrid frameworks are increasingly used: these may allow trade-offs within a defined subsystem (e.g., the building envelope) or provide designers with structured choices through libraries of pre-simulated reference buildings housed in specialized databases. As jurisdictions broaden performance pathways, the regulatory value proposition increases further when additional metrics, especially CO_2 emissions, are incorporated into compliance, enabling codes to align more directly with zero-carbon-ready trajectories rather than energy-only benchmarks [43-45].

A further institutional innovation is the growing adoption of "stretch" codes, alternative compliance pathways or supplemental codes that are intentionally more stringent than the base code. Stretch codes may be supported through utility incentives, adopted voluntarily by local jurisdictions, or designed explicitly as a transitional mechanism that is expected to become mandatory overtime. Illustrative examples include the Massachusetts Stretch Code, which establishes advanced requirements that municipalities may opt into, and the British Columbia Step Code, which structures compliance as a sequence of incremental performance tiers intended to culminate in net-zero-energy readiness by 2032 [46-48]. The stretch-code model offers several strategic advantages: it enhances regulatory predictability, provides industry with clearer forward signals, enables controlled experimentation with new provisions, and creates space for technical assistance (e.g., compliance tools and workforce training) before more stringent requirements are embedded in law. It also allows sub-jurisdictions to adopt more ambitious standards than their parent jurisdiction when justified by local market readiness, climatic conditions, or political priorities, thereby functioning as a policy laboratory for broader code evolution.

3. Conclusion

The present decade constitutes a decisive window for achieving the intermediate milestones required to transform the buildings sector in line with net-zero objectives by 2050. Yet, most of the technologies, deployment rates, and enabling approaches necessary to deliver zero-carbon-ready buildings remain misaligned with the trajectory implied by the IEA Net Zero Emissions by 2050 (NZE) Scenario, indicating a persistent implementation gap between ambition and realized progress. In addition, the urgency is acute. Rapid deployment of all currently available clean and high-efficiency building technologies throughout the 2020s must occur in parallel with strategic preparation for the next wave of innovations required to meet longer-term decarbonization imperatives. This acceleration must be pursued while also advancing co-benefits that are increasingly central to policy legitimacy and societal uptake: strengthening energy security, improving indoor comfort and health outcomes, lowering household and commercial energy expenditures, and supporting employment creation across construction, manufacturing, and services. The recent energy crisis, characterized by elevated and volatile energy prices and heightened geopolitical concerns surrounding supply security, has further amplified the strategic rationale for expediting the clean-energy transition in buildings, not merely as a climate necessity but as a resilience and affordability imperative.

Delivering this transition requires coordinated, system-level collaboration across the buildings value chain and its associated supply networks. Technology innovators, manufacturers, contractors, builders, architects, engineers, urban planners, regulators, and researchers must align design standards, product availability, workforce capabilities, and regulatory requirements, supported by policy frameworks that de-risk investment and accelerate adoption. When synchronized effectively, such collaboration can generate regionally tailored solutions that reduce fossil-fuel dependence across the full building life cycle, from material production and construction to operation, renovation, and end-of-life, while enabling scalable, cost-effective renovation pathways. In addition, end users can exert meaningful short-term influence on demand reduction through behavioral and operational measures, including adjustments to thermostat set points and energy-use practices in residential and commercial buildings, which can yield immediate reductions in energy consumption and peak loads.

A core constraint on achieving 2030-aligned milestones is the upfront capital cost of clean and efficient technologies, particularly when compared with incumbent fossil-based systems or lower-efficiency alternatives that may appear cheaper at the point of purchase. Addressing this barrier requires the rapid maturation of financial and business models that lower initial costs and improve affordability, such as targeted subsidies, concessional finance, preferential tariff structures, tax incentives, and other market-shaping instruments that accelerate deployment while reducing payback horizons. Moreover, Regulatory modernization is equally essential. Building codes, minimum energy performance standards, and compliance mechanisms must be strengthened and updated, with greater cross-country harmonization where feasible to reduce fragmentation and improve enforcement. Streamlined and standardized implementation practices can reduce transaction costs and enhance compliance at scale. Finally, the transition is constrained by a workforce bottleneck: expanding education and vocational training for the installation, commissioning, and maintenance of clean, efficient building technologies is critical to ensuring quality delivery, avoiding performance gaps, and sustaining market growth.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, M.A., and M.K.; methodology, M.A., and M.K.; validation, M.A., and M.K.; investigation, M.A., and M.K.; resources, M.A., and M.K.; data curation, M.A., and M.K.; writing, original draft preparation, M.A., and M.K.; writing, review and editing, M.A., and M.K.; visualization, M.A., and M.K.; project administration, M.A., and M.K.;

Funding: Please add: This research received no external funding.

Acknowledgments: The authors would like to express their sincere appreciation to the Libyan Center for Sustainable Development Research, Al-Khums, Libya, for its valuable academic support and institutional facilitation that contributed to the completion and publication of this article.

Conflicts of Interest: The authors declare no conflicts of interest.

References:

[1] F. Ascione, S. Nižetić, and F. Wang, "Future technologies for building sector to accelerate energy transition," *Energy Build.*, vol. 326, no. 115044, p. 115044, 2025.

[2] A. Horzela-Miś and J. Semrau, "The role of renewable energy and storage technologies in sustainable development: simulation in the construction industry," *Front. Energy Res.*, vol. 13, 2025.

[3] K. M. Omemen and M. O. Aldbbah, "Climate change: Key contributors and sustainable solutions," *IJEES*, pp. 10–27, 2025.

[4] M. W. Hassan, A. Manowska, and T. Kienberger, "A breakthrough in achieving carbon neutrality in Poland: Integration of renewable energy sources and Poland's 2040 energy policy," *Energy Rep.*, vol. 13, pp. 653–669, 2025.

[5] F. Khalifa and M. Marzouk, "Integrated blockchain and Digital Twin framework for sustainable building energy management," *J. Ind. Inf. Integr.*, vol. 43, no. 100747, p. 100747, 2025.

[6] A. M. Makhzom *et al.*, "Carbon dioxide Life Cycle Assessment of the energy industry sector in Libya: A case study," *IJEES*, pp. 145–163, 2023.

[7] B. Mignacca, T. Sainati, and G. Locatelli, "Financing energy technologies from invention to innovation: A novel analytical framework," *Renew. Sustain. Energy Rev.*, vol. 211, no. 115288, p. 115288, 2025.

[8] M. Khaleel and M. Elbar, "Exploring the rapid growth of solar photovoltaics in the European Union," *IJEES*, pp. 61–68, 2024.

[9] X. Tian, C. An, and Z. Chen, "The role of clean energy in achieving decarbonization of electricity generation, transportation, and heating sectors by 2050: A meta-analysis review," *Renew. Sustain. Energy Rev.*, vol. 182, no. 113404, p. 113404, 2023.

[10] Y. Nassar and M. Khaleel, "Sustainable development and the surge in electricity demand across emerging economies," *IJEES*, pp. 51–60, 2024.

[11] M. Khaleel, I. Imbayah, Y. Nassar, and H. J. El-Khozondar, "Renewable energy transition pathways and net-zero strategies," *IJEES*, pp. 01–16, 2025.

[12] L. Chen *et al.*, “Green building practices to integrate renewable energy in the construction sector: a review,” *Environ. Chem. Lett.*, vol. 22, no. 2, pp. 751–784, 2024.

[13] N. M. Muhaisen and M. M. Graisa, “The effect of biodiesel on the diesel engine,” *IJEES*, pp. 36–45, 2024.

[14] M. Khaleel, Z. Yusupov, B. Alfalh, M. T. Guneser, Y. Nassar, and H. El-Khozondar, “Impact of smart grid technologies on sustainable urban development: DOI: 10.5281/zenodo.11577746,” *IJEES*, pp. 62–82, 2024.

[15] J. Min *et al.*, “The effect of carbon dioxide emissions on the building energy efficiency,” *Fuel (Lond.)*, vol. 326, no. 124842, p. 124842, 2022.

[16] M. Khaleel *et al.*, “Battery technologies In electrical power Systems: Pioneering secure energy transitions,” *J. Power Sources*, vol. 653, no. 237709, p. 237709, 2025.

[17] D. Tirelli and D. Besana, “Moving toward net zero carbon buildings to face global warming: A narrative review,” *Buildings*, vol. 13, no. 3, p. 684, 2023.

[18] M. Khaleel, Z. Yusupov, and S. Rekik, “Advancing hydrogen as a key driver for decarbonized power systems,” *Unconventional Resources*, vol. 9, no. 100278, p. 100278, 2026.

[19] J. Morris, Y.-H. H. Chen, A. Gurgel, J. Reilly, and A. Sokolov, “Net zero emissions of greenhouse gases by 2050: Achievable and at what cost?,” *Clim. Chang. Econ. (Singap)*, vol. 14, no. 04, 2023.

[20] O. A. Marzouk, “Expectations for the role of hydrogen and its derivatives in different sectors through analysis of the four energy scenarios: IEA-STEPS, IEA-NZE, IRENA-PES, and IRENA-1.5°C,” *Energies*, vol. 17, no. 3, p. 646, 2024.

[21] S. Zhang *et al.*, “Estimation of global building stocks by 2070: Unlocking renovation potential,” *Nexus*, vol. 1, no. 3, p. 100019, 2024.

[22] S. Zhong, B. Su, J. He, and T. S. Ng, “Moving towards a net-zero emissions economy in Indonesia,” *Sci. Total Environ.*, vol. 1001, no. 180542, p. 180542, 2025.

[23] M. Mohamad and A. Hesri, “Hydrogen storage methods: Opportunities, safety, risk, and compliance assessment,” *IJEES*, pp. 17–32, 2025.

[24] M. Khaleel and Z. Yusupov, “Advancing sustainable energy transitions: Insights on finance, policy, infrastructure, and demand-side integration,” *Unconventional Resources*, vol. 9, no. 100274, p. 100274, 2026.

[25] M. Khaleel *et al.*, “Harnessing nuclear power for sustainable electricity generation and achieving zero emissions,” *Energy Explor. Exploit.*, vol. 43, no. 3, pp. 1126–1148, 2025.

[26] M. W. Akram, M. F. Mohd Zublie, M. Hasanuzzaman, and N. A. Rahim, “Global prospects, advance technologies and policies of energy-saving and sustainable building systems: A review,” *Sustainability*, vol. 14, no. 3, p. 1316, 2022.

[27] K. A. Barber and M. Krarti, “A review of optimization based tools for design and control of building energy systems,” *Renew. Sustain. Energy Rev.*, vol. 160, no. 112359, p. 112359, 2022.

[28] C. Ding, J. Ke, M. Levine, J. Granderson, and N. Zhou, “Potential of artificial intelligence in reducing energy and carbon emissions of commercial buildings at scale,” *Nat. Commun.*, vol. 15, no. 1, p. 5916, 2024.

[29] H. Adun, J. D. Ampah, and M. Dagbasi, “Transitioning toward a zero-emission electricity sector in a net-zero pathway for Africa delivers contrasting energy, economic and sustainability synergies across the region,” *Environ. Sci. Technol.*, vol. 58, no. 35, pp. 15522–15538, 2024.

[30] A. Phupadtong, O. Chavalparit, K. Suwanteep, and T. Murayama, “Municipal emission pathways and economic performance toward net-zero emissions: A case study of Nakhon Ratchasima municipality, Thailand,” *J. Environ. Manage.*, vol. 347, no. 119098, p. 119098, 2023.

[31] G. Vats and R. Mathur, “A net-zero emissions energy system in India by 2050: An exploration,” *J. Clean. Prod.*, vol. 352, no. 131417, p. 131417, 2022.

[32] D. Nong, G. Verikios, S. Whitten, T. S. Brinsmead, D. Mason-D’Croz, and S. Rodriguez, “Early transition to near-zero emissions electricity and carbon dioxide removal is essential to achieve net-zero emissions at a low cost in Australia,” *Commun. Earth Environ.*, vol. 6, no. 1, p. 653, 2025.

[33] F. Tori, W. Bustamante, and S. Vera, “Analysis of Net Zero Energy Buildings public policies at the residential building sector: A comparison between Chile and selected countries,” *Energy Policy*, vol. 161, no. 112707, p. 112707, 2022.

[34] H. S. Moon, Y. H. Song, J. W. Lee, S. Hong, E. Kim, and S. W. Kim, “Implementation cost of net zero electricity system: Analysis based on Korean national target,” *Energy Policy*, vol. 188, no. 114095, p. 114095, 2024.

[35] M. Chen Austin and K. Chung-Camargo, “A perspective on bio-inspired approaches as sustainable proxy towards an accelerated net zero emission energy transition,” *Biomimetics (Basel)*, vol. 10, no. 12, p. 842, 2025.

[36] A. Lennon, M. Lunardi, B. Hallam, and P. R. Dias, “The aluminium demand risk of terawatt photovoltaics for net zero emissions by 2050,” *Nat. Sustain.*, vol. 5, no. 4, pp. 357–363, 2022.

[37] B. I. Oladapo, M. A. Olawumi, T. O. Olugbade, and S. O. Ismail, “Data analytics driving net zero tracker for renewable energy,” *Renew. Sustain. Energy Rev.*, vol. 208, no. 115061, p. 115061, 2025.

[38] A. Le, N. Rodrigo, N. Domingo, and S. Senaratne, “Policy mapping for net-zero-carbon buildings: Insights from leading countries,” *Buildings*, vol. 13, no. 11, p. 2766, 2023.

[39] C. van Reenen, T. van Reenen, K. Surridge, and L. Reynolds, “Net zero carbon buildings: Progress and challenges in South Africa,” in *Lecture Notes in Civil Engineering*, Singapore: Springer Nature Singapore, 2025, pp. 207–221.

[40] M. Aboualnaga and M. Elsharkawy, “Climate neutrality and global perspective for net zero policies and buildings,” in *Innovative Renewable Energy*, Cham: Springer Nature Switzerland, 2025, pp. 419–436.

[41] L. N. Hasan, G. Lizarralde, and E. Lachapelle, “The legitimation of private net zero emission building standards in the context of global decarbonization goals,” *Constr. Manage. Econ.*, vol. 43, no. 5, pp. 360–380, 2025.

[42] D. Satola *et al.*, “Comparative review of international approaches to net-zero buildings: Knowledge-sharing initiative to develop design strategies for greenhouse gas emissions reduction,” *Energy Sustain. Dev.*, vol. 71, pp. 291–306, 2022.

[43] F. Yu, W. Feng, J. Leng, Y. Wang, and Y. Bai, “Review of the U.s. policies, codes, and standards of zero-carbon buildings,” *Buildings*, vol. 12, no. 12, p. 2060, 2022.

[44] C. van Reenen *et al.*, “Stakeholders and their roles in the net zero carbon construction industry,” in *Green Energy and Technology*, Singapore: Springer Nature Singapore, 2025, pp. 41–61.

[45] W. Obergassel, C. Xia-Bauer, and S. Thomas, “Strengthening global climate governance and international cooperation for energy-efficient buildings,” *Energy Effic.*, vol. 16, no. 8, 2023.

[46] N. A. C. Mohammed, K. S. Grewal, M. A. Adesanya, S. Debnath, A. A. Farooque, and G. S. Selopal, “Net zero energy-ready buildings: A Canadian construction perspective and evaluation,” *Adv. Sustain. Syst.*, vol. 8, no. 12, 2024.

[47] U. Bhatia, “Implementing SDGs, ESG, and net zero strategies in construction: A case study,” in *Handbook of Construction Project Management*, Singapore: Springer Nature Singapore, 2025, pp. 1327–1371.

[48] M. Euston-Brown, Z. Cilliers, and L. Sibanda, “Net zero buildings: exploring the complexity of sector-wide transition in the new buildings sector in South African cities,” in *Urban Energy Transition*, Elsevier, 2026, pp. 235–266.