Research on Decarbonisation Path and Technological Innovation of Architectural Design under the Perspective of Sustainable Development

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Abstract: As the main energy use and carbon emissions sector in terms of climate change and under dual carbon goals, building sector takes low-carbon transformation as an important part of sustainable development. It mainly compiles the research status of extant evaluation metrics for low-carbon buildings and expresses a necessity to integrate design low-carbon building from the ecological, economic and social aspects, which provides a methodological basis for harmonizing architecture with the regional environment development. For three “dimensions”—planning and design; construction and operation; policy and evaluation systems—it highlights the importance of managing carbon emissions across the life cycle, while allowing collaboration among multiple stakeholders. In summary, this paper is focused on cutting-edge innovations in particular and corresponds with both the bulk of technological advances such as digital intelligent technology, renewable energy integration as well as the new type of low-carbon construction materials widely studied and considered capable of promoting low-carbon transformation of buildings has gained great attention. The findings show that, in aligning the construction industry with "green development" and achieving the strategic goal of “dual carbon”, organic integration of low-carbon pathways and technological innovations will play a significant supporting role.

1. Introduction

Energy consumption and carbon emissions are one of the two most essential challenges to sustainable human development, especially under extreme global climate change [1]. Since the building sector accounts for a large share of global energy demand and carbon emissions, it has been identified as a key target area for enabling low-carbon transformation [2]. Architectural design is the primary determinant of a building's operational energy consumption and materials use, and ultimately sets the trajectory for all later phases of the building life cycle [3]. It is significantly meaningful both theoretically and practically to develop architectural design from the angle of Lower-carbon road [4]. Scholars both at home and abroad, and practitioners in the industry have long been talking about energy conservation technology design but also green technologies; therefore, a research framework built around building energy efficiency specification, renewable energy utilization has formed with green buildings standard as the focus [5]. However, challenges remain such as approaches not being systematic enough, lack of technological innovation and disconnect between policy and practice [6]. Therefore, based on the background of sustainable development and macro governance objectives, this paper analyses low-carbon architecture design logic and practical demand, technical solution states in planning construction operation mutually reinforcing three stages and innovative technological breakthrough in accelerating industrialization transformation to promote low-carbon transformation of architectural design industry [7]. Through theory review and pathway analysis, this paper aims to provide reference ideas for the construction industry on its journey towards green development, and also achieves certain theoretical and practical value assisting in the realization of the "dual carbon" goals [8].

2. The Sustainability Logic of Low-Carbon Architectural Design

From a general strategy of sustainable development perspective low-carbon architecture design

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originates [9] Sustainable development emphasises the overall balance between economic, social and environmental dimensions [10]. Architectural design pays attention not only to the functional and aesthetic performance of a building but also energy consumption, resource use, and ecotectonics as an integral part of human life in production. With this logic, low-carbon architecture design is not only a technical choice for energy conservation and emission reduction, but also one of the important ways to achieve sustainable transformation of social life. The construction of positive guidance architectural design in the direction of energy conservation, environmental protection and health can solve the ecological environment pressure of human building, so that people and nature harmonious coexistence. Building Energy Balance

$$E_{total}=E_{heating}+E_{cooling}+E_{lighting}+E_{appliances} \quad (1)$$

The environmental impact of an architectural design with low-carbon usage is a treasure. Energy consumption and carbon emissions during the building lifecycle constitute a large portion of global greenhouse gas emissions. The construction industry is becoming increasingly energy-intensive as urbanization threatens to outpace it. Integrating green principles and low-carbon strategies in the design phase can reduce energy consumption and greenhouse gas emissions at a reduced level, reducing ecological impacts. Similarly, purposeful design tactically derives natural ventilation, daylighting and thermal performance to minimize the dependability on mechanical systems and maximizing natural resource use for a harmonious synergy with the environment.

Low-carbon building design from the economic point of view can promote industrial upgrading and green economic development. While this might increase upfront construction costs, the economic benefits typically pay back for themselves over time with reduced operational energy and maintenance savings. Green finance policies and carbon market mechanisms will be increasingly developed to support low-carbon buildings through the policy and finance system with strong emphasis on their economic benefits. Lowcarbon Buildings not only improve value and control cost management for developers and users, but also is the effective means of enhancing their market competitiveness.

Humane care — low-carbon building design is the embodiment of social value From this basis, the design of low-carbon architecture guarantees that in such a healthy building condition, the quality of the indoor environment optimized more and for human comfort living working and application to be much higher thus promote better improve people with well-being. Sustainable construction efforts, such as promoting low-carbon building design, not only improve the public's awareness of environmental protection but also urge residents to live green. And social, it in addition to alleviate carbon emissions, will establish eco-friendly, shared and sustainable development model for your long-term overall health folks and societal advancement. Carbon Emission Calculation

$$C=\sum_{i=1}^{n}(E_i\times EF_i) \quad (2)$$

3. Exploring Pathways for Low-Carbon Building Design

The strategic goals of low-carbon building design seldom can be accomplished using a single-oriented approach, and thus should also systematically consider a whole life-cycle perspective and realized by multi-dimensional and multi-stage collaborative development. These three periods — the early phases through modeling, the mid-to-late-stage of construction and operation, and then transitioning to macro-level policy land scape and evaluation systems supporting these trajectories — are different but interdependent and represent the entire arc pathway through building decarbonization. Combining theoretical and practical aspects of design and with groundbreaking policy instrument could assist more plausibly in achieving not just conserve energy but also ensure carbon reduction and sustainability goal by construction industry.

3.1 Low-Carbon Pathways in Planning and Design

Planning and Design The first step in decarbonization for buildings The energy efficiency and environmental impact of a building is largely influenced by the site selection and overall layout. So scientific selection of site through the overall planning is conducive to avoid ecologically fragile areas and great energy consumption zone; Priority is given to convenient transportation, resource conditions, so as to achieve a reduction in the source of energy consumption carbon emissions. A orderly arrangement of building cluster at spatial organization level can enhance ventilation, daylighting and microclimate condition. This reduces reliance on mechanical systems in the operation phase, paving the way for future low-carbon design.

One of the important directions for energy conservation is passive design for low-carbon buildings. To optimize the building orientation, optimizing facade construction and shading systems by numerical simulation to provide the best result in indoor thermal comfort together with an amount of energy criteria for air conditioning energy and lighting energy. The introduction of natural daylight and ventilation results in reduced energy costs, higher efficiency, and improved quality of the indoor environment. Simultaneously, the combination of regional climate characteristics and local design characteristics such as high thermal insulation in cold areas and ventilation, self-dissipating heat in hot cites can also achieve great energy efficiency improvement. Life Cycle Carbon Emission (LCA):

$$C_{LCA}=C_{design}+C_{construction}+C_{operation}+C_{demolition} \quad (3)$$

Opting for shades of green also matters in the design phase. For this reason, designers should prioritize renewable materials and low-carbon building products and recyclable items to limit the carbon footprint throughout the lifecycle of the building. The project uses low carbon timber structures, recycled concrete and low-energy glass materialsIt will significantly reduce carbon emissions and contribute to the green transformation of the construction materials industry. On the material level this means that durability and also maintainability especially linked to visible characteristics has to be weighted in decision processes, to avoid incessantly replacing things which is an unavoidable waste of resources on the consumer side.

Integrated design principles provide a structured pathway to realise low-carbon buildings. Building Information Modeling (BIM) and other digital tools can be integrated during design to provide accurate simulations and forecasts of energy consumption and carbon emissions, thereby optimizing the design-development process at conceptual stages of development. This is where creating integrated design strategies, fostering more collaboration between disciplines—melding architecture with environmental science and engineering technology—will be much better figures of merit for the sustainability of your designs. So here also in the planning and design stages, low-carbon pathway is not a clumping of independent breakthroughs, rather it is a steady stream of systematic synergy process which provides favourable conditions for different aspects so as to solidify its foundation for low-carbon development at all scales.

3.2 Low-Carbon Strategies for Construction and Operations Phases

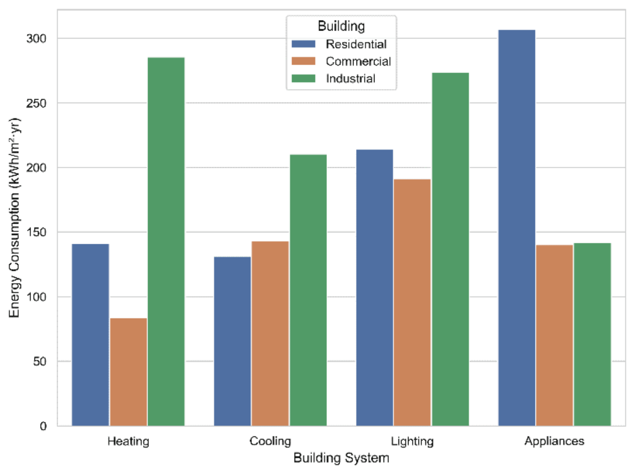

Figure 1 Building energy consumption by system and building type

The construction phase is also a critical point of resource consumption and greenhouse gas emissions in the life cycle of the building, such that how extensively low-carbon method are performed in this stage greatly influences final emission reduction performance. Promoting the use of prefabricated and modular building construction while preparing the site itself can significantly reduce both time and energy spent on its location, in addition to mitigating waste from construction activities. The introduction of sustainable construction-building materials waste classification and recycling, reclamation of water resources, energy-saving construction machinery and equipment greatly reduces environmental pollution during the building construction process, but also lays the foundation for sustainable dual development after completion as shown in fig. 1.

One of the key aspects or one part of low-carbon goals in building energy efficiency management is operation and maintenance energy management. The operations management of conventional buildings mistimed and leads to energy waste. Intelligent management systems in place allow real time monitoring and data analysis as well the provide insights based on operating conditions for dynamic adjustments across lighting, air-conditioning, elevators among other equipment to enhance energy utilization efficiency. Islam et al. proposed an IoT-based building energy consumption monitoring platform which is capable of issuing early warnings for abnormal energy usage and enable their owners to swiftly apply more effective energy-saving measures that significantly reduce operational carbon emissions.

Operators will need to use renewable energy as a primary operational carbon emissions control measure to account for the whole lifecycle of a building. A clean energy system that incorporates a high proportion of solar or wind (and/or geothermal heat pumps) within the building site achieves higher levels of energy independence from fossil fuels. Building Integrated Photovoltaics (BIPV) technology involves the combination of photovoltaic panels with building fa¿ades resulting in energy saving and power generation along with provision of clean energy for the functioning of buildings. Heat Transfer Through Building Envelope

$$Q=U\times A\times(T_{in}-T_{out}) \tag{4}$$

It is equally important to manage user engagement and behaviour for low-carbon operations. Also provide guidance and incentives for building occupants through intervention to develop energy saving awareness and green living habits help the building further reduce carbon emissions during run time. Second, an even more direct and low-tech way to help O&M & customers solicit feedback on performance facilitates detection of operational problems as they develop enabling gradual building adjustment and control. Apart from technologies and equipment, low-carbon pathways during construction as well operation & maintenance (O&M) phases also depend on the organic integration between management innovation and behavioral guidance to eventually realize minimal carbon objectives throughout the whole life cycle of buildings.

3.3 Policy and Evaluation System Support

Upscale and institutional controls will be required at the front of the low-carbon structures. National and local state, federal laws and regulations, clear energy efficiency standards and at least aspirational carbon reduction targets (of which there are many) clearly signal where the industry is headed. On the other hand, green building action plans, promulgation of rules for building energy efficiency codes and “dual carbon” strategy implementation have made phased objectives as well as regulations clearer to spur construction enterprises in design construction and operation process considering carbon emissions from a lifecycle view. These policies offer explicit limits and incentives for low-carbon action (as opposed to aspiration), even as prescriptive regulatory measures. Renewable Energy Contribution Ratio

$$R=\frac{E_{renewable}}{E_{total}}\times 100\% \tag{5}$$

The scientific metrics for low-carbon construction are featured by some green building evaluation systems. Including but not limited to globally recognized standards like LEED and BREEAM in the UK, – were further integrated into an international system more consistent with China’s existing Green Building Evaluation Labeling System that offers assessments based on multi-dimensional indicators for energy, materials, or environmental systems. These systems not only allow buildings to measure their low-carbon performance, but also give designers and developers intuitive blueprints for design optimization. Meanwhile, evaluation systems can not only provide a "yard-stick" but also a "path-guide," orienting the Construction industry to both sustainable development standards and more extensive approaches towards practice.

Low-carbon buildings policy is another area of concern around incentive mechanisms. Fiscal subsidies, tax breaks green finance and carbon trading; These are the ones that can make low-carbon construction better in economic conditions by governments. This is how you solve the capital insufficiency problem: by finding ways to pay for projects that meet certain criteria or certification levels related to clean energy systems, green building certifications. With the maturity of carbon market, carbon emission quota and building circulation right will be an important economic lever to actively promote enterprises to reduce emissions in the future.

An aspect of low-carbon buildings is less about how it serves each stakeholder more so than engaging the society. Governments, industry associations, research institutions and end-users have to collaboratively schedule a cooperative framework to propel interactions through the synergies of policymaking along with technology development and novel markets which act as facilitators for commercialization and actions facilitated by users on environmental processes. The low-carbon transition is fueled by user-driven elements such as green consumption and energy-conserve behaviors, while top-level design and technology-research institutions and intermediary associations can promote its objectives through standardization. This is not only the case of the role of restrictions and motivation towards policy and evaluation system support, but also a systematic low-carbon development security mechanism for the construction industry.

4. Technological Innovation and Future Trends in Building Decarbonization

The exciting actualization of building decarbonization is being driven by digital and intelligent technologies. --A better solution: Emerging technologies, including Building Information Modeling (BIM), the Internet of Things (IoT) and a digital twin enable architects and engineers fine-tune accurately simulate & predict a building energy consumption & its carbon emissions over its design entirely. This produces properly optimized design solutions, and truer wasted resources as a result. Simultaneously, intelligent management systems driven by big data and artificial intelligence enable real-time monitoring to control in a timely manner; help building equipment operate at the highest operating quality as much as possible, and greatly improve energy use. Not only the efficiency of lifecycle management is what move this transition attendance to digital space but technology creation as a mechanical driver realizing low carbon target,Invisible Green Performance in Figure 2 :

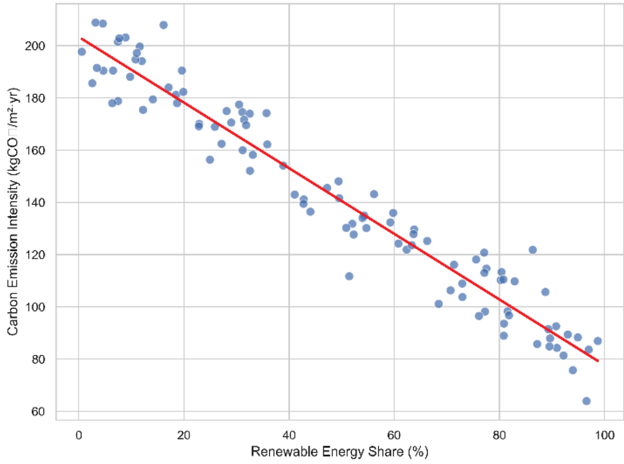

Figure 2 Carbon emission intensity vs renewable energy ratio

It proves clean energy generation by an integration of buildings with renewable energy source. Technologies that enable buildings to meet their own energy needs such as Building Integrated Photovoltaics (BIPV), Micro wind power systems, and ground-source heat pumps; make displacement of fossil fuel inputs related to heating a more likely event. The BIPV technology not only integrates the photovoltaic panels with the building body components (such as roof, curtain walls etc.) but also acts directly as electric power supplier in addition of protect structure: this is one approach for potential development direction identified towards the future developments of green buildings [10]. One among these promised options is the power storage expertise innovations, which can even improve the flexibleness and stability of constructing power methods hence cultivating self-reliant low-carbon buildings. Energy Saving Rate:

$$\eta=\frac{E_{baseline}-E_{optimized}}{E_{baseline}}\times 100\% \tag{6}$$

Selected renewable building materials and novel design configurations will provide additional opportunities for greenhouse gas (GHG) emissions reductions. Among these, carbon-capturing materials, ultra-high-performance concrete (UHPC), low energy-recycling variant achieving recycled concrete and Dual-Scale timber structures using glu-lam or cross laminated timber components receive significant consideration for the reduction of building frames carbon emissions. Timber, has a natural carbon sink property and self-renewability, low-carbon building design is one of the beneficial way out direction of timber structure. Optimization of energy consumption in the operational phase will again be ensured by the application of a modern insulating glass, low-emission coating and other optimal insulation materials. Invention of Materials Technology for carbon emissions production phase reduction drives Lead Industries Towards Sustainable Development.

Interdisciplinary and multilevel exploration will characterize the realization of future low carbon buildings. Low-carbon buildings must not only demand the best in a particular architectural discipline but should also call for innovative cross-pollination and analysis of multiple disciplines—such as environmental science, information science and materials science. It will gradually spread from the individual building to the overall aspects of community, and then focus on city and regional comprehensive planning for the utilization of concept low-carbon large-scale implementation. Furthermore, it will encourage regional gathering or form green cities a low-carob society . The gradual promotion of and construction in low-carbon transition mechanism in building sector will reduce policy support, meanwhile make the future development space more wider, which is one important way to realize "dual carbon" target as well as promote sustainable development.

5. Conclusion

The low-carbon transformation of the building sector, as one of the main industries contributing to energy consumption and carbon emissions, has gradually become an irresistible tide in recent years under the background of sustainable development and “dual carbon” goals. This paper, focusing on sustainable development top-level logic, analyses low-carbon building design systematically from the following perspectives: not just an environmental protection must but also a pillar to economic growth and social advancement. Architectural design, is the vital point of each life cycle, which is precisely a critical geometric position in its relation regarding green extent, since the later phases related to construction and operation process directly depend on it.

Based on the three coordination strata (planning / design, construction / operation and policy / evaluation systems), progress along a systematic constructing decarbonization path can only be accomplished by outlining the pathways that lead to more environment friendly low-carbon constructing design. In addition, low-carbon building certainly need to rely on scientific site selection and passive energy saving design in the early stage; green construction and intelligent management system during construction process and operation period; policy guidance as well as standardized evaluation system. This entire control can subsequently be spread across the industry ushering in a transition from particular person, ad hoc power effectivity remedies to systematic carbon discount regime.

This is mainly enabled by technological innovation, which makes it possible for low-carbon to be core to building. Smart is essential should increase a little bit further, the design/ deployment accuracy degree; RES integration gives its own independent energy clean system to net 0 buiding or houses. Novel low-carbon construction materials or structural innovations could offer new ways to reduce the total greenhouse gas emissions. Using multidisciplinary integration, low-carbon-building limits move from firm or structure-specific applications to urban and region-wide holistic optimization.

Low carbon buildings design is an important basis for achieving "carbon peak" and "carbon neutral", as well as the fundamental requirement to promote sustainable social development. In modern society, with the gradual strengthen of policy system improvement, technological innovation and public consciousness on environmental protection and lowcarbon advocating, in particular, the lowcarbon investment building will definitely play a more and more vital role for construction industry transformation and upgrading over time. This raises an area of interest for larger energy savings and emission reduction… without changing the function or quality of the built environment — an objective common to both academia and industry.

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