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Analysis of the Development Trends and Key Challenges of Zero Carbon Buildings in Tropical Islands

Qiankun Wang [1, 2, a], Ke Zhu [1, 2, b], Peiwen Guo [3, c],

Jiaji Zhang [1, 2, d], Zhihua Xiong [1, 2, e] and Haodong Wu [1, 2, f]

[1] Sanya Science and Education Innovation Park, Wuhan University of Technology, Sanya 572000, China;

[2] School of Civil Engineering and Architecture, Wuhan University of Technology, Wuhan 430070, China;

[3] School of Real Estate and Management Science, Chongqing University, Chongqing 400044, China .

[a] wangqk@whut.edu.cn, [b] zhuke2018@whut.edu.cn, [c] peiwen_guo@stu.cqu.edu.cn,

[d] zhangjiaji@whut.edu.cn, [e] 335255@whut.edu.cn, [f] 348458@whut.edu.cn

Abstract. In the context of global climate change, particularly in tropical island regions, the construction sector, a notable contributor to CO2 emissions, necessitates a concentrated effort towards enhancing energy efficiency and reducing emissions. This study delves into the evolution and the inherent challenges associated with the development of zero-carbon buildings in such environments. It commences with an examination of key global agreements and China's significant progress in its dual carbon strategy, with a specific focus on energy and emission reduction in the construction sector. The discourse then transitions to an in-depth analysis of the current state of zero-carbon building research in tropical islands, spotlighting the advancements made by Hainan's construction industry in the low-carbon transition and the deployment of zero-carbon technologies. The paper further articulates the emergence of zero-carbon buildings as a pivotal trend in future construction practices, underscoring the crucial role of integrated system design in realizing these objectives. Despite their theoretical and practical viability, zero-carbon buildings encounter significant implementation challenges in the unique context of tropical islands. These challenges include the need for precise system integration, the quantification of design parameters' impact on building performance, and the refinement of operational strategies for zero-carbon buildings. The study also highlights the critical need for targeted research and innovation in building materials and technologies, specifically adapted to the distinctive climatic conditions of tropical islands. This comprehensive analysis provides an extensive exploration of zero-carbon buildings in tropical settings, shedding light on the primary challenges and potential solutions, thereby offering valuable insights to foster sustainable growth in the construction sector.

Keywords: tropical islands; zero carbon buildings; research status; development trends; key challenges.

1. Introduction

The frequent occurrence of extreme weather events caused by climate change, rising sea levels, and damage to ecosystems pose significant risks to global society, economy, and environment [1]. The threat of global warming and extreme weather events is driving the international community to reach consensus on actions at multiple critical stages [2].

Promoting global energy conservation and carbon reduction is a continuous and arduous task. In 1992, the establishment of the United Nations Framework Convention on Climate Change (UNFCCC) laid the foundation for global climate action [3]. In 1997, Future Forest Company in the UK first proposed the concept of carbon neutrality. At the same time, the Kyoto Protocol establishes emission reduction responsibilities for both developing and developed countries [4]. However, it was not until the 21st COP (Conference of the Parties) in 2015 that the world finally established a more ambitious climate goal with the Paris Agreement [5]. The long-term goal of the Paris Agreement is to control the increase in global average temperature from pre industrial periods to within 2 degrees Celsius and strive to limit the temperature increase to within 1.5 degrees Celsius, in order to achieve a balance between anthropogenic emissions from greenhouse gas sources and removals by sinks by the second half of this century [6]. In 2018, the Intergovernmental Panel on Climate Change of the United Nations proposed in its Special Report on Global Warming of 1.5 ℃ that in order to achieve the goal of controlling global temperature rise at 1.5 ℃, net zero greenhouse gas emissions, also known as carbon neutrality [7], need to be achieved by 2050. Since 2019, more and more countries have proposed carbon neutrality goals, and the total number has exceeded 140. The concept of carbon neutrality is gradually gaining popularity in countries around the world.

According to data from the International Energy Agency (IEA), carbon emissions throughout the entire life cycle of buildings account for approximately 39% of global carbon dioxide (CO2) emissions, and the construction industry contributes significantly to global greenhouse gas emissions [8]. In order to achieve the carbon neutrality target by 2050 as scheduled, the construction departments of various countries have proposed a series of medium - and long-term emission reduction paths from the aspects of standard system, technological innovation, and policy system construction [9].

2. Research status

2.1 Implementing Carbon Strategy in Construction

In September 2020, China officially proposed the goals of peaking carbon emissions by 2030 and achieving carbon neutrality by 2060 at the 75th United Nations General Assembly [10]. In 2020, the national carbon dioxide emissions were 11.2 billion tons, including 4 billion tons of supply side carbon emissions and 7.2 billion tons of consumption side carbon emissions [11]. Supply side carbon emissions mainly include electricity and fuel, with electricity accounting for about 36%; The consumption side mainly includes industry, construction, transportation, etc., with industry accounting for 44%, construction accounting for 10%, and transportation accounting for 10%. The statistical results of global total annual fossil CO2 emissions by industry are shown in Figure 1.

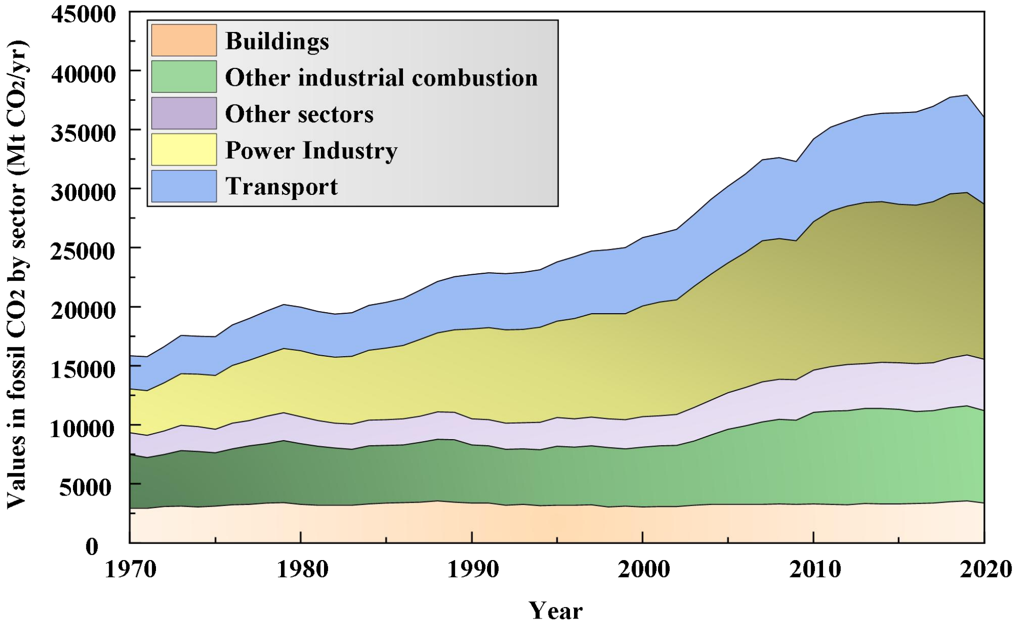

Figure 1 Global Annual Total Fossil CO_2 Emissions by Industry.

From the analysis in Figure 1, it can be seen that the percentage figures above refer to direct carbon emissions. Therefore, when discussing carbon emissions, we need to distinguish between direct carbon emissions, indirect carbon emissions, or implicit carbon emissions. For the convenience of statistical measurement, four direct carbon emission sectors were divided according to the IPCC definition [12]: industry, construction, transportation, and electricity. However, the carbon emissions of buildings are not only direct carbon emissions, but also indirect carbon emissions caused by the use of heat and electricity. Therefore, the combined direct and indirect carbon emissions of buildings are approximately 22%, with a portion of about 20% being implicit carbon emissions, mainly referring to carbon emissions caused by the consumption of building materials, which are actually related to industry [13]. Overall, the carbon emissions from the construction industry account for 42%, playing a crucial role in energy conservation and emission reduction [14].

2.2 Construction to zero-carbon buildings

China's building energy efficiency standards and strategies have undergone significant evolution and improvement from the basic concept of energy conservation in the early 1990s. In the 2000s, China implemented stricter building energy efficiency standards, mainly aimed at improving the energy efficiency of new buildings, including improving the thermal performance of building materials and introducing energy-saving technologies. In the 2010s, the concept of green buildings was introduced and expanded to include water efficiency, materials, and indoor environmental quality. The 13th Five-Year Plan (2016-2020) and the 14th Five-Year Plan (2021-2025) further emphasize the comprehensive implementation of green building standards and the energy-saving improvement of new buildings. The 40 year development history of building energy efficiency in China is shown in Figure 2 (Note: Figure 2 has been supplemented and improved on the basis of reference [15].).

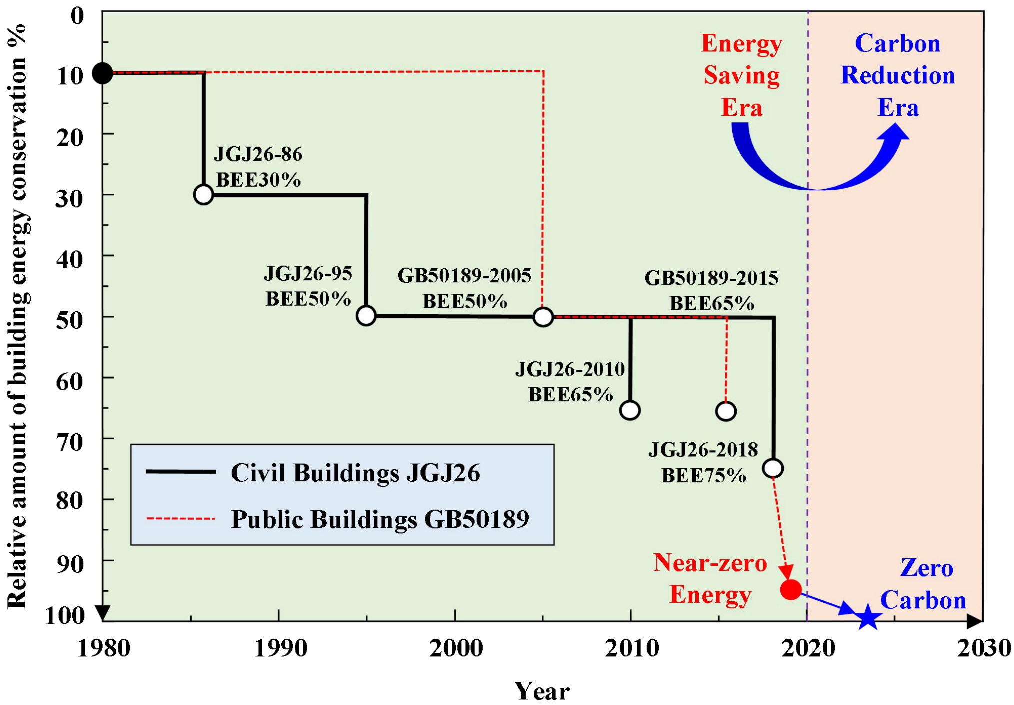

Figure 2 40 Year Development History of Energy Efficiency in Chinese Buildings.

Analysis of Figure 2 elucidates the evolutionary trajectory of China's building energy efficiency (BEE) standards over a span of 40 years, transitioning from rudimentary requirements to comprehensive criteria that encompass energy efficiency, environmental impact, and sustainability. This progression has marked a significant three-stage advancement in the energy efficiency rates for new buildings, achieving successive benchmarks of 30%, 50%, and 65% improvements. Building on these achievements, the "Design Standard for Energy Efficiency of Residential Buildings in Severe Cold and Cold Zones" (JGJ26-2018) has further propelled the adoption of a 75% energy-saving standard for residential buildings in regions characterized by severe cold. Concurrently, the "Technical Standard for Near-zero Energy Buildings" (GB/T51350-2019) has been pivotal in steering the industry towards realizing high energy efficiency and low energy consumption, thereby nearing the goal of zero energy consumption in buildings. The "Zero Carbon Building Technical Standards (Draft for Review)", authored by the China Academy of Building Research Co., Ltd. and the China Association of Building Energy Efficiency, successfully passed the review process in 2023. This standard, for the first time, defines the concepts of low-carbon, near-zero carbon, and zero-carbon buildings/regions. Furthermore, it introduces graded control indicators based on two metrics: absolute carbon emission intensity and relative carbon reduction rate. The enactment and application of these standards significantly bolster the shift in China's building sector from the "dual control" of energy consumption to the "dual control" of carbon emissions, playing a pivotal role in steering the transformation towards enhanced environmental sustainability.

The 40 years of development in building energy efficiency indicate that China has played a great potential in passive energy conservation in buildings, and changing the development path has become an inevitable measure. Zero carbon buildings not only focus on energy conservation, but also balance or reduce carbon emissions through the building's own production capacity [16]. The design of zero carbon buildings emphasizes energy efficiency and sustainability, striving to achieve the highest level of energy conservation. The development of zero carbon buildings is the trend.

3. Development trends

3.1 Clean Energy, Green Infrastructure

The 14th Five-Year Plan period is a crucial period for implementing the dual carbon goals, and building energy conservation and green building development face greater challenges [17]. The Implementation Plan for Science and Technology to Support Carbon Peaking and Carbon Neutrality (2022-2030) issued by nine ministries including the Ministry of Science and Technology of China requires a focus on decarbonization, emission reduction, and energy efficiency enhancement, promoting the improvement of building energy and carbon reduction standards and the full process of carbon reduction. The Ministry of Housing and Urban Rural Development has released the "14th Five Year Plan for Building Energy Conservation and Green Building Development", which elevates the traditional "energy conservation emission reduction" to "energy conservation production capacity carbon reduction", providing a new technological means for zero carbon buildings.

Hainan Island belongs to a tropical monsoon marine climate, with significant characteristics such as high temperature, high humidity, high salinity, high seismic fortification intensity, and frequent typhoons. The solar radiation ability is strong, and abundant renewable resources of light and heat can be utilized [18]. The entire island has a long summer and no winter, with a small temperature difference between day and night, and a high demand for building refrigeration energy consumption. Building a clean energy island in Hainan is inseparable from the clean and low-carbon transformation in the construction industry. The research and utilization of solar energy buildings with green, low-carbon, and zero carbon as the main body has become the main way to achieve energy conservation and carbon reduction in the tropical island construction industry.

According to the policy requirements of Hainan Province, the green upgrading of infrastructure will be basically completed by 2025, and the clean energy island will take shape. Green buildings account for 80% of newly built buildings, encouraging the research and development of green and low-carbon technologies, and strengthening the exploration and innovative practice of cutting-edge green and low-carbon technologies [19]. The 14th Five Year Plan for the development of the construction industry in Hainan Province clearly proposes key tasks to accelerate the development of low-carbon and zero carbon buildings, and encourages the integration of prefabricated buildings with green buildings, ultra-low energy buildings, zero carbon buildings and other green and low-carbon technologies for demonstration and application.

3.2 Zero carbon architecture, system integration design

At the current stage, there are different definitions of zero carbon buildings at home and abroad, and they are still in the initial development stage of policy promotion and demonstration applications. There is currently no technology system and successful experience to learn from. At the same time, the energy-saving design of buildings is shifting from a passive priority and active optimization model to a system integration model that combines the main and passive components [20]. This means that not only passive energy-saving measures of the building itself need to be considered, but also active energy-saving technologies such as intelligent control systems and renewable energy utilization need to be systematically integrated [21-25].

It is worth noting that system integration design, as a fundamental methodology, is a significant breakthrough in traditional architectural design concepts, providing an important reference framework and significant guidance for the design and implementation of zero carbon buildings. The integrated design of zero carbon building systems emphasizes the perspective of building energy and material flow, coordinating and integrating various aspects of the building from multiple dimensions, including energy consumption, energy conservation, production capacity, and intelligence [26]. This methodology has multiple benefits for achieving zero carbon building goals. From the perspective of energy consumption, system integration design focuses on considering energy efficiency in the early stages of building design, and reduces energy demand through passive design strategies such as optimizing building orientation, natural ventilation, and sunlight utilization. In terms of energy conservation, emphasis is placed on using efficient equipment and technologies, such as efficient insulation materials, LED lighting, and efficient HVAC systems, to reduce energy consumption. As for production capacity, system integration design promotes the integration of renewable energy technologies in buildings, such as solar photovoltaic panels and wind power generation, allowing buildings to not only meet their own energy needs, but also deliver surplus energy to the grid. In terms of intelligence, the use of intelligent design and management can improve the comprehensive energy efficiency of zero carbon buildings.

Overall, system integration design provides a diverse and comprehensive solution for zero carbon buildings. Although zero carbon building standards vary in different countries, the multi-dimensional and comprehensive methodology of system integration design provides strong guidance for achieving zero carbon emissions during building operation [27].

4. Key challenges

The analysis of research status and development trends shows that although system integration design provides a basic methodology for zero carbon buildings, the development of zero carbon buildings still faces many challenges in special environments such as tropical islands, especially in Hainan. These challenges mainly focus on: how to accurately identify energy saving and production capacity intelligent systems and their design parameters; How to finely quantify the relationship between system design parameters and building performance; How to actively optimize the technical and economic comprehensive goals of zero carbon operation design schemes. The exploration and resolution of these issues are key to promoting the transformation and upgrading of Hainan's construction industry and achieving green and sustainable development. The specific analysis is as follows:

(1) The integration of energy utilization and energy-saving systems is particularly crucial in the design of zero carbon buildings on tropical islands. The climate characteristics of tropical islands, such as sustained high temperatures, high humidity, and strong sunlight, pose special challenges to the energy consumption and comfort of buildings. Effective energy system design requires the use of natural ventilation and sunlight, while reducing reliance on artificial cooling systems. The design of energy-saving systems should consider efficient insulation materials and appropriate window designs to reduce the entry of heat and the loss of cold air.

(2) Accurate quantitative modeling is the technical foundation for achieving efficient operation of these systems. By utilizing advanced building simulation technologies and software, such as building information models and energy simulation tools, detailed predictions and analyses of building energy consumption, indoor environment, and renewable energy utilization can be made. This refined modeling method enables designers to more accurately understand and predict the performance of buildings in actual operation, and provides scientific basis for optimizing design.

(3) Optimizing the design of energy consumption, energy conservation, production capacity, and intelligent systems is a key step towards achieving zero carbon goals. In the unique climate context of tropical islands, optimizing design requires comprehensive consideration of the building's geographical location, structure, material selection, energy system, and intelligent management. For example, natural ventilation systems, solar photovoltaic panels, and intelligent energy management systems can be used to improve the energy efficiency of buildings and enhance user comfort.

(4) Faced with the special climate conditions and environmental requirements of tropical island areas, the design of zero carbon buildings requires more in-depth research and innovation. This includes considering local energy resources, such as abundant solar and wind energy, as well as building materials and technologies adapted to high humidity environments. In addition, the application of intelligent management systems, such as sensors and control systems for energy and environmental monitoring, will be key to achieving efficient energy conservation and user comfort.

In summary, although system integration design provides a basic framework for the development of zero carbon buildings on tropical islands, in practical applications, more in-depth analysis and optimization design of energy consumption, energy conservation, production capacity, and intelligent systems are still needed. By addressing these key issues, not only can we promote the transformation and upgrading of Hainan's construction industry, but we can also promote zero carbon buildings to become integrated new green building products, achieving green and sustainable development of the construction industry.

5. Conclusion

(1) Current Status: The world, particularly regions encompassing tropical islands, is confronting acute challenges posed by climate change. The construction sector, a significant contributor to CO2 emissions, has emerged as a critical area for energy efficiency and emissions mitigation. In response to these challenges, China has demonstrated notable advancements in executing its dual carbon strategy, particularly by integrating stringent energy-saving standards and the concept of sustainable architecture into its construction industry. This strategic shift is instrumental in aligning the sector with the objectives of zero-carbon development.

(2) Future Directions: The trajectory of the construction industry is increasingly veering towards zero-carbon buildings, viewed as a paradigm shift for future development. In tropical island environments, such as Hainan Island, the natural abundance of resources and specific climatic conditions favor the research and implementation of zero-carbon structures. The Hainan construction sector is actively enhancing the research, development, and application of green and zero-carbon building technologies. This proactive approach is pivotal in aiding the realization of carbon neutrality objectives.

(3) Critical Challenges: While zero-carbon buildings hold immense potential in tropical island settings, their realization faces a spectrum of challenges. Key among these is the precise identification and integration of systems for energy utilization, conservation, production, and intelligent control. Additionally, there is a need for meticulous quantification of the influence of system design parameters on the overall performance of buildings. Optimizing the design framework for zero-carbon operations is also crucial. Furthermore, the unique climatic conditions of tropical islands necessitate in-depth research and innovative approaches in building materials and technologies to ensure adaptability to high temperature and humidity environments.

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References

[1] Zhu Penghu，Zhang Zuopeng，Lin Boqiang. Understanding spatial evolution of global climate change risk: Insights from convergence analysis. Journal of Cleaner Production, 2023, 413: 137423. https://doi.org/10.1016/j.jclepro.2023.137423.

[2] Wang Changcheng，Geng Liuna，Rodr, et al. How and when higher climate change risk perception promotes less climate change inaction. Journal of Cleaner Production, 2021, 321: 128952. https://doi.org/10.1016/j.jclepro.2021.128952.

[3] The United Nations Framework Convention on Climate Change. What is the United Nations Framework Convention on Climate Change [Z]. 2022. Available online: https://unfccc.int/process-and-meetings/what-is-the-united-nations-framework-convention-on-climate-change (accessed on 7 October, 2023).

[4] The United Nations Framework Convention on Climate Change. The United Nations Framework Convention on Climate Change What is the Kyoto Protocol? [Z]. Available online: https://unfccc.int/zh/kyoto_protocol (accessed on 7 October, 2023).

[5] The United Nations Framework Convention on Climate Change. The Paris Agreement [Z]. Available online: https://unfccc.int/process-and-meetings/the-paris-agreement (accessed on 7 October, 2023).

[6] Sun Ruoshui，Gao Xiang，Deng Liangchun, et al. Is the Paris rulebook sufficient for effective implementation of Paris Agreement? Advances in Climate Change Research, 2022, 13(4): 600-611. https://doi.org/10.1016/j.accre.2022.05.003.

[7] Zhang Sirui，Bai Xiaoyong，Zhao Cuiwei, et al. China's carbon budget inventory from 1997 to 2017 and its challenges to achieving carbon neutral strategies. Journal of Cleaner Production, 2022, 347: 130966. https://doi.org/10.1016/j.jclepro.2022.130966.

[8] International Energy Agency. Global CO2 emissions by sector, 2019-2022 [Z]. 2022. Available online: https://www.iea.org/data-and-statistics/charts/global-co2-emissions-by-sector-2019-2022 (accessed on 7 October, 2023).

[9] Too Judy，Ejohwomu Obuks A.，Hui Felixnm K.P., et al. Framework for standardising carbon neutrality in building projects. Journal of Cleaner Production, 2022, 373: 133858. https://doi.org/10.1016/j.jclepro.2022.133858.

[10] Shi Xiaoliang，Zhang Jiayi，Lu Shuaiyu, et al. China carbon neutralization research status and research frontier tracking. Frontiers in Environmental Science, 2022, 10: 896524. https://doi.org/10.3389/fenvs.2022.896524.

[11] China Building Energy Conservation Association. 2022 China Urban and Rural Construction Carbon Emission Series Research Report [Z]. 2023. Available online: https://www.cabee.org/site/content/24420.html (accessed on 7 October, 2023).

[12] Iturbide M，Gutierrez JM，Alves LM, et al. An update of IPCC climate reference regions for subcontinental analysis of climate model data: Definition and aggregated datasets. Earth System Science Data, 2020, 12(4): 2959-2970. https://doi.org/10.5194/essd-12-2959-2020.

[13] En Lai Ke，Rahiman Nafisah Abdul，Othman Norazam, et al. Quantification process of carbon emissions in the construction industry. Energy and Buildings, 2023, 289: 113025. https://doi.org/10.1016/j.enbuild.2023.113025.

[14] Zhou Ying，Hu Dan，Wang Tong, et al. Decoupling effect and spatial-temporal characteristics of carbon emissions from construction industry in China. Journal of Cleaner Production, 2023, 419: 138243. https://doi.org/10.1016/j.jclepro.2023.138243.

[15] Xu Wei，Yang Xinyan，Zhang Shicong. Key issues and solutions for the development of near zero energy buildings in China. Building Science, 2018, 34(12): 165-173. https://doi.org/10.13614/j.cnki.11-1962/tu.2018.12.25.

[16] Ministry of Housing and Urban Rural Development of the People's Republic of China. Notice of the General Office of the Ministry of Housing and Urban Rural Development on Public Solicitation of Comments on the National Standard "Zero Carbon Building Technology Standard (Draft for Comments)" [Z]. 2023. Available online: https://www.mohurd.gov.cn/gongkai/zhengce/zhengcefilelib/202307/20230724_773337.html (accessed on 7 October, 2023).

[17] The Central People's Government of the People's Republic of China. Notice of the Ministry of Housing and Urban Rural Development on Issuing the 14th Five Year Plan for Building Energy Conservation and Green Building Development [Z]. 2022. Available online: https://www.gov.cn/zhengce/zhengceku/2022-03/12/content_5678698.htm (accessed on 7 October, 2023).

[18] Ministry of Housing and Urban Rural Development of the People's Republic of China. Hainan Building Prefabricated Buildings Suitable for Tropical Island Characteristics [Z]. 2023. Available online: https://www.gov.cn/zhengce/zhengceku/2022-03/12/content_5678698.htm (accessed on 7 October, 2023).

[19] Hainan Provincial Department of Housing and Urban Rural Development. Notice on Issuing the Three Year Action Plan for the Development and Improvement of Prefabricated Buildings (Green Buildings) in Hainan Province (2023-2025) [Z]. 2023. Available online: https://zjt.hainan.gov.cn/szjt/0404/202311/ee84db1de1e844bba234994c958c9579.shtml?ddtab=true (accessed on 7 October, 2023).

[20] Şirin Ceylin，Goggins Jamie，Hajdukiewicz Magdalena. A review on building-integrated photovoltaic/thermal systems for green buildings Applied Thermal Engineering, 2023, 229: 120607. https://doi.org/10.1016/j.applthermaleng.2023.120607.

[21] Kim Sojung，Kim Sumin. Design of an agrivoltaic system with building integrated photovoltaics. Agronomy, 2023, 13(2140): 2140. https://doi.org/10.3390/agronomy13082140.

[22] Gaur M. K.，Shrivastava Amit，Pandit R. K. Performance analysis and sustainability assessment of a building integrated solar PV system. International Journal of Ambient Energy, 2024, 45(1): 2283762. https://doi.org/10.1080/01430750.2023.2283762.

[23] Cho Mincheol，Aki Hirohisa，Kodaira Daisuke. Design and implementation of power management system integrated with cooperative systems for an apartment building. Journal of Building Engineering, 2023, 73: 106809. https://doi.org/10.1016/j.jobe.2023.106809.

[24] Zhao Guangling，Clarke Joanna，Searle Justin, et al. Economic analysis of integrating photovoltaics and battery energy storage system in an office building. Energy and Buildings, 2023, 284: 112885. https://doi.org/10.1016/j.enbuild.2023.112885.

[25] Naserabad Sadegh Nikbakht，Vakilabadi Moslem Akbari，Ahmadi Mohammad Hossein. Commercial building integrated energy system: Sizing and energy-economic assessment. International Journal of Low-Carbon Technologies, 2023, 18: 714-726. https://doi.org/10.1093/ijlct/ctad050.

[26] Zhang Shicong，Liu Changping，Wang Ke, et al. Research on the definition of zero-carbon buildings and carbon emission calculation boundaries. Building Science, 2022, 38(12): 283-290. https://doi.org/10.13614/j.cnki.11-1962/tu.2022.12.34.

[27] Liu Zhengguang. A review of data-driven smart building-integrated photovoltaic systems: Challenges and objectives Energy, 2023, 263(Part E): 126082. https://doi.org/10.1016/j.energy.2022.126082.