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Exploring Material Selection and Applications for Embedded Carbon Reduction in the Built Environment

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ABSTRACT
The building and construction industry is a significant contributor to global greenhouse gas emissions, with 37% of total emissions attributed to this sector. While efforts have primarily targeted operational carbon emissions, which stem from building operations like heating and cooling, the urgent need to address embodied carbon—associated with the materials used and their life cycle—has gained attention. This paper explores the critical role of material selection and innovative practices in reducing embedded carbon in the built environment. It highlights collaborative models and international cooperation essential for decarbonizing building materials to achieve net-zero emissions by mid-century. The findings underscore that embodied carbon currently represents a growing proportion of a building's overall carbon footprint, necessitating proactive measures in the design and construction phases. By integrating life cycle assessments and prioritizing sustainable material choices, stakeholders can significantly diminish carbon emissions and align with global climate goals. Through case studies and best practices, this research advocates for a comprehensive approach to carbon reduction that encompasses both operational and embodied emissions in the built environment.

Keywords: *embodied carbon, material selection, sustainable construction, life cycle assessment, net-zero emissions*

I. INTRODUCTION

The building and construction industry is by far the largest emitter of greenhouse gases, accounting for 37 percent of global emissions. The production and use of materials such as cement, steel and aluminum have a considerable carbon footprint. Historically, much of the industry's progress has focused on reducing buildings' "operational" carbon emissions - which come from heating, cooling, and lighting. Projections indicate that emissions from these operations will be reduced from 75 percent to 50 percent of the sector's total emissions over the next few decades.

However, solutions to mitigate the carbon emissions "embodied" in buildings - stemming from the design, production and deployment of materials such as cement, steel and aluminium - have fallen behind. [1]To effectively address this challenge, international action and cooperation must bring together all stakeholders across the entire life cycle of the construction sector, whether in informal or formal Settings.

Building Materials and Climate: Building a New Future, a report prepared by UNEP and the Yale Center for Ecosystems + Architecture within the framework of the Global Alliance for Architecture and Building and Construction (GlobalABC), highlights the urgent need for innovative collaborative models to decarbonize building materials[2-4]. These models are essential if we are to achieve the world's ambitious goal of net-zero emissions from the built environment sector by mid-century.

In addition, according to the International Energy Agency's 2023 accounting results on energy use and carbon emissions in the global construction industry in 2022, building operation and construction-related energy use accounts for 34% of global energy consumption, of which 30% is caused by building operation; Building operation and construction-related carbon emissions account for 37% of global carbon emissions, of which 27% are caused by building operation [5]. According to the Annual Development Research Report on China's Building Energy Efficiency in 2024, China's building carbon emissions account for 32% of the whole society's carbon emissions [6-9]. These construction carbon emissions are mainly caused by the energy consumption in the process of building operation and construction.

II. RELATED WORK

2.1. Carbon Reduction in the Built Environment

Embodied carbon is the carbon dioxide (CO2) emissions associated with materials and construction processes throughout the life cycle of a building or infrastructure. It includes any carbon dioxide produced during the manufacturing of building materials (material extraction, transportation to the manufacturer, manufacturing), transporting these materials to the work site, and the construction practices used.

Simply put, embodied carbon is the carbon footprint of a building or infrastructure project before it is put into operation[10]. It also refers to maintaining the carbon dioxide produced by the building and eventually dismantling it, transporting the waste and recycling it. Embodied carbon is not the same as operational carbon - carbon from energy, heat, lighting, etc. As progress has been made in reducing operational carbon, recent data from the World Green Building Council shows that embodied carbon is becoming a larger proportion of a building's overall carbon footprint.

In Xu et al.'s study[11] a hybrid price forecasting model was developed to tackle the inherent complexities of stock market predictions. By combining advanced artificial intelligence techniques with traditional time series forecasting, the model effectively captures non-linear dependencies and adapts to the dynamic nature of financial markets. The integration of machine learning algorithms, such as neural networks and ensemble methods, not only improves forecasting accuracy but also enhances robustness in volatile trading conditions. This innovative approach marks a significant advancement, providing a reliable tool for stock price prediction and decision-making in financial analytics.

Building on Xu et al.'s work, our research adopts their hybrid AI-based forecasting framework while incorporating [specific enhancement, e.g., a dynamic optimization algorithm or feature engineering strategy] to further refine model performance. By addressing limitations such as overfitting and computational complexity, our proposed method enhances scalability and precision in handling large-scale financial data. Leveraging Xu's foundation, our approach aims to set a new standard for adaptive forecasting systems in the stock market, ensuring improved predictive power and greater applicability to real-time trading environments.

The World Green Building Council's groundbreaking report, Bringing Embodied Carbon Forward: Coordinated Action for the Building and Construction Sector to address Embodied Carbon, calls for radical cross-sector coordination to revolutionize the building and construction sector towards a net-zero future and address embodied carbon emissions[12-13].

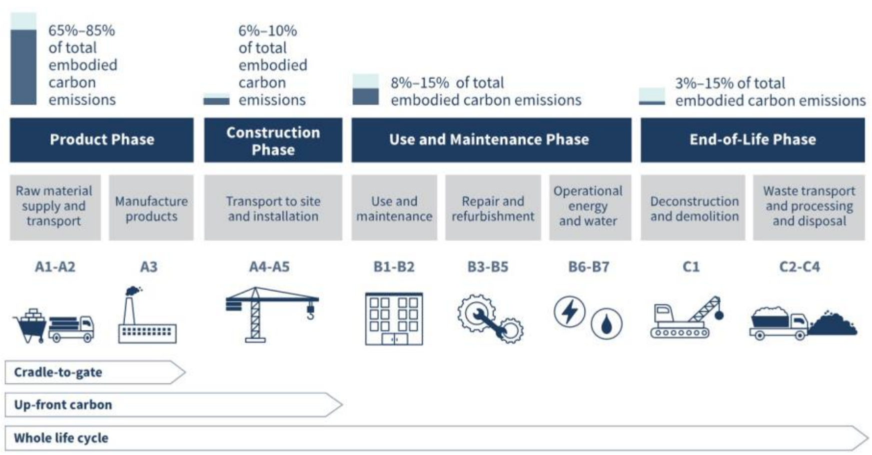

Figure 1: Data from WorldGBC's Call to Action report on carbon embodied in buildings

By advancing the Net Zero project, and in partnership with the European Climate Foundation, the Children's Investment Fund Foundation, C40 Cities and Ramboll, this WorldGBC 'Call to Action' report focuses on these emissions as part of a whole life cycle approach and the systemic changes needed to achieve full decarbonisation of the global building sector[14].

Currently, buildings account for 39% of global energy-related carbon emissions: 28% from operational emissions, from the energy needed to heat, cool and supply electricity, and the remaining 11% from materials and buildings.

Towards the middle of the century, as the world's population approaches 10 billion, the global building stock is expected to double. Between now and 2050, the carbon emissions released before construction assets are used, known as "upfront carbon," will account for half of the entire carbon footprint of new buildings, potentially consuming a significant portion of our remaining carbon budget. The built environment sector therefore has a vital role to play in addressing the climate emergency, and addressing the pre-carbon issue is a key and urgent priority[15].

2.2. The Construction Industry in Commercial Transformation

Energy consumption in the buildings sector accounts for about 40% of total energy consumption in the EU. With greenhouse gas emissions accounting for 35% of the total, it is one of the biggest challenges to meeting climate goals. Therefore, as part of the comprehensive measures and investments of the European Green Deal, the EU has set itself the goal of becoming the first climate-neutral continent by 2050 at the latest[16-18]. In addition to the transformation of the energy sector and the transformation of industrial production, the climate-friendly construction, governance and operation of the construction industry is also one of the key factors.

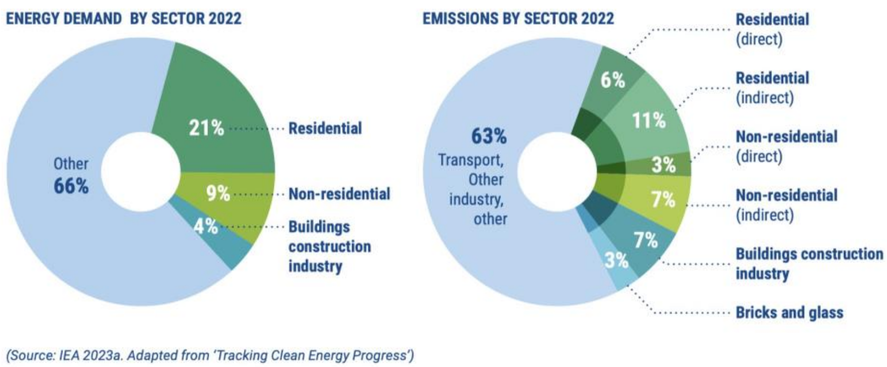

Figure 2: Share of buildings in total final energy consumptions in 2022 (left) and share of buildings in global energy and process emissions in 2022 (right)

In Germany, buildings also account for about 40% of total greenhouse gas emissions (Figure 2). About 33% of this comes from the operation of the building (electricity, heating, cooling), and about 7% comes indirectly from upstream processes[19]. The energy expenditures that occur during the manufacturing and disposal of building materials and the construction, retrofitting and demolition of buildings are also known as grey energy, and the resulting greenhouse gas emissions are grey emissions. Many other emissions from building operations have been decreasing over the past few decades due to higher requirements for energy efficiency and an increasing share of renewables. Even so, there is an urgent need for action, especially in the renovation of existing buildings, as the construction sector is the only one that has failed to meet Germany's 2020 climate targets[20-23].

But to date, there are no legal regulations or restrictions requiring less gray energy. The motivation of owners to adopt energy-saving measures is not only climate protection, but also obvious cost advantages; But so far, the gray energy space has few broad drivers, either legal or economic. Although the requirement for a holistic consideration of the building process is gradually being incorporated into legal frameworks promoting sustainable investment, such as the EU Classification Law; But reducing these "indirect" emissions has so far relied largely on the social responsibility and self-commitment of individual actors in the construction industry. In addition, in new construction, it is also important to identify opportunities to reduce gray emissions early[24-25]. Therefore, it is necessary to raise the awareness of all planners in order to develop comprehensive climate protection guidelines early in the project. Strategies and measures that can help projects develop and harness the emission reduction potential of new buildings are outlined below. Using the EDGE Suedkreuz Berlin project as an example, it shows how direction can be set early and consistently in the planning process to reduce emissions, especially from load-bearing structures.

2.3. Potential Emission Reduction during Construction

Recently, about 60 per cent of the carbon emissions generated over the life cycle of a typical building (more than 50 years of balance sheet preparation) are emissions during operation, and nearly 40 per cent are emissions from construction and upstream processes[26]. On average, almost two-thirds of emissions are caused by the main structure and envelope, which offer the greatest potential for energy savings. The remaining third is mainly caused by building expansions, construction equipment and material transportation (Figure 3).

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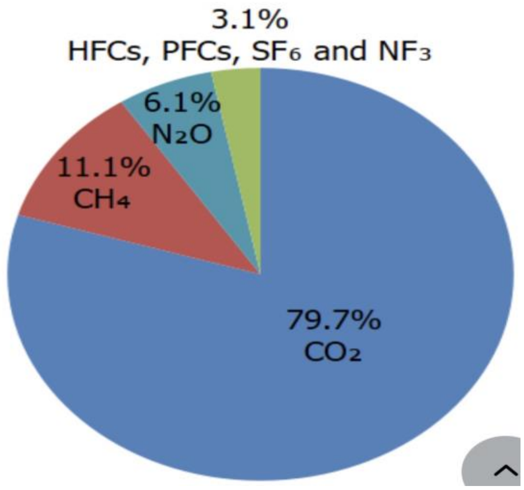

Figure 3: The average proportion of greenhouse gas emissions from each part of the construction process

Therefore, in order to reduce the emission of new buildings, special attention should be paid to structural design during construction. In the design of structural concepts, some choices are made in the early design stage, such as the selection of spans or materials, and adjustments in the later design process usually can only cost a lot of time and money[27]. The early stages of a project are particularly suitable for setting emission reduction guidelines. Starting with the initial phase, and at the latest the preliminary design and the scheme design, the emission reduction plan developed in these phases can make fundamental decisions about emission reduction in the building concept, so that these decisions are carried through all design stages at the lowest possible additional cost[28].

In many cases, developers value corporate sustainability goals, investor constraints, and other conceptual or figurative aspects, as proven and reliable GHG reductions can often be promoted to the public. Since building regulations do not take grey emissions into account, it is necessary for developers to proactively set targets in their projects. Tackling grey emissions is critical and should be complemented by professional advice on climate-friendly construction and life-cycle assessments. If life cycle assessment is integrated at the concept stage, different design and construction options can be compared and adjusted to achieve the best reduction in emissions[29].

III. EMISSION REDUCTION MEASURES IN BUILDING CONSTRUCTION

Depending on the specific building task, there are many different emission reduction measures that can be taken during building construction. In order to accurately quantify emissions and to weigh, check and validate different decisions, life cycle assessments should be introduced. This is an indispensable evaluation tool during the design phase. In addition, the emission reduction requirements, emission reduction targets and related specialties must be discussed early, and if necessary, adjustments must be made in the design process.

Specific procedures are described below under three overarching measures that summarise the main means of reducing emissions in building construction[30-32]: (i) Build less and lighter; (ii) Implementation of circular strategies; (iii) Use of low-carbon materials. It is often rare to use a single measure, but rather to combine different measures and integrate them into one overall concept. Each construction task also requires completely different solutions, so it is necessary to define, develop and implement different measures for each project.

3.1. Build Less and Lighter

Is it possible to renovate existing buildings instead of building new ones? When renovating an existing building, a large percentage of potential carbon emissions can be saved in advance by continuing to use structural components[33]. For example, the reuse of foundations helps to reduce the amount of concrete needed, thus reducing the amount of cement used, which is a major "carbon emitter." Even in purely new construction, it is important to minimize the proportion of materials with a high carbon footprint[33]. In terms of design, this can be achieved, for example, by reducing the self-weight of components, avoiding excessive load redundancy in the design, or by more efficient dimensional design.

3.2. Implement a Loop Strategy

If the End of Life of a building component has been considered in the planning of the building (end of life-EOL scenario), materials that are replaced or removed can be recycled, such as the envelope or an entire part of the building. [34-36]During the planning process, it is important to ensure that the disassembly of components is carried out smoothly and that different materials can be sorted and recycled. Therefore, welding and gluing connections need to be avoided at all times. The service life of individual building materials also needs to be considered. For example, some short-lived materials, even if they initially have the advantage of a low carbon footprint, may have a worse total carbon footprint at the end of the building's life cycle than initially expected due to rapid wear and frequent replacement.

3.3. Use Low Carbon Materials

Whether it is to reduce the total amount of material or to adopt the material recycling concept, the use of materials with low GWP can minimize the proportion of gray emissions in the building. In particular, buildings contain large amounts of concrete or cement, steel and aluminum, which are the biggest "carbon emitters." [37]It is therefore worth looking for alternative solutions in building materials. For example, the use of wood materials from sustainable forestry, due to wood's ability to fix carbon dioxide, can achieve negative carbon emissions in purely wooden buildings. In addition to renewable building materials, recyclable materials also reduce carbon emissions. In the case of steel, for example, steel that uses a lot of recycled materials has a significantly better carbon balance than steel made from only primary raw materials, which is determined by different manufacturing locations and manufacturing processes. [38]At present, the recovery rate of steel can reach almost 100%. At the bidding stage, Party A may also require bidders to provide building materials with the lowest carbon footprint.

IV. THE APPLICATION STATUS OF GENERATIVE AI TO ENHANCE ARCHITECTURAL DESIGN

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V. LOW CARBON MATERIALS IN COMMERCIAL BUILDINGS

The use of low-carbon materials in commercial buildings is increasing worldwide. By choosing low-carbon materials, these buildings reduce embedded carbon emissions and improve the overall environmental sustainability of the building.[45]The following are some examples of commercial buildings with low carbon materials, showing how different technology and material choices can reduce the carbon footprint.

5.1. Bullitt Center, Seattle, USA

Bullitt Center is an extraordinary building that is on its way to becoming the first large commercial office building to receive LBC certification. The six-story, 52,000-square-foot commercial building, owned (and housed) by the Bullitt Foundation, had its grand opening on Earth Day this year (especially fitting because Denis Hayes, the longtime president of the Bullitt Foundation, was the director of the first Earth Day in 1970).

The building was designed by Seattle-based Miller Hull Partnership with other members of the integrated design team, they include Point32, PAE Consulting Engineers, Foushee, Luma Lighting Design, 2020 Engineering and the Berger Partnership[46]. The building houses a number of companies as well as the Bullitt Foundation, an organization that aims to make the metropolitan area and other communities more environmentally friendly. Denis Hayes, president of the foundation, told a meeting of utility commissioners in Seattle last week that he hopes more builders adopt Bullitt's environmentally friendly concept.

"What we're doing with this building is we're trying to prosthetize it all over the country," he said. The Bullitt Center designers took on the Living Architecture Challenge, which requires builders to build structures that have a positive impact on nature while also being self-sufficient and beautiful.

The Building's Features Include:

1. Rainwater Collection

The building has a 56,000-gallon reservoir for storing rainwater collected on the roof. This water is filtered, multi-stage treated and polished to meet 100 percent of a building's water needs, including potable water, three ounces of water used per flush of a foam flush toilet, a bike commuter shower (there are showers on every floor) and landscape irrigation[47]. (The permit issue is still being worked out to allow the building to use only water harvested on site, but hopefully that issue will be resolved.) Interestingly, while Seattle is often cloudy (225 cloudy days per year) and often rains (150 days per year), Hayes told me that the total rainfall is moderate: just 37 inches per year on average, compared to 43 inches in Boston and 49 inches in New York City. The exception to an independent water supply system is a building's sprinkler system, which the city requires to be under municipal water pressure.

2. Compost Toilet

In order to keep the building's water consumption low enough to fully meet the water harvested on site, composting toilets are needed. Four foam flushing toilets on each floor (24 in total) feed waste to ten Phoenix composting units located in the basement. As far as I know, this is the only four-story building that relies entirely on composting toilets.

3. Durability

The building's wooden structure is designed to last 250 years, and the building shell (or skin) is expected to last 50 years before it needs to be replaced - which can happen without affecting the structure.

4. Local Materials

Reflecting the wood resources of the Pacific Northwest and the desire to minimize the energy embodied in the material, all of the building's structural wood is native Douglas fir from forests certified to Forest Stewardship Council (FSC) standards[48]. Glulam beams are produced from two-dimensional wood. Bullet Center, by the way, is the largest heavy wood building built in Seattle since the 1920s.

5. Safety Materials

Huge efforts have been made to avoid the use of hundreds of Red List chemicals. Manufacturers using products must prove that no Red List chemicals have been used through the Future of Living International Institute's Declaration program or by making a health product declaration. This feature of the Living Building Challenge has had a huge impact on the manufacturing of products today, resulting in products that are more environmentally friendly. Some manufacturers have changed their manufacturing to comply with LBC's requirements, so other (non-LBC) projects using these materials will benefit.

6. Occupant Comfort and Daylight

All tenants in the building have access to daylight, either from adjacent exterior walls or through glass interior partitions. Even the stairwell is completely white light, a special request from Hayes, who calls it an "irresistible staircase" that will encourage residents to walk rather than take the elevator. The view of downtown Seattle from the stairwell is worth a walk[49].

7. Cost

Unsurprisingly, the Bullitt Center is not a cheap building. According to the Bullitt Foundation, the value per square foot is $18.5 million, or $355, which is about $50 per square foot higher than the average for high-quality Class A office buildings in the area. But this shows pushing boundaries and proves that the environmental impact of buildings can indeed be greatly reduced[50].

Office space in the building rents for $28- $30 per square foot per year, slightly more than the Seattle average, but tenants get free electricity and water for that price - as long as they stay within their allotted limits. So, the Bullitt Center is truly a landmark green building - I believe one of the most important commercial buildings of the last 50 years.

VI. CONCLUSION

In conclusion, on the relationship between man and nature, Engels has a classic words worth pondering: "We should not be too intoxicated with the victory over nature, for every such victory, nature will take revenge on us." Global warming has reached a consensus in the scientific community and is also considered to be one of the greatest challenges facing human beings in environmental protection. The continuous warming of the global climate has caused many climate disasters and environmental problems, such as the rise of sea level, the reduction of glaciers, and the burning of large areas of tropical rainforests, and a series of extreme weather is increasing. [51-53]From 9 May 1992, the United Nations Framework Convention on Climate Change was adopted in New York; By 2015, the Paris Agreement has set a long-term goal of controlling the average global warming level below 1.5 ~ 2 ° C . In January 2022, the General Secretary specifically proposed in the study of the Political Bureau of the Central Committee that it is necessary to vigorously promote the optimization and upgrading of traditional industries such as building materials, steel, non-ferrous metals and petrochemical, and accelerate low-carbon process innovation and digital transformation in the industrial field [10-15]. Along the way, we can see that China has made solemn commitments to the international community on the issue of global warming. Up to now, the building materials industry is still one of the industrial sectors with the largest energy consumption and CO2 emission in China [16].

In order to further accelerate the carbon emission reduction work in the building materials industry, in January 2021, the China Building Materials Federation issued the Proposal for Promoting Carbon Peak and Carbon Neutrality in the Building Materials Industry, proposing that the building materials industry should fully achieve carbon peak before 2025, and the cement industry should take the lead in achieving carbon peak before 2023 [17-18]. Under the requirements of the double initiative, the carbon emission reduction work of the building materials industry has more highlighted the characteristics of "tight time and heavy task" [19].

At the same time, the building materials industry still has prominent problems such as large resource consumption, high pollution emissions, and extensive construction methods, which still have a certain gap with the requirements of the new development concept of "innovation, coordination, green, open and sharing" [20-21]. Therefore, considering a scientific and reasonable carbon emission reduction path is not only the urgent task for the building materials industry to achieve the "double carbon" commitment, but also the urgent need for the industry itself to move towards high-quality development, and the inevitable choice to achieve low-carbon transformation and sustainable development of the building materials industry.

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