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# Analysis of Carbon Emission Reduction Potential of Different Star Green Science and Technology Museums in Cold Regions of China

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**Abstract:** Low-carbon development in the field of buildings is an important means to achieve the goal of "carbon peaking and carbon neutrality". In public buildings, the operation of science and technology museum buildings (TMB) has high carbon emissions, and the application of green building technology for energy saving and carbon reduction has great potential. In this paper, typical TMB in cold areas are selected and built, and energy consumption is simulated by Designbuilder. The calculation boundaries and carbon emission factors of carbon emissions are set according to current standards, and the carbon reduction potential of green science and technology museum buildings (GTMB) under different levels is compared. The results show that compared with the benchmark building based on GB 55015-2021, the carbon emission of the GTMB is significantly reduced, and the carbon emission reduction rates of silver, gold, and platinum TMB are 7.9%, 13.4%, and 29.6%, respectively. Based on the existing optimization design of passive measures such as natural ventilation and natural lighting, the GTMB should pay more attention to the realization of its optimal control strategy and automatic control.

**Keywords:** green science and technology museum; green building; carbon emission

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## 1. Introduction

Global warming has had an extensive and far-reaching impact on the earth's ecosystem, environment, and human society, and is closely related to all fields of social and economic development. In social energy consumption, building energy consumption accounts for more than 40%, even higher in some areas, and the energy consumption of Chinese buildings is still increasing year by year [1]. In 2020, the carbon emissions of the building operation phase accounted for 21.7% of the national total carbon emissions [2]. After the "carbon peaking and carbon neutrality" policy was put forward, China's construction industry faced a series of influences and changes, such as energy structure adjustment, emission reduction technology innovation, policy support, and supervision strengthening. To improve the level of building energy conservation and carbon reduction, China has issued a full-text mandatory standard GB 55015-2021 [3], raising the average energy saving rate of public buildings to 72%. In the same year, T/CECS 851-2021 [4] was issued to improve the green performance of all aspects of the Science and Technology Museum building based on the existing energy-saving design standards and further strengthened the energy-saving and carbon reduction requirements of the Green Science and Technology Museum. Science and technology museums as an important part of public buildings, its carbon emission control has also become an important demand to achieve "carbon peaking and carbon neutrality" in the field of urban and rural construction.

Promoting the development of the Green Science and Technology Museum has become the main way of energy saving and carbon reduction of the Science and Technology

Museum. The existing research mainly focuses on the technology application and innovation of the GTMB [5–8] and innovation [9,10] or on the carbon emission assessment and impact of conventional green public buildings [11,12]. In addition, a substantial body of research has explored environmental policies and practices in museums. Fenn's [13] study highlights the importance of reducing carbon emissions and enhancing sustainability through government support. Jiang [9] proposed energy-efficient and eco-friendly museum designs, addressing urban planning, functional organization, and building materials. Qian also introduced methods to calculate energy consumption and carbon emissions. Cadelano [14] found that a high-temperature ground source heat pump system with advanced energy management can reduce energy costs by up to 66% in historic museums, while preserving collections and ensuring comfort. Sharanya B. K. et al. [10] examined green building practices, suggesting these can cut energy use by 40–50% and water use by 20–30%. Ge et al.'s [15] life cycle analysis of Hangzhou museums indicated that usage phase energy consumption and carbon emissions are dominant. Proposed measures, such as solid walls and shading, could reduce emissions by up to 30.58%. Vourdoubas's [16] study on the Museum of Eleutherna showed that renewable energy technologies can achieve net zero carbon emissions, reducing annual $CO_2$ emissions by 162 tons at a cost of 290.58 €/$m^2$. The above research mainly focuses on conventional museum buildings; there is little quantitative analysis on the carbon reduction effect of green science and technology museums. In the research on the carbon emission and carbon reduction effect of the application of green building technology in conventional public buildings, Wang Qingqin et al. [17] analyzed the carbon emission reduction of green buildings based on typical projects and found that compared with ordinary energy-saving office buildings, the lifetime carbon emission reduction of one-star, two-star and three-star green office buildings in each climate zone is from 10% to 12%, from 23% to 29% and from 34% to 50%, respectively. Pan Yiqun et al. [18] simulations of typical green office buildings and hotel buildings show that the carbon emission reduction rates of the two are 19% and 25%, respectively. It can be found that the quantitative research on the carbon reduction effect under the subdivision type of green buildings has gradually become a major demand for the low-carbon development of green buildings.

Given the ambiguity in the carbon emission reduction rate resulting from the adoption of current standards in green science and technology museums, this paper aims to analyze the low-carbon performance of such museums under different green rating levels, thereby providing fundamental data support for the formulation of standards and large-scale development of green science and technology museums in China. To this end, a typical science and technology museum in cold regions is selected for construction. Based on GB 55015-2021, and incorporating the latest requirements of T/CECS 851- and GB/T 50378-2019 [19] three technical application scenarios for green science and technology museums are established: Silver, Gold, and Platinum levels. These scenarios are then utilized to evaluate the carbon reduction potential of green science and technology museums with different star ratings. This study will address the gaps in research on the carbon reduction potential of green science and technology museums, providing quantitative data support for the selection of low-carbon technologies and the development of relevant standards. Furthermore, it will serve as a basis for the formulation of policies related to the green and low-carbon development of science and technology museums.

## 2. Evaluation Methods and Data of Carbon Emission Reduction Potential

### *2.1. Carbon Emission Calculation Method*

Existing research indicates that carbon emissions during the operational phase of a building account for 70% of its total lifecycle carbon emissions, making it a critical link in carbon emission control. For completed GTMB, their architectural structural forms and other aspects are already fixed. Evaluating the carbon reduction effects of various measures during their operational phase can provide a targeted reference for formulating plans to enhance its green and low-carbon performance. Therefore, the operational phase is chosen

in this research. GB/T 51366-2019 [20] puts forward a standard method for calculating building carbon emissions. For the operation phase, the total carbon emission per unit building area ($C_M$) is calculated according to the following formula:

$$C_M = \frac{[\sum_{i=1}^{n} (E_i EF_i) - C_P]y}{A} \quad (1)$$

$$E_i = \sum_{i=1}^{n} (E_{i,j} - ER_{i,j}) \quad (2)$$

where $C_M$ is the carbon emission per unit building area ($kgCO_2/m^2$) during the operation of the building, and $E_i$ is the annual energy consumption of the building type $i$ (unit/a). $EF_i$ is the carbon emission factor of type I energy, in which electric energy and thermal energy are according to the electric power and thermal carbon emission factors in the Beijing area, referring to the Beijing local standard DB11/T 1784-2020 [21]. The electric power carbon emission factor is 0.604 $CO_2$/kWh; and the thermal carbon emission factor is 0.11 $tCO_2$/GJ; $E_{i,j}$ is the annual energy consumption of category $i$ of class j system (unit/a); $ER_{i,j}$ consumes class $i$ energy provided by renewable energy systems for class $j$ systems (unit/a), which is obtained by energy consumption simulation; $i$ is the terminal energy type of building consumption; $j$ is the type of building energy system; $C_P$ is the annual carbon reduction of carbon sequestration in building green space ($kgCO_2/a$); $y$ is the design life of the building (a), and when calculating the annual carbon emissions, $y$ is 1; $A$ is the building area ($m^2$).

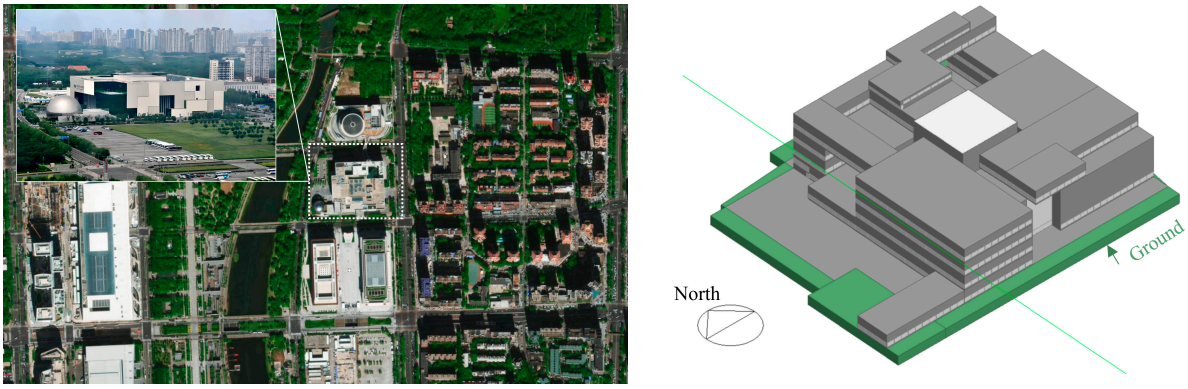
To explore the carbon reduction potential of different star green science and technology museums, the carbon reduction rate is used to express the carbon reduction effect of different green star requirements on the science and technology museum. The calculation formula for the carbon reduction rate is expressed as:

$$R_{ERj} = \left(1 - \frac{C_j}{C_1}\right) \times 100\% \quad (3)$$

In the formula, $R_{ERj}$ is the carbon reduction rate of class j green science and technology museum, which includes silver, gold, and platinum green science and technology museum technology application scenarios; $C_j$ is the carbon emission intensity of class j green science and technology museum, kg/($m^2$·a); $C_i$ is the benchmark building carbon emission intensity based on the requirements set by GB 55015-2021, kg/($m^2$ a).

### *2.2. Calculation of Building Energy Consumption Intensity of Science and Technology Museum*

A typical science museum architectural model, as depicted in Figure 1a, was selected for this study. Constructed in 2009, this building encompasses five thematic exhibition areas, a public space, and four special effects cinemas. Additionally, it boasts numerous laboratories, classrooms, science popularization lecture halls, multi-functional halls, and temporary exhibition halls, making it a comprehensive public building. The structure spans five floors above ground and one basement floor, with a total gross floor area of approximately 102,000 square meters and a shape factor of approximately 0.12. Utilizing DesignBuilder (v7.0.1), a physical model of the science museum was established, and subsequent simplifications were made to the model based on the architectural form's distinctive characteristics, as illustrated in Figure 1b.




(**a**) (**b**)

**Figure 1.** Simplified model of science and technology museum: (**a**) Building location and real-life image; (**b**) Model diagram in Design Builder.

Due to the different operation schedules of the personnel, lighting, and internal equipment of the Science and Technology Museum, will have a great impact on the building's energy consumption. Therefore, the simulation schedule of the Science and Technology Museum is set up concerning the JGJ/T 449-2018 [22], as shown in Figure 2. And GB/T51161-2016 [23] to revise the energy consumption index.

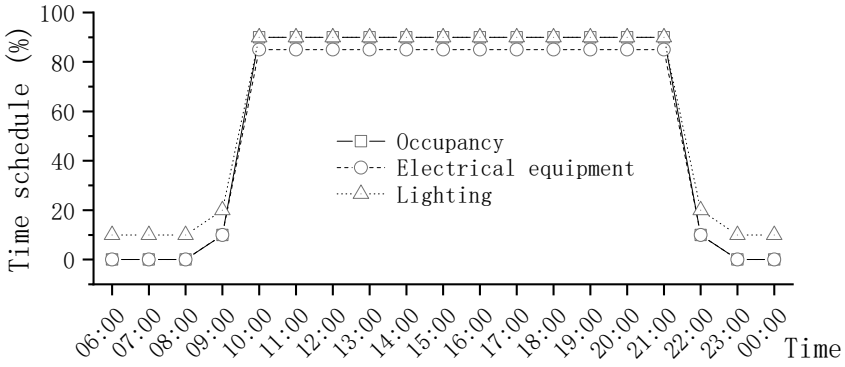



**Figure 2.** Operation schedule of Science and Technology Museum.

## 3. Green Building Technology Scenario Setting

According to the different requirements of architecture and humanities, energy and resources, environment and health, exhibition, and education, wisdom and service, innovation and development, T/CECS 851-2021 divides the Green Science and Technology Museum into silver, gold and platinum levels. The science and technology museums of different levels are divided based on the total score, and there are no fixed technical measures, but at present, most of the science and technology museum projects of the same level will be combined with cost considerations, and the choices of all kinds of technical solutions are relatively consistent. Therefore, based on the actual project investigation, the technologies commonly employed in silver, gold, and platinum science and technology museum projects can be selected as the corresponding technical solutions for green buildings of this level, with the technical level in each scenario being determined, and subsequently compared against the benchmark level situation, in order to evaluate the energy-saving and emission-reduction potential of green science and technology museums at varying levels.

### *3.1. Benchmark Building*

At present, as a full-text mandatory standard, GB 55015-2021 has been comprehensively promoted in China's building energy-saving and low-carbon design, and the TMB is

no exception. For the reference building, the model parameters such as the heat transfer coefficient of the enclosure, equipment parameters of the HVAC system, power density of lighting equipment, and power density of equipment are set according to the limit of GB 55015-2021, as shown in Table 1.

**Table 1.** Benchmark scenario parameters.

| Science and Technology Museum | Set Value |
|---|---|
| Roof heat transfer coefficient | 0.4 W/(m$^2$·K) |
| Heat transfer coefficient of exterior wall | 0.5 W/(m$^2$·K) |
| Non-heating and heating room partition | 1.2 W/(m$^2$·K) |
| Window heat transfer coefficient | 2.5 W/(m$^2$·K) |
| Solar heat gain coefficient | 0.4 |
| Cooling system form | Chillers + Fan coils + Independent fresh air |
| Heating system form | District central heating |
| Water chillers COP (nominal operating conditions) | 6.0 |
| Winter design temperature | 18 |
| Summer design temperature | 26 |
| Fan efficiency | 60% |
| Use time | From 10:00 to 22:00 |
| Personnel density | 4 m$^2$/person |
| Occupancy rate | Working hours 0.9, 0.1 per hour before and after working hours |
| Per capita fresh air volume | 20 m$^3$/(h·person) |
| Equipment power density | 10 W/m$^2$ |
| Lighting power density (exhibition hall) | 8 W/m$^2$ |

### *3.2. Performance Improvement of the Enclosure Structure*

GB/T 50378-2019 is currently under partial revision. In the partial revision request draft issued in 2023, the thermal performance of green building one-star, two-star, and three-star enclosure structures are required to be 0,5% and 10% lower than that of GB 55015-2021, respectively. Among them, for the heat transfer coefficient of outer windows, one-star green buildings should be reduced by 5%, and two-star and three-star green buildings should be reduced by 10%. The silver, gold, and platinum levels of the Green Science and Technology Museum correspond to one-star, two-star, and three-star green buildings respectively. Therefore, based on the GB 55015-2021 limit, the thermal performance of the exterior wall and roof of the Silver Science and Technology Museum remains unchanged, and the heat transfer coefficient of the exterior window is reduced by 5%; the heat transfer coefficient of the exterior wall and roof of the gold science and technology museum is reduced by 5%, and the heat transfer coefficient of the exterior window of the platinum science and technology museum is reduced by 10%.

### *3.3. Performance Improvement of the HVAC System*

HVAC energy consumption usually accounts for 25% to 40% of the total energy consumption of buildings. To reduce the energy consumption of HVAC systems, Article 7.2.5 of GB/T 50378-2019 stipulates that the coefficient of performance (COP) of variable frequency water cooling units is 6% or 12% higher than that of GB 55015-2021. Article 5.2.5 of T/CECS 851-2021 stipulates that the power consumption per unit air volume of the fan and the cooling (heat) consumption of the water pump are 20% lower than that of the

current national standard. According to the above analysis, the water cooling unit COP of the Gold and Platinum Science and Technology Museum is 6% and 12% higher than that of GB 55015-2021 respectively; the efficiency of the fan and water pump of the Platinum Science and Technology Museum is 20% higher, and the ground source heat pump system is used to replace the conventional municipal heat supply.

### 3.4. Natural Lighting and Improvement of Lighting Performance

The enhanced utilization of natural lighting is an important factor to be considered in the passive design of green buildings. Article 6.2.8 of T/CECS 851-2021 requires that the exhibition hall get 2 points for using natural lighting; the lighting illuminance value of 80% of the area of the main functional room can meet the requirements of not less than 4 h/d, and 60% of the inner area can meet the lighting requirements. In terms of lighting energy saving, Article 5.2.6 of T/CECS 851-2021 stipulates that the lighting power density of the main functional rooms can reach the requirements of the current national standard GB 450034 [24] can get 2 points; the lighting of public and office space lighting areas can be automatically adjusted with natural light can get 1 point; at the same time, the installation of intelligent lighting control system can get 4 points in Article 8.2.2.

Accordingly, silver, gold, and platinum science and technology museums are equipped with natural lighting, and platinum science and technology museums use light conduit technology to enhance natural lighting on the top floor and sub-top floor of the science and technology museum. The lighting power densities all meet the target requirements of GB/T 50034-2024. Among them, the gold and platinum science and technology museums adopt lighting automatic control regulation measures, and the adjustment mode is as follows: when the indoor illumination reaches the required illuminance (300 lx), with the increase of daylight, the lamps and lanterns change linearly from the maximum electric power and maximum light output to the minimum electric power and minimum light output. With the further increase of sunlight illuminance, the power remains at the lowest point.

### 3.5. Improvement of Natural Ventilation Performance

By optimizing the spatial layout of buildings and adopting modes such as mixed ventilation, natural ventilation can be effectively used to reduce building energy consumption. Article 6.2.8 of T/CECS 851-2021 stipulates that the exhibition hall gets 2 points when natural lighting is used. Article 6.2.9 stipulates that when the science and technology museum adopts natural or compound ventilation, the time proportion of indoor thermal environment parameters in the main function room in the adaptive thermal comfort zone is controlled, and the full score is higher than 50%. Therefore, for silver and gold science and technology museums, natural ventilation ($2\ h^{-1}$) is added based on the benchmark scenario, while platinum science and technology museums adopt mixed ventilation mode, which automatically turns on natural ventilation and turns off mechanical ventilation when the outdoor temperature is lower than 24 °C in summer and higher than 18 °C in winter.

### 3.6. Sunshade Performance Improvement

Outer louver shading can reduce the solar heat gain of outer doors and windows, thus reducing the cooling energy consumption of buildings. At the same time, the integrated control of the shading system and lighting system can significantly improve the comfort of the indoor light environment [9]. Article 6.2.10 of T/CECS 851-2021 stipulates that the Science and Technology Museum shall set up adjustable sunshade facilities to improve indoor thermal comfort, and score according to the proportion of the building's adjustable sunshade facility area to the transparent area of the outer window, with a full score of 55%. According to the rating of the proportion of adjustable sunshade facilities, the proportion of silver, gold, and platinum science and technology museums with adjustable sunshade facilities to the transparent part of the outer window is set to 25%, 35%, and 55% respectively; the adjustable sunshade facilities of platinum science and technology

museums are set to automatically adjust, and turn on automatically when the solar radiation intensity exceeds 120 W/m$^2$.

### *3.7. Utilization of Renewable Energy*

Article 5.2.7 of T/CECS 851-2021 stipulates the types and proportions of renewable energy systems used in buildings and the corresponding scoring requirements. Domestic hot water, HVAC, and other building electrical equipment can use renewable energy, including photovoltaic, photovoltaic, and all kinds of heat pump systems. According to the scoring requirements and the actual situation of the project, for silver and gold TMB, the proportion of domestic water provided by the photothermal system is 50%; the proportion of platinum science and technology museum is 80%. At the same time, the platinum-grade science and technology museum is set up to provide 4% of the electricity consumption of the building by the photovoltaic system.

Based on the explanations in Sections 3.2–3.7, the application of low-carbon measures becomes increasingly comprehensive as the green certification level advances from silver to gold and then to platinum. The parameter settings for different levels of green science and technology museums are summarized in Table 2.

**Table 2.** Parameter settings for different levels of green science and technology museums.

| Item | Control Parameters | | Silver | Gold | Platinum |
|---|---|---|---|---|---|
| Performance improvement of the enclosure structure | heat-transfer coefficient | wall | / | Reduce by 5% | Reduce by 10% |
| | | roof | / | Reduce by 5% | Reduce by 10% |
| | | window | Reduce by 5% | Reduce by 10% | Reduce by 10% |
| Performance improvement of the HVAC system | COP of chiller unit | | / | Increase by 6% | Increase by 12% |
| | Fan and water pump | | / | / | Increase by 20% |
| | Form of heat source | | district heating | district heating | ground source heat pump |
| Natural lighting | Forms of daylighting | | window daylighting | window daylighting | Window daylighting, along with light tubes on the top and penultimate floors. |
| improvement of lighting performance | automatically adjustable or not | | No | Yes | Yes |
| Improvement of natural ventilation performance | natural ventilation or not | | Yes (natural ventilation by window) | | Yes (Mixd ventilation) |
| Sunshade performance improvement | Adjustable sun shading ratio | | 25% | 35% | 55% (automated control) |
| Utilization of renewable energy | Proportion of domestic water provided by PT | | 50% | 50% | 80% |
| | Proportion of PV power generation to building electricity consumption | | 0 | 0 | 4% |

Note: "/" indicates consistency with the benchmark building.

## 4. Calculation Results and Analysis of Emission Reduction Potential

Based on the low-carbon performance description of silver, gold, and platinum TMB, the building energy consumption is simulated. The energy consumption index is revised according to GB/T 51161-2016. The calculation results of building energy consumption and carbon emission intensity in each scenario are shown in Table 3. Compared with the benchmark buildings, the energy consumption intensity of silver, gold, and platinum science and technology museums decreased by 5.4%, 12.6%, and 27.7%, respectively, and carbon emissions decreased by 7.9%, 13.4%, and 29.6%, respectively. These data exhibit approximately consistent patterns when compared with previous studies on other types of

public buildings [17,18]. Compared with the reduction ratio of energy consumption, the decline in carbon emissions is more significant, mainly due to the inconsistent reduction of building power consumption and heat consumption under the application of various green building technologies and affected by the reduction of water consumption and other factors.

**Table 3.** Simulation results of building energy consumption and carbon emissions.

| Type | Benchmark Scenario | Silver Scenario | Gold Scenario | Platinum Scenario |
|---|---|---|---|---|
| Energy intensity ($kWh/m^2 \cdot a$) | 157.6 | 149.1 | 137.8 | 113.9 |
| Water consumption (t/year) | 18,925 | 16,540 | 15,140 | 11,355 |
| Carbon emission intensity ($kgCO_2/m^2 \cdot a$) | 87.4 | 80.5 | 75.7 | 61.5 |

A sensitivity analysis of various measures was conducted based on the benchmark TMB, as shown in Figure 3a. The enhancement of the overall heat transfer coefficient (simultaneous proportional improvement of walls, roof, and windows) resulted in significant carbon reduction benefits. Notably, when the overall heat transfer coefficient was improved by 15%, the building's carbon reduction rate reached 11%. Figure 3b illustrates the carbon reduction achieved by enhancing the HVAC system in the reference building. When the COP of the unit increased by 18% and fan efficiency improved by 30%, carbon emissions were reduced by 5.3%. Figure 3c depicts the impact of natural lighting and adjustable shading on carbon emissions. In this analysis, natural lighting was assumed as the default, and the effect of adjustable shading was subsequently evaluated. It was observed that when 55% more adjustable shading measures were implemented in addition to natural lighting, the building's carbon reduction rate reached 7.5%. Additionally, converting from natural ventilation to a hybrid ventilation mode (Figure 3d), or significantly increasing the use of renewable energy sources (Figure 3e), both positively impacted the building's carbon reduction efforts.

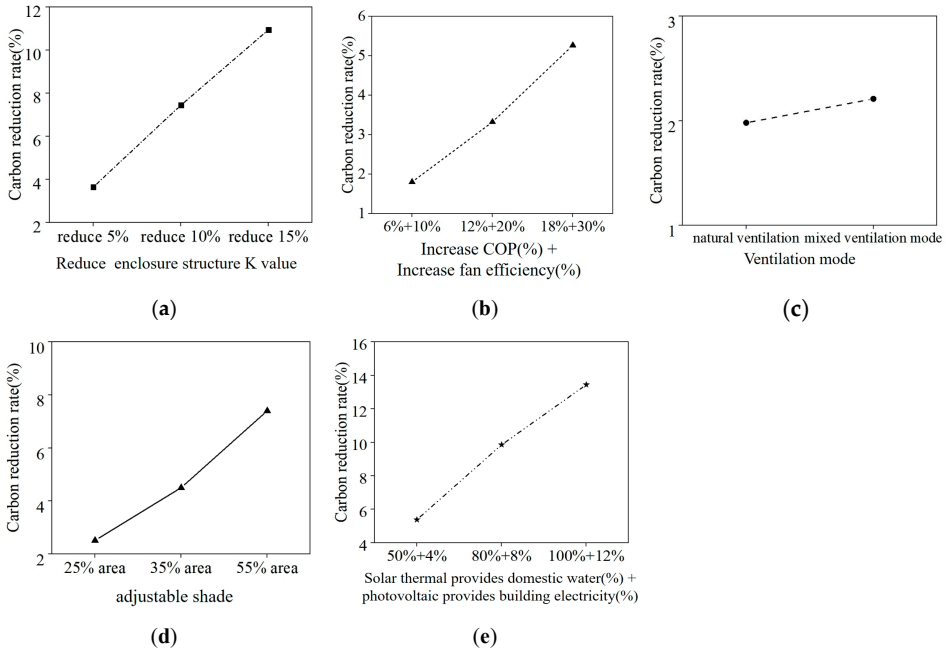



**Figure 3.** Carbon reduction rate of different measures for benchmark TMB: (**a**) Enclosure structure performance improvement; (**b**) HVAC system performance improvement; (**c**) Natural lighting and lighting performance improvement; (**d**) Natural ventilation performance improvement; (**e**) Use renewable energy.

Further, analyzes the impact of various green and low-carbon measures and their superposition on the carbon emissions of the Science and Technology Museum. Considering that the carbon emission reduction brought about by the simple action of each measure on the Science and Technology Museum can be added directly, the comprehensive carbon emission reduction brought about by the simultaneous implementation of various measures may not be the same, so the gradual superposition of various measures is adopted for analysis, as shown in Figure 4. The improvement of the performance of the enclosure structure of the Silver Science and Technology Museum has reduced the carbon emissions of the building operation by 2.7%. In the gold and platinum science and technology museums, due to the substantial improvement in the heat transfer performance of walls, roofs, and outer windows, their carbon emissions have been significantly reduced by 3.9% and 7.3% respectively.

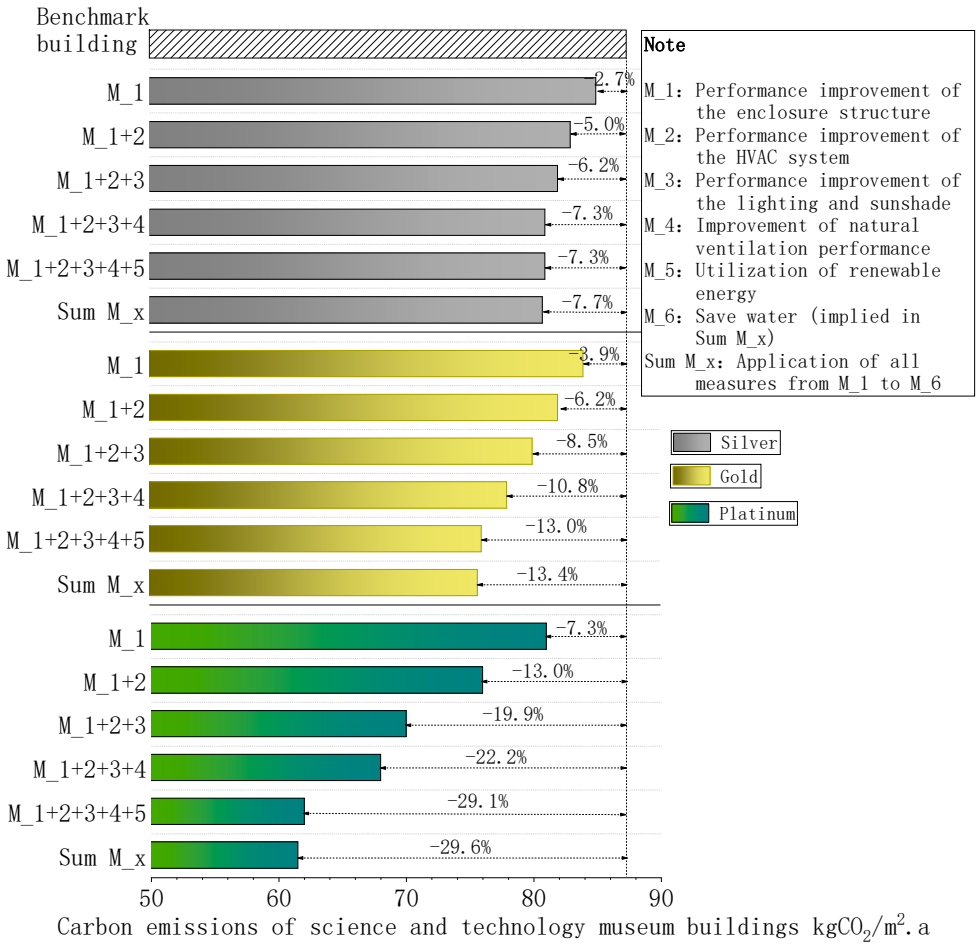



**Figure 4.** Carbon reduction effect of different Green and low carbon measures on Science and Technology Museum.

Although improving the thermal performance of the enclosure structure has a significant carbon reduction effect on the building, blindly reducing the heat transfer coefficient has a limited effect on energy saving and carbon reduction of the building. The heat load composition of the benchmark TMB is shown in Figure 5, and the heat load caused by fresh air ventilation is as high as 70%. To further reduce the carbon emissions of the GTMB, the performance level of the enclosure structure should be appropriately improved simultaneously, with the adoption of fresh air heat recovery and other technologies to reduce fresh air energy consumption.




**Figure 5.** Proportion of heat load of benchmark TMB in winter.

For gold and platinum GTMB, the improvement of the performance of enclosures and HVAC systems has reduced the refrigeration and heating carbon emissions of the science and technology museum by about 6.2% to 13%. The gradual enhancement and superposition of various measures have effectively promoted the reduction of overall carbon emissions. Energy-saving measures such as natural lighting, lighting, and natural ventilation are at a high level in benchmark buildings, so the carbon reduction effect of silver and gold science and technology museums on this measure is relatively limited. Platinum Science and Technology Museum has also achieved a carbon reduction rate of about 9.2% due to the use of more intelligent dimming control measures, a mixed ventilation system, and a larger adjustable sunshade area. Therefore, based on the existing design basis, the development of a more low-carbon control strategy and intelligent control mode is the key to carbon reduction in the operation of the Green Science and Technology Museum.

In terms of economic efficiency, the annual energy savings of silver, gold, and platinum-level science museums compared to standard buildings are 8.5 kWh/$m^2$, 19.8 kWh/$m^2$, and 43.7 kWh/$m^2$, respectively. The corresponding annual water savings are 0.02 t/$m^2$, 0.04 t/$m^2$, and 0.08 t/$m^2$. Based on an average commercial electricity price of CNY 0.5/kWh and an average water price of CNY 6/t, the annual operating cost savings for silver, gold, and platinum-level science museums amount to CNY 4.3/$m^2$, CNY 10.3/$m^2$, and CNY 23.5/$m^2$, respectively. According to the "Economic Indicators for Green Buildings (Draft for Public Comment)" published by the Ministry of Housing and Urban-Rural Development, the incremental costs for one, two, and three-star green public buildings are approximately CNY 20/$m^2$, CNY 60/$m^2$, and CNY 150/$m^2$, corresponding to the incremental costs of silver, gold, and platinum-level science museum buildings. Therefore, it can be concluded that the payback periods for the investments in silver, gold, and platinum-level science museums, through energy savings and carbon reduction during the operational phase, are approximately 4.6 years, 5.8 years, and 6.4 years, respectively.

## 5. Conclusions

Based on the carbon emission calculation method of the building operation phase in GB/T 51366-2019, this paper establishes a benchmark building model of a typical science and technology museum based on GB 55015-2021 and sets up the technology application situation of green science and technology museum such as silver, gold and platinum according to the requirements of T/CECS 851-2021 and GB/T 50378-2019 (Bureau revised draft). The carbon reduction potential of different star green science and technology museums in the operation stage is evaluated, and the following conclusions were drawn:

The application of the low-carbon technology system in green science and technology museums can effectively reduce carbon emissions. For typical TMB in cold regions, compared to the benchmark buildings, the energy consumption intensity of silver, gold, and platinum levels decreases by 5.4%, 12.6%, and 27.7%, respectively, with carbon reduction rates of 7.9%, 13.4%, and 29.6%. Platinum-level science and technology museums have significantly more stringent and effective requirements for energy savings and carbon reduction compared to silver and gold levels.

Under the high requirements of GB 55015-2021 for passive measures such as natural ventilation, daylighting, and shading design, GTMB should focus more on the optimization control strategies of various measures, such as intelligent mixed ventilation modes, automated dimming controls, and automated shading controls, to achieve more timely and effective energy-saving regulation. This part has a carbon reduction potential of approximately 9.2% compared to the benchmark buildings.

Enhancing the performance of the building envelope in silver-level science and technology museums reduces operational carbon emissions by 2.7%. In gold and platinum-level science and technology museums, due to significant enhancements in the thermal performance of walls, roofs, and external windows, carbon emissions are notably reduced by 3.9% and 7.3%, respectively. It is evident that comprehensive improvements to the building envelope are far more effective than partial improvements.

Green science and technology museums have high requirements for the performance of the building envelope but lack constraints on fresh air heat recovery. As places where large numbers of people gather, science and technology museums require a substantial amount of fresh air, with the thermal load from fresh air reaching up to 70%, far exceeding the thermal load of the building envelope. Therefore, in enhancing the performance of green science and technology museums, efforts should be focused on reducing the energy consumption of fresh air through measures such as fresh air heat recovery, rather than merely imposing requirements on the thermal transmittance of the building envelope.

The conclusions of this study are primarily derived from simulation analyses of typical cases. In the future, further research could be conducted based on actual operational data from more green science and technology museums to explore the correlation between simulation results and real-world performance. Additionally, the scope of research should be expanded to include various climate zones across the country, providing the government with more comprehensive data when formulating and evaluating standards for green science and technology museums and developing carbon peak policies.

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**Data Availability Statement:** Data is contained within the article.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Nomenclature

| | |
|---|---|
| TMB | Science and Technology Museum Building. |
| GTMB | Green Science and Technology Museum Building. |
| $C_M$ | The carbon emission per unit building area during the operation. |
| $E_i$ | The annual energy consumption of the building type *i*. |
| $EF_i$ | The carbon emission factor of type *i* energy. |
| $E_{i,j}$ | The annual energy consumption of category *i* of class *j* system. |
| $ER_{i,j}$ | Consumption of class *i* energy, which is provided by renewable energy systems, and used for class *j* systems. |
| $C_P$ | Annual carbon reduction of carbon sequestration in building green space. |
| y | The design life of the building. |
| $A$ | The building area. |

## References

1. Pei, K.Y.; Sun, Z.Z.; Huang, L.K. Global warming and carbon dioxide mitigation. *Energy Conserv. Technol.* **2005**, *23*, 239–243.
2. *2022 Research Report of China Building Energy Consumption and Carbon Emissions*; Professional Committee of Building Energy and Emissions: Chongqing, China, 2022.
3. *GB 55015-2021*; General Code for Energy Efficiency and Renewable Energy Application in Buildings. Ministry of Housing and Urban-Rural Development of the People's Republic of China: Beijing, China, 2021.
4. *T/CECS 851-2021*; Assessment Standard for Green Science and Technology Museum. China Association for Engineering Construction Standardization: Beijing, China, 2021.
5. Dang, X.H.; Jin, D.R. Design of Gansu Science and Technology Museum based on green evaluation standard. In Proceedings of the 2018 Annual Meeting of the Civil Architecture Society of Gansu Province, Lanzhou, China, 15–16 November 2018; pp. 43–50.

6. Li, C. Design of electrical system for a science and technology museum. *Mod. Archit. Electr.* **2023**, *14*, 53–56.
7. Wang, W.F.; Lyu, L.N.; Li, X.P.; Zhou, L.N.; Li, Y.T.; Tian, L. Energy saving benefit analysis of a large museum in north China. *Build. Energy Effic.* **2022**, *48*, 26–31.
8. Wang, F. The application of green energy-saving technology in building design—Take Zhejiang Water Control Museum architectural design as an example. *IOP Conf. Ser. Earth Environ. Sci. IOP Publ.* **2021**, *787*, 012075. [CrossRef]
9. Jiang, Q. Research on energy saving and emission reduction of ecological environment of modern green art museum. *IOP Conf. Ser. Earth Environ. Sci. IOP Publ.* **2021**, *629*, 032029.
10. Ghosh, S.; Bhandari, S.S.; Poudel, S.; Padikkal, G.M.; Kumar, M.C. Green and sustainable building practices for museums. *AIP Conf. Proc. AIP Publ.* **2018**, *2039*, 020010.
11. Guo, Z.W.; Wang, X.Y.; Luo, X.Y.; Zhao, N.; Wang, Q.Q. Study on the influencing factors of carbon emissions of green public buildings in the whole life cycle: A case study in hot summer and cold winter region. *Build. Sci.* **2024**, *40*, 12–18.
12. Zhang, J.W.; Yin, J.; Li, X.X.; Wang, Y.N. Life cycle carbon emission assessment and simulation of green buildings based on AnyLogic. *Green Build.* **2023**, 87–92.
13. Fenn, J. A Study to Reduce the Carbon Footprint of Museums and Galleries through Environmentally Sustainable Practices and Procedures. Master's Thesis, Carleton University, Ottawa, ON, Canada, 2012.
14. Cadelano, G.; Cicolin, F.; Emmi, G.; Mezzasalma, G.; Poletto, D.; Galgaro, A.; Bernardi, A. Improving the energy efficiency, limiting costs and reducing $CO_2$ emissions of a museum using geothermal energy and energy management policies. *Energies* **2019**, *12*, 3192. [CrossRef]
15. Ge, J.; Luo, X.; Hu, J.; Chen, S. Life cycle energy analysis of museum buildings: A case study of museums in Hangzhou. *Energy Build.* **2015**, *109*, 127–134. [CrossRef]
16. Vourdoubas, J. Possibilities of Creating Net Zero Carbon Emissions Cultural Buildings: A Case Study of the Museum at Eleutherna, Crete, Greece. *Am. Sci. Res. J. Eng. Technol. Sci. (ASRJETS)* **2019**, *56*, 207–217.
17. Wang, Q.Q.; Meng, C.; Zhu, R.X.; Li, J.Y. Research on carbon emission of green building based on life cycle theory. *Contemp. Archit.* **2022**, 14–16. [CrossRef]
18. Pan, Y.Q.; Wei, J.J.; Liang, Y.M.; Li, H.J.; Liang, H. Assessing carbon emission reduction potential of green building energy saving technologies in operation of typical public buildings. *Heat. Vent. Air Cond.* **2022**, *52*, 83–89.
19. *GB/T 50378-2019*; Assessment Standard for Green Building. Ministry of Housing and Urban-Rural Development of the People's Republic of China: Beijing, China, 2019.
20. *GB/T 51366-2019*; Standard for Building Carbon Emission Calculation. Ministry of Housing and Urban-Rural Development of PRC: Beijing, China, 2019.
21. *DB11/T 1784-2020*; Requirements for Carbon Dioxide Emission Accounting and Reporting Heat Production and Supply Enterprises. Beijing Municipal Administration for Market Regulation: Beijing, China, 2020.
22. *JGJ/T 449-2018*; Green Performance Calculation Standard for Civil Buildings. Ministry of Housing and Urban-Rural Development of the People's Republic of China: Beijing, China, 2019.
23. *GB/T51161-2016*; Civil Building Energy Consumption Standard. Ministry of Housing and Urban-Rural Development of the People's Republic of China: Beijing, China, 2016.
24. *GB/T 50034-2024*; Standard for Lighting Design of Buildings. Ministry of Housing and Urban-Rural Development of the People's Republic of China: Beijing, China, 2024.


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