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Sustainable Development Framework for Low-Carbon Building Transition

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Abstract: To achieve the dual carbon goals, effective approaches to building sustainability are proposed from four perspectives: low-carbon building design, low-carbon building energy use, low-carbon building materials, and low-carbon construction methods. How to achieve low-carbon building design is discussed through five aspects: the building itself, lighting, windows, landscape gardening, and rainwater recycling. Moreover, how to achieve low-carbon building energy use is explored through four aspects: solar energy, bioenergy, wind energy, and heating and cooling. Finally, the contributions of green transformation to sustainable development are summarized and concluded.

Keywords: Low-Carbon, Building, Sustainable Development

1. Introduction

On September 22,2020, President Xi Jinping announced at the 75th United Nations General Assembly that China aims to peak its carbon dioxide emissions before 2030 and achieve carbon neutrality by 2060[1]. On October 26,2020, the State Council released the 'Action Plan for Carbon Peak Before 2030' [2], emphasizing the integration of carbon peak goals into all aspects of economic and social development. Significant challenges are posed to the construction industry by achieving these dual carbon targets, which has high energy consumption and carbon emissions. According to the 2020 China Building Energy Consumption Research Report, the total energy consumption of buildings nationwide in 2018 was 2.147 billion tce, accounting for 46.5% of the country's total energy consumption, and the total carbon emissions from buildings nationwide in 2018 were 4.93 billion tons, representing 51.3% of the country's total carbon emissions[3]. The data indicates that steel and cement, the primary materials used in construction, account for approximately 28% of China's total CO_2 emissions, and the carbon emissions from the entire life cycle of buildings have surpassed 40% of China's total carbon emissions. Therefore, the construction industry will undergo significant changes, with carbon reduction efforts necessitating transformations and innovations in material selection, transportation, construction methods, design concepts, and construction models to achieve low-carbon and sustainable development.

2. Effective Ways to Realize the Sustainable Development of Architecture

2.1 Low-Carbon Building Design

Building Itself: At the initial stage of architectural design, architects should embrace green building and sustainable development concepts, while emphasizing architectural design technology and considering all aspects comprehensively. Passive design methods should be utilized as much as possible, controlling the building's shape coefficient, maximizing the use of natural light and ventilation. The overall layout should facilitate the absorption of sunlight and increase indoor solar radiation to minimize energy demand. This can be achieved by designing fully bright units, increasing south-facing orientations, reducing north-south depths, minimizing interior walls, and adding glass sun rooms. Additionally, effective shading in summer is crucial, which involves appropriately reducing the area of east-west windows and installing metal sunshades or other shading measures on exterior windows to reduce the summer solar radiation entering the room, thereby lowering cooling energy consumption. Figure 1 shows a residential building in Atherton, California, USA, featuring a butterfly-shaped roof. The building faces south and features a large overhanging eave and sliding glass doors. The design ensures natural ventilation and summer shading while also allowing for the installation of solar panels on the roof. Figure 2 illustrates the Australian National Archives, whose facade is made of prefabricated concrete slabs. The concave and convex facade design projects sun angles and shadows at different times of the day.

Figure 1: The Atherton House in California.

Figure 2: The National Archives of Australia.

Lighting: Based on the varying levels of sunlight in different indoor and outdoor areas, the lighting design can implement independent control schemes for each area, with zoning to minimize energy loss. The Guomao Tiancheng Community in Xiamen, completed in 2022, adopted a zoned lighting control system to significantly reduce electricity costs. The Public Housing Exhibition Center in Tianjin Eco-City features an intelligent lighting system with light sensors and light tubes. The artificial lighting system in the Hearst Building in the United States can automatically adjust based on outdoor light conditions, and the installed sensors can automatically adjust the lighting to an energy-saving mode based on the indoor occupancy level.

Windows: To achieve low-carbon and sustainable development in buildings, the design of windows must ensure high air tightness and thermal insulation to minimize heat exchange between the interior and exterior and maintain a stable indoor temperature. The goal is to maximize the solar radiation received by the windows while minimizing heat loss. Additionally, windows should prevent overheating and glare. Low-emissivity double-glazed windows, such as those with three layers and two cavities, filled with inert gases like argon or krypton, are recommended. The 123m high Chengdu Raffles City, an ultra-high-definition water concrete building with large cantilevers, large openings, and irregular tilts, uses low-emissivity energy-saving glass. This glass, which is highly transparent to light but less permeable to heat radiation, reduces energy consumption by about 70% compared to ordinary transparent glass [3] (Figure 3). The window frames can be made from materials with low thermal conductivity to reduce thermal bridging, such as ultra-insulating composite materials or wood. Passive windows and doors with low overall heat transfer coefficients and integrated frames and glass can maintain a comfortable indoor temperature during extremely cold nights in cold temperate climate zones, ensuring minimal energy consumption.

Landscape Gardening: Enhancing the greening of buildings and community landscapes can increase the green coverage rate, thereby increasing the carbon sink value of buildings. Drought-resistant and cold-hardy evergreen plants can be planted on building rooftops to reduce solar radiation and heat loss in winter, effectively mitigating the urban heat island effect and improving the microclimate. The landscaping rate in Xiamen's Guomao Tiancheng Community is as high as 23%. Located on the coast, the community makes full use of marine carbon sinks, with greenery including mangroves, seagrass beds, and salt marshes, which help release oxygen, absorb carbon, transpire heat, and reduce noise and dust (Figure 4). The Zero Carbon World Building in Hong Kong has a green coverage rate of 60%, becoming the city's first urban native forest, which effectively mitigates the urban heat island effect and improves the surrounding microclimate quality [4].

Figure 3: Chengdu Raffles Square.

Figure 4: Xiamen Guomao Tiancheng Community.

Rainwater Recycling: In the practice of zero-carbon buildings, the Beddington Zero Carbon Community has designed a specialized water collection facility. Rainwater is directed through this facility to a storage tank and then processed through an automatic purification filtration system for use in cleaning and irrigation. According to statistics, this method can reduce water consumption by about one-third. Additionally, the community uses reed wetlands to filter domestic sewage, and the treated water can be reused for toilet flushing and irrigation [4]. The Hearst Building in the United States has designed its rooftop platform with rainwater collection capabilities, reducing the amount of rainwater entering the sewers by about 25%. Rainwater flows into a water recovery tank at the bottom of the building, where part of it is used to replenish the water lost by the building's air conditioning system due to evaporation, and the remaining water is used for plant irrigation and to replenish the water source for the building's courtyard waterfall [4,5]. The Church Building on Castle Road in Sydney has implemented a water balance system. By adopting advanced water-saving technologies, installing water-saving devices, using vacuum toilet technology, and setting up rooftop rainwater recovery facilities, the building achieves self-sufficiency in water supply, meeting its water needs [4].

2.2 Low-Carbon Energy Use in Buildings

According to statistics, the energy consumption for heating and cooling buildings accounts for about 50% of the total energy consumption over their entire life cycle, while lighting energy consumption is about 30%. By using natural renewable energy to replace conventional energy sources, the energy consumption of buildings can be significantly reduced, promoting their sustainable development. Therefore, it is essential to broaden and increase the application of renewable energy, achieving the recycling and energy balance of solar, wind, biomass, and shallow geothermal energy, and accelerating the transition to low-carbon building energy use.

Solar Energy: Installing solar photovoltaic panels and thermal panels on building roofs, known as the Building Integrated Photovoltaic (BIPV) system, enables buildings to fully utilize solar energy. This system integrates photovoltaic, thermal, and energy storage technologies, meeting the building's heating and power needs, and supplying excess electricity to the external grid and community lighting. For sloping roofs, the installation angle of the equipment is determined based on the solar conditions in different regions. Solar photovoltaic systems can also be combined with zinc plate technology, using indoor sensors to monitor indoor humidity and temperature, and track the storage of surplus electricity. The first zero-energy substation facility building in the United States, the "PG&E Larkin Substation," has a rooftop photovoltaic system that meets all its energy needs (Figure 5). The "Childhood House" at the border between France and Switzerland features photovoltaic and solar panels, ceiling lighting, and zinc plate technology, effectively reducing the building's energy consumption (Figure 6). The Sun Valley Micro-Exhaust Building in Germany achieves grid-connected solar photovoltaic power generation, as well as hot water supply, heating, and cooling, with an overall energy efficiency of 88%, saving 6.6 million kW h annually and reducing pollutant emissions by 8,672.4 t [3]. The Green Tomorrow Project in South Korea uses a photovoltaic and solar thermal system covering approximately 163 m^2 [2].

Figure 5: PG&E Larkin Substation.

Figure 6: Childhood Home.

Biomass Energy: In Hong Kong, the Zero Carbon World Building uses waste cooking oil or biodiesel as a biofuel to generate about 70% of its electricity, with the remainder coming from solar photovoltaic panels. Annually, the building generates 225,000 kWh of electricity from biomass and solar energy, reducing energy consumption by approximately 45% compared to traditional buildings. The surplus power can be supplied to the public grid, stored, or used by nearby buildings (Figure 7). China's first zero-carbon public building, the Shanghai Expo Zero Carbon Pavilion, uses the biogas produced from food waste for power generation (Figure 8). The Church Building on Castle Road in Sydney, built in 1903, is a pioneer in technology application, using the' biomass gasification' process. This process uses biomass materials such as residues from the harvesting of artificial forests and waste, which undergo heating reactions in an oxygen-deficient environment to convert carbon and hydrogen into combustible gases, ultimately used for power generation [4]. The project embodies the innovative concept of sustainable development for historical buildings and has successfully achieved a six-star rating in the Australian Green Building Evaluation System (NABERS) [4].

Figure 7: Zero Carbon World in Hong Kong.

Figure 8: Zero Carbon Pavilion in Shanghai Expo.

Wind Energy: In areas with strong winds, wind energy should be harnessed effectively. Small-scale and localized wind power generation can be considered. Based on the dominant summer wind direction in different regions, passive ventilation systems driven by wind can be installed on rooftops to maximize the use of natural wind. These systems can be equipped with wind cooling and filtration systems, and heat exchangers can be added indoors to ensure fresh indoor air, dehumidification, and heat recovery. Indoor energy-saving technologies such as floor ventilation and low-speed fans can also be utilized. The Beddington Zero Energy Community in the UK uses a 'wind cap' ventilation system (Figure 9). The Hongliangzhong Light Steel Passive Expert Apartment Building in Yutian County, Tangshan City, and the Shandong Huajian Aluminum Industry Huangshan Ecological Park Reception Center in Linqiu County, Shandong Province, were built according to the German Passive House Institute (PHI) standards. Their ventilation systems are designed to organize air flow and include an internal circulation system. Fresh air is supplied from the bottom of clean areas, while polluted air is discharged from locations such as bathrooms. All supply fans, exhaust fans, and compressors use fully variable frequency components, making the operation more energy-efficient (Figure 10).

Figure 9: Beddington Zero Energy Community

Figure 10: Huajian Aluminum Huangshan Reception Center

Heating and Cooling: In areas with high groundwater levels and a certain flow rate, the Tongli New Energy Town in Suzhou can use ground-source heat pump systems for winter heating and summer cooling. The Shanghai Expo Zero-Carbon Pavilion utilizes the water from the Huangpu River through its water source heat pump system. The Dian Gu Jinjiang Hotel uses 7.37 million tons of sewage annually, employing sewage source heat pump technology to provide both heating and cooling while promoting the recycling of urban sewage [3]. In the atrium of the Hearst Building in the United States, pipes are pre-buried in the radiant stone floor, which uses hot water injected in winter and cold water in summer to regulate indoor temperatures. The cold beam air conditioning system ensures fresh indoor air quality. Additionally, industrial cities can consider utilizing industrial waste heat and indoor stone floor radiant heating systems.

The Sustainable Energy Technology Research Center building of the University of Nottingham Ningbo China, completed in September 2008, utilizes solar panels, solar collectors, wind turbines, geothermal water pumps, rainwater collection systems, and electric 'smart' windows [4,5]. By harnessing renewable energy sources such as sunlight, precipitation, and ground heat, it achieves self-sufficiency in power supply, water resource utilization, heating, and cooling, making it China's first zero-carbon building. It is estimated that over the next 25 years, the building will save 448.9 t of coal and reduce carbon emissions by 1081.8 t [4,5] (Figure 11). The Public Housing Exhibition Center building in Tianjin Eco-City, inaugurated in 2012, employs 13 energy-saving and environmental protection technologies. These include 2600m² photovoltaic panels on the roof, soil heat source pumps, solar thermal insulation, natural ventilation, high-space floor air supply, heat recovery, cold and hot radiant fresh air, rainwater collection and utilization, and green roofs, all contributing to its goal of zero energy consumption [4], making it Tianjin's first zero-carbon building. The building generates 240,000 kWh of electricity annually, exceeding its annual electricity consumption of 210,000 kWh (Figure 12).

Figure 11: Sustainable Energy Technology Research Center of the University of Nottingham.

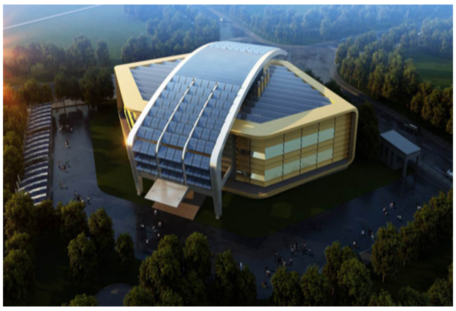

Figure 12: Public Housing Exhibition Center of Tianjin Eco-City.

2.3 Low Carbonization of Building Materials

Data indicates that 20% to 50% of the energy used for air conditioning heating and cooling is attributed to heat transfer through building exterior walls. Therefore, selecting appropriate thermal insulation materials for building wall structures and ensuring good sealing at the connections of the insulation layer are crucial. The thermal conductivity of the building envelope can be reduced by increasing the thickness of the insulation layer. For example, the roof, exterior walls, and floors can use thermal insulation materials, with the exterior walls using inorganic thermal insulation mortar. The thickness of the insulation layer must meet the standard requirements. In passive buildings, for instance, the thermal conductivity of the roof, exterior walls, and floors is reduced by 25%,46%, and 29% compared to ordinary energy-efficient buildings, respectively, with the insulation layer thickness being doubled. In the Hongliangzhong Light Steel Passive Expert Apartment Building in Yutian, Tangshan, the insulation material used is graphite polystyrene board and rock wool, which are installed between the main structure and the additional structure and bonded to ensure both insulation and fire protection, as well as a thermal break (Figure 13). The Country Garden Poly Nine Zhangtai Residential Project in Taizhou, China, uses a high-performance building envelope and an efficient full heat recovery fresh air system to achieve a constant temperature, humidity, and oxygen level in the living environment.

The building should primarily use non-transparent envelope structures, focusing on sustainable materials to minimize the use of steel and concrete, which are energy-intensive. For example, wooden building materials that can store carbon dioxide equivalent and avoid 50% of the carbon dioxide emissions from storage can be used. The Spokane Office Building in the United States, completed in September 2020, was designed to minimize the use of steel and concrete. It adopted an orthogonal glued timber frame structure, with the core cylinder made of large solid pieces of wood. The volume of wooden building materials exceeded approximately 3823 cubic meters (equivalent to storing 3713 tons of carbon dioxide equivalent, reducing 1437 tons of carbon dioxide emissions) (Figure 14). If the building is a reinforced concrete structure, gaps can be filled with hemp, lime, or coarse cotton insulation materials to enhance thermal inertia and seismic resistance. The envelope walls can use new eco-friendly porous bricks, hollow blocks, aerated concrete blocks, and additional thermal insulation layers. For interior walls, functional decoration materials can be used to improve indoor air quality.

Figure 13: Macro United Light Steel Passive Expert Apartment Building.

Figure 14: Spokane Office Building.

Concrete structures can use green, low-carbon, high-performance concrete to ensure strength while substituting limestone with other industrial waste materials, thereby reducing the carbon emissions from cement chemical reactions. High-performance fibers and other composite materials can be added to the cement matrix to enhance the tensile strength of concrete without increasing the cement content. Mineral admixtures, such as fly ash, industrial waste slag, tailings slag, or blast furnace slag (with a CO2 emission factor of 0.0265 kg-CO2/kg for blast furnace slag and 0.7466 kg-CO2/kg for cement), can be used to reduce the amount of cement that significantly increases carbon emissions. Recycled aggregates can be utilized to achieve secondary use of resources and promote the recycling of materials. For example, in the 330-meter-tall Guomao Phase III building tower A in Beijing, the 234-meter-tall CCTV new site building slab in Beijing, and the Datan Hydropower Station dam in Sichuan, the concrete strength grade exceeds C40, and more than 50% fly ash is added during design and construction. This ensures that the concrete meets the required strength while reducing dry shrinkage by over 20%. In the Shanghai World Expo Pudong temporary venue G area 1, slag powder and fly ash are used to replace 50%-60% of the cement content, and recycled aggregates, stone chips, and fine sand are used to replace 50%-60% of natural sand and gravel. This ensures the later strength and durability of the concrete, making it a typical example of low-carbon concrete technology application. For example, when the Hearst Building in the United States was built, its exterior wall, interior wall, floor and laying blocks were all selected from recyclable materials without pollutant discharge. In the process of material selection, the secondary use value of materials in the later period was fully considered. The building used a total of 10,480t of steel, with more than 85% of the recycled steel, saving about 26% of energy consumption compared with ordinary steel.

2.4 Low-Carbon Construction Method

Relevant data show that the energy saving incremental cost of green building in the construction stage accounts for about 60% of the total incremental cost, so it is necessary to establish the concept of green construction, realize the standardization of the whole process construction management, comprehensively consider the balance and coordination between economy and environment, and rationally use water resources.

In recent years, prefabricated construction has seen rapid development thanks to the strong promotion by the government. Prefabricated buildings have a short construction period and are characterized by mechanization and large-scale production, which results in lower carbon dioxide emissions and water conservation. Compared to traditional cast-in-place buildings, prefabricated buildings emit slightly more carbon dioxide during the production and transportation phases but significantly reduce emissions during construction. Additionally, their prefabricated components can be recycled and reused. Therefore, by controlling energy consumption in material production, reducing transportation distances, and improving transportation efficiency, prefabricated construction is an effective way for the construction industry to achieve the dual carbon goals and represents an inevitable trend in the industry's transformation and upgrading.

In construction, when attaching EPS board modules, special attention should be given to the corners of walls and door and window openings to ensure the integrity and thermal insulation of the wall. BIM technology can be used to construct a new energy system for ultra-low energy buildings and to create detailed three-dimensional simulations of construction nodes. Solid waste from construction can be processed using microbial treatment technology to convert waste into resources. Water-soluble high molecular flocculants can be used as slurry separation agents to effectively manage slurry pollution at construction sites.

3. Conclusion

To achieve the goals of carbon peak and carbon neutrality, it is essential for China's construction industry to pursue low-carbon and sustainable development. To meet these dual carbon targets, construction companies must undergo a green transformation to promote low-carbon development and energy conservation and emission reduction in the construction sector. From a policy perspective, it is crucial to strengthen energy-saving standards, enhance product efficiency, optimize industrial structures, fully tap into energy-saving potential, promote the use of efficient energy facilities, prioritize green building approvals, and provide economic incentives; continuously raise the energy-saving standards for new buildings, advance the energy-saving renovation of existing buildings, implement building energy consumption quotas and energy efficiency evaluation labels, and conduct performance assessments of low-carbon development in the construction sector. From an enterprise perspective, it is necessary to improve management mechanisms, set clear energy-saving goals, and enhance environmental protection awareness. From a technical perspective, it is essential to deepen the concept of energy conservation and emission reduction, prioritize passive energy-saving measures, accelerate the research and development of energy-saving materials, make rational use of geographical conditions, focus on operational energy consumption, and emphasize structural optimization analysis.

Therefore, it is essential to clarify the role of green transformation in sustainable development, accelerate the reform of production capacity framework in the construction industry, establish a low-carbon development system for green buildings, and promote the construction industry in China to develop towards low-carbon, green, and energy-efficient directions.

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